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16. Abstract

Turbo Roundabouts – an emergent and "new" concept in the design of roundabouts – has the potential to address the limitations experienced with the adoption of multi-lane (2x2) roundabouts. The turbo roundabout can effectively guide drivers within the roundabout by restricting lane-changing and reducing lane-change-related conflicts, which are common in multi-lane roundabouts. Within the U.S., the adoption/use of turbo roundabouts has been limited, and few recent applications. The overall goal of this project was to develop guidelines for the Nevada DOT that would assist with providing performance measures and aid potential installations of turbo roundabouts. This study performed microsimulation and driving simulator-based evaluations of basic and egg turbo roundabout designs, two popular versions of the turbo roundabout. Results showed that the theoretical capacities are always higher than the observed and microsimulation capacities, and there is some difference between the simulated and practical capacities. Surrogate safety analysis showed that a basic turbo-roundabout had 18-30% fewer traffic conflicts than a traditional two-lane roundabout for different traffic compositions. A set of driving simulator scenarios was executed to investigate drivers' navigational behavior(s) within turbo roundabouts. Participant drivers' performance was evaluated on three roundabout designs – a basic turbo, an egg turbo, and a two-lane roundabout. Results showed the critical gaps as 4.2 secs, 6.1 secs, and 3.9 secs for the basic turbo, egg turbo, and traditional two-lane roundabouts, respectively. Additionally, participant drivers' speed profiles depicted similar patterns among roundabout designs, where the speeds were relatively lower for the basic turbo roundabout than the two-lane roundabout along the approach legs. As a part of the project, a multi-criteria intersection control evaluation (ICE) tool was also developed and can be used to evaluate and select between roundabout designs. Lastly, a pilot field demonstration plan was developed to facilitate turbo roundabout pilot deployment in Nevada.

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EXECUTIVE SUMMARY

As intersection-related traffic crashes represent approximately 50% of total crashes, conversion of traditional intersections (i.e., two- and all-way stop-controlled and signalized) to roundabouts has been an emerging practice in many countries, including the U.S. The significant benefits of roundabouts include reducing crash severity and frequency, improving intersection capacity, and improving operational performance. A Federal Highway Administration (FHWA) study reported that a roundabout reduces intersection fatality by 90%, injury by 76%, and crash frequency by 35% compared to a traditional intersection. The user acceptance of roundabouts increases substantially after the installation as drivers become knowledgeable about navigating roundabouts. However, multi-lane roundabouts have several operational challenges, such as driver's improper lane choice decisions and traffic safety concerns due to traffic crashes from weaving movements within roundabout circular lanes. Emerging "turbo roundabout" can reduce several limitations of multi-lane roundabouts. Turbo roundabouts can effectively guide drivers within the roundabout by limiting lane-changing and reducing associated lane-change-related weaving conflicts/crashes common in multi-lane roundabouts. The turbo roundabout was first designed and implemented in the Netherlands. Turbo roundabouts have the same general operating characteristics as traditional roundabouts but utilize different geometrics and traffic control. Lane separator/barrier between circular lanes in turbo roundabout keeps vehicles in the same lane and prevents weaving maneuvers.

To investigate the implementation potentials of turbo roundabouts in Nevada, the research team conducted a microsimulation-based analysis to investigate the safety and operational impacts and a driving simulator-based analysis to study driver behavior in navigating basic and egg turbo roundabouts. Variations in traffic demand volumes and compositions (e.g., left turn percentage, major-minor split) were considered to investigate the suitability of basic and egg turbo roundabouts, compared with traditional single-lane and two-lane roundabouts. Operational measures such as delay, capacity, and Level of Service (LOS) were compared to determine appropriate roundabout types for different levels of traffic demand volumes. The capacity of simulated roundabout design alternatives was estimated based on the delay curve. In addition, the safety benefit of turbo roundabouts was assessed based on the surrogate safety indicators, Time-to-Collision (TTC), and Post Encroachment Time (PET). The major findings of the microsimulation assessment are as follows:

- Turbo roundabout inner radius did not affect the operational performance as throughput and delay were similar for four inner radius scenarios.
- At low left turn percentages (e.g., 10-20%), the delay was similar for traffic demand volumes up to 3,700 pcu/hr.
- The simulated capacity of an egg turbo roundabout was around 2,890 pcu/hr, which is between the simulated capacity of a traditional single-lane (2,200 pcu/hr) and a two-lane roundabout (3,300 pcu/hr).
- The simulated capacity of a basic turbo roundabout was 3,400 pcu/hr, comparable to the capacity of the two-lane roundabout (3,300 pcu/hr).
- Surrogate safety analysis showed that a basic turbo-roundabout had 18-30% fewer traffic conflicts than a traditional two-lane roundabout for different traffic compositions.

A set of driving simulator experiments was designed to understand driver behaviors, where drivers encountered three roundabout designs – a basic turbo, an egg turbo, and a traditional two-lane roundabout. Different driving performance data (e.g., gap acceptance, speed, braking) were collected as study participants drove the assigned driving simulation scenarios. These collected data were compared among roundabout designs to determine the safe and optimal performing design. Specifically, drivers' navigational performance regarding critical gaps and speed choices (at approach legs, circulatory lanes, and departure legs) were compared. A pre-and post-driving survey was conducted to understand participants' perceptions/acceptance of turbo roundabouts. The following results and observations were inferred from the gap analysis:

- The average accepted gap on an egg turbo roundabout was statistically significantly higher than the average accepted gap on a basic turbo roundabout and a two-lane roundabout.
- The average accepted gaps were not statistically significantly different between a basic turbo roundabout and a two-lane roundabout.
- The critical gap values were 4.2 secs, 6.1 secs, and 3.9 secs for a basic turbo roundabout, an egg turbo roundabout, and a two-lane roundabout, respectively.
- The speed profiles depicted that the curve for a basic turbo roundabout (both at entry and departure) is "smoother" than an egg turbo roundabout and a two-lane roundabout. Also, the speeds are relatively lower on a basic turbo roundabout than on a two-lane roundabout along the approach legs.

In addition to the driving performance data from the simulator, a pre-and post-driving simulation experiment survey was conducted to document participants' familiarity, comfort level, and preference for different roundabouts (in general), specifically for turbo roundabouts. The survey results showed that 75% of the participants (N = 18 out of 24) were familiar with single-lane roundabouts and two-lane roundabouts. Thus, it was evident that many participants had some level of experience with roundabouts (in general). However, as anticipated, 88% of participants were not familiar with turbo roundabouts, with only 13% mentioning mixed feelings (felt neutral) about their knowledge of turbo roundabouts. After driving through the turbo roundabouts in the driving simulation experiment, 63% of participant drivers did not oppose the installation of turbo roundabouts in their community. In comparison, 37% were undecided or opposed to installing turbo roundabouts. Regardless, there was a high willingness among drivers (86%) to receive additional information and education on turbo roundabouts if a turbo roundabout was constructed in their communities.

This study also developed an intersection control evaluation (ICE) tool to compare the operational and safety performances of a basic turbo roundabout, an egg turbo roundabout, a traditional two-lane roundabout, and a single-lane roundabout. Based on the capacity analysis results, a traditional single-lane roundabout can be implemented at a traffic demand volume of up to 2,200 pcu/hr. When traffic volume is less than 2,800 pcu/hr, an egg turbo roundabout could be adopted as an intersection control option. Based on capacity, a traditional two-lane roundabout can be implemented at a traffic demand volume of up to 3,300 pcu/hr. Finally, a basic turbo roundabout could be implemented up to a traffic demand volume of 3,400 pcu/hr. In addition, a basic turbo-roundabout had 18-30% fewer traffic conflicts than a traditional two-lane roundabout for different traffic compositions. The best intersection control type can vary depending on the left turn percentage and balanced (similar traffic on major and minor streets) and unbalanced (heavy traffic on major street compared to minor street) traffic scenarios.

Based on the findings of microsimulation and driving simulator experiments performed in this study, NDOT can consider a pilot deployment of a turbo roundabout and investigate its real-world operational and safety performance. The implementation plan could guide the selection of appropriate study locations and roundabout design features.

CHAPTER 1: INTRODUCTION

Multi-lane roundabouts have been deployed as a proven safety strategy to improve intersection safety by eliminating or altering conflict types and reducing crash severity. Despite these advantages, multi-lane roundabouts have several operational challenges, such as driver confusion on proper lane choice decisions, stripping and signing issues, and concerns about relatively high crash frequency (Leuer, 2016). A relatively new form of roundabout, known as "turbo roundabout," can improve safety without reducing operational performance compared to multi-lane roundabouts. A turbo roundabout was first designed and implemented in the Netherlands (Fortuijn, 2009), where a before and after safety analysis showed a 53% reduction in injury crashes (Debann, 2017). A turbo roundabout's configuration can effectively guide drivers to reduce lane-change conflicts common in multi-lane roundabouts (FHWA, 2019). A basic turbo roundabout has fourteen conflict points compared to twenty-four in a traditional 2×2 multi-lane roundabout (Vasconcelos et al., 2014). In addition to safety benefits, a turbo roundabout could provide higher capacity due to reduced conflict points (Engelsman and Uken, 2007). A turbo roundabout can be installed at locations where a single-lane roundabout does not provide enough capacity and a two-lane roundabout increases conflict. Figure 1 depicts the top view of a turbo roundabout and a traditional two-lane roundabout.

(a) Turbo roundabout, Netherland (b) Two-lane roundabout, Carmel, Indiana

Figure 1: Examples of a turbo roundabout and a traditional two-lane roundabout. (Image source: Google Maps)

While there are design standards/guidelines for turbo roundabouts in the context of transportation systems and roadway users' characteristics in several European countries, these standards cannot be readily transferable to the U.S. The European design vehicle (e.g., tractor-trailer) is shorter than the U.S. standard tractor-trailer. Wider circulating lanes or longer outer truck aprons are required to accommodate longer tractor-trailers in the U.S. For example, a wider opening width is needed to accommodate the swept path of the U.S. tractor-trailer, according to an analysis by Transoft Solution (Fortuijn, 2009). Besides, driver behavior and familiarity towards roundabouts (in general) and turbo roundabouts (in particular) are different (e.g., U.S. drivers are less familiar with roundabouts). Nevada Department of Transportation (NDOT) has been adopting traditional single- and multi-lane roundabouts to improve safety and operations at intersections and is considering the potential of turbo roundabout implementation. A detailed investigation of turbo roundabouts' potential safety and operational performance considering diverse roadway users (e.g., passenger cars, trucks, pedestrians, bikes) and traffic volume/composition is critical for developing design guidelines, installation criteria, and operational recommendations.

This project aims to synthesize and summarize current design practices, analyze turbo roundabout's operational and safety performance, and develop design guidelines for practitioners. To accomplish the project goal, the West Virginia University (WVU) and Ohio University (OHIO) team aims to accomplish the following specific research objectives:

1. Conduct an extensive review and synthesis of current published research and pilot projects to compile design and installation criteria, operation and maintenance challenges, and safety and operational performance of turbo roundabouts;
2. Perform traffic microsimulation-based investigation to quantify the impacts of different turbo roundabout design factors on safety and operational performance;
3. Conduct a driving simulator-based investigation to understand navigability differences between traditional and turbo roundabout designs; and
4. Develop an intersection control evaluation (ICE) tool to assist transportation engineers/professionals compare the performance of different intersection control design types.

Figure 2 presents the organization of this report and outlines the major tasks conducted to accomplish the above study objectives.

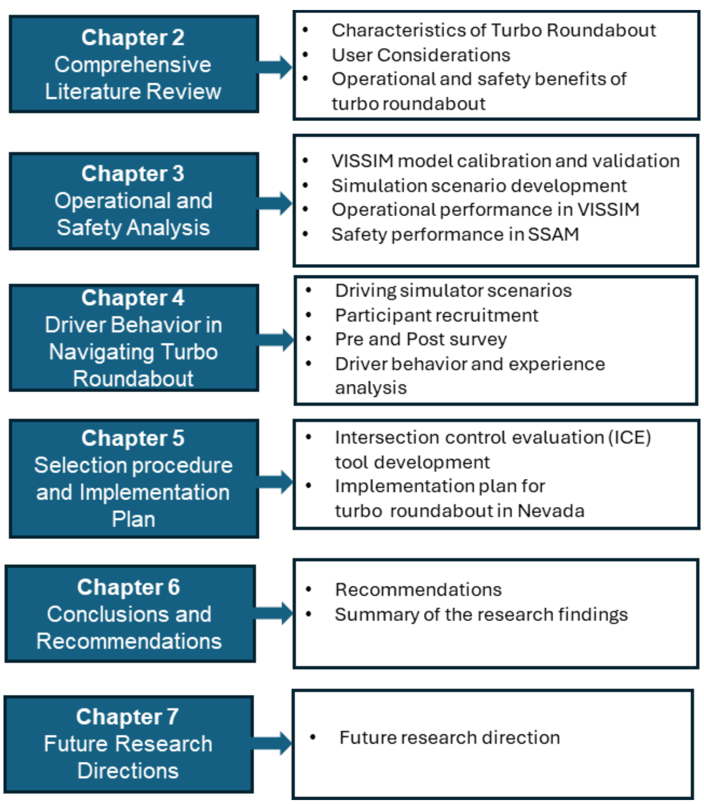


Figure 2: Overview of report content.

CHAPTER 2: LITERATURE REVIEW

As intersection-related traffic crashes represent approximately 50% of total traffic crashes, traffic engineers and researchers have explored geometric modifications to existing intersections over the years to improve intersection safety and operations. Conversion of traditional intersections (i.e., two- and all-way stop control and signalized) to roundabouts has been a growing practice in many countries around the world, including the U.S. – largely due to the benefits in terms of reduction in crash frequency and severity (Gallelli et al., 2021). Roundabouts improve intersection safety by eliminating or altering conflict types and reducing crash severity. Roundabout geometric designs require drivers to reduce speeds to navigate through intersections (Rodegerdts et al., 2010). Federal Highway Administration (FHWA) reported that a roundabout reduces intersection-related crash fatalities, injury, and crash frequency by 90%, 76%, and 35%, respectively, compared to a conventional intersection (Persaud et al., 2001). Moreover, converting an at-grade signalized intersection to a modern roundabout is expected to reduce the number of injury crashes by 78%, and converting a traditional two-way stop control intersection to a modern roundabout is expected to reduce the number of injury crashes by 82% (Rodegerdts, 2007). While most people oppose roundabouts before implementation in the U.S., acceptance increases substantially after installation over time as drivers become knowledgeable about navigating roundabouts (Hu et al., 2014). Based on a roundabout database maintained by Kittleson & Associates, there are 7,492 single-lane and 2,367 multi-lane roundabouts in the U.S. (Kittleson & Associates, 2023). FHWA Roundabout Guide (NCHRP 672) has estimated that the capacity of a multi-lane roundabout can be up to 45,000 entering vehicles per day (Rodegerdts et al., 2010), and reduce traffic congestion and delay (Leuer, 2016). While multi-lane roundabouts have high traffic capacity, they have several operational challenges, such as negative driver perceptions, improper lane choice decisions due to driver confusion, striping and signing issues, bicycle and pedestrian concerns, and Americans with Disabilities Act (ADA) compliance issue, and traffic safety concern due to higher traffic crash frequency (Leuer, 2016). Drivers are often confused about lane choice to correctly navigate a multi-lane roundabout, which leads to two major crash types –yielding to the traffic within the roundabout and changing lanes within the roundabout (Leuer, 2016).

A new form of roundabout known as "turbo roundabout" is designed to effectively guide drivers within the roundabout by limiting lane-changing and reducing associated lane-changing conflicts/crashes (FHWA, 2019). The first turbo roundabout design was implemented in the Netherlands in the 1990s (Fortuijn, 2009). A turbo roundabout has general operating characteristics similar to a multi-lane roundabout but utilizes different geometric and traffic control features (FHWA, 2019). One of the past studies reported that turbo roundabouts can reduce rear-end crashes by 79% and angled crashes by 60% compared to traditional two-lane roundabouts (Bulla-Cruz and Barrera, 2016). This chapter summarizes the existing design standards and safety and mobility benefits of turbo roundabouts in the following sections.

2.1 Turbo Roundabout Definition

A turbo roundabout is essentially a multi-lane roundabout, with spiral circulatory lanes that separate traffic flows at entrances, on the circulatory lanes within the roundabout, and at exits by raised/mountable lane dividers (Fortuijn, 2009). Drivers must choose the correct lane before entering a turbo roundabout to exit in the desired direction. Since lane changing within the roundabout is not permitted/restricted, weaving conflicts are eliminated, and sideswipe crashes are prevented. Some of the key geometric features of turbo roundabouts outlined by Fortuijn (2009) are as follows:

- At least one entry lane has a second circulatory lane.
- Approaching traffic must yield to traffic on two circulatory lanes on at least one approach leg.
- A spiral alignment encourages smooth traffic flow.
- Raised/mountable lane divider discourages lane changes within the roundabout.
- One circulatory lane at each entry approach allows drivers to choose whether to exit or circulate the roundabout.
- Minimum two exit legs have two lanes.
- A small roundabout diameter (148-180ft) encourages lower speeds within the roundabout.
- Roundabout configuration forces drivers to choose a lower speed as approach legs are at right angles to the circular lanes.
- A mountable apron offers sufficient width for larger vehicles.

2.2 Variants of the Turbo Roundabout

Turbo roundabout design can be modified by varying the number of lanes on the entry and exit legs. The typical four-legged turbo roundabout can have five variations (illustrated in Figure 3- (a) basic, (b) egg, (c) knee, (d) spiral, and (e) rotor (Figure 3)). A basic turbo roundabout has two entry lanes on each approach, whereas an egg turbo roundabout has only one on minor approaches. An inside lane is only added on one approach in a knee turbo roundabout. A spiral turbo roundabout has three circulatory lanes with three entry lanes on two approaches and two entry lanes on the remaining two minor approaches. A rotor turbo roundabout has three circulatory lanes with three entry lanes on each approach (FHWA, 2019). The suitability of an appropriate turbo roundabout design is determined based on diverse factors such as (1) saturation level, (2) average delay time, (3) right-of-way need, and (4) investment costs (Overkamp & van der Wijk, 2009).

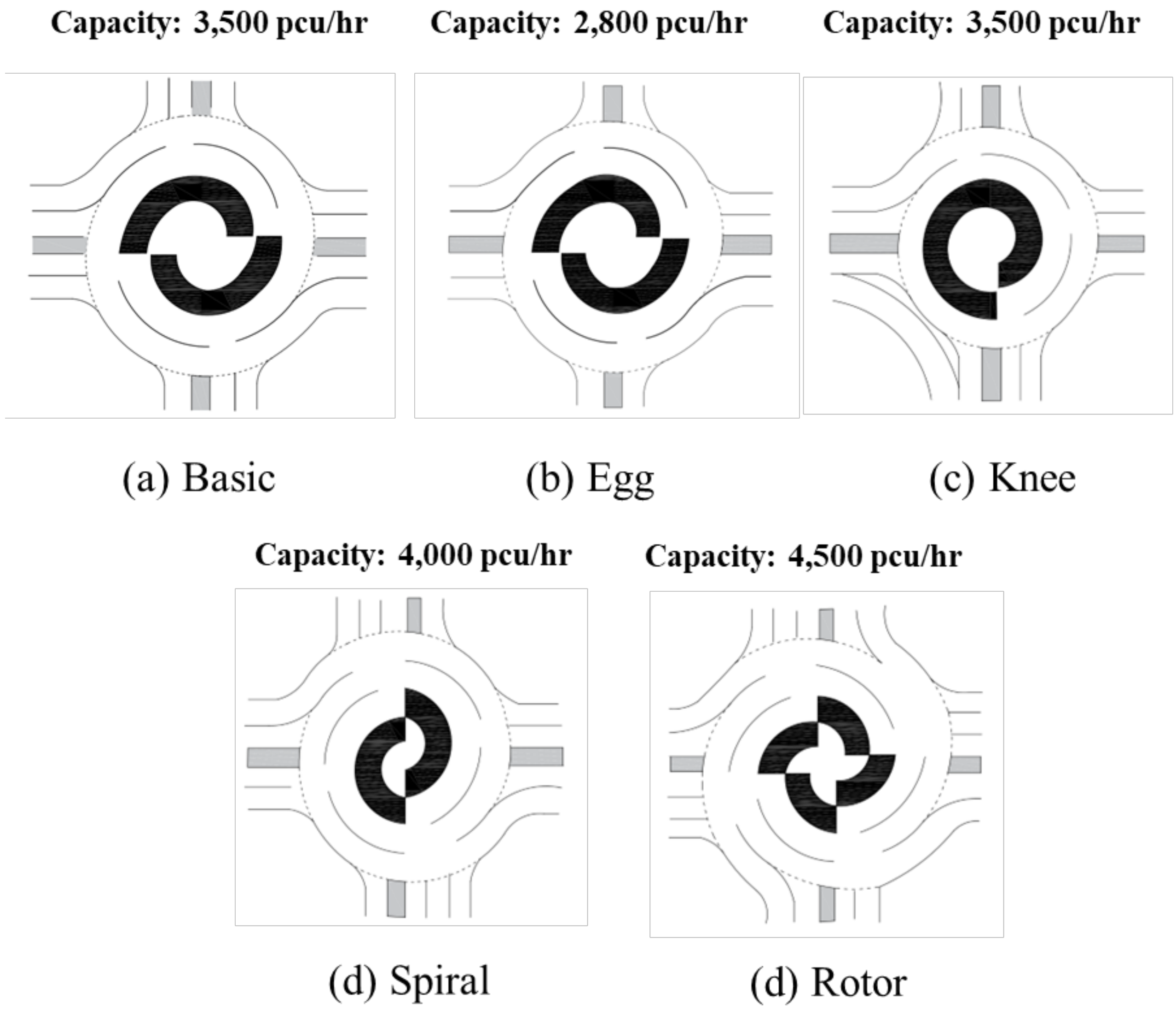


Figure 3: Different types of turbo roundabouts with capacity (Image modified from Džambas et al., 2017)

2.3 Benefits of Turbo Roundabout

The main advantage of turbo roundabouts is improved intersection safety due to reduced conflict points compared to traditional roundabouts. Figure 4 illustrates the differences in conflict points between a two-lane roundabout and a basic turbo roundabout. Two-lane roundabouts have 24 potential conflict points, whereas basic turbo roundabouts have 14. A turbo roundabout's raised circulatory lane divider prevents vehicles from changing lanes and restricts weaving maneuvers, which usually causes sideswipe collisions in a traditional two-lane roundabout. A study on seven intersections converted to turbo roundabouts from yield control, traffic signals, or an old-style rotary observed an 82% reduction in traffic crashes in the Netherlands (Fortuijn, 2009).

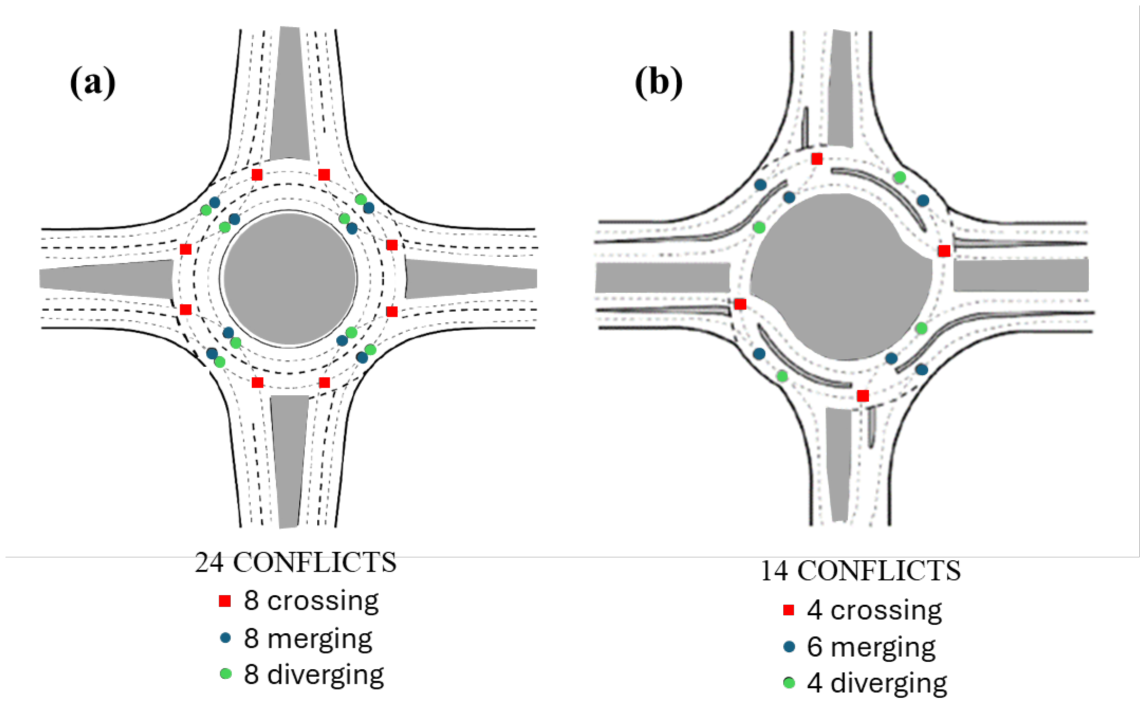


Figure 4: Conflict point frequency (a) a multi-lane roundabout and (b) a turbo roundabout (Images modified from Vasconcelos et al., 2014 and FHWA, 2019)

The main benefits of turbo roundabouts compared to other intersection control types are (Overkamp & van der Wijk, 2009):

- A turbo roundabout’s capacity is higher than a traditional single-lane roundabout (1.5 to 2.5 times) and a traditional two-lane roundabout (1 to 1.5 times).
- A turbo roundabout’s capacity is similar to or higher than a signalized intersection's.
- A turbo roundabout experiences lower delay than a signalized intersection.
- A turbo roundabout’s safety performance is better than a stop/yield-controlled intersection (70% reduction in fatal crashes and serious injuries) and traffic signals (50% reduction in fatal crashes and serious injuries).
- The right-of-way requirement of a turbo roundabout is similar to a signalized intersection.
- Turbo roundabout has lower life cycle and social costs with higher construction costs than an intersection with traffic signals.

2.4 User Considerations in Turbo Roundabout Design

The accommodation of different roadway user groups (i.e., motorists, pedestrians, bicyclists, motorcyclists, and freight/large vehicles) at turbo roundabouts is discussed in this section.

2.4.1 Motorists

Drivers are required to select the proper lane before entering a turbo roundabout depending on their destination and yield to vehicles when entering a turbo roundabout. Turbo roundabouts guide motorists before entering the intersection to choose the correct lane for a right turn/through/left turn/U-turn movement by entry geometry, enhanced delineation of lanes, and proper road marking and signage. Drivers are required to identify acceptable gaps in no more than two conflicting lanes at an entry approach of a turbo roundabout. Current design practices used roadside guide signs at 1,312 ft and overhead directional signs at 131 ft from the turbo roundabout entry points (Porter et al., 2020). Vehicles enter a turbo roundabout almost perpendicularly rather than at an angle standard in traditional roundabouts. A turbo shield/sign is installed at the central island to catch the driver's attention, block the horizon's view, and guide the driver to enter the turbo on the right. Unlike traditional multi-lane roundabouts, vehicles in a turbo roundabout cannot make U-turns from all approaches. A turbo roundabout's radial entry and approach curvature requires vehicles to reduce speed in navigating curvature safely (Rodegerdts et al., 2010).

2.4.2 Pedestrians and Bicyclists

Navigation of pedestrians through a turbo roundabout is similar to traditional single-lane and multi-lane roundabouts. According to Rodegerdts et al. (2010) and Schroeder et al. (2016), the guidelines from NCHRP Report 834 can be followed to safely accommodate pedestrians at the turbo roundabout. At a turbo roundabout, bicyclists are provided a separate or shared lane with the motor vehicle traffic. Need for bicycle facilities depends on many factors such as bicycle traffic volume, availability of existing bicycle facilities, automobile traffic volume, roundabout design, surrounding infrastructure/land use, and right-of-way. The following factors can be considered to accommodate bicyclists at a turbo roundabout (FHWA,2019; Rodegerdts, 2010):

- Keeping a turbo roundabout's radius small reduces vehicle speeds and improves bicyclists' navigational comfort.
- Terminating bicycle lanes 100 ft ahead of circulatory lane edges and pedestrian crosswalks at the approach legs.
- Introduce bicycle lanes on exit legs downstream of crosswalks.
- If bicyclists share the sidewalk, design sidewalks to meet shared-use path width requirements. In most scenarios, a minimum sidewalk width of 10 ft is recommended.
- If bicyclists have to cross at grade on approaches, whether on a designated crossing or a pedestrian crosswalk, a pavement-level cut-through of the splitter island can be provided.

2.4.3 Freight/Large Trucks

As vehicles aren't allowed to change lanes within a turbo roundabout, providing sufficient space for large vehicles to complete the movements/turning is critical. In European turbo roundabout design guidelines, large design vehicles are considered so that the design vehicle does not track into adjacent lanes (Džambas et al., 2017), which are the same as the design guidelines for multilane roundabouts in the U.S., such as NCHRP 672 (Rodegerdts et al., 2010), Washington State Department of Transportation Design Manual (WSDOT, 2019), and South Carolina Department of Transportation (SCDOT, 2017), allow U.S. large trucks in determining the whole width of the circulatory roadway of a roundabout. When a raised lane divider option is used in a turbo roundabout, a traversable, demarcating feature can be provided at the origin of the raised divider to ease the entrance of larger vehicles (FHWA, 2019). U.S. large trucks entering the inside lane of a turbo roundabout need a wider opening to accommodate their larger swept paths. A central truck apron is provided in turbo roundabouts to help larger vehicles navigate the turbo roundabout circulatory lanes. Aprons can also be provided on the perimeter of the turbo roundabout to provide more turning space for large vehicles (FHWA, 2019).

2.5 Installation Location Considerations

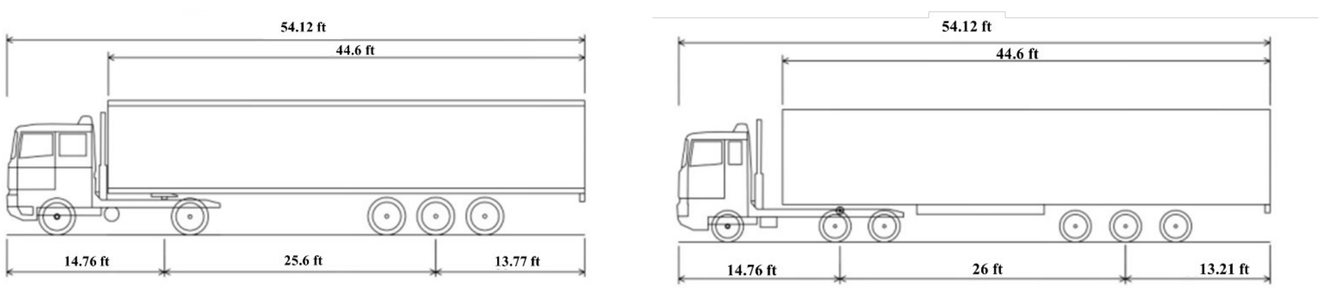
Site characteristics such as available right-of-way, intersection skewness, winter maintenance needs, adjacent traffic generators that require pre-emption, and downstream bottlenecks can influence the feasibility of a turbo roundabout (Rodegerdts et al., 2010). Turbo roundabouts may be considered at an intersection where traffic demand indicates the need for a multi-lane roundabout (FHWA, 2019).

2.6 Geometric Design of Turbo Roundabout

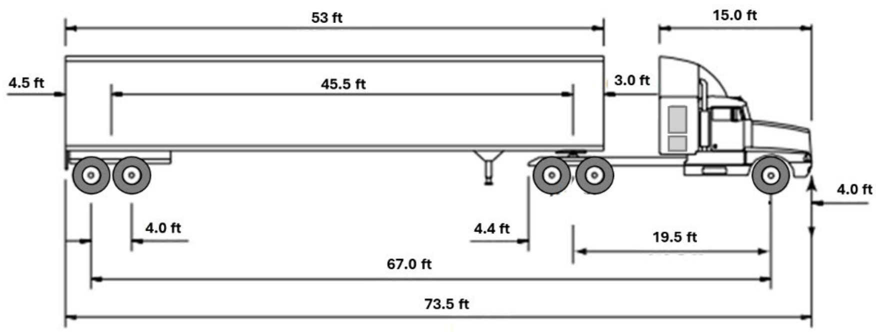
The geometric design of a turbo roundabout depends on the desired capacity and characteristics of a design vehicle's horizontal swept path. The geometric design of a turbo roundabout is an iterative process. The first step is to select a design vehicle based on the local traffic composition and design practices. After choosing the design vehicle, an initial scheme of a standard turbo roundabout template can be selected. The projected traffic demand and the approach roadway cross-sections determine the number of lanes and their arrangement and dictate the type of turbo roundabout to be considered. After selecting the roundabout type, a horizontal swept path analysis of the design vehicle is done to decide on lane width and other lane width-related considerations (e.g., right-of-way, considerations for all vehicle types and users). The turbo roundabout type and lane widths are combined to construct the turbo block, which guides the geometric design of the circulatory roadway (FHWA, 2019). The geometric design elements of a turbo roundabout are briefly explained below.

2.6.1 Design Vehicle

The choice of appropriate design vehicle depends on the roadway classification, traffic composition, surrounding land use characteristics, and consultation with local jurisdictions and transportation agencies (Džambas, 2017). Based on the swept path analysis, the least favorable vehicle should be chosen for the design of the turbo roundabout geometric features. The swept path analysis in past studies showed that the least favorable vehicles were two tractor-semitrailer combinations (Aurell and Wadman, 2007). A two-axle truck tractor with a three-axle semitrailer has been used as the design vehicle in the Netherlands, Germany, Slovenia, and Serbia (Figure 5a). A three-axle truck tractor with a three-axle semitrailer is the design vehicle in Croatian (Figure 5b) (Džambas, 2017). NCHRP report 672 on roundabout design recommends WB-67 (Figure 5c) trucks or oversized vehicles for interstate freeway ramps and intersections on the state highway network and smaller design vehicles for local street intersections (Rodegerdts et al., 2010).



(a) (b)



(c)

Figure 5: Design vehicle dimensions (a) Netherlands, Germany, Slovenia, Serbia (b) Croatia; (c) United States. (Images based on Džambas et al., 2017 and Hancock and Wright, 2013)

2.6.2 Turbo Block

A turbo block is an auxiliary construction used to create an initial scheme of the turbo roundabout design (Fortuijn, 2009). Turbo blocks regulate the circulatory roadway design, which consists of circular arcs with centers on a reference line known as a "translation axis." The arcs represent each lane's inner and outer edges (Džambas *et al.,* 2017). The inner radius of a turbo block represents the radius of the central island and is selected based on the anticipated size of the turbo roundabout. The lane width is the arc shift along the translation axis from the center. The turbo block and angle of the translation axis differ for each turbo roundabout type. Figure 6 shows the design elements of a turbo block for a turbo roundabout.

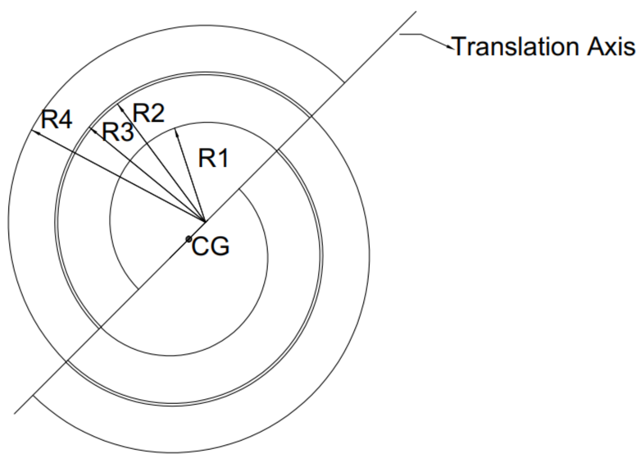


Figure 6: Sample turbo block design elements (Image based on Džambas et al., 2017)

A turbo block is defined by the characteristics shown in Figure 6. The center point (CG) is the intersection of the approach centerlines. The orientation of the translation axis is defined in relation to the major road approaches. The rotation angle for the translation axis can be adjusted to provide smooth, spiral vehicle paths for all vehicular movements. R1, R2, R3, and R4 are the radii of the circles (Figure 7). R1 is the radius of the inside edge of the inside lane. R2 is the outside edge of the inside lane. The difference between R2 and R1 is the width of the inside travel lane plus additional width for the edge lines delineating the raised lane divider (Džambas *et al.,* 2017). R3 is the inside edge of the outside lane. The difference between R2 and R3 is the width of the lane divider. R4 is the outer edge of the outside lane.

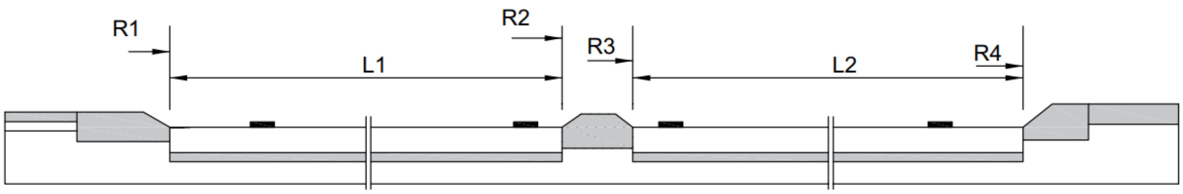


Figure 7: Cross section of a turbo block at the translation axis (Image based on Džambas et al., 2017)

Distances between the arc center points are another key set of dimensions used in defining the turbo block (Džambas et al., 2017). The shift is the distance between the centers of the arcs. The shift can differ for the R1, R2, R3, and R4 centers if the inside lane width differs from the outside roadway lane. The shift for the R1 centers is achieved by sliding the two arcs defined by R1 in opposing directions away from CG. Based on international practice, the shift ranges between 8.5 and 9.5 ft (for total shifts between 17 and 19 ft), as shown in Figure 7. The shift for the R2, R3, and R4 centers is the distance between the outside edge of the inside lane and the outside edge of the outside lane (also the difference between the values used for R4 and R2). The shift for the R2, R3, and R4 centers is achieved by sliding the arcs defined by R2, R3, and R4 in opposing directions away from CG. This value typically ranges between 7.5 and 8.5 ft (for a total shift of 15 to 17 ft). If the inside and outside lanes have the same width, the shift value for all radii is the same. Internationally, the radius (R1, R2, R3, and R4) for basic turbo roundabouts have ranged from 34 to 66 ft for R1, 52 to 82 ft for R2, 53 to 83 ft for R3, and 70 to 100 ft for R4 (Džambas *et al.,* 2017). The turbo roundabout's nominal diameter is two times R4 plus the width of R2/3/4 shift. Assuming a shift of 15 ft, the inscribed circle for basic turbo roundabouts ranges from 155 to 215 ft.

2.6.3 Cross-Section Elements

2.6.3.1 Central Island

Central island in a turbo roundabout performs functions similar to those in a traditional roundabout and consists of a traversable apron. The width of the traversable apron depends on its functionality. The typical width of a traversable apron is 16.4 ft, allowing larger trucks to travel over the apron when vehicles are traveling on the inside lane. On the other hand, when the apron is only used for emergency vehicles and stops, the recommended width is 6.56-8.2 ft. The non-traversable portion of the central island is typically used for signage. A sample roundabout center island directional arrow sign is shown in Figure 8. The central island geometry depends on the starting curvature of the inside lane. In the Netherlands, the inside lane was designed using a smooth curvature matching the entering vehicle path (Figure 9a). However, this design approach led vehicles from the right approach lane to enter the inner lane. A flat lane addition approach for the inside lane has been adopted to avoid this confusion (Figure 9b).

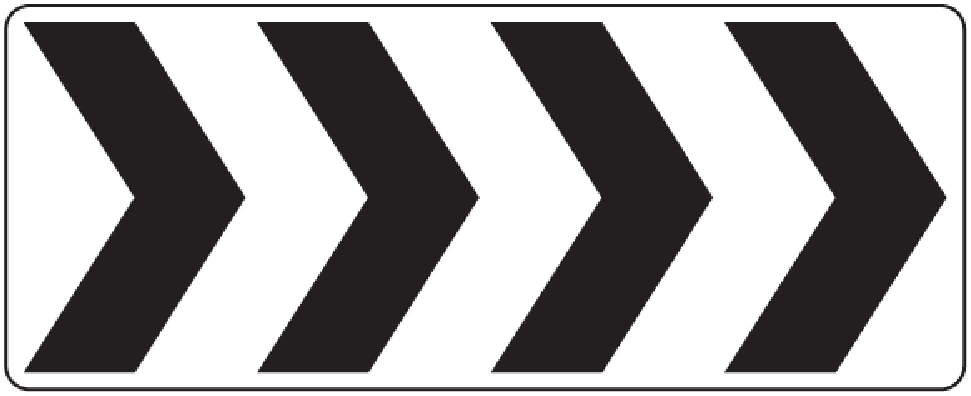


Figure 8: Directional arrow sign for central island (Image source: FHWA)

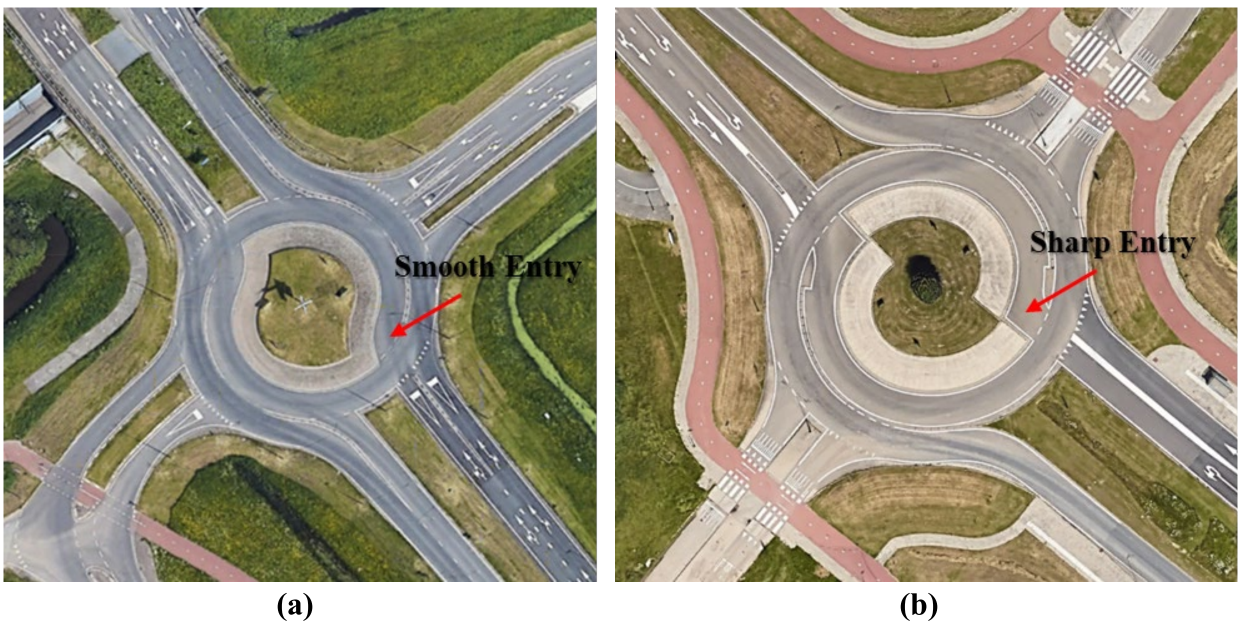


Figure 9: (a) Initial design for starting the inside lane in the Netherlands; (b) New Design for starting the inside lane. (Image Source: Google Earth)

2.6.3.2 Lane Divider

A lane divider between circulating lanes is an essential feature of a turbo roundabout and serves four functions (Overkamp & van der Wijk, 2009):

- Eliminates weaving and cut-off movements/conflicts,
- Restricts vehicles from ignoring circular lane curves during low-volume off-peak periods,
- Reduces potential conflicts with vehicles on other circular lanes, and
- Provides higher intersection capacity due to lower vehicular speed around turbo roundabout.

Lane dividers in a turbo roundabout can be of two types- raised and not raised. A raised lane divider is often introduced with a traversable, demarcating feature to allow turning by large trucks. Turbo roundabouts without raised lane dividers are implemented to facilitate motorcyclists and snow plowing operations (Fortuijn, 2009). Alternatives to the raised lane divider include striping and colorized or textured pavement, milled rumble strips or rumble stripes, or a double solid white lane (FHWA,2012). Figure 10 shows examples of lane dividers used in a turbo roundabout.

Figure 10: Examples of lane dividers (Image source: Google Street View)

The design of a lane divider can be altered to meet location-specific needs. Figure 11 (b) shows a modification of the original lane divider (Figure 11 (a)) to accommodate snow plowing. However, even the modified design may not be suitable for areas that experience heavy snowfall. Heavy snow could cover the dividers completely, making the raised curb invisible to snowplow drivers during snow events. Turbo roundabouts without raised lane dividers might work best for areas with heay snow.

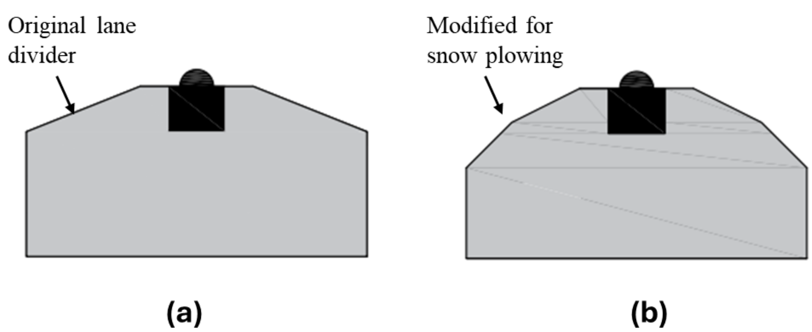


Figure 11: Types of lane dividers (a) raised lane divider with no modifications; (b) modified lane divider for snow plowing (Images modified from Overkamp & van der Wijk, 2009)

2.6.4 Approach Geometry

According to NCHRP 672, three approach geometry types can be adopted for traditional multilane roundabouts: radial, offset left, and offset right. For turbo roundabout design, radial approaches are used, which reduces the alignment changes along the approach roadway and maintains exit curvature that encourages drivers to choose slower speeds (Fortuijn, 2009). Turbo roundabouts are built with little or no flare or deflection and a smaller entry radius. Potential disadvantages include drivers errantly hitting the central island, making wrong-way left turn maneuvers to enter the roundabout, and making wrong-way exit maneuvers into entrance approach lanes (Rodegerdts, 2010). A turbo roundabout directional arrow sign (Figure 8), placed on the central island in the line of sight of approaching drivers, can direct drivers always to enter right and increase the conspicuity of the central island and the need for a forgiving design of the central island and sign (FHWA, 2019). Turbo roundabout entry radius ranges from 39 to 50 feet (Džambas et al., 2017; Overkamp & van der Wijk, 2009) compared to traditional multi-lane roundabout's entry radius of more than 65 ft, and single-lane roundabout's entry radius ranging from 50 to 100 ft.

2.7 Signing and Markings

Lane selection signage and pavement markings on the approaches are critical for motorists and other users to identify and select appropriate lanes before entering a turbo roundabout. MUTCD and NCHRP Report 672 describe applications of lane control signage for roundabout approaches (Rodegerdts et al., 2010; FHWA, 2012) and can be supplemented using pavement marking arrows (FHWA, 2019). Signage can also direct pedestrians and bicyclists to designated facilities and drivers to appropriate lane selections and communicate the presence of a raised lane divider (if used). If the lane divider includes grooved, textured, or brick pavements, consideration can be given to including sign W8-15 to inform road users (FHWA, 2012). Pavement markings shall be used to delineate the edges of the approach and circulatory lanes. Additionally, supplemental delineation can be achieved using reflectors or light-emitting diodes (LEDs) to illuminate the edges of the apron and lane dividers (FHWA, 2019; FHWA, 2012). Figure 12 shows an example of traffic sign used by Caltrans before entering a turbo roundabout (Overkamp & van der Wijk, 2009).

Figure 12: Sign used on entry lanes ahead of a turbo roundabout (Image source: Caltrans, 2023)

2.8 Capacity and Operational Performance

Similar to traditional roundabouts, turbo roundabout capacity is measured at the approach level. Past studies reported that basic turbo roundabouts have similar capacities as traditional two-lane roundabouts with two entry and two circulating lanes. A Netherlands study reported an estimated 3,500 pcu/hr capacity for a basic turbo roundabout, assuming conflicting traffic volumes between 1,900 and 2,100 pcu/hr (Overkamp & van der Wijk, 2009). Also, a turbo roundabout exhibits lower speeds than a two-lane roundabout.

2.9 Driver Behavior on Turbo Roundabout

Few studies have examined driving behavior outside the Netherlands in navigating turbo roundabouts. Guerrieri et al. (2019) studied the driver behavior at a turbo roundabout in Maribor, Slovenia. Rodegerdts (2010) compared average critical and follow-up headways between single-lane roundabouts and multi-lane roundabouts. Wankogere et al. (2017) conducted a driving simulator-based experiments to study driver behaviors in multilane roundabouts and turbo roundabouts in the U.S.

2.10 Safety Performance

As turbo roundabouts are an emerging concept, past safety studies based on crash data are limited. Seven intersections were converted to turbo roundabouts in the Netherlands, and an 82% reduction in injury crashes was reported (Fortuijn, 2009). A Polish study found that turbo roundabouts with a raised lane divider experienced a lower crash frequency than those with paint stripes only and observed lower severity crashes in both scenarios (Macioszek, 2015). Surrogate safety measures based on microsimulations (e.g., time-to-collision, vehicle speeds, vehicle conflicts, incorrect movements, and incorrect paths) have also indicated that turbo roundabouts are likely to experience less frequent and less severe crashes than multi-lane roundabouts due to the fewer conflict points and the lower speeds required in navigating turbo roundabouts (e.g., Bulla-Cruz and Barrera, 2016; Chodur and Bąk, 2016; Kieć et al., 2019). Findings on the safety performance of turbo roundabouts in different countries are summarized in Table 1.

Table 1: Safety performance of turbo roundabout

<table>
<tr><th>Country</th><th>Findings</th></tr>
<tr><td rowspan="2">Netherlands (Fortuijn, 2009; Fortuijn, 2007; Wijk, 2009)</td><td>Injury risk following a road traffic crash at a turbo roundabout is 80% and 70% lower than traditional multilane and single-lane roundabouts.</td></tr>
<tr><td>Turbo roundabouts are 70% and 50% safer than intersections without traffic signals and with traffic signals, respectively.</td></tr>
<tr><td rowspan="2">Italy (Mauro and Cattani, 2010; Giuffrè et al., 2010)</td><td>Turbo roundabout’s safety improvement depends on the traffic organization, intensity, and directional traffic composition and ranges from a 40 to 50% reduction in traffic crashes.</td></tr>
<tr><td>After reconstructing three intersections into turbo roundabouts, road safety conditions improved while driving speed was reduced considerably.</td></tr>
<tr><td>Slovenia (Brilon, 2008)</td><td>No traffic crashes with serious injury consequences were recorded based on analysis at one location.</td></tr>
<tr><td>Slovakia (Tollazzi et al., 2011)</td><td>Turbo roundabouts were characterized as a solution with a very high level of safety improvement.</td></tr>
<tr><td>Colombia (Bulla-Cruz and Barrera, 2016)</td><td>Turbo roundabouts exhibited a 22% improvement in road safety.</td></tr>
<tr><td rowspan="2">Poland (MacioSzEK, 2013)</td><td>After the reconstruction of a roundabout into a turbo roundabout (with lane dividers in the form of a single continuous line), the number of traffic crashes declined by 80%.</td></tr>
<tr><td>• No fatalities were reported during the analysis period. Property damage only (PDO) was predominant (95.98%) among the recorded traffic crashes.
• Most frequent traffic crashes were rear-end collisions, driving into an obstacle, side-impacts, and overturning.</td></tr>
</table>

	• Most frequent causes were not giving way, excessive speed, lack of safe distance from the preceding vehicle, and illegal lane changing/overtaking.

Portugal's first turbo roundabout replaced a single-lane roundabout (Vasconcelos and Seco, 2013). Before implementation, a study evaluated a turbo roundabout's safety and operational performance. For comparison, three layouts were modeled in Aimsun – the existing single-lane solution, a traditional two-lane, and a turbo-roundabout. All three models were simulated with the current traffic demand, and the safety analysis was done by using the Surrogate Safety Assessment Model (SSAM). The two-lane roundabout showed the worst performance in the number and severity of conflicts, primarily due to the weaving maneuvers. Compared with the single-lane roundabout, the turbo-roundabout had fewer conflicts (but more severe due to the increased angle between entry and circulating trajectories). Another study on turbo roundabouts performed safety analysis using the VISSIM microsimulation model of a two-lane roundabout in Bogota and reported a 72% reduction in traffic conflicts compared to a two-lane roundabout (Bulla-Cruz and Barrera, 2016).

2.11 Construction Cost

As turbo roundabouts are similar to multilane roundabouts, they are expected to have similar construction costs. Depending on the design, turbo roundabouts may require slightly larger right-of-way than multilane roundabouts. A radial entry with no flare and a smaller entrance radius require a larger swept path for large vehicles, leading to wider circular lanes than a comparable multilane roundabout. However, there may not be significant changes to the alignment of the approach roadway for the turbo roundabout entry geometry (FHWA, 2019).

CHAPTER 3: MICROSIMULATION-BASED ANALYSIS OF TURBO ROUNDABOUTS

Traffic microsimulation-based assessments have been utilized extensively to develop and evaluate the performance effectiveness of a broad range of road traffic management and control (Bulla-Cruz and Barrera, 2016; Chimba and Mbuya, 2019; Naik et al., 2021). Microsimulation models "mimic the stochastic and dynamic nature of vehicle-to-vehicle and vehicle-to-traffic control interactions within the transportation system" (Appiah et al., 2011). A microsimulation-based approach was adopted in this study to quantify the performance of different turbo roundabout designs. This study investigated the safety and operational impacts of different turbo roundabout design features, varying traffic demand scenarios, and traffic compositions. This chapter presents findings from this microsimulation-based assessment using the VISSIM software developed by PTV Group (2020). The microsimulation model development process was divided into four stages, as depicted in Figure 13. The details of data collection, calibration and validation steps, and roundabout alternative designs are presented in Appendix A. A brief overview of microsimulation model development and calibration is presented in sections 3.1 and 3.2.

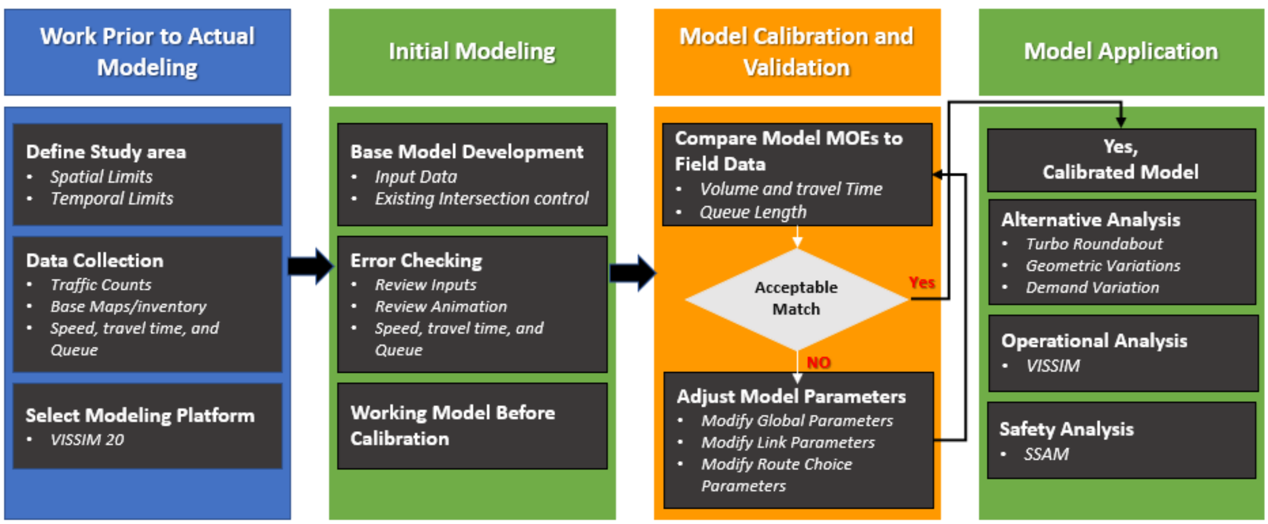


Figure 13: Microsimulation model development in VISSIM and application process (Adopted from Dowling et al., 2004)

3.1 Model Development

With assistance from the project technical committee members, an existing multi-lane roundabout at the intersection of Neil Road and Kietzke Lane in Washoe County, NV, was identified as a potential location for a turbo roundabout. Google Earth imagery of the roundabout (shown in Figure 14) was used as the background to develop a base model in VISSIM 2020. The base model was modified by varying turbo roundabout design geometric features (e.g., turbo block, inner radius, and approach geometry), passenger vehicle/truck/pedestrian volume, turning movements, and major street-minor street traffic volume splits. The following two sub-sections discuss the turbo-roundabout design procedure, scenario development, and VISSIM modeling.

Figure 14: Two-lane Roundabout at Neil Road and Kietzke Lane (Image Source: Google Maps)

3.1.1 Turbo Roundabout Model Development

The geometric design of a turbo roundabout can be varied based on the number of approach lanes on the entry and exit legs. As basic and egg turbo roundabouts are widely adopted in Europe, this study modeled and investigated the performance of these two turbo roundabouts. "TORUS," a turbo roundabout design software (Transoft Solutions, 2022), was used to design basic and egg turbo roundabouts in this study. A typical layout of a basic turbo roundabout and an egg turbo roundabout is shown in Figure 3 (Chapter 2). A basic turbo roundabout has two entry lanes on all approaches (Figure 3a), while an egg turbo roundabout has one lane on minor entry approaches (Figure 3b). A traditional two-lane and a single-lane roundabout were also designed to compare performance with turbo roundabouts. All four roundabout design alternatives were designed for a WB-67, a design vehicle recommended in NCHRP 672 for roundabouts.

3.1.2 Traffic Scenarios for Microsimulation Analysis

The microsimulation scenario development considered variation in turbo roundabout types (i.e., basic and egg turbo roundabouts), turbo inner radius (adopted from Džambas et al., 2017, 2020), traffic volumes, major street-minor street traffic volume split, left turn volume, and pedestrian volumes. More specifically, the following values were considered:

- Inner radius of 35, 40, 50, and 65 ft.
- Traffic demand volume of 2,000 to 7,000 vehs/hr (at 500 vehs/hr increment).
- Major street-minor street traffic volume split of 70%-30% (unbalanced scenario), 60%-40% (unbalanced scenario), and 50%-50% (balanced scenario).
- Left turn percentages of 10% to 70% (at 10% increment).
- Right turn percentage of 25%.
- Heavy vehicle percentage of 5%.
- Pedestrian volume scenarios- no pedestrian, 200 /hr, and 400 /hr.

Based on the geometric design of roundabouts using TORUS, 720 simulation scenarios (15 different random seeds used for each scenario) were developed for microsimulation analysis using VISSIM software. Figure 15 illustrates the different geometric features and traffic combinations considered.

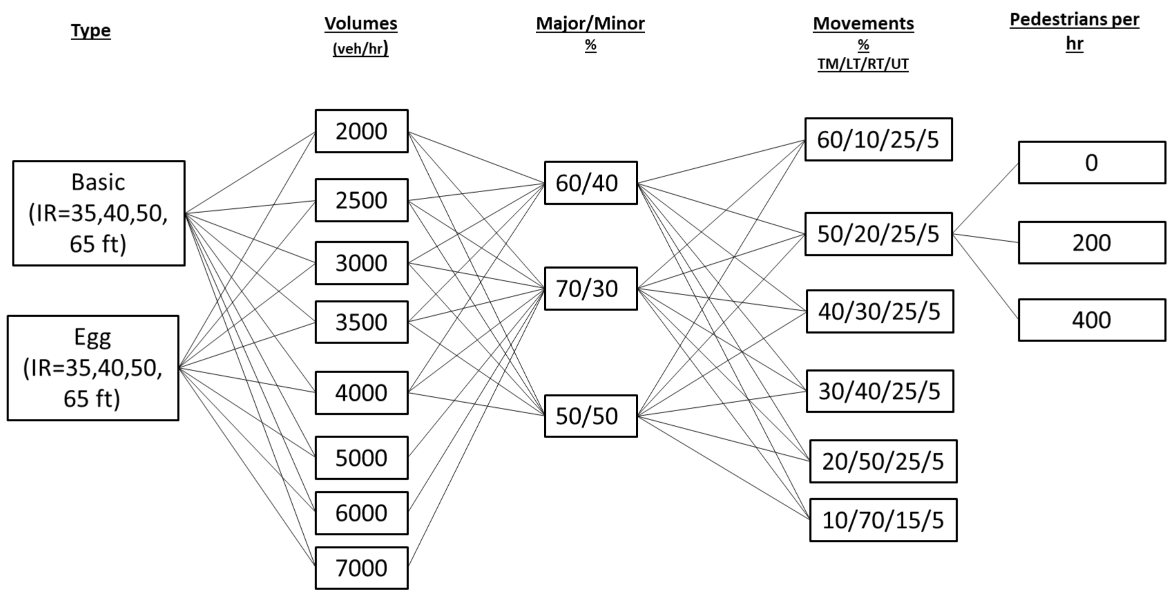


Figure 15: Simulation Scenario Flow Chart (IR=Inner Radius; TM=Through Movement; LT=Left Turn; RT= Right Turn; UT=U-Turn)

3.2 Microsimulation Model Calibration and Validation

For the developed VISSIM model to mimic driving conditions experienced in the real world, calibration and validation of the simulation model are mandatory. Field data (e.g., speeds, traffic volumes, traffic composition, travel time) for the multi-lane roundabout at Neil Road and Kietzke Lane in Washoe County, NV, was collected to develop a base simulation model. This intersection is located close to the Interstate 580 ramps on Neil Road. Most of the traffic on the South bound approach of Kietzke Lane originates from S McCarran Boulevard. On the West bound approach of Neil Road, traffic originates from the exit ramps of I-580 and S Virginia Street. This roundabout is located in an urban land-use environment.

Field traffic data was collected during weekday morning and evening peak periods using a wide-angle video camera. The origin-destination (O-D) matrix, traffic volumes, turning movement count, % of passenger cars, % of heavy vehicles, and standstill distances were extracted from recorded video. Field travel times and speed for all movements were also extracted from the recorded video to calibrate and validate the VISSIM simulation model. The calibration and validation of the developed base model for the existing traffic scenario were performed following the guidelines proposed by FHWA (Dowling et al., 2004). In this study, "Wiedemann 74" car-following model was utilized to calibrate the driving behaviors in the field conditions as the operations within the study roundabout were similar to urban traffic. In addition, lane change parameters and priority rule parameters were also calibrated to reflect the field driving condition. Three field measures, traffic volumes, travel times, and queue lengths, were selected for validation purposes. The calibrated parameters are shown in Table 2. Appendix A presents a detailed comparison of the calibrated base model's traffic volumes, travel times, and queue lengths with field data.

Table 2: VISSIM microsimulation calibration parameters

Parameter	Calibrated Value	Default Value
Vehicle Fleet	North America Default File	
Lane-Change Model		
Maximum deceleration-Own (ft/s^2)	-15.0	-13.12
Maximum deceleration-Trailing (ft/s^2)	-12.0	-9.84
Minimum headway (ft)	1.5	1.64
Safety distance reduction factor	0.4	0.60
Car-following model (Wiedemann 74)		
Average standstill distance (ft)	4	6.56
Additive part of safety distance	1	2
Multiplicative part of safety distance	2	3
Priority rules		
Minimum gap time for passenger cars (sec)		
For right entry lanes	2.6	3
For left entry lanes	2.6	3
Minimum gap time for heavy vehicles (sec)		
For right entry lanes	3.6	3
For left entry lanes	3.6	3

3.3 Simulation Operational Performance Evaluation

Four performance measures- throughput, travel times, delay, and capacity, were estimated for each simulation scenario to assess the operational performance of roundabout design alternatives.

3.3.1 Throughput Under Varying Traffic Demand

Intersection throughputs were estimated and compared for the roundabout design alternatives (i.e., basic turbo roundabout, egg turbo roundabout, traditional two-lane roundabout, and single-lane roundabout). Figure 16 depicts the maximum throughput volumes for different variants of basic and egg turbo roundabouts, with major and minor streets split of 60%-40% and turning volumes of 15% left and 25% right turning scenario. As shown in Figure 16, variation in turbo roundabout inner radius (R1) had a relatively minimal impact on the throughput for both basic and egg turbo roundabouts. However, for traffic demand volumes greater than 4,000 vehs/hr, changes in the throughput among the roundabout alternatives were observed. A traditional two-lane roundabout demonstrated a maximum throughput of 5,300 vehs/hr, whereas a basic turbo roundabout's maximum throughput was capped between 4,700 and 4,970 vehs/hr, and an egg turbo roundabout had a maximum throughput of 4,500 veh/hr. In addition, both basic turbo roundabout and two-lane roundabout performed similarly up to traffic demand volume of 4,000 vehs/hr. As expected, the single-lane roundabout had the lowest throughput due to having one entry and exit lane at all approaches.

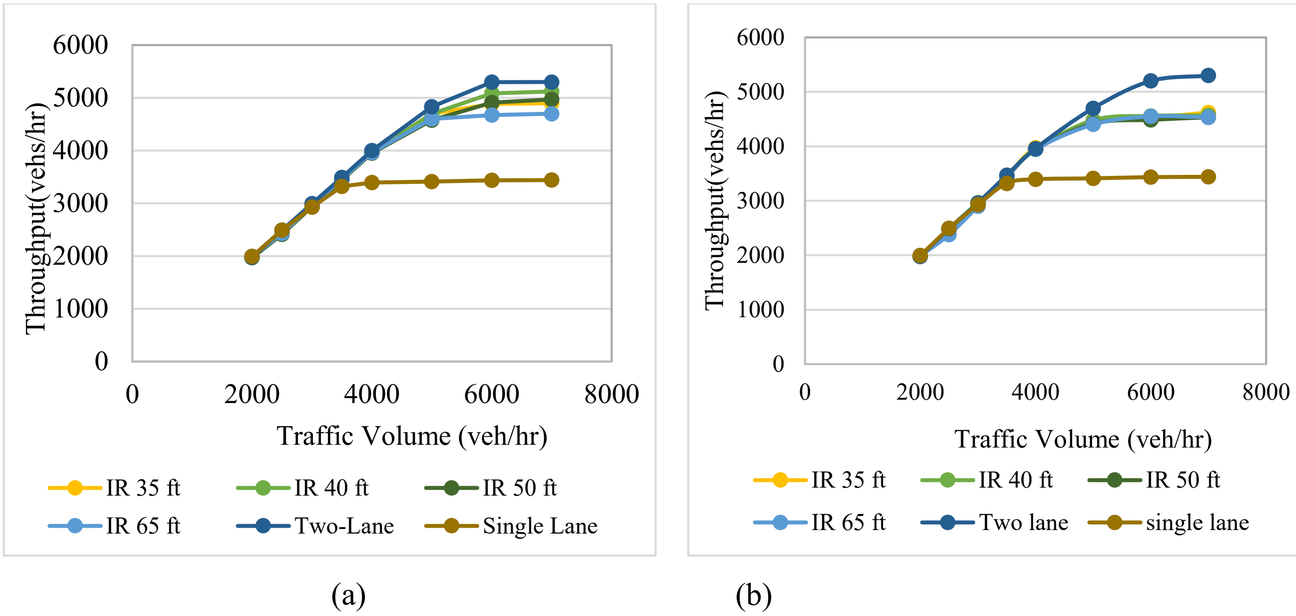


Figure 16: Traffic demand volume versus maximum throughput volume for (a) Basic turbo roundabout, and (b) Egg turbo roundabout.

3.3.2 Vehicular Delay under Different Traffic Demand Volumes and Left-Turning Vehicles

The difference between the actual travel time and the hypothetical (ideal) travel time is used to calculate the average delay, expressed as the total delay per vehicle. The hypothetical/ideal travel time is required to cross the entire route without any other vehicles, traffic controls, or other stops (Ardalan et al., 2020). In VISSIM, the average delay is the sum of control and geometric delay. Control delay is the delay (secs) caused by the driver decelerating on the approach to a queue, awaiting an acceptable gap to enter circular lanes as the first vehicle on the approach queue, and accelerating out of the approach queue. Delay experienced due to physical and basic traffic controls while navigating an intersection by a vehicle without any other vehicle's presence is considered geometric delays. This study calculated the average delay from each turbo roundabout approach entrance.

Presented in Figure 17 are average delays for four roundabout types under varying inner radii and traffic demand volumes. The plots depict a similar trend for turbo and two-lane roundabouts. For traffic demand volumes up to 3,500 vehs/hr, the average delay is below 5 secs/veh, mainly due to the stop line delay at the entrance of the circulatory lanes. On the other hand, there was a substantial jump in average delay for traffic demand volumes greater than 4,000 vehs/hr. However, a comparison among the varying radius designs (for basic and egg turbo roundabouts) depicts that the average delay is relatively similar. Overall, there are no major differences in average delay between the turbo roundabouts and the two-lane roundabouts. The single-lane roundabout experienced significant delays after the traffic demand volume of 3,000 vehs/hr (demand above single-lane roundabout's capacity).

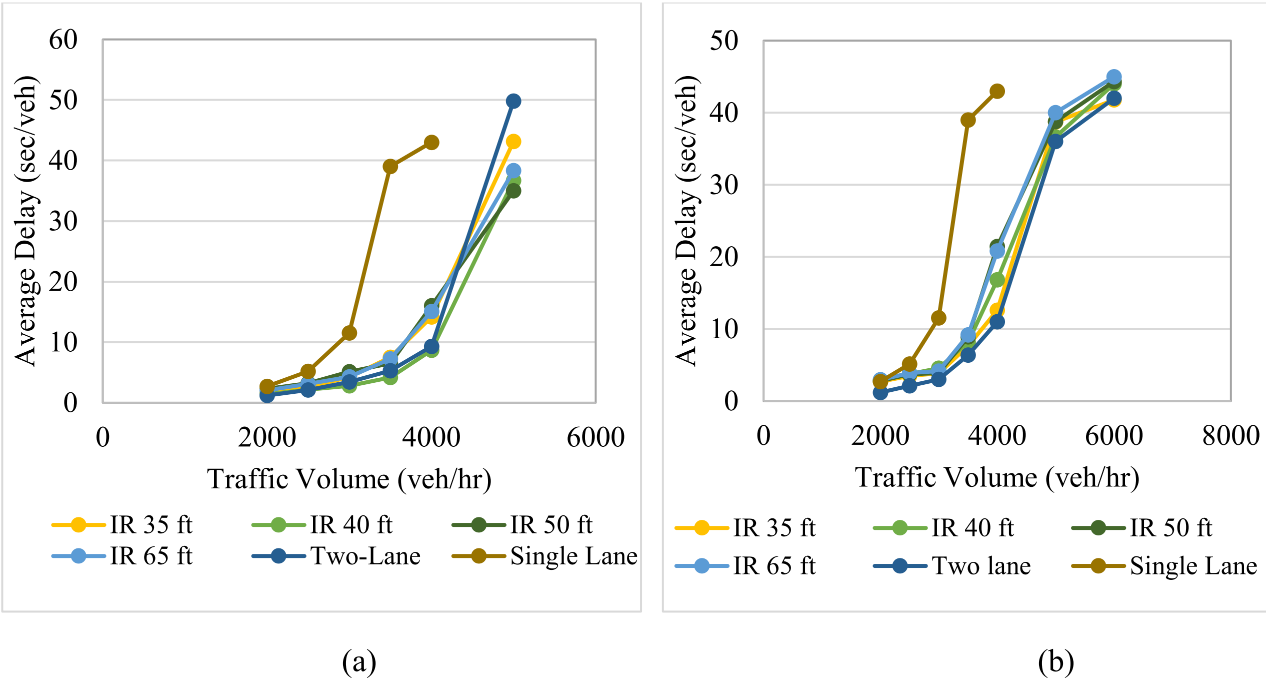
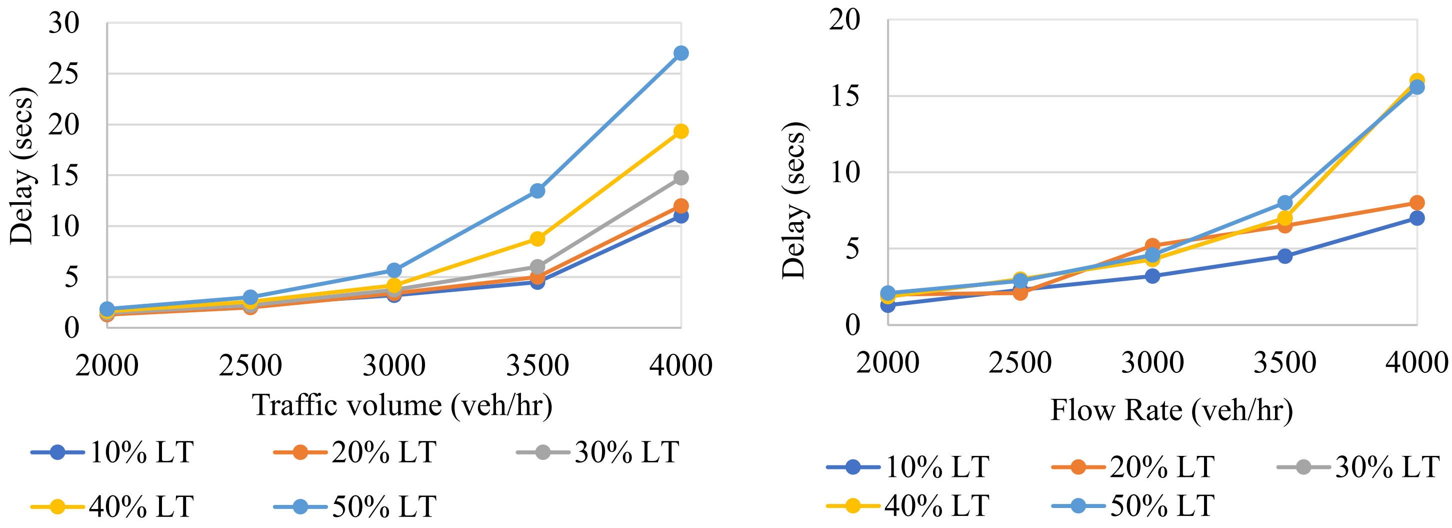


Figure 17: Traffic demand versus average delay for (a) Basic turbo roundabout, and (b) Egg turbo roundabout.

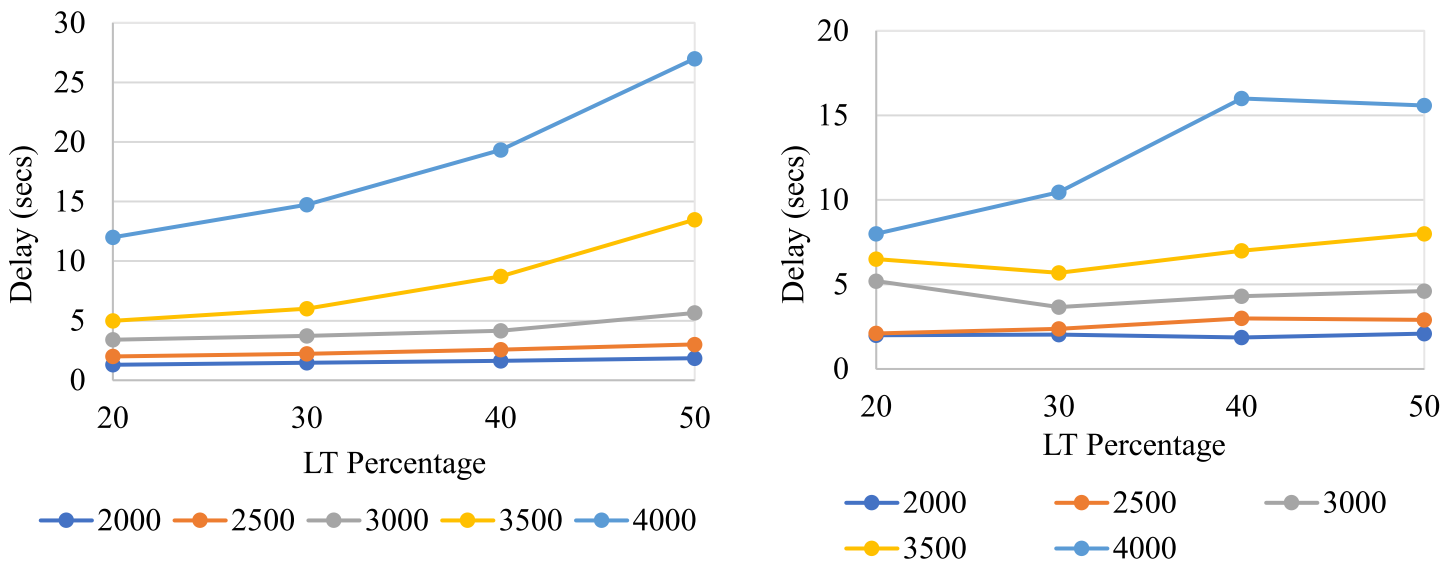
Figure 18 depicts the average delay under varying traffic demand volume and left turn percentages for major and minor approaches. A basic turbo roundabout with a 40 ft inner radius and major street-minor street volume split of 60%-40% was used to explore the effect of traffic demand volume and LT percentages on average delay. It can be observed that there are minor differences in average delay at different LT percentages on both major and minor approaches at traffic volume of 2,000-2,500 vehs/hr, and differences increase for traffic demand greater than 2,500 vehs/hr.

Similarly, Figure 19 presents the average delay for different LT percentages and traffic demands. A basic turbo roundabout with a 40 ft inner radius (R1) with a major street-minor street volume split of 60%-40% was used to demonstrate the effect of left turn percentages at different traffic volumes. The average delay at low left turn rates increased slowly with higher traffic volume. For traffic volumes between 2,000 vehs/hr and 3,000 vehs/hr, the delay was close to 5 secs/veh. A similar pattern was observed for both minor and major approaches. As left turn increased to 50%, there was a noticeable increase in average delay for traffic volume of 3,500 vehs/hr and above. Figure 19 shows that LT percentages had a greater impact on the delay at high traffic volumes than low traffic volumes. In addition, the minor approach observed lower delays than the major approach for all traffic demand volume scenarios.



(a) (b)

Figure 18: Delays for different traffic flow rates (a) Major Approach; (b) Minor Approach.



(a) (b)

Figure 19: Delays for different left turn percentages (a) Major Approach; (b) Minor Approach.

3.3.3 Turbo Roundabout Capacity

The capacity of a turbo-roundabout is an important measure for evaluating its suitability compared to other intersection control types. Past studies have reported a basic turbo roundabout capacity to be similar to or higher than a traditional two-lane roundabout and significantly higher than a single-lane roundabout (Fortuijn, 2009; Porter et al., 2019). Generally, the capacity of a roundabout depends on the capacity of each entering lane. Moreover, according to the theoretical roundabout capacity definition presented in *NCHRP report 672: Roundabouts: An Informational Guide*, roundabout entry capacity is a function of circulating or conflicting flow. Delay depends on circulating and entry flow rates for a specific roundabout geometric design and the corresponding critical gap value (Yin and Qiu, 2011).

Figure 20 (a) depicts the correlation between (i) average delay and (ii) circulating flow and entry flows at a basic turbo roundabout with an inner radius of 40 ft. Figure 20 (b) shows a schematic diagram of entry and circulating flow for the eastbound approach. Assuming level-of-service (LOS) E exists when the control delay is between 35 to 50 seconds (Rodegerdts et al., 2010), the capacity of a basic turbo roundabout will be between 3,070 and 3,400 pcu/hr with an average of 3,235 pcu/hr (Figure 20 (a)). Similarly, the capacity of an egg turbo roundabout was estimated to be between 2,450 pcu/hr and 2,890 pcu/hr, with an average of 2,670 pcu/hr.

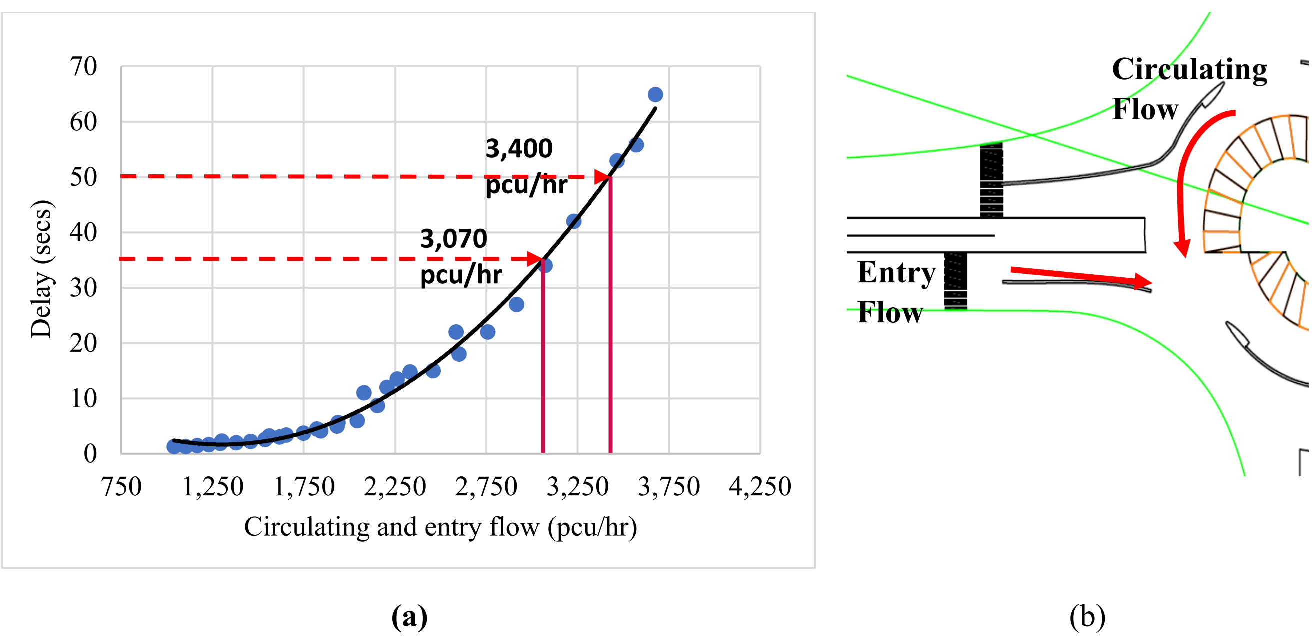


Figure 20: (a) Delay vs. the sum of circulating and entry flow; (b) example circulating and entry flow.

Table 3 summarizes the theoretical, observed, and simulated capacity values for single-lane, two-lane, basic turbo, and egg turbo roundabouts. Theoretical capacity is always higher than the observed and simulated capacity, whereas the simulated and observed capacity is relatively similar. It is evident that the capacity of a basic turbo roundabout is consistently higher than that of traditional two-lane and single-lane roundabouts, and the capacity of an egg turbo roundabout is consistently higher than that of a single-lane roundabout.

Table 3: Comparison of the capacity of the roundabouts

Roundabout Type	Theoretical Capacity [a] (pcu/hr)	Observed Capacity [a] (pcu/hr)	Simulated Capacity [b] (pcu/hr)
Single-lane Roundabout	2,700	2,000	2,250
Two-lane Roundabout	4,000	3,500	3,300
Basic Turbo Roundabout	3,800	3,500	3,400
Egg Turbo Roundabout	--[c]	2,800	2,890

[a] Field observed and theoretical capacity values under peak hour operations, collected from Overkamp & van der Wijk, 2009; [b] Capacity calculated from VISSIM simulation and delay curve; [c] No past studies reported theoretical capacity of egg turbo roundabout.

3.3.4 Impact of Pedestrians on Turbo Roundabout Performance

As roundabouts have been installed in urban and rural environments, it is important to understand the impacts of pedestrian presence on turbo roundabouts' performance. Three simulation scenarios (i.e., no ped, 200 peds/hr, and 400 peds/hr) were developed by distributing pedestrians equally on four crosswalks on four approaches. The scenarios were developed for different traffic demand volumes with a major street-minor street volume split of 70%-30% and a left turn percentage of 20%. The results showed that the average delay did not change substantially due to pedestrian presence within a basic turbo roundabout's capacity (up to 3,400 veh/hr). To demonstrate the effect of pedestrian volume on delay, Figures 21 and 22 present results for a basic turbo roundabout with an inner radius of 35 and 65 ft, respectively, with 0, 200, and 400 peds/hour.

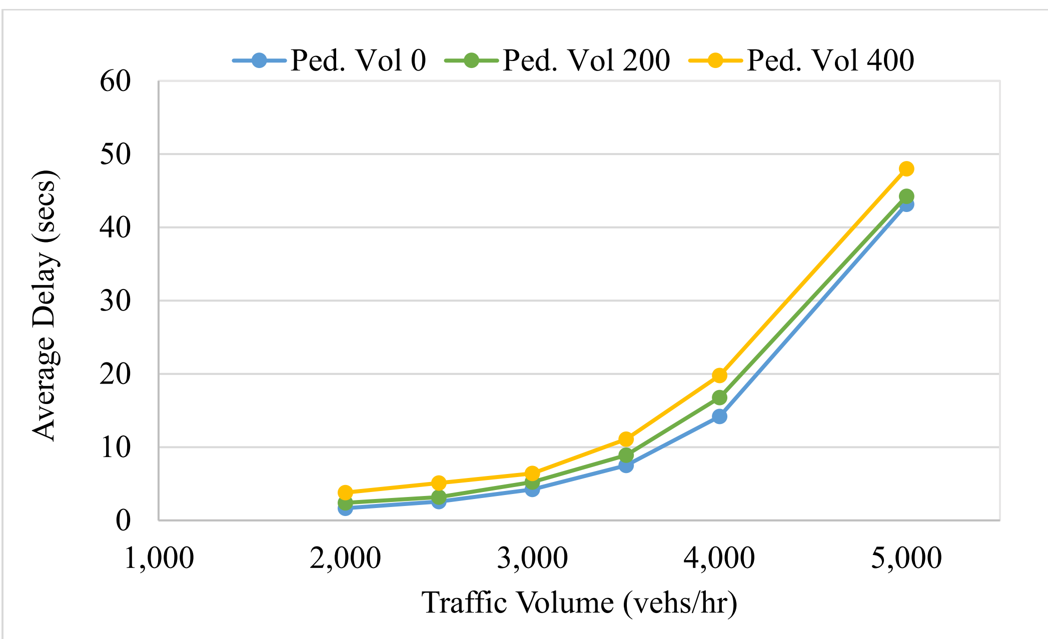


Figure 21: Average delay at different pedestrian volumes (IR-35 ft).

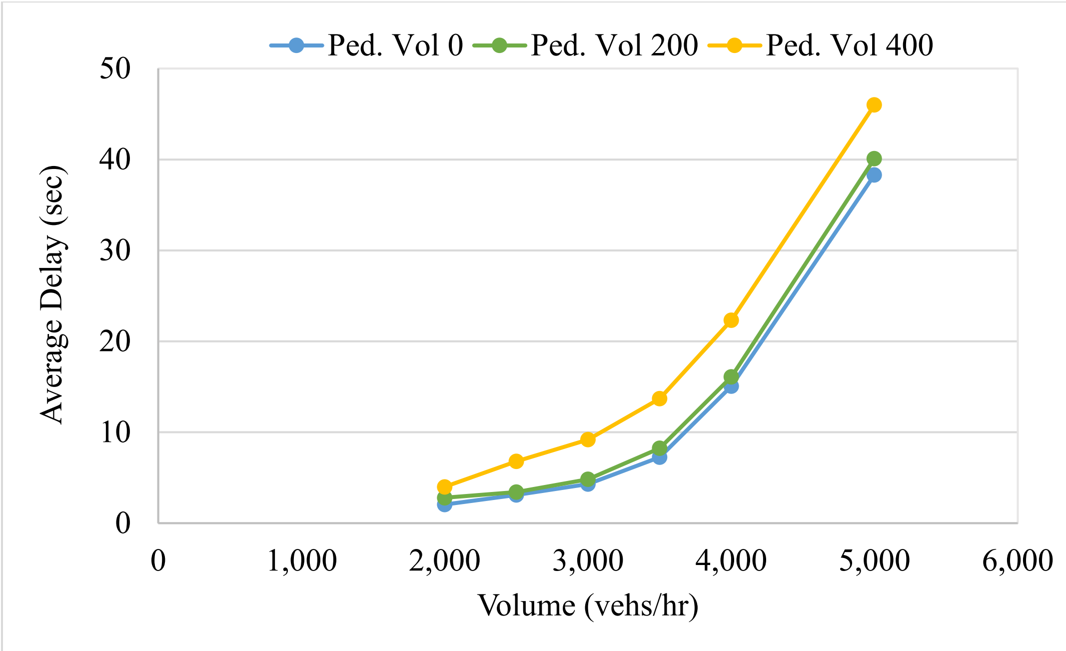


Figure 22: Average delay at different levels of pedestrian volumes (IR- 65 ft).

3.3.5 Turbo Roundabout Safety Performance

This study adopted a surrogate safety analysis approach to estimate simulated traffic conflicts. Vehicle trajectories obtained from the VISSIM simulation models were post-processed with the Surrogate Safety Assessment Model (SSAM) software to estimate traffic conflicts. The output from SSAM is based on two widely used surrogate safety performance measures, time-to-collision (TTC) and post-encroachment time (PET). TTC is the minimum time between two vehicles before a collision if both vehicles' trajectories are not altered. PET is the time difference between the first vehicle exiting and second vehicle's arrival at the conflict spot. Based on past studies (e.g., Giuffrè et al., 2021), the TTC value was set to 1.5 seconds to identify a conflict (i.e., a high collision probability). Figure 23 shows the total number of conflicts calculated at different traffic volume levels for the basic turbo, egg turbo, single-lane, and two-lane roundabouts. As observed, conflicts increased with higher traffic volume for all roundabout types. The relationship is not linear as conflicts have almost doubled between 3,000 vehs/hr and 3,500 vehs/hr. The total number of conflicts was much higher in single-lane roundabouts than in basic and egg turbo roundabouts. The number of conflicts for a single-lane roundabout increased exponentially beyond 2,500 vehs/hr. Additionally, Figure 23 depicts that considering all traffic demand volume scenarios, a basic turbo roundabout reduced traffic conflicts by 18-30% compared to a traditional two-lane roundabout. On the other hand, there was 1-6% conflict reduction with an egg turbo-roundabout compared to a two-lane roundabout.

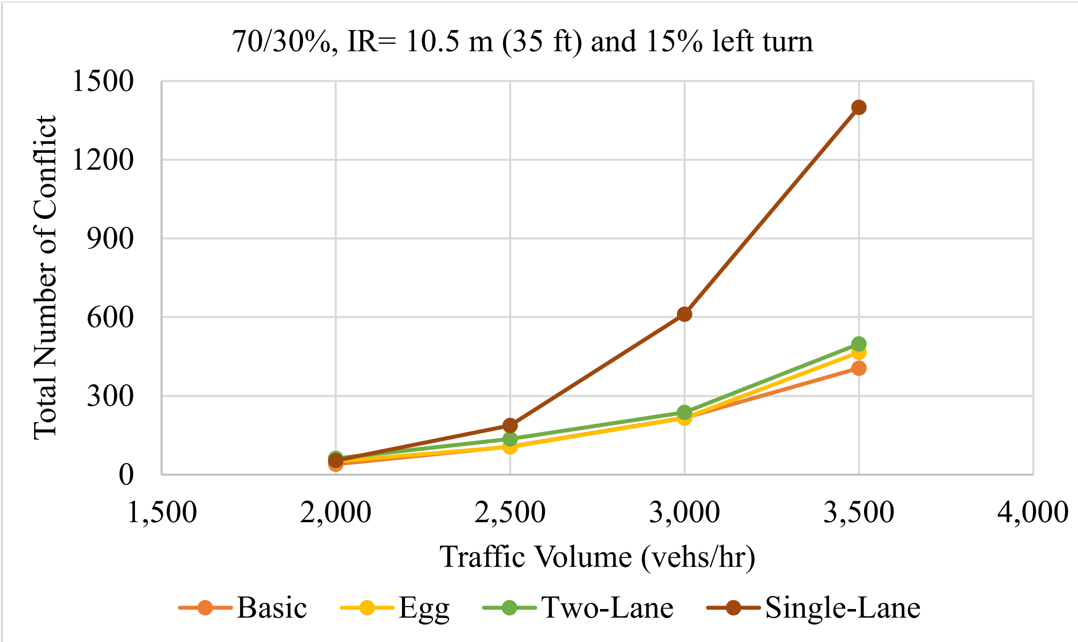


Figure 23: Total conflicts at different traffic demand volume scenarios for Basic and Egg turbo roundabouts.

Figure 24 shows the number of conflicts at different traffic volumes for five LT volume scenarios. The number of conflicts increased with the higher LT percentages. The difference was small for traffic demand volumes between 2,000 and 2,500 vehs/hr. The effect of LT percentages increased significantly with higher traffic volume. For the traffic volume of 3,500 vehs/hr, the number of conflicts for 50% left turn percentage was nearly five times compared to the 10% LT percentage.

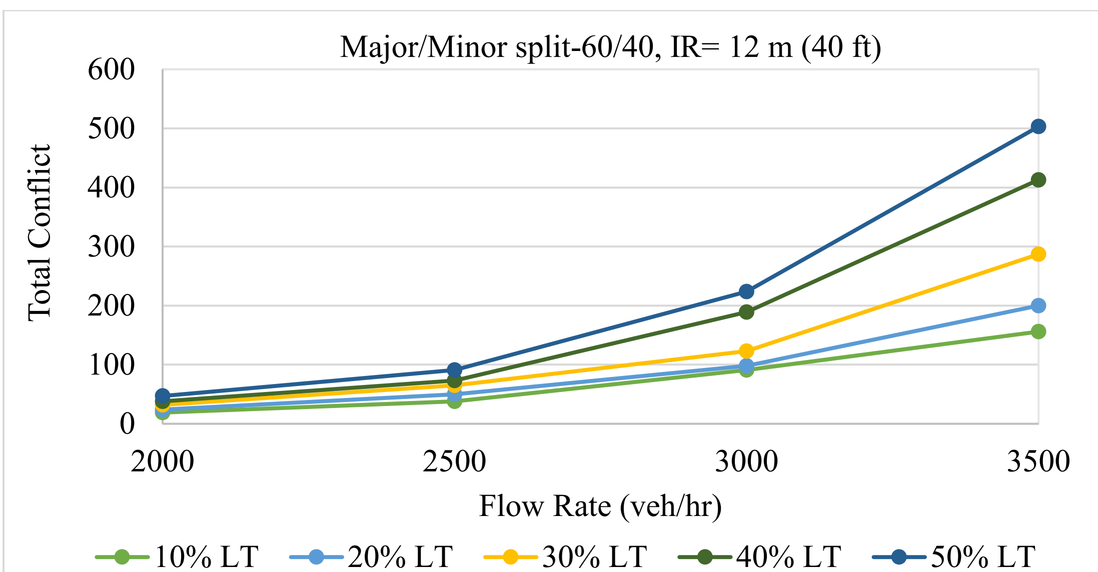


Figure 24: Total conflicts at different traffic demand volumes for Basic and Egg turbo roundabouts under varying left turn percentages.

3.4 Summary of Microsimulation Analysis

Turbo roundabouts' operational and safety performance was compared with traditional single-lane and two-lane roundabouts to assist NDOT in selecting the proper intersection control. Seven hundred twenty simulation scenarios were developed considering variations in turbo roundabout types, inner radii, traffic volumes, major-minor street split proportions, left turn percentage, and pedestrian volumes. Based on the microsimulation-based operational and safety analysis conducted in this study, the major findings can be summarized as follows:

- Based on microsimulation analysis, the simulated capacity of single-lane, two-lane, egg turbo, and basic turbo roundabouts are 2,250 pcu/hr, 3,300 pcu/hr, 2,890 pcu/hr, and 3,400 pcu/hr, respectively.
- The inner radius of a turbo roundabout did not impact the operational performance substantially as throughput and delay were similar for the inner radius ranging from 35 to 65 ft.
- For both two-lane and turbo roundabouts, average delay increased significantly for traffic demand volumes greater than 3,500 vehs/hr as demand exceeds capacity.
- Left turn percentages of 10-20% caused minimum delays up to 3,500 vehs/hr traffic demand volume. However, delays increased substantially above 3,500 vehs/hr, and left turn percentages of 30%.
- The average delay in a turbo roundabout did not change substantially due to pedestrian presence on approach crosswalks.
- Based on surrogate safety analysis findings, basic and egg turbo roundabouts were safer than traditional two-lane roundabouts. A basic turbo roundabout experienced 18-30% less, and an egg turbo roundabout experienced 1-6% fewer conflicts than a two-lane roundabout.

CHAPTER 4: DRIVER BEHAVIOR IN NAVIGATING TURBO ROUNDABOUT

Turbo roundabout design offers promising improvement in terms of intersection crash reduction. However, from a human factors' perspective, what is the best design alternative considering the complex driving behavior (that differs within any driver population based on factors such as age, gender, and years of driving experience, among others) is often overlooked, which limits the achieved benefits and effectiveness of safety improvements. Specific to roundabout designs, one of the factors that negatively affect the adoption of roundabouts is public attitudes (FHWA, 2018). McKnight et al. (2008) hypothesized that confusion in navigating a roundabout would depend on the amount of knowledge of the driver. Drivers who oppose roundabouts and those who are not confident in navigating the intersection were also found to have less knowledge of proper navigation. Fear of roundabouts has been found in different studies and thought to be a product of driver confusion, vulnerability, and lack of navigational understanding (Shrestha, 2002; Savolanien et al., 2012). Therefore, in developing design guidelines for any roadway facility– in this case, turbo roundabouts – it is important to incorporate the drivers' experience, especially since any advantages (or disadvantages) attributed to the facility depend upon drivers' understanding and behavior. In transportation engineering, driving simulators (i.e., human-in-the-loop simulations) have been used to study different roadway geometric designs and their alternatives, study signal controls, study signs and pavement markings, collision studies, distracted driving, or only for visualization and training purposes (Allen et al., 2012; Sahami & Sayed, 2013).

As such, this chapter presents the results of the driving simulator study that investigated the driver experiences in navigating a turbo-roundabout compared to a traditional two-lane roundabout. The goal was to gain insight – from a human factors' perspective – into any differences between driver performances with the navigation of a turbo roundabout compared to a traditional two-lane roundabout.

4.1 Driving Simulator Experiment Design

A set of driving simulator scenarios was developed to investigate driver behaviors where drivers would encounter two commonly adopted turbo designs – basic and egg- and a traditional two-lane roundabout. These experiments were performed using a level 3 driving simulator at the Safety & Human Factors Facility, Ohio University. Recruited participants drove through the simulator scenarios in the driving simulator experiment. As each participant drove a simulation scenario, different driving experience/performance data (e.g., gap acceptance, speed choice, braking pattern) were recorded and compared among three roundabout designs (i.e., traditional two-lane, basic turbo, and egg turbo roundabouts). Additionally, a pre-and post-driving simulator experiment survey was executed to quantify user understanding and perceptions/acceptance of turbo-roundabouts. Figure 25 presents a flowchart that summarizes the general experiment process adopted. Interested readers can reference specific details in Appendix B.

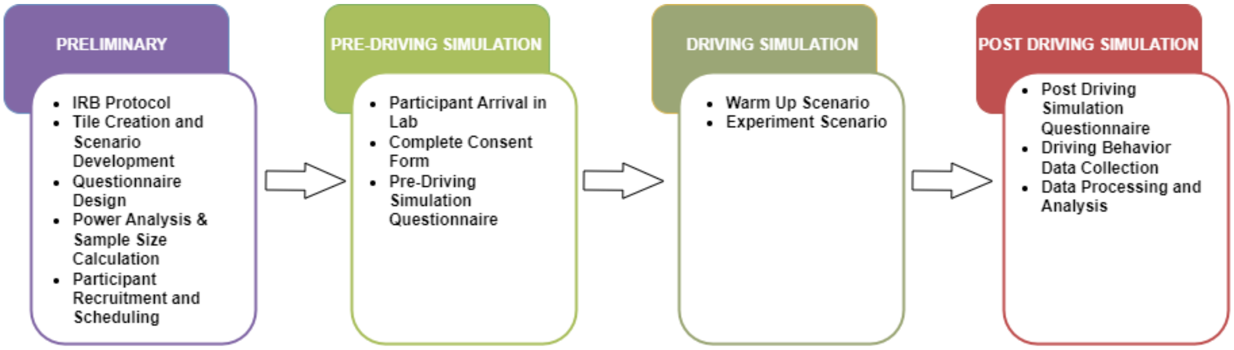


Figure 25:Flowchart of driving simulator experiment.

4.1.1 Driving Simulator

This study was conducted using a DS-600 DriveSafety driving simulator (DriveSafety, 2024). The simulator is a partial Ford Focus vehicle featuring a full-width interior, equipped with driver and passenger seats, and standard driving controls, including a steering wheel, brake pedal, gear control, dashboard, and other components typically found in a conventional automobile. The visual display system utilized three projector screens (1,024 X 768 pixels of resolution), offering a 180-degree field of view to provide drivers with an immersive and realistic view of the software-generated road environment, as depicted in Figure 26.

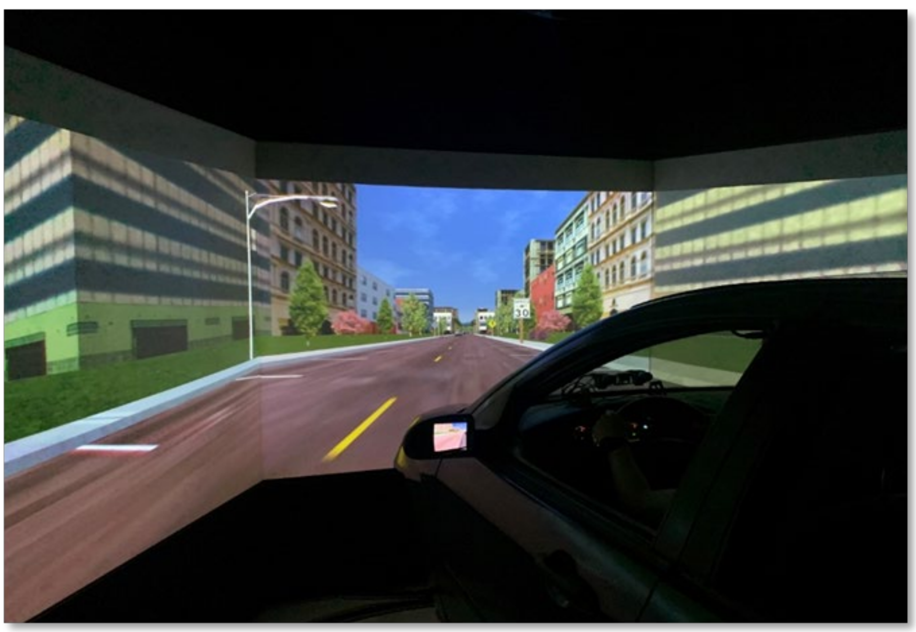


Figure 26: Driving scenario during simulation.

4.1.2 Simulation Scenario and Driving Task

The scenario was designed to reflect real-world driving environments; hence, a typical environment consisted of roundabouts in rural, urban, or suburban locations, with various land use types along the route. Traffic conditions included a mix of transportation modes, including bicycles, pedestrians, motorcycles, vehicles of different classifications, and day/night scenarios.

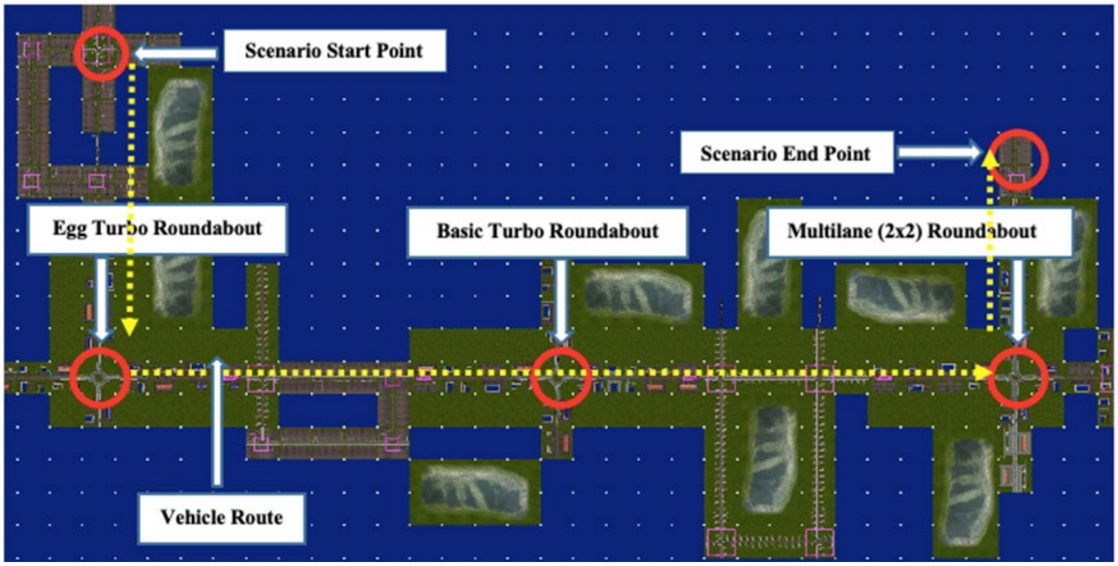


Figure 27:Driving path for simulation scenario.

Since turbo roundabouts were the treatments of interest, all drivers drove through a basic turbo roundabout, an egg turbo roundabout, and a two-lane roundabout (Figure 27). At each roundabout, drivers were offered gaps between successive oncoming vehicles on all roundabouts. Drivers' gap acceptance and rejection times were recorded as they decided whether to accept or reject a gap.

4.1.3 Experiment Procedure and Driving Task

Study participants were 18 years and older with a valid U.S. driver's license and required to have two years or more driving experience to participate in driving simulator experiments. The appropriate sample size was calculated based on a desired power of 80%, which was selected due to the need to balance the power and the cost-effectiveness (Sheta et al., 2020). Based on the previous studies and power analysis, a minimum of 25 participants was required for this study. A total of 24 participants were included in the final data analysis, which is consistent with similar past studies.

The driving simulation experiment took approximately 40 minutes to complete. Participants were required to complete a consent form outlining the study's purpose and the associated risks and discomforts of driving in the simulator before participating. Participants received no specific instructions except to follow traffic rules and drive as they normally would in a real environment. They were instructed to get comfortable with the vehicle controls and drive as they would in real life. The participants drove through a series of roundabouts, and driving performance data was recorded for each movement as they drove through the scenario. Data on drivers' behavior, such as gap acceptance and lane decisions, were recorded.

4.2 Human Factors Assessment Results

4.2.1 Driver Behaviors

The critical gap is an important parameter in estimating a roundabout's capacity, and it is measured by the minimum time gap accepted by a driver when entering the roundabout's circular lanes (Lee et al., 2018). Using a revised Raff's method, this study calculated critical gaps for the basic and egg turbo roundabouts and the two-lane roundabout. A detailed formulation of Raff's method is presented in Appendix B.

Accepted and rejected gaps by each participant were collected for three different roundabout types (i.e., basic turbo, egg turbo, and two-lane). Then, Raff's method was used to the critical gap (Raff et al., 1950). A paired samples t-test was conducted to assess statistical differences between the accepted gaps among the three roundabout types. The following results and observations were inferred:

- The average accepted gap on the egg turbo roundabout (M = 7.13 secs, SD = 2.15) was statistically significantly higher (1.21 secs) than the average accepted gap on the basic turbo roundabout (M = 5.92 secs, SD = 1.91).
- The average accepted gap on the egg turbo roundabout (M = 7.13 secs, SD = 2.15) was statistically significantly higher (1.73 secs) than the average accepted gap on the two-lane roundabout (M = 5.32 secs, SD = 1.32).
- The average accepted gaps were not statistically significantly different when comparing the basic turbo roundabout and the two-lane roundabout (M = 0.41 secs, SD = 1.76, t = 1.09, p = 0.289, df = 21).

Further analysis of the accepted and rejected gaps was performed to determine a critical gap for each roundabout type. The calculated critical gap values were 4.2 secs, 6.1 secs, and 3.9 secs for the basic turbo, egg turbo, and two-lane roundabouts, respectively. Note that the estimated critical gap for the two-lane roundabout in this study directly compares to estimated field values from previous research – 3.1 to 4.7 seconds by Clara and Castaneda (2018), and provides validation for the virtual environment created in the driving simulator and can be deemed a reliable tool for estimating the critical gap values for the turbo roundabouts in this study.

Speeds (approach, circulating, and departure) Behaviors – participants' speeds navigating turbo roundabouts and two-lane roundabouts were analyzed. The speeds followed by study participants were recorded along the entry approach lanes, on circular lanes, and along the departure approach lanes at 100 ft intervals. Figures 28 and 29 depict the study participants' average and 85th-percentile speed profiles.
A visual inspection of both (50^{th} and 85^{th} percentile) speed profiles shows an expected driving behavior in navigating different roundabouts. Speed profiles for three roundabout types follow the typical speed behavior expected for roundabouts and align with previous research (Fernandes et al., 2016). The typical driver behavior involves drivers reducing speed on a roundabout approach, entering and negotiating the circular lanes, and then accelerating to their desired (or posted) speed on departure from a roundabout. A closer look at the profiles depicts that the curve for the basic turbo roundabout (both at entry and departure) is "smoother" and does not have irregular spikes. In addition, speeds are relatively lower for the basic turbo roundabout than that of the two-lane roundabout along the approach leg. These results suggest that participant drivers were more comfortable navigating the basic turbo roundabout (smoother speed profile). The profile for the egg turbo suggests some concern with participant drivers' ability to navigate the roundabout comfortably and safely. In addition, the speeds among the roundabout alternatives were compared statistically, and the participants' self-reported speeding behaviors were analyzed. Refer to Appendix B for the specific results.

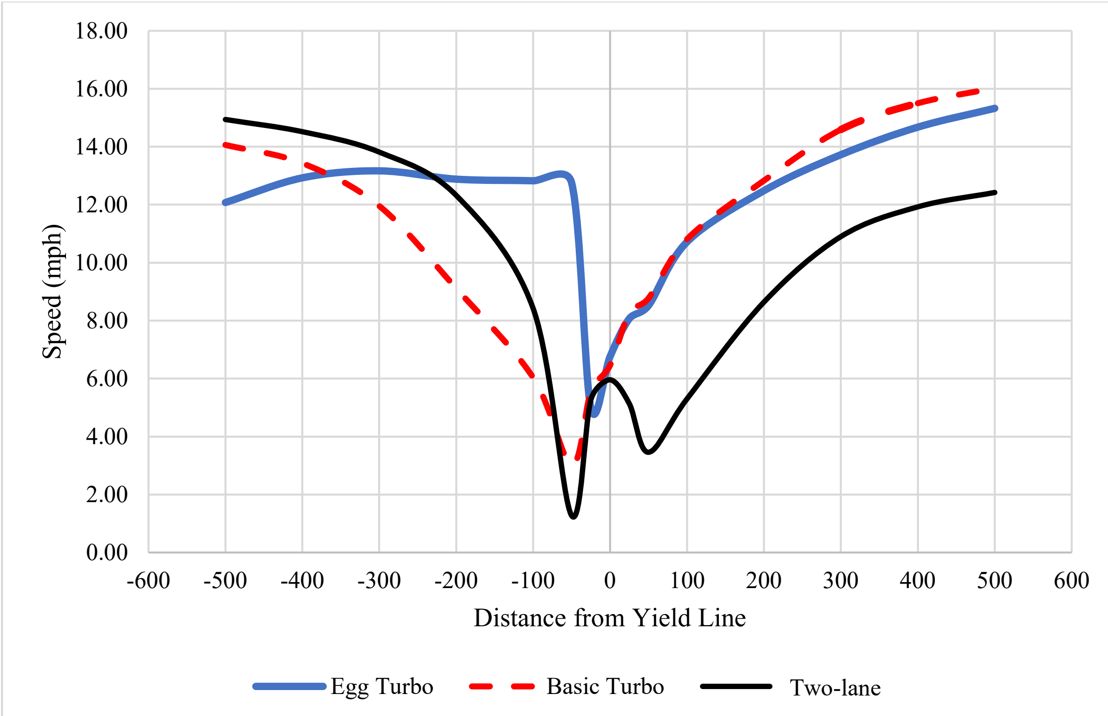


Figure 28: Average speed profiles of participant drivers.

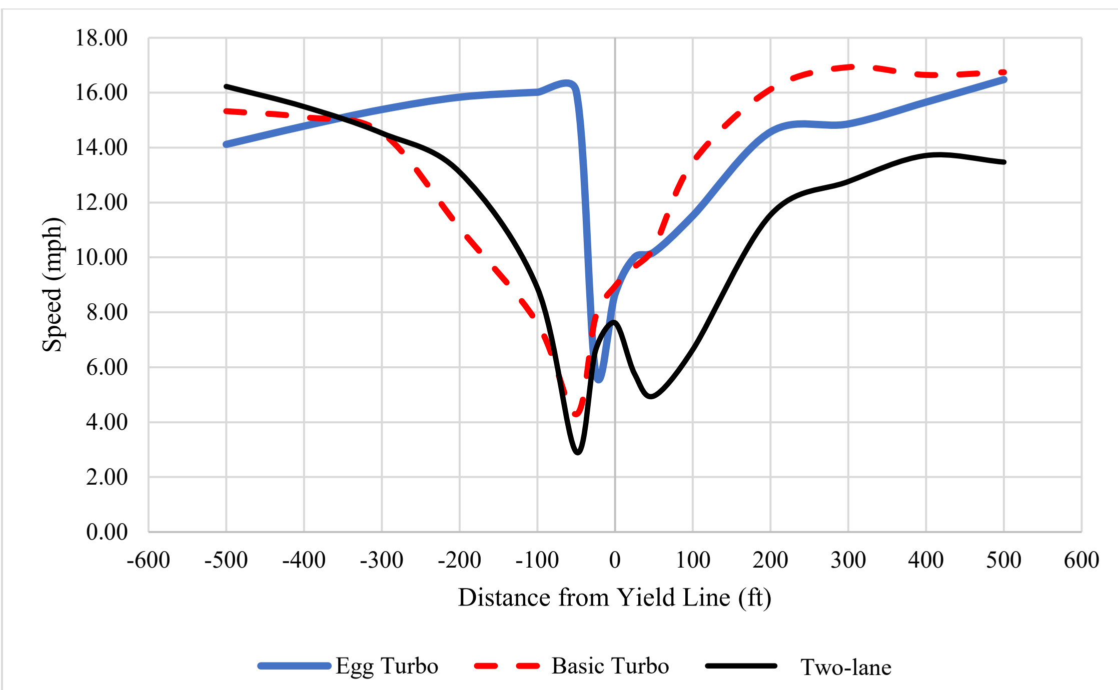


Figure 29: 85th Percentile speed profiles of participant drivers.

4.2.2 Driver Perception Towards Turbo Roundabouts

In addition to the driving performance data from the driving simulator, a pre-and post-driving simulation survey was conducted to understand participants' familiarity, navigation comfort level, and preference for different roundabouts. The survey (Appendices C and D) consisted of 33 questions in two major parts. Each volunteer driver completed the pre-test survey, then participated in the driving simulator experiment, and finally completed the post-test survey. Key survey findings are presented below. Appendix B explains details of the driving simulator experiments.

- 75% of the participants were familiar with single-lane roundabouts and two-lane roundabouts. Thus, it was evident that a large proportion of participants had some level of experience with traditional roundabouts. However, 88% of participants were not familiar with turbo roundabouts, with only 13% mentioning mixed feelings (felt neutral) about their knowledge of turbo roundabouts.
- Regarding the level of familiarity with roundabouts, each participant's specific comment(s) were categorized into three themes: (1) *lack of knowledge or experience with turbo roundabouts*, (2) *limited exposure to multi-lane roundabouts*, and (3) *general uncertainty or lack of confidence in navigating roundabouts*. Based on matching the themes and comment(s), the overall results suggested that participants had varying levels of familiarity with roundabouts, with experience mainly with traditional single and two-lane roundabouts. As expected, participants generally had little or no knowledge of turbo roundabouts, suggesting a likelihood of benefiting from additional education and training on the different types of roundabouts and strategies for navigating them safely and confidently.
- With respect to preferred methods of receiving education and training on turbo roundabouts, 71% of participants indicated social media platforms as a preferred avenue to receive information regarding the operations of turbo roundabouts. Traditional media (radio and television) was the second most preferred method (i.e., 67% of responses). Other preferred methods were as follows: 50% preferred dissemination of information through a driver's license manual, 42% through a driving course/class, 46% were in favor of using information brochures, and 58% stated the use of webinars and video demonstrations. It should be noted that many participants were less than 40 years of age and more prone to using technology such as smartphones, tablets, laptops, etc., that support social media and other tech-savvy media broadcast platforms.
- 76% of participants perceived roundabouts (in general) as safe from a driver's perspective, while 25% were neutral. From a cyclist's perspective, 17% agreed that roundabouts were safe, while 58% were neutral. Lastly, 37% stated that roundabouts were unsafe for pedestrians, while 38% were neutral.
- After driving through the turbo roundabouts in the driving simulation experiment, 63% of participant drivers did not oppose the installation of turbo roundabouts in their community. In comparison, 37% were undecided or opposed to installing turbo roundabouts. Regardless, there was a high willingness among drivers (86%) to receive additional information and education on turbo roundabouts if a turbo roundabout was constructed in their communities.
- While 68% of participant drivers wanted to be able to switch lanes within a roundabout – especially when they are in the wrong lane, 76% found the presence of a lane divider on a turbo roundabout as a useful feature to discourage lane changing.

- 72% of participant drivers agreed to install pavement markings before approaching a turbo roundabout and adequate signage to enhance visibility and aid in lane selection for desired travel direction. It appears that even though lane dividers were present on the turbo roundabouts in the simulation, lane-changing conflicts were still of concern to drivers.
- Nearly half of the respondents (47%) agreed with keeping the diameter of a turbo roundabout small to encourage lower speeds. A similar percentage of drivers (43%) favored having mountable truck aprons to allow for sufficient maneuvering space for larger vehicles.
- 67% of participant drivers felt confident in selecting the correct entry lane, while 34% were neutral or not confident. With respect to merging onto the circulatory roadway, 79% of participant drivers felt confident in their ability to merge onto the circulatory roadway by identifying suitable gaps. In comparison, only 21% were either neutral or not confident. Lastly, 88% of participants felt confident in traversing the circle, while almost 96% felt confident in their ability to exit the turbo roundabouts in their intended direction.
- 96% of participant drivers reported being aware of pedestrians on crosswalks when approaching a roundabout. While 67% of participants reported being cautious of pedestrians when exiting a roundabout, all the drivers did not expect a pedestrian on the circulatory roadway of a roundabout and hence did not think to watch out for pedestrians on the circulatory lanes while navigating roundabouts.

CHAPTER 5: IMPLEMENTATION PLAN

This study conducted operational and safety analysis and driving behavior experiments to measure the effectiveness of the turbo roundabout compared to traditional two-lane and single-lane roundabouts. An implementation plan can help determine the most suitable intersection locations for turbo roundabout pilot deployment and enable NDOT to integrate turbo roundabout alternatives as intersection control options. This chapter presents a pilot field demonstration plan for turbo roundabouts in Nevada. The outcomes of a research project can be one of five stages- (1) Concept stage, (2) Laboratory prototype stage, (3) Controlled field demonstration stage, (4) First application (contract) field pilot stage, and (5) Specification and standards with full corporate deployment stage. This project is identified as the stage 2 "Laboratory prototype" project, as major research tasks were executed in microsimulation and driving simulator environments. This implementation plan aims to define the next steps/initiatives necessary to accomplish stages 3 to 5.

After this project, NDOT could explore a pilot turbo roundabout deployment. For the pilot deployment and subsequent turbo-roundabout performance evaluation in real-world traffic environments, an implementation plan can be executed following four steps (outlined in Figure 30). The steps for the implementation plan are described below:

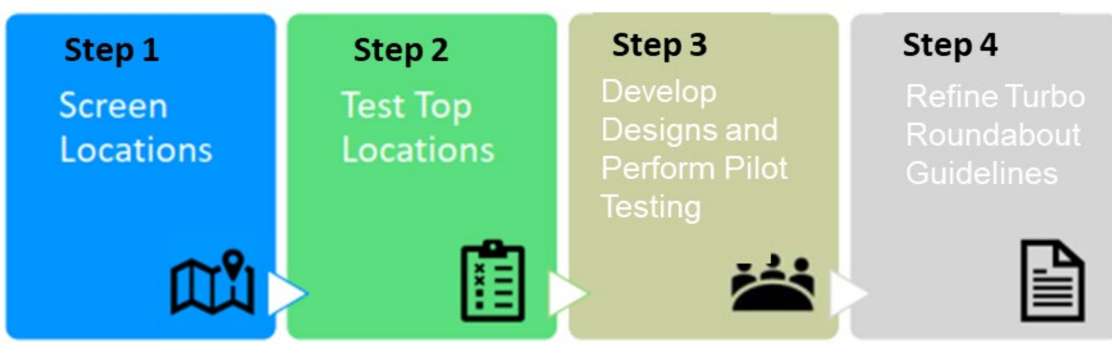


Figure 30: Flowchart showing the implementation steps (Source: City of Rancho Cordova, 2023)

Step 1: Screen Candidate Intersections

The first step in the implementation plan is to identify a list of candidate intersections for potential turbo roundabout installation. Current and design year traffic demand, surrounding land use, current intersection geometric characteristics, and crash history (e.g., higher sideswipe crashes at an existing two-lane roundabout) can be used as screening criteria. Intersections with traffic demand volume higher than the capacity of a turbo roundabout should be excluded from the list. In addition, intersections that have more than two entry lanes should be excluded, as widely used basic and egg turbo roundabout types have a maximum of two entry lanes on major approaches. A ranking approach can be applied to rank the intersections based on the overall traffic operational and safety improvement potentials. Intersections with the highest scores should be considered for further investigation in Step 2.

Step 2: Comparison of Top Candidate Intersections

During this step, further evaluation (e.g., pre-construction evaluation) of selected candidate intersections (from Step 1) can be performed to identify the most suitable intersection(s) for pilot turbo roundabout deployment. Criteria such as right-of-way availability for design vehicles, construction and maintenance cost, and funding availability can be used to narrow down the most suitable intersection(s) for pilot deployment.

Step 3: Develop Designs for Construction and Execute Pilot Deployment

Once pilot deployment intersection(s) are finalized, preliminary design alternatives of the turbo roundabout can be compared using the intersection control evaluation (ICE) tool developed in this project to identify the best turbo roundabout design alternative. A bid package can be developed with a detailed design and cost estimates to select the most qualified contractor. Following the pilot turbo roundabout(s) construction, continuous safety and operational performance monitoring should be conducted by collecting field performance data. User experience surveys can be executed to identify users' experiences, perceptions, and navigation challenges. As monitoring of the pilot site continues, key observations and findings can be documented to revise design practices and improve effectiveness. By the end of the analysis period, lessons learned throughout planning, construction, and field performance evaluation can be further documented to facilitate continuous improvement of turbo roundabout design practices.

Step 4: Gather Feedback and Refine Turbo Roundabout Guidelines

Based on the field performance evaluation and lessons learned from the pilot deployment(s), educational materials, turbo roundabout design, and construction guidelines can be updated. The primary target audience/users of this project's research findings are NDOT's intersection improvement planning personnel and consultants. Additional stakeholders related to turbo roundabout deployment (e.g., NDOT divisions, local agencies, Department of Public Safety/DPS, and Department of Motor Vehicles/DMV) should be identified and educated on turbo roundabouts and lessons learned using updated educational materials. An educational outreach initiative for road users about the benefits of turbo roundabouts and navigation rules can be executed through the most popular public information sources, such as social media platforms and DMV educational programs.

Educational Materials: Transportation agencies conduct public outreach activities to educate the general public about new forms of intersection controls (e.g., mini roundabout, turbo roundabout) before deployment. Generally, a multi-prong approach to reach a maximum number of citizens is recommended as there are differences in how people receive news (e.g., social media, radio, television, print media). This project developed two educational materials (i.e., flyers and recorded presentation) summarizing turbo roundabouts' unique design and operational features to inform Nevada transportation engineers, planners, and consultants. The survey questionnaire used for feedback collection on educational materials is provided in Appendix F. Educational materials were revised for broader dissemination based on feedback from the NDOT project technical panel. Links to a short presentation and a two-page flyer are provided in Appendix F.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

As intersections are high-risk crash locations in a surface transportation network, converting traditional stop-controlled and signalized intersections to roundabouts has become a popular practice in the US. The significant benefits of roundabouts include reducing crash frequency and severity, capacity improvement, and operational improvement. Microsimulation and driving simulator-based driver behavior analysis were executed in this study to compare the performance of traditional single-lane and two-lane roundabouts and basic and egg turbo roundabouts. For microsimulation analysis, 720 simulation scenarios were developed by varying turbo roundabout designs (i.e., turbo types, inner radius), traffic demand volume, major street and minor street traffic split, left turn traffic percentage, and pedestrian volumes. Geometric features of basic and egg turbo roundabouts and traditional single-lane and two-lane roundabouts were designed using TORUS software. Operational and safety analyses of the designed roundabout and traffic scenarios were conducted using the VISSIM simulation platform to compare the benefits of turbo roundabouts to those of traditional roundabouts. A set of driving simulator experiments were performed to quantify driver behavior and challenges in navigating the turbo roundabouts. An intersection control evaluation (ICE) tool was developed to identify the best-performing roundabout types at different current and future traffic demand levels. Based on the findings of microsimulation and driving simulator experiments, the following main recommendations are proposed for NDOT:

- Based on the capacity analysis results, a traditional single-lane roundabout can be implemented up to a traffic demand volume of 2,200 pcu/hr. When traffic demand volume is less than 2,800 pcu/hr, an egg turbo roundabout could be adopted as an intersection control option.
- Traffic microsimulation assessment showed that the simulated capacity was 2,890 pcu/hr for an egg turbo roundabout and 3,400 pcu/hr for a basic turbo roundabout, compared to the simulated capacity of 2,250 pcu/hr and 3,300 pcu/hr for a single-lane roundabout and a two-lane roundabout, respectively. While basic turbo roundabouts have a capacity similar to traditional two-lane roundabouts, basic turbo roundabouts showed higher safety performance (i.e., lower traffic conflicts). In addition, drivers' speed selection in navigating a basic turbo roundabout was lower and smoother than other roundabout types. Drivers were also confident in navigating turbo roundabouts.
- As both traditional two-lane roundabouts and basic turbo roundabouts had similar capacities, a basic turbo roundabout performs better up to a traffic volume of 3,400 pcu/hr considering diverse performance measures (i.e., delay, queue length, LOS, total conflicts). Based on capacity, a traditional two-lane roundabout can be implemented up to a traffic volume of 3,300 pcu/hr.
- Based on driving simulator experiment participants' responses to a pre-and post-driving simulation survey, most participant drivers did not oppose the installation of turbo roundabouts in their community. In addition, simulator experiment participants emphasized the importance of installing pavement markings before approaching a turbo roundabout and adequate signage to enhance visibility and aid in lane selection for desired travel direction. Despite drivers' unfamiliarity with turbo roundabouts, most participants felt confident in their ability to select the correct entry lane when driving through a turbo

roundabout. These findings support the NDOT's initiative to explore the installation of turbo roundabouts in Nevada.

CHAPTER 7: FUTURE RESEARCH DIRECTION

Based on this study's operational and safety analysis, a basic turbo roundabout performs better than a traditional two-lane roundabout. NDOT can consider a pilot implementation of a turbo roundabout to measure its real-world performance. This study can guide the design process and select appropriate study locations for the pilot implementation (as outlined in implementation plan). However, additional research emphasizing specific design features of turbo roundabouts will help traffic engineers improve turbo roundabout design and understand implementation challenges. Future studies presented below could provide in-depth understanding of the effect of signage, pavement marking, specific geometric features (e.g., lane opening, lane separator), and pedestrian treatments on turbo roundabout design and performance.

1. **Effectiveness of traffic signs and pavement markings on driver's lane choice in a turbo roundabout**

One of the standout features of a turbo roundabout is the lane divider that discourages/prevents lane-changing inside the circulatory lanes. Driving simulator experiments in this study revealed the participant's challenge in selecting the correct lane before entering the turbo roundabout to exit in the intended direction. Thus, effective traffic signs and pavement markings are important in driver navigational performance in turbo roundabouts. Future research should explore the effectiveness of different pavement markings and signs in drivers' lane choice decision-making and investigate the effectiveness of different pavement markings and signage in terms of driver understanding.

2. **Effect of circulatory lane opening and lane separator in drivers' speed choice in a turbo roundabout**

Driving simulator experiments revealed that smaller-diameter turbo roundabout encourages lower speeds. Past studies reported that turbo roundabout circulatory lane opening width and the lane separator type (raised or not) influence the driver's speed choice behavior. In addition, the Dutch turbo roundabout design recommends using a smooth curvature for the inside lane that matches the entering vehicle's path. However, this design approach led some vehicles from the right approach lane to enter the inner lane. A flat lane addition approach for the inside lane was installed to eliminate driver confusion. Future research should explore the impact of different turbo diameters, different circulatory lane opening widths, and lane separator types on the driver's speed choice to quantify the effects of circulatory lane opening and lane separator.

3. **Driver responses to different pedestrian treatments at turbo roundabouts**

Pedestrians face difficulties while navigating through roundabouts. Geometric features of a roundabout are designed to ensure speed reduction before and within the roundabout and speed increase after exiting the roundabout. Due to this phenomenon, driver yielding rates to pedestrians on the roundabout exit leg are low. Different pedestrian treatments (e.g., Pedestrian Hybrid Beacon/PHB, Rectangular Rapid Flashing Beacon/RRFB) can be installed to improve pedestrian safety and driver compliance rates. Future research could explore the effectiveness of these pedestrian treatments at a turbo roundabout.

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APPENDICES

Appendix	Description
A	Microsimulation Assessment
B	Human Factor Assessment
C	Pre-Driving Simulation Survey
D	Post-Driving Simulation Survey
E	Turbo Roundabout Selection Procedure: Multi-criteria Assessment
F	Survey on Educational Materials

APPENDIX A

MICROSIMULATION ASSESSMENT

1. Introduction

Traffic microsimulation-based analysis was conducted to evaluate the performance of select roundabout design alternatives based on operational and safety performance. A summary of the microsimulation assessment is presented in Chapter 3 of this report. This appendix presents site selection, data collection, turbo roundabout design procedure, and VISSIM model calibration and validation details.

2. Site Selection and Data Collection

2.1 Site Selection

Based on consultations with the project technical panel, one multi-lane roundabout in Nevada was identified for data collection and potential turbo roundabout installation in the future. The selected multi-lane roundabout is located at Neil Rd and Kietzke Ln intersection in Washoe County, NV (see Figure A-1). This intersection is located near the Interstate I-580 ramps on Neil Road. The North and South bound approach to this roundabout is Kietzke Lane. The East bound approach is Del-Monte Road, and the West bound approach is Neil Road. Most of the traffic on the South bound approach of Kietzke Lane originates from S McCarran Boulevard. On the West bound approach of Neil Road, traffic originates from the exit ramps of Interstate 580 and S Virginia Street, and the roundabout is located in an urban land-use environment.

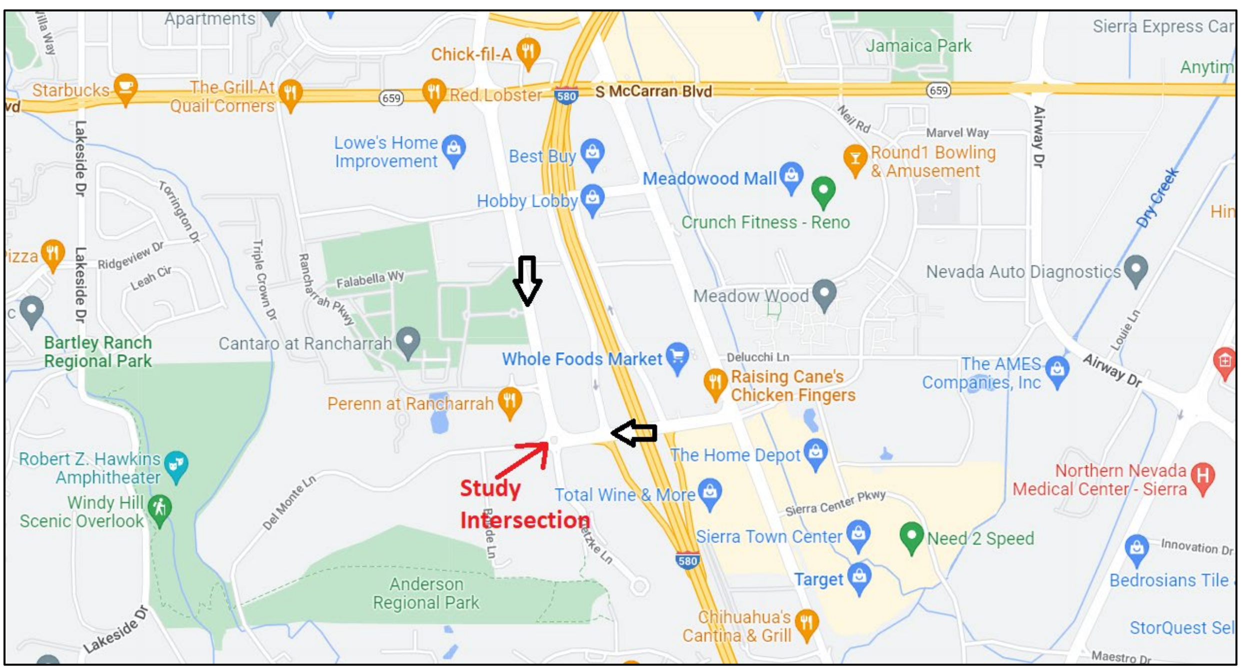


Figure A-1: Study Area Arial Map (**Source:** Google Maps)

The Google Earth image of the Neil Road and Kietzke Lane roundabout is shown in Figure A-2. The geometric properties of the roundabout were collected from Google Earth images and are summarized in Table A.1. The roundabout has four approaches, where the South and West bound approaches are the major approach with the highest traffic volume. The roundabout has two circulatory lanes from the north-to-south direction. The rest of the roundabout has only one circulatory lane. A dedicated right turn lane is present from the West bound approach to the North exit (Figure A-2). All the approach legs have two lanes except Del Monte Road, which has only one lane. The lane configuration for the approach and exit legs is shown in Figure A-3. The approach legs, circulatory lanes, and center island dimensions were measured from Google Earth. The inscribed circle diameter of the roundabout is 200 ft with a central island of 100 ft diameter and a traversable truck apron of 12 ft. All the entry lanes are 12 ft wide, and the circulatory lane is 15 ft wide.

Figure A-2: Two-lane Roundabout at Neil Road and Kietzke Lane

(a) South bound Approach-Kietzke Lane

(b) North bound Approach-Kietzke Lane

(c) West bound approach-Neil Road (d) East bound Approach-Del Monte road

Figure A-3: Approaches and lane configuration of the selected roundabout

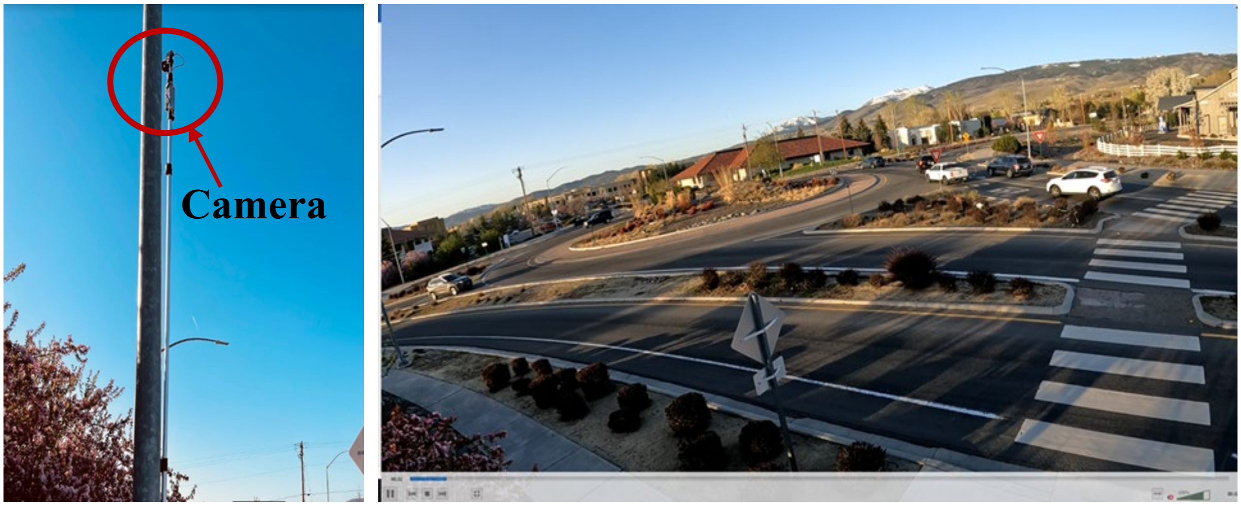
Table A.1: Geometric Properties of Selected Roundabout

Geometric Property	NB	SB	EB	WB
Number of Approaches	4			
No. of Entry Lanes	2	2	1	2
Approach Lane Widths	12 ft	12 ft	12 ft	12 ft
Splitter Island Widths	11 ft	11 ft	20 ft	15 ft
Central Island Radius	50 ft			
Inscribed circle diameter	200 ft			
Number of continuous circulatory lanes	1			
Circulatory lane width	15 ft			
Traversable apron width	12 ft			

2.2 Data Collection at Study Site

Field traffic data was collected during weekday morning and evening peak periods (Morning- 7:00 AM-10:00 AM and Evening - 3:30 PM-6:30 PM). Traffic movement data was collected using a wide-angle video camera. Occlusion is a major issue when installing camera equipment for field data collection. Occlusion occurs when one vehicle overlap another vehicle travelling in other lane and make the vehicle entirely or partly blocked/not visible. If there is no occlusion issue, the video camera can be installed on a 12 ft pole with one/two wide-angle video cameras to record traffic movements (Jensen et al., 2018). The data collection team installed an ultra-wide-angle camera at 15 ft height, considering the occlusion issue at the Neil Rd and Kietzke Ln intersection. The video camera setup is shown in Figure A-4. The viewing angle of the camera setup is also presented in Figure A-4b.

The origin-destination (O-D) matrix (number of vehicles making left turn, right turn or through movement), percentage of passenger cars (PC), and heavy vehicles (HV) were collected from the recorded video data. Field travel times and travel speed for all the movements within the roundabout were also calculated from the recorded video data for calibration and validation of the VISSIM simulation model.



(a) (b)

Figure A-4. (a) Camera setup at the Neil Rd and Kietzke Ln intersection/roundabout location; (b) Sample view of the intersection from the recorded video.

3. Development of Calibrated Simulation Model

PTV VISSIM 2020 was used as the micro-simulation tool (PTV Group, 2020). VISSIM is a microsimulation analysis software that explicitly models traffic movements based on geometric features, traffic volumes, traffic compositions, intersection control characteristics, and driver behavior. VISSIM can provide network-wide and intersection-level measures of effectiveness (MOEs), which can be used for intersection improvement assessment for different design alternatives.

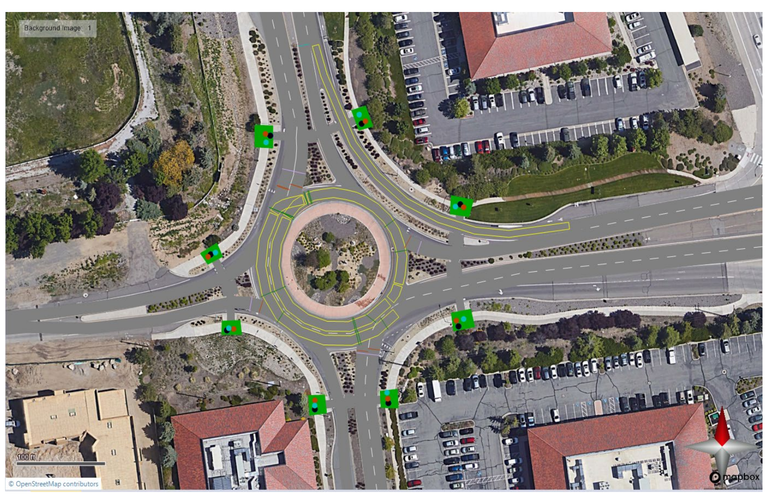


Figure A-5. VISSIM model of the existing roundabout.

3.1 Base Model Development

The base model depicting the field conditions was designed to simulate the traffic flow and for model calibration and validation. The VISSIM base model is shown in Figure A-5. The composition of vehicle fleets was modified for both simulated passenger vehicles and simulated heavy vehicles for North American Vehicle models and distributions. One-hour morning peak (7:30 AM-8:30 AM) traffic data was used as vehicle inputs in the VISSIM simulation model. The vehicle composition (i.e., % of PC and HV) on each approach was modified in VISSIM based on field data. Morning and evening peak hour traffic volume count and turning movement counts are summarized in Tables A.2 and A.3, respectively.

Speed distributions in the VISSIM model were modified based on field video data to simulate real-world traffic conditions at the study roundabout. Vehicle speed for different intersection movements (i.e., left turn, right turn, and through movements) were modified based on field video data. Vehicle circulating speed and dedicated right turn lane speed distribution from West bound approach to North exit were also extracted from the video data as this movement's speed distribution differed from other lanes. The extracted speed distributions are presented in Figure A-6. Circulating speed at the roundabout was relatively lower, ranging from 12 mph to 18 mph, compared to speed distributions in other study roundabout segments. The speed distribution at the dedicated right turn lane from the west approach to the north exit was higher than that of the left, right and through movements from all other approaches. The average speed within the roundabout and approaches was 19.24 mph, whereas the mean speed in the dedicated right turn lane was 33 mph.

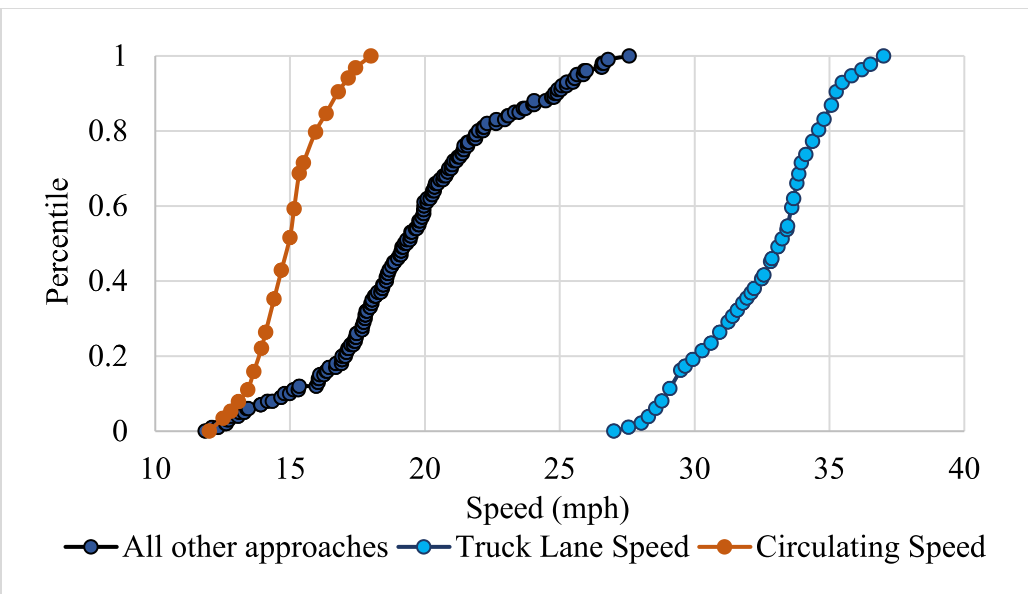


Figure A-6. Desired speed distribution for the vehicles in the approaches, truck lanes, and circulating lanes

3.2 Base Simulation Model Error Checking

Before starting the calibration and validation process, it is necessary to review and debug the developed simulation model adequately, as errors in the developed model can cause incorrect calibration parameter choice and, subsequently, an inaccurate model. Error checking of the base model before calibration was done in three stages: (i) software error checking, (ii) input coding error checking, and (iii) animation checking to spot less obvious input errors (Dowling et al., 2004).

3.3 Calibration and Validation of the Base Model

Rigorous calibration and validation of a micro-simulation model is necessary to ensure that the simulation model represents field traffic conditions. The calibration and validation of the base model was performed following the guidelines proposed by FHWA (Dowling et al., 2004). The detailed process of the calibration and validation is discussed below.

Step 1: Determination of Minimum Number of Simulation Runs

Eleven initial simulation runs were conducted following the VISSIM guidelines adopted by Florida, Oregon, and Washington State DOTs (ODOT, 2011; WSDOT, 2014; FDOT, 2014 to obtain initial base model results. The results from the initial simulation runs were used to calculate the required number of runs to produce statistically valid results.

The following equation (Equation A-1), outlined in the Federal Highway Administration's (FHWA) traffic analysis toolbox (Dowling et al., 2004), was used to calculate the required number of simulation runs.

$$N = \left(2 * t_{1-\alpha/2,\ N-1} * \frac{S}{R}\right)^2 \qquad \text{(A-1)}$$

Where, R represents confidence interval range of the true mean for traffic volumes; S represents the standard deviation of traffic volumes; $t_{1-\alpha/2,\ N-1}$ represents the t-statistic, and N-1 is the degrees of freedom (for initial run N-1=10); N represents the required number of simulation runs; and α represents the significance level. Based on VISSIM guidelines adopted by Michigan DOT, the confidence interval range for the true mean of the traffic volumes was set to 50 (MDOT, 2020). The results for minimum simulation runs required for all entries and exits are shown in Table A 4. WB entry was the most critical approach due to the high deviation in traffic volume, and 15 simulation runs were required for WB entry, which was adopted for micro-simulation analysis. A sample calculation of the minimum number of runs needed for the most critical location (i.e., WB entry of the Neil Rd and Keitzke Ln roundabout) is shown below. For the WB entry, the standard deviation of the traffic volumes from the initial simulation run was 43.01 vehs/hr.

$$N = \left(2 * t_{1-\alpha/2,\ N-1} * \frac{S}{R}\right)^2 = \left(2 * 2.228 * \frac{43.01}{50}\right)^2 = 14.69 \sim 15$$

This result indicates that 15 minimum simulation runs were required to ensure that reported results from the VISSIM model are representative of the field condition at the study roundabout. Thus, the final models in VISSIM were run 15 times using the different random seeds.

Table A.2. Peak Hour Traffic Volumes for Keitzke and Neil Road Roundabout

Roundabout	Keitzke and Neil Road												
Approach	Southbound			Westbound			Northbound			Eastbound			15-min volume
Vehicle Class	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	
	Morning peak hour 7:30-8:30 a.m. (peak hour volume = 2,161 vehicles per hour)												
7:30-7:45	239	5	244	194	4	198	11	0	11	12	0	12	465
7:45-8:00	229	4	233	239	5	244	19	0	19	13	0	13	509
8:00-8:15	282	6	288	309	6	315	18	1	19	25	1	26	648
8:15-8:30	228	5	233	252	5	257	15	0	15	33	1	34	539
Total	978	20	998	994	20	1,014	63	1	64	83	2	85	2,161
	Evening peak hour 4:00-5:00 p.m. (peak hour volume = 2,735 vehicles per hour)												
4:00-4:15	322	7	329	260	6	266	66	1	67	27	1	28	690
4:15-4:30	296	6	302	225	4	229	80	1	81	32	1	33	645
4:30-4:45	316	6	322	259	5	264	84	2	86	22	0	22	694
4:45-5:00	319	7	326	261	6	267	86	2	88	25	0	25	706
Total	1253	26	1,279	1005	21	1,026	316	6	322	106	2	108	2,735

Note: PC = passenger cars; HV = heavy vehicles.

Table A.3. Turning Movement Counts during Peak Hours at Neil Rd and Keitzke Ln Roundabout

Roundabout	Keitzke and Neil Road															
Approach	Southbound				Westbound				Northbound				Eastbound			
Vehicle Class	All classes				All classes				All classes				All classes			
Movement	R	TH	L	U	R	TH	L	U	R	TH	L	U	R	TH	L	U
Peak hour	7:30-8:30 a.m.															
7:30-7:45	16	30	196	2	127	17	53	1	5	5	1	0	0	6	6	0
7:45-8:00	8	32	192	1	168	18	58	0	9	10	0	0	1	10	2	0
8:00-8:15	13	41	231	3	237	17	57	4	6	12	1	0	4	15	7	0
8:15-8:30	12	31	188	2	195	16	43	3	5	9	1	0	2	26	6	0
Total	49	134	807	8	727	68	211	8	25	36	3	0	7	57	21	0
Peak hour	4:00-5:00 p.m.															
4:00-4:15	9	24	294	2	211	25	29	1	40	27	0	0	0	15	13	0
4:15-4:30	18	22	257	5	203	14	12	0	50	30	0	1	3	21	9	0
4:30-4:45	14	22	274	12	232	20	11	1	41	45	0	0	1	11	10	0
4:45-5:00	12	21	282	11	235	18	12	2	46	42	0	0	1	13	11	0
Total	53	89	1,107	30	881	77	64	4	177	144	0	1	5	60	43	0

Note: L = left turn; R = right turn; TH = through; U = U-turn.

Table A.4. Minimum simulation runs required for all entries and exits

Key location	Standard Deviation of traffic volume, S	Range of confidence interval, R	Two-sided t-statistics for 95% CI and 10 DoF	Minimum simulation runs, N
NB entry	6.40	50	2.228	0.33
SB entry	20.37	50	2.228	3.30
EB entry	10.28	50	2.228	0.84
WB entry	**43.01**	**50**	**2.228**	**14.69**
NB exit	34.97	50	2.228	9.72
SB exit	14.26	50	2.228	1.62
EB exit	22.88	50	2.228	4.16
WB exit	7.34	50	2.228	0.43

Step 2: Driver Behavior Input

Calibration of the VISSIM's driving behavior and gap acceptance parameters is necessary as these parameters could influence the simulation result considerably (MassDOT, 2020). Driving behavior in the VISSIM software is controlled by five models: car-following, gap acceptance, lane changing, lateral positioning, and signal control models. Car-following and gap acceptance models are the most important for roundabout calibration as these models are related to follow-up headway and acceptable gap times.

VISSIM had two different car-following models- Wiedemann 74 and Wiedemann 99. Among these two models "Wiedemann 74" is used for urban driving conditions, and "Wiedemann 99" is used for freeway traffic conditions (MassDOT, 2020). In this study, "Wiedemann 74" was utilized to simulate the driving behaviors in the field conditions as roundabouts are similar to urban traffic condition.

The adopted default and calibrated values of the driving behavior parameters used in the VISSIM simulation are presented in Table A.5. In "Wiedemann 74" model, the average standstill distance is defined as the distance between two stopped vehicles. The additive part of the safety distance presents the fixed average headway, and the multiplicative part changes the headway as a function of vehicle speed. The yielding behavior of the approaching vehicles at the roundabout is determined by the driver's acceptance or rejection of a gap to safely enter the circulatory lanes. In VISSIM, the yielding behavior is controlled by the gap acceptance parameters of the priority rules modules (MassDOT, 2020). For a roundabout, the minimum gap time is defined as the minimum time interval that safely allows an entry lane vehicle to enter the conflict zones in the circular lanes (Elhassy et al., 2021). A decrease in the minimum gap acceptance values indicates more aggressive yielding behavior and could lead to capacity increase. The VISSIM default value of the minimum gap acceptance parameter was 3 secs for passenger cars and heavy vehicles. As heavy vehicles require higher gap time, the values of these gap acceptance times for left and right entry lanes for heavy vehicles were increased to 3.6 secs in the calibration process. The values of the passenger car minimum gap acceptance time were decreased to simulate the field conditions (Table A.5). For the lane change model, the *maximum deceleration* of the own and trailing vehicles was increased to 15 ft/s^2 and 12 ft/s^2, respectively. The calibrated model also decreased *minimum headway* and *safety distance reduction factors* (Table A.5).

Table A.5. VISSIM calibration parameter for the base model

Parameter	**Calibrated Value**	**Default Value**
Vehicle Fleet	North America default file	
Lane-Change Model		
Maximum deceleration-Own (ft/s^2)	-15.0	-13.12
Maximum deceleration-Trailing (ft/s^2)	-12.0	-9.84
Minimum headway (ft)	1.5	1.64
Safety distance reduction factor	0.4	0.60
Car-following model (Wiedemann 74)		
Average standstill distance (ft)	4	6.56
Additive part of safety distance	1	2
Multiplicative part of safety distance	2	3
Priority rules		
Minimum gap time for passenger cars (sec)		
For right entry lanes	2.6	3
For left entry lanes	2.6	3
Minimum gap time for heavy vehicles (sec)		
For right entry lanes	3.6	3
For left entry lanes	3.6	3

Step 3: Selection of Measures of Effectiveness (MOEs)

WSDOT and MDOT recommend using at least two calibration targets based on two different MOEs for the calibration process to be effective (WSDOT, 2014; MDOT, 2020). WSDOT and MDOT recommended calibration MOEs are traffic volumes and speed/travel times, as they influence the other operational characteristics of the roundabout, such as density and delay. Moreover, the field values of these two parameters are easy to obtain. In addition to travel times and traffic volumes, another good MOE is queue length. In this study, three MOEs were selected for the calibration and validation of the base model, which are (i) traffic volumes, (ii) travel times, and (iii) queue lengths. Guidelines adopted by the FHWA and several other state DOTs were consulted in this study to set the calibration and validatin targets for each MOE (Elhassy et al., 2021).

Step 4: Calibration for traffic volumes

The first MOE for the calibration is how closely the simulated traffic volumes match the field traffic volume for each entry and exit. The GEH statistics is used to compare micro-simulation data with real-world data. The GEH statistics can be presented as:

$$GEH = \sqrt{\frac{2(m-c)^2}{m+c}} \quad \text{(A-2)}$$

Where, *m* denotes simulated traffic volume (vehs/hr), and *c* denotes field traffic volume (vehs/hr).

For a well-calibrated model, GEH statistics should be below 5 for all the entry and exit lanes. GEH calculation result for each entry and exit legs are presented in Table A.6. For all entry and exit legs, the GEH statistics was lower than the critical GEH value of 5.00. As such, the base model was successfully validated for the traffic volume criterion.

Table A.6. GEH Calculations for calibration and validation of the Base Model.

Key location	m	c	$m-c$	$m+c$	$(m-c)^2$	$2*(m-c)^2$	GEH value	GEH criterion
	Calibration of Keitzke and Neil road roundabout base model (morning peak hour)							
NB entry	63	64	-1	127	1	2	0.13	<5.00
SB entry	980	998	-18	1978	324	648	0.57	<5.00
EB entry	86	85	1	171	1	2	0.11	<5.00
WB entry	1003	1014	-11	2017	121	242	0.35	<5.00
NB exit	786	792	-6	1578	36	72	0.21	<5.00
SB exit	346	352	-6	698	36	72	0.32	<5.00
EB exit	881	897	-16	1778	256	512	0.54	<5.00
WB exit	119	120	-1	239	1	2	0.09	<5.00
Total entry	2132	2161	-29	4293	841	1682	0.63	<5.00
Total exit	2132	2161	-29	4293	841	1682	0.63	<5.00
	Validation of Keitzke and Neil Road roundabout base model (evening peak hour)							
NB entry	315	322	-7	637	49	98	0.39	<5.00
SB entry	1263	1279	-16	2542	256	512	0.45	<5.00
EB entry	107	108	-1	215	1	2	0.10	<5.00
WB entry	1016	1026	-10	2042	100	200	0.31	<5.00
NB exit	1080	1085	-5	2165	25	50	0.15	<5.00
SB exit	159	159	0	318	0	0	0.00	<5.00
EB exit	1335	1348	-13	2683	169	338	0.35	<5.00
WB exit	119	130	-11	249	121	242	0.99	<5.00
Total entry	2701	2735	-34	5436	1156	2312	0.65	<5.00
Total exit	2693	2722	-29	5415	841	1682	0.56	<5.00

Note: m = simulation traffic volume (vehs/hr); c = field traffic volume (vehs/hr).

Step 5: Calibration for travel times

Travel time was used to calibrate roundabout simulation models. The simulated travel times and field travel times for major traffic movements with the highest traffic volumes (i.e., SB LT, and WB RT) are listed in Table A.7. The maximum allowable difference between the field and simulated travel times was estimated using the following equation:

$$\Delta = \frac{1}{\frac{1}{t} - \frac{0.1*5280*S}{3600*L}} - t \quad \text{(A-3)}$$

where t is field travel times (secs); S is free flow speed (mph); L is the length of travel time measurement segment (ft); and Δ is maximum difference in field and simulated travel times. As shown in Table A.7, the base model satisfied the travel time calibration criterion. The posted speed limit was considered to be the free-flow speed (FFS) (WSDOT, 2014). The field travel time was measured from the video data. Hourly average travel times from the VISSIM simulations for these two critical movements were measured by setting up the travel time measurement segments. As seen in Table A.7, the allowable difference between the field and simulated travel time for SB LT and WB RT in the morning was ±2 and ±0.57 seconds, respectively. The calculated difference between the simulation and the field travel times was -1.9 and -0.31 seconds for SB LT and WB RT, respectively. Similarly, the travel time differences for evening peak were also within the allowable values, which means the model was successfully calibrated for the travel times.

Table A.7. Travel Time Criterion for Calibration and Validation of the Base Model

Traffic movement	Field		Simulation		Difference	Free flow speed (FFS), S (mph)	Length of route, L (ft)	Allowable variation in secs (Δ)
	Vehicles	Travel time, t (secs)	Vehicles	Travel time (secs)				
Model	Calibration of the base model (morning peak hour)							
SB LT	807	15.54	794	17.43	-1.9	20	400	2.00
WB RT	727	4.54	721	4.85	-0.31	25	150	0.57
Model	Calibration of the base model (evening peak hour)							
SB LT	1107	7.19	1092	7.31	-0.12	20	400	0.40
WB RT	881	7.05	876	7.11	-0.06	25	400	0.49

Note: *SB LT = southbound left turn traffic; WB RT = westbound right turn traffic.*

Step 6: Calibration for queue lengths

Similar to travel time, queue length is another MOE used to calibrate roundabouts (MassDOT, 2020). Queue length can be observed from the field by recording the number of vehicles queued at set time intervals at a roundabout entry. Then, the field-collected queue lengths are compared with the VISSIM queue length results. Several DOTs (i.e., MassDOT, WSDOT) stated that the difference between the simulated and the observed queue length should be within 20%. Figure A-7 shows a 20-minute sample of field and simulated queue length at the SB entry in five-minute intervals. The simulated queue lengths were within the allowable 20% values of observed queue lengths. Apart from quantitative comparison, a qualitative comparison can be done by visually observing field and simulation queue lengths. There were no substantial differences in observed and simulated queue length (i.e., unrealistic long or short queue lengths were not observed). Thus, the base simulation model was also considered calibrated regarding queue length MOE.

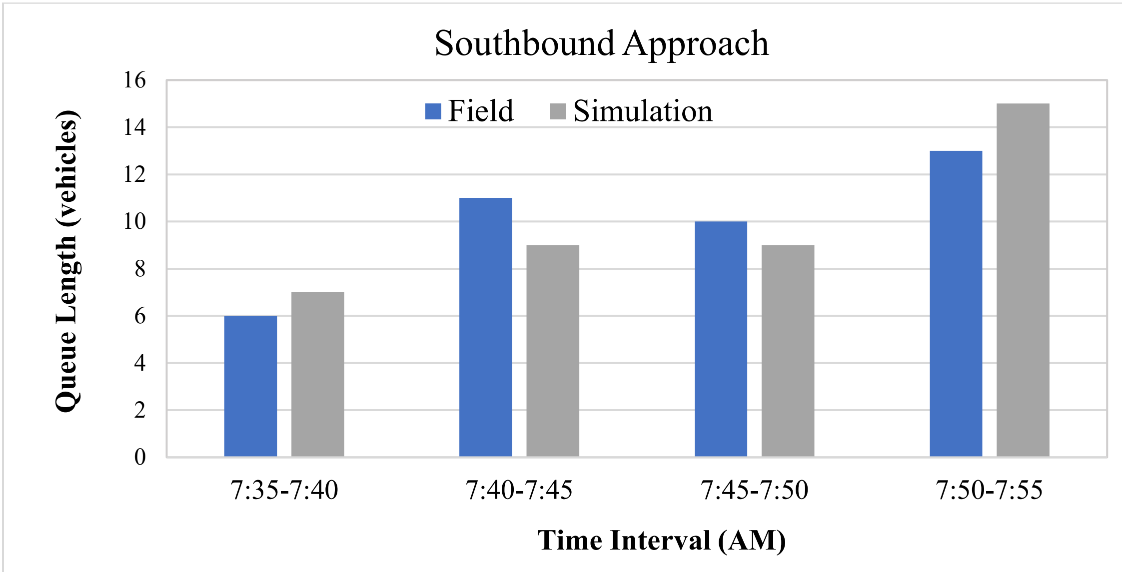


Figure A-7: Visual Calibration of Queue Lengths

The Neil Rd and Keitzke Ln roundabout base simulation model was successfully calibrated on the abovementioned calibration and validation steps.

4. Design of Turbo, single-lane, and Two-lane roundabout in TORUS

Different versions of turbo roundabouts, a two-lane roundabout, and a single-lane roundabout were designed using TORUS 6.0. Turbo roundabout design involves several steps. The following sections briefly describe the turbo roundabout's design process and performance checks.

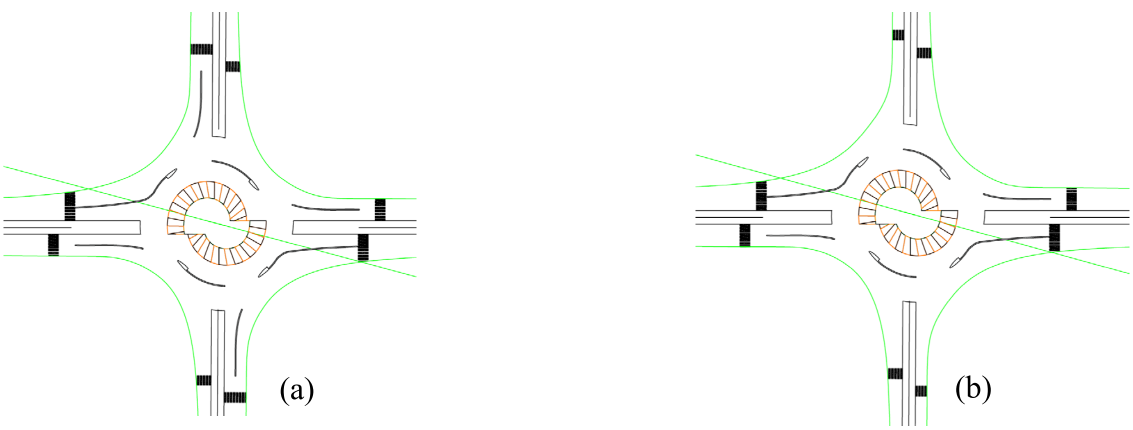
4.1 Design Process Overview

At first, the default turbo roundabout design was modified to accommodate the design vehicle selected for this study and the different geometrical properties of the developed scenarios. Geometric elements of the turbo roundabout were designed based on the swept path analysis of the design vehicle for four variations of circulatory roadway inner radius R1. The turbo block's four inner radii (R1= 35, 40, 50, and 65 ft) were selected based on the existing turbo roundabout design guidelines. According to the Croatian design guidelines, circular arcs on one side of the translation axis were designed such that they entirely overlap with circular arcs on the other side of the translation axis (Džambas et al., 2020). After selecting the inner radii (R1), outer circulatory lane width, inner circulatory lane width, circular arc radii (R2, R3, and R4), and distance between circular arcs' outer and inner centers at the translation axis were determined. TORUS 6.0 software was used to design the geometric elements of the turbo. According to the Dutch guidelines, the truck apron width was set to 16.4 ft. The turbo roundabouts were designed with four approach legs aligned radially under a 90° angle such that their axes intersect in the turbo roundabout geometric center. The approach legs, lane width, and crosswalk elements were designed based on Dutch guidelines. Finally, circulatory lane opening width was determined based on the design vehicle swept path analysis using TORUS 6.0. The design elements and their dimensions are summarized below in Table A.8.

Table A.8. Turbo Roundabout design summary

Geometric Features	Design Values	Dutch Guideline (CROW, 2008)
Inner radius (R1)	10.5, 12, 15, and 20 m (35, 40, 50, and 65 ft)	10.5, 12, 15, and 20 m (35, 40, 50, and 65 ft)
Max. Circulatory Lane width (m)	6 m (19.68 ft)	5.25 m (17.22 ft)
Truck apron width (m)	5 m (16.4 ft)	5 m (16.4 ft)
Splitter island width (m)	4 m (13.12 ft) (parallel sides)	≤3 m (9.84 ft) (parallel sides)
Entry lane width (m)	3.5 m (11.48 ft)	-
Exit lane width (m)	3.5 m (16.40 ft)	-
Min. Entry radius(m)	12 m (39 ft)	≥12 m (39 ft)
Min. Exit radius (m)	15 m (49 ft)	≥15 m (49 ft)

According to the Dutch guidelines, swept path analysis and fastest path vehicle speed analysis should be conducted to check and finalize the geometric design of the turbo roundabout (CROW, 2008). However, German guideline for turbo roundabout design does not recommend fastest-path vehicle speed analyses as the performance check measure, and they recommends speed to be regulated using traffic signs (FGSV, 2015). To compare the operational and safety performance of the turbo roundabout with typical intersection types, two-lane and single-lane roundabouts were also designed in TORUS 6.0. Figure A-8 shows the designed Basic (Figure A-8a) and Egg (Figure A-8b) turbo roundabout with an inner radius of 40 ft and the single-lane and two-lane roundabout (Figure A-8c and d).



(a) (b)

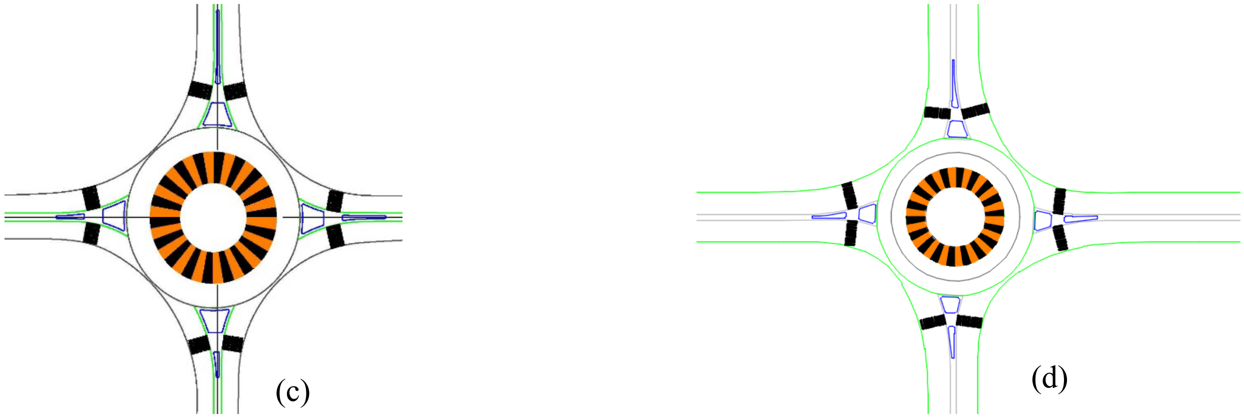
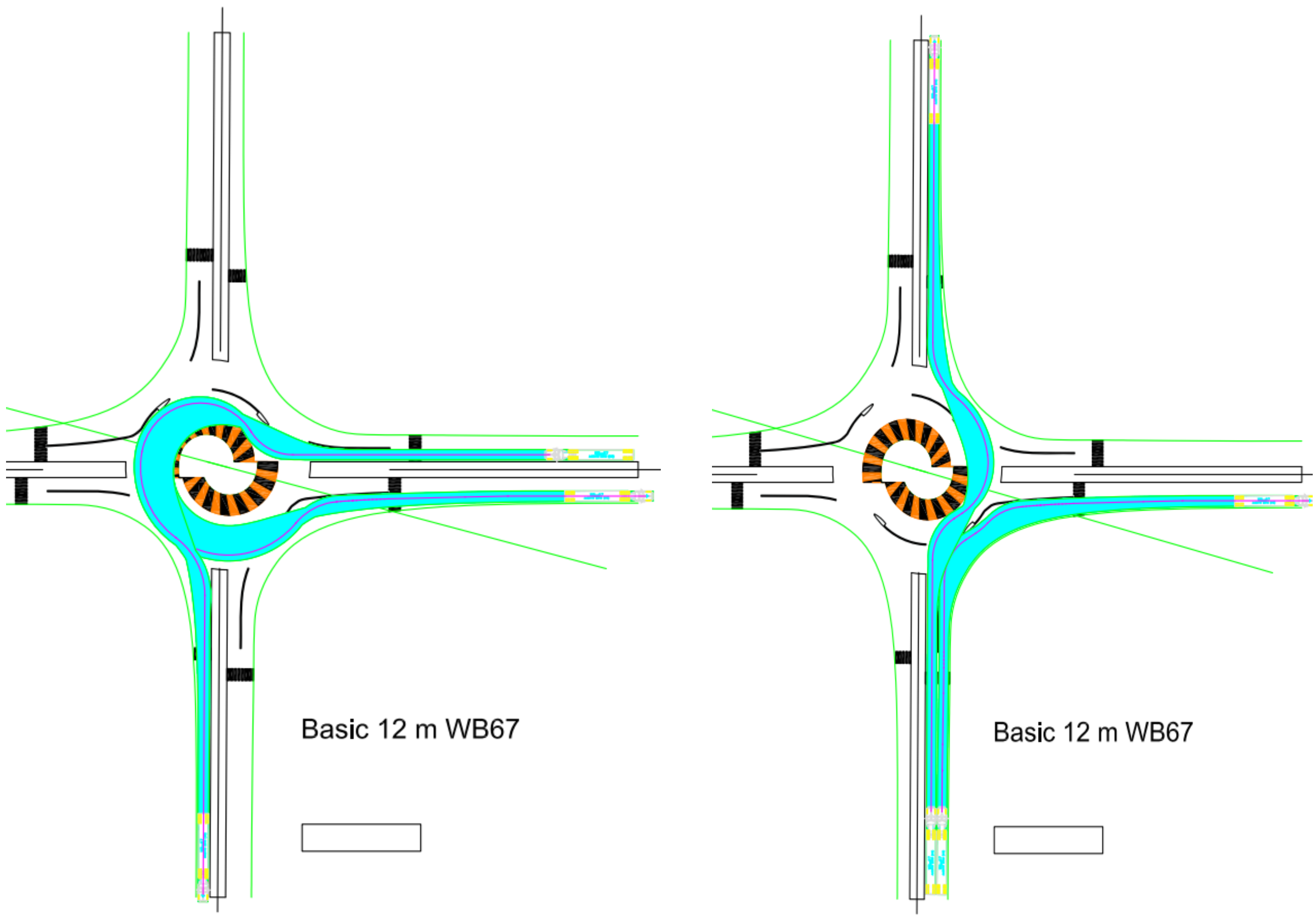


Figure A-8: Types of intersections designed in TORUS (a) Basic Turbo roundabout with an inner radius of 40 ft; (b) Egg Turbo roundabout with an inner radius of 40 ft; (c) Single-lane roundabout; (d) **two**-lane roundabout

4.2 Swept Path Analysis

Existing guidelines presented different horizontal swept path requirements for turbo roundabouts. For example, according to the Croatian, Slovenian, and Serbian technical specifications, the design vehicle can track over the traversable beginning portion of the raised lane divider and must not track over the central apron or the raised lane divider (Džambas et al., 2017). On the other hand, according to the Dutch guidelines, this design feature is recommended but not mandatory (CROW, 2008). According to the NCHRP report 672, truck aprons can be used by the large vehicles when making turning movements, which can minimize other roundabout dimensions (Rodegerdts et al., 2010). In this study, turbo roundabouts were designed such that the design vehicle can use the truck apron while performing turning movements.

The design vehicle swept path analysis of the turbo roundabout is shown in Figure A-9. Figure A-9(a) shows the left turn and U-turn swept path when entering the Basic turbo roundabout from the West bound approach. On the other hand, Figure A-9(b) shows the swept path for the right turn and through movement when entering the Basic turbo roundabout from the North bound approach. While performing left turn and U-turn movements, the design vehicle runs over the truck apron (Figure A-9(a)). For through movement (Figure A-9(b)), the design vehicle runs over the truck apron and the traversable lane divider. The design vehicle did not track over the neighboring lanes for all four movements, which is prohibited in the German guidelines. Similarly, horizontal swept path analysis for all versions of the designed turbo roundabouts was conducted to ensure the guideline requirements were followed.



(a) (b)

Figure A-9. Horizontal swept path analysis of the Basic turbo roundabout with 12 m (40 ft) turbo block (a) For Left turn and U-turn from East approach; (b) Right turn and through movement from North approach.

5. Additional Simulation Results

Impact of traffic demand on vehicular travel times and Delay: Impact on travel times for four through movements (i.e., North to South, South to North, East to West, and West to East) were calculated for different traffic volumes and two different inner radii (i.e., 35 and 65 ft). Figures A-10 and A-11 depict that a basic turbo roundabout can process up to 3,500 vehs/hr without necessarily significantly impacting the travel times. Similar to the average delay, for a demand greater than 3,000 vehs/hr, the travel times increase faster as the traffic demand volume reaches above capacity.

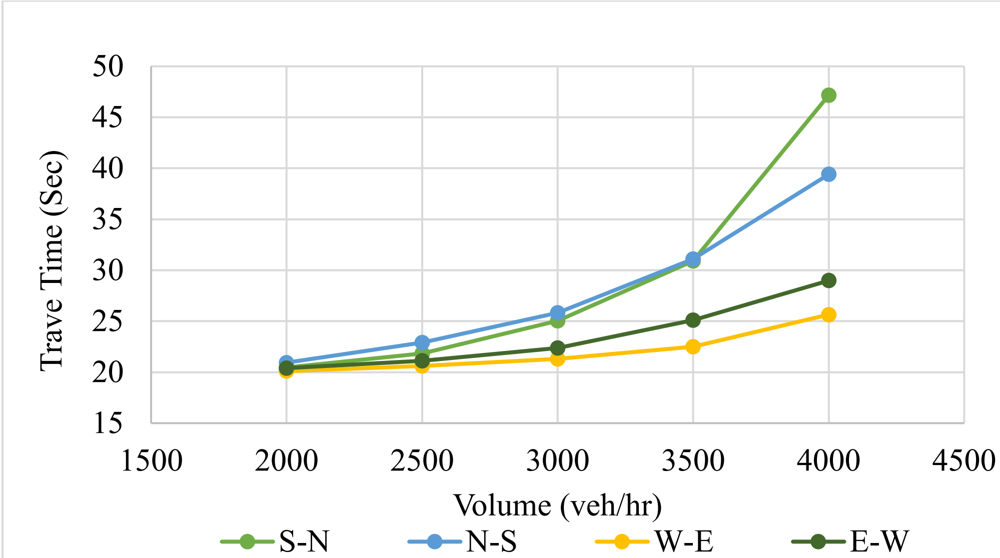


Figure A-10: Travel time at different traffic volumes for a basic turbo roundabout with an inner radius of 35 ft.

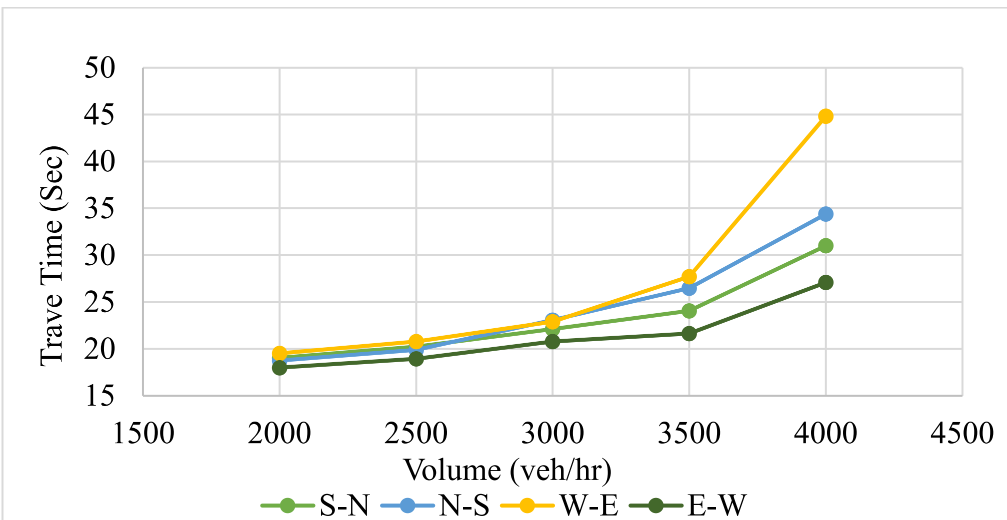


Figure A-11: Travel time at different traffic volumes for Basic turbo roundabout with an inner radius of 65 ft.

Figure A-12 shows the effect of traffic volume on average vehicle delay for all four alternatives considered in this study, such as the example scenario of 50% LTs and major-minor directional split of 70%-30%. As seen from the figure, after traffic volume of 2,600 pcu/hr, average delay in egg turbo roundabout increased exponentially. When comparing he delay at traffic volume of 3,500 pcu/hr, average delay in basic turbo roundabout was the lowest with an value of 14 seconds per vehicle.

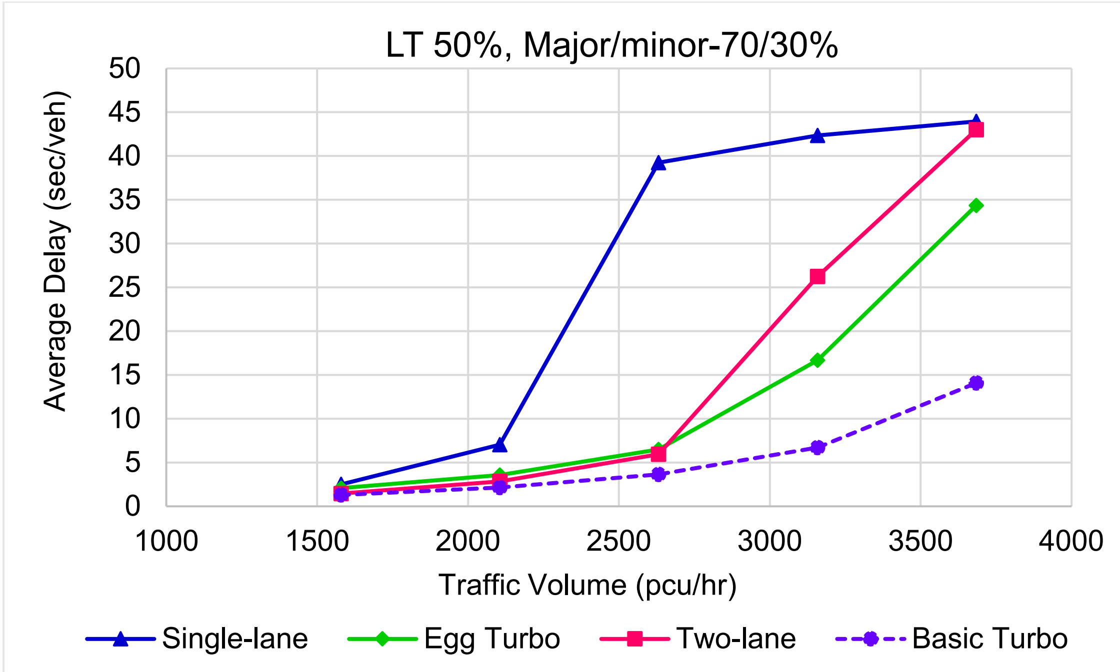


Figure A-12: Effect of traffic demand on average dealy.

APPENDIX B

HUMAN FACTOR ASSESSMENT

1. Introduction

In light of the safety issues associated with single and multi-lane roundabouts, the turbo roundabout was developed by Dutch engineer Lambertus Fortuijn in the mid-1990s. The turbo roundabout offers promising means to improve roundabout operations and safety (Bai et al., 2021; Engelsman & Uken, 2007; Fortuijn, 2009a, 2009b; Giuffrè et al., 2021; Kocianova, 2016; Petru & Krivda, 2021). Several past studies performed turbo roundabout capacity and operational analysis. Also, a considerable portion of this literature is focused on evaluating the applicability of gap acceptance capacity models on turbo roundabout capacity analysis. (Eva & Andrea, 2017; Fortuijn, 2009b; Krivda & Petru, 2018; MacIoszek, 2016; Šarić & Lovrić, 2017). Overall, a turbo roundabout offers reducing traffic crashes related primarily to navigation into, within, and while departing a roundabout.

Over the past three decades, primarily in Europe, there has been increasing use of the turbo roundabout. In fact, 25 countries have adopted turbo roundabouts or variations thereof; a total of 700 have been constructed as of January 2023 (De Baan, 2023). Despite their emergence decades ago across the world, it was not until the late 2010s that their implementation in the U.S. became a subject of interest. Two documents that effectively summarize the efforts by the FHWA on how to adopt the turbo roundabout in the U.S. are "*Advancing Turbo Roundabouts in the United States: Synthesis Report*" (Porter et al., 2019) and "*Turbo Roundabouts: An Informational Primer*" (FHWA, 2019). These documents provide preliminary consideration of the characteristics of the turbo roundabout, its operational and safety advantages, and geometric design in the context of the established practices in the U.S.

Despite the abundance of research on turbo roundabouts, no studies have presented an estimation of typical gap acceptance parameters, such as critical gap, time or follow-up headway based on drivers' data in the U.S. Additionally, from the implementation and human factors' perspective, there are unanswered questions regarding turbo roundabout performance within the U.S., given a variety of reasons: a lack of turbo-specific design guidelines, environmental, and more critically, general unfamiliarity or confusion in navigating roundabouts in the U.S. Moreover, studies in the U.S. report a fear of roundabouts (in general), which is thought to be a product of driver confusion, vulnerability, and lack of navigational understanding (Shrestha, 2002; Savolainen et al., 2012). Limited previous researchers have studied the turbo roundabout from a U.S. context (Elhassy et al., 2020, 2021; Fernandes et al., 2017; Wankogere et al., 2017a), with very little attention placed on the performance of the turbo roundabout from the human factors perspective. Only Wankogere et al. (2017) considered the driver by assessing how different signs and pavement marking schemes influence drivers' performance at turbo roundabouts. This gap in the literature is the motivation behind the research work presented in this human factor assessment.

Driving simulators have become a widely accepted research tool for clinical research studies (Barkley et al., 2002; Bharadwaj et al., 2021; Cox et al., 2000; Dugdale et al., 2021; Horberry et al., 2006; Randall et al., 2021; Roenker et al., 2003), as well as for transportation-related studies

(Bella, 2013; Calvi, 2015; Calvi et al., 2015; Matsumoto & Peng, 2015; Silva et al., 2014; Törnros, 1998; Yang et al., 2018). Specific to transportation engineering, driving simulator based human factor studies have been used to investigate impact of different roadway geometric design alternatives (Chen et al., 2018), traffic control types, study signs and pavement markings (Wankogere et al., 2017b), collision studies, distracted driving (Deschamps et al., 2013; Saxby et al., 2013), or only for visualization and training purposes (Kihl et al., 2006; Kuhl et al., 1995; Robin & Knipling, 2001; Strayer et al., 2005). Driving simulators have a high-fidelity nature and can recreate nearly realistic driving scenarios (Sheta et al., 2020). Also, simulators provide a controlled and safe environment for conducting experiments, reducing the risks involved in real-life scenarios and allowing for complex scenarios with varying weather conditions and roadway configurations (Bella, 2009). The ability to conduct research in a 'safe and controlled environment' is, perhaps, one of the main reasons researchers opt to use simulators over real-life experimental setups.

The primary aim of human factor assessment in this research project was to explicitly investigate the experience(s) of the driver with respect to navigating a turbo roundabout. The goal was to gain insight – from a human factors' perspective – into any differences between driver performances with the navigation of turbo versus two-lane roundabout designs. It was anticipated that the performance would be measured in terms of gap acceptance, approach versus circulating speed, and lane selection to identify the reason(s) for driver confusion during roundabout navigation.

2. Methodology

This portion of the report presents a detailed methodology of the driving simulator experiments.

2.1 Driving Simulator and Simulation Environment Design

2.1.1 Driving Simulator

A high-fidelity driving simulator, a regular-size Ford Focus car equipped with many real-vehicle features was used in this study. Figures B-1 and B-2 show the driving simulator's exterior features with an infrared Eyetracker (FaceLab 5) on vehicle's dashboard.

Figure B-1. Simulator car exterior features.

Figure B-2. Simulator car (while running simulation).

2.1.2. Institutional Review Board approval

Institutional Review Board's (IRB's) approval was processed to ensure that the study were conducted in a risk-free and privacy protected environment for study participants. Moreover, according to the IRB, informed consent must be obtained from each participant before starting their participation in simulator experiment. For this portion of the project, Ohio University IRB reviewed and provided approval for driving simulator experiments.

2.1.3. Participant Recruitment

Driving performance data of 24 participants were used in final driver behavior data analysis. Some participants were excluded as they could not complete the entire simulation experiment due to simulator sickness or fatigue or those who exhibited significant deviations from their usual driving behavior, potentially stemming from challenges with the driving simulator or erratic driving maneuvers during the test. In total, data from three drivers were excluded from the final dataset.

Due to the limited number of participants in driving simulation experiments, previous studies have used a 10% ($p < 0.10$) significance level for a 90% confidence level of the unknown parameters (Liu et al., 2021). Hence, consistent with prior research conducted on driving simulation, using parameters of $Z = 1.25$, $\delta = 0.4$, and $E = 10\%$ (Lerman, 1996; Liu et al., 2021), a minimum of 25 participants was required. In addition, the calculated sample size was consistent with similar driving simulation studies, as summarized in Table B-1.

Table B-1. Driving Simulation Studies and Sample Sizes Used

Reference	Study Objective	Sample Size
Yang et al., 2018	Analyzed the impact of dynamic factors on driving behavior at roundabouts and developed a predictive model using the random forest method	10

Burt et al., 2021	Investigated the correlation between drivers' subjective perceptions of their condition and objective measurements of their driving performance.	10
Törnros, 1998	Validated driving behavior in a simulated road tunnel.	20
Rengifo et al., 2021	Assessed how the motion perception model impacts motion cueing algorithms in driving simulators.	20
Chen et al., 2018	Examined how geometric road design influences lane departures in mountainous freeways.	30
Haque et al., 2016	Investigated gap acceptance behavior of distracted young drivers at roundabouts.	32
Yang et al., 2018	Investigated the impact of different roadside configurations, geometric elements, and guardrail barrier placements on driver behavior.	33
Burt et al., 2021	Examined how mobile phone distractions affect drivers' behavior, considering factors such as driving demands, individual traits, and secondary tasks.	35
Campbell et al., 2021	Examined the behavior/performance of "right-way" drivers during a wrong-way driving event.	71

On a scheduled date and time, a qualified participant would arrive at the Safety and Human Factors lab, meet with a research assistant to get a briefing on the study, and then complete an IRB-approved consent form. The consent form summarized the purpose of the study and the risks and discomforts associated with driving in the simulator. No specific instructions were given to a participant, except instruction to observe all traffic rules and regulations and to drive in a manner that replicated a participant's normal driving in a real environment. A pre-driving simulation questionnaire was administered to an individual who consented to participate in the study. Following this, a participant was taken to the driving simulator and was asked to complete a warm-up test drive. Prior to driving, each participant was given the following instructions: *"Get in the car and get comfortable, please, make sure you're comfortable with the controls and try to drive as you normally would in real life. I am going to give you a warmup scenario, and only when you are comfortable and ready to proceed with the test will you be introduced to two other scenarios where we will be collecting your driving data as you drive. Let me know when you're ready to proceed."* After the warm-up test drive, participants were requested to drive the first of potentially two simulation scenarios. Participants were given the option to take a short break after completing the first driving scenario. They were given a second scenario only when they showed no signs of motion sickness and were willing to complete the second drive. Table B-2 presents a breakdown of the simulation study process encountered by each participant and the approximate times for each specific task.

Table B-2. Simulation Study Process with Approximate Times for Activities.

Task	Activity	Time (minutes)
	Arrival at safety and human factors lab	**0**
1	Study briefing and signing consent form	5

2	Pre-driving simulation questionnaire	10
3	Warm-up driving simulation	5
4	Driving simulation scenario 1	15
5	Driving simulation scenario 2	15
6	Post-driving simulation questionnaire	10
7	Debriefing	5
	Total Time	**65**

Participants were categorized based on age into two age groups: novice drivers, who were 25 years old or younger, and experienced drivers, who were above 25. The thresholds were defined based on the need to categorize drivers according to their experience level. The Nevada Department of Transportation's (NDOT) highway safety plan (NDOT, 2021) identifies drivers below the age of twenty (20) as 'young'. Similarly, in Ohio, where this study was conducted, the 2020 Strategic Highway Safety Plan (SHSP) classifies drivers below 25 as 'young'. Younger drivers, often less experienced, frequently encounter difficulties maintaining their lane on narrow roads and may tend to overcompensate when departing from the travel lane (ODOT, 2020). Due to the uneven gender-distribution in students, faculty, and staff at Ohio University engineering departments, 72% (N = 17) of study participants were male.

Figure B-3 depicts the participant's self-reported driving experiences. Of the 24 total participants, about 75% (N = 18) reported having at least three years of driving experience, while the remaining 25% (N = 6) had between one and three years of experience. As well, 42% (N = 10) of participants reported commuting between 0 to 5 miles per day, 25% (N = 6) commuted between 5 to 10 miles per day, 29% (N = 7) commuted between 10 to 50 miles per day, and 4% (N = 1) commuted 50 miles or more per day. Additionally, as shown in Figure B-4, 67% (N = 16) of participants drove most days (4 to 7 days per week), further indicating a high level of driving experience. Furthermore, 67% (N = 16) of participants drove through a roundabout twice a week.

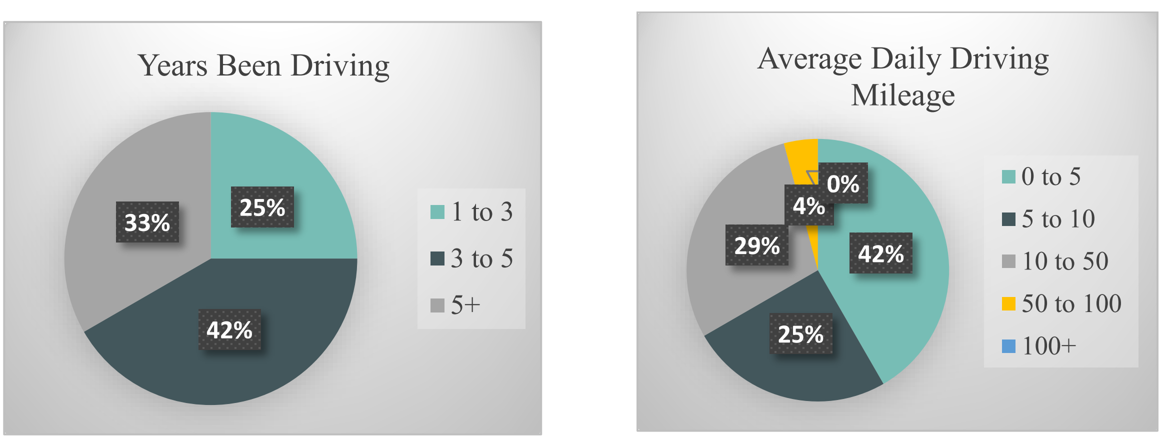


Figure B-3: Participant driving experience and weekly driving mileage.

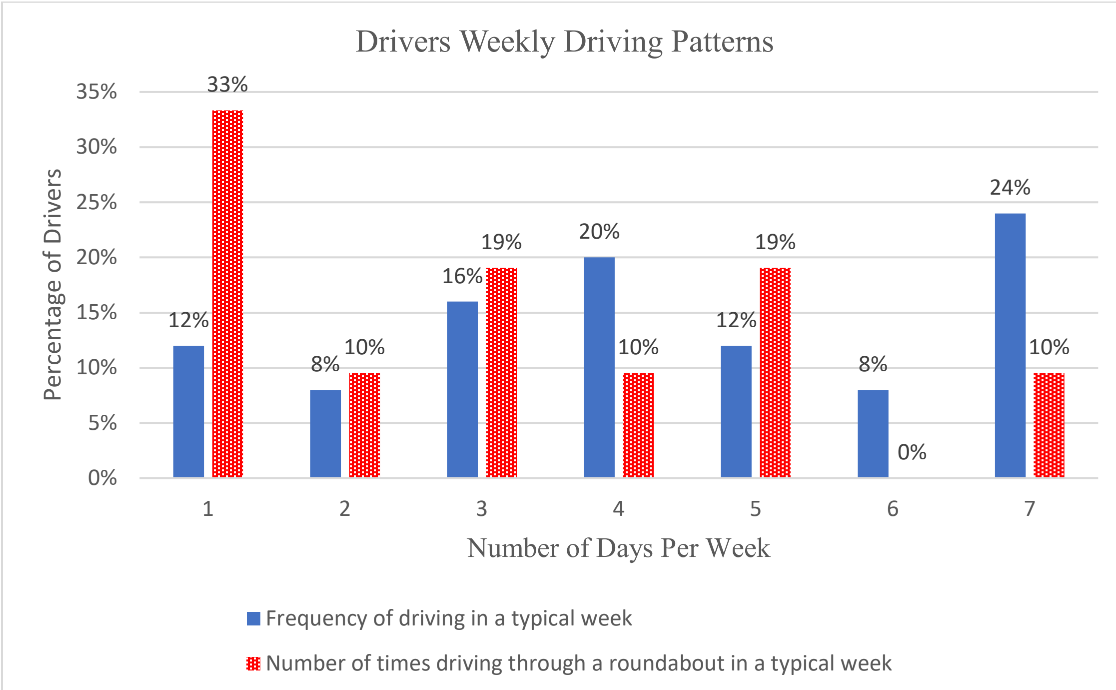


Figure B-4: Weekly driving and roundabout driving frequency.

2.1.4. Driving Scenarios

All drivers participated voluntarily and completed a warm-up scenario and a maximum of two actual test scenarios during which data were collected. The warm-up scenario was required to familiarize drivers with the driving simulator's instrumentation, controls, and sensitivity. The warm-up scenario is also helpful and has been used in several studies involving driving simulators to gauge participants' propensity to suffer from simulation or motion sickness during the experiment (Overton, 2012). Participants who were likely to suffer from motion sickness either dropped out of the experiment after the warm-up scenario or at any point during the simulation if a higher level of motion sickness was reported.

The two test scenarios consisted of an environment that mimicked an urban area and consisted of intersections (stop-controlled and signalized), arterial roads, and roundabouts. Since roundabouts were the treatment of interest, each participant drove through a series of roundabouts, including a basic turbo roundabout, an egg turbo roundabout, and a traditional two-lane roundabout. The significant difference between the two test scenarios was driving conditions – day or night. Traffic conditions included a mix of transportation modes, including bicycles, pedestrians, and motorcycles. Regardless of the day/night scenario, a participant driver's journey began by traveling straight for 650 feet from a start point (shown in Figure B-5). After that, the driver encountered a stop-controlled intersection. At this point, the driver was required to come to a complete stop, assess traffic conditions, and proceed straight ahead when it was safe. Following the stop-controlled intersection, the driver continued straight for 3,600 feet to the egg turbo roundabout (Figure B-6a). At the egg turbo roundabout, participants were required to take the third exit, guided by appropriate signage and pavement markings. The driver continued the route for approximately 1.5 miles through several stop/signalized intersections until arrival at the basic turbo roundabout (Figure B-6b). At the basic turbo roundabout, participants had to take the second exit, proceed straight ahead, and travel for another 1.5 miles before reaching the two-lane roundabout (Figure B-6c). The driver took the third exit at the two-lane roundabout, guided by the appropriate signage or markings provided. Finally, the driver proceeded straight for about 1,000 feet before reaching the designated scenario endpoint.

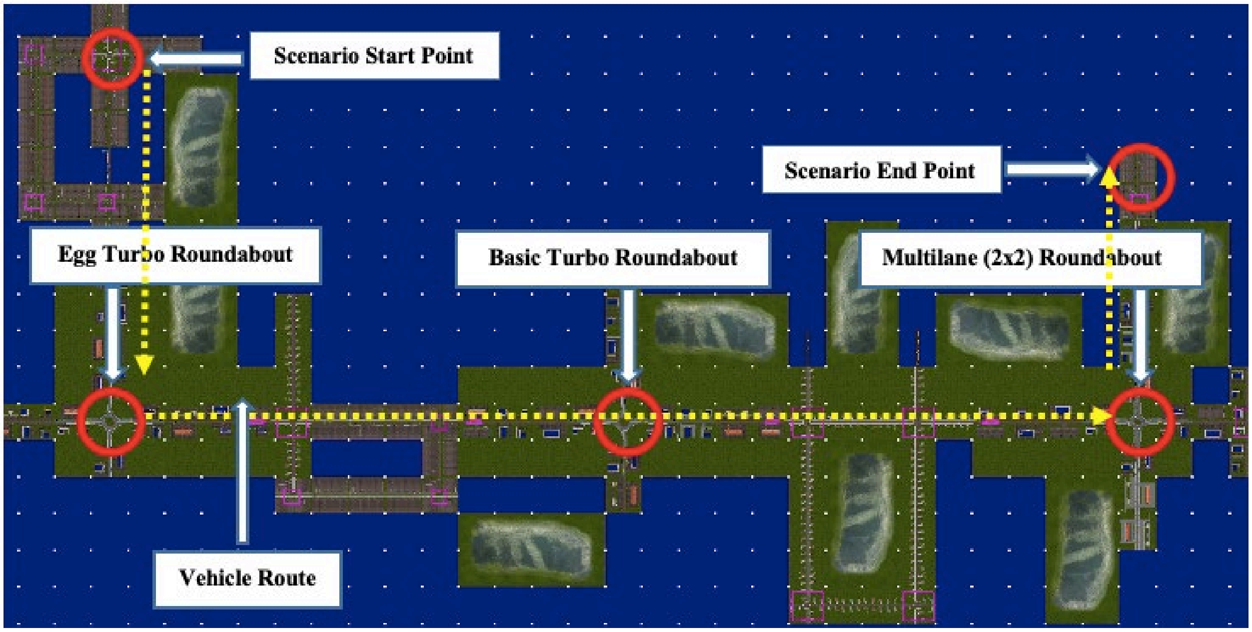


Figure B-5. Simulation path for driving participant.

(a) Egg Turbo Roundabout.

Characteristics: Minor approaches consist of a single lane in each direction.

- Major approach runs East-West,
- Minor approach runs North-South.

(b) Basic Turbo Roundabout.

Characteristics: Inside lane on major approach and two lanes on each approach.

- Major approach runs East-West,
- Minor approach runs North-South.

(c) Two-lane Roundabout.

Characteristics: Circular central island and two lanes on each approach.

- Major approach runs East-West,
- Minor approach runs North-South.

Figure B-6. Simulated roundabout designs.

Participant drivers had no prior knowledge of the actual intent of the experiment except for a general description of the research. They were encouraged to exhibit their natural driving behavior during participation in the study. To minimize the propensity of participants getting motion sickness – especially, due to the frequent curved sections –the driving routes were kept to straight segments except at the circular sections of the roundabouts where drivers needed to negotiate a curve.

2.1.5. Pre-/Post-Simulation Survey

In addition to the driving simulation approach described above, a two-parts questionnaire (pre- and post-simulation) was administered to each participant. The questionnaire aimed to understand driver preferences, perceptions, and opinions about turbo roundabouts, its characteristics, and its potential implementation in the U.S. The questionnaire (refer to Appendices C and D) consisted of a total of 33 questions organized into five sections, with questions covering general demographic information, driving experience, familiarity, subjective safety and preferences, roundabout information and operations, turbo roundabouts: operation, attitude opinions, preferences, and education. The questionnaire was administered to all participants in English.

3. Human Factor Assessment Results

3.1. Analysis of Gaps and Determination of Critical Gap

A critical gap is an important parameter in the roundabout capacity estimation, and measured by the minimum time gap accepted by a driver when merging into the roundabout circular lanes (Lee et al., 2018). Using a revised Raff's method, this study calculated critical gaps for the basic and egg turbo roundabouts and the two-lane roundabout.

Due to bias in the original Raff's method (Troutbeck, 2016), Miller (1974) modified Raff's method, which is known as the revised Raff's method. Figure B-7 illustrates the critical gap determination process applying the revised Raff's method (Miller, 1974):

$$1 - F(t_r), F(t_a)$$

Where, t_a = accepted gap

t_r = rejected gap

$F(t_r)$ = cumulative distribution function of rejected gap

$F(t_a)$ = cumulative distribution function of accepted gap

From Figure B-7, the critical gap is the intersection point of the cumulative accepted gap and rejected gap curves. Most drivers accept any gap larger than critical gaps. The results for accepted and rejected gaps of each participant for all three roundabout types are presented in Table B-3.

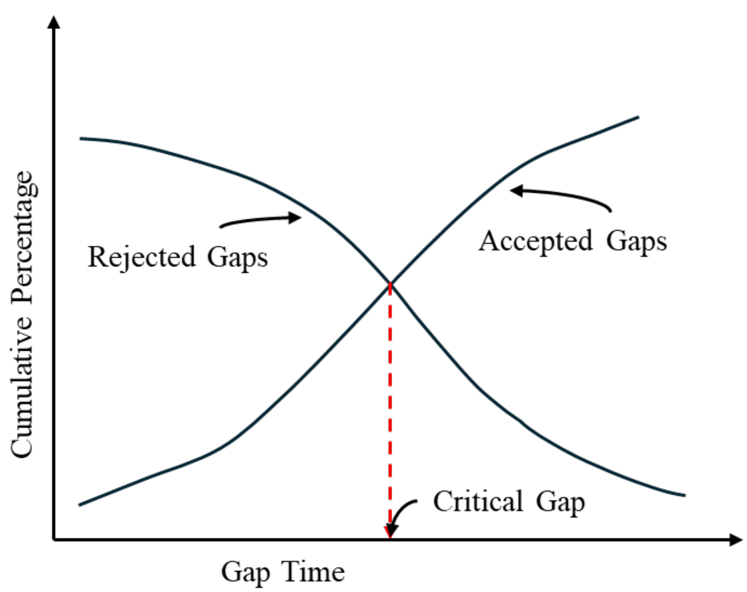


Figure B-7. Critical gap determination process, based on revised Raff's method (Image based on Shaaban & Hamad, 2018)

Table B-3. Observed Accepted Gaps on Two-lane, Egg Turbo, and Basic Turbo Roundabouts

Participant	Egg Turbo Gap Time (s)	Basic Turbo Gap Time (s)	Two-lane Gap Time (s)
1	9	6	5
2	7	6	7
3	7	5	6
4	6	5	6
5	5	7	3
6	11	7	6
7	5	4	4
8	4	5	5
9	7	5	7
10	11	11	6
11	5	6	5
12	5	5	N/A
13	7	5	4
14	7	7	7
15	7	5	4
16	7	7	6
17	11	3	6
18	9	7	6
19	7	5	6
20	5	4	3
21	6	6	5
22	5	4	3
23	11	11	N/A
24	7	6	7

To assess any statistically significant differences, a paired samples t-test was conducted between the accepted gaps among roundabout types. The results are summarized in Table B-4 and Table B-5. It can be observed that the average accepted gap for the egg turbo roundabout (*M = 7.13 secs, SD = 2.15*) was statistically significantly higher (1.21 secs) than the average accepted gap on the basic turbo roundabout (*M = 5.92 secs, SD = 1.91; t = 2.99, p < 0.05, df = 23*). The difference was even greater (1.73 secs) when accepted gaps were compared to the two-lane roundabout (*M = 5.32 secs, SD = 1.32; t = 4.43, p < 0.001, df = 21*). The results also indicated that the difference (0.41 secs) was not statistically significant when the accepted gaps for the basic turbo roundabout were compared to those of the two-lane roundabout (*t = 1.09, p = 0.289, df = 21*).

Table B-4. Descriptive Statistics for Accepted Gaps

Roundabout type	N	Min. Accepted Gap (sec)	Max. Accepted Gap (sec)	Mean	Std. Dev	Variance
Egg Turbo	24	4	11	7.13	2.15	4.64
Basic Turbo	24	3	11	5.92	1.91	3.64
Two-lane	22	3	7	5.32	1.32	1.75

Table B-5. Results of a Paired-Sample t-test on Accepted Gaps

Comparison Pair	Mean	Std.Dev	Std. Error	t	Df	Significance One-Sided p	Significance Two-Sided p
Egg Turbo – Basic Turbo	1.21	1.98	0.4	2.99	23	<u>**0.003**</u>	0.006
Egg Turbo – Two-lane	1.73	1.83	0.39	4.43	21	<u>**<.001**</u>	<u>**<.001**</u>
Basic Turbo – Two-lane	0.41	1.76	0.38	1.09	21	0.144	0.289

* Note: highlighted cells indicate statistical significance at a 95% confidence level (p<0.05).

In addition, to investigate the influence of driver familiarity on the accepted gaps measured across the three roundabout designs, a single-factor within-subjects analysis of variance (repeated-measures ANOVA) was employed. The repeated-measures ANOVA aims to ascertain whether the accepted gap values measured at the three roundabouts represent distinct populations with different mean values. In this context, the collected accepted gap values constitute three dependent samples, and the primary objective of the repeated-measures ANOVA used here is to assess the potential effect of familiarity on drivers' accepted gaps. Specifically, the analysis explores the significance of the interaction effect between familiarity and the accepted gap values observed across the three roundabout designs. From the results shown in Figure B-8, Mauchly's W (0.959) is not significant ($p > 0.05$), suggesting the assumption of homogeneity of variance (or sphericity) is satisfied.

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Epsilon[b] Huynh-Feldt	Epsilon[b] Lower-bound
Roundabouts	.959	.664	2	.718	.961	1.000	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Familiarity_Multi
Within Subjects Design: Roundabouts

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Figure B-8. Result from test for homogeneity of variance (Mauchly's test of sphericity).

Results from the repeated-measures ANOVA (shown in Figure B-9) indicated that the accepted gap values measured at the egg turbo, basic turbo, and two-lane roundabouts were statistically significantly different ($F\ (2) = 6.534,\ p = 0.004$). Furthermore, there was no statistically significant interaction between the accepted gaps and familiarity ($F = 0.839,\ p = 0.575$), suggesting no difference in accepted gap values between the three roundabout designs as a function of familiarity. In other words, familiarity did not influence driver's gap acceptance between the roundabout designs. From an experimental design perspective, this suggests that the order in which each driver was presented with a roundabout design during the driving simulation did not influence their gap acceptance. Hence, if there were shorter acceptable gaps on roundabouts encountered later during the simulation, it does not mean drivers learned and became familiar with navigation from roundabouts they encountered earlier during the simulation.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Roundabout Gaps	Sphericity Assumed	23.802	2	11.901	6.534	.004	.278
	Greenhouse-Geisser	23.802	1.922	12.385	6.534	.005	.278
	Huynh-Feldt	23.802	2.000	11.901	6.534	.004	.278
	Lower-bound	23.802	1.000	23.802	6.534	.020	.278
Roundabout Gaps * Familiarity_Multi	Sphericity Assumed	12.229	8	1.529	.839	.575	.165
	Greenhouse-Geisser	12.229	7.688	1.591	.839	.572	.165
	Huynh-Feldt	12.229	8.000	1.529	.839	.575	.165
	Lower-bound	12.229	4.000	3.057	.839	.519	.165
Error(Roundabout Gaps)	Sphericity Assumed	61.922	34	1.821			
	Greenhouse-Geisser	61.922	32.672	1.895			
	Huynh-Feldt	61.922	34.000	1.821			
	Lower-bound	61.922	17.000	3.642			

Figure B-9. Results of repeated-measures ANOVA test

Based on Raff's method, the cumulative distribution functions shown in Figures B-10 to 12 were developed. It can be observed that the critical gap values for the egg turbo, basic turbo, and two-lane roundabouts were determined as 6.1 secs, 4.2 secs, and 3.9 secs, respectively.

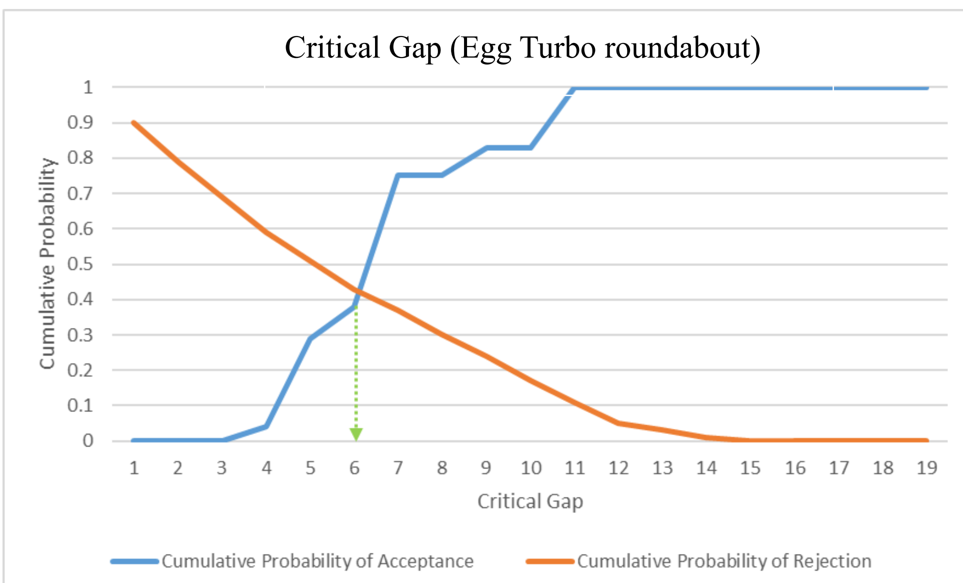


Figure B-10. Cumulative distribution function of gaps on Egg turbo roundabout

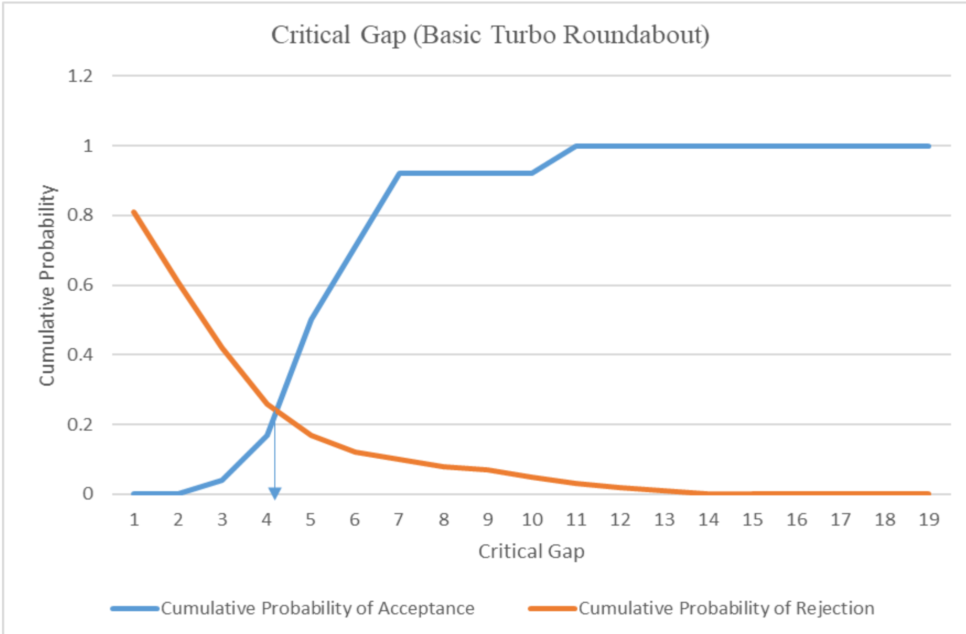


Figure B-11. Cumulative distribution function of gaps on Basic turbo roundabout

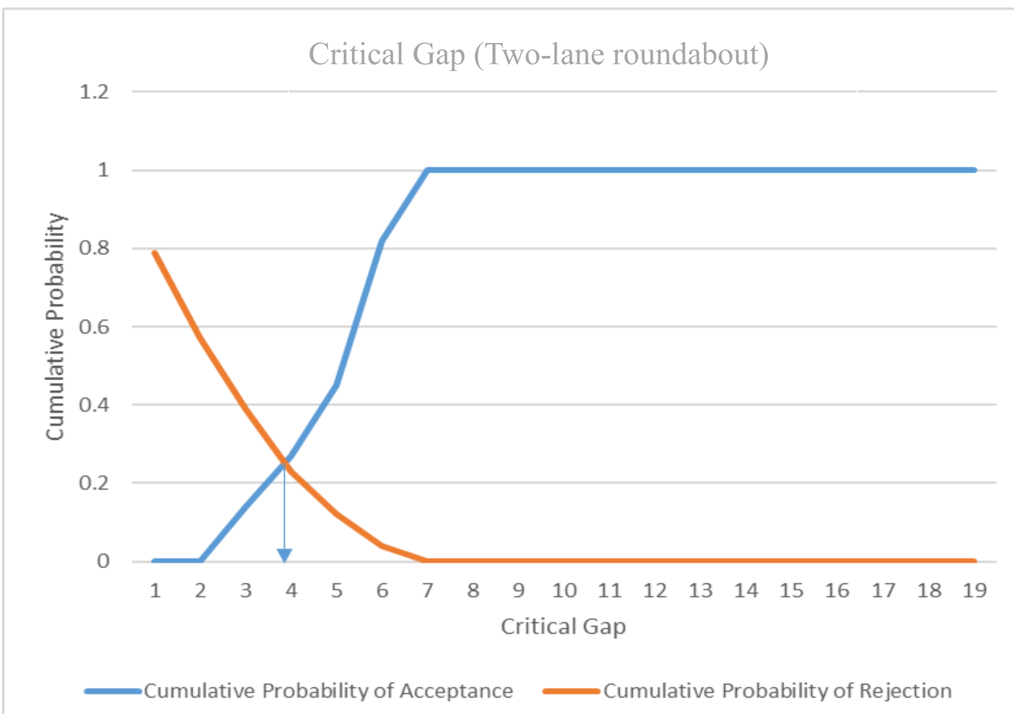


Figure B-12. Cumulative distribution function of gaps on the two-lane roundabout

The critical gap is crucial in analyzing the performance of unsignalized intersections and roundabouts (Guerrieri et al., 2018). Given that turbo roundabouts are still in the infancy of adoption in the U.S., the findings provide a basis for operational analysis of turbo roundabouts.

While current editions of the Highway Capacity Manual (HCM) do not provide recommended critical gap values for turbo roundabouts, the findings of this study provide valuable guidance in the selection of critical gap values for capacity analysis, development of microsimulation models and gap acceptance models specific to turbo roundabouts.

While critical gap values have previously been estimated for single-lane and multi-lane roundabouts in the U.S., those for turbo roundabouts have been limited. This study estimated the critical gap (3.9 secs) for a two-lane roundabout using data obtained from a driving simulator. This value is consistent with findings from previous research, including:

- 3.1 to 4.7 secs (mean of 3.9 secs) at four roundabouts in Connecticut by Guerrieri et al. (2018);
- 4.4 secs on a three-legged single-lane roundabout in China by Zhang et al. (2020).

The estimated critical gap value from the two-lane roundabout was compared to the values from previous research, providing validation for the driving simulator. Therefore, the virtual environment created in the driving simulator can be deemed reliable for estimating critical gap values for the turbo roundabouts under study.

To the authors' knowledge, no U.S.-based research studies have estimated critical gaps for turbo roundabouts – primarily due to the lack of implementation and driver's gap acceptance data. This study estimated the critical gap for a basic turbo roundabout (i.e., 4.2 secs) and an egg turbo roundabout (6.1 secs). These values are consistent with other studies conducted outside the U.S., including:

- 4.03 to 5.48 secs for different legs at a turbo roundabout in Slovenia by Guerrieri et al. (2018);
- 3.42 to 4.93 secs for different legs at a basic turbo roundabout in the Netherlands by (Fortuijn, 2009a); and
- Current Dutch guidelines recommend specific values based on the approach and lane position on turbo roundabouts. That is,
    - On major approaches, 3.56 secs and 3.80 secs for inner and outer lanes, respectively, and
    - On minor approaches, 3.15 secs and 3.70 secs for inner and outer lanes, respectively.

3.2. Analysis of Speeds

Study participants driving speeds were recorded along the entry approach, within the circular lanes, and departure lanes (at 100 ft intervals) as they drove through the simulator scenarios. Table B-6 summarizes the speed data as 15th, 50th, and 85th percentiles by roundabout design. The results of a dependent samples t-test on the average (50th percentile) speed suggested no evidence from the observed data of statistically significant differences between the egg turbo roundabout and the two-lane roundabout ($t = 2.869, p = 0.09$). Similarly, there was no evidence of statistically significant differences between the basic turbo and the two-lane roundabout ($t = -1.563, p = 0.132$). However, the differences between the egg turbo and basic turbo roundabouts were statistically significant ($t = 5.165, p < 0.05$).

In addition, the 50th percentile (Figure B-13) and 85th percentile (Figure B-14) values were plotted to obtain driver speed profiles. A visual inspection of both (50th and 85th percentile) speed profiles depicts expected driving behavior on the roundabouts. Generally, the speed profiles (all roundabout designs) follow the typical, expected trend for roundabouts – drivers reduce their speed on a roundabout approach, entering and negotiating the circular lanes, and then accelerating to a desired (or posted) speed when departing a roundabout. This observation is consistent with previous research (Fortuijn, 2009). A closer look at the profiles also depicts that the curve for the basic turbo roundabout (both at entry and exit) is much "smoother" and does not have irregular spikes. Also, the speeds are relatively lower for the basic turbo roundabout than for the two-lane roundabout along the approach leg. These observations suggest drivers were more comfortable navigating the basic turbo roundabout (smoother speed profile), which is a much safer roundabout type (lower speeds). The profile for the egg turbo suggests some concern with drivers' ability to navigate the roundabout comfortably and safely.

To complement the findings from the observed speeds, the survey questionnaire aimed to seek self-reported speeding behaviors from the participants. The responses to these questions are summarized in Figure B-15, Figure B-16, and Figure B-17. As depicted in Figure B-15, about 92% (N = 22) of participant drivers reported consistently slowing down on the approach to a roundabout. Only about 30% (N = 7) of the participants reported consistently adhering to the speed limit because, as depicted in Figure B-16, they slowed down. On the contrary, while departing a roundabout, 96% (N = 23) of participants reported increasing their speed, 55% (N = 13) maintained their speed, and 76% (N = 18) rarely or never slowed down while departing a roundabout.

With regards to the circulatory lanes of a roundabout, the participant responses suggest a variety of behaviors while traversing the circulatory lanes. Figure B-16 depicts that participants do not increase speed within the circulatory portion; 92% (N = 22) of participants reported rarely, never, or occasionally increasing their speed. Some 30% (N = 7) of participants always or frequently slow down while traversing the circulatory lanes, while about 40% (N = 10) rarely or never slow down. However, 71% (N = 17) reported consistently maintaining a safe speed while traversing the circulatory portion of a roundabout. Note that, generally, the ability to navigate within the circulatory/curvy section of roadways safely depends on several factors, ranging from individual driving ability, speed, and diameter of the curve to driver risk-taking tendencies.

Table B-6. Driver Speed Data on Roundabout Designs

Egg Turbo Roundabout															
				Approach				Circulatory				Departure			
Distance from yield line (ft)	**-500**	**-400**	**-300**	**-200**	**-100**	**-50**	**-25**	**0**	**25**	**50**	**100**	**200**	**300**	**400**	**500**
50th	12.08	12.93	13.17	12.88	12.83	12.76	4.99	6.76	8.07	8.52	10.72	12.48	13.73	14.68	15.33
15th	9.67	10.51	10.56	10.71	10.53	9.67	3.39	4.71	6.00	6.30	9.28	10.41	11.68	11.87	12.32
85th	14.12	14.78	15.39	15.84	16.02	16.05	5.81	8.67	10.00	10.19	11.52	14.57	14.86	15.66	16.48
Basic Turbo Roundabout															
				Approach				**Circulatory**				**Departure**			
Distance from yield line (ft)	**-500**	**-400**	**-300**	**-200**	**-100**	**-50**	**-25**	**0**	**25**	**50**	**100**	**200**	**300**	**400**	**500**
50th	14.06	13.43	11.96	9.11	6.04	3.03	5.53	6.46	8.27	8.77	10.81	12.83	14.59	15.5	16.02
15th	12.11	11.67	10.75	6.25	4.47	2.04	4.22	4.33	6.82	7.61	8.65	10.93	12.79	13.91	13.69
85th	15.33	15.11	14.54	11.08	7.61	4.29	7.83	8.95	9.65	10.36	13.47	16.12	16.93	16.65	16.75
Two-lane Roundabout															
				Approach				**Circulatory**				**Departure**			
Distance from yield line (ft)	**-500**	**-400**	**-300**	**-200**	**-100**	**-50**	**-25**	**0**	**25**	**50**	**100**	**200**	**300**	**400**	**500**
50th	14.94	14.52	13.82	12.32	8.42	1.27	5.27	5.96	5.13	3.46	5.3	8.64	10.9	11.93	12.42
15th	11.10	10.48	10.41	9.37	5.14	0.21	4.09	4.73	3.58	2.09	3.61	6.02	9.17	9.78	10.97
85th	16.23	15.49	14.53	13.11	8.89	2.92	6.62	7.62	5.76	4.95	6.65	11.55	12.76	13.71	13.47

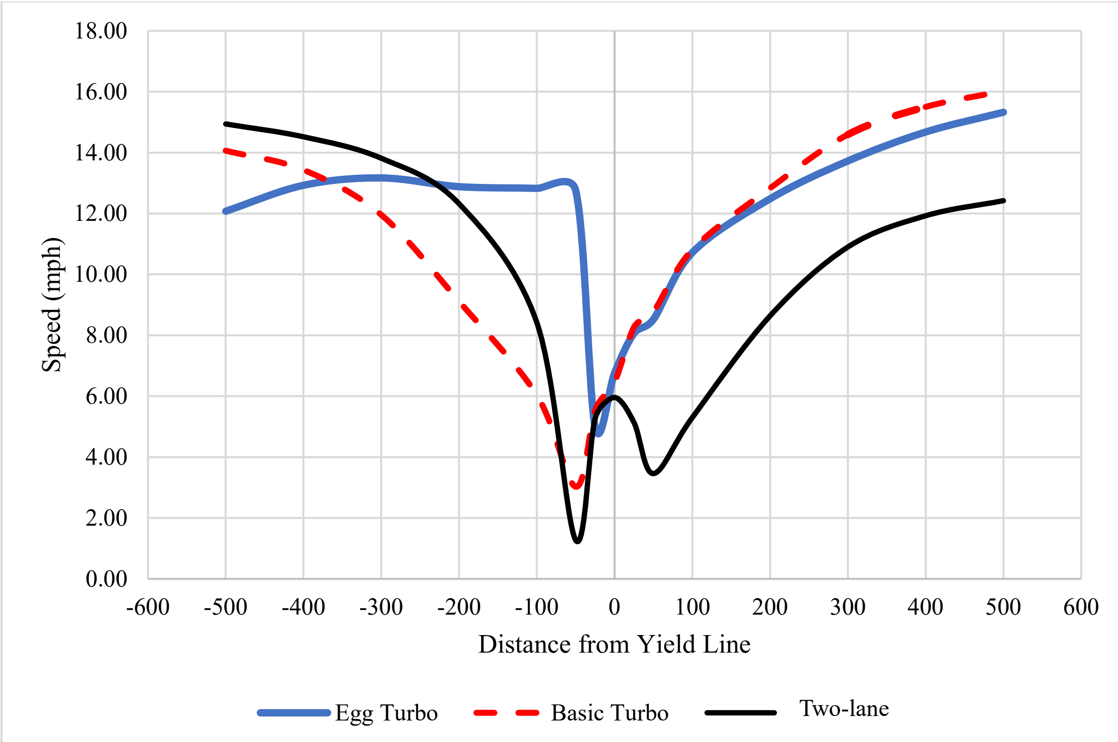


Figure B-13. Drivers average (50th percentile) speed profile.

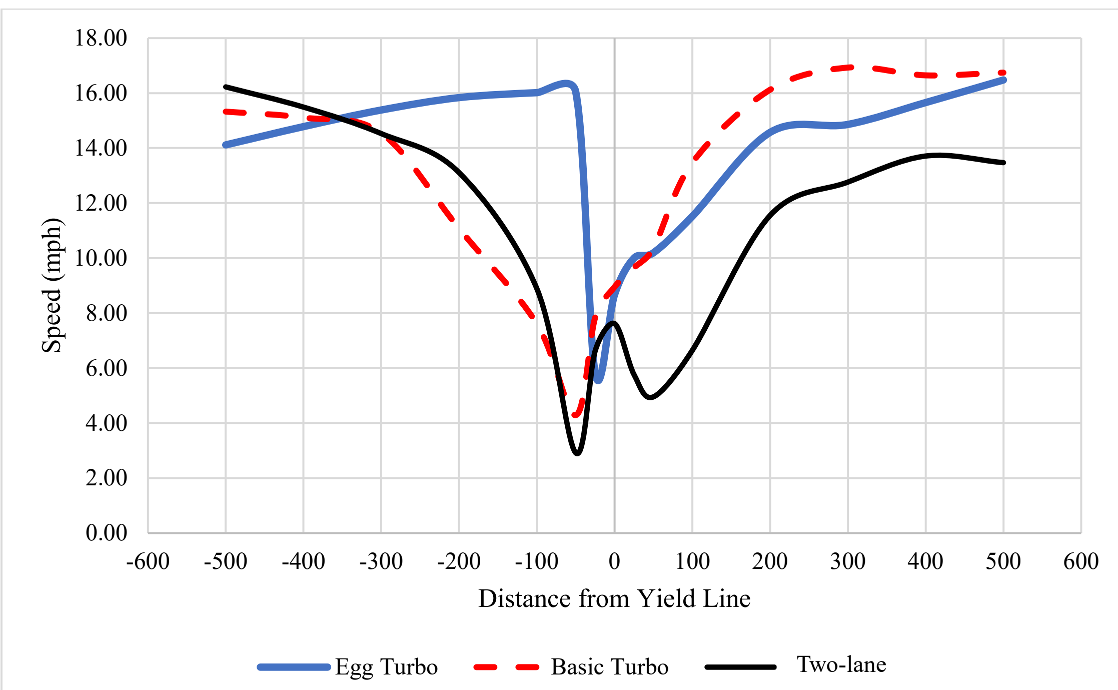


Figure B-14. Drivers 85th percentile speed profile.

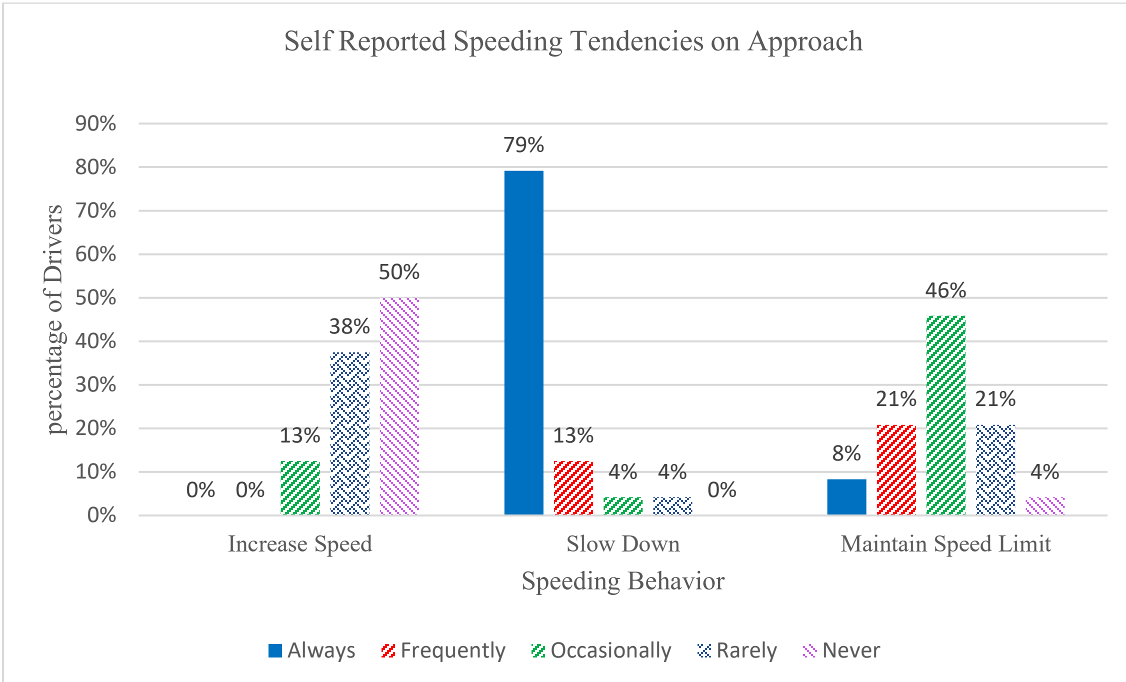


Figure B-15 Self-reported speeding behavior on the approach to a roundabout.

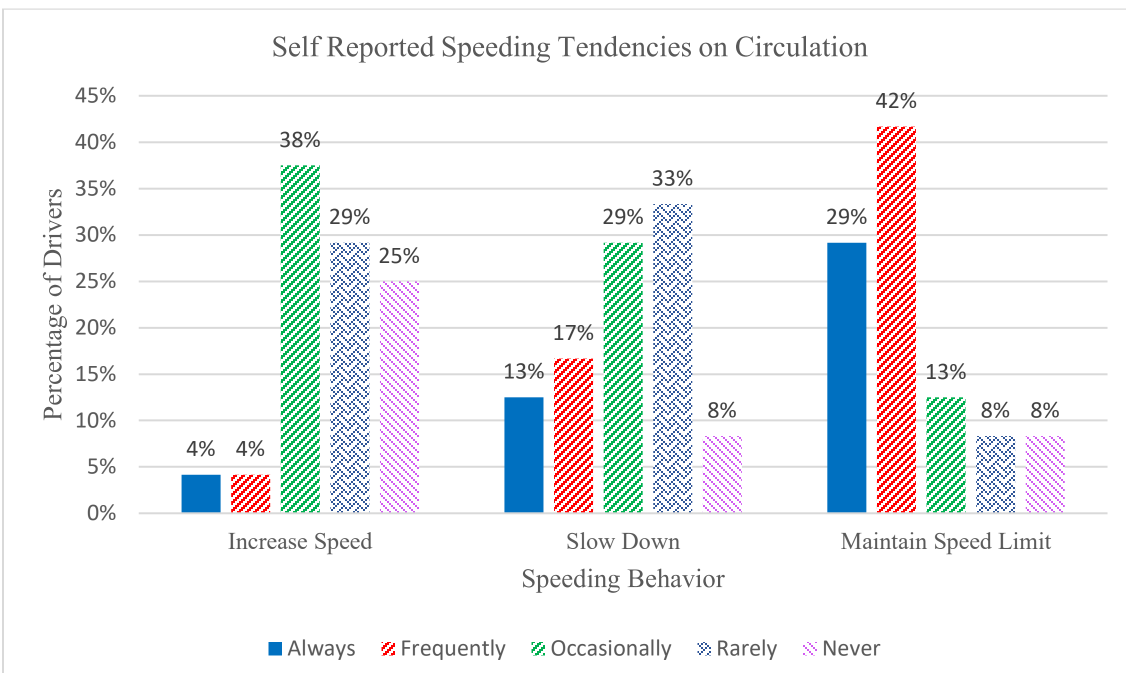


Figure B-16. Self-reported speeding behavior within the circulatory area of a roundabout.

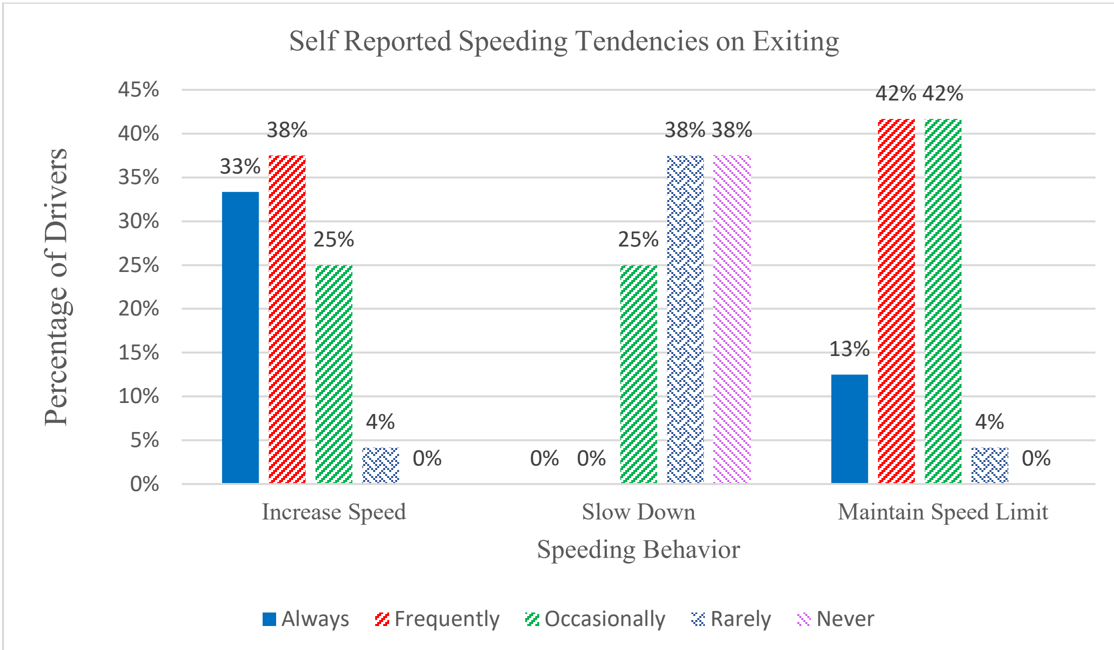


Figure B-17. Self-reported speeding behavior while departing a roundabout.

3.3. Analysis of Pre- and Post-Survey Responses

The pre- and post-survey aimed to understand the participants' perceptions regarding the turbo roundabout design. The purpose of gaining an understanding of the views of participants was two-fold – (i) with limited implementations in the U.S., it is unknown how drivers will accept and perceive turbo roundabouts, and (ii) the construction of roundabouts (in general) has the potential to generate considerable controversy. Hence, the analysis presented here focuses on participant drivers' opinions, attitudes, preferences, and perceptions regarding turbo roundabouts.

3.3.1. Drivers' Familiarity and Experience with Turbo Roundabouts

Question 9 on the pre-driving simulation survey (Appendix C) required participant drivers' to rate their familiarity with a specific roundabout type (i.e., single-lane, two-lane, or turbo) based on a five-point Likert scale. The results indicated that participants were highly familiar with single and two-lane roundabouts, as depicted in Figure B-18. Approximately 89% (N = 21) of the responses inferred being familiar with single-lane roundabouts, while about 75% (N = 18) were familiar with two-lane roundabouts. Thus, it is evident that many participant drivers had some level of experience with roundabouts. As anticipated, it can also be inferred from the responses that 88% (N = 21) of participants were unfamiliar with turbo roundabouts. Only a small number of participants had mixed feelings (felt neutral) about their knowledge of roundabouts: 6% (N = 1) for single-lane, 21% (N = 5) for two-lane, and 13% (N = 3) for turbo roundabouts.

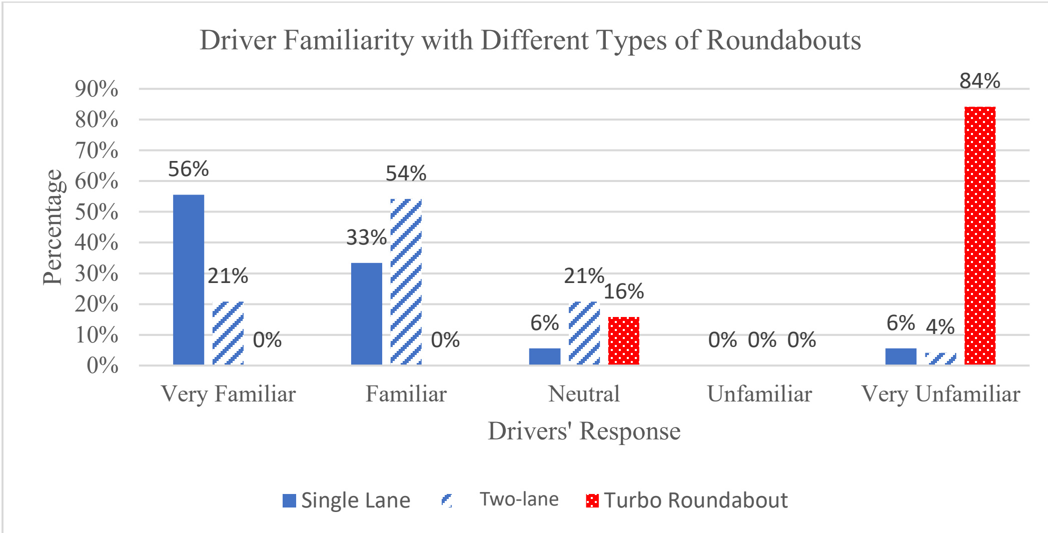


Figure B-18. Drivers' familiarity with different roundabout types.

A paired samples t-test was used to evaluate whether there were any statistical differences between participants' familiarity among the three roundabout types: single-lane, two-lane, and turbo roundabout. Table B-7 presents the descriptive statistics for responses to the familiarity question (Question 9), and Figure B-19 presents the output from the statistical analysis.

Table B-7. Summary of Driver's Responses to Familiarity with Different Roundabout Types.

Roundabout Types	N	Mean	S.E.	S.Dev
Single lane Roundabout	24	3.92	0.282	1.381
Two-lane Roundabout	24	3.75	0.193	0.944
Turbo Roundabout	24	1.46	0.147	0.721

Paired Samples Test

		Paired Differences							Significance	
					95% Confidence Interval of the Difference					
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	One-Sided p	Two-Sided p
Pair 1	Singlelane - Multilane	.167	1.435	.293	-.439	.772	.569	23	.287	.575
Pair 2	Singlelane - Turbo	2.458	1.474	.301	1.836	3.081	8.172	23	<.001	<.001
Pair 3	Multilane - Turbo	2.292	.999	.204	1.870	2.714	11.237	23	<.001	<.001

Figure B-19. Results of paired samples t-test.

From the results, it can be inferred that there were no statistically significant differences in drivers' familiarity between single-lane and two-lane roundabouts ($t = 0.569$, $p = 0.287$). However, there were statistically significant differences in the level of understanding between single-lane and turbo roundabouts ($t = 8.172$, $p < .001$) and also between two-lane and turbo roundabouts ($t = 11.237$, $p < 0.001$). These results are unsurprising, given there are limited turbo roundabouts in the U.S.

3.3.2. Drivers' Comments on Familiarity

To further probe participants on their level of familiarity and knowledge of roundabouts, question 10 on the pre-driving simulation survey (Appendix C) requested additional comment(s) on their familiarity with single-lane, two-lane, and turbo roundabouts. Table B-8 presents the summarized comments from participants. Based on participant comments, specific themes of unfamiliarity were identified and categorized into three main groups: *(1) lack of knowledge or experience with turbo roundabouts*, (2) *limited exposure to two-lane roundabouts*, and (3) *general uncertainty or lack of confidence in navigating roundabouts*.

The first theme of unfamiliarity was related to turbo roundabouts, as indicated by comments such as "I have never used a turbo roundabout," "I have only heard about turbo roundabouts but never used one," and "unfamiliar with turbo roundabouts." These comments suggest that respondents are generally unfamiliar with turbo roundabouts and lack knowledge or experience navigating them.

The second theme was limited exposure to two-lane roundabouts, as indicated by comments such as "I have only seen one multi-lane roundabout in the U.S. " and "I may have driven through a single-lane a couple of times." These comments suggest that some respondents have limited experience with two-lane roundabouts, which may contribute to their unfamiliarity or uncertainty in navigating them.

The third theme of unfamiliarity was related to general uncertainty or lack of confidence in navigating roundabouts (in general), as indicated by comments such as "I just follow traffic in many scenarios" and "I have experienced multiple roundabouts encountered in Athens, but I am not sure if I have encountered a turbo roundabout." These comments suggest that some respondents may feel uncertain or lack confidence in navigating roundabouts effectively, contributing to their unfamiliarity with different roundabouts.

Overall, the themes identified suggest that participant drivers have varying levels of familiarity with roundabouts (in general), with experience mainly with single and two-lane roundabouts. The participant drivers generally have little or no knowledge of turbo roundabouts. The themes of unfamiliarity suggest that respondents may benefit from additional education and training on the different types of roundabouts and strategies for navigating safely and confidently.

Table B-8. Participants' comments on familiarity with roundabouts.

ID	Participant Summarized Comment
P01	I just follow traffic in many scenarios.
P02	I only know of one kind of roundabout. The type I use regularly.
P03	A single lane has one lane; a multilane has more than one lane, on a turbo roundabout one cannot change lanes after entering the circle.
P04	I have gone through many single-lane roundabouts, and I have used the Richland Avenue roundabouts often, but I have never used a turbo roundabout.
P05	With single lanes, there are no extra lanes to allow passing. Multilane allow other vehicles to move alongside while traversing the roundabout.
P06	I frequently drive single and multilane roundabouts in Athens, OH. I have never driven through a turbo roundabout.
P07	I am familiar with correctly making my way through a single and multilane roundabout safely as there are numerous roundabouts in New Albany. I have never driven a turbo roundabout.
P08	In high school, the way to get to the high school from my house would involve a multilane roundabout, so typically I drove through it twice a day. There are occasions when I've driven through a single-lane.
P09	Use of single and multilane. Never heard of turbo.
P10	In Mexico, we use single-lane roundabouts a lot. I've only seen one multilane roundabout in the US, and I've never heard of a turbo
P11	Have driven through single and multilane. Not driven a turbo as far as I know.
P12	I drive through a single-lane roundabout very often as it is close to my house.
P13	Single lane roundabout is less complicated.
P14	I drive through a multilane roundabout every day, Richland Ave. I may have driven through a single lane a couple of time
P15	I did not know about turbo roundabouts existed until just now. Athens has several roundabouts that are very small and comfortable. So, I am used to them.
P16	I have never driven in a roundabout.
P17	I have experienced multiple roundabouts encountered in Athens, but I am not sure if I have encountered a turbo roundabout
P18	I drive in roundabouts very often. There are many single-lane roundabouts, but only 1 multilane roundabout I drive through
P19	I have driven both single and multilane roundabouts before and I drive them regularly. I have only heard about turbo roundabout but never used one.

3.3.3. Preferences for Roundabout Educational Material

Question 16 on the post-driving simulation survey (Appendix D) required participant drivers to indicate their preferred methods of receiving education and training on turbo roundabouts. The results are presented in Figure B-20**.** Social media platforms were the means by which 71% (N = 17) of participants preferred to receive information related to turbo roundabouts. Traditional media (radio and television) was the second most preferred method for 67% (N = 17) of the participant drivers. Other preferred methods that were selected are the use of webinars/video demos/simulations (58%, N = 14), dissemination using the driver's license manual (50%, N = 12), use of information brochures (46%, N = 11), and through a driving course/class (42%, N = 10).

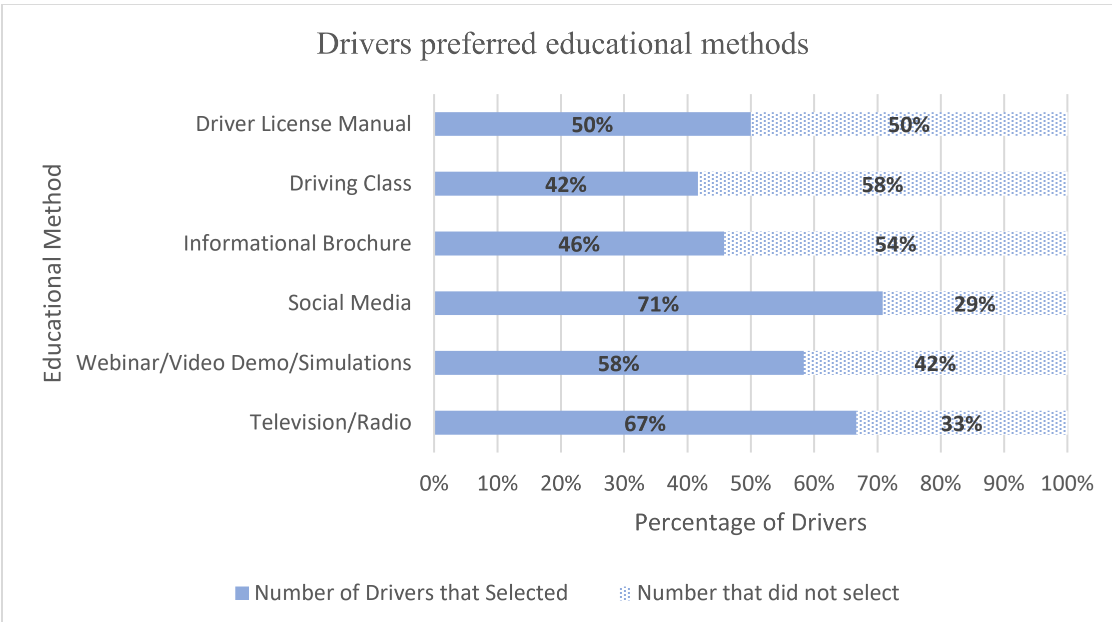


Figure B-20. Drivers preferred education methods.

3.3.4. Subjective Safety Perception of Roundabouts

Understanding the user's safety perception of turbo roundabouts is an important factor to consider in ensuring acceptance and subsequent smooth implementation. This study measured participant drivers' safety perception based on their responses to questions 11, 12, and 13 on the post-driving simulation survey (Appendix D). The questions were developed such that the respondent visualized themselves as drivers, cyclists, or pedestrians using a turbo roundabout. Figure B-21 presents the participants' responses.

From a driver's perspective, 76% (N = 18) of participants perceived roundabouts as safe, while 24% (N = 6) were neutral. From a cyclist perspective, 17% (N = 4) thought that roundabouts were safe, while more than half (58%, N = 14) were neutral. Lastly, from a pedestrian perspective, 37% (N = 9) of participants stated that roundabouts were unsafe, while 38% (N = 8) were neutral.

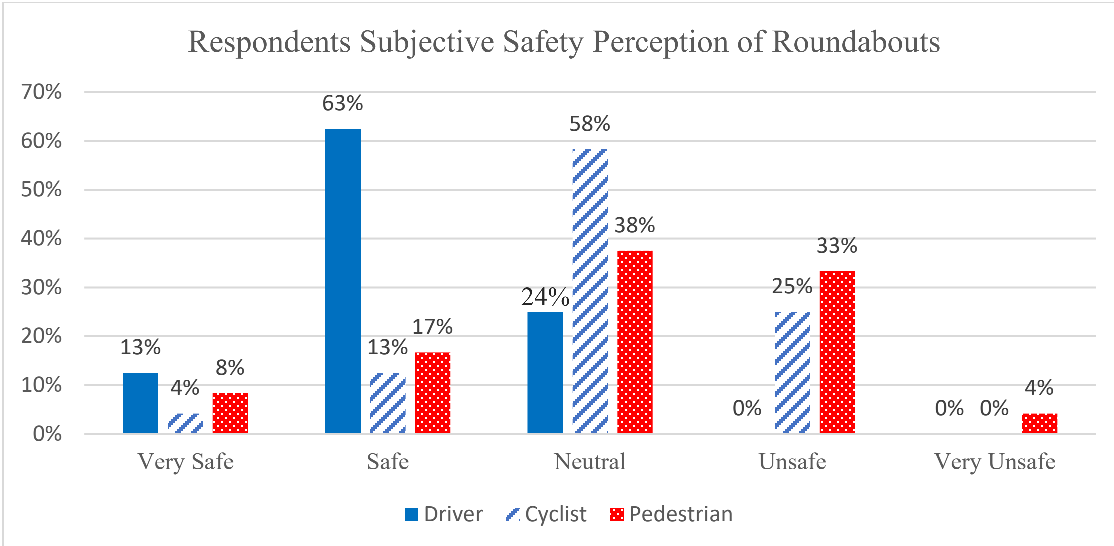


Figure B-21. Safety perception of roundabouts

A paired sample t-test on responses to the subjective safety perception questions (see Figure B-22) indicated that opinions regarding the safety of roundabouts differ among drivers, cyclists, and pedestrians. A statistically significant difference in subjective safety opinions between drivers and cyclists (*$t = 4.609$, $p < 0.001$*) was observed (Table B-9). Pedestrian opinions regarding safety were also statistically significantly different when compared to drivers (*$t = 3.808$, $p < 0.001$*). However, cyclists and pedestrians seemed to share similar views on the safety of roundabouts as differences in their perspective of roundabout safety were not statistically significantly different (*$t = 0.253$, $p = 0.401$*).

Table B-9. Summary of Participants Subjective Perceptions

	N	**Mean**	**Std. Error**	**Std. Dev.**
Driver	24	3.88	0.125	0.612
Cyclist	24	2.96	0.153	0.751
Pedestrian	24	2.92	0.208	1.018

Paired Samples Test

		Paired Differences							Significance	
					95% Confidence Interval of the Difference					
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	One-Sided p	Two-Sided p
Pair 1	Driver - Cyclist	.917	.974	.199	.505	1.328	4.609	23	<.001	<.001
Pair 2	Driver - Pedestrian	.958	1.233	.252	.438	1.479	3.808	23	<.001	<.001
Pair 3	Cyclist - Pedestrian	.042	.806	.165	-.299	.382	.253	23	.401	.802

Figure B-22. Results of paired samples t-test

Furthermore, based on responses to question 14 (pre-test questionnaire), only 4% (N = 1) reported having intentionally avoided a roundabout. While the survey did not seek the rationale behind participants' avoidance of roundabouts, two possible explanations for this behavior could be drivers' lack of familiarity with roundabouts and/or negatively held perceptions of roundabouts.

3.3.5. Public Acceptance, Opinions, and Preferences

Question 14 on the post-simulation survey assessed participant drivers' perceptions and acceptance of the turbo roundabout. The results (summarized in Figure B-23) indicated that 63% (N = 15) of drivers, after experiencing turbo roundabouts in the simulator, did not oppose their installation, with 37% (N = 9) either undecided or opposed to installation. However, there was a high willingness from participant drivers (84%, N = 20) to receive additional information and/or education regarding turbo roundabouts if a turbo roundabout was constructed in their communities.

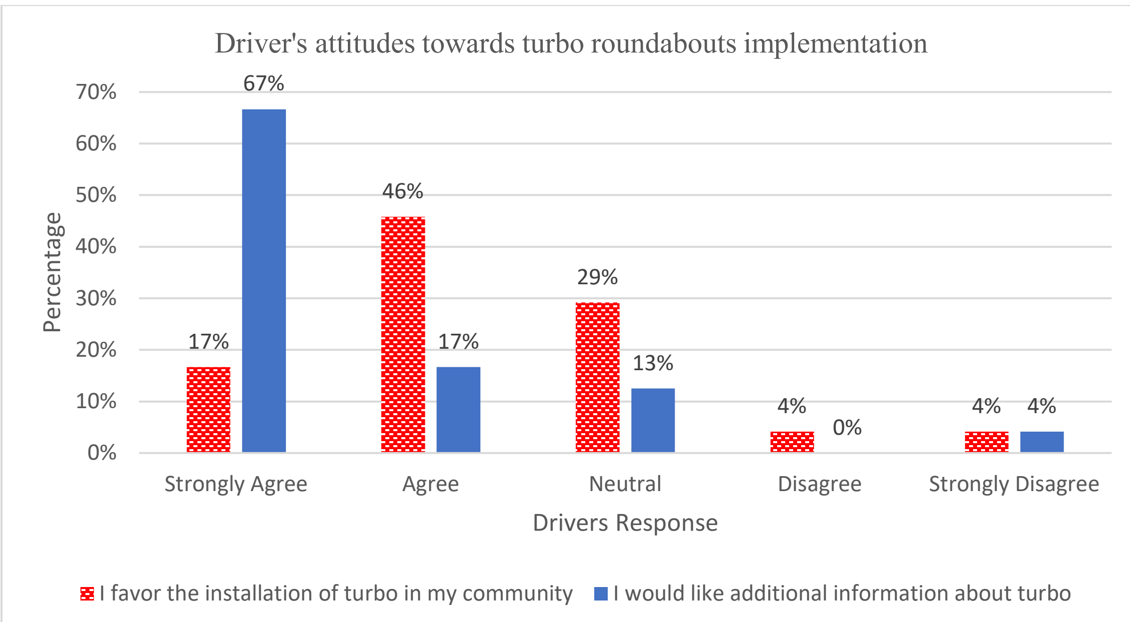


Figure B-23. Participant preference for turbo roundabout and additional information.

Table B-10 summarizes participant drivers' responses to several survey questions concerning the sentiments, behaviors, and preferences for turbo roundabouts. The value in the 'mean' column is the average value of the driver's response converted from 5-point Likert scale ratings (strongly disagree (1) to strongly agree (5)).

Table B-10. Driver Behavior and Preference for Turbo Roundabouts.

Survey Item	Pre-Driving Simulation Questions	N	Mean	SD	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
17a	I like roundabouts	24	3.88	0.83	28%	32%	40%	0%	0%
17b	I feel safe driving in a roundabout	24	4	0.65	20%	60%	20%	0%	0%
17c	I like the concept of the turbo-roundabouts	24	3.08	0.49	0%	4%	88%	4%	4%
17d	I would like to drive in a turbo roundabout	24	3.64	0.76	12%	32%	52%	0%	4%
17e	While going through a roundabout, I want to be able to switch lanes in certain cases. For example, if I am in the wrong lane	24	3.80	1.19	36%	32%	8%	24%	0%
17f	Before going into a roundabout, I usually check the signs to help me know how to move around in it	24	3.92	1.00	32%	40%	16%	12%	0%
	Post-Driving Simulation Questions								
9a	I like turbo roundabouts	24	3.50	0.89	8%	50%	25%	17%	0%
9b	Based on my driving experience in the simulator, it is easy to drive through a turbo roundabout	24	3.54	1.10	21%	38%	17%	25%	0%
9c	I would like to drive in a turbo roundabout	24	3.75	0.90	21%	42%	29%	8%	0%
9d	I feel safe navigating through a turbo roundabout because their restrictive lane-changing features	24	4.00	0.83	29%	46%	21%	4%	0%

3.3.6 Driver Preferences Regarding Geometric Features of Turbo Roundabouts

Question 15 on the post-simulation survey examined participant drivers' preferences for turbo roundabout features such as diameter, mountable aprons, pavement markings, and signage. Table B-11 summarizes participant drivers' average rating of geometric features of a typical turbo roundabout. Mean values represent values from a 5-point Likert scale rating.

Table B-11. Descriptive Statistics of Driver's Preferences for Geometric Features on Turbo Roundabouts

Survey Item	Geometric Feature	Mean	S.E.	Std. Dev
Q15a	"*Lane dividers discourage lane changing within the roundabout. Drivers, therefore, must select the proper lane before entering the roundabout*"[1]	4.292	0.195	0.955
Q15b	"*Mountable aprons offer sufficient maneuvering space for longer vehicles*" [1]	3.417	0.158	0.776
Q15c	"*The diameter of the roundabout is kept small to encourage lower speeds through the roundabout*" [1]	3.375	0.189	0.924
Q15d	"*Roundabout directional arrow signs direct drivers and increase the conspicuity of the central island*" [1]	3.958	0.175	0.859

[1] adopted from Federal Highway Administration. (2019). Turbo Roundabouts: Informational Primer. Federal Highway Administration, Report No. FHWA-SA-20-019, Washington, D.C. https://safety.fhwa.dot.gov/intersection/innovative/roundabouts/docs/fhwasa20019.pdf in Table B-11 and Figure B-24

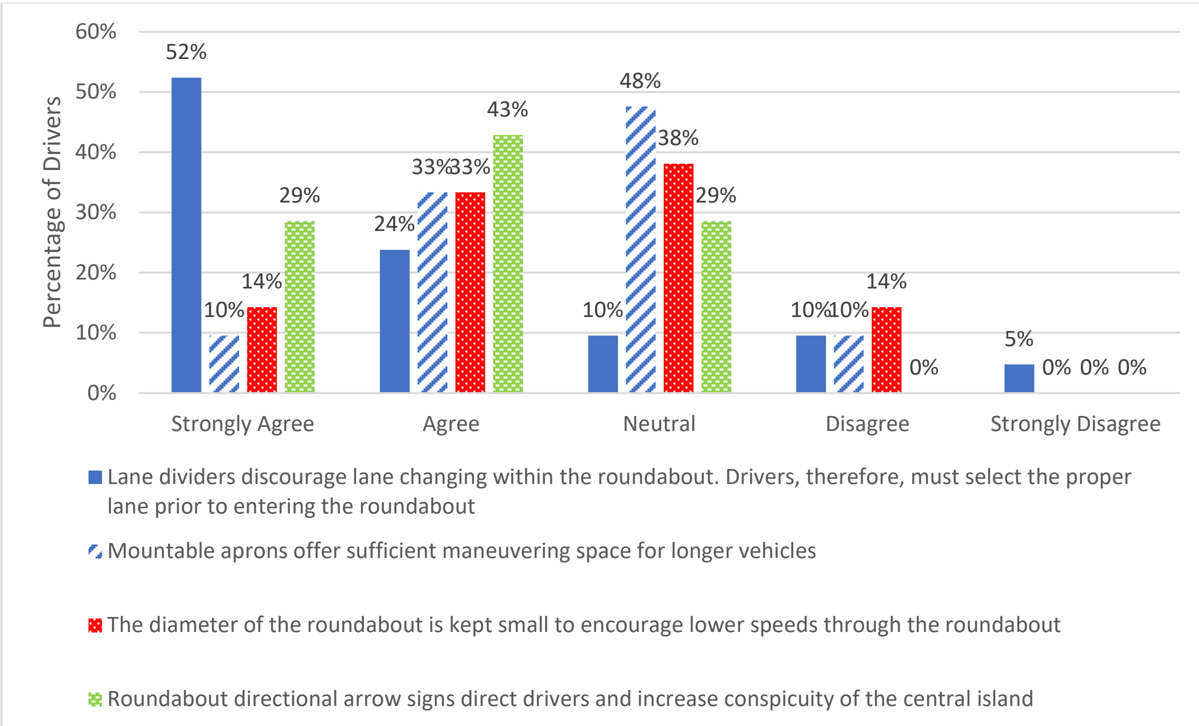


Figure B-24. Participant drivers' preferences for geometric features on turbo roundabout[1]

Figure B-24 summarizes responses regarding preferred geometric features on a turbo roundabout. About 76% (N = 24) of participant drivers thought a lane divider on a turbo roundabout was a useful feature to discourage lane changing. While lane dividers can prevent crashes related to lane changing within a roundabout, they are also likely to cause frustration for some drivers. In the case of participants in this study, 68% (N = 16) wanted to be able to switch lanes within a roundabout, especially when they are in the wrong lane – intuitively not favoring the presence of the lane dividers in the turbo roundabout.

About 72% (N = 17) of drivers agreed to the necessity of having prior pavement markings and adequate signage to enhance the turbo roundabout's visibility and aid in lane selection on entry into the roundabout. Based on this finding, it appears that even though lane dividers were provided on turbo roundabouts to eliminate potential lane-changing conflicts, this is still of concern to drivers. This finding reinforces a common challenge faced in the design of roundabouts – that while the proper placement of markings and signage should assist drivers, many drivers do not follow appropriate traffic control. Hence, the necessity of adequate pavement markings and directional signs cannot be over-emphasized to ensure a positive driver experience while transitioning from traditional two-lane roundabouts to turbo roundabouts.

Nearly half of the respondents (47%, N = 11) agreed with keeping the diameter of the turbo roundabout small to encourage lower speeds. A similar percentage of the drivers (43%, N = 10) favored having mountable truck aprons to allow for sufficient maneuvering space for larger vehicles such as semi-trailers. These results are vital as they provide valuable public input to developing geometric design guidelines for turbo roundabouts.

3.3.7. Driver Confidence Navigating Turbo Roundabouts

This study assessed drivers' confidence in navigating a turbo roundabout and public acceptance of its implementation. While the rules of operation for turbo roundabouts are similar to those of single and two-lane roundabouts, the geometric differences and restrictive lane-changing require approaching vehicles to select entry lanes appropriately and exhibit good negotiation behaviors within the turbo roundabout. Given that participating drivers were unfamiliar with turbo roundabouts (i.e., based on survey results presented in the previous section), it can be argued that drivers will likely rely on their previous experiences with navigating single/two-lane roundabouts when navigating turbo roundabouts for the first time. The underlying assumption here is that if drivers are confident in their ability to navigate roundabouts (in general), they will experience less difficulty negotiating turbo roundabouts and will likely display a positive perception of them. From an implementation standpoint, this could mean receiving less resistance from the public as drivers would positively perceive the turbo roundabout.

To investigate this hypothesis, participants were asked (question 4 on the post-driving survey) to rate their confidence in completing specific maneuvers at a roundabout (in general), including selecting the correct entry lane, merging and entering, driving within the circulatory region, and exiting. Figure B-25 summarizes drivers' confidence in completing these maneuvers. The results indicated that 67% (N = 16) of the respondents felt confident in selecting the correct entry lane, while 34% (N = 8) were either neutral or not confident. With respect to merging/entry, an increasing percentage (79%, N = 19) felt confident in their ability to merge/enter a roundabout by identifying suitable gaps, while only 21% (N = 5) were either neutral or not confident. A larger number of drivers (88%, N = 21) felt confident in traversing the circulatory area, while almost all drivers (96%, N = 23) felt confident in their ability to exit a roundabout at their intended exit.

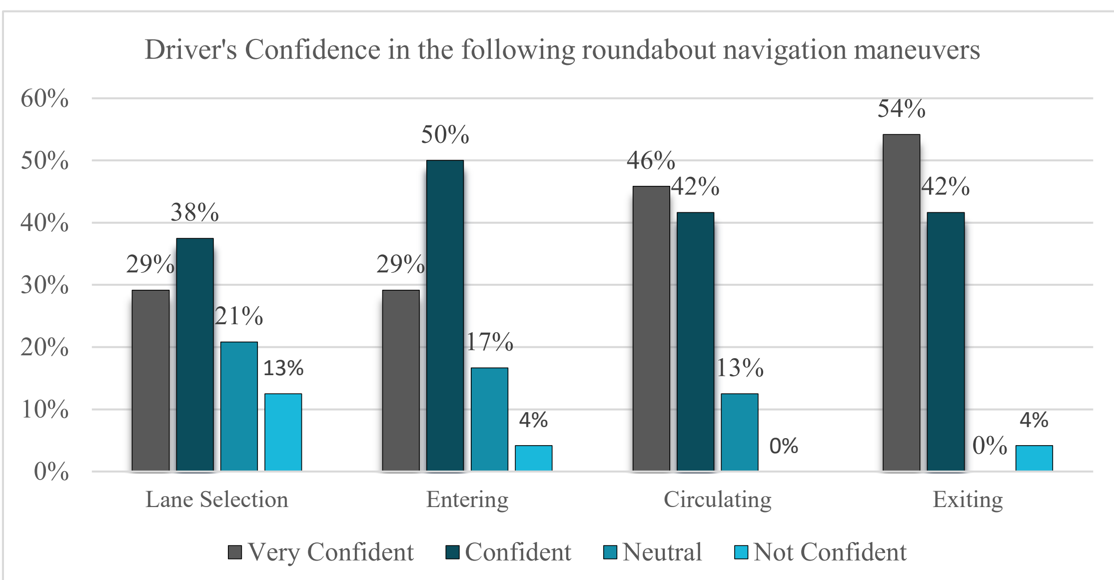


Figure B-25. Driver’s confidence in navigating a roundabout.

3.3.8. Driver Awareness of Pedestrian and Bicycle Users

In designing and implementing roundabouts, it is crucial to consider the needs of all user groups, especially vulnerable road users (VRUs) such as pedestrians and bicyclists. In this study, participant drivers were assessed for their awareness of VRUs when approaching a roundabout. Figure B-26 presents results from the post-test survey questionnaire. The results revealed that 96%

(N = 23) of participating drivers when approaching a roundabout (in general), were aware of the presence of pedestrians on crosswalks. While 67% (N = 16) of the drivers reported being cautious of pedestrians when exiting a roundabout, all the drivers (100%, N = 24) did not expect a pedestrian on the circulatory roadway of a roundabout, hence did not think about being cautious of pedestrians on the central portion of a roundabout while navigating the circle. It is important to note that navigation through a turbo roundabout by a pedestrian is similar to single-lane and/or two-lane roundabouts. To ensure that driver expectations are not entirely altered, retaining the best pedestrian and bicyclist accommodation practices in implementing turbo roundabouts is important.

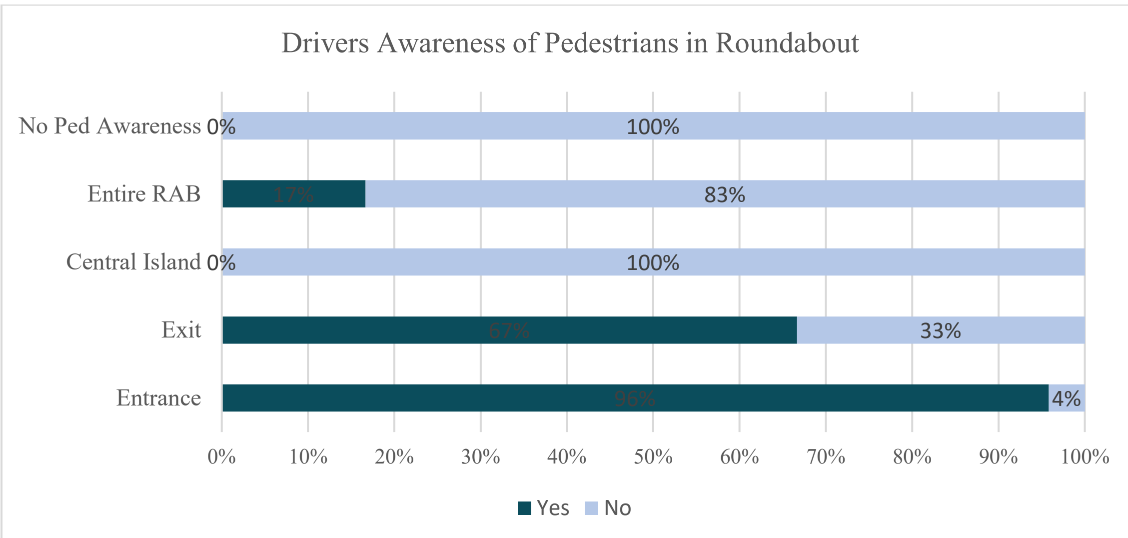


Figure B-26. Driver's awareness of pedestrians in roundabouts.

APPENDIX C

PRE-DRIVING SIMULATION SURVEY

PRE-TEST QUESTIONNAIRE

Section A: General Information and Driving Experience

1. What is your gender?
   Female [ ]
   Male [ ]
   Prefer not to answer [ ]
   Other (please specify) [ ]

2. What is your age group?
   18 – 25 [ ]
   26 – 40 [ ]
   41 – 55 [ ]
   56 – 65 [ ]
   65+ [ ]

3. How many years have you been driving for?
   1 to 3 years [ ]
   3 to 5 years [ ]
   More than 5 years [ ]

4. On average how many miles do you driver per day
   0 – 5 miles [ ] 5 – 10 miles [ ] 10 -50 miles [ ]
   50 – 100 miles [ ] 100 + miles [ ]

5. On average how many days per week do you drive?
   1 [ ] 2 [ ] 3 [ ] 4 [ ] 5 [ ] 6 [ ] 7 [ ]

Section B: Familiarity, Subjective Safety and Preferences

Familiarity with a roundabout can include knowledge of the proper way to navigate a roundabout, understanding of the traffic signs and signals, and awareness of the potential hazards or challenges associated with driving in a roundabout. It also includes the level of experience a driver has with driving in roundabouts, as well as their confidence and comfort level when navigating them.

6. As a driver, have you ever driven through a roundabout? If No, Skip to question 7
   Yes [ ] No [ ]

7. How frequently do you drive through a roundabout as you go about your weekly routine?
   1 day per week [ ] 2 days per week [ ] 3 days per week [ ] 4 days per week [ ]
   5 days per week [ ] 6 days per week [ ] 7 days per week [ ]

8. Which of the following modes have you traveled through a roundabout with you as the main operator/user/driver? (Select all that apply)
   Walking [ ] Bicycle [ ] Automobile [ ]
   Motorcycle [ ] Commercial Motor Vehicle (i.e., semi) [ ]

9. How would you rate your level of familiarity with the following types of roundabouts on a scale from 1(very familiar) to 5 (very unfamiliar).

1: Very Familiar 2: Familiar 3: Neutral 4: Unfamiliar 5: Very Unfamiliar

Single Lane Roundabout	1 [ ]	2 [ ]	3 [ ]	4 [ ]	5 [ ]
Multilane Roundabout	1 [ ]	2 [ ]	3 [ ]	4 [ ]	5 [ ]
Turbo Roundabout	1 [ ]	2 [ ]	3 [ ]	4 [ ]	5 [ ]

10. Can you please provide a little more detail regarding your level of familiarity with any of the roundabouts listed in question 9 above?

11. As a driver, how safe do you perceive roundabout when you drive through? Please rate your safety perception on a scale from 1 (feel very safe) to 5(feel very unsafe)

Very Safe	Safe	Neutral	Unsafe	Very Unsafe
[ ]	[ ]	[ ]	[ ]	[ ]

12. As a cyclist, how safe do you feel when driving through any type of roundabout? Please rate your safety perception on a scale from 1 (Very Safe) to 5(Very Unsafe)

Very Safe	Safe	Neutral	Unsafe	Very Unsafe
[ ]	[ ]	[ ]	[ ]	[ ]

13. As a pedestrian, how safe do you feel when driving through any type of roundabout? Please rate your safety perception on a scale from 1 (feel very safe) to 5(feel very unsafe)

Very Safe	Safe	Neutral	Unsafe	Very Unsafe
[ ]	[ ]	[ ]	[ ]	[ ]

14. Have you ever or do you intentionally avoided a roundabout when traveling?
Yes [ ] No [ ]

15. If yes to question 14, why:

16. How strongly do you agree or disagree with the following statements? Indicate your opinions on the following statements using the provided scale

17. **1 Strongly Agree 2 Agree 3 Neutral 4 Disagree 5 Strongly Disagree**

[ ] I like roundabouts
[ ] I like turbo-roundabouts
[ ] I would like to drive in a turbo roundabout
[ ] I feel safe navigating than a turbo roundabout because of their restrictive lane changing features
[ ] While going through a roundabout, I want to be able to switch lanes in certain cases, for example if I am in the wrong lane
[ ] Before going into a roundabout, I usually check the signs to help me know how to move around in it

APPENDIX D

POST-DRIVING SIMULATION SURVEY

POST-TEST QUESTIONNAIRE

Section D: Roundabout Information and Operations

1. To what extent do the following characteristics of roadway infrastructure (such as roundabouts, traffic signals, and interchanges) affect your overall positive perception of them.

	Extremely	Highly	Moderately	Slightly	Not at all
Safety	[ ]	[ ]	[ ]	[ ]	[ ]
Operational efficiency	[ ]	[ ]	[ ]	[ ]	[ ]
Complexity	[ ]	[ ]	[ ]	[ ]	[ ]

**safety: how safe you feel while driving through*
** operational efficiency: less delay encountered*
** complexity: less confusion on the rules and how they operate*

2. What is the direction of travel within roundabouts?
   [ ] Clockwise   [ ] Counterclockwise

3. Which driver is required to yield at a roundabout?
   [ ] The driver entering the roundabout
   [ ] The driver already in the roundabout
   [ ] None, there is no yield requirement at a roundabout
   [ ] Other (please specify)

4. How confident/comfortable are you with the following maneuvers at a roundabout?

	Very Confident	Confident	Neutral	Not Confident
Choosing the proper lane prior to entering a roundabout	[ ]	[ ]	[ ]	[ ]
Merging/entering a roundabout	[ ]	[ ]	[ ]	[ ]
Circulating in a roundabout	[ ]	[ ]	[ ]	[ ]
Exiting a roundabout	[ ]	[ ]	[ ]	[ ]

5. When approaching a roundabout during your normal daily routine, how often do you perform the following actions.

	Always	Frequently	Occasionally	Rarely	Never
Increase driving speed	[ ]	[ ]	[ ]	[ ]	[ ]
Slow down	[ ]	[ ]	[ ]	[ ]	[ ]
Maintain the speed limit	[ ]	[ ]	[ ]	[ ]	[ ]

6. When driving in the circle of a roundabout during your normal daily routine, how often do you perform the following actions.

	Always	Frequently	Occasionally	Rarely	Never
Increase driving speed	[ ]	[ ]	[ ]	[ ]	[ ]
Slow down	[ ]	[ ]	[ ]	[ ]	[ ]
Maintain the speed limit	[ ]	[ ]	[ ]	[ ]	[ ]

7. When exiting a roundabout during your normal daily routine, how often do you perform the following actions.

	Always	Frequently	Occasionally	Rarely	Never
Increase driving speed	[ ]	[ ]	[ ]	[ ]	[ ]
Slow down	[ ]	[ ]	[ ]	[ ]	[ ]
Maintain the speed limit	[ ]	[ ]	[ ]	[ ]	[ ]

8. In which regions of a roundabout do you exercise the most caution regarding the presence of pedestrians? Select all that apply
   [ ] Entrance
   [ ] Exit
   [ ] Central island
   [ ] Throughout the entire roundabout
   [ ] I do not have a specific focus on the presence of pedestrians when navigating a roundabout
   [ ] Other (please specify)

Section E: Turbo Roundabouts: Operations, Attitude, Opinions and Preferences

9. Please indicate the extent to which you agree or disagree with the following statements using the provided scale:
   1: Strongly Agree 2: Agree 3: Neutral 4: Disagree 5: Strongly Disagree

   [ ] I like turbo-roundabouts
   [ ] Based on my driving experience in the simulator, it is easy to drive through a turbo roundabout
   [ ] I would like to drive in a turbo roundabout
   [ ] I feel safe navigating through a turbo roundabout because their restrictive lane changing features

10. How safe do you perceive the turbo roundabout to be in comparison the following types of intersection types.

	Very Safe	Safe	Somewhat	Safe	Not Safe al all
4-way stop intersection	[ ]	[ ]	[ ]	[ ]	[ ]
Signalized intersection	[ ]	[ ]	[ ]	[ ]	[ ]
Single-lane roundabout	[ ]	[ ]	[ ]	[ ]	[ ]
Multilane roundabout	[ ]	[ ]	[ ]	[ ]	[ ]

11. While driving in the simulator, did you notice any difference between the turbo and multilane roundabout? If skip the next question
    [ ] Yes No

12. If yes, indicate what were the differences? [Select all that apply]
    [ ] Ease of navigation
    [ ] Difference in geometry
    [ ] Other (please specify)

13. When navigating a turbo roundabout in the driving simulator, did you

    [ ] Yes[ ] No Adhere to posted speed limits?
    [ ] Yes[ ] No Utilize pavement markings to select the appropriate lane
    [ ] Yes[ ] No Reduce speed?
    [ ] Yes[ ] No Monitor oncoming traffic?

14. How strongly do you agree or disagree with the following statements? Indicate your opinions on the following statements using the provided scale

1: Strongly Agree 2: Agree 3: Neutral 4: Disagree 5: Strongly Disagree

[ ] I favor the installation of a turbo roundabout in my community
[ ] I would like additional information about how to navigate a turbo roundabout if it is built in my community

15. The turbo roundabout is a relatively new type of roundabout that has been designed to be safe and efficient under certain conditions by implementing specific geometric features. Please rate the extent to which you find the following characteristics of the turbo roundabout, as a driver, to be favorable using the provided scale.

[ ] Lane dividers discourage lane changing within the roundabout. Drivers, therefore, must select the proper lane prior to entering the roundabout.
[ ] Mountable aprons offer sufficient maneuvering space for longer vehicles
[ ] The diameter of the roundabout is kept small to encourage lower speeds through the roundabout
[ ] Roundabout directional arrow signs direct drivers and increase conspicuity of the central island
[ ] I like that I must select the right lanes before entering the turbo roundabout

Section F: Education

16. If a transportation agency were to develop educational materials on how to navigate a turbo roundabout, which of the following mode(s) of delivery would be most helpful to you? Select all that apply.
[ ] Television and/or Radio
[ ] Webinars/Video Demonstration/Simulations
[ ] Social Media (e.g., Fakebook, Twitter, Website etc.)
[ ] Informational brochure
[ ] Driving Course/Class
[ ] Driver License Manual
[ ] Other (please specify)

APPENDIX E

INTERSECTION CONTROL SELECTION PROCEDURE

1. Introduction

With recent innovations, engineers have more control options to manage traffic at an intersection (NDOT, 2021). In the past, installing a traffic signal at an intersection was thought to be the only solution to traffic delays and safety problems. Recently, intersection control options such as roundabouts, reduced access intersections, and higher capacity intersections have become feasible alternatives. Selection of an intersection control design requires optimizing traffic/operation efficiency and safety in addition to available right-of-way, traffic characteristics, and local constraints. Turbo roundabouts improve traffic safety while also maintaining a higher level of traffic efficiency. A decision support system could help intersection control designers decide when to adopt turbo roundabouts instead of traditional single-lane and two-lane roundabouts and aid the selection of the most suitable intersection control type. This study developed an intersection control evaluation (ICE) tool applying a multi-criteria analysis approach to compare candidate intersection control types considering multiple performance measures and their relative importance.

2. Multi-Criteria Analysis (MCA) Tool Development

Multi-criteria Analysis (MCA) is a decision-making framework that is highly reliable in situations where performance measures have different measurement units. This method allows decision-makers to consolidate a variety of criteria (with varying units of measurement) into a single evaluation score for each alternative/option. By enabling comprehensive comparisons, MCA allows decision-makers to assign different importance to different performance measures when all measures are not equally important. Steps in executing an MCA development process are illustrated in Figure E-1. The first step for an MCA procedure is to develop a decision context. Criteria/performance measures can be selected based on the analysis's objectives and the availability of relevant performance data. The performance measures can have qualitative and quantitative attributes. After choosing the performance measures, relative importance/weights can be assigned to each performance measure based on their relative importance in the decision-making context (based on stakeholders' consensus). The following equation can be used to calculate the overall performance score of candidate alternatives:

$$S_i = w_1 S_{i1} + w_2 S_{i2} + \cdots \ldots\ldots\ldots\ldots .. + w_n S_{in} = \sum_{j=1}^{n} w_j S_{ij} \qquad \text{(E-1)}$$

Where,

S_i is the overall weighted score for each alternative (e.g., roundabout design),

w_j is the weight for each performance measure,

S_{ij} is the normalized scores of roundabout design i on performance measure j, and

n is the number of performance measures.

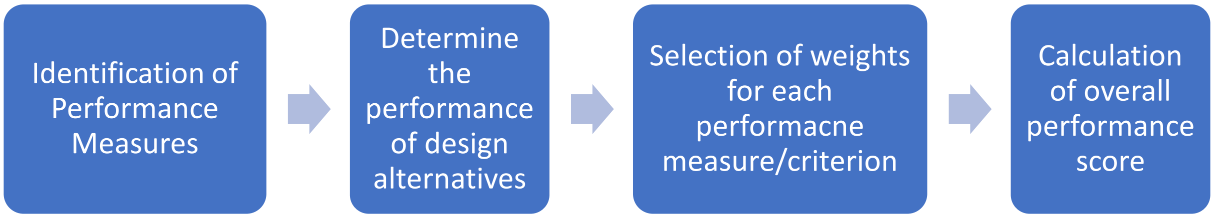


Figure E-1: MCA Steps

2.1 Identification of Performance Measures

As discussed before, this study considered four roundabout types for MCA analysis: basic turbo roundabout, egg turbo roundabout, traditional two-lane roundabout, and traditional single-lane roundabout. The performance measures were selected based on the project technical panel's input and presented in Table E-1. The relative importance of each performance measure needs to be selected based on the involvement of stakeholders in the intersection control selection process. The safety and operational performance measures of different design alternatives to be considered in this study were estimated using VISSIM simulation and SSAM safety analysis (presented in Chapter 3).

Table E-1: Selected performance measures

Performance measure Category	Performance Measures	Description
Traffic Efficiency	Volume to capacity (v/c) ratio	The volume-to-capacity ratio for the roundabout types at the existing traffic volume
	Delay	Average intersection delay at the intersection in seconds/vehicle for design year volume
Traffic Safety	Estimated number of conflicts	Total number of conflicts derived from SSAM
Cost	Relative Construction and Maintenace Cost	Relative cost of the alternatives (based on past studies).

2.2 Selection of Performance Measure Weights

The assigned weight to each performance measure depends on the relative importance of each measure in selecting the most suitable intersection control types. Considering their relative importance, stakeholders involved in intersection control planning, designing, operations, and maintenance can choose weights. Based on the engineering judgment, the researchers assigned weights to four performance measures listed in Table E-1 for demonstration purposes. A summary of assigned weights to four selected criteria is shown in Table E-2. **Note:** The stakeholders can modify the weights for performance measures depending on the importance of each measure to the respective stakeholder(s). A Microsoft Excel-based intersection control evaluation (ICE) tool was developed to assist stakeholders in weight selection and overall performance score calculation for each intersection control design alternative.

Table E-2: Weights assigned to four performance measures

Performance Measure	Description	Adjusted Weight
1	Estimated number of conflicts	33%
2	Volume-to-capacity (v/c) ratio for design year traffic volume	21%
3	Average intersection delay for design year volume	21%
4	Construction and maintenance cost	25%

2.3 Calculation of Cumulative Performance Scores

For demonstration purposes of the ICE tool, a traffic demand scenario with a traffic volume of 3,000 vehs/hr, 50% left turn volume, and a major street-minor street split of 70%-30% was used. Total number of conflicts, volume to capacity (v/c) ratio, and average delays for this specific traffic demand scenario were collected from the VISSIM simulation and SSAM analyis (Chapter 3), and relative construction costs were calculated based on cost estimates from past studies (Porter et al., 2019; Robert, 2021) (summarized in Table E-3). The basic turbo roundabout was the best intersection control alternative for the selected traffic demand scenario (applying the weights assigned to performance measures in Table E-2), with the highest score of 75, and the two-lane roundabout was the second-best alternative, with a score of 74.

Table E-3: Score values for the alternatives for four performance measures

Alternative	Total number of conflicts	Volume to Capacity Ratio	Average Delay (secs/veh)	Relative Cost
Single-lane	1,107	1.33	42.35	1
Two-lane	1,034	0.91	26.23	1.66 times of single-lane
Egg turbo	753	1.04	16.68	1.25 times of single lane
Basic turbo	269	0.88	6.7	1.66 times of single-lane

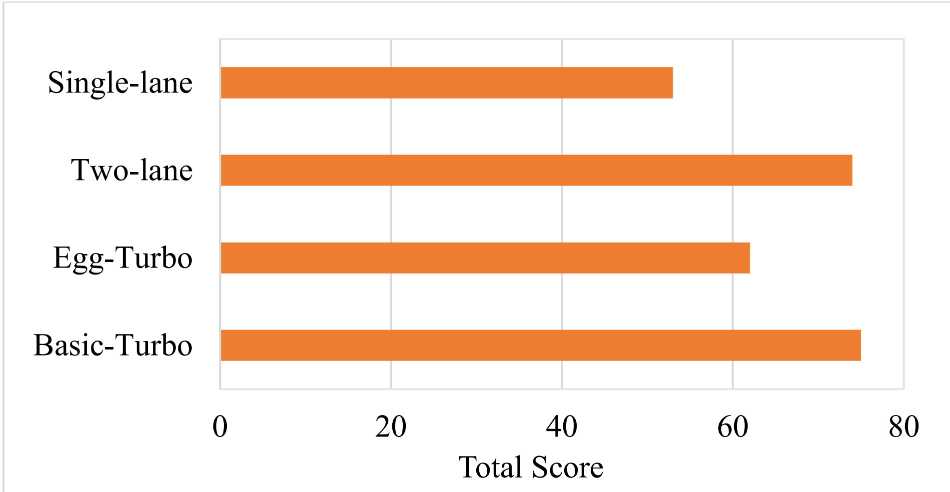


Figure E-2: Overall score of the alternatives for traffic volume of 3,000 veh/hr, a major street-minor street split of 70%-30%, and 50% left turn traffic.

2.4 Impact of traffic demand volume and composition on intersection control selection

An analysis was conducted for different traffic demand volumes, major street-minor street traffic volume split, and left turn percentage to examine which roundabout design alternative suits a particular traffic composition considering four performance measures. Traffic volumes varied from 1,500 pcu/hr to 3,500 pcu/hr with an increment of 500 pcu/hr. This analysis considered two scenarios of major-minor splits (balanced condition/major-minor split of 50%-50% and unbalanced condition/ major-minor split of 60%-40%) and left-turn traffic percentages of 20% and 50%. A total of eighty simulations from the 720 simulation scenarios (from Chapter 3) were used in this analysis, and a cumulative performance score was calculated for each intersection control design alternative. The best alternatives for different traffic compositions (for assigned weights in Table E-2) are summarized in Table E-4. Overall, traditional single-lane roundabouts perform best at lower traffic volume, and basic turbo and two-lane roundabouts perform best at higher traffic volume.

Table E-4: Optimal roundabout type for various traffic volumes and vehicle movements.

Traffic volume (pcu/hour)	Traffic Variations			
	Balanced 20% LT[(a)]	Balanced 50% LT[(b)]	Unbalanced 20% LT[(c)]	Unbalanced 50% LT[(d)]
1,500	Traditional single-lane	Traditional single-lane	Traditional single-lane	Traditional single-lane
2,000	Traditional single-lane	Egg Turbo	Traditional single-lane	Egg Turbo
2,500	Egg Turbo	Egg Turbo	Egg Turbo	Egg Turbo
3,000	Traditional two-lane	Basic Turbo	Traditional two-lane	Basic Turbo
3,500	Basic Turbo	Basic Turbo	Basic Turbo	Basic Turbo

Note: (a) Balanced condition with 20% Left turn; (b) Balanced condition with 50% left turn; (c) Unbalanced condition with 20% left turn; and (d) Unbalanced condition with 50% left turn.

APPENDIX F

SURVEY ON THE EDUCATIONAL MATERIAL

Dear Traffic Engineering Professional,

You are requested to participate in a survey conducted for the Nevada Department of Transportation (NV DOT) funded research project conducted by West Virginia University. This research project aims to investigate the implementation potential of turbo roundabouts in Nevada. As Turbo Roundabout is new to transportation practitioners in the United States, we have developed two educational materials (one two-page flyer and one 5-minute video). We seek your feedback on the sufficiency of introductory information on Turbo Roundabout in these two documents. Your responses will be kept private and grouped with others, and your individual comments will not be identified.

If you have any questions, please contact the project principal investigator, Dr. Kakan Dey, at kakan.dey@mail.wvu.edu.

Do you wish to continue the survey?

- Yes
- No

General Information

a. Name of the Agency:	
b. Name of the Respondent:	
c. Job Title:	
d. Email address:	

Section 1: Familiarity With Conventional Roundabouts and Turbo Roundabouts.

Q1. How familiar are you with roundabouts?

- Extremely familiar
- Moderately familiar
- Somewhat familiar
- Slightly familiar
- Not at all familiar

Q2: "Turbo Roundabout" is a new form of roundabout widely used in several European countries. Are you familiar with the design and operational features of turbo roundabouts?

- Yes
- No
- Not Sure

Section 2: Turbo Roundabout Educational Materials.

In this section, a short presentation (about five minutes) and a two-page flyer on the unique design, operational, and benefits features of Turbo Roundabout are presented to you. After watching the presentation and flyer, please provide your input on the following questions.

Q3: The short presentation video of Turbo Roundabout helped me understand its unique design, operational features, and safety benefits.

- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

Q4: The short presentation and flyer were simple, easy to understand, and did not contain too much technical content.

- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

Q5: Rank the following features of the short presentation, where 10 for the highest quality and 1 for the lowest quality.

	0 1 2 3 4 5 6 7 8 9 10
Contents on operational benefits of Turbo Roundabout	
Contents on safety benefits of Turbo Roundabout	
Overall features and characteristics of Turbo Roundabout	
Presentation pace of the video presentation	
Length of the Presentation	
Others (specify): ()	
Others (specify): ()	

Q6: Rank the following features of the flayer, where 10 for the highest quality and 1 for the lowest quality.

	0 1 2 3 4 5 6 7 8 9 10
Contents on operational benefits of Turbo Roundabout	
Contents on safety benefits of Turbo Roundabout	
Overall features and characteristics of Turbo Roundabout	
Others (specify): ()	
Others (specify): ()	

Q7: What additional information could be shared in the short presentation?

- Geometric features of Turbo
- Design features of Turbo
- Operational features of Turbo
- Comparison with conventional roundabout
- Others:

Q8: What additional information could be presented on the flyer?

- Geometric features of Turbo
- Design features of Turbo
- Operational features
- Comparison with conventional roundabout
- Others:

Q9: Please feel free to share any other comments or thoughts on the educational materials.

Final Version of the Two-Page Flyer

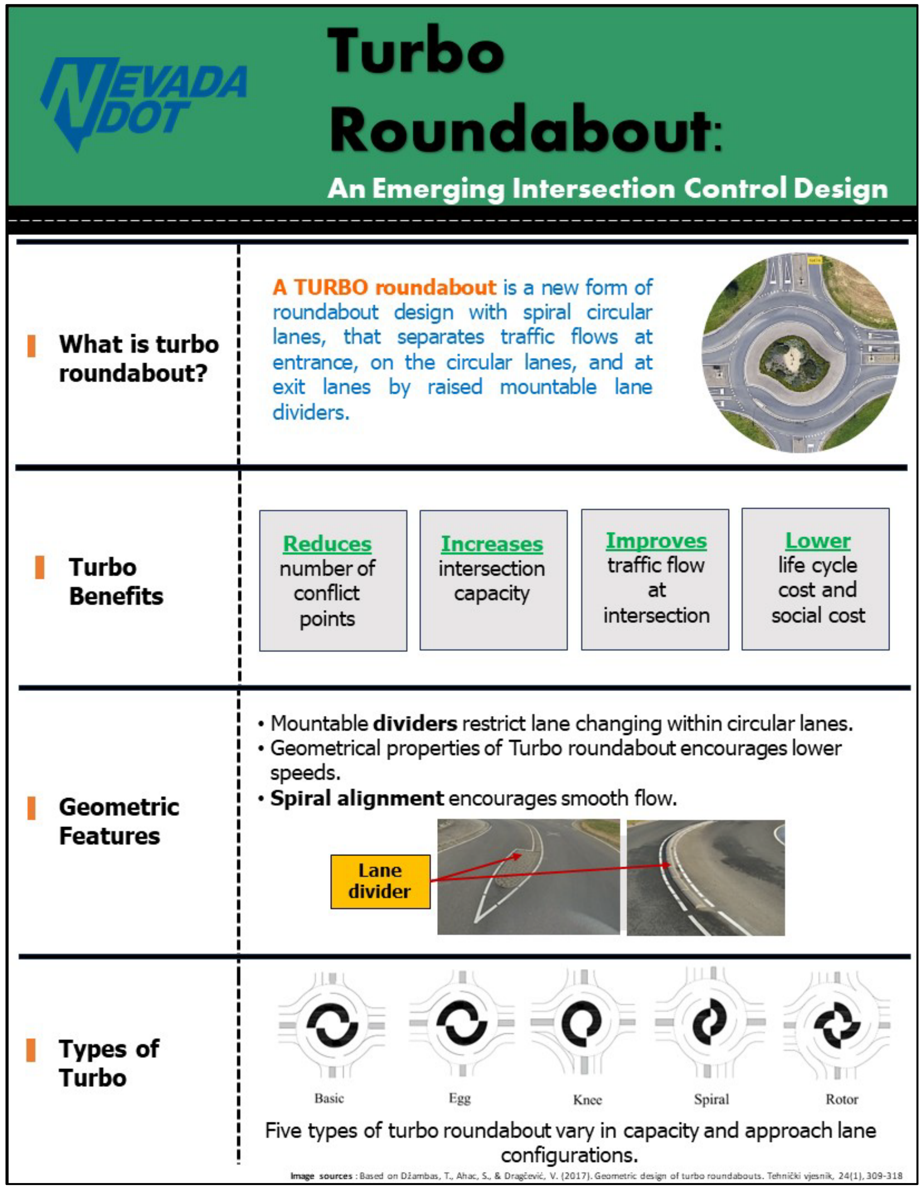


Figure F-1: Turbo flyer page 1

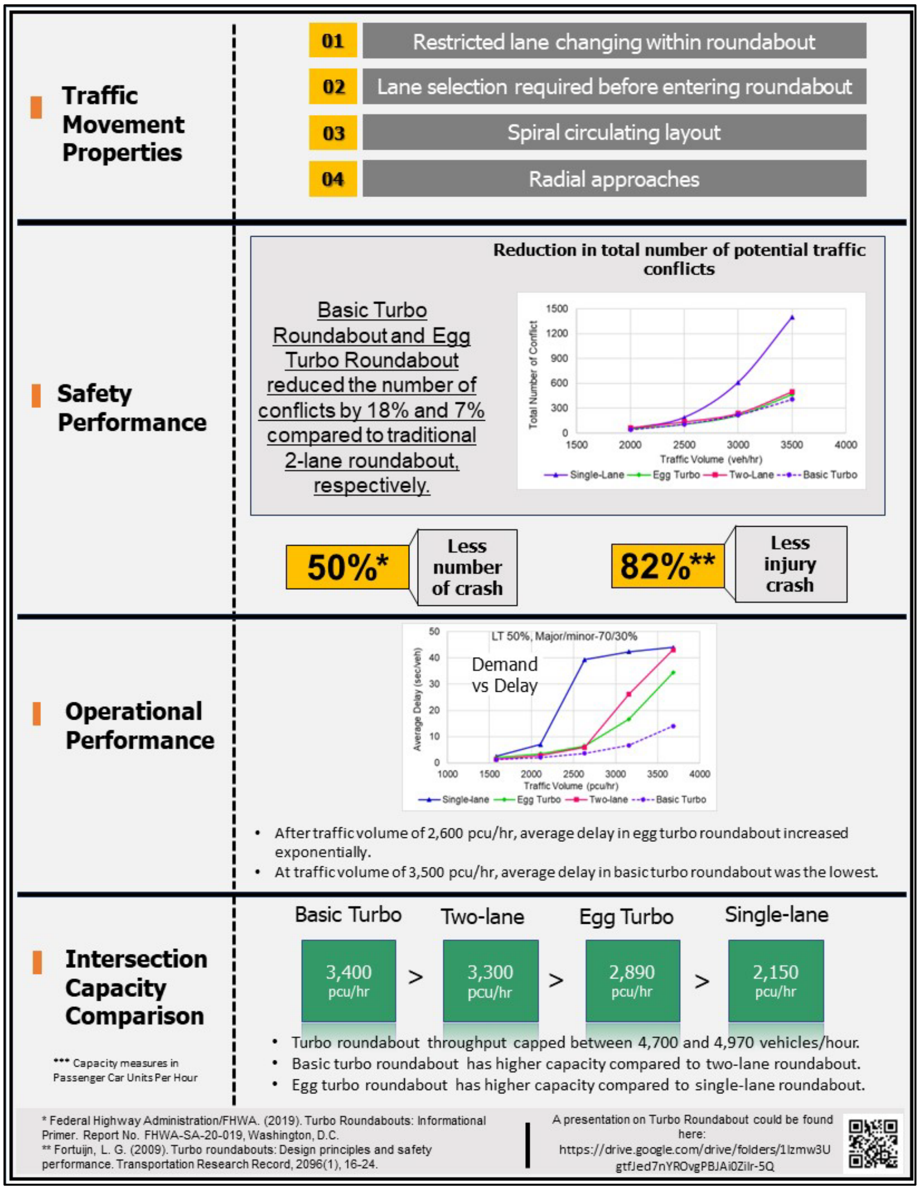


Figure F-2: Turbo flyer page 2

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