Intersection Modifications Using Mini-/Modular-Roundabout Methods.

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16. Abstract

Conversion of traditional intersections (stop controlled and signalized) to modern RABs has been a growing practice in many countries around the world including the U.S. – largely due to the benefits of reduction in crash frequency and severity, capacity improvement, and operational improvement. However, construction of traditional RABs is costly and requires additional right-of-way (ROW) which can deter roundabout installation on local transportation systems that have budgetary and/or available ROW restrictions. The main objective of this project was to develop guidelines for ORIL on the installation and performance of mini-/modular-RABs considering characteristics of Ohio's local transportation system. Based on published guidelines and from existing pilot implementations (both international and within U.S.), current design practices considering traffic condition and roadway conditions were identified. Based on survey findings, there was a reasonably high level of familiarity with mini-RABs among respondents. Most agencies consider reduction of crashes/severity and improved traffic operations in installation of mini-RABs. Major concern with mini-RABs is drivers neglecting the central island and driving straight through thus causing the mini-/modular-RAB to lose its integrity. Agencies typically place mini-/modular-RABs on two-lane highways with low traffic volumes (<15,000 vpd); and/or peak-hour volumes of 1,600 to 1,800 vehicles. Based on driving simulator experiments, there are no differences in critical gap as driver's maneuvered through mini-RAB of different ICDs. Operations-wise, Mini-RABs with larger ICDs performed better than those with smaller ICDs.

17. Keywords

Roundabouts, Intersection Control, Mini-Roundabouts, Modular-Roundabouts, Geometric Design, Life Cycle Cost Analysis.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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1.0 PROBLEM STATEMENT

According to the World Health Organization (WHO), road traffic crashes kill approximately 1.2 million people annually, which puts road traffic casualties among the top causes of deaths worldwide (WHO, 2015). Injuries from road traffic crashes alone account for over 22% of all deaths globally (Mathers et al., 2003). Aware of this plague, initiatives such as the *Decade of Action for Road Safety 2011-2020* (Lee, 2011) and the *Towards Zero Deaths: A National Strategy on Highway Safety* (TZD, 2015) have been established primarily to stabilize and reduce the number of road traffic fatalities; and moreover, work toward no fatalities across all transportation modes. The Ohio Department of Transportation (ODOT) and other state agencies have been collaborating in implementing programs to achieve the "TOWARDS ZERO FATALITY" target (Ohio SHSP, 2019).

To specifically address intersection related safety, which represents approximately 40% of total traffic crashes (Choi, 2010), geometric modifications to existing intersections are recommended. Conversion of traditional intersections (i.e., two- and all-way stop control and signalized) to modern roundabouts (RABs) 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, capacity improvement, and operational improvement. A study by the Federal Highway Administration (FHWA) reported that a RAB reduces intersection fatalities by 90%, injury by 76% and crash frequency by 35% in comparison to a traditional intersection (Persaud et al., 2001). While most people are opposed to RABs before implementation, the acceptance increases substantially after installation over time as drivers become knowledgeable on navigating RABs (Hu, 2014).

However, with traditional RABs there are high associated construction costs and also the need for additional right-of-way (ROW) which can deter their installation on local transportation systems that have budgetary and/or available ROW restrictions. In this scenario (limited budget and restricted ROW), a viable alternative is the use of mini-/modular-RABs that can be installed within the current intersection geometry with minimum modification in a cost-effective manner. Mini-RABs have a smaller footprint with a mountable central island for large vehicles such as large trucks and buses (Robinson et al. 2000); and costs $250,000 on average compared to an average $2.05 million for a multi-lane RAB (Pochowski et al., 2016).

As with traditional RABs; mini-RABs are safe and efficient (operation-wise), but it is their attractive low installation costs and ability to build within existing ROW that has prompted local transportation officials (cities/counties/townships/villages) in Ohio to become interested in their implementation. Though, with very limited use in the U.S. (Pochowski et al., 2016) and only few studies and pilot projects, there is no comprehensive study or report (ORIL, 2019) that can be used by local transportation officials to plan, design and implement this version of a RAB in their local jurisdictions. Therefore, there is a need to synthesize and summarize current research, and more importantly, be able to develop a mechanism that guides local transportation officials on how to decide on matters pertaining to mini-/modular-RAB such as design, materials, costs, and installation.

2.0 RESEARCH BACKGROUND

The 1990s witnessed a re-introduction of the modern RAB in the U.S. and since then RABs (single and double-lane) have been constructed at an increased rate. The increased adoption was primarily due to the documented safety, operational, environmental, and aesthetic advantages the modern RAB provides over the other intersection control types (yield, stop, or signalization). While the modern RAB has proved advantageous, there has been a recent decline in their implementation. Major factors that have contributed to this slowed rate of adoption include: high capital costs, negative public attitudes; and larger right-of-way (ROW) requirements.

Initial capital costs of construction range from $100,000 to $5 million for a single-lane roundabout, and $200,000 to $6 million for a multi-lane roundabout (FHWA, 2018). Additionally, there are costs associated with temporary traffic controls during construction. A survey of FHWA division offices and state DOTs revealed the presence of strong public opposition to roundabout adoption (FHWA, 2018). While there are focused efforts, using education programs, that target the negative perspectives on RABs there still remains the concern of familiarity with navigation. Toussant (2016) surveyed drivers in southeast Ohio and showed there were relative gaps in familiarity/unfamiliarity with regard to navigation knowledge of RABs. Results showed that younger drivers (18-25 years) had significantly more knowledge regarding lane choice and priority; and as age increased, knowledge of lane assignment and priority rules decreased. These navigation issues (lane changing and priority) are an even greater concern on double-lane RABs where unfamiliar drivers are forced to try to apply progressive thinking (knowledge-based behaviors) under pressure and subsequently diminishes safety and operations. At a minimum, a single-lane RAB requires 90 to 180-feet to accommodate its inscribed circle diameter (ICD) whereas a multi-lane RAB would need 150 to 300-feet (FHWA, 2010). With the addition of lanes and the other RAB features, additional right-of-way (ROW) will be required. Local transportation agencies with limited budgets and restricted ROW are constrained to adopting phased RAB implementation. Fortunately, the concept of the mini-/modular-RABs is something worth considering and researching.

A mini-RAB is similar to a modern RAB – must be laid out by considering the desired vehicle paths; and more importantly getting drivers to circulate around a traversable island, and forcing a deflected path for the movements that cross one another's paths ("right" turns). The difference lies in a mini-RAB having a smaller ICD, reduced entry speed, and can have no solid (or in some cases an elevated curb) central island that is traversable by large vehicles. The reported benefits of mini-RABs are lower installation costs, smaller footprint, improved safety and operation performance, and quick installation times (short periods of road closure) etc. (Dept. of Transport and County Surveyors Society, 2006; FHWA, 2009). Mini-RABs, while common to the U.K. and France, are a promising alternative to the modern RAB and there has been a growing interest in mini-/modular-RABs with a number of pilot projects having been undertaken. However, any detailed guidance that can assist with decision making is scanty and vaguely available.

The overall goal of this project was to develop guidelines for Ohio's Research Initiative for Locals (ORIL) program on the installation and performance of mini-/modular-RABs considering characteristics of Ohio's local transportation system. The specific objectives were as follows:

1) Examine the state-of-the-practice and then develop a synthesis of current published research and pilot projects that will be exclusive to the design, installation, operation, and maintenance of mini-/modular-RABs.
2) Investigate the current practices (if any) of practitioners and local transportation professionals in Ohio and identify important factors that relate to the installation of mini-/modular-RABs.
3) Investigate navigability differences between different mini-RAB designs and subsequently identify improvements or precautions (if any) that would be needed in developing guidelines.
4) Conduct a traffic microsimulation based investigation to provide insights on different design factors and their importance in developing guidance on installation, safety and operations, and maintenance.

5) Use findings from (1, 2, & 4) to develop a Life Cycle Cost Analysis (LCCA) tool to compare different alternative mini-/modular-RAB designs.
6) Use findings from (1, 2, & 4) to develop a procedure and tool on multi-criteria analysis based decision making for location-specific mini-/modular-RAB design selection.
7) Develop installation guidelines for use of mini-/modular-RABs specific to Ohio's local transportation system.

3.0 RESEARCH APPROACH

Based on the original research scope defined by the RFP (see Appendix A), the research team identified 10 specific tasks necessary to achieve the goals of this project. Details of these tasks can be found in the approved work plan which is included in Appendix B. The specific tasks that were completed are depicted in Figure 1. This section of the report documents the description of methods and findings/outcomes from work completed during Tasks 2 through 9. The corresponding sub-sections are organized by task.

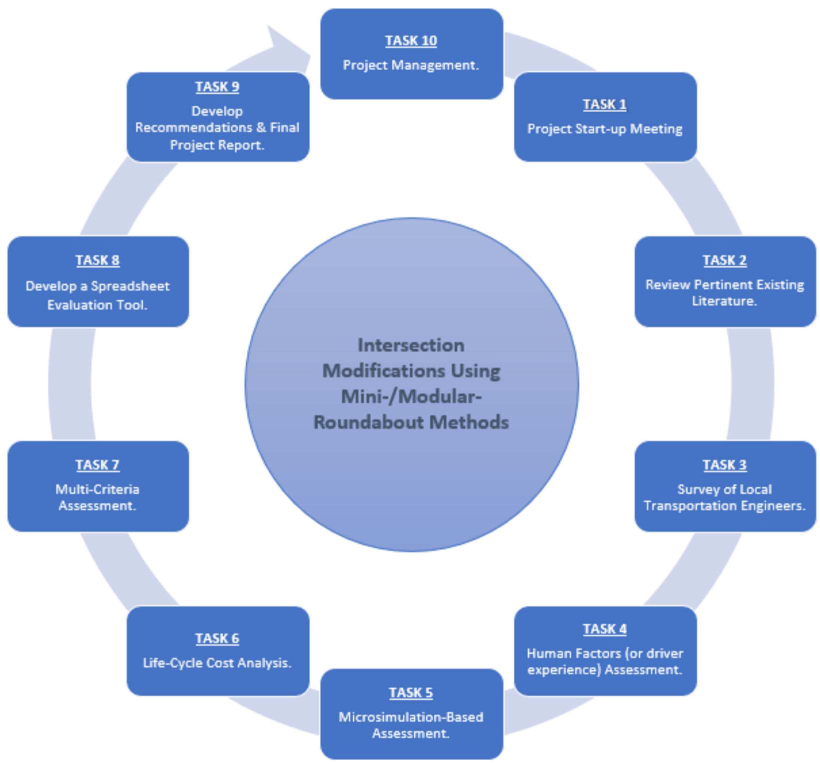

Figure 1. Tasks completed for project titled – *Intersection modifications using mini-modular-roundabout methods*.

TASK 2: A LITERATURE REVIEW on MINI-ROUNDABOUTS.

The purpose of this task was to conduct an extensive review and synthesis of current published research and pilot projects. The review would target the design, installation, operation, and maintenance of mini-/modular-roundabouts (RABs).

Methodology for Review.

The literature reviewed was assembled by performing keyword searches of several industry, research-, and or academic-related resources. The searched databases included the Transportation Research International Database, NCHRP Projects, Google Scholar, ScienceDirect, JSTOR, BIOSYS, and Researchgate. Additionally, given there has already been some traction gained with mini-RABs in the sense of early adoption and pilot projects; this literature search also summarized the experiences from these pilots. This task would entail a desktop review and also direct communication with responsible parties in situations where project specific information is not readily available or partially available online.

The goal of Task 2 was to provide comprehensive and detailed insights on mini/modular RABs including (but not limited to) the following:

- Design criterion (radii, entry point features, markings, signage, etc.) that are standard, have been developed, and adopted by other states/cities/localities for their mini/modular RABs.
- Specific considerations that need to be in place for suitable adoption (and/or removal). Examples include, traffic/pedestrian/bike volumes, roadway elements, environmental, safety, locale requirements.
- Benefits and/or performance advantages attained by installing mini/modular RABs from operations (reduced speeds, delay, etc.), safety (crash frequency/severity), and environmental perspectives.
- Costs, construction/installation methods, materials, and timelines, for construction of mini/modular RABs; and any sustainable practices and/or means of providing mini/modular RABs.
- Any specific guidance – "best" practices, maintenance procedures, right-of-way requirements, work zones considerations, materials, etc. – in the use of mini/modular RABs.

A comprehensive state-of-the-practice literature review containing the summaries and critiques organized from different perspectives including; geometric design, construction and maintenance, operations, safety, and driver experience was then prepared.

LITERATURE REVIEW RESULTS

In general, mini-/modular-RABs are similar in operational characteristics to modern (or traditional) RABs. Though, mini-/modular-RABs are different in that they have a smaller inscribed circle diameter (ICD), reduced entry speed, and can have painted-flush (or in some cases an elevated curb) central island that is traversable by large vehicles. As is the case with traditional roundabouts, the geometric design of a mini-/modular-RAB requires the need to balance competing design objectives including; safety, operational performance, accommodation of design users, and construction/maintenance costs.

Mini-RABs, while common to the UK and France, are a promising alternative to the modern roundabout and are progressively emerging in the U.S. As such, the review of literature compared guidance internationally (across different countries in the world) and locally (across state DOTs in the U.S). These guidelines are summarized in the following subsections; with specific detailed findings available in Appendix C.

Site specific considerations for placement – *International Practice*.

Mini-/modular-RABs are commonly found to be advantageous in space constrained locations. That is in locations with restricted/limited available right-of-way (ROW). For the most part, a determination for placement is based on availability of ROW, traffic volumes, approach speeds, and turn proportions. Table 1 presents minimum conditions (traffic volume, speed, and/or turning proportion) that are used to warrant the need to consider a mini-/modular RAB in different countries across the world where specific mini-RAB guidance is available. A more specific warrant-based determination for placement was only available in South Africa.

Table 1. Minimum Guidance Parameters for Placement of Mini-/Modular Roundabouts.

Country	Traffic Volume	Approach Speed
United States	Total Entering Daily Volume ≤ 15,000 vpd Truck Traffic ≤ 3%	≤ 30 to 35-mph
United Kingdom	2-way predicted AADT ≤ 500 vpd on a single approach Approach traffic flows and/or turn proportions significantly different	≤ 30 to 35-mph
South Africa	Total Entering Daily Volume ≤ 3,000 vph (3-leg intersection) and 4,000 vph (4-leg intersection) Other criteria available (see Appendix C for details)	None specified
Switzerland	Total Entering Daily Volume ≤ 15,000 vpd Sum of traffic load at entry lane and in the circle < 1,200 vph Pedestrain volumes not especially high.	None specified
Germany	Total Entering Daily Volume ≤ 20,000 vpd Not recommended for use in isolation	≤ 30-mph

Besides the specific considerations discussed above, a number of factors (common across various countries) were also considered and likely to impede the installation of mini-/modular-RABs. These factors include:

- expected high volumes of large vehicles (trucks, buses, delivery vehicles);
- expected large proportion of U–turning truck traffic;
- forecasted light volumes of minor street traffic or unreasonably varying proportional split between major and minor street traffic;
- at or near direct accesses or intersections where turns into or out from side roads are prohibited, because drivers do not expect to see vehicles U–turning on mini–RABs;
- five or more approach legs; and
- minimum design requirements cannot be applied (or fulfilled) at location(s).

Design criteria and specific considerations – *International Practice*.

Minimum criterion pertaining to the design/specifications of mini-/modular-RABs were gathered by searching documented guidelines from different countries across the world. These design guidelines are depicted in Figure 2.

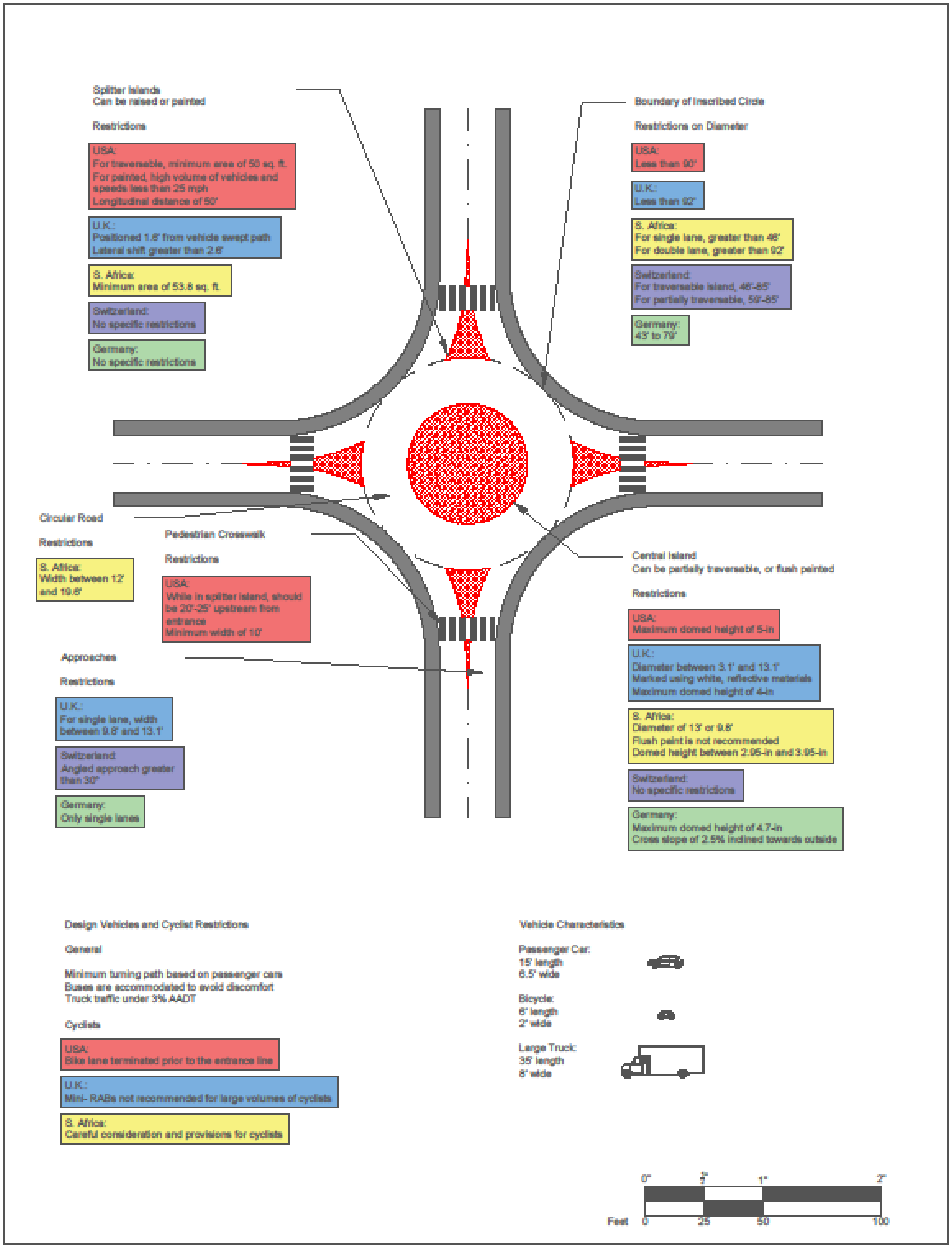

Figure 2. Comparison of international design criteria (minimum) for components of mini-/modular roundabouts.

Site specific considerations for placement – *Local Practice*.

A desktop analysis of geometric design manuals from state DOTs revealed that, at a minimum, 27 out of 50 state DOTs (54%) have included content provided in *NCHRP 672 Roundabouts: An Informational Guide* and also the *Mini-Roundabouts: Technical Summary*. In addition, 17 state DOTs have included some additional criteria pertaining to mini-RAB design (see Table 2.3 in Appendix C).

Table 2.4 and Table 2.5 (refer to Appendix C) provide a list of locations within the US at which mini-/modular-RABs have been installed over the years and also additional information such as design features, installation costs, site conditions prior to (and after) installation. The site conditions that were common to many of the mini-RABs on this list; and that essentially prompted the thought of adopting a mini-/modular-RAB are summarized in Table 2.

Design criteria and specific considerations – *Local Practice*.

Table 3 presents the minimum criterion pertaining to design/specifications of mini-/modular-RABs in the US.

Table 2. Minimum (US local) Guidance Parameters for Placement of Mini-/Modular Roundabouts.

Traffic Conditions	▪ Total entering ADT no more than FHWA recommended 15,000 vpd at most locations. More specifically: o 1,500 vpd (minimum) and 18,500 vpd (maximum; o 10,000 to 12,000 vpd (median range) ▪ Peak hour traffic volumes of 1,150 and 1,400 vph. ▪ An approximatley 60/40 split between major/minor approach volumes. ▪ Truck volumes (where present) minimum was 3% and maximum was 4%. ▪ Pedestrian/bike volumes not explicitly reported except one case study as 25-55 peds/hr.
Roadway Conditions	▪ Located on intersection of minor arterials and/or collectors; with 2-lanes (in rare cases 3-lanes). ▪ Speed limit (or 85% observed speed) in the 15 to 40 mph range. ▪ Existing intersection control is stop-controlled – mostly all-way and rarely two-way. ▪ Approaches intersect at 90° and are rarely skewed; with mostly 4-approaches (rarely 3-approaches). ▪ Installed at intersections with limited available right-of-way.
Other Conditions	▪ Observed unsafe driver behavior and/or maneuvers (left-turning, running stop signs, speeding). ▪ Evidence of obstructed or restricted sight distance at intersection. ▪ Observed congestion and the presence of long queues. ▪ Reported high frequency of crashes and crash severity.

Table 3. Minimum (US local) Design Criteria for Components of Mini-/Modular Roundabouts.

Mini-/Modular RAB Component	Design Specification	
	Minimum/Maximum Value	Commonly Adopted Value
Inscribed Circle Diameter	90-feet Maximum	Between 70 to 80-feet
Central Island Diameter	70-feet Maximum 15-feet Minimum	Between 45 to 55-feet Between 20 to 30-feet
Central Island Height	5-inch Maximum	Between 2 to 3-inches
Circulating Lane Width	20-feet Maximum 12-feet Minimum	Between 15 to 18-feet
Entry Lane Width	15-feet Maximum 10-feet Minimum	Between 12 to 14-feet
Splitter Island Length (Maj. Approach)	200-feet Maximum 15-feet Minimum	Between 60 to 70-feet Between 40 to 50-feet
Splitter Island Length (Min. Approach)	150-feet Maximum 15-feet Minimum	Between 50 to 60-feet Between 35 to 45-feet
Approach Speeds	25-mph Maximum 10-mph Minimum	Between 15 to 20-mph
Pedestrian Crosswalk Width		Between 8 to 10-feet

Costs, Materials, and Maintenance.

Generally, installation of mini-/modular-RABs is relatively less costly and requires less routine maintenance. Moreover, there are also reduced costs associated with items such as crash costs, safety, operations, quick installation, etc. A significant cost advantage of mini-/modular-RABs is with their limited right-of-way requirement and require minimum to no cost in terms of right-of-way acquisition. Based on a pilot study conducted in Dimondale, MI, the benefit-to-cost ratio for mini-RABs was approximated to being 14.5:1 (Waddell, 2005). Given below is a summary of cost information extracted from in-service mini-/modular-RABs.

- range from $10,000 to $650,000; with average costs being approximately at $150,000.
- costs for modular-RABs will vary based on the design specifications.

Mini-RABs are commonly constructed using materials and methods same as for traditional RABs; that is, with a composition of asphalt, concrete, and other paving materials. Though, due to their smaller footprint, there are alternate materials and/or methods that have been proposed (or are being tested) such as recycled plastic materials and prefabricated construction – aka modular-RABs. Refer to Table 2.2 of Appendix C for specific details.

Overall Advantages of Mini-/Modular Roundabouts.

Table 4 presents the findings from research and observational studies that highlight on advantages of mini-/modular RABs from operational and safety viewpoints.

Table 4. Reported Benefits of Adopting Mini-/Modular Roundabouts.

OPERATIONAL BENEFITS	SAFETY BENEFITS
▪ Increases intersection capacity and LOS. ▪ Reduces directional delay. ▪ Improves traffic flow (especially from minor approaches). ▪ Reduces speeds (by 6 to 20-mph approx.). ▪ Reduces vehicle emissions. ▪ Smaller physical footprint.	▪ Reduces crash frequency and rates. ▪ Reduces crash severity. ▪ Improves safety and mobility for pedestrians and/or cyclists. ▪ Reduces risky driver behaviores safety and mobility for pedestrians and/or cyclists. ▪ Improves driver compliance.

TASK 3: SURVEY of PRACTITIONERS.

The purpose of this task was to administer an online survey to practitioners and local transportation professionals; with the goals of investigating their current practices (if any) pertaining to mini-/modular RABs, and identifying the relative importance of factors that relate to the installation of mini/modular-RABs.

Survey Methodology.

A survey questionnaire (see Appendix D) was developed and administered with the goal of gaining an understanding from practicing traffic engineers' regarding their knowledge of the design, operation, safety, and maintenance aspects of mini-/modular-RABs. In addition to respondent demographic information, the survey collected data on information including (but not limited to):

- prior knowledge of traditional-/mini-/modular-RABs;
- reason your agency would install a mini-/modular-RAB;
- observed results (if any) after a mini-RAB was installed;

- where a mini-/modular-RAB should be placed, and if there are any limitations to this type of intersection; and
- any design guidelines that were followed, cost, and materials used in the construction of mini-RABs in their specific jurisdictions.

SURVEY RESULTS

A total of 92 responses were received from participants across the US; with almost half (N=52) of respondents based in Ohio. Many of the respondents were familiar with RABs and reported that they have at least one in their jurisdiction. Key findings from the survey are presented below; with specific detailed findings available in Appendix D.

- Safety related factors are of higher priority to agencies when considering the installation of a mini-/modular RAB;
- Safety related improvements (primarily reducing crash severity) are of higher importance than operational improvements when considering the installation of mini-/modular-RABs;
- Concerns with mini-/modular RABs include drivers neglecting the central island and driving straight through, unfamiliarity of navigation, and roadway maintenance during inclement weather operations (difficulty with snow plowing);
- Agencies consider two lane highways (peak-hour volumes of 1,600 to 1,800 vehicles and/or speeds <35-mph) as suitable locations for placing mini-/modular RABs;
- Agencies consider two lane highways (peak-hour volumes of 1,600 to 1,800 vehicles) as suitable locations for placing mini-/modular RABs;
- Agencies reported the cost of mini-RABs ranging from $150,000 to $3,000,000; with most projects costing less than $1,000,000.
- Overall, there is negative public perceptions prior to construction of mini-RABs however, after construction and use, the public opinions are mostly positive.
- Modular-RABs are advantageous for temporary traffic control during events such as natural disasters, concerts, football games etc.
- Most agencies adopt NCHRP 672 guidelines for designing their mini-/modular RABs.

TASK 4: HUMAN FACTORS (or DRIVER EXPERIENCE) ASSESSMENT.

The purpose of this task was to explicitly investigate the experience(s) of the driver with respect to navigating a mini-/modular-RAB. The goal was to understand any correlations that may exist between driver performances with mini-/modular-RAB navigation in terms of different mini-/modular-RAB design configurations. The content in this portion of the document present the findings of this human factors-based assessment.

Methodology.

In an effort to investigate driver behaviors as they navigate through RABs, a set of driving simulator scenarios were developed whereas drivers would encounter various mini/modular RAB geometric design configurations. This portion of the overall study was performed (IRB protocol # 19-X-166) using a level 3 driving simulator that is available in the Safety & Human Factors facility at Ohio University. Driving participants (both male and female) from different age groups were recruited and asked to drive through the simulator scenarios. As each participant drove a simulation scenario, their data (e.g. gap acceptance, speed, braking, etc.) was collected. This collected data was compared among mini-RAB designs (ICDs of 45, 60, 75, and 90-feet) and also a single-lane roundabout (120-ft ICD); to determine optimal design parameters for mini-RAB design. Specifically, driver's navigability differences (performance) in terms of their critical gaps and speeds (approach, circulatory, and exit) were compared. Additionally, a pre- and post-driving survey was administered; and participants responses to the questionnaire were analyzed to gauge understanding of perceptions/acceptance of mini-RABs. Specific details of the methodology, data collected, and analysis are provided in Appendix E.

HUMAN FACTORS ASSESSMENT RESULTS

Driver Behaviors

Gap Acceptance – the accepted and rejected gaps for participants (50 total) as they navigated through four mini-RABs of differing ICDs (45-ft, 60-ft, 75-ft, and 90-ft) and also a single-lane roundabout (120-ft ICD) were collected. These accepted and rejected gaps were then used to obtain a value for the critical gap using the modified Raff's method (Shaaban and Hamad, 2018). The critical gap was computed (overall value); and also categorized by day/night scenario, participant gender, and participant age. Figure 3 depicts a plot of the computed critical gaps based on the specific ICD and by category.

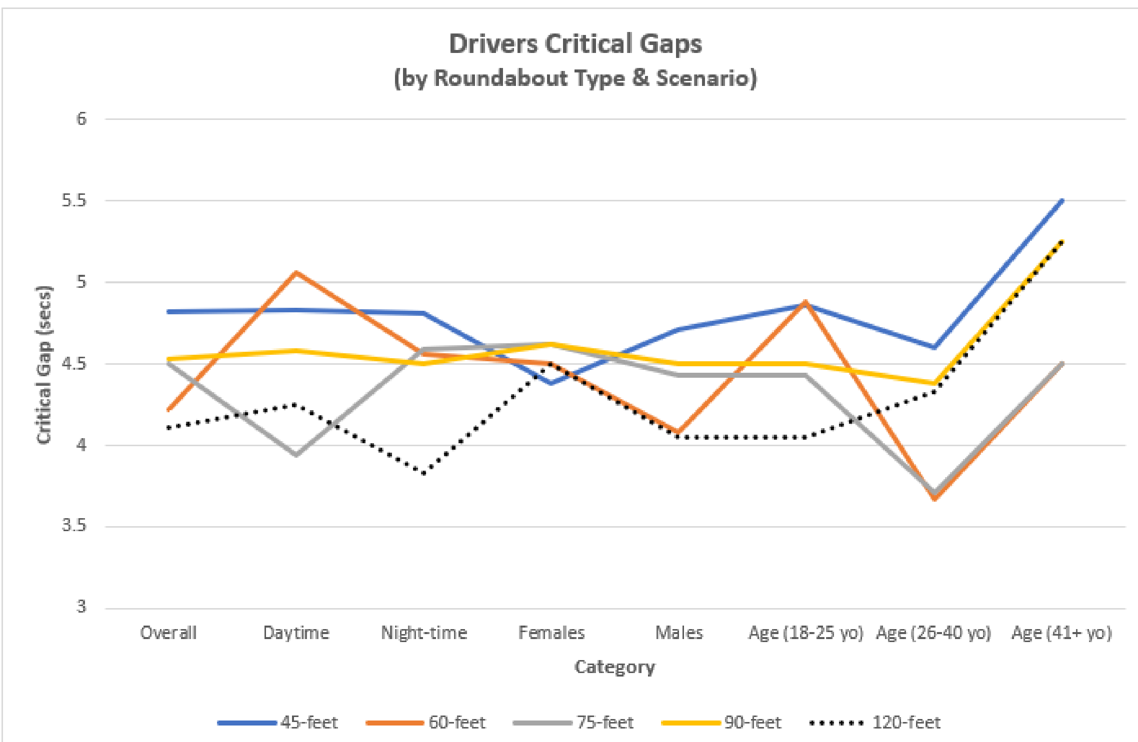

Figure 3. Comparison of driver critical gaps for mini-RAB alternatives.

Based on the plots in Figure 3 and making comparison with the observed critical gap from the single-lane RAB (120-ft), the following observations can be made:

- The overall critical gap, is not significantly different among the mini-RAB alternatives. The gap ranges from 4.22 to 4.82; and assuming the critical gap for a single-lane RAB (4.11 secs) is a measure for driver comfort when navigating RABs, then a mini-RAB with 60-feet ICD would be comparable in performance.

- The critical gap for the mini-RAB (ICD = 45-ft) is higher across categories. This was expected as the ICD is small and drivers cautiously navigated through this mini-RAB.
- Based on daytime or night-time driving; the observed critical gap for participants on the single-lane RAB was 4.25 secs (daytime) and 3.83 secs (night-time). Participants used similar critical gaps for mini-RABs with ICD = 75-feet (3.94 secs) and ICD = 90-feet (4.50 secs).
- While driving the single-lane RAB, the critical gap for female participants was 4.50 secs and that of male participants was 4.05 secs. For both sets of drivers (female/male) it was the 60-feet ICD mini-RAB in which the critical gap was comparable.

Speeds (approach, circulating, and exit) Behaviors – participant speeds as they navigated through the mini-RABs and also the single-lane roundabout were analyzed. The speeds were recorded at points along the entry approach (500-feet prior to yield-line and at 100-feet intervals), in the circulatory area, and also along the exit approach (500-feet after exiting yield-line and at 100-feet intervals). A preliminary analysis of the data showed that, across all RAB types, participants exhibited significant speed differentials at specific locations only – along entry approach (500, 200, 100-feet prior to yield-line, and also at yield-line), a single location within circulatory area, and along exit approach (at exiting yield-line, and also at 100, and 500-feet after exiting yield-line). It was at these locations that statistical comparisons of speeds (see Table 6) among the different RABs was performed. Figure 4 presents the average speeds for drivers (N=50) as they approached, circulated, and exited the roundabouts. The navigating speeds among the mini-RAB alternatives were also compared by additionally categorizing them by day/night driving, participant gender, and participant age. Refer to Appendix E for specific results.

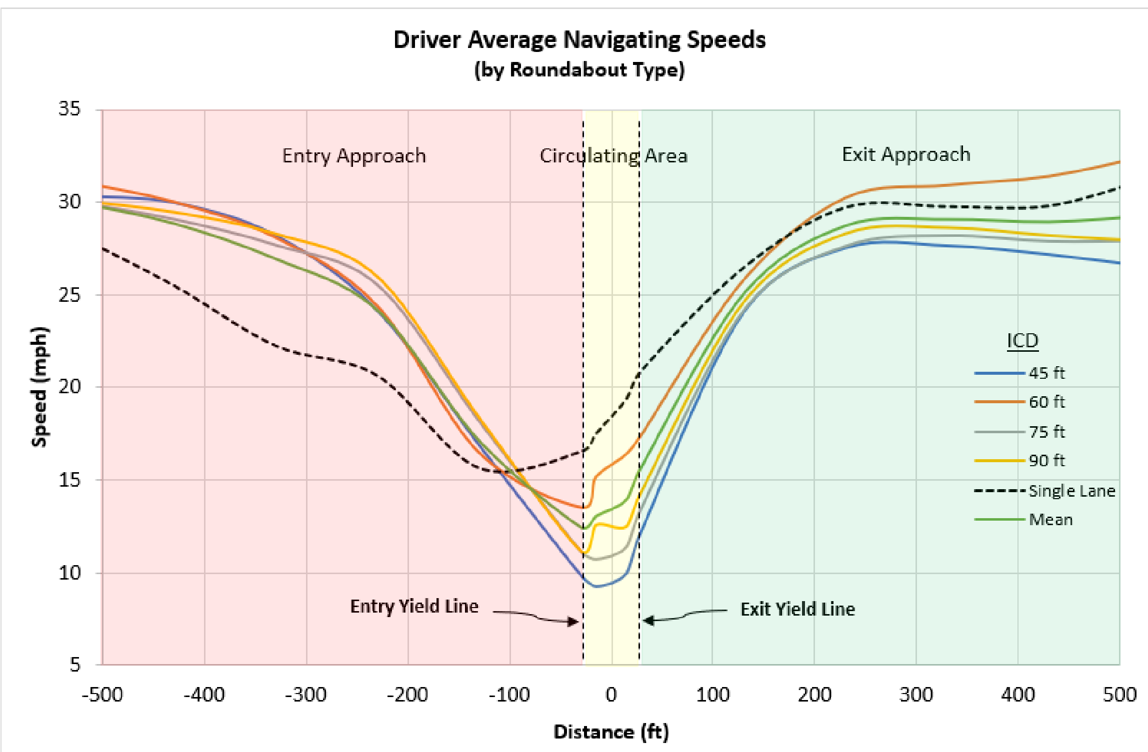

Figure 4. Driver approach/circulating/exit speeds for roundabout alternatives.

Table 5. Summarized Results of Speed Comparisons among Mini-RAB Designs.

Approach	Location along approach	Roundabout ICDs with significant speed differences?	Average speed difference (mph)	Std. error
Entry	500-ft prior to yield line	none	-	-
	200-ft prior to yield line	ICD 90-ft vs. 45-ft	5.35	0.86
	100-ft prior to yield line	none	-	-
	at entry yield line	ICD 120-ft vs. 45-ft	6.69	0.84
		ICD 120-ft vs. 75-ft	5.38	0.90
		ICD 120-ft vs. 90-ft	5.32	0.83
Circulatory Area		ICD 60-ft vs. 45-ft	5.95	0.73
		ICD 120-ft vs. 45-ft	8.29	0.81
		ICD 120-ft vs. 75-ft	6.79	0.84
Exit	at exit yield line	ICD 60-ft vs. 45-ft	5.18	0.80
		ICD 120-ft vs. 45-ft	8.65	0.74
		ICD 120-ft vs. 75-ft	7.41	0.76
		ICD 120-ft vs. 90-ft	6.49	0.81
	100-ft past exit yield line	none	-	-
	500-ft past exit yield line	ICD 60-ft vs. 45-ft	6.03	1.22

Based on the speed plots (Figure 4) and Table 5, the following observations can be made:

- In relation to the single-lane RAB (ICD = 120-ft), it can be observed that the mini-RAB speed curves are generally taking a similar trend; with higher values on the entry approach regardless of ICD size. However, at 100-ft prior to the approach yield-line, the speeds are about 5-mph lower for the mini-RAB alternatives.
- As expected, regardless of ICD size, speeds within the circulatory area and the exiting approach are lower for the mini-RAB alternatives in comparison to the single-lane RAB.

Driver Perceptions of Mini-RABs

Participant responses to a pre-/post-driving simulation survey were gathered and analyzed to gain insight into their familiarity, comfort, and preference for traditional single/double-lane RABs, mini-RABs, as well as stop-controlled intersections. The survey (see appendix E) consisted of two major parts with a combined total of 16 questions. Each simulator participant (total of 51) participated in the pre-test survey, driving simulator experiment and the follow-up post-test survey. Key findings from the pre-/post-test survey are presented below; with specific detailed findings available in Appendix E.

- Prior to driving, participants reported to having some level of familiarity with the concept of a RAB – 76% (N=39) very familiar, and 24% (N=12) somewhat familiar. However, there was a diverging sentiment toward mini-RABs – only 20% (N=10) reported being very familiar, 41% (N=21) somewhat familiar, and 39% (N=20) not familiar.
- 51% (N=26) participants reported to having driven through a mini-RAB while 49% (N=25) had not driven through a mini-RAB. However, in response to a post-test question, all participants reported to being able to notice a mini-RAB as they approached one in the simulation environment. Moreover, 92% (N=47) could differentiate between RAB types in terms of the 'feel' associated with the navigation, size or other self-reported differences.

- Post driving, and based on navigating/maneuvering comfort, 51% (N=26) participants ranked stop-controlled intersections as their first preference, 34% (N=16) ranked traditional RAB first in their order of preference, while 15% (N=7) ranked mini-RABs first in their order of preference. Mini-RABs were the least preferred with 68% of participants ranking this type of intersection control at third in their order of preference.

TASK 5: MICROSIMULATION ASSESSMENT of MINI-ROUNDABOUTS.

The purpose of this task was to complement the findings from the literature review (Task 2) by conducting a traffic microsimulation-based assessment. Essentially, this task would take a select mini-/modular-RAB design alternatives (e.g., central island radius, corner radius, flare angle, etc.) and evaluate their operational and safety performance.

Methodology.

Figure 5 depicts a high-level view of the assessment with inputs, assessment tools, and output (or performance measures).

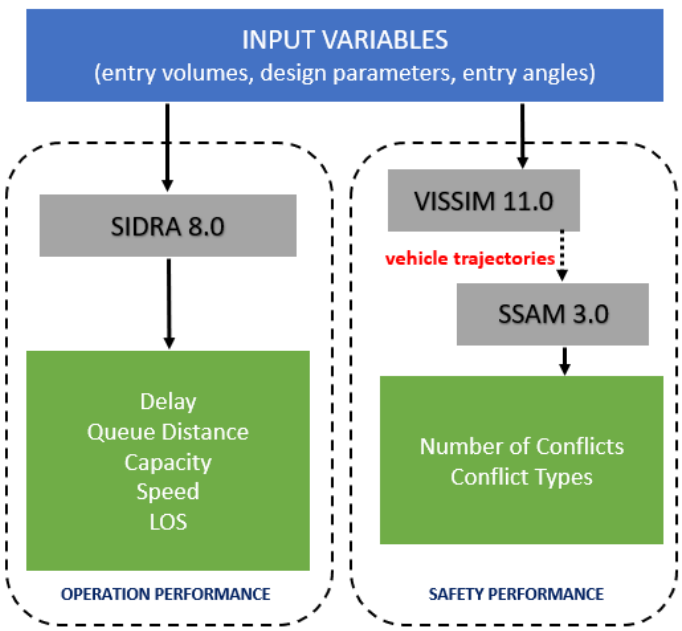

Figure 5. Methodology for assessing mini-roundabouts.

For the *operation performance assessment*; a set of 256 simulation scenarios were developed for a four-legged mini-RAB by varying geometric features and traffic compositions – inscribed circle diameter (ICD), entry angle (EA), and entering traffic volumes (major approach, M and minor approach, m). More specifically, combinations of ICD (45, 60, 75, or 90-ft); EA (50, 60, 75, 90 degrees), M (100, 200, 300, 400 veh/hr), and m (100, 200, 300, 400 veh/hr). Other parameters (refer to Appendix E) were kept constant in all simulation scenarios and their values adopted based on the literature review findings.

Additionally, the performance of mini-RABs was compared to that of stop-controlled intersections. An additional 16 scenarios were developed with combinations of M (100, 200, 300, 400 veh/hr/approach), m (100, 200, 300, 400 veh/hr/approach), and types of intersection control (i.e., Two way stop control- TWSC, All way stop control- AWSC).

For the *safety performance analysis*; the total number of conflicts and also different types of conflicts were estimated. Using a mini-RAB with ICD = 90-feet and EA = 50° (yields best results based on operational performance); four scenarios were created by varying the approach volumes (i.e., 500, 800, 1000, and 1600 veh/hr). In addition, a *sensitivity analysis* was also performed to evaluate the effects of traffic volume (i.e., two-way major approach volume, and turn volume).

16 simulation scenarios were developed to measure the effect of two-way major approach volume on number of conflicts and another 16 simulation scenarios were developed to measure the effect of turn percent on number of conflicts. Two-way major approach volume was varied between 400 and 1000 veh/hr (i.e., 400, 600, 800, and 1000 veh/hr) and the turn volume was varied between 5% to 20% of each approach volume (i.e., 5%, 10%, 15%, and 20%).

MICROSIMULATION RESULTS (Operational Performance)

Table 6 presents summarized findings in terms of operational performance measures for the microsimulation-based assessment. Refer to Appendix E for detailed results.

Table 6. Microsimulation Assessment Findings – *Performance Measures*.

Performance Measure	Findings
Average control delay Delay (in secs) experienced as a driver decelerates on approach to a queue, awaits an acceptable gap in the mini-RAB circulating flow while at the front of queue, and accelerates out of queue.	▪ Lowest average control delay observed for mini-RAB with an EA = 50°, ICD = 90-feet; and both major and minor volume = 100 veh/hr/approach ▪ Compared to TWSC/AWSC, mini-RABs generate much lower average control delay for traffic volumes between 100 to 400 veh/hr/approach. ▪ Compared to TWSC, mini-RABs generate lower control delay at higher traffic volume (200-400 veh/hr/approach) with higher ICD and lower EA. ▪ Control delay increases with higher traffic volume on minor approaches without any changes to major approach volumes.
Average geometric delay Delay experienced by a vehicle when navigating an intersection in the absence of any other vehicles - estimated by comparing travel time of an unconstrained vehicle passing through a RAB to travel time of an unconstrained vehicle that does not pass through the RAB.	▪ In general, for higher ICDs, the average geometric delay is lower. ▪ Compared to TWSC/AWSC, mini-RABs produces lower average geometric delay. ▪ From the simulation results, it is evident that EA and major road volume do not have any significant effect on average geometric delay.
95% back-of-queue distance (worst lane) The distance between the yield line of a roundabout and the end of an upstream queue, expressed as a number of vehicles or distance is called the queue distance.	▪ Queue distance decreases with larger inscribed circle diameter, and increases with higher entry angle and traffic volumes. ▪ ICD of 90-feet and an EA of 50° results in the lowest queue distance (all simulation scenarios). ▪ Compared to TWSC/AWSC, mini-RABs create much lower queue length for traffic volume > 200 veh/hr/approach.
Effective intersection capacity Effective intersection capacity is determined as the ratio of total intersection demand flow to the intersection degree of saturation, where the intersection degree of saturation is the largest lane degree of saturation considering all lanes of the intersection.	▪ In general, effective intersection capacity increases with larger ICD, lower traffic volume on major approach, and smaller EA. ▪ Highest effective intersection capacity observed for mini-RAB with ICD = 90-feet, EA = 50°, major approach volume = 100 veh/hr/approach and minor approach volume = 100 veh/hr/approach. ▪ Compared to TWSC/AWSC, mini-RABs have higher effective intersection capacity than AWSC intersections for traffic volume between 100 to 400 veh/hr/approach. ▪ Compared to TWSC, mini-RABs produce higher effective intersection capacity at traffic volume between 300-400 veh/hr/approach.
Average travel speed The travel distance divided by the average travel time where the average travel time includes the effects of intersection delays and delays due to other causes of interruption as well as the traffic delay (uninterrupted flow delay) due to bunching in uninterrupted sections of travel is defined as the average travel speed.	▪ In general. the average travel speed decreases with larger ICD (up to 75-feet) and higher traffic volume on major approaches. ▪ EA does not have any significant influence on average travel speed. ▪ Highest average travel speed observed for mini-RAB with ICD = 75-feet, and both the major and minor approach volumes = 100 veh/hr/approach. ▪ Similar results observed for mini-RAB with ICD = 75-feet, minor approach volumes of 200 to 400 veh/hr/approach, and major approach volumes of 100 veh/hr/approach. ▪ Compared to TWSC/AWSC, mini-RABs experience higher average travel speed for traffic volume between 100 to 400 veh/hr/approach. ▪ TWSC displayed higher travel speed than a mini-RAB with ICD = 45-feet and minor approach traffic volume < 300 veh/hr/approach.

Level 0f service (LOS) Quantitative stratification of a performance measure that represent quality of service.	▪ As expected, LOS for mini-RABs deteriorates as entering traffic volume increases. ▪ For total entering volume > 1400 veh/hr, the LOS decreases from A to B. ▪ LOS deteriorates with smaller ICD and larger EA. ▪ Overall, for simialar traffic volumes, mini-RABs provide better LOS in comparison to AWSC.

MICROSIMULATION RESULTS (Safety Analysis)

- For a mini-RAB with ICD = 90-feet and EA = 50°, the number of conflicts increases as the entry volumes increases – an expected result. While, a consistent pattern was not evident between traffic volumes and conflicts, it was seen that entering volumes < 1000 veh/hr created much smaller number of conflicts (< 20 conflicts/hr) than volume > 1600 veh/hr.
- The sensitivity analyses revealed the following:
  - A mini-RAB with 2-way major approach volume < 800 veh/hr and a 2-way minor approach volume = 400 veh/hr performs best in terms of total number of conflicts (< 50 conflicts/hr). For higher approach volumes; the total number of conflicts increases exponentially. A ratio of 2:1 (or less) between major and minor approach volumes with a total entering volume < 1200 veh/hr will create minimum safety concerns.
  - Percentage of vehicles making left or right turns did not have significant effect on total number of conflicts when the 2-way major approach volume was between 400 to 600 veh/hr and the 2-way minor approach volume was 400 veh/hr. But, when 2-way major approach volume exceeds 600 veh/hr (i.e., 800, and 1000 veh/hr) with a 2-way minor approach volume of 400 veh/hr, turning volume greater than 15% (i.e., 20%) produces more conflicts.

TASK 6: LIFE CYCLE COST ANALYSIS.

The purpose of this task was to develop a Life Cycle Cost Assessment Tool that would consider factors such as inscribed circle and central island radii, construction materials; and different construction means and methods; with the goal of being able to compare between alternatives over the life-cycle of a specific type of RAB.

Methodology.

The Life Cycle Cost Assessment Tool for Roundabouts (LiCAR) was developed using benefit-cost analysis (BCA) concepts. The steps involved during the development process include conceptualization, detailed planning, tool programming, and testing/debugging phases. During the conceptualization phase, the research team determined tool inputs, process, and outputs. The inputs of the tool were determined for the design (planning) phase, the construction phase, and the operations and maintenance (O&M) phases. A detailed tool logic flowchart is presented in Figure 6.1 (refer to Appendix G).

OUTCOMES

An MS EXCEL spreadsheet-based tool - LiCAR was developed and made available with this report. LiCAR analyzes the Benefit and Cost Ratio based on the user's input of the project information and the outputs of each roundabout types. Appendix G provides details on LiCAR including information on required inputs of the tool, and also accessing a user guide to the LiCAR tool.

TASK 7: MULTI-CRITERIA ASSESSMENT.

The purpose of this task was to develop an assessment methodology that combines together different factors (safety performance, operational performance, etc.) having specific measurement units in order to obtain a single relative score. Therefore, the multi-criteria assessment provides an overall performance score to each mini-RAB design alternative considering different performance measures and will assist in determining the most preferred option in terms of an overall performance score.

Methodology.

The steps followed in developing the MCA are described below.

Step 1: *Identification of mini/modular-roundabout performance measures/factors*

The survey of transportation professionals (Task 3), identified and provided the importance score of eight factors considered when installing mini-RABs including; (i) safety improvement, (ii) operational performance improvement, (iii) requirement of right-of-way (ROW) for installation, (iv) construction cost, (v) operation and maintenance (O&M) cost, (vi) construction duration, (vii) improvement of intersection aesthetics, and (viii) reduction of environmental impact. However, only operational performance, ROW requirement, construction cost, construction duration, and aesthetics were considered, as the other factors cannot be assessed, quantified, or difficult to quantify. Details regarding these factors and their range of values adopted in the MCA analysis are presented in Table 7.

Table 7. Multi-Criteria Factors.

MCA Factor	Factore details and value range
Operational Peformance Factor (obtained from Task 5)	Average Control Delay o < 5 secs, 5 to 10 secs, 10 to 20 secs, 20 to 30 secs, > 30 secs.
	Average Geometric Delay o 0.5 sec for 90-ft ICD, 1 sec for 75-ft ICD, 1.6 secs for 60-ft ICD, 2.2 secs for 45-ft ICD.
	Back of Queue Distance o < 50-ft, 50 to 100-ft, 100 to 200-ft, > 200-ft.
	Effective Intersection Capacity o < 2000 veh/hr, 2000 to 3000 veh/hr, 3000 to 4000 veh/hr, > 4000 veh/hr.
	Average Speed o < 17 mph, 17 to 18 mph, 18 to 19 mph, 19 to 20 mph.
Right-of-Way	o Categorized as low (ICD = 45-ft), medium (ICD = 60-ft), high (ICD = 75-ft).
Construction costs	Based on survey responses, typical installation costs range from $150K to 300K. Therefore, o $150K for ICD = 45-ft, $200K for ICD = 60-ft, $250K for ICD = 75-ft, $300K for ICD = 90-ft.
Construction Duration	o Categorized as low (ICD = 45-ft), medium (ICD = 60 to 75-ft), high (ICD = 90-ft).
Improvement of Aesthetics	Considered constant for all alternatives.

Step 2: *Selection of mini-RAB design alternatives*

Inscribed circle diameter (ICD) and entry angle (EA) were considered as the key design factors for MCA. Four values of ICD (45-ft, 60-ft, 75-ft, and 90-ft) and four values of EA (50°, 60°, 75°, and 90°) were considered in all design scenarios/alternatives. Traffic volumes on major and minor approaches were varied between 100 to 400 veh/hr (100, 200, 300, and 400 veh/hr/approach) as discussed in simulation analysis (Task 5).

Step 3: *Development of weight(s) for each performance evaluation factor*

A total of 100 points/weight were distributed to the five evaluation criteria (i.e., operational performance, ROW, construction and maintenance cost, construction duration, and aesthetics).

Based on the survey responses, the average importance score given to these five criteria on a scale of 5 were 4.2, 3.6, 3.0, 2.4, and 2.3, respectively. From these average scale values, the relative importance score/weight was calculated for each factor – that is, operational performance = 30, ROW = 20, construction cost = 20, construction duration = 15, and aesthetics = 15. The weight of operational performance (30) was assigned evenly to the five operational performance criteria (i.e., each operational performance criteria was assigned 6 points/weight). Note, these weights can be modified by practitioners when calculating the overall performance score for design alternatives (using the MS EXCEL based MCA tool) depending on their personal/agency specific importance of different factors.

Step 4: *Calculation of overall performance score (i.e., weighted score)*

The weighted/overall performance score for each mini-RAB design alternative was calculated by multiplying performance score (discussed earlier) for each performance indicator with respective weights, to determine overall performance score out of 100. The different design alternatives are than ranked based on this overall performance score (i.e., higher overall performance score indicating better performance of that alternative in terms of the above-mentioned evaluation criteria.

OUTCOMES

An MS EXCEL spreadsheet-based tool – was produced and is made available with this report. Note this spreadsheet tool was mentioned as a deliverable for Task 8 – *Develop a Spreadsheet Evaluation Tool*. The tool essentially, converts the MCA model developed in this task to a spreadsheet tool (in MS EXCEL platform). Appendix H provides details on this MCA tool.

4.0RESEARCH FINDINGS

1. Based on published guidelines and also from existing pilot implementations (both international and within the U.S.), the following site conditions would necessitate consideration of mini-RABs:

Traffic Conditions

- Total entering intersection ADT is in the range of 1,500 and 15,000 vpd; can go to a maximum 18,000 vpd.
- Peak hour traffic volumes are in the range of 1,150 and 1,400 vph.
- Proportion of major/minor approach volumes is in the range 60/40 to 70/30 (major/minor).
- Truck volumes should not exceed 3% (min) and 4% (max).
- Pedestrian/bike volumes must be "high" (no numeric value); except single study stating 25-55 peds/hr.

Roadway Conditions

- Intersection is located of minor arterials and/or collectors; with 2-lanes (in rare cases 3-lanes).
- Speed limit (or 85% observed speed) is in the range of 15 to 40 mph.
- Existing intersection control is stop-controlled – mostly all-way and rarely two-way. In some cases intersection is signalized but a recent signal warrant analysis suggests otherwise.
- Approaches must intersect at 90° and rarely skewed. Additionally, intersections are mostly 4-legs, but in rare instances can be 3-legs (T-intersections).
- Intersection has limited available right-of-way.
- Not recommended in isolated locations outside of urban areas.

Other Conditions

- Observed unsafe driver behavior and/or maneuvers (left-turning, running stop signs, speeding).
- Evidence of obstructed or restricted sight distance at intersection.
- Observed congestion and the presence of long queues.
- Reported high frequency of crashes and crash severity.

2. Based on published guidelines and also from in service mini-RABs (both international and within the U.S.), the following are minimum (and maximum) design specifications being adopted for mini-RABs:

- Inscribed Circle Diameter (ICD)
  - 90-ft (maximum); with desirable dimensions of 70 to 80-ft.
  - 40-ft (minimum).
- Central Island Diameter
  - 70-ft (maximum); with desirable dimensions of 45 to 55-ft.
  - 15-ft (minimum).

  NOTE: Central island should create deflective path for entering vehicles and encourage counter-clockwise circulation. Design using inside turning path of design vehicle.

  - Typical to raise 5-in (maximum); with 2 to 3-in being common.
  - Recommend to be dome shaped with a 2.5% cross-slope.

  NOTE: Central island can be paint/brickwork/stamped concrete etc. that can either be flush or raised. When raised, it should be traversable by HGVs, EMS or other large vehicles that are likely to use the mini-/modular-RAB less frequently. If the central island is not traversable (some sort of aesthetic feature included), it ceases to be a mini-/modular-RAB.

- Circulating Lane Width
  - At a minimum 12-ft and a maximum 20-ft; with desirable dimensions of 15 to 18-ft.
- Entry Lane Width
  - 15-ft (maximum); with desirable dimensions of 12 to 14-ft.
  - 10-feet (minimum).
- Splitter Island Length (Major approach)
  - 200-ft (maximum); with desirable dimensions of 60 to 70-ft.
  - 15-ft (minimum); the desirable dimensions of 40 to 50-ft.
- Splitter Island Length (Minor approach)
  - 150-ft (maximum); with desirable dimensions of 50 to 60-ft.
  - 15-ft (minimum); with desirable dimensions of 35 to 45-ft.
- Splitter Island Width (Major/Minor approach)
  - At a minimum 6-ft and a maximum 20-ft; with desirable dimensions of 10 to 15-ft.

  NOTE: Splitter islands shall be provided at all approaches to separate opposing vehicles, provide a deflection path for entering vehicles and increase conspicuity; and provide a refuge area for pedestrians (where crosswalks are included). At a minimum, the splitter island area should be 50-ft^2. Splitter islands should be raised and may be flush. When raised, splitter islands should be traversable by HGVs, EMS or other large vehicles.

- Flared or not flared?

    - Not desirable to have flaring but there is no recommended guidance.
- Approach Speeds (posted)
    - At a minimum 10-mph and a maximum 25-mph; with desirable values of 15 to 20-mph.
- Pedestrian Crosswalks
    - Recommend widths of 8 to 10-ft.
    - If crosswalk is included in splitter island, recommended location is 20 to 25-ft upstream of entrance line; and enough to include a single vehicle waiting to enter the RAB.
- Design Vehicle
    - Recommended design vehicle is a standard passenger car; though it is desirable, and primarily to avoid passenger discomfort, that buses are accommodated.
    - Where low to moderate bicyclists are presents; these shall navigate in similar manner as vehicle within the mini-RAB. It is recommended that bike lane(s) be terminated prior to the entrance (yield) line.

NOTE: Not recommended to adopt mini-/modular-RABs for routes frequently used by large vehicles (trucks, RVs, HGVs), however, to accommodate any infrequent large sized trucks and/or emergency vehicles, it is recommended the central island (and sometimes splitter islands) be traversable.

3. There are no reported signage and marking requirements specific to mini-RABs. The recommended signage and marking (based on MUTCD) for modern-RABs are applicable to mini-RABs.

4. Mini-RABs are commonly constructed using materials and methods same as for traditional RABs; that is, with a composition of asphalt, concrete, and other paving materials. In-service mini-RABs costs range from minimum $10,000 to maximum $650,000; with average costs being approximately at $150,000.

5. Alternate materials and/or methods that have been proposed (or are being tested) such as recycled plastic materials and prefabricated construction – aka modular-RABs. In essence, the modular-RAB system consists of modular precut and predrilled blocks (made of recycled materials), and components for assembly on site. Their prefabricated nature allows shorter timelines for onsite installation activities (1-2 days) and therefore do not require long-term work-zone installations. Costs for modular versions of mini-RABs are greatly dependent on the specific design and will vary from location-to-location. In the US, development of modular-RABs has been spearheaded by a company called Vortex. European-based modular systems (e.g., Zipper) are available as well. Modular-RABs are advantageous for temporary traffic control during events such as natural disasters, concerts, football games etc.

6. From a practitioner's perspective (survey-based), within Ohio and across the US, the following are findings that were compiled regarding mini-RABs:
    - There was a reasonably high level of familiarity with mini-RABs among respondents.
    - Several agencies have used mini-RABs as alternative in locations where traffic signals are no longer warranted.

- In spite of the advantages (i.e., low costs of installation and maintenance, shorter construction timelines, etc.) the important factors agency consider in installation of mini-RABs were reduction of crashes/severity and improved traffic operations.
- Major concerns with mini-RABs that were identified are:
    - Drivers neglecting the central island and driving straight through thus causing the mini-/modular-RAB to lose its integrity.
    - Difficulty with performing winter (other inclement weather) maintenance operations (snow plowing).
- Agencies determine the suitability of a location for installation of a mini-/modular-RAB on current intersection geometry, traffic flow patterns, availability of ROW, need for low speeds, and presence of low traffic volumes.
- Agencies typically place mini-/modular-RABs on two-lane highways with low traffic volumes (< 15,000 vpd); and/or peak-hour volumes of 1,600 to 1,800 vehicles.

7. From a driver's perspective (based on a driving simulator study), the following high-level findings can be compiled:
    - There are no differences in critical gap values as driver's maneuvered through mini-RAB of different ICD. The estimated critical gap ranged from 4.22 to 4.82 secs.
    - In general, the observed critical gap for participants was longer during daytime driving than night-time driving scenarios. This is likely because it is easier to become aware of the difference in RAB size during the day than night and drivers adjusted better during the day than night.
    - Speed curves (along entry approach, circulatory area, exit approach) for mini-RABs of varying ICDs showed similar trends as speed curves for a single-lane RAB (of 120-ft ICD). This is indicative of a "positive" response in that drivers were able to navigate the mini-RABs reasonably similar to a traditional RAB design they are familiar with (single-lane RAB).
    - While there was a lack of knowledge on the concept of a mini-RAB among drivers, they still reported to being able to notice a mini-RAB as they approached one in the simulation environment. As expected, mini-RABs regardless of ICD size, caused drivers to slow down along entry approach and within the circulatory area (i.e., act as a traffic calming measure).

8. Operations-wise, Mini-RABs with larger ICDs performed better than those with smaller ICDs. The entry angle (EA) affects operations on mini-RABs; with an EA of 50° being the most effective. In general, mini-RABs showed better operational performance when compared to stop control (two-way and all-way).

9. A safety assessment (simulation-based) showed that two-way major and minor approach volumes of < 800 veh/h and < 400 veh/h respectively perform best in terms of the minimum number of conflicts. Also, the number of conflicts were not affected by the turn proportions.

5.0 RECOMMENDATIONS FOR IMPLEMENTATION

Based on the finding of this research project, the following recommendations are suggested:

1. Mini-RABs (and their modular version) are an excellent intersection control alternative for Ohio's local transportation system. In general, mini-RABs can be adopted on two-lane roadways with

low entering volumes, and where there is limited ROW. They can be considered at intersections currently using stop-control (TWSC or AWSC) and needing upgrades; and at signalized intersections where a warrant analysis shows the need to downgrade. It is not recommended that mini-/modular-RABs be considered for isolated intersections.

2. The site-specific considerations for placement (of mini-RABs) and design guidelines presented in the research findings (section 4.0 and items 1 & 2) are good reference points for any potential implementations of mini-RABs. These reference guidelines are based on a detailed review of all international, federal, and state-based design practices. However, it should be understood that these are only minimum specifications and that engineering judgement and site-specific needs should also be considered.

3. Based on *observed driving behavior* data (from a driving simulator experiments), it is recommended that the ICD for mini-/modular-RABs should be between 60 and 90-ft. A mini-RAB with an ICD in the suggested range is likely to reduce driver speeds by approximately 5-mph in comparison to a single-lane RAB (of 120-ft ICD).

4. From an *operational performance perspective*, mini-RABs with ICD of 70 and 90-ft; and EA of 50° performs best in terms of operational performance measures (i.e., control delay, queuing, LOS, etc.). Recommend major and minor approach traffic volumes are within a ratio of 2:1 or less.

5. *Among the public*, there is a lack of knowledge about mini-RABs (i.e., what is a mini-RAB?) and how to navigate them. Even with the less-steeper "learning curve" associated with mini-RABs because of prior experience with navigating single-lane RABs (as seen from results in this study), there is still a need among the public to view the "positive side" of mini-RABs. As more implementations begin to take place, it is recommended that there also be a focus towards creating awareness among the public of this new intersection concept. Drivers may view mini-RABs as traffic calming devices and this can trigger improper navigation (i.e., driving straight through) which is likely to deem the mini-RAB a failed intersection control measure. Therefore, it is recommended that public education campaigns, driver training, and media broadcasts specific to mini-/modular-RABS be a focus as well.

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APPENDIX A

RFP Solicitation.

Ohio's Research Initiative for Locals
Request for Proposals

RFP Solicitation Number: 2020-ORIL1

Research Title: Synthesis on Mini-Roundabout Designs for Local Transportation Systems

Problem Statement
Modifications to existing intersections to improve safety for motorists, pedestrians and cyclists as well as improve level of service using modern roundabouts can be cost prohibitive as well as lengthy if additional right of way is needed. Utilizing the mini-roundabout design concept has emerged as an option where existing conditions provide limited right of way. As a result, this system is of particular interest to local transportation officials (e.g.: cities, counties, townships, and villages). There have been previous research studies and pilot projects focused on mini-roundabout applications; however, information on these findings may not be easily accessible. In order to provide local transportation officials with the information needed to make decisions on the appropriate utilization of mini-roundabouts, research is needed.

Goals and Objectives
The goal of this research is to provide clarification on the installation and performance of mini-roundabouts on a local transportation system. The objective is to synthesize and summarize current research and pilot projects pertaining to mini-roundabouts, including modular mini-roundabouts, in a manner that is concise, understandable and relatable to local transportation professionals.

Proposed Research
This research is expected to include consideration for the items listed below. Researchers are expected to provide specific details in the proposal as to how they intend to address these items. Additional or alternate activities may be proposed at the researcher's discretion in order to achieve the stated goals and objectives.

- Literature review and summary of relevant studies, papers and pilot projects.
- Key findings should be synthesized in a user-friendly matrix depicting, at a minimum, the following items:
  - Various products/designs currently available. Analysis should include both mini-roundabouts and modular mini-roundabouts.
  - Cost (inclusive of materials and labor) and time of installation
  - Overall performance of the system
  - Summary of conditions before installation of mini-roundabout (traffic control, volumes (vehicle/ped/bike) by approach, LOS, crash history, ROW)
  - Summary of conditions after installation of mini-roundabout (ICD, splitter island lengths, LOS, crash summary, ROW takes)
  - Impacts to safety (e.g.: crash frequency and severity)
  - Impacts to ongoing maintenance efforts within the footprint of the modified intersection (in particular to the approach area)
  - Comparison of each identified product/design to standard construction methods (i.e.: modern roundabout).
- Provide recommendations for the use of mini-roundabouts, including modular mini-roundabouts, within Ohio. Indicate any special considerations or modifications that should be considered by a local transportation official prior to the pursuing the implementation of mini-roundabouts within their locality.

Requirements of the Research Team:
Due to the nature of this study, the proposed research team must include individuals with knowledge in roadway design, general engineering practices and roundabout design and implementation. Previous experience conducting cost assessment is also required. The proposal must demonstrate that these requirements are met in the "Qualifications of the Research Team" section as well as in the attached resumes. Contracting requirements of the State of Ohio require the inclusion of an Ohio-based entity on the research team.

Assistance from Locals
During the course of this research, the researcher can expect to receive the following assistance from the Technical Advisory Committee:

- Technical direction and clarification.
- Review of project reports.
- Participation in meetings.

Project Specific Deliverables

In addition to the standard research contract deliverables, the researcher is expected to provide following project specific deliverables by the completion date of the project:

1. Synthesis and summary findings and recommendations as appropriate.
2. Comparison matrix of key findings.

Research Contract Deliverables

The following are standard deliverables required of the contract. You may add reports (i.e.: interim, monthly, technical brief) as necessary.

1. Quarterly progress reports (provided electronically).
2. Electronic copies of the draft final report and draft executive summary shall be submitted 120 days prior to the contract completion date.
3. Electronic copies (PDF and MS DOC versions) of an approved final report and approved fact sheet shall be submitted by the contract completion date.
4. Article for the Research newsletter (to be provided upon request).
5. Participation in the following meetings: project start-up, monthly status calls, research review session (1 per year), and research results presentation.

Benefits

The results of this research will provide local officials with enhanced knowledge and information to aid in determining the viability of mini-roundabout installations within their jurisdictions. The results of the study would benefit counties, cities, villages, townships, as well as all motorist classifications. If results are favorable, locals may be presented with a potential for cost savings in terms of infrastructure installation and maintenance.

Potential Application of Research Results

The findings of this research will be of interest to municipalities, townships and counties within Ohio as well as other states and localities nationwide. The matrix will provide local decision makers with a tool to assist them in determining the most appropriate installation given the parameters of the site where a mini-roundabout is being considered.

Preliminary Literature Search Results

A preliminary literature search identified various publications pertaining to this topic. Researchers are expected to perform a more in-depth literature search to ensure this research does not duplicate existing efforts.

2019 TRB Annual Meeting Online Content provides multiple papers and presentations concerning roundabouts.
http://amonline.trb.org/search-results/site-search-7.291302?tag_co=&tag_lo=&ev=&tr=&tag_or=&tag_ta=&ty=&pe=&q=roundabouts&tag_su=&pn=&tag_pe=&qr=1

FHWA Research and Technology Evaluation: Roundabout Research Final Report 2018
FHWA-HRT-17-040. June 2018
https://www.fhwa.dot.gov/publications/research/randt/evaluations/17040/17040.pdf

NCHRP 03-130: Guide for Roundabouts 2018
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4354

Local Road Mountable Roundabouts: Are There Safety Benefits
Nimmi Candappa, Monash University Accident Research Centre
Proceedings of the 2015 Australasian Road Safety Conference
http://acrs.org.au/files/papers/arsc/2015/CandappaN%20200%20Local%20road%20mountable%20roundabouts.pdf

Temporary Modular Mini-Roundabout Pilot (Annendale, VA)
http://www.virginiadot.org/projects/northernvirginia/ravensworth_roundabout.asp

Determination of Mini-Roundabout Capacity in the United States
Taylor W. P. Lochrane, A.M. ASCE; Nopadon Kronprasert, Ph.D.; Joe Bared, Ph.D., P.E.; Daniel J. Dailey, Ph.D.; and Wei Zhang, Ph.D., P.E.
Journal of Transportation Engineering, June 2014.
http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000700
https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29TE.1943-5436.0000700

Unclog Local Network Congestion Using High Capacity Mini-Roundabout: A Feasibility Study
Wei Zhang, Nopadon Kronprasert, Joe Gustafson.
TRB 2014 Annual Meeting
http://docs.trb.org/prp/14-4225.pdf

National Cooperative Highway Research Program report 672: Roundabouts: An Informational Guide (Second Edition)
http://www.virginiadot.org/business/resources/NCHRP_Report_672_Roundabout_Informational_Guide_2nd_Edition2010.pdf

NCHRP Synthesis 488 Roundabout Practices
https://www.nap.edu/catalog/23477/roundabout-practices

Mini-Roundabouts: Technical Summary 2010
FHWA-SA-10-007
http://safety.fhwa.dot.gov/intersection/roundabouts/fhwasa10007/fhwasa10007.pdf

Mini Roundabouts for the United States
ITE Journal, Volume 82, Issue 11 February 2009
http://www.dot.state.mn.us/stateaid/trafficsafety/roundabout/jb09ba46.pdf

The Dimondale Mini: America's First Mini-Roundabout
Edmund Waddell, James Albertson
TRB International Conference on Roundabouts, 2005.
http://onlinepubs.trb.org/Onlinepubs/circulars/ec083/28_Waddellpaper.pdf

Highway 27 Sundre Mini-Roundabout Pilot Project, Alberta, Canada March 2018
(ZKxKZ LLC Proprietary supplier on project)
https://www.cea.ca/files/TriParty2018-Presentations/Forum%204%20-%20Stuart%20Richardson%20&%20Kirk%20Kwan%20-%20Sundre%20Mini%20Roundabouts.pdf
Lessons learned, Public feedback survey

Mini-Roundabouts in Urban Areas
2nd International Conference on Road and Rail Infrastructure 7-9 May 2012 Dubrovnik, Croatia
https://master.grad.hr/cetra/ocs/index.php/cetra/cetra2012/paper/viewFile/165/100
Guidelines of UK, US, Switzerland, Germany

Duration
Total duration of the project is 12 months. The draft final report and draft fact sheet should be submitted for review within 8 months of the contract start date.

APPENDIX B

Work Plan.

Synthesis on Mini-Roundabout Designs for Local Transportation Systems.

Project Schedule

Start Date	Jul 1, 2019

# Month (i.e.-1 represents first full month completed)		1	2	3	4	5	6	7	8	9	10	11	12	13	14	Notes
Month:	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
Task 1: Hold Project Start-Up Meeting.																
Task 1 Deliverable: Consensus agreement and finalization of methodology, scope, and detailed work plan.																No specific submission will be made to ODOT.
Task 2: Review of Pertinent Existing Literature.																
Task 2 Deliverable: Comprehensive literature review with summaries & critiques; matrix of design variables; and short-list of viable alternatives for Ohio.																No specific submission will be made to ODOT. Will be added to draft final report.
Task 3: Survey of Local Transportation Engineers.																
Task 3 Deliverable: Analysis of Ohio's local transportation needs, guidance on importance of different evaluation factors in selection of mini-/modular-roundabout designs.																No specific submission will be made to ODOT. Will be added to draft final report.
Task 4: Perform Human Factors Assessment.																
Task 4 Deliverable: Analysis of alternatives from user perspective.																No specific submission will be made to ODOT. Will be added to draft final report.
Task 5: Perform Microsimulation Assessment.																
Task 5 Deliverable: Analysis of operational performance of selected mini-/modular-roundabout design alternatives.																No specific submission will be made to ODOT. Will be added to draft final report.
Task 6: Perform Life Cycle Cost Analysis.																
Task 6 Deliverable: Comparison of alternatives based on benefits-costs.																No specific submission will be made to ODOT. Will be added to draft final report.
Task 7: Conduct Multi-Criteria Assessment.																
Task 7 Deliverable: Findings of multi-criteria assessment in terms of evaluating design alternatives and selection of best design option.																No specific submission will be made to ODOT. Will be added to draft final report.
Task 8: Develop a Spreadsheet Evaluation Tool.																
Task 8 Deliverable: Electronic copy of spreadsheet tool.																
Task 9: Develop Recommendations and Final Project Report.									Review Period							
Task 9 Deliverable: Final report.								X				X				
Task 10: Conduct Project Management Tasks.																
Task 10 Deliverable: Quarterly report and Monthly Status Updates.				X			X			X						

APPENDIX C

Literature Review

Task 2

TASK 2: A LITERATURE REVIEW on MINI-ROUNDABOUTS.

1. INTRODUCTION

The purpose of Task 2 was to conduct an extensive review and synthesis of current published research and pilot projects. The review would target the design, installation, operation, and maintenance of mini-/modular-roundabouts (RABs). The content in this portion of the document presents a review of the existing literature.

1.1 Methodology for Review.

The literature reviewed was assembled by performing keyword searches of several industry, research-, and or academic-related resources. The searched databases included the Transportation Research International Database, NCHRP Projects, Google Scholar, ScienceDirect, JSTOR, BIOSYS, and Researchgate. Additionally, given there has already been some traction gained with mini-roundabouts in the sense of early adoption and pilot projects; this literature search also summarized these experiences. This task would entail a desktop review and also direct communication with responsible parties in situations where project specific information is not readily available or partially available online.

1.2 Areas that have been Reviewed.

The goal of Task 2 was to provide a comprehensive and detailed insights on mini/modular RABs including (but not limited to) the following:

- Design criterion (radii, entry point features, markings, signage, etc.) that are standard, have been developed, and adopted by other states/cities/localities for their mini/modular RABs.
- Specific considerations that need to be in place for suitable adoption (and/or removal). Examples include, traffic/pedestrian/bike volumes, roadway elements, environmental, safety, locale requirements.
- Benefits and/or performance advantages attained by installing mini/modular RABs from operations (reduced speeds, delay, etc.), safety (crash frequency/severity), and environmental perspectives.
- Costs, construction/installation methods, materials, and timelines, for construction of mini/modular RABs; and any sustainable practices and/or means of providing mini/modular RABs.
- Any specific guidance – "best" practices, maintenance procedures, right-of-way requirements, work zones considerations, materials, etc. – in the use of mini/modular RABs.

A comprehensive state-of-the-practice literature review containing the summaries and critiques organized from different perspectives including; geometric design, construction and maintenance, operations, safety, and driver experience was then prepared.

2. LITERATURE REVIEW RESULTS

In general, mini-/modular-RABs are similar in operational characteristics to modern (or traditional) RABs. Though, mini-/modular-RABs are different in that they have a smaller inscribed circle diameter (ICD), reduced entry speed, and can have painted-flush (or in some cases an elevated curb) central island that is traversable by large vehicles. As is the case with traditional roundabouts, the geometric design of a mini-/modular-RAB requires the need to balance competing design objectives including; safety, operational performance, accommodation of design users, and construction/maintenance costs.

Mini-RABs must be laid out by considering the desired vehicle paths; and more importantly getting drivers to circulate around a traversable island, and forcing a deflected path for the movements that cross one another's paths—"right" turns (Sawers, 2009). Mini-RABs, while common to the UK and France, are a promising alternative to the modern roundabout and are progressively emerging in the US. The reported benefits of mini-roundabouts are lower installation costs, smaller footprint, improved safety and operation performance, and quick installation times (short periods of road closure) etc. (Dept. of Transport and County Surveyors Society, 2006; FHWA, 2009).

2.1 Assessment of International Guidelines.

In general, and as is the case with traditional RABs, the geometric design of a mini-/modular-RAB requires the need to balance competing design objectives including; safety, operational performance, accommodation of design vehicle, and construction/maintenance costs. The subsequent sub-sections present guidance on "starting-point" criteria that have been made available to design mini-/modular RABs by different international road/highway agencies.

2.1.1. Definitions of mini-/modular RABs

Mini-/modular-RABs are defined in an explicit and/or inexplicit manner in various available guidelines. The essential differences occur between definitions from the United States (US) and the United Kingdom (UK). In the US, an inexplicit functional-based definition is provided as "*type of roundabout characterized by a small diameter and traversable central and splitter islands*" (Robinson et al., 2000; FHWA, 2010). Additionally, mini-RABs can be used at physically-constrained (i.e., limited existing ROW) intersections in place of stop-control or signalization (FHWA, 2010). In the UK, a mini-RAB is defined as a "*type or form of junction control at which vehicles circulate around a solid-white, reflectorized, central circular road marking (central island)*" (Department of Transport, 2006).

In many other countries (where mini-RABs are used) variations of either the UK or US definitions are adopted with some being more explicit. For example, in Australia, mini-RABs are defined as "*small, flushed or raised (up to 6-mm) fully mountable roundabouts that can be traversed by larger vehicles*" (Shafi, 2017). Modular-RABs have no specific definitions as they are similar in design to mini-RABs; except they are prefabricated units made from recycled material that are quick and simple to install, and are considered a low-cost alternative.

Regardless, it is common among the various definitions that, mini-/modular-RABs are similar to traditional US roundabouts (i.e., operation-wise) except that, both mini-/modular-RABs are characterized by a smaller ICD with central and splitter islands which are traversable by vehicles; and for modular-roundabouts the geometric footprint elements are made of temporary and/or sustainable materials.

2.1.2. Site specific considerations for placement.

Mini-/modular-RABs are commonly found to be advantageous in space constrained locations. That is in locations with restricted/limited available right-of-way (ROW). In the US, they are recommended for intersections where the total entering daily traffic volumes are no more than 15,000 vehicles and truck traffic is not more than 3%; and they are less suitable for roadways where speeds are more than 30 to 35-mph (50 to 55-kph) (FHWA, 2010). Similar roadway speed criteria are adopted in the UK, and it is recommended that mini-RABs should not be installed where the predicted 2-way AADT on any approach is below 500-vpd and/or the traffic flows or turning proportions differ significantly between approaches (DMRB, 2020).

Guidelines from South Africa present warrants for placement of mini-RABs. In general, mini-RABs should be constructed as a part of an overall traffic calming scheme instead of implementing them in isolation (South Africa Department of Transport, 1997). The flow chart depicted in Figure 2.1 illustrates the manner in which the warrants should be applied. The specific warrants for placement of mini-RABs are presented below:

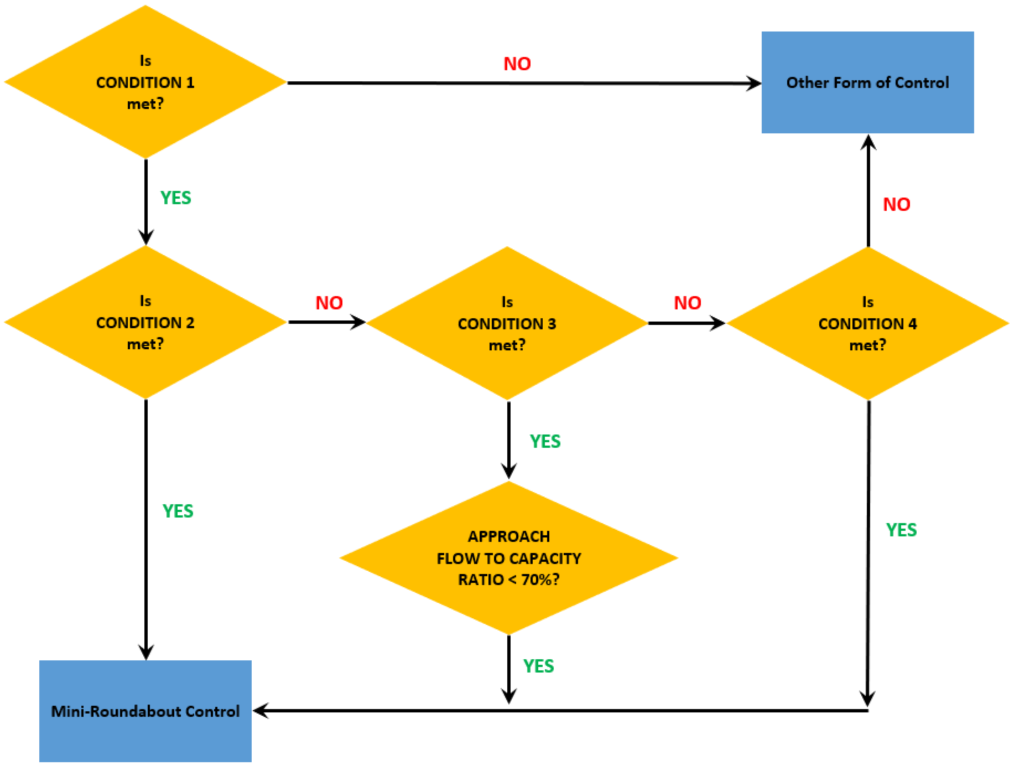

Figure 2.1. Warrants for mini-roundabouts as intersection control (South Africa Dept. of Transport, 1997).

- Condition 1: Entering traffic volumes should be <3000-vph (3-leg intersection); and 4000-vph (4 -leg intersection).
- Condition 2: Proportional splits (i.e., major/minor approaches) should meet criteria in Table 2.1.

Table 2.1. Recommended Major/Minor Proportional Splits (South Africa Dept. of Transport, 1997).

Number of Approaches	Entering Volumes (vph)	Proportional Split (%)
3	< 1500	70/30
	> 1500	60/40
4	< 2000	70/30
	> 2000	60/40

- Condition 3: One major movement has a predominant through movement which is:
  a. 50% ≤ approach volume ≤ 80%
  b. 25% ≤ intersection volume ≤ 40%

- Condition 4: If right-turn volume is more than 25% and which experience:
    a. Long delays (>15 seconds per vehicle)
    b. High incidence of right-angle accidents

In the case that a mini-RAB is not recommended following the conditions stated above, a traffic calming measure is adopted. Additionally, mini-RABs are only recommended for roadways classified as district distributors and/minor arterials or local distributors or residential access roads (i.e., class 3 and lower).

Mini-RABs in Switzerland are recommended only for roads in urban areas, while only exceptionally on roads outside populated areas (i.e., when application of other types of roundabouts or other intersection control types are not possible) (Sordonja, 2012). In addition, placement is restricted to locations where the total entering ADT is less than 15,000-vpd or when the sum of the traffic load at the entry lane and in the circle is less than 1200-vph; and where pedestrian volumes are not especially high. In Germany, mini-RABs are recommended only for urban intersections with a capacity up to a maximum 20,000-vpd, and on roadways having a maximum allowable speed of 30-mph (50-kph). They are not recommended for use in isolation and outside of built-up areas due to safety concerns (Brilon, 2005).

Besides the specific considerations discussed above, a number of factors (common across various countries) are also considered and likely to impede the installation of mini-/modular-RABs. These factors include:

- expected high volumes of large vehicles (trucks, buses, delivery vehicles);
- expected large proportion of U–turning truck traffic;
- forecasted light volumes of minor street traffic or unreasonably varying proportional split between major and minor street traffic;
- at or near direct accesses or intersections where turns into or out from side roads are prohibited, because drivers do not expect to see vehicles U–turning on mini–RABs;
- five or more approach legs; and
- minimum design requirements cannot be applied (or fulfilled) at location(s).

2.1.3. Design criteria and specific considerations.

United States

The ICD should be made as large as possible within the existing ROW, but is not to exceed 90-ft (30-m approx.); this maximum ICD is large enough to accommodate typical design vehicles navigating around a raised central island (FHWA, 2010). The central island should create a deflective path for entering vehicles and encourage counterclockwise circulation; and is typically traversable and may either be domed or raised with a mountable curb and flat top for larger islands. Surdonja et al. (2012) suggested the central island be domed using a 5 to 6% cross slope, with a maximum height of 5-in (13-cm approx.).

With respect to splitter islands; a general recommendation is to adopt raised rather than flush islands. Some general (not mandatory) guidelines that are presented by the FHWA (2010) include:

- For *non–traversable (raised) splitter islands* – can be adopted where either (i) all design vehicles are expected to navigate the mini-/modular-RAB without tracking over the splitter island area; (ii) there is sufficient space available for a splitter island with a minimum area of 50-ft^2 (4.6-m^2 approx.); or (iii) there is an expected medium to high amount of pedestrian activity at the intersection with regular frequency.
- For *traversable (mounted) splitter islands* – can be adopted where either (i) some design vehicles must travel over the splitter island and truck volumes are expected to be minor; and (ii) there is sufficient space available for a splitter island with a minimum area of 50-ft^2 (4.6-m^2 approx.).

- For *flush (painted) splitter islands* – can be adopted where (i) a relatively high frequency of vehicles are expected to travel over the splitter island area; (ii) an island with a minimum area of 50-ft^2 (4.6-m^2 approx.) cannot be achieved; or (ii) the mini-modular RABs approach has low vehicle speeds (preferably no more than 25-mph [40-kph]) (FHWA, 2010).

The longitudinal dimension of a splitter island is recommended to be a desirable 50-ft (15.2-m), regardless of a pedestrian crosswalk being included or not. If a pedestrian crosswalk is included in the splitter island, the recommended location is between 20 to 25-ft (6.1 to 7.6-m) upstream of the entrance line and enough to include a single vehicle waiting to enter the RAB (FHWA, 2010). Crosswalks should ideally be a minimum width of 10-ft (3-m); with a "cut-through" being incorporated for raised/mountable splitter islands.

Placement of yield lines (or shark's teeth) is important and likely to introduce undesirable driver behavior(s); especially in cases where there are large differences between the diameter of the ICD and that of the central island. Some suggested placement options include either advancing yield line(s) forward, or simultaneously enlarging the central island and reducing the circulatory roadway width; with the yield line(s) coincident with the inscribed circle of the mini-/modular-RAB (FHWA, 2010).

United Kingdom

The maximum ICD shall be approximately 92-ft (28-m); with a white central island having a diameter ranging between 3.2 and 13.1-feet (1 and 4-m) and vehicles can drive over it (DMRB, 2020). The central island must be marked using white reflectorized materials. The positioning and sizing of the central island should be done using the inside of the swept path of passenger cars and in a manner that discourages driving on it or passing on wrong side of it while entering the RAB. In addition, the central island can be flush or domed to a recommended maximum height at the center of 4-in (100-mm); and the circular marking can be edged with curbs provided the maximum height above the road surface at the perimeter does not exceed 0.23-in (6mm) (DMRB, 2020). In order to increase the deflection and conspicuity of the mini-RAB, a concentric overrun area (not to exceed 24.6-ft (7.5-m) including central island) may be used.

Curbed traffic islands (splitters) shall be provided at approaches to separate opposing vehicle flows, provide a deflection path for approaching vehicles, for pedestrian usage, and to increase conspicuity (DMRB, 2020). Splitter islands shall be positioned at least 1.6-ft (0.5-m) clear of any vehicle swept path; and the approaches can be single or double-lane but no more. For single lane approaches, the width shall be minimum 9.8-ft (3.0-m) and maximum 13.1-ft (4.0-m); whereas for double lane approaches the minimum width can be reduced to 8.2-ft (2.5-m). Splitter islands should have a lateral shift of minimum 2.6-ft (0.8-m) at entry points to cause vehicles to deflect and subsequently slow down on approach.

Republic of South Africa

The ICD should be minimum 46-ft (14-m) at minimum for a single lane approach and 92-ft (28-m) for a double lane approach (South Africa Dept. of Transport, 1997). The diameter of the central island should be 13-ft (4-m); and if necessary can be reduced to 9.8-ft (3-m). Additionally, a flush painted central island is not recommended, and it should be 75 to 100-mm (2.95 to 3.95-in) high (South Africa Dept. of Transport, 1997). It is encouraged that the width of the circular path in the mini-RAB is between 16 to 19.6-ft (5 to 6-m) to accommodate larger vehicles.

Deflection islands (splitters) should exceed 53.8-ft^2 (5-m^2) in area and placed on all approaches to discourage right turns (left in the US) and guide vehicles into the curvature. The design is based on the circular paths of passenger cars and in some cases buses.

Switzerland

The ICD should not be less than 46 to 85-ft (14 to 26-m). More specifically, for a mini-RAB with a traversable central island, the minimum ICD is 46-ft (14m); whereas with a partially transit (partially traversable) central island, the minimum ICD is 59-ft (18-m). The center of the RAB should be located at the intersection of all approach axes, and the arrangement of approaches should prevent passing without turning. The entrance angle should be carefully chosen so as to prevent tangent entry into the curvature. The smallest angle between the major/minor approaches should not be less than 30 degrees (Surdonja et al., 2012).

Germany

The recommended ICD should be between 43-ft (13-m) and 79-ft (24-m); with a circular roadway width between 15-ft (4.5-m) and 20-ft (6-m). As with other country guidelines, larger vehicles can override the central island as far as their swept path (Brilon, 2005). At the center, the central island should have a maximum height of approximately 4.7-in (12-cm) above the circular lane; with a cross slope of 2.5% inclined towards the outside. In addition, entries/exits should be only single-lane and have no flaring.

2.1.4. Design vehicles and pedestrians.

It is common across all the reviewed international guidelines that mini-/modular RABs should be designed for passenger cars; with the minimum turning path requirements for a standard passenger car being used for design. It is desirable, and primarily to avoid passenger discomfort, that buses are accommodated (FHWA, 2010). All the international guidelines that were reviewed also stipulate the inappropriateness of mini-/modular-RABs for routes frequently used by large vehicles (trucks, RVs, HGVs). However, to accommodate any infrequent large sized trucks and/or emergency vehicles, it is recommended that the central island (and sometimes the splitter islands) be traversable. Besides, the low-speed environment enhances the mini-/modular RAB intersection for non-motorized operators.

Given the typical on-road bicycle speeds (i.e., 12 to 20-mph (20 to 30-kph)) are similar to vehicle speeds; no specific provisions are necessary for bicycles – bicycles are encouraged to navigate in similar manner as vehicles within the mini-/modular RAB. In the US, for approaches leading to a mini-/modular RAB that have bike lanes, it is recommended that the bike lane be terminated prior to the entrance line – for example 100-ft (30-m) prior to entrance line (FHWA, 2010). In the UK, mini-/modular RABs are not recommended for locations where large volumes of cyclists, motorcyclists, or inexperienced cyclists (e.g., on routes to schools) are expected (DMRB, 2020) however, no specific values to determine what constitutes “large” volumes of cyclists/motorcycles are provided. In South Africa, it is believed mini-RABs have negative implications for both cyclists and pedestrians therefore it is recommended that careful consideration must be given to these users and, where necessary, provision made to accommodate them (South Africa Dept. of Transport, 1997).

2.1.5. Costs, Materials, and Maintenance.

Overall, the construction cost for a mini-RAB is much less than that of a traditional RAB. According to the FHWA (2010), the cost of a mini-RAB ranges from approximately $50,000 (for an installation consisting entirely of pavement markings and signage) to $250,000 or more (for installation that includes raised islands and pedestrian improvements). In the UK, local authority consultants estimate the costs for mini-RABs with three approaches to be between £10,000 to £30,000 (approx. $13,000 to $39,500 in 2020) and between £15,000 to £50,000 (approx. $19,800 to $65,800 in 2020) for mini-RABs with four approaches (Dept. for Transport and the County Surveyors Society, 2006). These costs include the planning, design, and construction.

Mini-RABs are commonly constructed using materials and methods same as for traditional RABs; that is, with a composition of asphalt, concrete, and other paving materials (FHWA, 2000; Middleton, 2013). Though, due to their smaller footprint, there are alternate materials and/or methods that have been proposed (or are being tested) such as recycled plastic materials and prefabricated construction – aka modular-RABs. In essence, the modular-RAB system consists of modular precut and predrilled blocks (made of recycled materials), and components for assembly on site. Table 2.2 presents the common materials used for construction of mini-RABS and the advantages/disadvantages of each material.

Table 2.2. Summary of Common Materials for Mini-/Modular-Roundabouts.

Material	Advantages/Disadvantages	Source
Asphalt	• Many previous cases. • Stable and durability. • Corrosion resistant.	• Alberta Government, 2018 • NCHRP, 2016 • Zhang, 2010
Concrete	• Aesthetic and decoration with stamped concrete. • Precast concrete mounts.	• Nebraska DOT, 2019 • TRB, 2017
Recycled Plastic	• Rapidly installed (2-5 days). • Traffic accommodation. • Various color options. • Can be built during winter.	• Alberta Government, 2018 • Fanucci, 2020 • NCHRP, 2016
Thermo-plastic	• Rapidly installed.	• NCHRP, 2016
Hard rubber	• Minimize noise.	• NCHRP, 2011
Paint	• Difficult to control traffic speed. • Paint durability.	• Alberta Government, 2018

In the US, the development of modular-RABs has been spearheaded by a company called Vortex. Vortex (with funding from the US DOT) has tested prototypes of their modular-RABs which, among other advantages; are customizable, easy to install, made from recycled materials, are highly durable, and easy to repair (Vortex, 2020). Additionally, the Vortex modular-RAB system comes in custom colors that can be themed for a city or a university; and can be installed during winter since it does not require concrete/asphalt (Fanucci, 2020). The Vortex system has been deployed at a number of pilot projects including Bozeman, MT; Annandale, VA; Jackson, GA; and Sundre, Alberta (Canada) (TRB Webinar, 2017; Vortex 2020).

Similarly, the Zipper system has also been developed and used for modular-RABs in Europe (ZICLA, 2020). The merits of the Zipper system include adaptability to any road type, ease of installation (and removal), and it is competitive in that it has low design and customization costs (ZICLA, 2020). More recently, a unique prefabricated concrete mini-RAB, has also been installed in the Dutch province of Noord Brabant (Mammoet, 2020). This project constructed the mini-RAB off-site, slid the prefab components into place; and connected all components on-site – avoiding traffic diversions, which would otherwise result in traffic congestion and reduced traffic safety (Mammoet, 2020).

2.2. Comparison of Guidance between US State DOTs.

A desktop analysis of geometric design manuals from state DOTs revealed that, at a minimum, 27 out of 50 state DOTs (54%) have included content provided in *NCHRP 672 Roundabouts: An Informational Guide* and also the *Mini-Roundabouts: Technical Summary*. In addition, 17 state DOTs have included some additional criteria pertaining to mini-RAB design. Table 2.3 presents a list of state DOTs that have included the NCHRP guidance specific to mini-RABs in their design manuals, and it also presents any additional state-specific criteria that is provided.

2.3 Assessment of Practical Implementations in the US.

In 2009, the FHWA funded a first study to assess the viability of mini-RABs for use in the US. Since then, there have been approximately 100+ additional locations within the US where this alternate roundabout type has been adopted as a low-cost solution for improving intersection operations, capacity and safety without the need for acquiring additional right-of-way. The findings presented in this section are based on a review of existing literature (presentations/web resources etc.); and a detailed filtering and subsequent analysis/compilation of a national roundabout database maintained by Kittelson and Associates. The Kittelson and Associates database (roundabouts.kittelson.com) is an inventory of roundabouts that has coverage of the US, Canada, and is recently expanding to other countries (Kittleson and Associates, 2020).

Presented in Table 2.4 and Table 2.5 are a list of locations within the US at which mini-/modular-RABs have been installed over the years. Additionally, information pertaining to the mini-modular-RABs such as design features, installation costs, site conditions prior to (and after) installation are included.

2.3.1. Site specific considerations for placement.

Given below is a summary of site conditions that were common to many of the mini-RAB sites in US; and that also prompted the thought of adopting a mini-/modular-RAB.

Table 2.3. State Specific Use of NCHRP 672 Guidelines for Design of Mini-Roundabouts.

State Agency	State Design Manual includes specific content on Mini-RABs?	Additional criteria/deviations beyond NCHRP 672 guidelines
Alabama	**Yes** - NCHRP 672 guidance	Truck volume < 3% (based on local study).
Alaska	**Yes** - NCHRP 672 guidance	Circulating roadway width >= 15-feet.
Arizona	**Yes** - NCHRP 672 guidance	ICD range is 50 to 90-feet.
Arkansas	**Yes** - NCHRP 672 guidance	
California	**Yes** - NCHRP 672 guidance	
Colorado	**Yes** - NCHRP 672 guidance	
Connecticut	**Yes** - NCHRP 672 guidance	
Delaware	**Yes** - NCHRP 672 guidance	
Georgia	**Yes** - NCHRP 672 guidance	ICD range is 70 to 90-feet. Truck volume < 5% (based on local study). Operating speed < 35-mph.
Illinois	**Yes** - NCHRP 672 guidance	Central island diameter < 13-feet.
Indiana	**Yes** - NCHRP 672 guidance	ICD range is 45 to 110-feet.
Iowa	**Yes** - NCHRP 672 guidance	Minimum 10% side street volume.
Kansas	**Yes** - NCHRP 672 guidance	ICD range is 50 to 90-feet. Central island diameter range is 16 to 45-feet. Operating speed < 35-mph.
Maryland	**Yes** - NCHRP 672 guidance	
Massachusetts	**Yes** - NCHRP 672 guidance	Circulating roadway width range is 14 to 16-feet.
Michigan	**Yes** - NCHRP 672 guidance	Circulating roadway width range is 14.5 to 16-feet. Central island diameter range is 20 to 50-feet. Entry lane width range is 13 to 15-feet. Operating speed < 35-mph.
Minnesota	**Yes** - NCHRP 672 guidance	ICD range is 50 to 80-feet. Central island diameter range is 16 to 45-feet. Entry lane width ramges is 10 to 11-feet. Peak all entering traffic demand < 1,600-vph. Truck volume < 5%. Operating speed range is 35 to 45-mph.
Montana	**Yes** - NCHRP 672 guidance	
Nevada	**Yes** - NCHRP 672 guidance	
Ohio	**Yes** - NCHRP 672 guidance	Circulating roadway width range is 14 to 16-feet.
Oregon	**Yes** - NCHRP 672 guidance	Central island diameter < 13-feet.
Pennsylvania	**Yes** - NCHRP 672 guidance	ADT range is 12,250 to 15,500-vpd. Operating speed < 35-mph.
South Carolina	**Yes** - NCHRP 672 guidance	
Tennessee	**Yes** - NCHRP 672 guidance	ADT range is 10,000-vpd.
Texas	**Yes** - NCHRP 672 guidance	
Virginia	**Yes** - NCHRP 672 guidance	Central island diameter range is 25 to 50-feet. Circulating roadway width range is 14 to 16-feet. Peak all entering traffic demand range is 900 to 1,600-vph. Truck volume < 5% (based on local study). Approach lane width range is 10 to 11-feet (to reduce speeds). Crosswalk should be placed 25-feet before yield line. Splitter islands width >= 4-feet.
Washington	**Yes** - NCHRP 672 guidance	ICD range is 50 to 85-feet. Circulating roadway width range is 16 to 18-feet. ADT < 10,000-vpd. Entry lane width range is 14 to 15-feet.

Table 2.4. Characteristics of In-Service Mini-Roundabouts (based on Kittleson Database).

	City, State County Country	Intersection (Lat, Lng)	Control Type / Other Control Type	Approaches / Driveways	Year Completed	Inscribed Central Diameter (ft)	Central Island Diameter (ft)	Circulating Lane Width (ft)	Entry Lane Width (ft)	Splitter Island Length (Major) (ft)	Splitter Island Length (Minor) (ft)	Splitter Island Width (ft)	Smallest Angle of Intersection	Flare	Daily Traffic (veh/day)	Speed Limit (mph)	Pedestrian Crosswalk Width (ft)
1.	**Soldotna, AK Kenai Peninsula United States**	N Binkley St./W Redoubt Ave. (60.48781, -151.07231)	All-Way Yield None	4 Approaches 0 Driveways	2014	75	30	22	14	72	50	10	90	No	8060	25*	10
2.	**Soldotna, AK Kenai Peninsula United States**	S Binkley St./Wilson Ln. (60.48344, -151.07215)	All-Way Yield None	3 Approaches 1 Driveways	2014	75	25	25	16	72	50	10	65, skewed 35	No	6590*	25*	10
3.	**Conway, AR Faulkner Co. United States**	Van Ronkle St./Markham St./Chestnut St. (35.09176, -92.44000)	All-Way Yield Rectangular Rapid Flashing Beacon (RRFB)	4 Approaches 0 Driveways	2019	76	36	20	13.5	20	20	10	Skewed	Yes			10
4.	**San Luis, AZ Yuma Co. United States**	Main St./Urtuzuastegui St. (32.48698, -114.78233)	All-Way Yield None	3 Approaches 0 Driveways	2015	70	24, not raised	23	14	50	50	12	90	Yes	18484*	15	10
5.	**Grass Valley, CA Nevada Co. United States**	Olympia Park Cir./(parking lot) (39.23248, -121.03766)	All-Way Yield None	2 Approaches 1 Driveways	2014	74	40, not raised	17	17	35, not raised	25, not raised	10, not raised	85	No		15	None
6.	**Redding, CA Shasta Co. United States**	Shasta St./Olive Ave. (40.58343, -122.40524)	All-Way Yield None	4 Approaches 0 Driveways	2006	50	25	12	14	30, not raised	30, not raised	8, not raised	90	No	1875	None	None
7.	**Arcata, CA Humboldt Co. United States**	Sunset Ave./Foster Ave./Jay St. (40.87972, -124.08482)	All-Way Yield None	4 Approaches 0 Driveways	2014	84	46	18	14	45	35	10	70, skewed	Yes		25*	8

8.	**Loveland, CO Larimer Co. United States**	Aries Dr./Saint John Pl. (40.39440, -105.03312)	All-Way Yield None	3 Approaches 0 Driveways	2013	75	50	12	12	50	30	15	90	No			10
9.	**Loveland, CO Larimer Co. United States**	N Garfield Ave./W 7th St. (40.39864, -105.07792)	All-Way Yield None	4 Approaches 0 Driveways	2016	60	34	13	14	25	25	10	90	No	7335	20, school zone	10
10.	**Golden, CO Jefferson Co. United States**	Heritage Rd./W 4th Ave. (39.72190, -105.21004)	All-Way Yield Unknown	4 Approaches 0 Driveways	2015	60	36	12	10	20	15	6	90	Yes	14083	25*	10
11.	**Snowmass Village, CO Pitkin Co. United States**	Wood Rd./Carriage Way (39.21000, -106.94756)	All-Way Yield Unknown	3 Approaches 0 Driveways	2016	50	20	15	13	100	40	6	120, skewed	Yes		15*	10
12.	**Kissimmee, FL Osceola Co. United States**	**E Monument Ave./Lakeview Dr.** (28.29192, -81.40460)	All-Way Yield None	4 Approaches 0 Driveways	2010	80	50	15	10	45	22	8	90	No	8049*	15	8
13.	**Kissimmee, FL Osceola Co. United States**	Lakeshore Blvd./(parking lot) (28.28792, -81.40889)	All-Way Yield None	4 Approaches 0 Driveways	2011	80	50	15	10	50	50	8	80	No		15	8
14.	**Port St Lucie, FL St. Lucie Co. United States**	SW Tulip Blvd./SW College Park Rd. (27.25803, -80.37393)	All-Way Yield None	4 Approaches 0 Driveways	2019											15*	
15.	**McDonough, GA Henry Co. United States**	GA 81/Snapping Shoals Rd./Jackson Lake Rd. (33.46282, -83.96860)	All-Way Yield None	4 Approaches 0 Driveways	2017	85	50	18	11	80, not raised	45, not raised	20, not raised	60, skewed	Yes	5410	25	None
16.	**Macon, GA Bibb Co. United States**	US 32 (Riverside Dr.)/Bass Rd./Arkwright Rd.	All-Way Yield None	4 Approaches 0 Driveways	2017	85	50	18	13	40	12	10	65, skewed	No	14065	25	None

	(32.93662, -83.71736)															
17. Jackson, GA Butts Co. United States	Keys Ferry Rd./Barnetts Bridge Rd./Hwy 36 (33.38354, -83.90331)	All-Way Yield None	4 Approaches 0 Driveways	2017	90	50						90, Modular, Rapid-Install Roundabout	No	6510	25	10
18. Kealakekua, HI Hawaii Co. United States	Halekii St./Mamao St. (19.51783, -155.92400)	Two-Way Stop Unknown, Traffic Circle	4 Approaches 0 Driveways		45	20, not raised	13	14	None	None	None	75, skewed	No		15	10
19. Kealakekua, HI Hawaii Co. United States	Halekii St./Muli St. (19.51673, -155.92736)	Two-Way Stop Unknown, Traffic Circle	4 Approaches 0 Driveways		45	20, not raised	15	14	None	None	None	90	No		15	10
20. Coralville, IA Johnson Co. United States	12th Av./ Holiday Rd. (41.69491, -91.58287)	All-Way Yield None	4 Approaches 0 Driveways	2015	60	35	13	11	50	50	8	90	No	13557	15	8
21. Marion, IA Linn Co. United States	29th Ave./35th St. (42.05043, -91.57448)	All-Way Yield Unknown	4 Approaches 0 Driveways	2016	80	50	15	12	95	50	13	90	Yes	8325	15	10
22. Millbury, MA Worcester Co. United States	Elm St/Elm Ct/Rte 146 Ramps (42.18783, -71.76618)	All-Way Yield None	4 Approaches 0 Driveways	2018	80	50	15	12				80, skewed	No	15100*	15*	10
23. Fitchburg, MA Worcester Co. United States	Main St./River St. (42.58718, -71.80861)	All-Way Yield None	3 Approaches 0 Driveways	2017	55	28	14	12	50	12	12	60, skewed	Yes	17500	15	10
24. Bel Air, MD Harford Co. United States	**Tollgate & MacPhail Rd** (39.51916, -76.35227)	All-Way Yield None	4 Approaches 0 Driveways	2012	60	30	15	12	55	25	12	90	Yes	13056	15	10
25. Columbia, MD Howard	**Golden Straw Ln./Davis Rd.** (39.21597, -76.81084)	All-Way Yield None	4 Approaches 0 Driveways	2000	45	20	13	11	15	15	10	90	No		15*	None

United States																
26. Baltimore, MD Baltimore United States	Canterbury Rd./W 39th St. (39.33569, -76.62047)	All-Way Yield None	4 Approaches 0 Driveways	2013	64	32	16	13	45	45	10	60, skewed	Yes	6350*	15	10
27. Baltimore, MD Baltimore City United States	Guilford Ave./22nd St. (39.31441, -76.61263)	All-Way Yield None	4 Approaches 0 Driveways	2012	40	15	13	10	None	None	None	90	No	1440*	15*	10
28. Baltimore, MD Baltimore City United States	Guilford Ave./E 24th St. (39.31650, -76.61276)	All-Way Yield None	4 Approaches 0 Driveways	2012	40	15	13	10	None	None	None	90	No	2510*	15*	10
29. Baltimore, MD Baltimore City United States	Guilford Ave./E 32nd St. (39.32703, -76.61345)	All-Way Yield None	4 Approaches 0 Driveways	2012	40	15	13	10	None	None	None	90	No	1440*	15*	10
30. Stevensville, MD Queen Annes United States	Thompson Creek Rd./US 50 EB Ramps (38.97599, -76.31046)	All-Way Yield None	4 Approaches 0 Driveways	2007	75	40	18	14	90, not raised	30, not raised	12, not raised	120, skewed	Yes	5154*	15	None
31. Ypsilanti, MI Washtenaw Co. United States	Textile Rd./Hitchingham Rd. (42.20169, -83.62088)	All-Way Yield None	4 Approaches 0 Driveways	2015	90	50	20	14	150	30	15	85	Yes	12917	15	None
32. Ypsilanti, MI Washtenaw Co. United States	**Textile Rd./Stony Creek Rd.** (42.20172, -83.62311)	All-Way Yield None	4 Approaches 0 Driveways	2016	90	50	20	15	230	20	15	50, skewed	Yes	10850	15	None
33. Saline, MI Washtenaw Co. United States	Ann Arbor-Saline Rd./Textile Rd. (42.19859, -83.79691)	All-Way Yield None	4 Approaches 0 Driveways	2016	90	45	22	15	185	100	14	90	Yes	11670	15	None

34. Shakopee, MN Scott Co. United States	CR 79 (Spencer St. S)/Vierling Dr. (44.78335, -93.52016)	All-Way Yield None	4 Approaches 0 Driveways	2014	75	45	15	15	180	150	12	90	Yes	12400	15	10
35. Elk River, MN Sherburne Co. United States	Railroad Dr & Thrid St & Irving Ave (45.30450, -93.56572)	All-Way Yield None	4 Approaches 0 Driveways	2013	85	50			35	15		30, skewed	No	1695	15*	10
36. St James, MN Watonwan Co. United States	1st Ave. S/Armstrong Blvd. N (43.98198, -94.62838)	All-Way Yield Unknown	4 Approaches 0 Driveways	2017								90		12252	15*	10
37. St James, MN Watonwan Co. United States	1st Ave. S/7th St. S (43.98246, -94.62703)	All-Way Yield Unknown	4 Approaches 0 Driveways	2017								90		10241	15*	10
38. Anoka, MN Anoka Co. United States	S 4th Ave./Washington St./Military Rd. (45.19165, -93.38535)	All-Way Yield None	5 Approaches 0 Driveways	2017	90	65	13	13	25	25	10	60, skewed	Yes	4700	15*	10
39. Lakeland, MO Miller Co. United States	US 54 Business/N Shore Dr. (38.21423, -92.62436)	All-Way Yield None	3 Approaches 0 Driveways	2014	80	30	25	18	None	None	None	75, skewed	Yes	12576	15	None
40. Midtown, MO Greene Co. United States	Commercial St./Washington Ave. (37.23001, -93.28546)	All-Way Yield None	4 Approaches 0 Driveways	2016	75	40	17	13	None	None	None	95, skewed	Yes	13870	15*	8
41. Colonial Gardens, MO Boone Co. United States	Rollins Rd./S Fairview Rd. (38.94681, -92.38090)	All-Way Yield Unknown	4 Approaches 0 Driveways	2013	60	30	15	12	80	40	10	85, skewed	No	10500	15*	10

42.	**Columbia, MO Boone Co. United States**	Grant Ln./Trailside Dr./Post Oak Dr. (38.92438, -92.39510)	All-Way Yield Unknown	4 Approaches 0 Driveways	1995	70	40	15	14	60, not traversable	35, not traversable	10, not traversable	85, skewed	No	251*	15	10
43.	**Jackson, MS Hinds Co. United States**	E Capitol St./West St. (32.29975, -90.18412)	All-Way Yield None	4 Approaches 0 Driveways	2014	70	45	12	13	55	35	10	90	No	11750		10
44.	**Jackson, MS Hinds Co. United States**	E Capitol St./Lamar St. (32.30000, -90.18602)	All-Way Yield None	4 Approaches 0 Driveways	2014	70	45	12	13	60	50	10	90	No	12250		10
45.	**Jackson, MS Hinds Co. United States**	Capitol St./Farish St. (32.30034, -90.18851)	All-Way Yield None	4 Approaches 0 Driveways	2014	70	45	12	13	40	40	10	80, skewed	Yes	9590		10
46.	**Missoula, MT Missoula Co. United States**	**Scott St./Toole Ave.** (46.87803, -114.00632)	All-Way Yield None	4 Approaches 0 Driveways	2014	75	45	15	13	50	50	12	80, skewed	No	7161	15	10
47.	**Wilmington, NC, New Hanover Co. United States**	**Tanbridge Rd./Wells Rd.** (34.24406, -77.83776)	All-Way Yield None	4 Approaches 0 Driveways	2009	55	18	18	11	15	8	8	90	No		10	None
48.	**Wilmington, NC New Hanover Co. United States**	**Windemere Rd./Camberly Dr.** (34.24265, -77.84314)	All-Way Yield None	4 Approaches 0 Driveways	2009	60	25	18	10	12	12	8	90	No		10	None
49.	**Durham, NC Durham Co. United States**	Broad St./Carver St./Kenan Rd. (36.04004, -78.90837)	All-Way Yield Unknown	4 Approaches 0 Driveways	2016	65	35	15	12	45	45	8	85	No	10395	15	None
50.	**Cary, NC Wake Co. United States**	Wellingborough Dr./Forest Park Way (35.74966, -78.76117)	All-Way Yield None	3 Approaches 0 Driveways	2009	65	30	16	12	40	30	14	130, skewed	Yes		15	8

51. Fayetteville, NC Cumberland Co. United States	Augusta Dr./Commerce St. (35.04725, -78.89901)	All-Way Yield None	4 Approaches 0 Driveways	2009	60	30	15	14	20, not raised	20, not raised	10, not raised	90	No		15*	None
52. Mooresville, NC Iredell Co. United States	College St./S Church St. (35.57668, -80.81736)	All-Way Yield None	4 Approaches 0 Driveways	2014	50	27	12	10	10, not raised	10, not raised	5, not raised	90	No		15	7
53. North Wilkesboro, NC Wilkes Co. United States	Fairplains Rd./Reynolds Rd. (36.19561, -81.14437)	All-Way Yield Unknown	3 Approaches 0 Driveways	2017	40	15	13	10	20, not raised	20, not raised	8, not raised	90	No	2680*	10	None
54. Lincoln, NE Lancaster Co. United States	S 11th St./D St. (40.80254, -96.70560)	All-Way Yield Unknown	4 Approaches 0 Driveways	2013	60	30	15	10	20	20	10	90	No	5440	15*	10
55. Omaha, NE Douglas Co. United States	**S 63rd St./Shirley St.** (41.24148, -96.00960)	All-Way Yield None	4 Approaches 0 Driveways	2017	70	35	17	12	50, not raised	30, not raised	10, not raised	90	Yes	3813	15	7
56. Elmira, NY Chemung Co. United States	**Maple Ave./Caldwell Ave.** (42.08399, -76.79589)	All-Way Yield Unknown	4 Approaches 0 Driveways	2012	60	30	15	10	65, not raised	30, not raised	12, not raised	90	No		15	7
57. Elmira, NY Chemung Co. United States	**Maple Ave./Horner St.** (42.08282, -76.79445)	All-Way Yield Unknown	4 Approaches 0 Driveways	2012	55	30	13	10	65, not raised	30, not raised	12, not raised	90	Yes		15	7
58. Newark, OH Licking Co. United States	N 3rd St./N Park Pl. (40.05829, -82.40281)	All-Way Yield None	3 Approaches 0 Driveways	2016	80	45	18	14	45	45	12	90	No	2816	None	8
59. Newark, OH Licking Co. United States	S 3rd St./S Park Pl. (40.05716, -82.40227)	All-Way Yield None	3 Approaches 0 Driveways	2016	80	50	15	14	45	45	12	90	No	2792	None	8
60. Newark, OH Licking Co. United States	S 2nd St./S Park Pl. (40.05760, -82.40059)	All-Way Yield None	3 Approaches 0 Driveways	2016	80	50	15	14	45	45	12	90	No	5554	None	8

61. Newark, OH Licking Co. United States	N 2nd St./N Park Pl. (40.05874, -82.40112)	All-Way Yield None	3 Approaches 0 Driveways	2016	80	50	15	14	45	45	12	90	No	5578	None	10
62. Portland, OR Multnomah Co. United States	SW 47th Dr./SW 43rd Ave. (45.49245, -122.72111)	All-Way Yield None	3 Approaches 0 Driveways	2007	44	22, not raised	12	13	None	None	None	85	No		15	10
63. Lancaster, PA Lancaster Co. United States	N Plum St & E New St & Park Ave (40.05000, -76.29883)	Unknown Unknown	4 Approaches 0 Driveways	2019												10
64. Lincoln, RI Providence Co. United States	School St./Main St./Briarwood Rd. (41.95141, -71.45445)	All-Way Yield Unknown	4 Approaches 0 Driveways	2017	70	30, not fully traversable	20	12	40, not raised	10, not raised	15, not raised	70, skewed	Yes	9100	20*	10
65. Chattanooga, TN Hamilton Co. United States	4th Ave./E 37th St (35.00101, -85.28883)	All-Way Yield None	4 Approaches 0 Driveways	2013	60	25, flexible post used	17	12	20, flexible post used	20, flexible post used	6, flexible post used	90	No	5574*	15	None
66. Bryan, TX Brazos Co. United States	Esther Blvd./Bennett St. (30.65622, -96.35323)	All-Way Yield None	3 Approaches 0 Driveways	2018								90				10
67. Canyon Rim, UT Salt Lake Co. United States	S 23rd E St./E Vimont Ave. (40.71203, -111.82460)	All-Way Yield None	4 Approaches 0 Driveways	2017	70	25	17	13	15, not raised	10, not raised	6, not raised	70, skewed	Yes	3910*		10
68. Canyon Rim, UT Salt Lake Co. United States	Heritage Way/Claybourne Ave. (40.71132, -111.82322)	All-Way Yield Unknown	3 Approaches 0 Driveways	2017	55	15	20	10	20, not raised	15, not raised	6, not raised	120, skewed	No			10
69. Lynchburg, VA Lynchburg City United States	University Blvd./Williams Stadium Rd. (37.35301, -79.17631)	All-Way Yield None	3 Approaches 0 Driveways	2015	65	35	15	15	45	35	10	120, skewed	No			10

70. Annandale, VA Fairfax Co. United States	Ravensworth Rd/Jayhawk St/Fountain Head Dr (38.82630, -77.19993)	All-Way Yield Unknown	4 Approaches 0 Driveways	2018								90, Modular, Rapid-Install Roundabout		14850	15	10
71. Warrenton, VA Fauquier Co. United States	E Shirley Ave./Falmouth St. (38.69843, -77.78795)	All-Way Yield Unknown	3 Approaches 0 Driveways	2018								60, skewed, mini-roundabout with bypass lane		13700	15	10
72. Charlottesville, VA Charlottesville United States	109 Burnet St (38.02424, -78.48827)	All-Way Yield Unknown	3 Approaches 0 Driveways	2017	60, not fully traversable	20	40	10	25, not raised	10, not raised	6, not raised	90	No		15*	10
73. Vienna, VA Fairfax Co. United States	Park St. SE/Locust St. SE (38.90205, -77.26091)	All-Way Yield None	3 Approaches 0 Driveways	2018	60	30	15	12	115	115	8	90	Yes	16800*	10	10
74. Manchester, VT Bennington Co. United States	Main St./Bonnet St. (43.17692, -73.05688)	All-Way Yield Unknown	3 Approaches 0 Driveways	2013	65	32	17	15	150	45	6	75, skewed	No	11850	15*	10
75. Issaquah, WA King Co. United States	Maple St. NW/(parking lots) (47.54340, -122.05121)	All-Way Yield None	4 Approaches 0 Driveways	2017	70	40	15	14	100	10, not raised	8	90	No	8732*	15	10
76. Wenatchee, WA Chelan Co. United States	S Miller St/Red Apple Rd (47.40797, -120.32456)	All-Way Yield Unknown	4 Approaches 0 Driveways	2018								90			15	10
77. Federal Way, WA King Co. United States	S 308th St./14th Ave. S (47.32601, -122.31601)	All-Way Yield Rectangular Rapid Flashing Beacon (RRFB)	4 Approaches 0 Driveways	2014	60	34	13	10	95, not raised	80, not raised	10, not raised	90	No	6040	15	10
78. Bellingham, WA Whatcom	Everson Goshen Rd./E Smith Rd.	All-Way Yield None	4 Approaches 0 Driveways	2015	75	40	17	12	50	50	6	90	No	6810	10	10

Co. United States	(48.83263, -122.37755)															
79. Lynden, WA Whatcom Co. United States	SR 546/Northwood Rd. (48.96424, -122.40709)	All-Way Yield None	4 Approaches 0 Driveways	2016	85	50	17	12	60	20	12	90	No	8914	10	10
80. Mount Vernon, WA Skagit Co. United States	Anderson Rd./Cedardale Rd. (48.39915, -122.32710)	All-Way Yield None	4 Approaches 0 Driveways	2013	80	35	17	13	120, not raised	30, not raised	15, not raised	90	Yes	9807	10	10
81. Kennewick, WA Benton Co. United States	W Metaline Ave./N Nevada St./W Montana St. (46.22031, -119.23826)	All-Way Yield None	3 Approaches 0 Driveways	2013	60	30	15	12	20, not raised	20, not raised	6, not raised	65, skewed	Yes		10-15	10
82. Mill Creek, WA Snohomish Co. United States	SE 116th St./56th Ave SE (47.89201, -122.15856)	All-Way Yield None	4 Approaches 0 Driveways	2012	65	30	17	14	140	15	8	65, skewed	Yes	3746	10-15	10
83. Lake Stevens, WA Snohomish Co. United States	N Davies Rd./Frontier Village Access Rd. (48.00447, -122.10403)	All-Way Yield None	4 Approaches 0 Driveways	2012	60	25	17	12	150, not raised	45, not raised	10, not raised	90	Yes	8001*	15	10
84. Lake Stevens, WA Snohomish Co. United States	Vernon Rd./N Davies Rd. (48.00495, -122.10586)	All-Way Yield None	3 Approaches 0 Driveways	2012	60	25	17	14	110, not raised	25, not raised	8, not raised	90	Yes	10970	15	10
85. Marysville, WA Snohomish Co. United States	**25th Ave. NE/174th St. NE** (48.15374, -122.19930)	All-Way Yield None	3 Approaches 0 Driveways	2017	100	70	15	14	75	60	20	80, skewed 10, flared, compact roundabout	Yes		15	10

86. White Center, WA King United States	**9th Ave. SW/SW 100th St.** (47.51379, -122.34640)	All-Way Yield None	4 Approaches 0 Driveways	2006	60	25	17	12	75	15	10	90	Yes		15	10
87. White Center, WA King United States	10th Ave. SW/SW 100th St. (47.51379, -122.34770)	All-Way Yield None	4 Approaches 0 Driveways	2006	60	25	17	12	50	15	10	90	No		15	10
88. Redmond, WA King United States	Eastridge Dr. NE/244th Pl. NE (47.68499, -122.01300)	All-Way Yield None	3 Approaches 1 Driveways	2014	70	35	17	12	40	40	8	90	No		15	10
89. Federal Way, WA King Co. United States	Military Rd. S/S 298 St. (47.33514, -122.29673)	All-Way Yield None	4 Approaches 0 Driveways	2019								65, skewed		12980	10-15	10
90. Ferndale, WA Whatcom Co. United States	Slater Rd./I-5 NB Ramps (48.81737, -122.54604)	All-Way Yield None	3 Approaches 0 Driveways	2014	90	54	18	12	40	15	15	80, skewed	No	14335	10	10
91. Ferndale, WA Whatcom Co. United States	Slater Rd./I-5 SB Ramps (48.81707, -122.55050)	All-Way Yield None	3 Approaches 0 Driveways	2014	90	55	18	12	50	20	20	85, skewed	No	18220	10	10
92. Ferndale, WA Whatcom Co. United States	Slater Rd./Pacific Hwy. (48.81718, -122.54435)	All-Way Yield None	4 Approaches 0 Driveways	2014	75	40	17	12	25	25	10	85, skewed	No	9705	10	10
93. Ferndale, WA Whatcom Co. United States	Portal Way/I-5 NB Ramps (48.85836, -122.58613)	All-Way Yield None	3 Approaches 0 Driveways	2019								70, skewed	No	11660	10	10
94. Shelton, WA Mason Co.	N 1st St./W Alder St.	All-Way Yield None	4 Approaches 0 Driveways	2019								90		11032	10-15	10

United States	(47.21590, -123.09963)															
95. Renton, WA King Co. United States	SE 176th St./SE 171st Way (47.44500, -122.14831)	All-Way Yield None	3 Approaches 0 Driveways	2019								90		12611	10-15	10
96. Eastgate, WA King Co. United States	SE 40th St./138th Ave. SE (47.57459, -122.15670)	All-Way Yield None	4 Approaches 0 Driveways	2019	60	35						90	No		10-15	10
97. Burlington, WA Skagit Co. United States	E George Hopper Rd./S Walnut St. (48.45200, -122.33174)	All-Way Yield None	4 Approaches 0 Driveways	2015	85	45	20	15	15	15	10	70, skewed	No	7032*	15	10
98. Burlington, WA Skagit Co. United States	Marketplace Dr./S Walnut St. (48.44859, -122.33169)	Other None	4 Approaches 0 Driveways	2015	65	30	17	12	15	15	10	90	No		15	10

P.S: The difference between 90 degrees and the smallest acute angle between the intersection legs is referred to as the intersection skew angle.

Table 2.5. Characteristics of In-Service Mini-Roundabouts (sourced from literature).

Mini-Roundabout Location	Conditions Existing Prior to Placement of Mini-RAB	Key Design Features	Installation Cost	Other Reported Findings
Intersection: Creyts Rd. & East Rd. **City/State**: Dimondale, MI. (*Waddell, 2005*)	Entering ADT = 5,550 vpd (1998); Forecast 2020 ADT = 9,550 vpd Truck volumes = 4% Pedestrian/Bike volumes = high Number of lanes = 2 Speed limit = 25-mph Intersection control = stop-controlled Intersection angle = skewed Unsafe left-turning behavior Pedestrian/Bike/Vehicle conflicts Speeding complaints on specific approaches Did not meet signal warrant analysis	ICD = 69-feet Central Island = 13-feet	$47,000	
Intersection: Parker Blvd. & Decatur Rd. **City/State**: Tonawanda, NY. (*Jones & Sargeant, 2017*)	Entering ADT = approx. 12,000 vpd (2014) Pedestrian/Bike volumes = high Number of lanes = 2 Speed limit = 35-mph Intersection control = signalized (unwarranted) Crashes: 40 reported (2014-2016)	ICD = 75-feet Central Island = 45-feet Circulatory Roadway Width = 15-feet Design Speed = 15 to 20-mph Throat widths: Approach = 10-feet; Departure = 10 to 12-feet Crosswalk Setback = 20-feet Splitter Islands Height = 4-inch		
Intersection: Parker Blvd. & Harrison Ave. **City/State**: Tonawanda, NY. (*Jones & Sargeant, 2017*)	Entering ADT = approx. 12,000 vpd (2014) Pedestrian/Bike volumes = high Number of lanes = 2 Speed limit = 35-mph Intersection control = stop-controlled Crashes: 40 reported (2014-2016)	ICD = 60-feet Central Island = 30-feet Circulatory Roadway Width = 15-feet Design Speed = 15-mph Throat widths: vary between 10 to 12-feet Crosswalk Setback = 20-feet Splitter Islands Refuge Width = 6-feet (minimum) Flush Splitter Islands		
Intersection: 132nd/133rd St. & Hemlock Ave. **City/State**: Overland Park, KS. (*HNTB Corporation, 2017*)	Entering ADT = 13,520 vpd Peak hour = approx. 1,200 vph (2017) Number of lanes = 2 Intersection control = stop-controlled Crashes: 7 reported (2014-2016); 5 angle & 2 rear-end	ICD = 100-feet Crosswalk Setback = 20-feet	$180,000	

Intersection: 132nd St. & Foster St. **City/State**: Overland Park, KS. (*HNTB Corporation, 2017*)	Entering ADT = 13,570 vpd Peak hour = approx. 1,300 vph (2017) Number of lanes = 2 Intersection control = stop-controlled Crashes: 4 reported (2014-2016); 1 head-on & 3 rear-end	ICD = 70-feet Crosswalk Setback = 20-feet	$80,000	
Intersection: Tollgate Rd. & MacPhail Rd. **City/State**: Bel Air, MD. (*Stratmeyer & Banigan, 2017*)	Entering ADT = approx. 11,800 vpd (2012) Peak hour = approx. 1150 vph Number of lanes = 2 with LT lanes (3 approaches) Speed limit = 40-mph Intersection control = stop-controlled Crashes: 9 reported (2008-2011); 5 injury & 1 serious	ICD = 67-feet Central Island = 37-feet Circulatory Roadway Width = 15-feet Throat widths: Approach = 13-feet; Departure = 15-feet	$100,000	Reported crashes reduced from 8 to 2 Constructed in 2012
Intersection: CR 79 & Vierling Dr. **City/State**: Shakopee, MN. (*Boarini, 2014; Winiecki, 2017*)	Entering ADT = approx. 12,000 vpd (2012) Peak hour = 1,200 vph Number of lanes = 2 Intersection control = all-way stop-controlled Congestion and long vehicle queues High crash rate and severity	ICD = 75-feet Central Island = 45-feet Circulatory Roadway Width = 30-feet	$338,000	
Corridor: Textile Rd. **Intersection #1**: Stoney Creek Rd. **Intersection #2**: Hitchingham Rd. **City/State**: Ypsilanti Twp, MI. (*McCulloch, 2017*)	Entering ADT = approx. 10,000 vpd Truck volumes = 4% Design speed = 45 to 55-mph	ICD = 90-feet	$840,000	Constructed in 2015
Intersection: SR 11 & SR 124. **City/State**: Jackson Cty, GA. (*Zhang, 2013*)	Entering ADT = approx. 17,000 vpd Number of lanes = 2 Intersection control = all-way stop-controlled 50 cars recurring queue	ICD = 90-feet	$63,000	Constructed in 2013 No observed recurring queues post installation
Corridor: N Davies Rd. **Intersection #1**: Vernon Rd. **Intersection #2**: Local Un-named Rd. **City/State**: Lake Stevens, WA. (*Zhang, 2013*)	Number of lanes = 2 Intersection control = stop-controlled (T-intersection) Queuing as drivers get out of shopping center Drivers running stop signs		$20,000	Constructed in 2010 No observed recurring queues post installation Businesses reported 10-15% increase in sales

City/State: Takoma Park, MD. (*Zhang, 2013*)	Number of lanes = 2		$25,000	
City/State: Snohomish Cty., WA. (*Bloodgood, 2013*)	Entering ADT = approx. 2,500 vpd Number of lanes = 2 85% speed = 33 to 36-mph 8-10% grades Sight distance restrictions	ICD = 70-feet Central Island = 30-feet Design Speed = 15-mph Mountable Islands = 3-inch Height Contrasting material colors	$367,000	Constructed in 2012
City/State: Bel Air, MD. (*Zhang, 2013*)	Number of lanes = 2		$172,000	Crash frequency reduced Improved pedestrian safety
City/State: Elmira, NY. (*Zhang, 2013*)	Number of lanes = 2		$97,500	
City/State: Jefferson, GA. (*Zhang, 2013*)	Number of lanes = 2 Design speed = 55-mph Intersection control = all-way stop-controlled		$63,353	
City/State: Annandale, VA. (*Zhang, 2013*)	Entering ADT = approx. 13,000 vpd Peak hour = 1,400 vph Number of lanes = 2			Modular mini-roundabout Installation time = 7 days Installed in 2018
City/State: Newark, OH. (*Morehead, Schultz, & Call, 2019*)	Entering ADT = approx. 6,000 vpd (2013) Truck volumes = 4% Pedestrian volumes = 20 to 55 peds/hr Number of lanes = 2 Speed limit = 25-mph Intersection control = signalized	ICD = 80-feet Central Island = 50-feet		45 to 65% reduction in all crashes/yr 100% reduction in injury crashes 2% reduction in ped/bike related crashes > $120 million public/private investment since 2014
Corridor: Baker Rd. **Intersection #1**: Shield Rd. **Intersection #2**: Dan Hoey Rd. **City/State**: Washtenaw Cty, MI. (McCulloch, 2020)	Entering ADT = approx. 18,000 vpd Truck volumes = 3%	ICD = 100-feet (Shield Rd.) ICD = 105-feet x 95-feet (Dan Hoey Rd.)	$1.3 million	
Intersection: SR 5 & SR 16/US27 Alt. **City/State**: Whitesburg, GA. (*Zhengraff, 2019*)	Entering ADT = approx. 14,500 vpd Number of lanes = 2 Speed limit = 35-mph	ICD = 90-feet	$152,430	
Intersection: SR 81 & Jackson Lake Rd. **City/State**: Henry Cty., GA. (*Zhengraff, 2019*)	Entering ADT = approx. 8,500 vpd Number of lanes = 2	ICD = 85-feet	$255,879	Temporary RAB Constructed in 2016

Intersection: SR 87 & Bass Rd. **City/State**: Bibb Cty., GA. (*Zhengraff, 2019*)	Entering ADT = approx. 12,000 vpd Number of lanes = 2	ICD = 95-feet	$200,000	Constructed in 2017
Intersection: SR 36 & Keys Ferry Rd. **City/State**: Butts Cty., GA. (*Zhengraff, 2019*)	Entering ADT = approx. 8,100 vpd Number of lanes = 2 Intersection control = signalized	ICD = 68-feet	$44,437	Modular mini-roundabout Installed in 2017
Corridor: SR 14 **Intersection #1**: Hal Jones Rd. **Intersection #2**: Green Top Rd. **City/State**: Coweta Cty., GA. (*Zhengraff, 2019*)	Entering ADT = approx. 13,700 vpd (SR14/Hal Jones Rd.) Entering ADT = approx. 12,000 vpd (SR14/Green Top Rd.) Number of lanes = 2 T - intersection	ICD = 87-feet (Hal Jones Rd.) ICD = 74-feet (Green Top Rd.)	$398,818	Constructed in 2018
Intersection: SR 212 & SR 36. **City/State**: Newton Cty., GA. (*Zhengraff, 2019*)		ICD = 104-feet	$57,490	Constructed in 2015
Intersection: SR 5 & Old Hwy 27. **City/State**: Carroll Cty., GA. (*Zhengraff, 2019*)		ICD = 90-feet	$10,000	Constructed in 2000
Intersection: Flat Shoals Rd. & McPherson. **City/State**: Atlanta, GA. (*Zhengraff, 2019*)		ICD = 48-feet	$100,000	Constructed in 2013 Part of enhancement project
Intersection: SR 16 & SR 54. **City/State**: Coweta Cty., GA. (*Zhengraff, 2019*)		ICD = 78-feet	$77,100	Constructed in 2016
City/State: Bozeman, MT. (*Fanucci, 2017*)		Central Island = 24-feet	$25,000 (for circle)	Modular mini-roundabout Installation time = 1 day
Intersection: Bliley Rd. & Blakemore Rd. **City/State**: Richmond, VA. (*Flynn, 2013*)	Number of lanes =2	Central Island = 26-feet	$50,000	Constructed in 2013

Traffic Conditions

- Total entering ADT was no more than the FHWA recommended 15,000 vpd at most locations. More specifically,
    - 1,500 vpd (approx.) being lowest;
    - 10,000 to 12,000 vpd (approx.) being median range; and
    - 18,500 vpd (approx.) being the highest.
- Peak hour traffic volumes in the range of 1,150 and 1,400 vph.
- Volumes on major approaches are higher than on the minor approaches; with an approximately 60/40 split (major/minor).
- Truck volumes not explicitly reported; indicating that at most locations there was very minimal truck (large vehicle) activity. Where truck percentages were available the minimum was 3%, and the maximum was 4%.
- Pedestrian/bike volumes not explicitly reported at many locations, indicating this was not of concern during design. Where pedestrian/bike volumes were provided, these were presented as being either "high" with no numerical values given; or in one case study as 25-55 peds/hr.

Roadway Conditions

- Located on intersection of minor arterials and/or collectors; with 2-lanes (in rare cases 3-lanes).
- Speed limit (or 85% observed speed) is in the range of 15 to 40 mph.
- Existing intersection control is stop-controlled – mostly all-way and rarely two-way. However, there were cases of exiting control being all-way yield; and in one case, intersection was signalized but a recent signal warrant analysis deemed otherwise and a mini-RAB was installed.
- Approaches intersect at 90 degrees and are rarely skewed. Additionally, mostly 4-approaches, but a few instances of 3-approaches (T-intersections).
- Installed at intersections with limited available right-of-way.

Other Conditions

- Observed unsafe driver behavior and/or maneuvers (left-turning, running stop signs, speeding).
- Evidence of obstructed or restricted sight distance at intersection.
- Observed congestion and the presence of long queues.
- Reported high frequency of crashes and crash severity.

2.3.2. Design criteria and specific considerations.

Given below is a summary of design specifications extracted from in-service mini-/modular-RABs.

- Inscribed Circle Diameter (ICD)
    - 90-feet (maximum); the more commonly adopted dimensions are in the 70 to 80-feet range.
    - 30-feet (minimum); the more commonly adopted dimensions are in the 40 to 50-feet range.
- Central Island Diameter
    - 70-feet (maximum); the more commonly adopted dimensions are in the 45 to 55-feet range.

  - 15-feet (minimum); the more commonly adopted dimensions are in the 20 to 30-feet range.
  - Central island can be paint/brickwork/stamped concrete etc. that can either be flush or raised. When raised, it should be traversable by HGVs, EMS or other large vehicles that are likely to use the mini-/modular-RAB less frequently. If the central island is not traversable (some sort of aesthetic feature included), it ceases to be a mini-/modular-RAB.
  - Typical to raise 5-inches (maximum); with 2 to 3-inches being common.
- Circulating Lane Width
  - 20-feet (maximum);
  - 12-feet (minimum);
  - the more commonly adopted dimensions are in the 15 to 18-feet range.
- Entry Lane Width
  - 15-feet (maximum);
  - 10-feet (minimum);
  - the more commonly adopted dimensions are in the 12 to 14-feet range.
- Splitter Island Length (Major approach)
  - 200-feet (maximum); the more commonly adopted dimensions are in the 60 to 70-feet range.
  - 15-feet (minimum); the more commonly adopted dimensions are in the 40 to 50-feet range.
  - these can be flush or raised (note: when raised they should be traversable by HGV, EMS)
- Splitter Island Length (Minor approach)
  - 150-feet (maximum); the more commonly adopted dimensions are in the 50 to 60-feet range.
  - 15-feet (minimum); the more commonly adopted dimensions are in the 35 to 45-feet range.
  - these can be flush or raised (note: when raised they should be traversable by HGV, EMS)
- Splitter Island Width
  - 20-feet (maximum);
  - 6-feet (minimum);
  - the more commonly adopted dimensions are in the 10 to 15-feet range.
- Smallest Angle of Intersection
  - most mini-/modular-RABs are placed at intersections that intersect at 90-degrees.
- Flared or not flared?
  - not common to have flare but there are some applications that do have flare.
- Approach Speeds (posted)
  - 25-mph (maximum);
  - 10-mph (minimum);
  - the more commonly adopted values are in the 15 to 20-mph range.
- Pedestrian Crosswalk Width
  - If pedestrian crosswalks are present; these are 8 to 10-feet wide.

2.3.3. Costs, Materials, and Maintenance.

Generally, installation of mini-/modular-RABs is relatively less costly and requires less routine maintenance. Moreover, there are also reduced costs associated with items such as crash costs, safety, operations, quick installation, etc. A significant cost advantage of mini-/modular-RABs is with their limited right-of-way requirement and require minimum to no cost in terms of right-of-way acquisition. Given below is a summary of cost information extracted from in-service mini-/modular-RABs. Note that these costs are specific to mini-RAB and time of installation and are not converted to an equivalent 2020 dollars value.

- range from minimum $10,000 to maximum $650,000; with average costs being approximately at $150,000.
- costs for modular RABs will vary based on the design specifications.

Besides the modular version, the materials that have most commonly been used in construction are a composition of asphalt, concrete, and other paving materials. To reduce costs, alternate materials and/or methods were also used; and are specific to location. For example, in Snohomish County, WA reduced construction cost using subgrade materials for the road and islands (Bloodgood, 2013). The practical implementations depict flexibility in design with regards to materials and methods.

The construction period for mini-RABs varies from one day (modular version) to less than a week for typical mini-RABs such as one in Jackson County, GA (Fanucci, 2020; NCHRP, 2016; Transportation Tracks, 2018). In addition, modular mini-RABs do not require closure of the entire construction zone during the construction period, since the materials are prefabricated and onsite installation activities can be finished within a day or two (Fanucci, 2020).

Overall, the cheaper installation and maintenance cost and overall operational and safety benefits give mini-RABs a very good value in terms of return on investment. A pilot study conducted in Dimondale, MI, found the benefit-to-cost ratio for mini-roundabouts to be 14.5:1 (Waddell, 2005).

2.4 Overall Advantages of Mini-Roundabouts.

In sections presented above, highlights of the advantages of mini-/modular RABs from a purely design perspective were presented – smaller footprint and can be installed within the current intersection geometry with minimum modification in a cost-effective manner. The subsequent sub-sections present findings from research and observational studies that highlight on advantages of mini-RABs from operational and safety viewpoints.

2.4.1. Operational Benefits.

Several research studies (Candappa, 2015; Zhang, 2013) and observations from practical implementations have investigated the operational improvements attained after implementation of mini-/modular-RABs in the US. Overall, this type of roundabout can have significant impacts on traffic flow, travel speed, traffic congestion, and the efficiency of intersection operations. More specifically, the operational improvements/impacts discussed in past studies include traffic operations (delay and congestion), traffic calming or reduction in speeding events, and environmental impacts including right-of-way considerations.

Traffic Operation Improvements (Delay and Congestion)

Mini-/modular-RABs transform normal stop-controlled intersections (three-/four-way) into yield control. The intersection capacity increases after the transformation to mini-/modular-RAB (Zhang, 2011). Due to the circular movement, there can be as many as four vehicles in the intersection at a time, much greater than a typical stop-controlled intersection configuration. Furthermore, the configuration of a mini-RAB reduces the prevalence of higher traffic flow from a single approach; consequently, this characteristic of mini-/modular-RABs reduces directional delay and improves traffic flow from minor streets at a two-way stop-controlled intersection (Dept. for Transport and County Surveyor Society, 2006). Delay and recurring queues on minor streets have been shown to be reduced (if not eliminated) after the placement of mini-/modular RABs (Zhang, 2013; Winiecki, 2017). Also, at locations with relatively high number of large/long trucks, the traversable island enables efficient movement with minimum to no delay to other vehicles (Dept. for Transport and County Surveyor Society, 2006).

A high-level concept engineering study using data from two intersections in Overland Park, KS depicted that placement of mini-RABs improved overall level-of-service (LOS), though at specific approaches LOS did not change but to a lesser extent (shorter queues) than the existing stop-controlled intersections (HNTB, 2017). A comparison between an all-way stop-control (AWSC) and a mini-RAB shows that, mini-RAB can handle greater than 200 pedestrians/cyclists with a LOS A (Winiecki, 2017).

Traffic Calming

An important purpose for installation of mini-/modular RABs is their ability to reduce speeding along a corridor. Given, a mini-/modular-RAB transforms the intersection geometry from a straight movement to a circular movement, drivers have to slow down to navigate as well as yield to oncoming vehicles. In comparison to a traditional RAB, the design of a mini-/modular-RAB causes slowing down of through moving vehicles but does not increase travel time significantly due to the smaller inscribed circular diameter (FHWA, 2010). Mini-/modular-RABs are best utilized for low-volume intersections usually in residential and/or rural areas where the potential for speeding is greater. A study from Australia showed a significant decrease in the average speeds – 20 to 14-mph (approx. 31 to 22-kph) – between control and treated sites (i.e., regular intersection vs. modular-RAB) (Candappa, 2015). Similarly, in the US, observations of the 85^{th} percentile speeds for approaching vehicles showed reductions ranging between 8 and 23-mph (Waddell, 2005; Stratmeyer and Banigan, 2013).

Environmental Benefits

With improved efficiency in operations (no delay and congestion) at an intersection converted to a mini-/modular-RAB there comes environmental benefits in the form of emissions reduction (Rice, 2010). Typically, when vehicles are stopped in approach queues waiting to enter a stop-controlled intersection, their idling (in the queue) increases vehicle emissions. The configuration of mini-/modular-RABs reduces queue lengths and decreases emissions (Waddell, 2005). Field observations at two intersections (converted to mini-RABs from AWSC) in Lake Stevens, WA; showed reductions of 0.024 gal/veh (fuel consumption), 0.022 g/veh (nitrogen oxide), 0.275 g/veh (carbon monoxide), and 210 g/veh (carbon dioxide) (Zhang, 2013). Moreover, the construction of mini-/modular-RABs is beneficial to the environment than a traditional roundabout; in that they can be constructed within an intersection with a relatively smaller need for additional right-of-way and the construction can be completed quickly with minimum impact on traffic movements during construction (Zhang, 2011).

2.4.2. Safety Benefits.

Several studies have examined the safety improvements associated with mini-/modular-RABs (e.g. Zhang, 2011; Russell, 2017). Moreover, field observations from field implementations have also demonstrated safety improvements. Overall, the mini-/modular-RAB configuration reduces travel speeds at an intersection and along a corridor which improves safety of drivers, cyclists, and pedestrians. More specifically there are reductions in frequency and severity of vehicle crashes, improvement in safety and mobility for vulnerable road users (pedestrians and cyclists) along a corridor, and an improvement in perceived safety by drivers/public.

Reduction in Crash Frequency and Severity

In essence, transforming a stop-controlled intersection (three/four-way) to a mini-RAB decreases the propensity for drivers to run a stop sign; due to the route disruption (i.e., from straight line to circular movement) and it also becomes difficult to speed through the intersection and as a result, decreases the likelihood of a severe crash. An evaluation performed in Germany found that mini-RABs were the safest option and had significantly reduced accident rates from 0.79 to 0.56 crashes/million vehicles. The researchers used accident cost rate as a measure of crash severity, where unsignalized and signalized intersections had cost rates at least double that of mini-RABs (Brilon, 2005). Furthermore, a pilot study in Australia found that, there was a 78.9% reduction in all crash types over a three-year time frame at intersections converted to mini-RABs. A marked reduction (6 to 0) in severe crashes was also observed at the studied intersection (Delbosc, 2017).

In the US, before-after observations performed at intersection locations that were converted from AWSC to mini-RABs show similar trends of reductions in crash frequency and injury severity. The New York State DOT reported a 50 to 70% reduction in crashes and injuries at mini-RABs – 39% reduction in all crashes; with 76% reduction in injury crashes and 89% reduction in fatal or incapacitating crashes (NYDOT, 2017). Other specific studies found in the literature and their findings include:

- Dimondale, MI – reduction average annual cost of crashes decreased by 3.9% (Waddell, 2005). Moreover, use of alcohol was cited as the primary cause of crashes after the mini-RAB was installed.
- Bel Air, MD – crashes reduced from 8 crashes with 3 reported injuries to 2 crashes with 1 reported minor injury (Zhang, 2013).
- King County, WA – crash reduction of 100% in 5 years since mini-RAB placement (HNTB, 2017). That is from nine crashes between 1998 and 2006 to zero crashes between 2006 and 2017 (Dovey, 2017).
- Harford County, MD – there are fewer crashes and chance of fatality reduced significantly (HNTB, 2017). Specifically, from eight reported crashes (3 injury and 1 fatal) between 2008 and 2011 to 8 reported (1 injury) between 2012 and 2016 (Stratmeyer and Banigan, 2017).

Pedestrian/Cyclist Safety and Mobility

Due to the high pedestrian and cyclist activity in many urban areas, it is recommended that the safe movement of these vulnerable users must be accounted for in the design of mini-modular-RABs. Most mini-RABs are constructed with a "splitter island" which is used to channelize traffic in the correct direction around the central island. This splitter island also serves as a pedestrian "refuge island" which significantly increases both pedestrians' safety and their overall comfortability in crossing the street (FHWA, 2010). For example, in Scott County, MI; a mini-RAB was installed near a school to improve pedestrian mobility and safety for children walking to school. Fewer conflicts between pedestrians and vehicles at the intersection were observed after the installation (Russell, 2017).

Several studies documented the increased safety benefits of a mini-/modular-RABs for cyclists. One study found that cyclist safety was improved, especially due to the slower vehicle speeds enforced and caused by the reconfiguration of the intersection (Sawers, 2009). Furthermore, a study done in Denmark looked at the specific designs of all mini-RABs and their effect on cyclist mobility and safety. The most significant design feature that the researchers found effected cyclist safety was the height of the central island – higher the central island, the safer the cyclist would be (Jensen, 2017). While mini-RABs are designed to have a traversable central island, a cyclist-friendly design would make the central island high enough to prevent passenger vehicles from traversing, still allowing trucks to utilize the traversable island.

Driver/Public Complaints and Comfortability

A major hindrance to safety at all roundabouts is the public's perception/attitude toward these types of intersection. A driver's comfort while traversing a roundabout is paramount in ensuring they safely travel through the corridor ensuring safety of themselves and others. The operational rule of mini/modular roundabouts is relatively easy to learn and easy to navigate, due to the low traffic volume, and low traffic speed. A general trend that one researcher found about driver's perception of any kind of roundabout was that younger drivers were more capable and understood roundabouts quicker than their older counterparts (Toussant, 2016). Therefore, as the population grows older and the implementation of more mini-RABs increases, then the anxiety and unfamiliarity felt from drivers about roundabouts will decrease. A study on the effects before and after the installation of two mini-roundabouts in Australia found that after implementation, risky driver behavior decreased, and compliant behavior increased. The researchers found higher compliance in stopping and yielding at the intersections after implementation (Delbosc, 2017). Moreover, drivers were able to safely and legally make a U-turn at mini-/modular-RABs. An "invitation to comment" page on Facebook about the addition of a new roundabout in Newark, OH reported that while residents were hesitant at first, after driving through the roundabout, they became more comfortable and appreciated the facility more (Mallett, 2017).

2.5 Estimating Capacity of Mini-RABs.

In the UK, the Transport Research Laboratory developed an empirical based model to analyze the capacity of mini-RABs (Cicu et al., 2011). Lochrane et al. (2013) conducted research work to develop design recommendations and capacity models for mini-RABs using data from the US. Using a simulation approach (in VISSIM) and real data from a mini-RAB located in Stevensville, MD; capacity models for an ICD of 50 and 75-feet were developed. Furthermore, estimates of mini-RAB capacity were compared to that of an AWSC intersection and a single-lane modern RAB. The results of this comparison indicate that capacity for a mini-RAB is higher than that of an AWSC intersection, but lower than that of a single-lane modern RAB (Lochrane et al., 2013). Also, the entry capacity per area for each mini-RAB studied was larger than that of the single lane RAB – suggesting the area is more efficiently used in mini-RABs based on the demand of the entering capacity (Lochrane et al., 2013). Overall, this study concluded that in order to increase capacity and optimize existing land in urban areas, mini-RABs can be a very useful design.

APPENDIX D

Survey of Practitioners

Task 3

TASK 3: SURVEY of PRACTITIONERS.

1. INTRODUCTION

The purpose of Task 3 was to administer an online survey to practitioners and local transportation professionals; with the goals of investigating their current practices (if any) pertaining to mini-/modular RABs, and identifying the relative importance of factors that relate to the installation of mini/modular-RABs.

1.1 Survey Methodology.

To the knowledge of the authors, there are no existing studies that synthesize the experiences and perceptions of practicing engineers in implementing mini-/modular-RABs. A survey questionnaire (included at end of Appendix D) was developed to collect data on practicing traffic engineers' knowledge of the design, operation, safety, and maintenance aspects of mini-/modular-RABs. The questionnaire was developed using the Qualtrics survey platform, and was administered online between December 2019 and January 2020. A link to the survey was distributed via email courtesy of the Ohio LTAP to potential respondents in Ohio and other states in the US. The potential respondents included engineers/professionals involved with roundabouts such as state DoT traffic engineers, county engineers, private sector consultants, and city engineers.

In addition to respondent demographic information, the survey collected data on information including (but not limited to):

- prior knowledge of traditional-/mini-/modular-RABs;
- reason your agency would install a mini-/modular-RAB;
- observed results (if any) after a mini-RAB was installed;
- where a mini-/modular-RAB should be placed, and if there are any limitations to this type of intersection; and
- any design guidelines that were followed, cost, and materials used in the construction of mini-RABs in their specific jurisdictions.

Questions were designed to prompt responses about mini-/modular-RABs that are already constructed and/or being planned to be constructed in jurisdiction of the respondent. The research team addressed mutual exclusiveness through the number of allowable answers in the questions. Therefore, when questions were not mutually exclusive, respondents could select all answers that applied to a question; whereas when questions have mutually exclusive answers, only one answer was allowed. Questions needing in-depth responses (e.g., safety observations, RAB location, RAB limitations, etc.) were created as open-ended, allowing respondents to provide their personalized responses (Fries, 2012).

In order to obtain a relatively high response rate, reminders were sent out to potential respondents. Additionally, to increase the number of completed surveys and the validity of responses, the survey logic advanced each respondent to the next appropriate question. This tool helps decrease the time needed to complete a survey; and is likely to lead to an increased number of responses (Fries, 2012). A mobile version of the survey was also created through Qualtrics; allowing respondents to complete the survey using a mobile device (tablet, cell phone, etc.) and subsequently leading to an increased number of responses. Follow-up phone interviews were conducted with multiple survey participants to complement their response in the online survey.

2. SURVEY RESULTS

2.1 Demographics

A total of 92 responses were received from participants across the US, but especially in Ohio. Many of the responding engineers were familiar with RABs and reported that they have at least one in their jurisdiction. Figure 3.1 shows a map of US states; with the green colored states indicating locations from which survey responses were received. Almost half (N=52) of the respondents were from Ohio and at least one agency responded from Florida, Illinois, Indiana, Kentucky, Pennsylvania, Utah, Washington, District of Columbia, West Virginia, Michigan, and North Carolina. Approximately 27% (N=25) respondents did not provide information on their agency's identity/location.

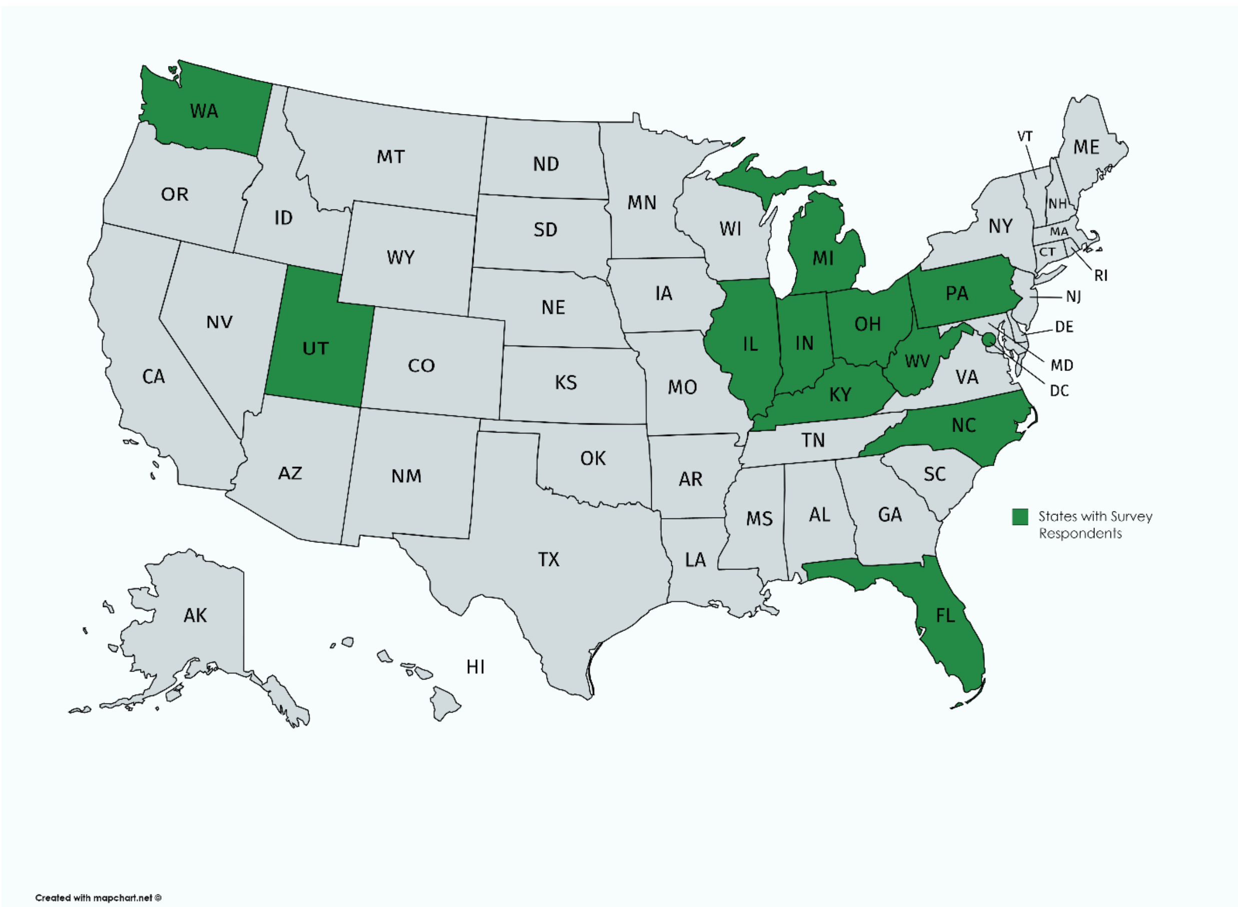

Figure 3.1. Map of US states that responded to the survey (Respondents states in Green).

In terms of working experience, 84% (N=77) of respondents inferred to having worked as a transportation/traffic engineer for more than 10 years. Table 3.1 presents details on distribution of respondents and their work experience. Approximately 91% (N=84) of respondents reported to being *somewhat* to *very familiar* with mini-/modular-RABs. Table 3.2 presents a detailed distribution of respondents and their familiarity with mini-/modular-RABs. From the respondent demographics, it can be observed that many of the respondents were very experienced and informed about mini-/modular-RABs.

Table 3.1. Composition of Survey Participants Experience as an Engineer.

Years of experience as a practicing transportation/traffic engineer	Reponses from outside the state of Ohio	Responses from within the state of Ohio	Total
1-3 Years	0 (0%)	4 (7.69%)	4 (4.30%)
4-8 Years	6 (15%)	5 (9.62%)	11 (12.0%)
9-15 Years	13 (32.5%)	9 (17.31%)	22 (23.9%)
15+ Years	21 (52.5%)	34 (65.38%)	55 (59.8%)
Total	40 (100%)	52 (100%)	92 (100%)

Table 3.2. Familiarity with Mini-/Modular-Roundabouts.

Familiarity with the mini/modular roundabouts	Reponses from outside the state of Ohio	Responses from within the state of Ohio	Total
Not Familiar	3 (7.5%	5 (9.62%)	8 (8.70%)
Somewhat Familiar	22 (55%)	35 (67.31%)	57 (62.0%)
Very Familiar	15 (37.5%)	12 (23.08%)	27 (29.3%)
Total	40 (100%)	52 (100%)	92 (100%)

The type of RABs that have being installed by survey participants' agencies are shown in Table 3.3. Thirty-two agencies reported having at least one mini-RAB in their jurisdiction. Several agencies have installed mini-RABs as an alternative to traffic signals in situations where a traffic signal was no longer warranted. One agency installed a mini-RAB as an alternative to a 5-way signalized intersection.

Table 3.3. Type of Roundabouts in the Agencies.

Roundabout Type	Outside the state of Ohio	Within the state of Ohio
Traditional	14 (41.2%)	28 (70%)
Mini	0 (0.0%)	4 (10%)
Both	20 (58.8%)	8 (20%)
Total	34 (100%)	40 (100%)

Figure 3.2 illustrates the average score (on a scale of 1-5, 1 meaning least important and 5 meaning most important) of different factors/criteria considered by agencies for the installation of a mini-RAB. Factors related to safety are of higher priority over all other factors for most agencies. Of the least important factors (i.e., average scores less than 2.5) were factors such as the duration of construction, aesthetics, and public reactions/complaints.

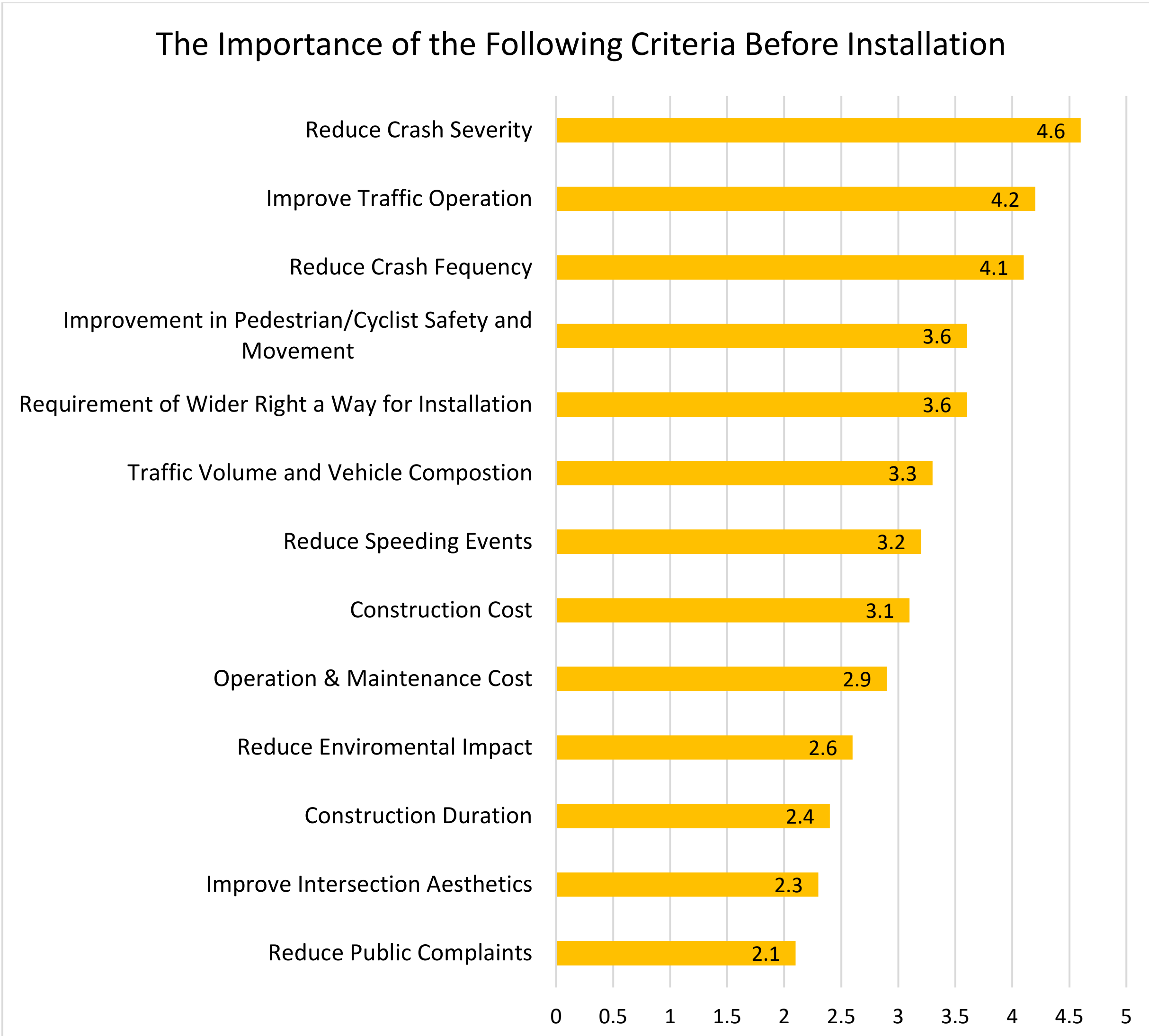

Figure 3.2. Importance ranking of factors/criteria for mini-roundabout installation.

Table 3.4 summarizes the relative importance of safety and operational improvements based on agencies' consideration in the installation of mini-/modular-RABs. Approximately 56% of respondents reported safety improvements as being the most important when considering the installation of mini-/modular-RABs, whereas 44% of respondents reported operational improvements as being an important consideration. Additionally, nearly every agency that responded with safety improvements trumping operational improvements justified their answers by the need to improve the public welfare, by installing safe facilities that reduce both crash frequency and severity. These agencies felt that operational improvements are a positive effect of the safety improvements. However, those who listed the operational improvement as more important justified their response by stating the operational improvements will be more recognizable to the public.

Table 3.4. Priority of Safety and Operational Improvements.

Split	Percent Average (%)	Percent Median (%)	Percent Range (%)	Standard Deviation
Safety Improvement	55.7	55	30-100	16.9
Operational Improvement	44.3	45	0-70	16.9

Table 3.5 lists common rationale that agencies use to justify adoption of a mini-RAB in terms of safety considerations. Each rationale was ranked on a scale of 1 to 4 (1 being the most important, and 4 being the least). Reducing crash severity was the most important safety improvement that agencies considered when installing a mini-RAB. Speeding and reducing crash frequency were very equally ranked in terms of their safety importance considerations. This finding indicates that agencies are most concerned with limiting the severity of crashes (reducing the number of people who are seriously injured and/or killed); which is consistent with the mini-/modular-RAB installation priority criteria presented in Figure 2.

Table 3.5. Prompts for Safety Improvements.

Safety Improvements Prompts	Average Rank	Median Rank
Reduce Crash Severity	1.2	1
Speeding	2.7	3
Reduce Crash Frequency	2.8	2
Better Pedestrian/Cyclist Facilities	3.6	4

Mini-RABs are also used as a traffic calming device by reducing traffic speed through an intersection, but at the same time they keep traffic moving, leading to a reduction in queues and increased traffic flow (Rice, 2010). Survey respondents ranked speeding as the second most important safety consideration when improving an intersection (as seen in Table 5).

In areas where mini-RABs were installed to improve the safety of an intersection, survey respondents stated that they found that overall safety had improved – reduction in crash frequency and severity. The crash modification factors (CMF) varied by location, but a negative trend was reported at every location. One agency reported that, over a period of 13 years, there was a 100% reduction in crashes at two locations. Additionally, an Ohio-based agency reported a 44% reduction in all crashes, with a 100% reduction in crashes that resulted in an injury and pedestrian and cyclist crashes. However, agencies did find an increase of crashes in the short term (in first few years), most likely due to the adjustment drivers needed to make when encountering a new traffic control device (in this case a mini-RAB).

Despite the safety improvement, survey respondents did mention having some concerns with mini-RABs. Firstly, due to the small and seemingly traversable central island, respondents identified the concern of drivers neglecting the central island and driving straight through. If drivers began to exhibit this behavior, the RAB may lose its integrity. Also, respondents have concerns with driver unfamiliarity of navigating a traditional-/mini-/modular-RAB. Secondly, respondents also stated the concern of maintaining the roadway at a Mini-RAB during inclement weather operations (snow plowing). For example, one agency was concerned with the maintenance and usefulness of the RAB in winter after a snowfall, when pavement markings may not be visible. Similar issues may occur while it is raining, especially at night.

2.2. Potential Locations for Installation of Mini-/Modular-Roundabouts.

In general, the survey results indicated that transportation agencies considered factors such as current intersection geometry, traffic flow patterns, availability of right of way, low speeds, and low traffic volumes to determine the suitability of an intersection for installation of a mini-/modular-RAB. Intersections with high crash severity are considered as priority for mini-RAB installation by most agencies. This high importance for reducing crashes was also evident earlier (see Figure 2), as reducing crash severity and frequency are ranked the first and third most important issues when installing a mini-RAB. If a mini-RAB improves intersection safety and is cost-effective; agencies can consider this as an alternative to a stop controlled or signalized intersection. One city engineer from Ohio felt that the efficiency and safety advantages given by a RAB make them a superior traffic facility and would prefer installing more roundabouts in future.

Agencies have also considered a mini-RAB at locations with poor traffic operations. As shown in Figure 3.2, improving traffic operations is the second most important consideration when installing a mini-RAB. A Mississippi State DOT study reported that, at a RAB they had installed, they witnessed reduced delay (up to 24%) and increased the overall Level of Service from an "E" to "D" (Uddin, 2011). This intersection also experienced an average speed increase of 6 mph (from 9 mph to 15 mph) during the peak hour.

Consistent with the literature, mini-RABs are also installed as an alternative to larger traditional RABs when there are right-of-way (ROW) concerns. Respondents ranked ROW as the fifth most important factor when installing mini-RABs in their jurisdictions (Figure 3.2). Based on survey responses, a diameter of 45 to 90-feet is used, to fit a mini-RAB in many already built intersections. Agencies typically place mini-RABs on two lane highways, where traditional RABs are deemed large and expensive.

Agencies consider highways with low volumes of traffic as suitable candidates for a mini-RAB; and peak-hour volumes between 1,600 and 1,800 vehicles were provided. Whereas, FHWA guidelines recommend mini-RABs for intersections where total entering daily traffic volumes are no more than 15,000 vehicles, agencies did report adopting mini-RABs at locations that handle AADT of higher amounts (i.e., approx. 15,000 to 18,000 vpd). One North Carolina based agency stated that "their mini-RABs will be able to handle traffic growth over the next 10 years," which is expected to be around 25,000 AADT. Survey responses also suggest mini-RABs are commonly constructed on roadways with low speeds, typically less than 35mph. Other locations that are eligible for a mini-RAB are roadway intersections with unevenly balanced directional volumes (i.e., one direction not stopping); leading to a queue of cars due to queue front vehicle attempting to turn left.

Agencies also use cost comparisons when determining potential location of mini-RABs. Agencies reported the cost of mini-RABs ranging from $150,000 to $3,000,000. This cost range is dependent on specific area/location considerations. Urban mini-RABs tend to cost more because agencies are more concerned with aesthetic upgrades in the vicinity of the mini-RAB. Acquiring ROW and utility relocation add to the cost of installation. However, most projects cost less than $1,000,000. This is compared to the $ 1,082,736 cost of a traffic signal installation (City of Rochester, 2015).

2.3. Pedestrian and Bicycle Safety with Mini-Roundabouts.

Respondents inferred to making considerations for the safety of pedestrians and bicyclists when finalizing a mini-RAB design. Specific things that were mentioned include:

- Providing adequate sight distance – allows vehicles to see vulnerable road users (VRUs) easily, and with the associated lower speeds; pedestrians felt much safer navigating mini-RABs.
- There is a positive relationship between vehicles and VRUs when it comes to mini-RABs – the slower vehicle speeds improved VRU comfort in the intersection.
- It was recommended that pedestrians still be considered in any potential mini-RAB design at locations with no existing sidewalks. For example, in North Carolina a mini-RAB was designed with future sidewalks in mind – thus, any future VRU needs can be accommodated by simple retrofitting sidewalks with minimal costs; and the central island can act as a pedestrian refuge area.
- A "best" practice for maximizing pedestrian safety is to install raised crosswalks which allow greater visibility of pedestrians crossing at the approaches, and it acts as a speed hump for vehicles, further slowing them down. However, a downside is that snowplows may have difficulty clearing the raised cross walks.
- Based on experience at locations with some cyclist activity (in North Carolina), the use of mini-RABs eliminates crashes involving vehicles and cyclists. However, there is need to address concerns of vehicles not yielding appropriately to cyclists. It was recommended that signage, markings, and education on mini-RABs all be included in the design of mini-RABs.

2.4. Public Perception of Mini-Roundabouts.

Respondents acknowledged to performing field observations after the installation of mini-RABs; primarily to assess functionality of the facility and to collect public opinions. Overall, there was mention of negative public perceptions prior to construction of mini-RABs. However, after construction and use, the public opinions were mostly positive. Some complaint's that agencies mentioned receiving included mini-RABs would slow down traffic and that the facility was too small. Moreover, large vehicle (buses and trucks) operators complained that turning maneuvers became more difficult after the installation of the mini-RAB.

Engineers felt there was a need among the public to see the "positive side" of mini-RABs so there could be more installations of this type of intersection control in future. Suggestions of public education campaigns, driver training, and media broadcasts were presented. As an example, a North Carolina based respondent reported of conducting several forums/classes for local school bus, garbage truck, and other city vehicle drivers informing them of a mini-RAB – resulting in positive feedback on classes and heavy vehicle operators felt comfortable maneuvering around the mini-RAB after the classes.

2.5. The Use of Modular Roundabouts.

Modular-RABs have found a niche in the transportation intersection landscape. Their portability and ease of setting up are advantageous for temporary traffic control during events such as natural disasters, concerts, football games etc. As an example, one responding agency reported of deploying modular-RABs at intersections that were signalized prior to a hurricane in the area. The agency used traffic cones over spray-painted spots on the asphalt, to create a circle within intersections that experienced loss of electric power. Temporary signage was installed to signal yielding, turning maneuvers, and lane usage. Additionally, a police vehicle (with lights flashing) was stationed in the center of the modular-RAB to maintain safe operations. The agency has received positive feedback on their design and have been asked by several other agencies across the US for their detailed plans on the modular-RAB.

Additionally, the same agency also reported using a temporary modular-RAB at a site where a traffic signal was to be installed, but due to the 2020 Covid-19 pandemic and a shipping conflict, the signals took several months to arrive. The same principles were used here, as in the disaster scenario. Traffic was forced into one lane, and temporary signage as well as cones were used to control traffic. Due to the Covid-19 related travel restrictions, traffic volumes were lower than usual. No incidents were reported, and anecdotally, the intersection was serviceable until the signal was installed.

2.6. Design Guidelines for a Mini Roundabout.

In designing a mini-RAB, most respondents reported of adopting the guidelines presented in NCHRP Report 672. These NCHRP 672 guidelines are discussed in detail in the literature review portion of this report. Agencies also mentioned consulting their local state guidelines and standards.

Agencies mainly used three different types of construction materials when constructing mini-RABs – asphalt, brick, and concrete. The circulating roadway is built to the same standards as any other road. Nearly all agencies use asphalt on the roadways and the central islands is built using brick, concrete, or both. A few agencies used brick for aesthetic reasons, while others used concrete for its lower cost. Crosswalks were constructed using brick or paint. These decisions varied from agency to agency.

SURVEY QUESTIONNAIRE

Project Title: Intersection Modifications Using Modular and Mini-roundabout Methods
Funded by the Ohio Department of Transportation for the ORIL (Ohio's Research Initiative for Locals) Program

Dear Transportation Engineering Professional,

This letter is a request for you to take part in a research project titled “Intersection Modifications Using Modular and Mini-Roundabout” **funded by the Ohio Department of Transportation for the ORIL (Ohio's Research Initiative for Locals) program** in aims to understand and also evaluate best practices in the use of mini and/or modular roundabouts. This study involves a survey that will allow transportation professionals (engineers/practitioners/researchers) to share their insights on the design and use of roundabouts as options for intersection modifications. Dr. Kakan Dey, in the Department of Civil and Environmental Engineering at West Virginia University, and Dr. Bhaven Naik, in the Department of Civil Engineering at Ohio University, are responsible for conducting this project.

If you agree to participate in this survey, you will be asked about your insights/experiences as a transportation engineering professional regarding roundabouts. The expected time to respond to this survey is 15-20 minutes. **You are not eligible to participate in this study if you are under 18 years, or a transportation engineer with no knowledge/experience in designing/maintaining roundabouts.** Your responses to this survey are completely voluntary and will be kept as confidential as legally possible. All data will be reported in the aggregate. You will not be asked any questions that could lead back to your identity as a participant. You may skip any question that you do not wish to answer, and you may discontinue participation at any time. West Virginia University's Institutional Review Board (IRB) acknowledgment or approval of this project is on file. You can provide your email address and phone number if you are willing to participate in a follow-up phone interview for additional information.

If you have any questions about this research project, please feel free to contact: Kakan Dey – West Virginia University. Phone: (304) 293-9952, email: kakan.dey@mail.wvu.edu. Bhaven Naik – Ohio University. Phone: (740) 593-4151, email: naik@ohio.edu. If you have any questions about your rights as a research participant, please contact the WVU Office of Human Research Protection by phone at (304) 293-7073 or by email at IRB@mail.wvu.edu.

We hope that you will participate in this online survey, as it could help us better understand and assist in developing guidelines for the design, construction, and maintenance of mini/modular roundabouts. Your insights and experiences will help researchers of this project in developing standards for the design and implementation of mini/modular roundabouts.

Thank you for your time and consideration.

Sincerely,

Kakan Dey, PhD, PE - Assistant Professor, West Virginia University.

Bhaven Naik, PhD, PE, PTOE, RSP - Assistant Professor, Ohio University.

WVU IRB protocol number: 1911776115

- ○ Yes, I have read the cover letter and I agree to participate in this survey.
- ○ No, I do not agree to participate in this survey.

Skip To: End of Survey If = No, I do not agree to participate in this survey.

According to a Federal Highway Administration Report: A mini/modular roundabout is a form of a traditional roundabout with a smaller inscribed circle diameter ranging from 45-90 feet, having a central island that in most cases is traversable by large vehicles. The difference between mini and modular roundabouts is that mini-roundabouts are permanent facilities while modular roundabouts are temporarily constructed with temporary materials.

Figure 1: Mini Roundabout

Figure 2: Modular Roundabout

Q1 **Which city/state/county transportation agency in the United States do you work?**

____

Q2 **How many years of experience do you have as a transportation/traffic engineer?**

- ◯ Less than a year
- ◯ 1-3 years
- ◯ 4-8 years
- ◯ 9-15 years
- ◯ More than 15 years

Q3 **Are you familiar with the mini/modular roundabouts?**

- ◯ Not familiar
- ◯ Somewhat familiar
- ◯ Very familiar

Q4 **Does your agency use/adopt roundabouts in your transportation system?**

- ◯ Yes
- ◯ No

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = Yes

Q5 **What type of roundabout(s) does your agency adopt? (*select all that apply*)**

☐ **Traditional roundabouts:** A circular intersection with entry yield control and non-traversable center island.

☐ **Mini roundabout:** A smaller version of a traditional roundabout with an inscribed diameter between 45 and 90 feet as well as a traversable center island

☐ **Modular roundabout**: A temporary version of a mini roundabout implemented by installing temporary facilities on an existing intersection geometry.

Display This Question:
If What type of roundabout(s) does your agency adopt? (select all that apply) = Mini roundabout: A smaller version of a traditional roundabout with an inscribed diameter between 45 and 90 feet as well as a traversable center island
Or What type of roundabout(s) does your agency adopt? (select all that apply) = Modular roundabout: A temporary version of a mini roundabout implemented by installing temporary facilities on an existing intersection geometry.

Q6 **When was the first mini/modular installed in your jurisdiction? (e.g., Year 1990)**

____

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = Yes

Q7 How many **traditional/mini/modular roundabouts** has your agency installed as of December 2019?

○ Traditional roundabouts ____

○ Mini roundabouts ____

○ Modular roundabouts ____

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = Yes

Q8 **What criteria are used by your jurisdiction to determine the installation of roundabouts? (*select all that apply*)**

- ☐ Improvement in Traffic Flow
- ☐ Improvement in Safety
- ☐ Reduction in Frequency of Crashes
- ☐ Reduction in Severity of Crashes
- ☐ Reduction in Driver Speeds
- ☐ Reduction in Driver Complaints
- ☐ Reduction in Construction Costs
- ☐ Reduction in Operations and Maintenance (O&M) Costs
- ☐ Others, please explain____
- ☐ Not Applicable

Q7 **Is there any plan for mini/modular roundabouts in your jurisdiction in the future? Please briefly explain.**

- ○ Yes
- ○ No

Please briefly explain

____

Display This Question:

If Does your agency use/adopt roundabouts in your transportation system? = No

And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Or If

Does your agency use/adopt roundabouts in your transportation system? = Yes

And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q8 On a scale of 1-5 **(1 meaning least important and 5 meaning most important)**, score the following criteria/factors in terms of the level of importance that you would consider before implementing a **mini/modular roundabout**. Then provide a brief justification for your scoring.

	1	2	3	4	5
Improvement in Traffic Operation (e.g. reduce travel/intersection delay)	○	○	○	○	○
Reduction in Crash Frequency	○	○	○	○	○
Reduction in Crash Severity	○	○	○	○	○
Reduction in Speeding Events	○	○	○	○	○
Reduction in Driver/Public Complaints (i.e., unfamiliarity with driving through a mini/modular roundabout)	○	○	○	○	○
Construction Cost	○	○	○	○	○
Operations and Maintenance Cost (O&M)	○	○	○	○	○
Construction Period/Duration	○	○	○	○	○
Reduction in environmental impacts	○	○	○	○	○
Requirement of Wider Right of Way for installation	○	○	○	○	○
Traffic Volumes and Vehicle Composition (%trucks, %cars)	○	○	○	○	○
Improvement in Pedestrian/Cyclist Safety and Movement	○	○	○	○	○
Improvement in Intersection Aesthetics	○	○	○	○	○

Please provide a brief justification for your scoring:

____

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = No
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q9 **What would you consider to be the split in importance (operational improvements vs. safety improvements) for the adoption of a mini/modular roundabout?** For example: Equal importance (50%-50%); or mainly Operational improvements (~10%-90%); or mainly Safety improvements (~90%-10%). Please slide the dot to the left or right to adjust the value.

_______ Safety Improvements (1)
_______ Operational Improvements (2)

Please provide a brief justification for the split:

____

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = No
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q10 **In terms of Operational Improvements, what factors would prompt you to install a mini/modular roundabout in your jurisdiction?** Rank the criteria/factors listed below according to their importance by dragging each item up/down (most important at top!).

______ Reduce Congestion
______ Improve Efficiency of Intersection
______ Improve Pedestrian/Bicyclist Mobility throughout the corridor
______ Other (please briefly explain):

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = No
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q11 **In terms of Safety Improvements, what factors would prompt you to install a mini/modular roundabout in your jurisdiction?** Rank the criteria/factors listed below according to their importance by dragging each item up/down (most important at top!).

______ Crash Frequency Reduction
______ Crash Severity Reduction
______ Speeding (act as Traffic Calming)
______ Better Pedestrian/Cyclist Facilities
______ Other (please briefly explain):

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q12 **In what intersection geometry and traffic condition do you consider the implementation of mini/modular roundabout over a traditional roundabout?** (e.g., limited right of way availability, used a temporary traffic control at an intersection)

____

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q13 **What were the driver/public feedback after implementation of mini/modular roundabout?**

____

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q14 **What were the observed operational impacts of the mini/modular roundabout?** (e.g., reduced delay by 20%, reduce queue length on certain approaches)

____

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q15 **What were the observed safety impacts of mini/modular roundabout?** (e.g., reduced crash frequency of 20%)

____

Display This Question:

If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q16 **How were the operational and safety impacts of mini/modular roundabouts measured?** (e.g., field data collection/observation, simulation)

____

Display This Question:

If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No
Or If
Does your agency use/adopt roundabouts in your transportation system? = No
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q17 **In your opinion, do you think mini/modular roundabouts can be utilized to improve safety and operations improvements at low volume intersections?**

◯ Yes

◯ No

Please briefly explain your answer to the previous question

____

Display This Question:

If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes
Or If
Does your agency use/adopt roundabouts in your transportation system? = No
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No

Q18 **In your opinion, what type of roadways are suitable for a mini/modular roundabout? (*Select all the apply*)**

▢ Low volume 2-lane rural (one lane each direction)

▢ Low volume 2 lane urban (one lane each direction)

▢ Low volume 3-lane rural (one lane each direction and one two-way left-turn lane)

▢ Low volume 3-lane urban (one lane each direction and one two-two way left-turn lane)

▢ Low volume roads with speed limit < 35 mph

▢ Low volume roads with speed limit > 35 mph

▢ Other(s) (Please explain): ____

Display This Question:

If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes
Or If
Does your agency use/adopt roundabouts in your transportation system? = No
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No

Q19 **What are the limitations of mini/modular roundabouts from your perspective?** (e.g., requires wider right-of-way, costly, unfamiliarity with driving through a mini/modular roundabout)

____

Display This Question:

If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q20 **What specific design guidelines/reports are followed in the design of mini/modular roundabouts in your jurisdiction?**

____

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q21 **Based on your experience, what is the typical *construction cost* of a mini/modular roundabout? Please explain which factors affect the construction cost.**

Mini Roundabout:____

Modular Roundabout:____

Display This Question:
If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q22 **Based on your experience, what is the typical *operations and maintenance (O&M) cost* of a mini/modular roundabout? Please explain which factors affect the O&M cost.**

Mini Roundabout:____

Modular Roundabout:____

Display This Question:

If Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = No
Or If
Does your agency use/adopt roundabouts in your transportation system? = Yes
And Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q23 **Based on your experience, what types of *materials* are used for mini/modular roundabout construction?**

Mini roundabout:____

Modular Roundabout:____

Display This Question:

If Does your agency use/adopt roundabouts in your transportation system? = Yes
Or Is there any plan for mini/modular roundabouts in your jurisdiction in the future? = Yes

Q24 Please provide your contact information if you are willing to share any available data/studies and/or additional information that you may have regarding mini/modular roundabouts. Please also specify the type of data you are willing to share.

Name:____

Email:____

Phone #____

APPENDIX E

Human Factors Assessment

Task 4

TASK 4: HUMAN FACTORS (or DRIVER EXPERIENCE) ASSESSMENT.

1. INTRODUCTION

The purpose of this task was to explicitly investigate the experience(s) of the driver with respect to navigating a mini-/modular-RAB. The goal was to understand any correlations that may exist between driver performances with mini-/modular-RAB navigation in terms of different mini-/modular-RAB design configurations.

1.1. Methodology.

In an effort to investigate driver behaviors as they navigate through RABs, a set of driving simulator scenarios were developed whereas drivers would encounter various mini/modular RAB geometric design configurations. This portion of the overall study was performed (IRB protocol # 19-X-166) using a level 3 driving simulator that is available in the Safety & Human Factors facility at Ohio University. Driving participants (both male and female) from different age groups were recruited and asked to drive through the simulator scenarios. As each participant drove a simulation scenario, their data (e.g. gap acceptance, speed, braking, etc.) was collected. This collected data was compared among mini-RAB designs (ICDs of 45, 60, 75, and 90-feet) and also a single-lane roundabout (120-ft ICD); to determine optimal design parameters for mini-RAB design. Specifically, driver's navigability differences (performance) in terms of their critical gaps and speeds (approach, circulatory, and exit) were compared. Additionally, a pre- and post-driving survey was administered; and participants responses to the questionnaire were analyzed to gauge understanding of perceptions/acceptance of mini-RABs.

1.2. Driving Simulator and Simulation Environment.

1.2.1. Driving simulator

The driving simulator, manufactured by DriveSafety, is a regular width Ford Focus car, which was recovered from a traffic crash. The car is equipped with all the realistic features of an actual vehicle including steering wheel, blinkers, gear shift, accelerator and brake pedal; and rear-view and side mirrors. The simulator's Q-Motion platform provides real time motion simulation – a unique feature which makes the car shift forward when the driver presses the brake pedal and backward when the driver presses the accelerator. This also helps the car to shift in response to roadway curbs, sidewalk, grade and other roadway elements. The simulator also consists of three 9-foot-wide display screens which are used to display the traffic scenes within the virtual environment. A speaker is located behind the gearshift to provide the sound of the car engine and the surrounding vehicles in the simulation. Figure 4.1 and 4.2 show the exterior features of the driving simulator. In addition, an Infrared Eyetracker (FaceLab 5) is located on the top of the vehicle dashboard. The eyetracker gets a participant's pupil diameter, pupil coordinates, gaze, saccades, blinking, head position using the infrared cameras.

1.2.2. Institutional Review Board approval

Any research involving human subjects requires the Institutional Review Board (IRB) approval – to ensure that the research will be conducted at a risk-free environment and the personal privacy of the human subjects will be protected. Moreover, an informed consent has to be obtained from each participant before starting any experiment according to the IRB. For this portion of the project, IRB approval was given under protocol 19-X-166 (refer to end of Appendix E).

Figure 4.1. Simulator car exterior features.

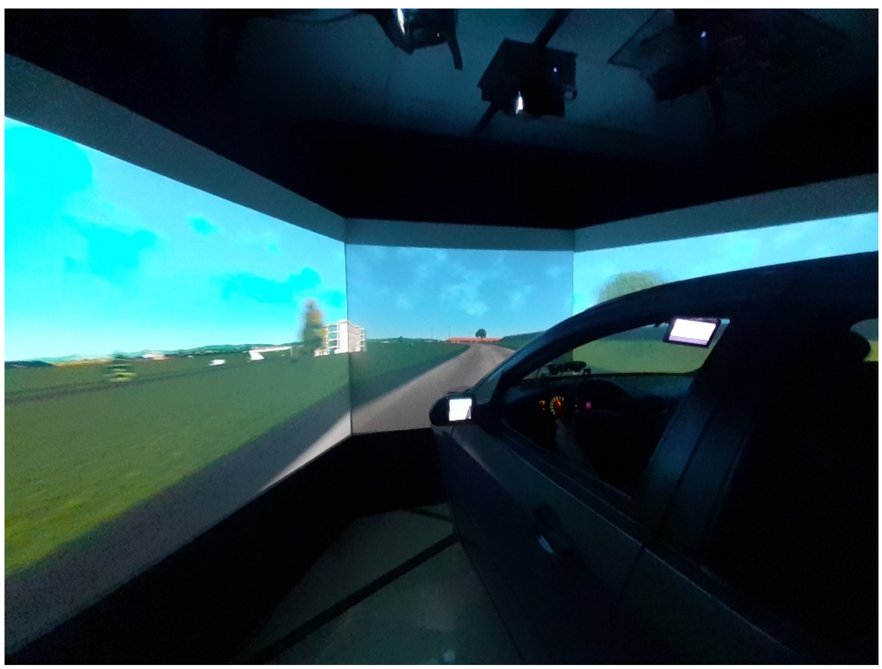

Figure 4.2. Simulator car (while running simulation).

1.2.3. Participant recruitment

In order to participate in the driving simulator experiment, a volunteer driver was required to be 18 years and older, have a valid US driver's license, and have driving experience no less than two years. The overall plan, based on a suitable power for statistical analyses, was to recruit 32 to 52 participants. A total of 51 participants finally drove in this simulation study.

Participants were categorized into three age groups: 18-25 years (N=25), 26-40 years (N=21), and 41-65 years (N=5). Note, there was a lack in participants from the 41-65+ age group – due in part to the location of the simulator (Ohio University campus) and the higher risk of demonstrating motion sickness among individuals in the 41-65+ year age group. Additionally, 78% (N=40) of participants were male and the remaining 22% (N=11) were female. The uneven gender-based distribution is due to the increased percentage of male students, faculty and staff within the engineering department than the female students.

1.2.4. Driving scenarios

To evaluate the performance of each participant as he/she navigated through different mini-RABs, a route that consisted of four mini-RABs (ICD = 45, 60, 75, and 90-ft) and also a single-lane RAB (ICD = 120-ft) was developed. This route was fine-tuned into four unique scenarios with each scenario running approximately 13-15 minutes long, depending on a participant's driving speed. The significant differences between the four scenarios were driving conditions (day or night), and the presence/absence of pedestrian/bicyclist crossings at entry to the mini-RABs.

Table 4.1. Simulation Scenarios Features.

Scenario	Driving Condition	Presence of Pedestrian/Bicyclist Crossing at Mini-RAB
1	Day-time	No
2	Night-time	No
3	Day-time	Yes
4	Night-time	Yes

Each participant was asked to drive two (of the four) randomly selected scenarios and his/her driving data such as speed, brake force, gap acceptance, and acceleration were recorded. Additionally, a five-minute-long warm-up scenario was also designed to allow each participant to get adapted to the simulation environment. This warm-up scenario was provided at the start of the experiment and before the actual scenarios from which data were collected. Therefore, if a participant successfully completed the warm-up scenario, was comfortable to continue the driving, and agreed to proceed; the main scenarios were given.

1.2.5. Pre-/Post-simulation survey

To understand driver's familiarity, comfort with, and preference for traditional RABs and/or mini-RABs, a questionnaire consisting of two major parts (pre- and post-test); with a combined total of 16 questions was administered to each participant.

Pre-test questionnaire – was completed by each participant prior to driving the simulator. Participants responded to a total of nine questions that assisted in determining (i) level of general knowledge with respect to RABs, (ii) familiarity with mini-RABs, and (iii) whether or not respondents had received prior information on how to navigate a mini-RAB. Additionally, demographic information (age, gender) as well as driver experience measured in terms of how often participants drive per week were collected.

Post-test questionnaire – was completed after a participant finished the driving simulator test. Questions on this portion of the survey pertained to (i) driver comfort while navigating the different driving scenarios, (ii) driver's ability to recognize size and/or navigational differences in the RABs, and (iii) preferences between having bike paths and pedestrian crosswalks integrated into the RAB designs.

2. HUMAN FACTORS RESULTS

2.1. Analysis of Critical Gaps

Critical gap is an essential parameter in the process of estimating capacity of a roundabout (RAB). The minimum time gap accepted by an entering driver to merge into the circulating lane of a RAB is called the critical gap (Lee et al., 2018). Any time gap less than the critical gap is rejected and any gap larger than the critical gap is accepted. In this study, critical gaps for the mini-RABs and also the single-lane RAB were calculated using a revised Raff's method.

The original Raff's method was developed to evaluate critical lag from the accepted lags and rejected lags. The procedure was biased and it was mostly dependent on the probability density function of the lags offered to the drivers (Troutbeck, 2016). Miller (1972) modified Raff's method and included the gap data instead of lags only which is known as the revised Raff's method. Figure 1 depicts how the critical gap is determined using the revised Raff's method from the intersection point between two functions (Shaaban & Hamad, 2018):

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

where: $\mathrm{t_a}$ = accepted gap

$\mathrm{t_r}$ = rejected gap

$\mathrm{F(t_r)}$ = cumulative distribuition function of rejected gap

$\mathrm{F(t_a)}$ = cumulative distribuition function of accepted gap

From Figure 4.3, the critical gap can be found from the intersection point of the cumulative distribution function curves. The horizontal axis value of the intersection point is the critical gap. This is called the critical gap as most vehicles accept any gap larger than this gap and any gap less than this value is rejected (Shaaban & Hamad, 2018).

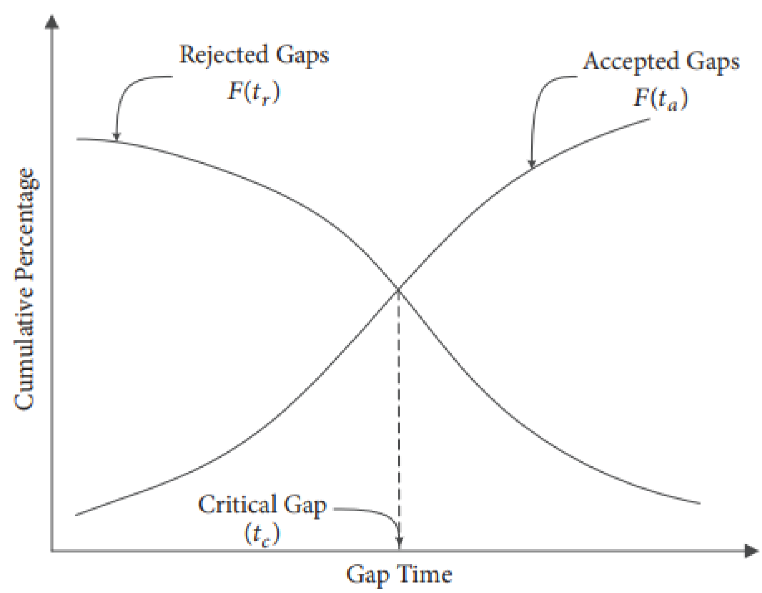

Figure 4.2. Critical gap based on revised Raff's method (Shaaban & Hamad, 2018).

Using the modified Raff's method as described above, the critical gaps for each of the mini-RAB alternatives were calculated. While a critical gap value was estimated for all scenarios, the critical gaps were also estimated by driving condition (day/night), gender (male/female), and age group (18-25, 26-40, and 41+). Table 4.2 presents the results of the critical gap analysis.

Table 4.2. Estimated Critical Gaps.

Simulation Scenario	Mini-RAB Inner Circle Diameter				Single-lane RAB
	45-feet	60-feet	75-feet	90-feet	120-feet
Overall Critical Gap Size (secs)	4.82	4.22	4.50	4.53	4.11
Daytime Critical Gap Size (secs)	4.83	5.06	3.94	4.58	4.25
Night-time Critical Gap Size (secs)	4.81	4.56	4.59	4.50	3.83
Females Critical Gap Size (secs)	4.38	4.50	4.62	4.62	4.50
Males Critical Gap Size (secs)	4.71	4.08	4.43	4.50	4.05
Age (18-25 yo) Critical Gap Size (secs)	4.86	4.88	4.43	4.5	4.05
Age (26-40 yo) Critical Gap Size (secs)	4.6	3.67	3.71	4.38	4.33
Age (41+ yo) Critical Gap Size (secs)	5.5	4.5	4.5	5.25	5.25

Based on the estimated critical values reported in Table 4.2, the following observations can be made:

- Regardless of ICD size and categorization, the estimated critical gap values fall within the NCHRP Report 672 recommended critical gap values of 4.2 to 5.9 seconds.
- The Highway Capacity Manual (HCM) uses a critical gap value for RABs of 4.1 seconds; which is equal to the critical gap estimated for the single-lane RAB (4.11 secs) from the driving simulator data. This is a good indicator that participants in this study are driving in a manner that replicates reality.
- Intuitively, it is expected the critical gap values for daytime driving would be shorter than for night-time driving. However, this is not the case – the critical gap during night-time was shorter than day-time.
- Based on age groups, the critical gaps estimated for the 41+ age group were higher. This is expected as most drivers in this age group are less risky drivers and would take longer gaps when merging into the RABs. By contrast, the estimated critical gaps for the 26-40 age group were the shortest – indicating a rather risky driving behavior. The 18-25 age group exhibited critical gaps that were larger than the other age groups; which is expected likely due in part to their lack of driving experience.
- Critical gap values for the 45-feet mini-RAB were the highest – indicating that drivers took longer to merge into the circulating traffic – very likely to affect operations and safety.

2.2. Analysis of Speeds

As each participant drove through the simulator scenarios, his/her driving speeds were recorded at different locations along the entry approach, circulatory area, and exit approach for each RAB alternative. More specifically, the speeds were recorded at points along the entry approach (500-feet prior to yield-line and at 100-feet intervals), in the circulatory area, and also along the exit approach (500-feet after exiting yield-line and at 100-feet intervals). As a preliminary step, an Analysis-of-Variance (ANOVA) test was performed to identify specific locations where significant speed variations are present. The ANOVA results (Table 4.3) indicated that, across all RAB types, participants exhibited significant speed differentials at specific locations only – along entry approach (500, 200, 100-feet prior to yield-line, and also at yield-line), a single location within circulatory area, and along exit approach (at exiting yield-line, and also at 100, and 500-feet after exiting yield-line). It was at these locations that further statistical comparisons of speeds among the different RABs was performed. Table 4.4 presents descriptive statistics of the observed speeds at the RAB alternatives specific to the selected analysis locations. Additionally, post-hoc tests (see Table 4.5) were performed on the speed data among the mini-RAB alternatives.

Table 4.3. ANOVA Results for Speed Differentials.

Location	F	p-value
Entry speed at 500 ft	2.421	0.049
Entry speed at 200 ft	11.936	0.000
Entry speed at 100 ft	3.795	0.005
Entry speed at yield line	24.421	0.000
Circulating speed	37.68	0.000
Exit speed at 0 ft	42.108	0.000
Exit speed at 100 ft	3.744	0.006
Exit speed at 500 ft	11.591	0.000

Note: If p-value < 0.05, then significant at 95% confidence level

Table 4.4. Descriptive Speed Statistics at Different RABs.

Location	Roundabout ICD (ft)	N	Mean Speed (mph)	Std. Deviation (mph)	Std. Error
Entry speed at 500 ft	45	46	30.363	5.3912	0.79489
	60	47	31.1851	4.379	0.63874
	75	50	30.07	4.16512	0.58904
	90	50	30.144	4.60683	0.6515
	Single Lane	50	28.346	4.70281	0.66508
	Total	243	30.0016	4.71232	0.3023
Entry speed at 200 ft	45	46	24.1457	4.2665	0.62906
	60	47	24.4064	4.02764	0.58749
	75	50	25.546	4.9857	0.70508
	90	50	25.992	4.45466	0.62998
	Single Lane	50	20.64	3.67501	0.51973

	Total	243	24.1428	4.68145	0.30031
Entry speed at 100 ft	45	46	16.8826	4.08043	0.60163
	60	47	16.4596	3.71271	0.54155
	75	50	18.184	4.68229	0.66218
	90	50	18.394	3.55983	0.50344
	Single Lane	50	15.644	4.84718	0.68549
	Total	243	17.1247	4.31199	0.27661
Entry speed at 0 ft	45	46	9.8413	2.94313	0.43394
	60	47	13.5255	3.36132	0.4903
	75	50	11.152	3.75256	0.53069
	90	50	11.206	2.946	0.41663
	Single Lane	50	16.534	5.14161	0.72713
	Total	243	12.4815	4.39896	0.28219
Circulating speed	45	46	9.2196	2.97042	0.43796
	60	47	15.1702	4.02837	0.5876
	75	50	10.72	3.51928	0.4977
	90	50	12.594	3.23825	0.45796
	Single Lane	50	17.512	4.84825	0.68565
	Total	243	13.0798	4.80156	0.30802
Exit speed at 0 ft	45	46	12.2935	2.4983	0.36835
	60	47	17.4745	4.78714	0.69828
	75	50	13.536	2.83554	0.40101
	90	50	14.45	3.48965	0.49351
	Single Lane	50	20.944	4.56232	0.64521
	Total	243	15.7749	4.85888	0.3117
Exit speed at 100 ft	45	46	24.0457	3.98457	0.58749
	60	47	25.8064	4.27604	0.62372
	75	50	24.144	3.19094	0.45127
	90	50	24.612	3.41089	0.48237
	Single Lane	50	26.484	4.46389	0.63129
	Total	243	25.0247	3.97695	0.25512
Exit speed at 500 ft	45	46	26.5043	4.72835	0.69716
	60	47	32.534	6.87103	1.00224
	75	50	27.934	4.07048	0.57565
	90	50	27.9	3.92558	0.55516
	Single Lane	50	31.324	5.80906	0.82152
	Total	243	29.2436	5.62048	0.36055

Table 4.5. Post-Hoc Test Results.

Location	Post-Hoc Test	(I) Roundabout Dia. (ft)	(J) Roundabout Dia. (ft)	Mean Difference (I-J)	Std. Error	Sig.
Entry500	Tukey HSD	60	Single Lane	2.83911*	0.94633	0.025
Entry200	Tukey HSD	45	Single Lane	-3.50565*	0.88018	0.001
			60	-3.76638*	0.87529	0
			75	-4.90600*	0.86165	0
			90	-5.35200*	0.86165	0
Entry100	Tukey HSD	75	Single Lane	-2.54000*	0.84314	0.024
			90	-2.75000*	0.84314	0.011
Entry0	Games-Howell	45	60	-3.68423*	0.65475	0
			Single Lane	-6.69270*	0.84678	0
		60	45	3.68423*	0.65475	0
			75	2.37353*	0.72251	0.012
			90	2.31953*	0.64341	0.005
			Single Lane	-3.00847*	0.87699	0.008
		75	Single Lane	-5.38200*	0.9002	0
		90	Single Lane	-5.32800*	0.83803	0
Circulating	Games-Howell	45	60	-5.95065*	0.73286	0
			90	-3.37443*	0.63367	0
			Single Lane	-8.29243*	0.81359	0
		60	75	4.45021*	0.77005	0
			90	2.57621*	0.74498	0.007
		75	Single Lane	-6.79200*	0.84724	0
		90	Single Lane	-4.91800*	0.82452	0
Exit0	Games-Howell	45	60	-5.18099*	0.78948	0
			90	-2.15652*	0.61582	0.006
			Single Lane	-8.65052*	0.74295	0
		60	75	3.93847*	0.80523	0
			90	3.02447*	0.85507	0.006
			Single Lane	-3.46953*	0.95073	0.004
		75	Single Lane	-7.40800*	0.75967	0
		90	Single Lane	-6.49400*	0.81231	0
Exit100	Tukey HSD	45	Single Lane	-2.43835*	0.79468	0.02
		75	Single Lane	-2.34000*	0.77794	0.024
Exit500	Games-Howell	45	60	-6.02969*	1.22087	0
			Single Lane	-4.81965*	1.07747	0
		60	75	4.60004*	1.1558	0.001
			90	4.63404*	1.14573	0.001
		75	Single Lane	-3.39000*	1.00313	0.009
		90	Single Lane	-3.42400*	0.99152	0.007

*** The mean difference is significant at the 0.05 level.**

From the descriptive statistics and ANOVA tests, the RABs which show significant difference in mean speeds can be determined. Considering only the mean differences which are greater than 5-mph, the following conclusions can be made:

- The entry speed at 200-ft distance from the entry of the ICD=90-ft mini-RAB (M = 25.992) is 5.35 mph higher than the entry speed at 200-ft distance from the entry of the ICD=45-ft mini-RAB (M = 24.146). This difference is statistically significant (p = 0.00 < 0.05).
- The entry speed at the yield line of the single-lane RAB (M = 16.534) is 6.69 mph higher than the entry speed at the yield line of the ICD=45-ft mini-RAB (M = 9.8413). This difference is statistically significant (p = 0.00 < 0.05). The entry speed at the yield line of the single-lane RAB (M = 16.534) is also significantly higher than the entry speed at the yield line of the ICD=75-ft (M = 11.152) and ICD=90-ft mini-RAB (M = 11.206).
- The circulating speed of the ICD=60-ft mini-RAB (M = 15.17) is 5.95 mph higher than the circulating speed of the ICD=45-ft mini-RAB (M = 9.22). This difference is statistically significant (p = 0.00 < 0.05).
- The circulating speed of the single-lane RAB (M = 17.51) is significantly higher than the circulating speed of the ICD=45-ft and ICD=75-ft mini-RAB.
- The speed at the exit point of the ICD=60-ft mini-RAB (M = 17.47) is 5.18 mph higher than the circulating speed of the ICD=45-ft mini-RAB (M = 12.293). This difference is statistically significant (p = 0.00 < 0.05).
- The exit speed at the exit point of the single-lane RAB (M = 20.944) is significantly higher than the exit speed at the exit point of the ICD=45-ft (M = 12.293), ICD=75-ft (M = 12.293) and ICD=90-ft mini-RAB (M = 12.293).
- The exit speed at 500-ft distance from the exit of the ICD=60-ft mini-RAB (M = 32.53) is 6.03 mph higher than the entry speed at 200-ft distance from the entry of the ICD=45 ft mini-RAB (M = 26.504). This difference is statistically significant (p = 0.00 < 0.05).

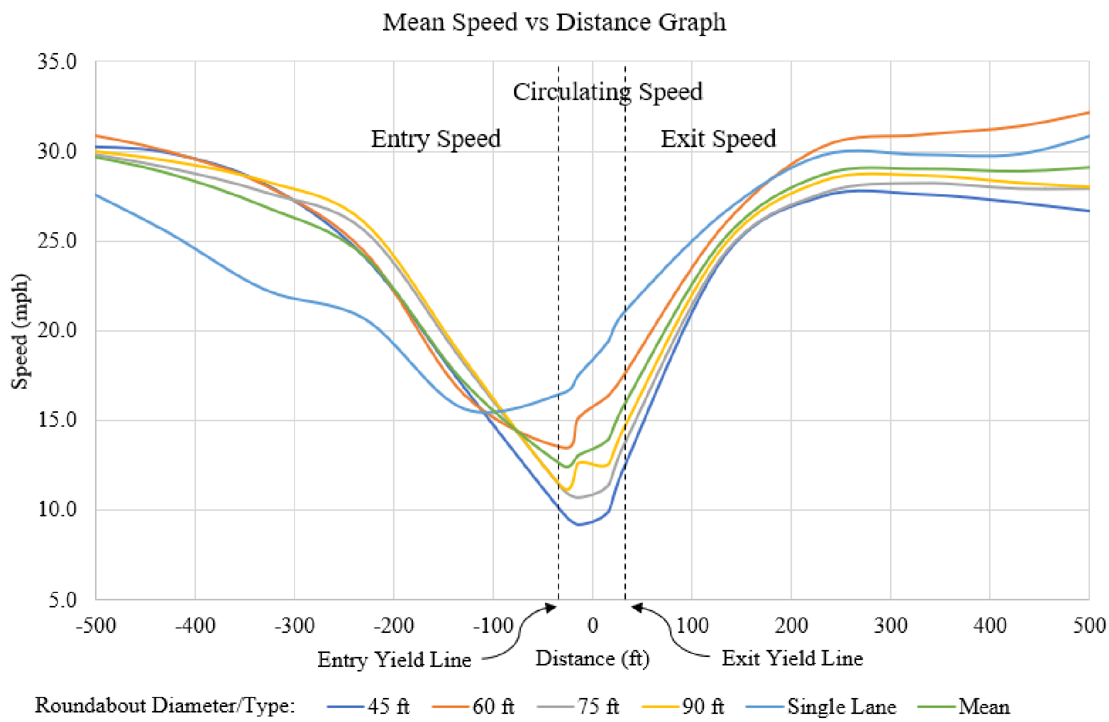

Figure 4.3. Participant mean speeds along entry & exit approaches and circulatory area.

2.3. Analysis of Speed by Age Group

The speed data were separated by Age Group (18-25, 26-40, and 41+) and analyzed to determine if the participant age has any effect on approach, circulatory, and exit speeds. For this test, the Repeated Measures ANOVA was performed as the variables are subjected to repeat observations (i.e., same driver experiencing different treatments). Table 4.6 presents results of the Tests of Between-Subjects Effects for the variable age group. Table 4.7 shows the pairwise comparisons.

Table 4.6. Tests of Between-Subjects Effects: Age Group.

Location	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Entry speed at 500 ft	257.862	2	128.931	2.159	0.128	0.091
Entry speed at 200 ft	200.886	2	100.443	1.914	0.16	0.082
Entry speed at 100 ft	129.266	2	64.633	1.281	0.288	0.056
Entry speed at yield line	110.708	2	55.354	1.498	0.235	0.065
Circulating speed	166.84	2	83.42	2.106	0.134	0.089
Exit speed at 0 ft	424.042	2	212.021	5.002	0.011	0.189
Exit speed at 100 ft	363.543	2	181.772	3.523	0.038	0.141
Exit speed at 500 ft	562.727	2	281.364	4.039	0.025	0.158

Table 4.7. Pairwise Comparisons: Age Group.

Location	(I) Age	(J) Age	Mean Difference (I-J)	Std. Error	Sig.b
Exit speed at 0 ft	18-25	26-40	1.531	0.931	0.322
		41-65	4.095*	1.335	0.011
Exit speed at 100 ft	18-25	26-40	1.346	1.027	0.591
		41-65	3.819*	1.473	0.039
Exit speed at 500 ft	26-40	18-25	2.006	1.194	0.3
		41-65	4.899*	1.772	0.025
Based on estimated marginal means					
* The mean difference is significant at the .05 level.					
b Adjustment for multiple comparisons: Bonferroni.					

Based on the Between-Subjects Effects and the pairwise comparisons, the following conclusions can be made:

- The age group is a significant factor for the drivers exit speeds at the exit locations on exit approach of the RABs ($p < 0.05$).
- The mean speed is significantly higher for drivers from the 18-25 age group than from the 41+ age group at 0-ft and 100-ft from the exit of the RABs ($p < 0.05$).
- The mean speed is significantly higher for drivers from the 26-40 age group than from 41+ age group at 500-ft from the exit of the RABs ($p < 0.05$).

2.4. Analysis of Speed by Gender.

The speed data at different RABs was also analyzed based on gender. Table 4.8 shows the Tests of Between-Subjects Effects for the variable gender. Table 4.9 shows the pairwise comparisons.

Table 1.8. Tests of Between-Subjects Effects: Gender

Location	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Entry speed at 500 ft	87.355	1	87.355	1.404	0.242	0.031
Entry speed at 200 ft	244.739	1	244.739	4.865	0.033	0.1
Entry speed at 100 ft	89.215	1	89.215	1.777	0.189	0.039
Entry speed at yield line	22.358	1	22.358	0.586	0.448	0.013
Circulating speed	174.203	1	174.203	4.52	0.039	0.093
Exit speed at 0 ft	214.541	1	214.541	4.645	0.037	0.095
Exit speed at 100 ft	166.74	1	166.74	3.038	0.088	0.065
Exit speed at 500 ft	563.635	1	563.635	8.282	0.006	0.158

Table 4.9. Pairwise Comparisons: Gender

Location	(I) Gender	(J) Gender	Mean Difference (I-J)	Std. Error	Sig.b
Entry speed at 200 ft	Male	Female	2.600*	1.179	0.033
Circulating speed	Male	Female	2.194*	1.032	0.039
Exit speed at 0 ft	Male	Female	2.435*	1.13	0.037
Exit speed at 500 ft	Male	Female	3.946*	1.371	0.006
Based on estimated marginal means					
* The mean difference is significant at the .05 level.					
b Adjustment for multiple comparisons: Bonferroni.					

Based on the Between-Subjects Effects and the pairwise comparisons, the following conclusions can be made:

- Gender is a significant factor for drivers' entry speeds at 200-ft from the entry of the RAB and for the circulating speed. Gender is a significant factor also for the drivers exit speeds at the exit point, and 500-ft from the exit of the RABs ($p < 0.05$).
- The mean speed is significantly higher for the male drivers than the female drivers at 200-ft from the entry of the RAB, in the circulating area, at 0-ft and 500-ft from the exit of the RABs ($p < 0.05$).

2.5. Analysis of Speed by Daylight Condition

The speed data at different RABs was also analyzed based on daylight condition. Table 4.10 shows the Tests of Between-Subjects Effects for the variable daylight condition. Table 4.11 shows the pairwise comparisons.

Table 4.10. Tests of Between-Subjects Effects: Daylight Condition.

Location	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Entry speed at 500 ft	263.113	1	263.113	4.518	0.039	0.093
Entry speed at 200 ft	282.939	1	282.939	5.724	0.021	0.115
Entry speed at 100 ft	63.657	1	63.657	1.253	0.269	0.028
Entry speed at yield line	77.604	1	77.604	2.104	0.154	0.046
Circulating speed	53.088	1	53.088	1.286	0.263	0.028
Exit speed at 0 ft	56.504	1	56.504	1.135	0.292	0.025
Exit speed at 100 ft	13.538	1	13.538	0.232	0.633	0.005
Exit speed at 500 ft	130.277	1	130.277	1.672	0.203	0.037

Table 4.11. Pairwise Comparisons: Daylight Condition.

Location	(I) Condition	(J) Condition	Mean Difference (I-J)	Std. Error	Sig.b
Entry speed at 500 ft	Day	Night	-2.139*	1.006	0.039
Entry speed at 200 ft	Day	Night	-2.218*	0.927	0.021
Based on estimated marginal means					
* The mean difference is significant at the .05 level.					
b Adjustment for multiple comparisons: Bonferroni.					

Based on the Between-Subjects Effects and the pairwise comparisons, the following conclusions can be made:

- The daylight condition is a significant factor for the drivers entry speeds at 500 ft and 200 ft from the entry of the roundabout ($p < 0.05$).
- The mean speed is significantly higher at day conditions than night conditions at 500 ft and 200 ft from the entry of the roundabout ($p < 0.05$).

2.6. Analysis of Pre-/Post-Simulation Survey.

The following sections present results from both pre and post-test questionnaire responses.

2.6.1. Demographics

A total of 51 participants completed the survey; with 80.4% (N= 41) male participants and 19.6% (N=10) female participants. Table 4.12 and Figure 4.4 present respondent demographics based on gender and age groups.

Table 4.12. Respondent Age Distributions.

Age Group	No. of Males	No. of Females	Total	% of Total
18-25	21	4	25	49
26-40	19	2	21	41.2
41-55	1	3	4	7.8
56-65	0	1	1	2
65+	0	0	0	0
Total	41	10	51	100

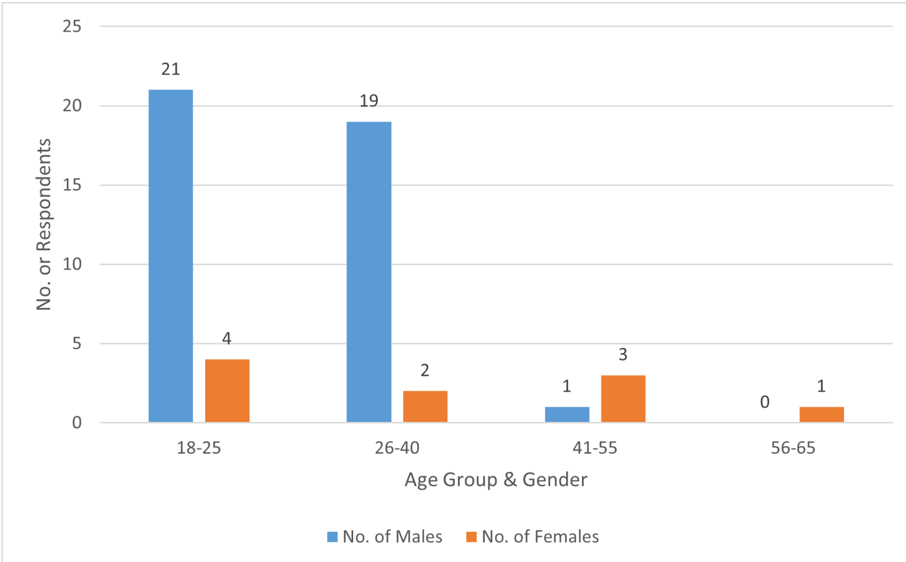

Figure 4.4. Participant age distribution by gender.

2.6.2. Driving experience.

Question 3 (pre-test) was intended to gather data on how frequently respondents drove per week. Table 4.13 shows that a majority of respondents had considerable driving experience with a driving frequency of at least 1 day per week. 34% (N=17) of respondents drove between two to four days per week and a total of 92% (N=46) of the total respondents driving between two to seven days of the week.

Table 4.13. Respondent Driving Frequency Per Week.

Driving frequency (days/week)	No. of Drivers	% Total
0-1	4	8
2-4	17	34
5-7	29	58

Gathering data on the driving experience/frequency by respondents gave preliminary insights into how often respondents were on the road driving and the likelihood that they may have encountered road features such as RABs, stop controlled intersection and perhaps, mini RABs. It was not surprising that when asked (in several pre-test questions) about their familiarity with RABs and other road geometric features such as mini-RABs and intersections there was a high level of familiarity with RABs, even among respondents who drove between 0-1 day per week. The subsequent sections present survey results on the levels of familiarity among respondents.

2.6.3. Driver familiarity with traditional/mini-RABs

Data on drivers' level of familiarity with respect to traditional single-/double-lane RABs and more specifically, mini-RABs, were collected prior to participants navigating/maneuvering RABs and mini-RABs in a simulated environment. Three out of the nine pre-test questions asked whether drivers were familiar with the concept of mini-RABs and RABs, generally. Self-reported responses to these questions were categorized into the following: 'not familiar', 'somewhat familiar', and 'very familiar'. It was also important to obtain survey data on whether drivers had driven through a mini-RAB, hence a question was asked to that effect.

Overall, survey results from the pre-test familiarity questions (Q 4-6) showed that drivers reported to have a strong familiarity of the concept of a RAB (Q4). About 76% (N=39) of respondents were very familiar with RABs, whereas about 24% (N=12) of respondents had an appreciable level of familiarity with RABs, as evidenced by the answer choice of 'somewhat familiar' when asked the question on mini-RABs. Figure 4.5 summarizes the survey responses.

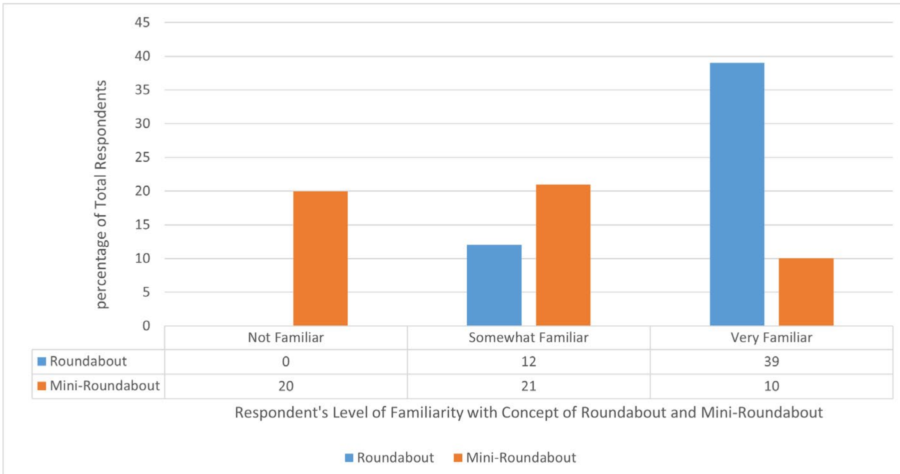

Figure 4.5. Respondent self-reported roundabout familiarity levels (pre-test).

Even though drivers reported to having a strong familiarity with RABs; when asked a similar question with regard to mini-RABs, there was a diverging sentiment toward mini-RABs. There was a general reduction in the percentage of respondents who reported to be familiar with mini-RABs (Q5) who were familiar with RABs (Q4). Only 20% (10 out of 51) reported to having very familiar knowledge of the concept of a mini-RAB; this represents an approximately 56% percent reduction in the number of respondents who reported being very familiar with RABs generally.

On the other hand, there was increase in the number of respondents who were 'somewhat familiar' with mini-RABs as there was approximately 17% (N=9) increase in the number of respondents who were somewhat familiar with standard/traditional RABs when asked the same question with regard to mini-RABs. Overall, 41% (N=21) of total respondents were not entirely conversant with mini-RABs, which could be inferred from their answer- 'somewhat familiar'- when asked the familiarity question with mini-RABs. In addition, 39% (N=20) of total respondents were categorically not familiar with the concept of a mini-RAB.

A possible explanation of this skepticism with familiarity of mini-RABs, is that participants may have had limited information on mini-RABs and/or how to navigate them and were not entirely sure what a mini-RAB was, even if they have driven through a mini-RAB in the past. Responses to the question, 'have you ever driven through a mini-RAB?' showed that 51% (N=26) had driven through a mini-RAB and the remaining 49% (N=25) had not driven through a mini-RAB. Responses to a follow-up question (Q7) showed that even though drivers may have driven through a mini-RAB, they reported to have received limited information on how to navigate mini-RABs. Also, responses from Q1 (pos- test) showed that irrespective of level of familiarity with mini-RABs, participant drivers were able to notice a mini-RAB when they approached them in the simulation.

Figure 4.6 shows results of the percentage of respondents that stated having driven through a mini-RAB and based on their having received information on how to navigate RABs. Responses to Q7 (pre-test) show that 80% (N=40) of drivers stated receiving information providing knowledge on how to navigate a traditional-RAB (single-lane and/or double-lane), 16% (N=8) a mini-RAB; and 2% (N=1) other RAB types such as turbo-RABs. Moreover, 14% (N=7) reported to having received no prior education/information on navigating any kind of RAB type.

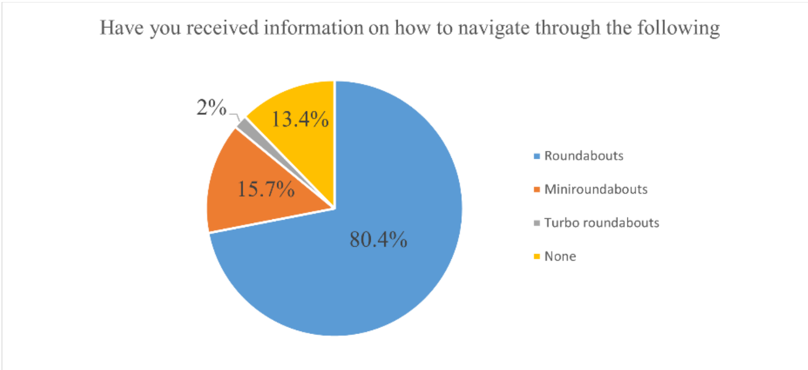

Figure 4.6. Information on different RABs received by respondents.

A follow-up to Q7 (pre-test) was for drivers to provide details on how they gained prior knowledge of navigating RABs. The most prevalent source of education/information was through some form of formal driving school/education with an instructor. Other reported informational sources included demonstration by parents/friends, as well as resources such as BMV websites, handbook for driver license/driver's manual, online demonstration video, college level class. Drivers that had not received any formal information averted to gaining their navigation skills by simply reading RAB signage and markings on approach to a RAB and based on their personal interpretation of the signage and/or markings.

Regardless of whether drivers had received some form of education/information about the concept of mini-RABs, or whether they have ever driven through a mini-RAB; the majority of participants when driving the simulated environment were able to identify the differences between the RAB types. In an attempt to assess whether driver familiarity could affect their perception of mini-RABs, Q1 (post-test) asked participants whether they noticed or felt any difference in terms of navigation and size when they drove through the simulated scenarios. Only 8% (N=4) participants did not notice any difference in the RAB types. However, 92% (N=43) drivers could differentiate between the RAB types in terms of the 'feel' associated with the navigation, size or other self-reported differences.

Figure 4.7 shows the summary of noticeable differences by participant drivers in terms of the size and navigation through the different RAB scenarios in the driving simulator. It can be seen that size of a mini-RAB was a major characteristic that allowed mini-RABs noticeable to participant drivers. As participants drove the simulation scenarios, 41% (N=21) noticed a difference only in the size, and 41% (N=21) noticed a difference in both navigation and the size. Navigation alone was not enough to differentiate between the RAB types.

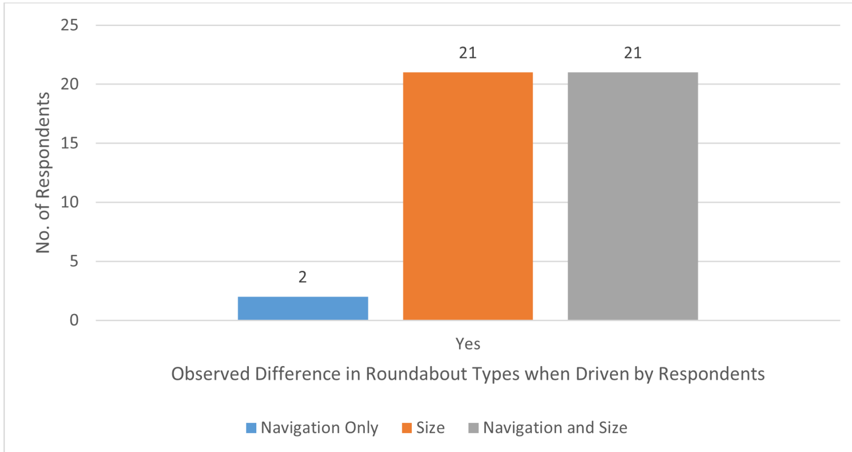

Figure 4.7. Observed difference in RAB types when driven by respondents.

2.6.4. Preferred educational sources on RABs.

Even though the self-reported pre-test responses indicated that participants had a high level of familiarity with traditional and/or mini-RABs, the post-test findings revealed that in spite of their experience driving the simulator, participants did not rank mini-RABs higher in their order of preferences/comfort when asked to rank between different intersection control types. Q8 (pre-test) asked respondents what information sources would be most helpful to them in understanding how to navigate through a RAB – Figure 4.8 depicts the compiled responses.

To 65% (N=33) of participants, it was resources using forms of video/film that were more appealing resources; and 51% (N=26) mentioned demonstrations as a great source of information and education. The willingness of respondents to select a video and/or demonstration is important because, in developing educational resources and licensing policies, video resources and perhaps, an on-site demonstration/training through a driving education/school by an instructor may be widely accepted and yield positive acceptance by drivers.

Presenting information in driving manuals was also appreciated by respondents, as about 28% (N=14) participants were of the opinion that a driver's manual would be a great source of information on how to drive through/navigate a roundabout. Other sources of roundabout information which were selected include through brochure (12%), website/BMV website (12%), presentation (10%).

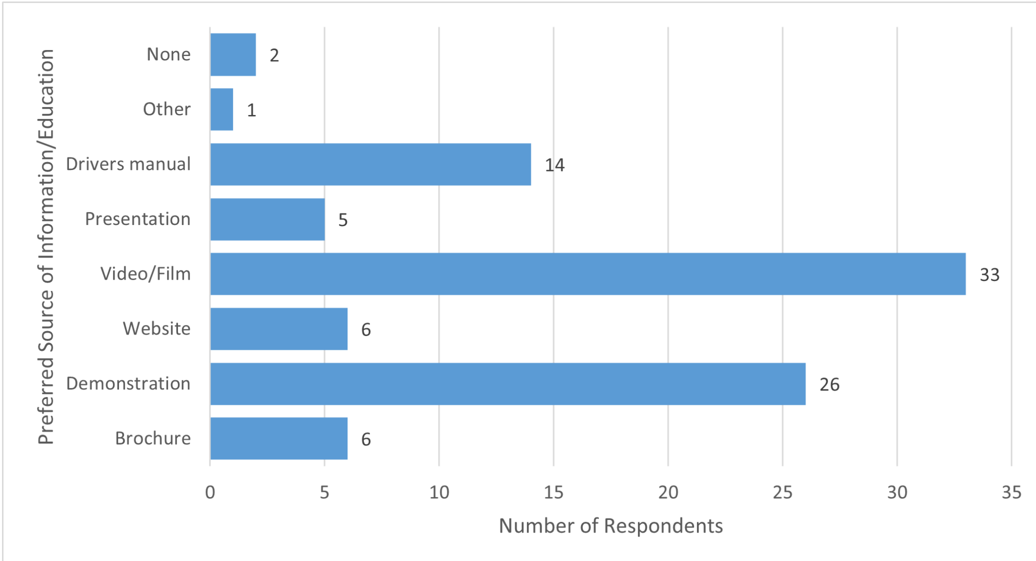

Figure 4.8. Respondents preferred sources of information/education on RABs

In terms of roadside signage and/or markings, as shown in Figure 4.9, about 52% (N=26) of participants thought having both a RAB sign and the 'CAUTION: ROUNDABOUT AHEAD' message would be beneficial as they approach a mini-RAB. 36% (N=18) drivers would rather have only a RAB sign instead of also communicating the same message in writing. Only 10% (N=5) thought having the 'CAUTION: ROUNDABOUT AHEAD' text only would be beneficial in communicating to them when approaching a roundabout.

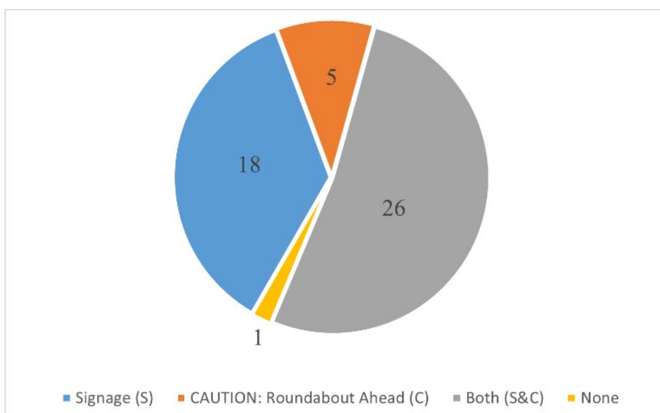

Figure 4.9. Respondents preferences on RAB signage/symbol.

2.6.5. Driver comfort and preferences.

Q2 (post-test) required participants to rank their level of comfort at the start of the simulation as well as while maneuvering through several scenarios with different intersection control. Figure 4.10 shows the compiled results obtained from participant responses to Q2 (post-test). Subsequently, Q3 (post-test) required participants to indicate their order of preference among intersection controls types (see Figure 4.11 for results).

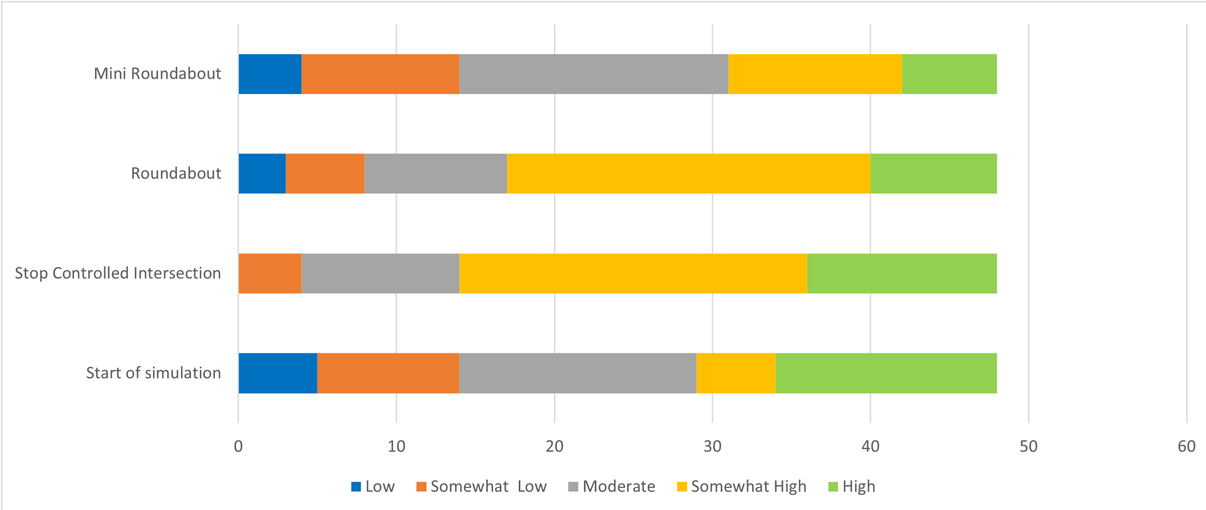

Figure 4.10. Participant level of comfort after driving simulator scenarios.

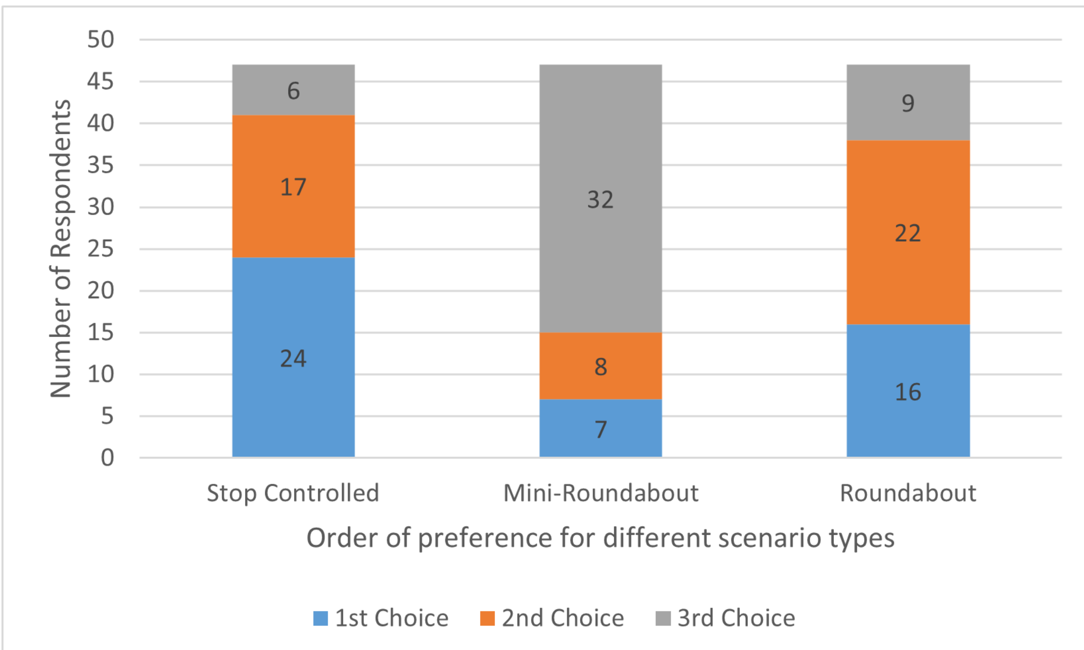

Figure 4.11. Respondents order of preference among different intersectional control.

An analysis of compiled responses yielded interesting results which did not confirm the expected outcome. Based on how comfortable they were while navigating/maneuvering in the simulator, 51% (N=26) ranked stop-controlled intersection as their first preference, 34% (N=17) ranked a traditional-RAB first in their order of preference, while 15% (N=7) ranked mini-RABs first in their order or preference. Moreover, mini-RABs were the least preferred; with 68% (N=35) participants ranking mini-RABs third in their order of preference.

Results from the ratings are interesting, because given the high level of (reported) familiarity by respondents, it was expected, familiarity would influence their comfortability after driving through RABs (traditional/mini) and result in higher rating of RABs and mini-RABs in their order of preference. A possible explanation would be that respondents overrated their knowledge and familiarity of what a RAB is and how to navigate one, or they may have received limited or possibly inaccurate information on how to navigate a RAB, specifically mini-RABs.

Also, the rating results are valuable, because they point to a possible direction where educational effort, resources and policies could be directed to properly educate and inform drivers on the concept of a RAB, the different variations of RABs and how to navigate them safely.

2.6.6. Pedestrian and bike crossings at RABs.

Questions 4, 5, and 6 (post-test) were intended to gain insight into how comfortable drivers are with having pedestrian crossing and bike lanes within RABs. Simulation scenarios in which respondents drove included a combination of pedestrian crosswalk and/or bicycle lanes. As shown in Figure 4.12, there is mixed preferences on whether drivers were comfortable with having pedestrian crosswalks at mini-RABs –50% answered 'YES' and the other 50% answered 'NO' to the presence of pedestrians at RABs. There is, however, an increase in the number of drivers who would not be comfortable with bike lanes/crossing at mini-RABs – 62% answered 'NO' to the presence of bicycle lanes/crossing.

About 38% (N=19) of drivers were comfortable having RABs with bike crossing/lanes. Furthermore, 65% of the drivers that were comfortable with having bicycle lanes/crossing prefer bicycles in pedestrian crossing to bicycle lanes operating with regular traffic (55%).

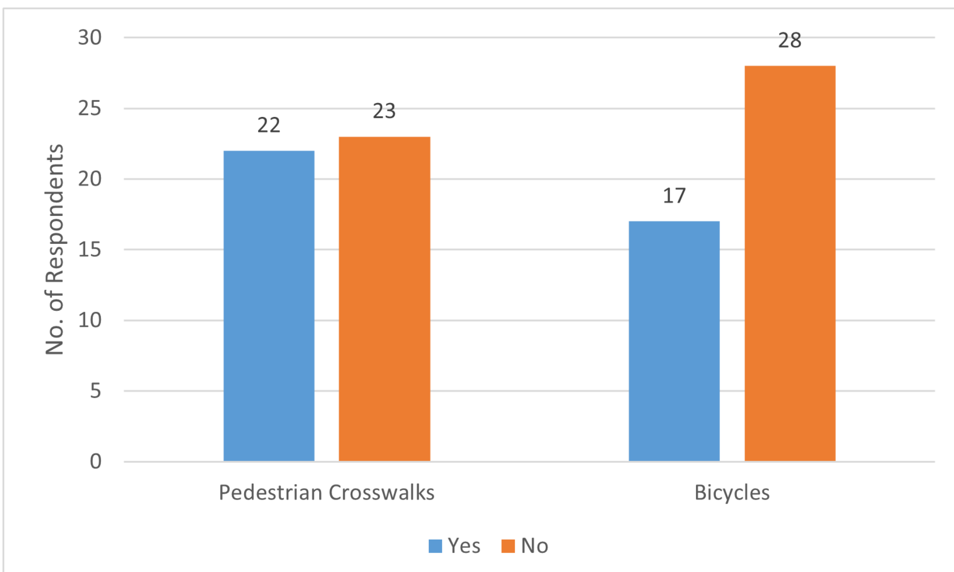

Figure 4.12. Driver preference for pedestrian crosswalks and bike-lanes.

Institutional Review Board (IRB) Approval

Project Number	19-X-166
Project Status	APPROVED
Committee:	Social/Behavioral IRB
Compliance Contact:	Rebecca Cale (cale@ohio.edu)
Primary Investigator:	Bhaven Naik
Project Title:	Intersection Modifications Using Modular/Mini-Roundabout Methods
Level of Review:	EXPEDITED

The Social/Behavioral IRB reviewed and approved by expedited review the above referenced research. The Board was able to provide expedited approval under 45 CFR 46.110(b)(1) because the research meets the applicability criteria and one or more categories of research eligible for expedited review, as indicated below.

IRB Approved:	09/11/2019 08:41:11 AM
Expiration:	09/11/2020
Review Category:	4,7

Waivers: No waivers are granted with this approval.

If applicable, informed consent (and HIPAA research authorization) must be obtained from subjects or their legally authorized representatives and documented prior to research involvement. In addition, FERPA, PPRA, and other authorizations / agreements must be obtained, if needed. The IRB-approved consent form and process must be used. Any changes in the research (e.g., recruitment procedures, advertisements, enrollment numbers, etc.) or informed consent process must be approved by the IRB before they are implemented (except where necessary to eliminate apparent immediate hazards to subjects).

The approval will no longer be in effect on the date listed above as the IRB expiration date. A Periodic Review application must be approved within this interval to avoid expiration of the IRB approval and cessation of all research activities. All records relating to the research (including signed consent forms) must be retained and available for audit for at least three (3) years after the research has ended.

It is the responsibility of all investigators and research staff to promptly report to the Office of Research Compliance / IRB any serious, unexpected and related adverse and potential unanticipated problems involving risks to subjects or others.

This approval is issued under the Ohio University OHRP Federalwide Assurance #00000095. Please feel free to contact the Office of Research Compliance staff contact listed above with any questions or concerns.

The approval will no longer be in effect when the Primary Investigator is no longer under the auspices of Ohio University, e.g., graduation or departure from Ohio University.

Research Compliance
117 Research and Technology Center 740.593.0664
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APPENDIX F

Microsimulation Assessment

Task 5

TASK 5: MICROSIMULATION ASSESSMENT of MINI-ROUNDABOUTS.

1. INTRODUCTION

The purpose of Task 5 was to complement the findings in the literature (Task 2) by conducting a traffic microsimulation-based assessment to evaluate performance of select mini-RAB design alternatives (e.g., central island radius, corner radius, flare angle, etc.) on operational performance. The content in this portion of the document present the findings of this microsimulation-based assessment.

1.1 Methodology.

The assessment in Task 5 was performed using three widely used simulation tools – SIDRA INTERSECTION 8.0, VISSIM 11.0, and SSAM 3.0. Figure 5.1 depicts a high-level view of the assessment with inputs, assessment tools, and output (or performance measures).

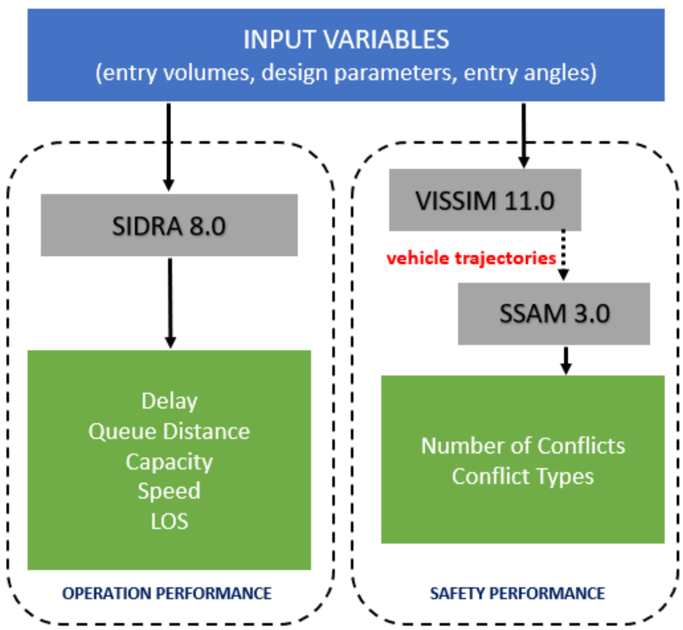


Figure 5.1. Methodology for assessing mini-roundabouts.

As shown in Figure 5.1; the operational performance analysis portion was performed using SIDRA 8.0 whereas, the safety analysis portion was performed using a combination of VISSIM 11.0 and SSAM 3.0. SIDRA allows analysis of single-lane and multi-lane RAB by applying a combined (hybrid) geometry and gap-acceptance modelling approach to calculate the effect of roundabout geometry on driver behavior directly through gap-acceptance modelling. VISSIM was used to model various simulation scenarios and collect simulated vehicle tracking data (trajectories) that were subsequently analyzed using the Surrogate Safety Assessment Model (SSAM). The integration of microsimulation and surrogate safety performance measures allows for the assessment of the benefits (safety) in-lieu of observed traffic and crash data. SSAM based indirect safety assessment and the findings provide us with insight on potential conflicts arising from design changes.

1.2 Simulation Scenarios.

A variety of simulation scenarios were developed and the subsequent sub-sections present details on these scenarios developed for both the operations and safety assessments.

1.2.1. Simulation scenarios - operations

Microsimulation scenarios for a 4-legged mini-RAB were developed based on four key geometric features and traffic compositions – inscribed circle diameter (ICD), entry angle (EA), and entering traffic volumes (major approach, M and minor approach, m). More specifically, combinations of ICD (45, 60, 75, or 90-ft); EA (50, 60, 75, 90 degrees), M (100, 200, 300, 400 veh/hr), and m (100, 200, 300, 400 veh/hr). A total of 256 scenarios were simulated and the relevant output analyzed. To mimic the peak hour volumes (1150 – 1400-veh/hr) obtained from the literature, the different combinations of traffic volume on major and minor approaches were set to vary between 400 to 1600 veh/hr. As well, the heavy vehicle percentages used were 5% for all scenarios. In addition, the following simulation parameters were kept constant in all scenarios and their values ascertained based on the literature.

- Circulating roadway width (1 lane) –15-feet (Zhang, et al., 2017).
- Width at entry of approaches (1 lane) – 12-feet (SIDRA INTERSECTION 8 User Guide).
- Entry radius – 45-feet (minimum recommended in NCHRP 672 for multilane roundabout).
- Left turn percent – 10% (NCHRP 672).
- Right turn percent – 10% (NCHRP 672).
- U-turn percent – 0% (NCHRP 672).
- Entry design speed – 20 mph (NCHRP 672).
- Exit speed – 20 mph (NCHRP 672).
- Peak hour factor (PHF) – 0.95 (SIDRA INTERSECTION 8 Manual).

To compare the operational performance of mini-RABs with that of stop-control intersections, an additional 16 scenarios were developed. More specifically, combinations of M (100, 200, 300, 400 veh/hr), m (100, 200, 300, 400 veh/hr), and intersection control (TWSC, AWSC). It was assumed that when volume on major approach was greater than minor approach then intersection was TWSC; with AWSC being used when the volumes on both major and minor approaches are equal. Entry width of approaches, heavy vehicle %, left, right, and U-turn %, entry and exit speed, and peak hour factor were all kept constant (i.e., same as mini-RAB scenarios).

1.2.1.1. Mini-roundabout Entry Angle and Entry Radius

The entry angle corresponds to the angle of conflict between the entering and circulating streams. Entry radius is measured as the minimum radius of curvature of the outside kerb line at entry (i.e., at the give-way/yield line). Figure 5.2 depicts how the EA and entry radius for both left- and right-hand drive rule (SIDRA INTERSECTION 8. User Guide).

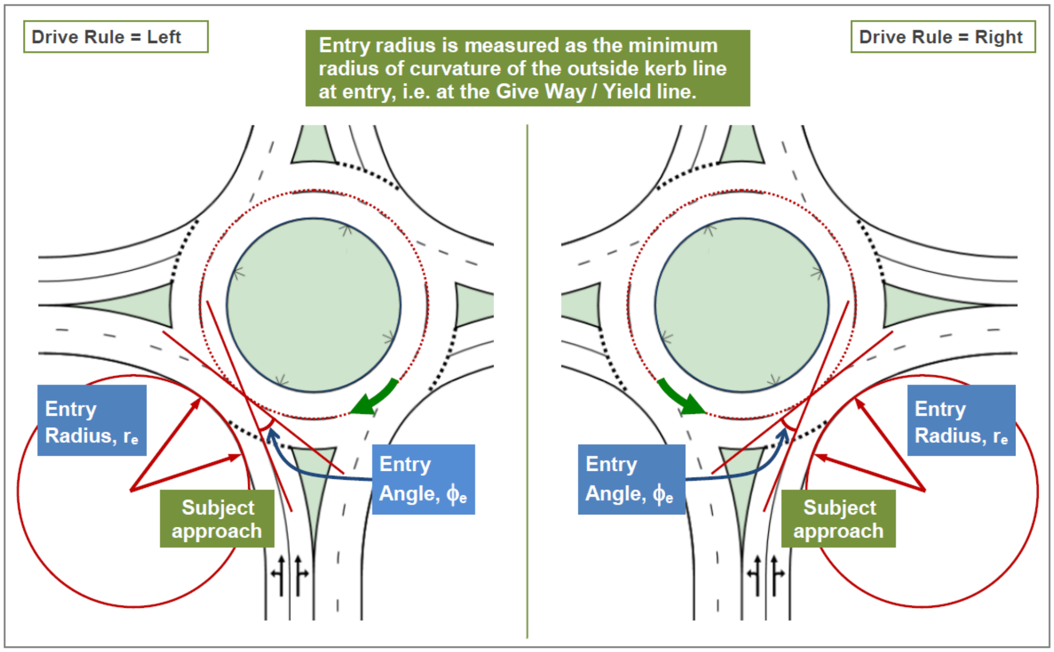


Figure 5.2. Definition of Entry Angle and Entry Radius

1.2.2. Simulation scenarios - safety

For the safety analysis, mini-RAB geometrics (ICD = 90-feet, entry angle = 50 degrees) that yielded best results from the operational analysis were used; with variation in traffic volumes. Four scenarios were created as shown in Table 5.1.

Table 5.1. Scenarios for Safety Analysis.

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Heavy Vehicle (%)
	Total Volume (veh/hr)	Dist. (%)	Total Volume (veh/hr)	Dist. (%)	Total Volume (veh/hr)	Dist. (%)	Total Volume (veh/hr)	Dist. (%)	
East Bound (Major)	200	RT = 10	400	RT = 10	200	RT = 10	400	RT = 10	3
		Th = 80		Th = 80		Th = 80		Th = 80	
		LT = 10		LT = 10		LT = 10		LT = 10	
West Bound (Major)	200	RT = 10	400	RT = 10	200	RT = 10	400	RT = 10	
		Th = 80		Th = 80		Th = 80		Th = 80	
		LT = 10		LT = 10		LT = 10		LT = 10	
North Bound (Minor)	50	RT = 30	100	RT = 30	200	RT = 30	400	RT = 30	
		Th = 40		Th = 40		Th = 40		Th = 40	
		LT = 30		LT = 30		LT = 30		LT = 30	
South Bound (Minor)	50	RT = 30	100	RT = 30	200	RT = 30	400	RT = 30	
		Th = 40		Th = 40		Th = 40		Th = 40	
		LT = 30		LT = 30		LT = 30		LT = 30	

* RT = Right Turn, Th = Through, and LT = Left Turn.

2. MICROSIMULATON ASSESSMENT RESULTS

2.1 Operational Performance Analysis.

For operational performance analysis, six performance indicators were selected – average control delay, 95% back of queue distance, average geometric delay, effective intersection capacity, average travel speed, and level of service. The following sub-sections present the results by performance measure.

2.1.1. Average control delay

Control delay is the delay (secs) that is experienced as a driver decelerates on approach to a queue, awaits an acceptable gap in the circulating flow while at the front of queue, and accelerates out of queue. Control delay can be estimated by measuring the average time it takes vehicles to travel between a control point upstream of the maximum queue in a lane and a point immediately downstream of the entry. It is the difference between the measured travel time and the travel time needed by an unconstrained vehicle (one that did not queue or need to yield at entry) (NCHRP 672).

Figures 5.3 to 5.6 illustrate the average control delay (secs) at a mini-RAB in terms of different traffic volume (major and minor streets) and geometric configurations (ICD and EA). Also shown is a "base" condition – that is, no mini-RAB but a traditional intersection (stop control). Overall, the figures depict that the average control delay (i) decreases as the ICD increases; (ii) increases as the entry angle becomes larger; and (iii) increases as the traffic volumes increase. These trends are expected given that EA, traffic volumes, and ICD affect the gap acceptance ability for entering vehicles.

An ICD of 90-feet and an EA of 50° results in the lowest average control delay among all simulation scenarios. This observation is similar across Figures 5.3 through 5.6. When compared to a traditional intersection (TWSC/AWSC), the results show that a mini-RAB provides much lower average control delay for traffic volumes between 100 to 400 veh/hr/approach (Figure 5.3 to 5.6). Compared to a TWSC intersection, a mini-RAB produces lower average control delay at higher traffic volume (200-400 veh/hr/approach) with higher ICDs and lower EAs (Figure 5.5 to 5.6).

2.1.2. Influence of approach volumes on average control delay

Figures 5.7 to 5.10 illustrate the effect of variations in approach volumes on average control delay. Overall, the average control delay increases with higher traffic volume on minor approaches while the major approach volumes are kept constant. A mini-RAB with EA of 50°, an ICD of 90-feet and major and minor road traffic volume of 100 veh/hr/approach produces the lowest average control delay (Figure 5.8d). Similar observation can be made in Figure 5.8 (EA of 60°), Figure 5.9 (EA of 70°), and Figure 5.11 (EA of 90°).

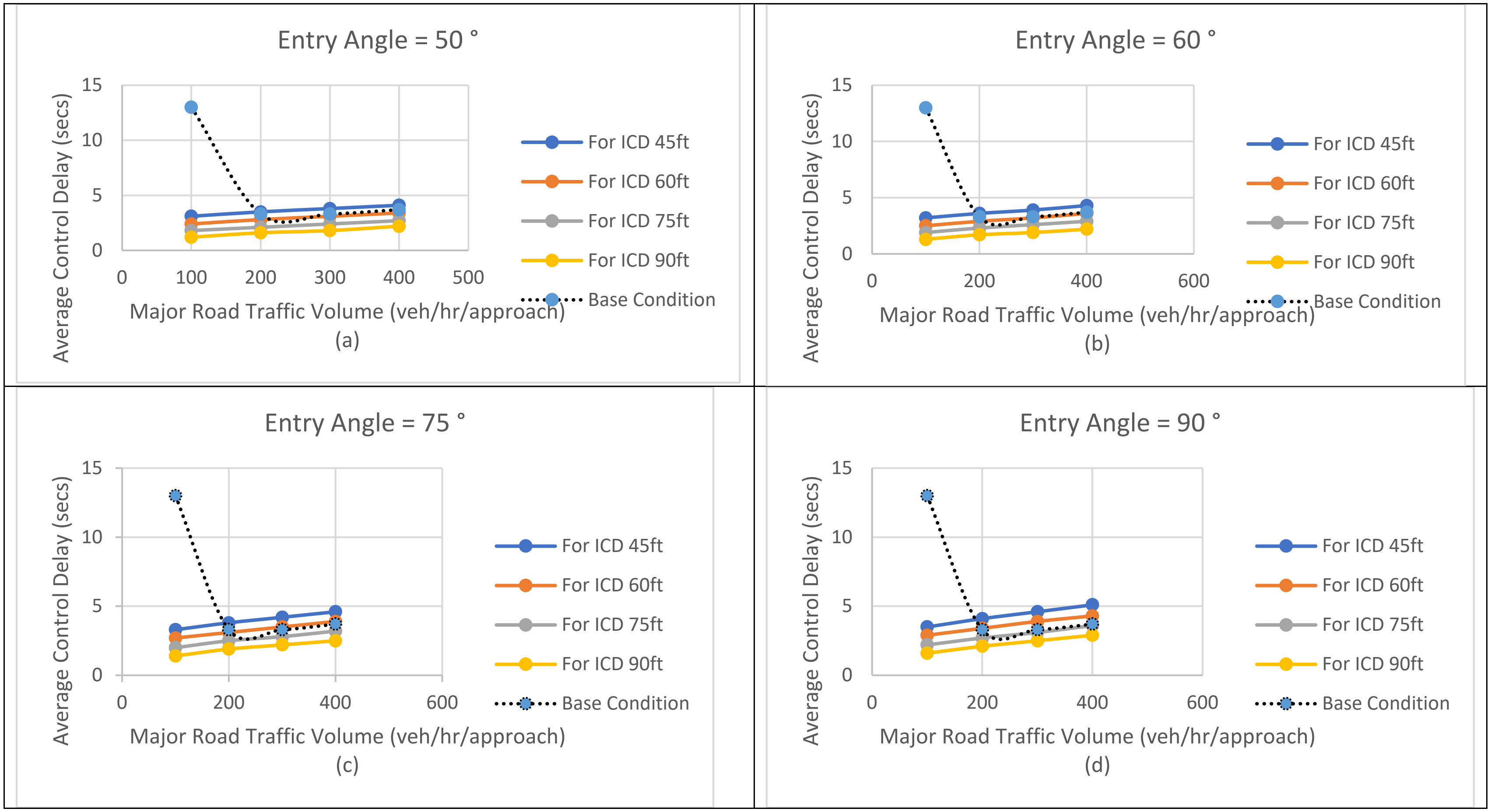


Figure 5.3. Average control delay (secs) based on major road volume, ICD, and EA.
(with minor road volume = 100 veh/hr/approach)

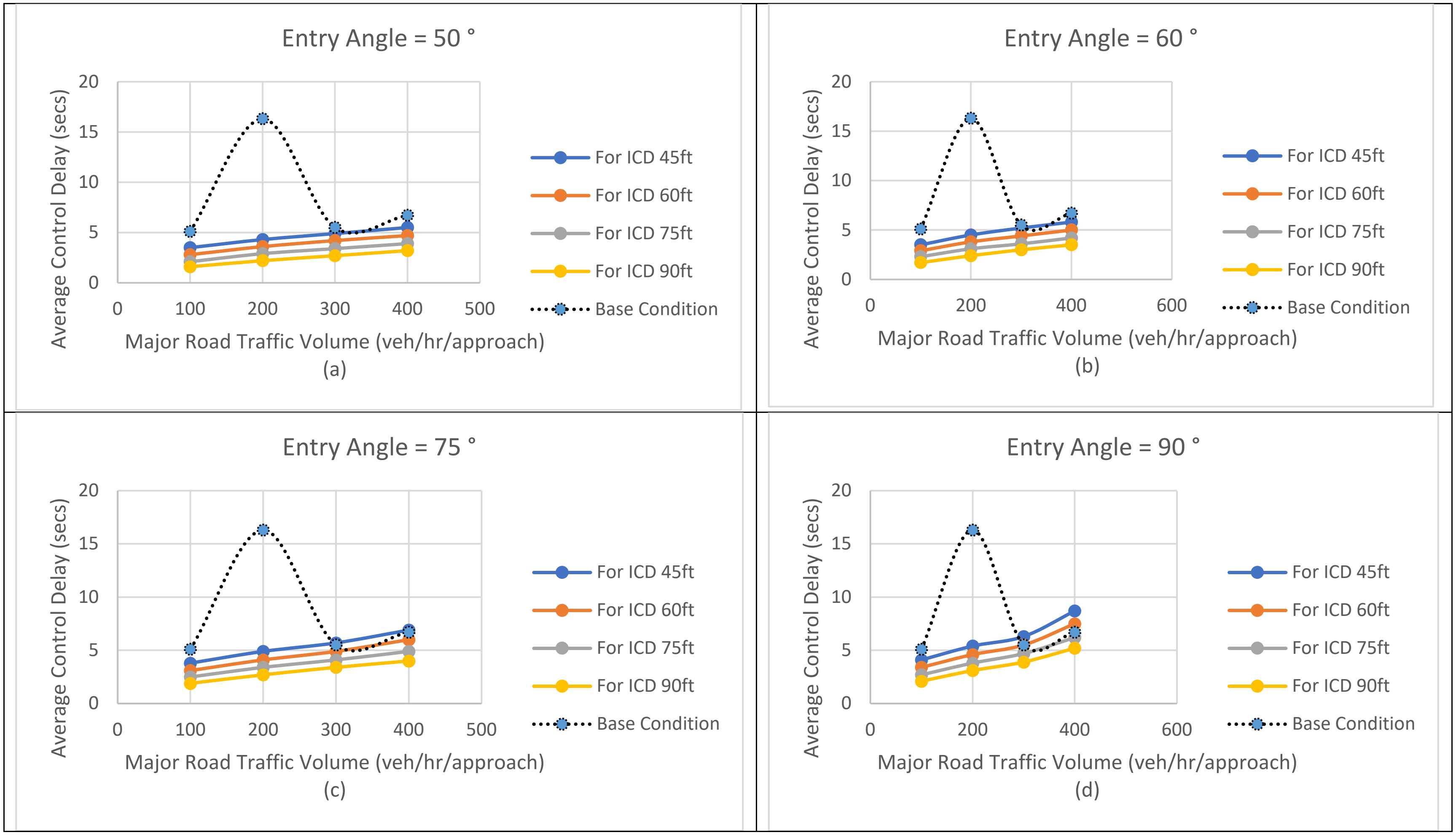


Figure 5.4. Average control delay (secs) based on major road volume, ICD, and EA. (with minor road volume = 200 veh/hr/approach.

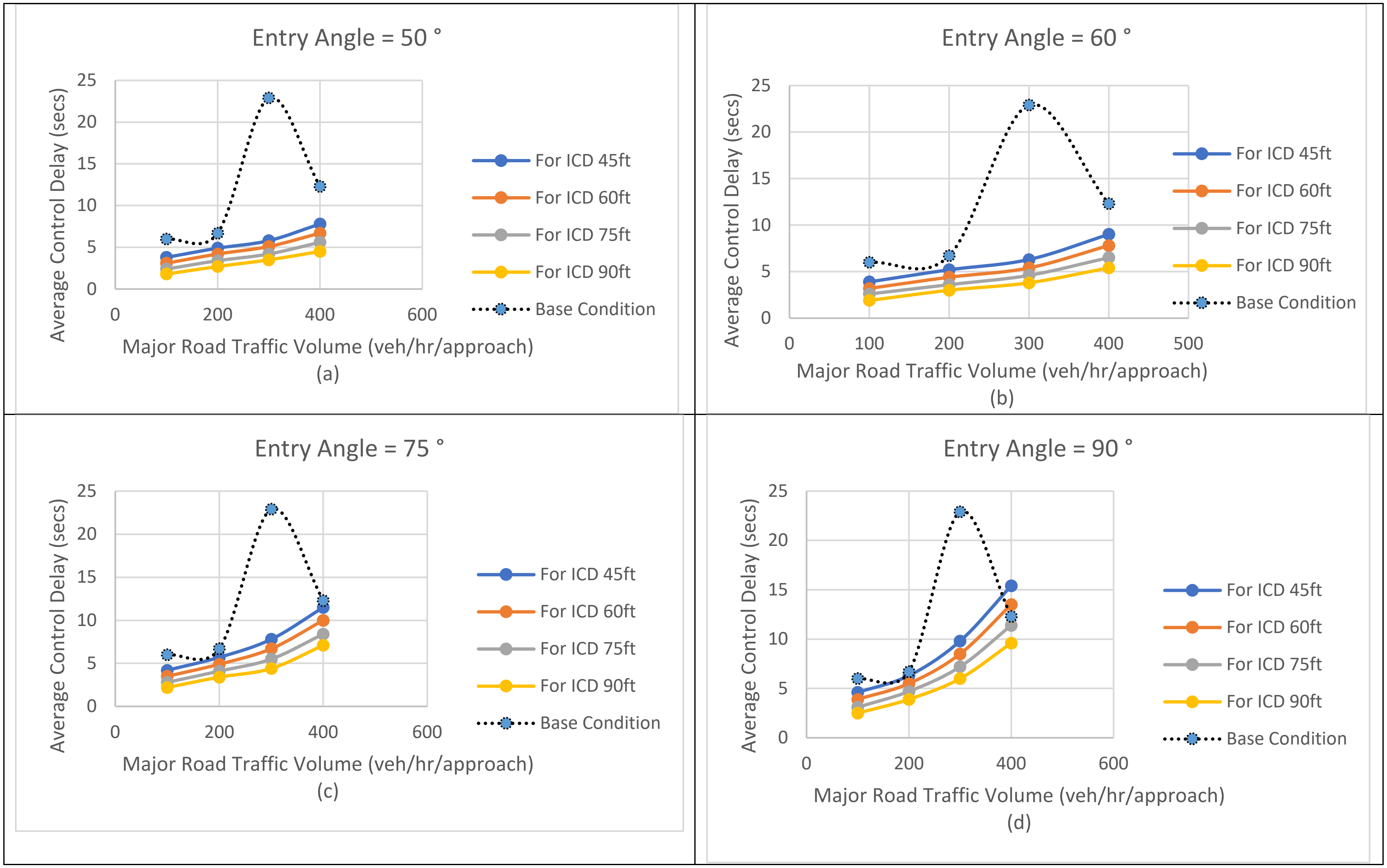


Figure 5.5. Average control delay (secs) based on major road volume, ICD, and EA.
(with minor road volume = 300 veh/hr/approach).

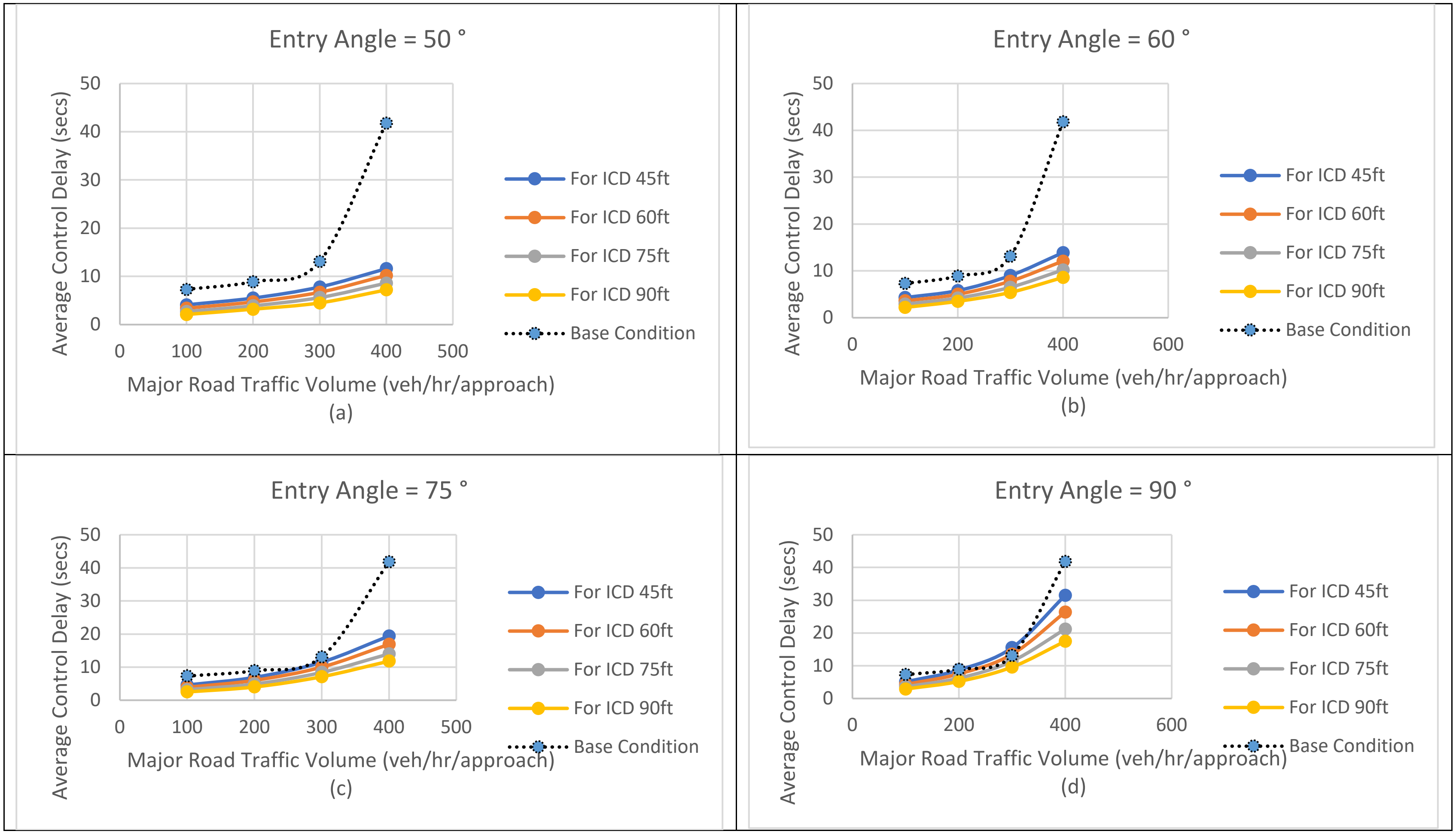


Figure 5.6. Average control delay (secs) based on major road volume, ICD, and EA. (with minor road volume of 400 veh/hr/approach).

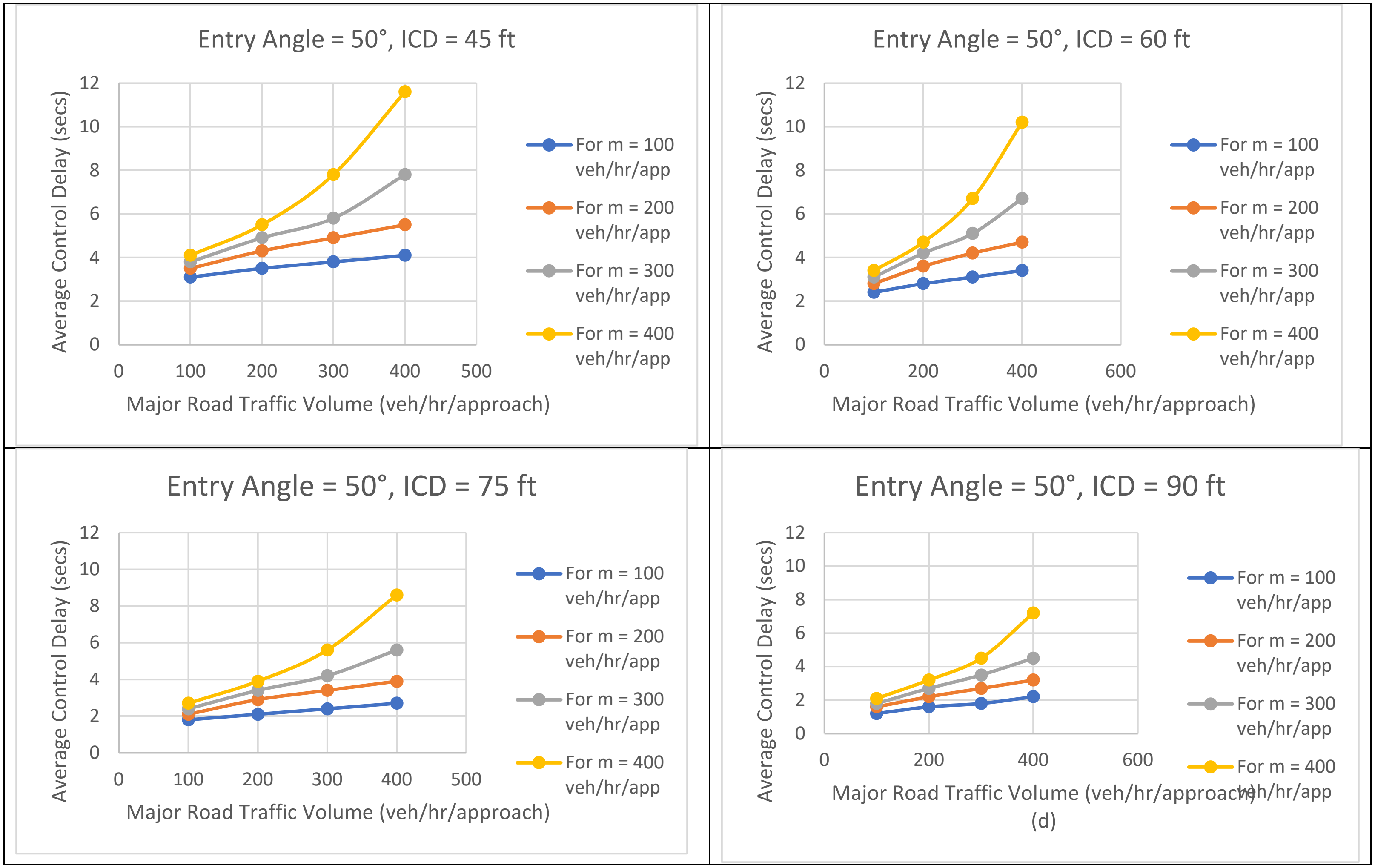


Figure 5.7. Average control delay (secs) based on approach volume and ICD. (with entry angle of 50°)

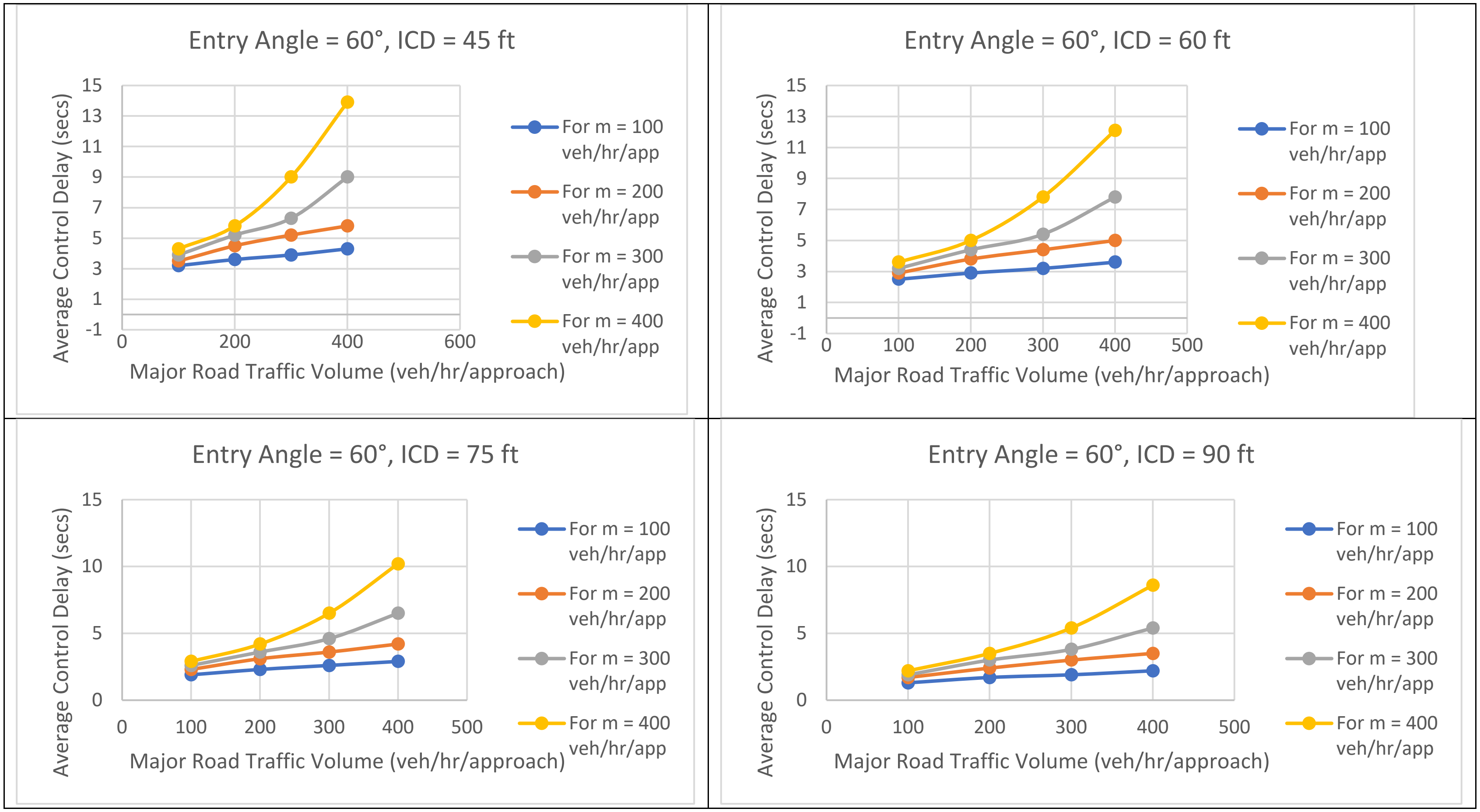


Figure 5.8. Average control delay (secs) based on approach volume and ICD.
(with entry angle of 60°)

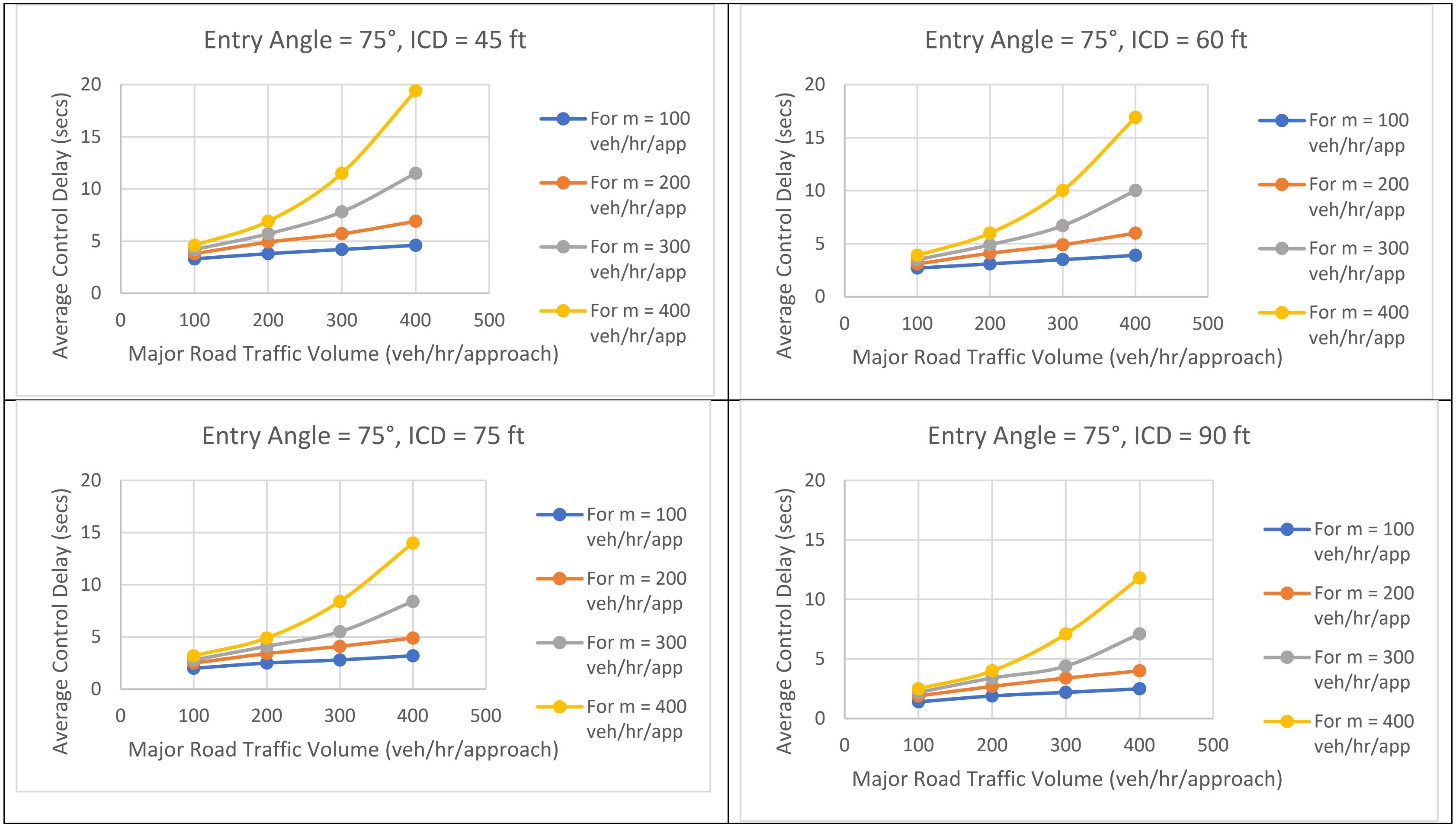


Figure 5.9. Average control delay (secs) based on approach volume and ICD. (with entry angle of 75°)

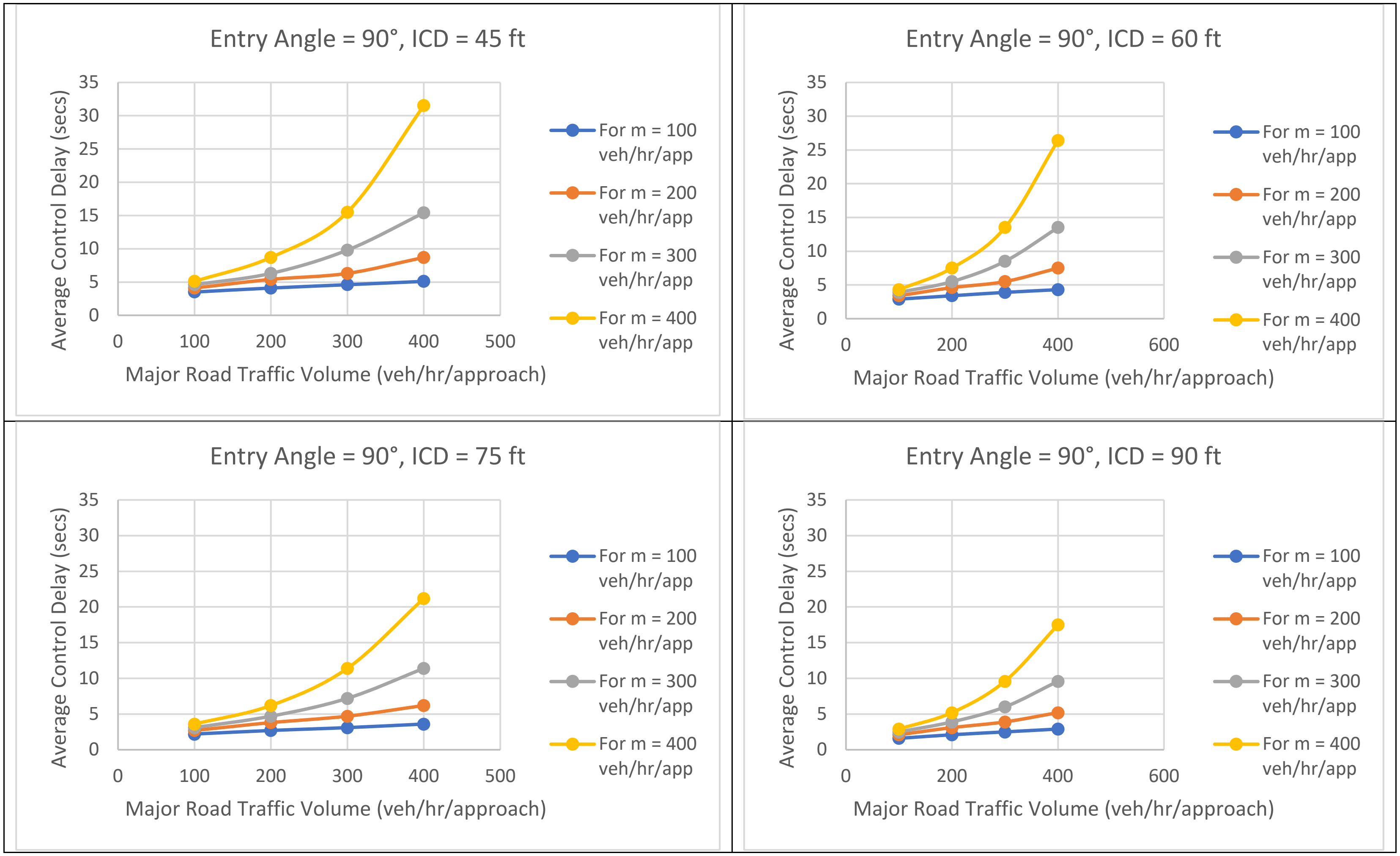


Figure 5.10. Average control delay (secs) based on approach volume and ICD. (with entry angle of 90°)

2.1.3. Average geometric delay

Average geometric delay is defined as the delay experienced by a vehicle due to physical and basic traffic controls whilst navigating an intersection in the absence of any other vehicles and it can be estimated by comparing the travel time of an unconstrained vehicle passing through a roundabout to that needed by an unconstrained vehicle that does not pass through the geometric features of the roundabout (either measured before construction or estimated). Geometric delay is of particular importance when comparing travel times along a corridor (NCHRP 672).

Figure 5.11 illustrates variation of average geometric delay for variable ICD and major road volume, and entry angle of 90° and minor road volume of 400 veh/hr/approach. For higher ICD, average geometric delay is lower. Compared to traditional intersections (TWSC/AWSC), a mini-RAB produces lower average geometric delay. From the simulation results, it can be concluded that entry angle and major road volume do not have any effect on average geometric delay.

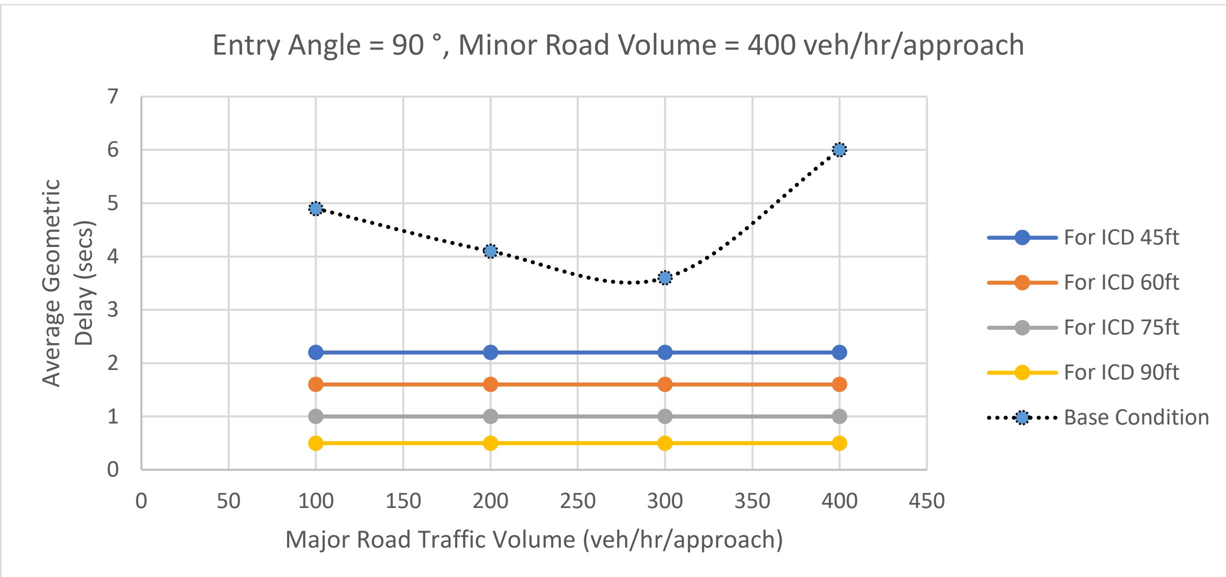


Figure 5.11. Average geometric delay (secs) based on major approach volume and ICD. (with minor road volume of 400 veh/hr/approach)

2.1.4. 95% back-of-queue distance (worst lane)

The distance between the yield line of a roundabout and the farthest reach of an upstream queue, expressed as a number of vehicles or distance value is called queue distance (NCHRP 672). Figures 5.12 to 5.15 illustrate performance of a mini-RAB in terms of 95% back-of-queue distance (worst lane) for different traffic volume (i.e., major, and minor approach) and geometric configurations (ICD and EA). Also shown is a “base condition” – that is, no mini-RAB but a traditional intersection (stop control). Overall, the figures depict that the queue distance (i) decreases as the ICD increases, and (ii) increases as the entry angle, and also traffic volumes increase. As with the average control delay, these trends are expected given that EA, traffic volumes, and ICD affect the gap acceptance ability for entering vehicles.

An ICD of 90-feet and an EA of 50° results in the lowest queue distance among all simulation scenarios. This observation is similar across Figures 5.12 through 5.15. When compared to a traditional intersection (TWSC/AWSC), a mini-RAB produces much lower queue for traffic volume more than 200 veh/hr/approach (Figure 5.14 and 5.15). However, for traffic volume less than 200 veh/hr/approach (Figure 5.12 and 5.13), a mini-RAB produces higher queue distance.

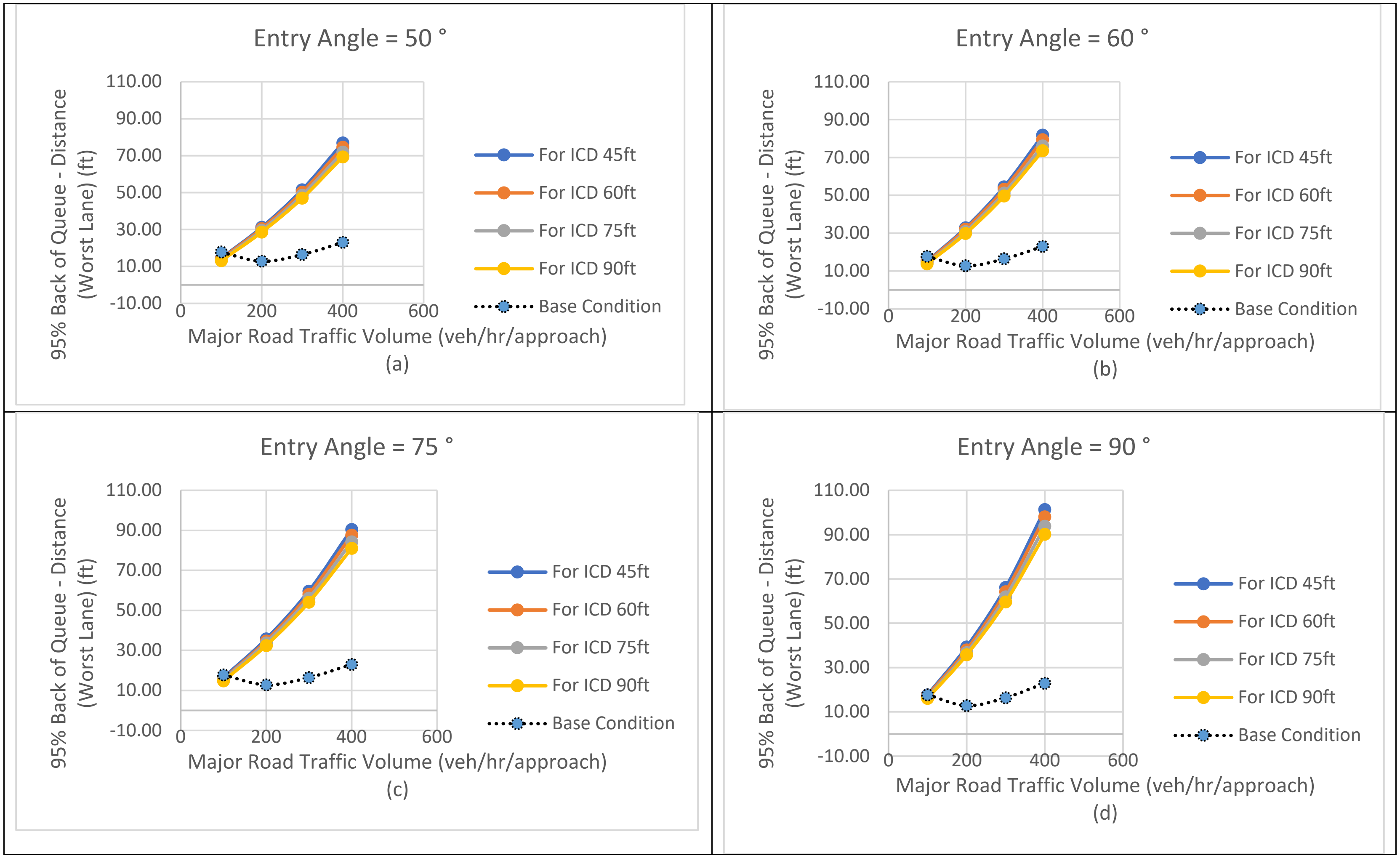


Figure 5.12. 95% back-of-queue distance based on major road volume, ICD, and EA.
(with minor road volume of 100 veh/hr/approach)

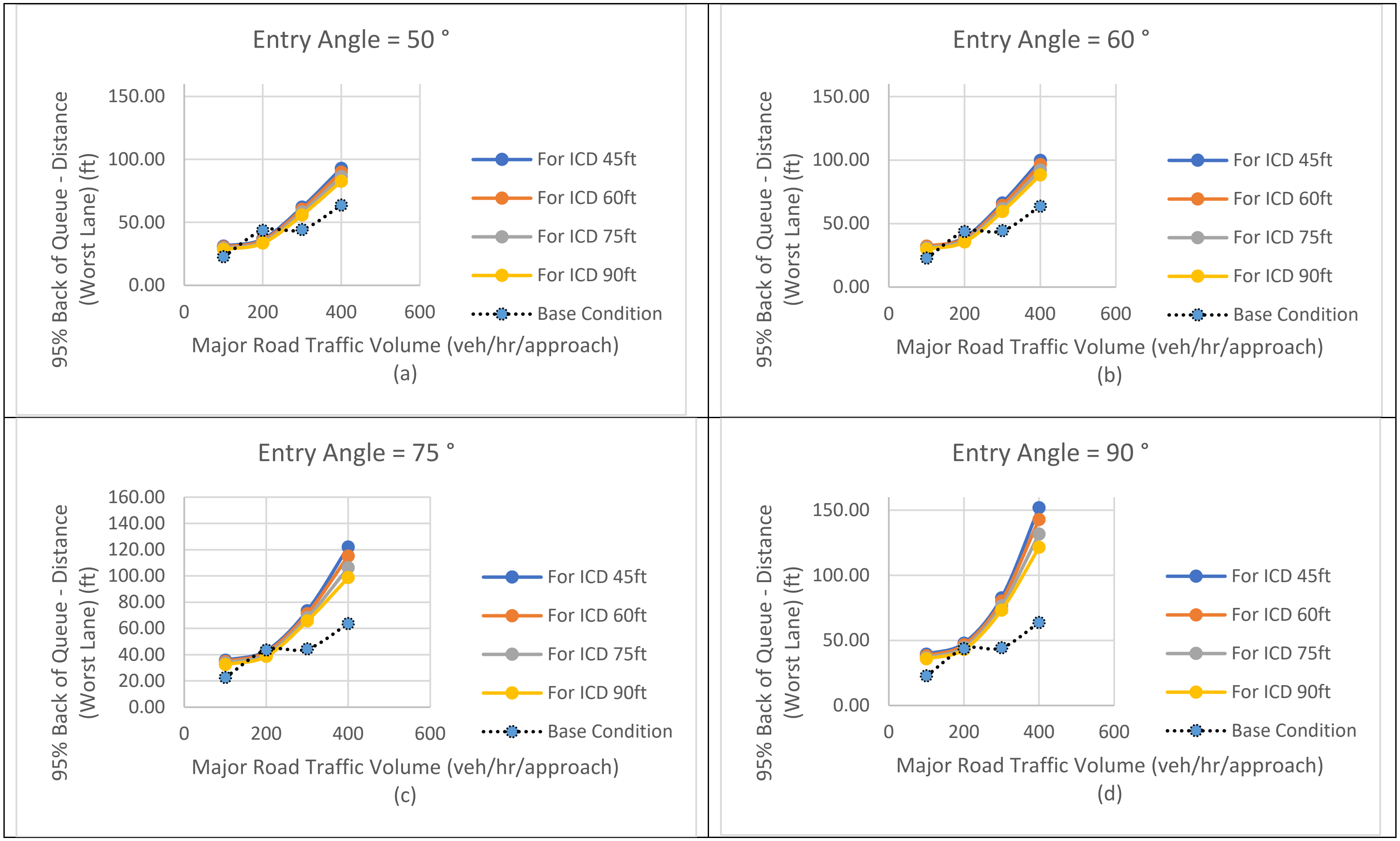


Figure 5.13. 95% back-of-queue distance based on major road volume, ICD, and EA. (with minor road volume of 200 veh/hr/approach)

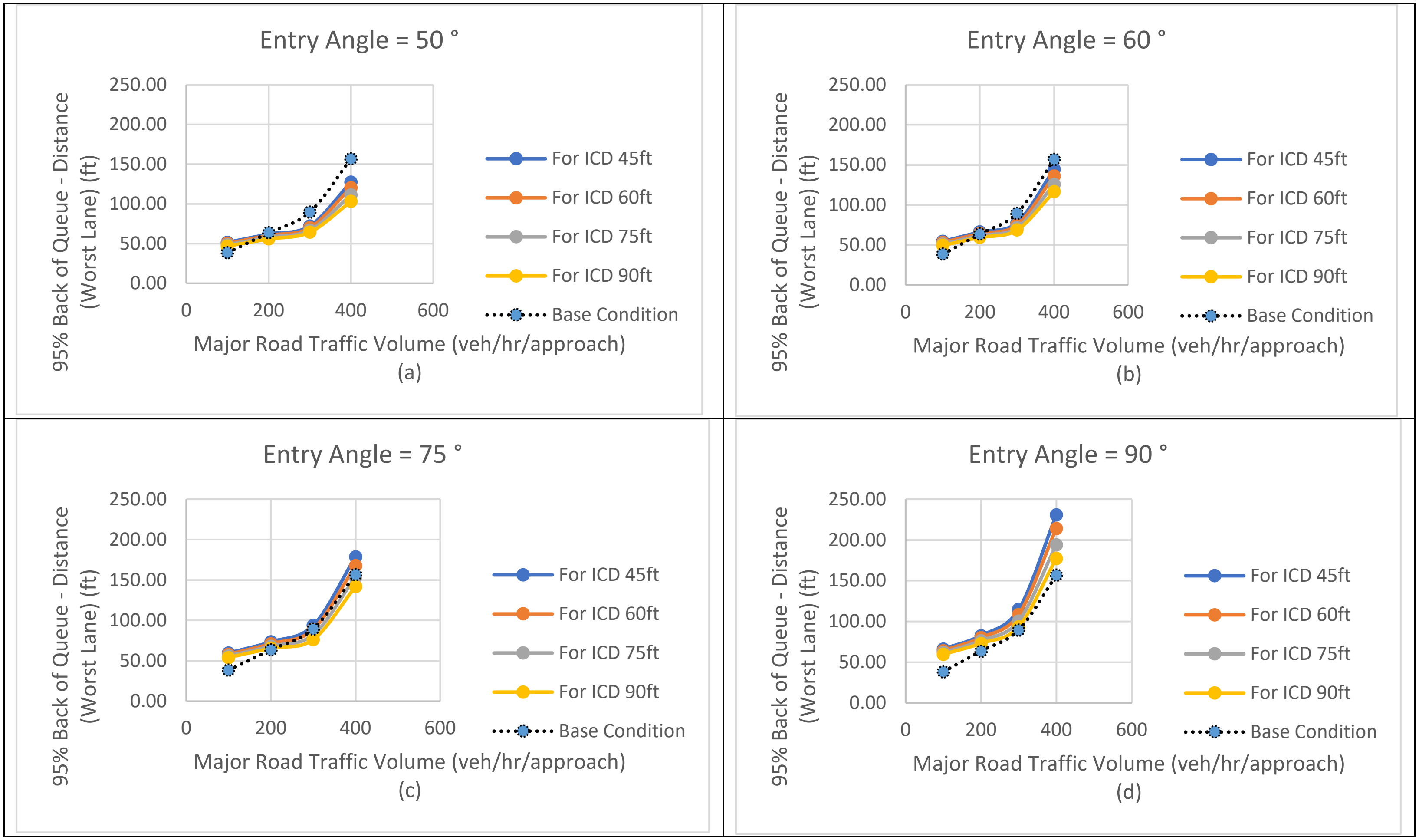


Figure 5.14. 95% back-of-queue distance based on major road volume, ICD, and EA. (with minor road volume of 300 veh/hr/approach)

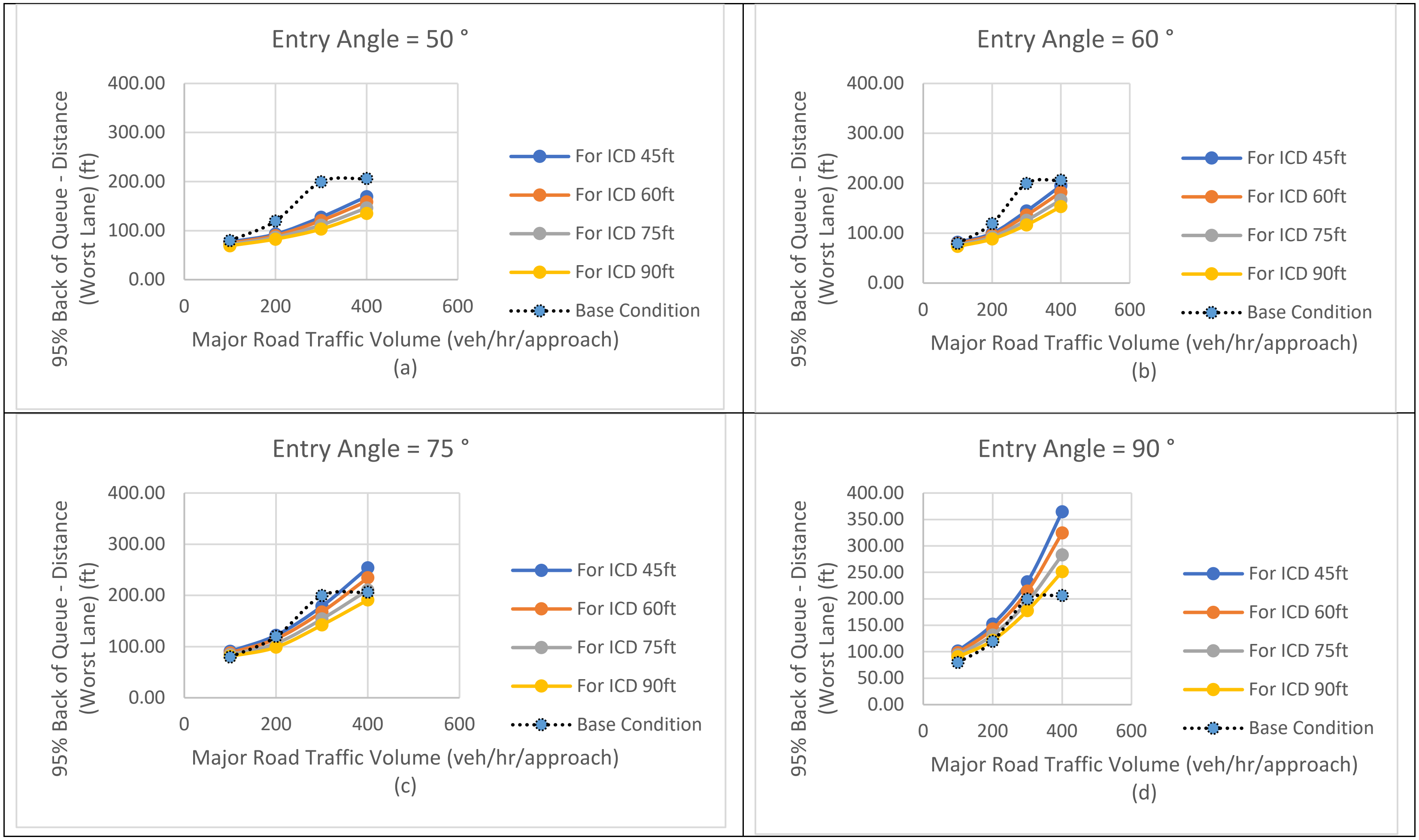


Figure 5.15. 95% back-of-queue distance based on major road volume, ICD, and EA. (with minor road volume of 400 veh/hr/approach)

2.1.5. Effective intersection capacity

Effective intersection capacity is determined as the ratio of total intersection demand flow to the intersection degree of saturation, where the intersection degree of saturation is the largest lane degree of saturation considering all lanes of the intersection (SIDRA). Figures 5.16 to 5.19 illustrate the performance of a mini-RAB in terms of effective intersection capacity for different traffic volume (i.e., major, and minor street traffic volume) and geometric configurations (ICD, and EA). It also shows a "base condition" of traditional intersection with TWSC and AWSC. Overall, the effective intersection capacity increases with increasing ICD, decreasing traffic volume on major approach, and decreasing EA.

An ICD of 90-feet, EA of 50°, and major approach volume of 100 veh/hr/approach with minor approach volume of 100 veh/hr/approach results in the highest effective intersection capacity (Figure 15a). Moreover, the effective intersection capacity is highest when the approaches to the mini-RAB have balanced traffic volumes (Figure 5.17 to 5.19).

When compared to a traditional intersection (TWSC/AWSC), a mini-RAB produces higher effective intersection capacity than AWSC intersections for traffic volume between 100 to 400 veh/hr/approach (Figure 5.17 to 5.20). But, compared to a TWSC intersection, a mini-RAB produces higher effective intersection capacity at traffic volume between 300-400 veh/hr/approach (Figure 5.18 and 5.19).

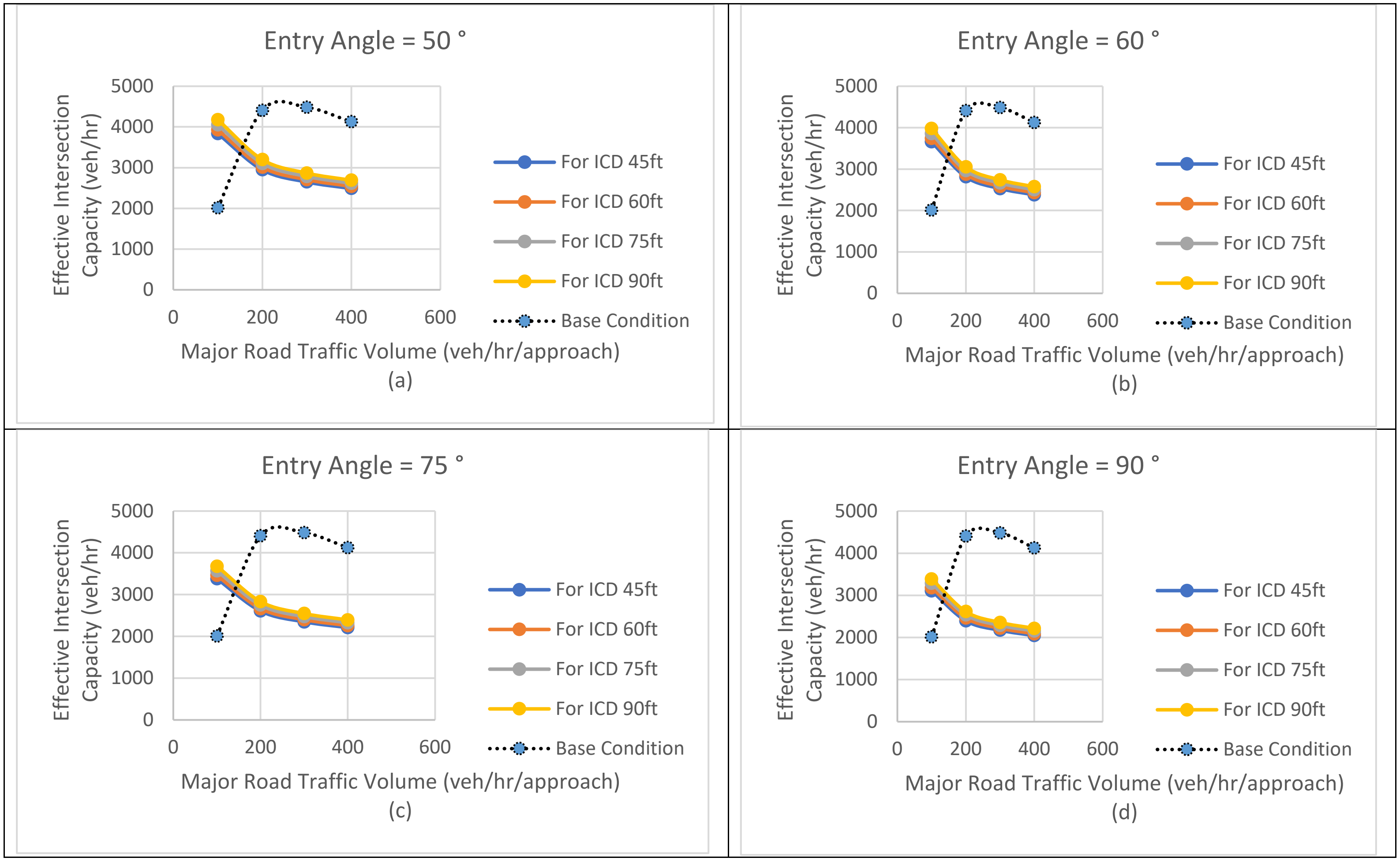


Figure 5.16. Effective intersection capacity based on major road volume, ICD, and EA. (with minor road volume of 100 veh/hr/approach)

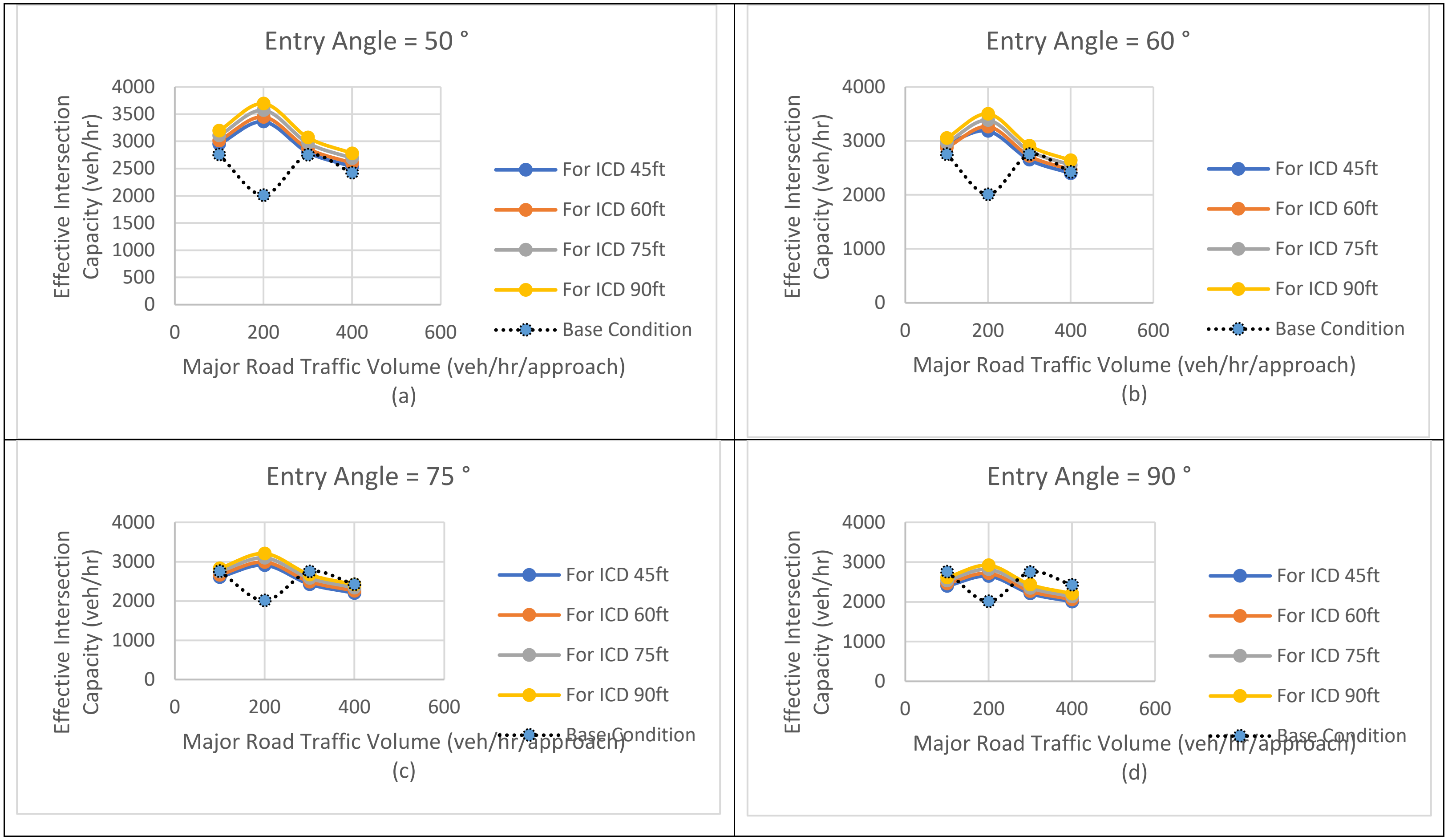


Figure 5.17. Effective intersection capacity based on major road volume, ICD, and EA.
(with minor road volume of 200 veh/hr/approach)

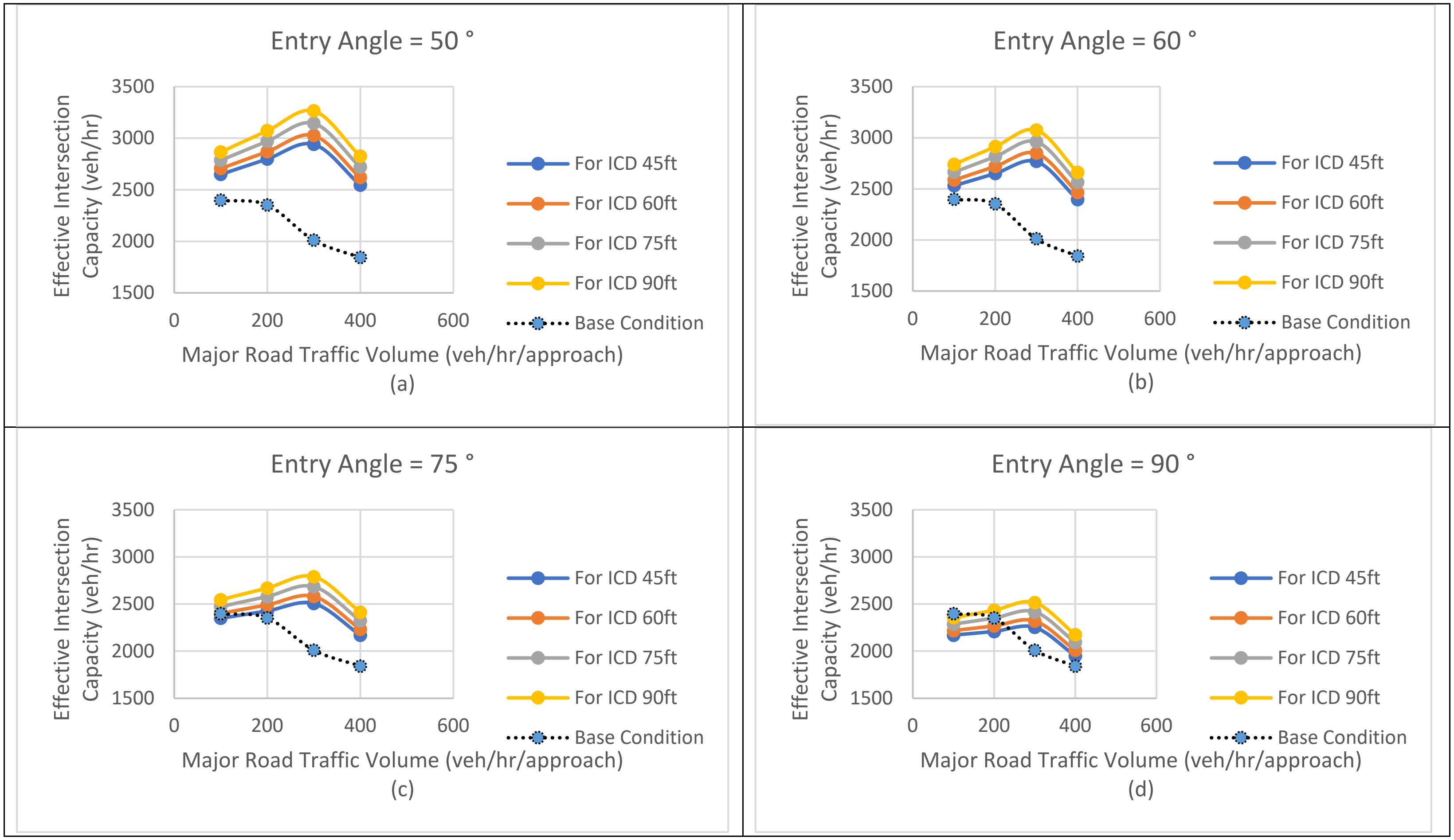


Figure 5.18. Effective intersection capacity based on major road volume, ICD, and EA. (with minor road volume of 300 veh/hr/approach)

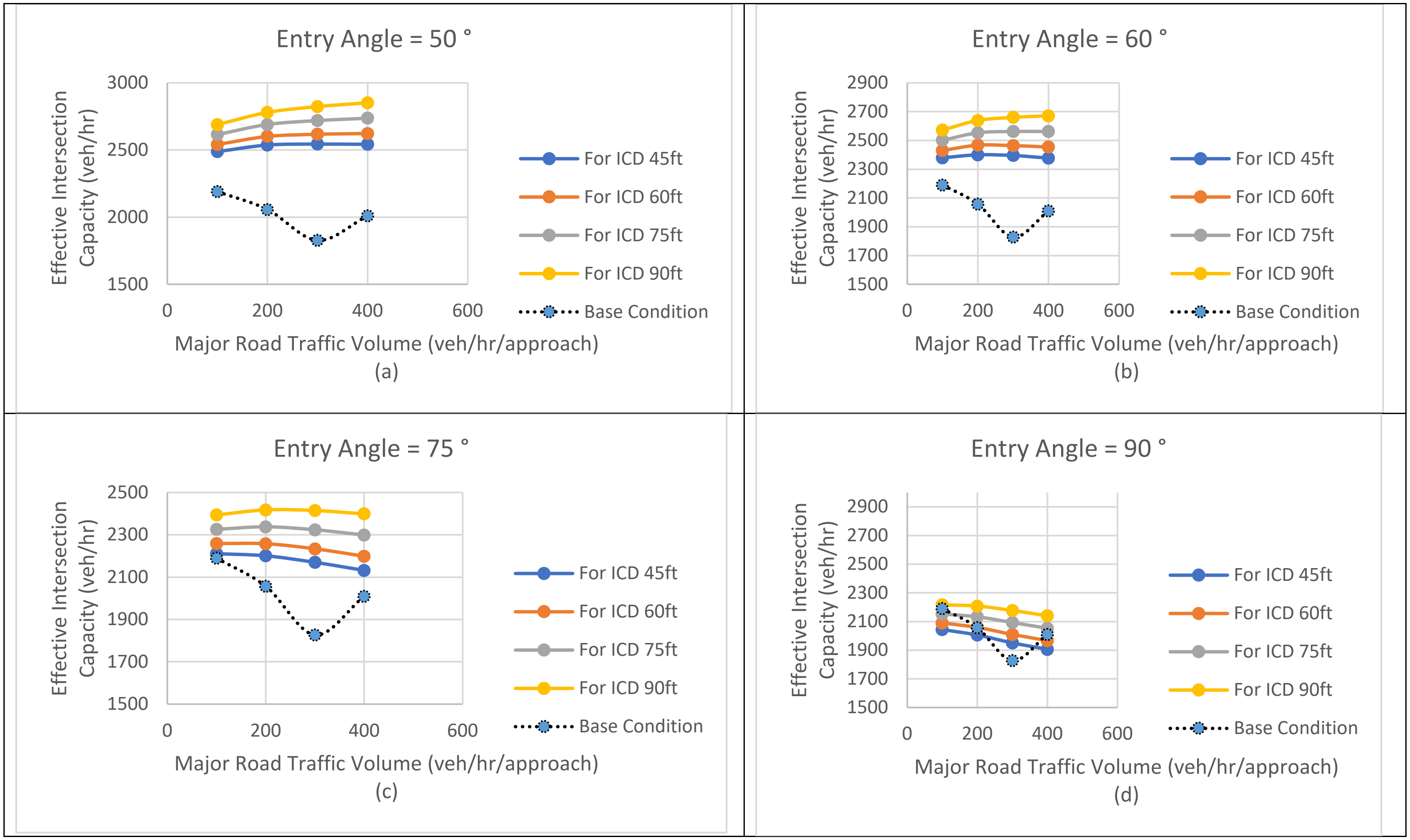


Figure 5.19. Effective intersection capacity based on major road volume, ICD, and EA.
(with minor road volume of 400 veh/hr/approach)

2.1.6. Average travel speed

The travel distance divided by the average travel time where the average travel time includes the effects of intersection delays and delays due to other causes of interruption as well as the traffic delay (uninterrupted flow delay) due to bunching in uninterrupted sections of travel is defined as the average travel speed (SIDRA).

Figures 5.20 to 5.23 illustrate the performance of a mini-RAB in terms of average travel speed (secs) for different traffic volume (i.e., major and minor approaches) and geometric configurations (ICD and EA). Overall, the average travel speed decreases with increasing ICD (upto 75-feet), and increasing traffic volume in major approach. The EA doesn't seem to have any influence on average travel speed.

An ICD of 75-feet, with major and also minor approach volume of 100 veh/hr/approach results in the highest average travel speed (Figure 5.20). This is consistent in Figure 5.21 to 5.23 as well with minor road traffic volume 200 veh/hr/approach to 400 veh/hr/approach. When compared to "base conditions" (stop control), a mini-RAB demonstrates higher average travel speed for any traffic volume between 100 to 400 veh/hr/approach (Figure 5.20 to 5.23). For a 45-feet ICD and lower minor road traffic volume (i.e., less than 300 veh/hr/approach), a TWSC intersection displays higher average travel speed (Figure 5.20 and 5.21).

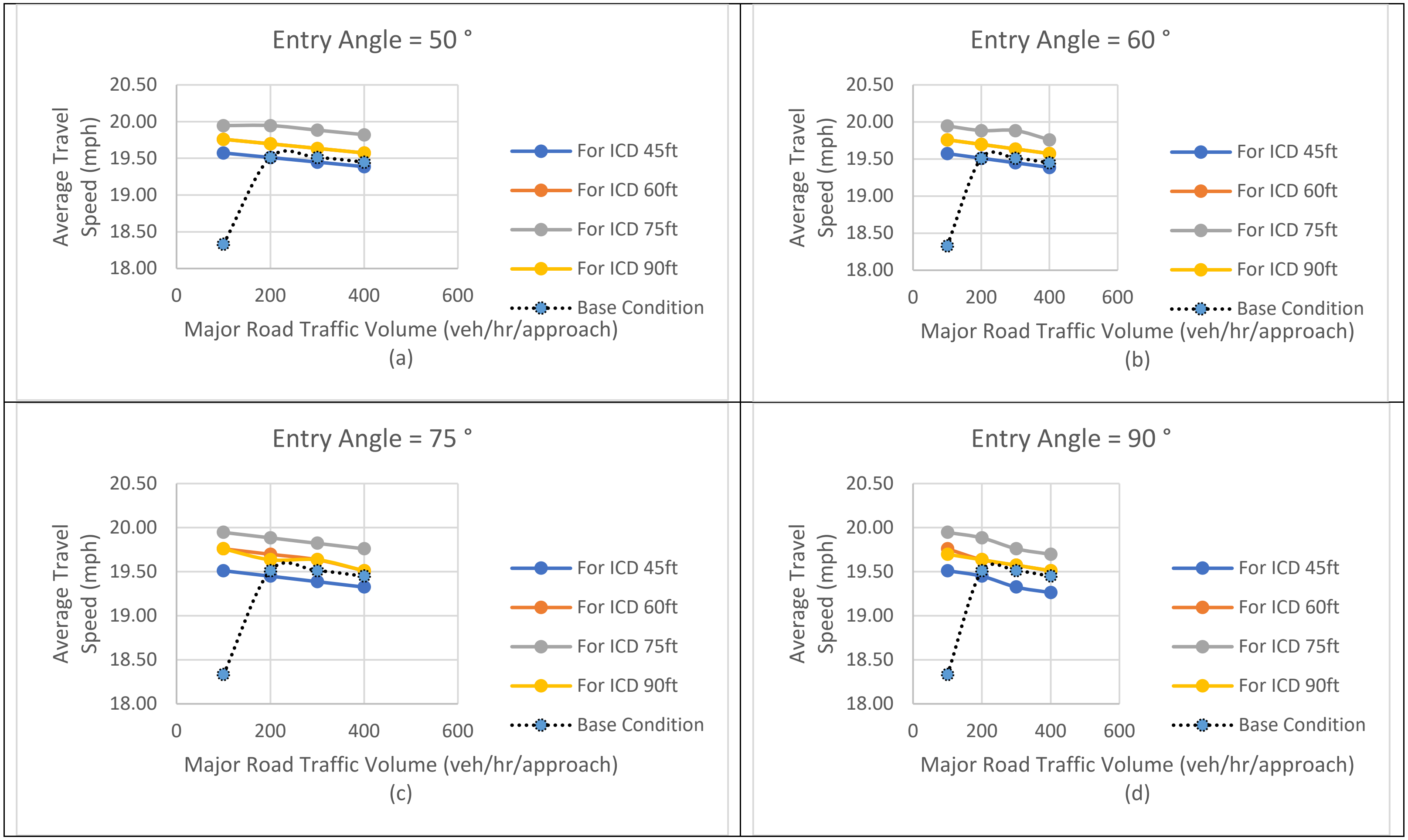


Figure 5.20. Average travel speed based on major road volume, ICD, and EA.
(with minor road volume of 100 veh/hr/approach)

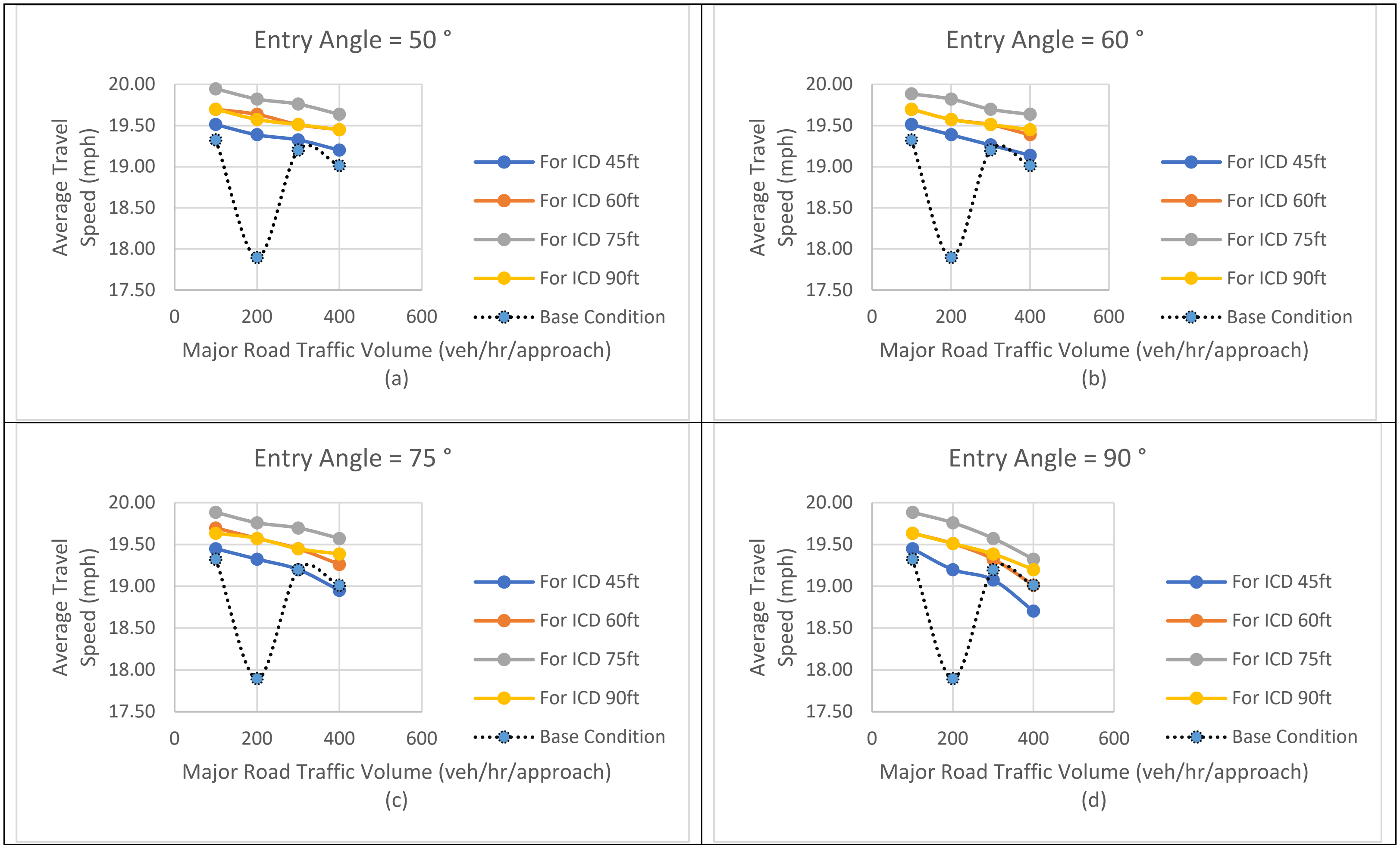


Figure 5.21. Average travel speed based on major road volume, ICD, and EA.
(with minor road volume of 200 veh/hr/approach)

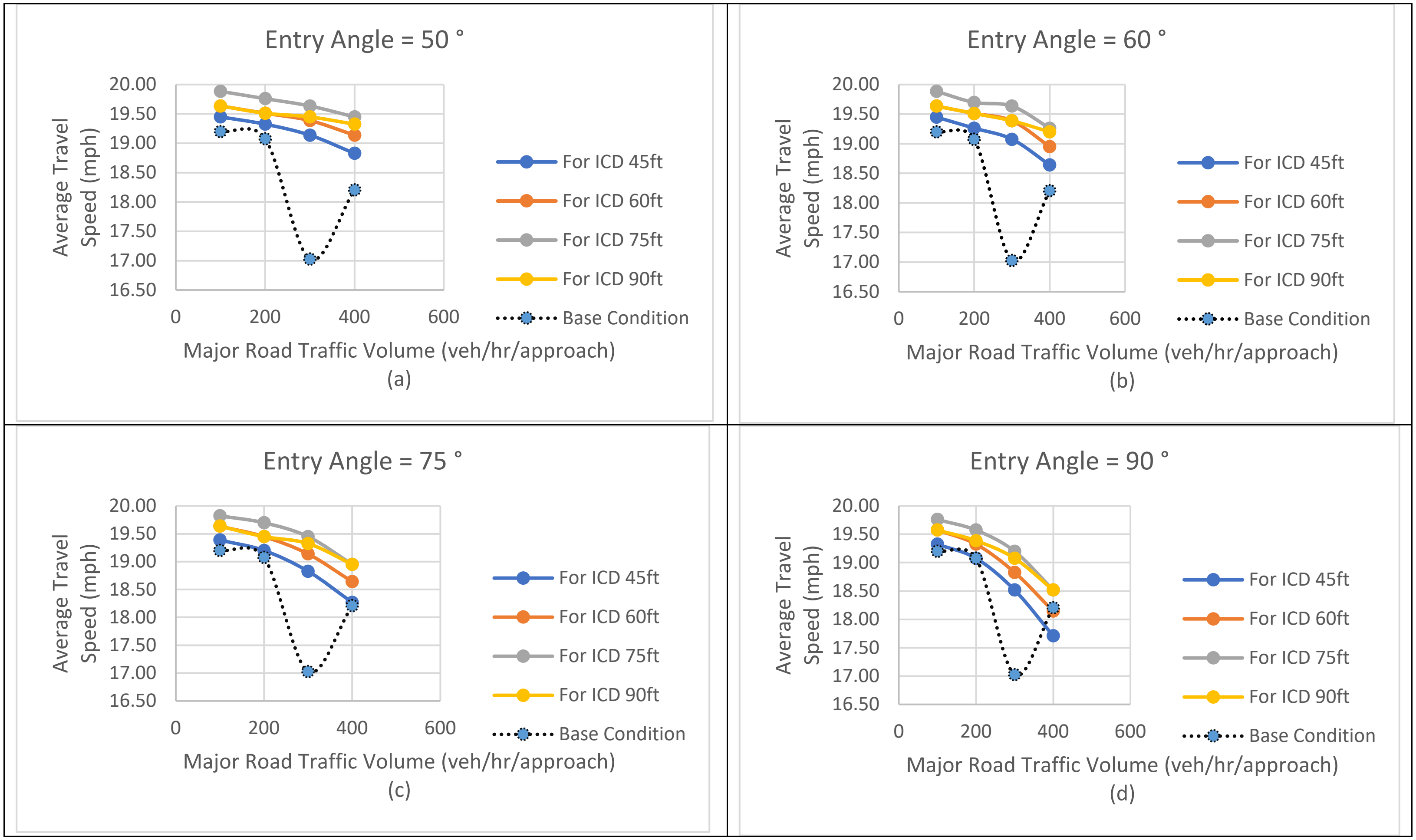


Figure 5.22. Average travel speed based on major road volume, ICD, and EA.
(with minor road volume of 300 veh/hr/approach)

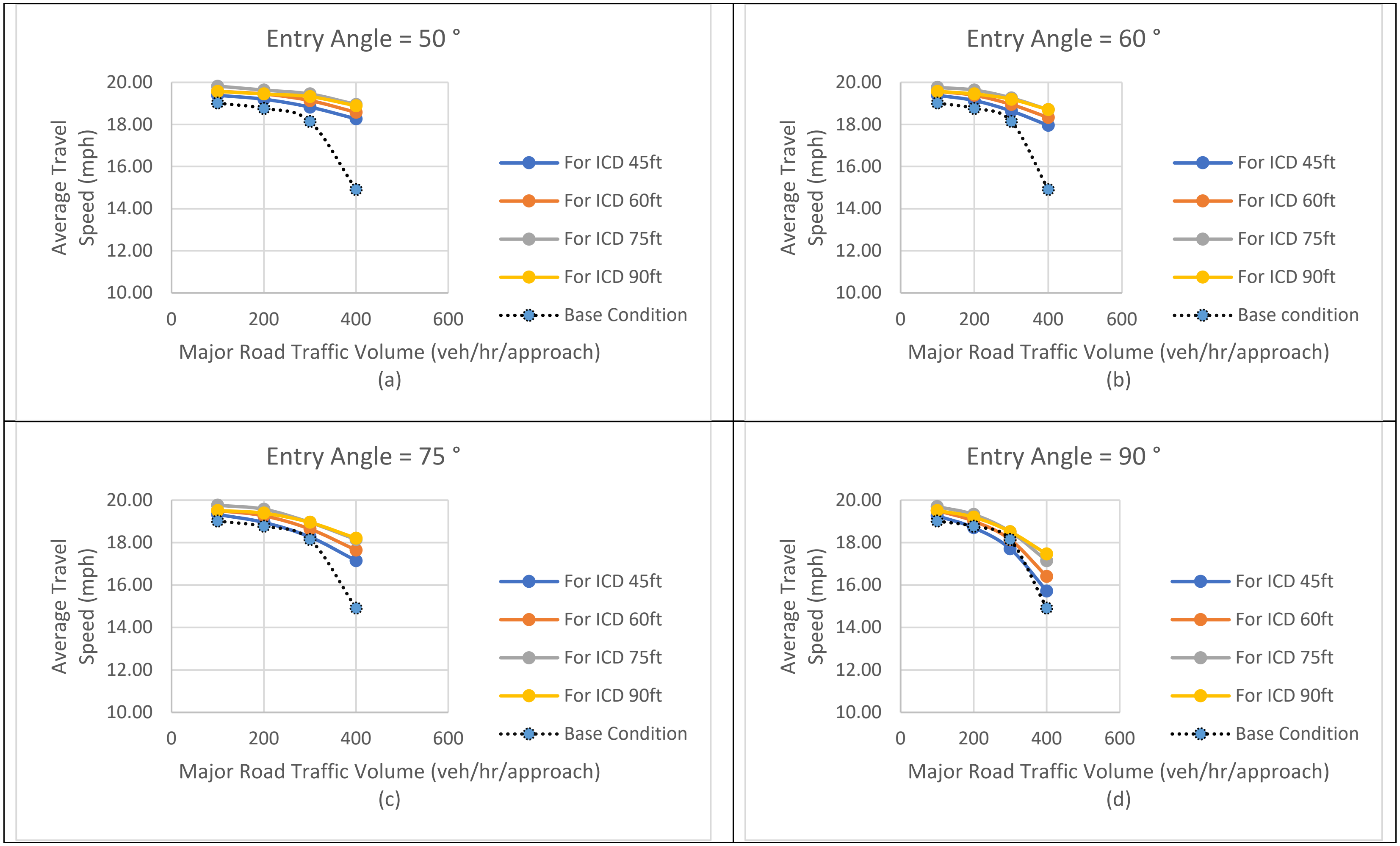


Figure 5.23. Average travel speed based on major road volume, ICD, and EA. (with minor road volume of 400 veh/hr/approach)

2.1.7. Level of Service (LOS)

LOS is a quantitative stratification of a performance measure that represent quality of service. The Highway Capacity Manual (HCM) defines six levels of service, ranging from A to F where LOS A represents the best operating conditions from the traveler's perspective and LOS F the worst. LOS by approaches for all simulated scenarios are presented in Table 2 of the Appendix. From the results, it can be seen that, overall and as expected, the LOS decreases with increased traffic volume. When the total entering volume was greater than 1400 veh/hr, the LOS decreases from A to B. Also, with decreasing ICD and increasing EA, LOS decreases – this is expected since a smaller ICD relates to more vehicles whereas, an increasing EA causes queuing.

Compared to an AWSC intersection, a mini-RAB demonstrates better LOS for similar traffic volumes. For example, with a traffic volume of 400 veh/hr/approach on all four approaches, the lowest LOS for a mini-RAB is C, whereas for a AWSC intersection it is E (Table A4).

2.2. Safety Performance Analysis.

For the safety performance analysis, total number of conflicts and different types of conflicts (crossing, rear-end, and lane-change) were estimated. VISSIM 11.0 was used to generate vehicle trajectory files for various scenarios; and these trajectory files were analyzed using SSAM 3.0.

2.2.1. Conflicts – frequency and type

The simulation scenarios presented in Table 1 were modeled in VISSIM and later in SSAM with the results presented in Table 5.2.

Table 5.2. Output of Safety Analysis from VISSIM and SSAM.

Scenarios	Total number of collisions	Collision Type		
		crossing	rear end	lane change
S1	1	0	1	0
S2	16	1	14	1
S3	8	0	8	0
S4	120	0	118	2
Total	145	1	141	3

Each of the four-simulation scenarios were run for an hour and collision data collected. It was observed that the number of conflicts increases with the increased demand volume however, the relationship is not linear. There is a sudden increase of conflicts after the demand volume crosses 1000 veh/hr. Based on safety alone, the optimum demand volume is between 800 and 1000 veh/hr. Both combination of approaches (i.e. major-minor, and major-major) performs well at this volume range. Details of safety analysis scenarios and outputs are in the Appendix.

2.3. Sensitivity Analysis.

A sensitivity analysis was also performed to evaluate the effect of traffic conditions (i.e., major road volume, and turn percent) on safety performance (number of conflicts) of mini-RAB. A total of 16 simulation scenarios were run to measure the effect of major road volume on number of conflicts (analysis

1) and another 16 simulation scenarios were run to measure the effect of turn percent on number of conflicts (analysis 2). SIDRA, VISSIM, and SSAM were used for sensitivity analysis. Detail of sensitivity analysis are in Appendix D.

2.3.1. Effect of approach volume on total number of conflicts

Two-way major approach volume upto 800 veh/hr with a two-way minor approach volume of 400 veh/hr performs the best in terms of total number of conflicts (around 50) for a mini-RAB. Beyond these approach volumes, the total number of conflicts increases sharply. Hence, from the sensitivity analysis it can be concluded that, the optimal ratio between major and minor approach volume should be 2:1 and the total entering volume of a mini-RAB should be less than 1200 veh/hr.

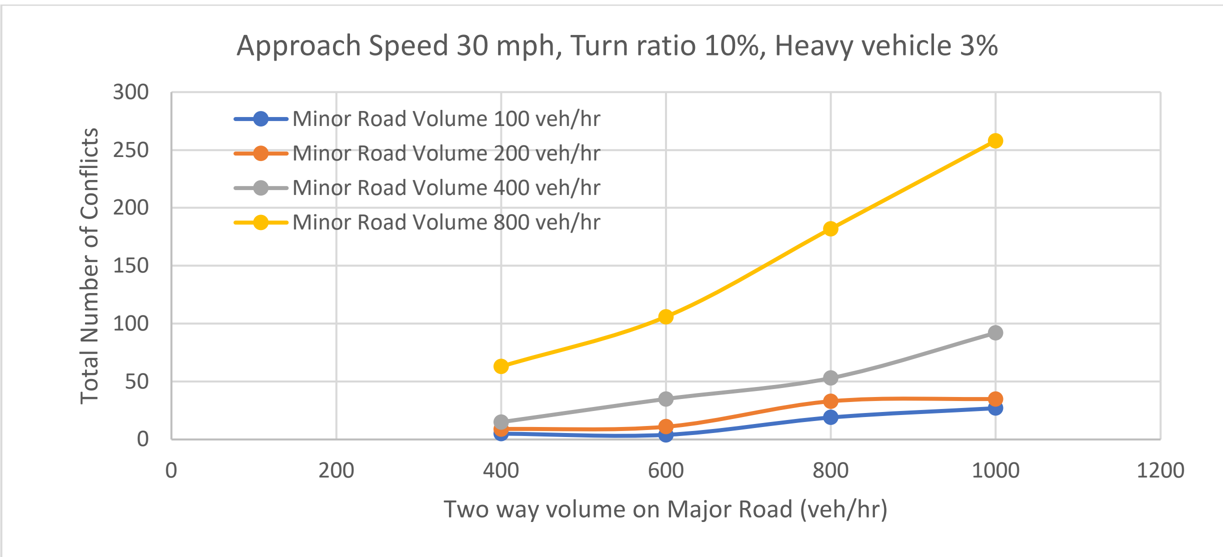


Figure 5.24. Effect of major approach volume on total number of conflicts.

2.3.2. Effect of turning volume on total number of conflicts

Turn percentages do not seem to have much effect on total number of conflicts for two-way major approach volume upto 600 veh/hr with a two-way minor approach volume of 400 veh/hr. But, when two-way major approach volume exceeds 600 veh/hr with a two-way minor approach volume of 400 veh/hr, turn percent more than 15% produces more conflicts. So, when the major approach volume is more than 600 veh/hr with minor approach volume is 400 veh/hr (or total entering volume is 1000 veh/hr), turning percent should not be more than 15%.

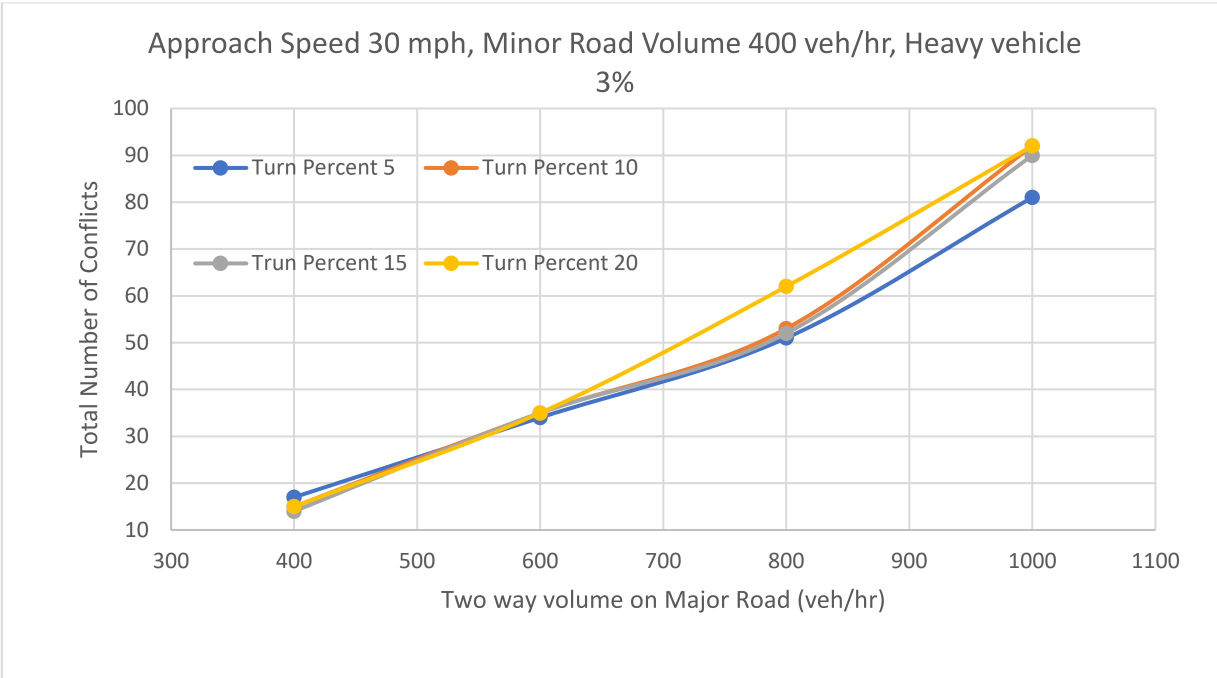


Figure 5.25. Effect of turn percentages on total number of conflicts.

Additional Description of Microsimulation Assessment

Objective

The objective of this research was to conduct a simulation study to investigate the impacts of different mini-roundabout design features and traffic composition to assist transportation engineers in deploying mini roundabout in their jurisdictions. The simulations were conducted to evaluate the effects of variable design characteristics of mini-roundabouts on the intersection's operational and safety performance. The design parameters being studied were inscribed circle diameter, entry angle, number of approaches, and total vehicular flow and configuration. For operational performance analysis, five operational performance indicators were selected (i.e., effective intersection capacity, control delay, geometric delay, 95% back of queue distance, and average travel speed) for evaluation. For safety analysis, total number of conflicts and different types of conflicts (i.e., crossing, rear end, and lane change) were taken as indicators for evaluation. The results of this simulation study will be helpful to (i) provide insight into selecting appropriate design dimensions of mini-roundabout for specific locations and traffic conditions, and (ii) guide decisions regarding the installation and/or removal of mini/modular roundabouts arising from anticipated changes in demand.

Methodology

For this simulation study, SIDRA INTERSECTION 8.0, VISSIM 11.0, and SSAM 3.0 softwares were used. For operational performance analysis SIDRA was used and for safety analysis VISSIM along with SSAM were used. SIDRA allows analysis of single-lane and multi-lane roundabouts. It employs a combined (hybrid) geometry and gap-acceptance modelling approach in order to calculate the effect of roundabout geometry on driver behavior directly through gap-acceptance modelling. The operation of vehicular traffic at a roundabout is determined by gap acceptance: entering vehicles look for and accept gaps in circulating traffic. The low speeds of a roundabout facilitate this gap acceptance process. Furthermore, the operational efficiency (capacity) of roundabouts is greater at lower circulating speed because of the following two phenomena: 1. The faster the circulating traffic, the larger the gaps that entering traffic will comfortably accept. This translates to fewer acceptable gaps and therefore, more instances of entering vehicles stopping at the yield line. 2. Entering traffic, which is first stopped at the yield line, requires even larger gaps in the circulating traffic in order to accelerate and merge with the circulating traffic. The faster the circulating traffic, the larger this gap must be. This translates into fewer acceptable gaps and therefore longer delays for entering traffic (NCHRP Report 672). Sidra Intersection software includes templates for roundabouts including all roundabout examples given in MUTCD 2009 (i.e., template name- Rou 4-way 1&2-Lane R, MUTCD (FHWA 2009) example number: 3C-4) and TRB/FHWA 2010 Roundabout Informational Guide (NCHRP Report 672) (i.e., template name- Rou 4-way 1&2-Lane R, Roundabout Guide (TRB 2010) example number: A-3). A recent NCHRP survey of US state transport agencies found that Sidra Intersection is the most widely used software tool in the US for roundabout analysis (Alek et. al, 2016). VISSIM was used to model simulation scenarios which provides simulated vehicle tracking data (trajectories). These trajectory data can be analyzed using the Surrogate Safety Assessment Model (SSAM) developed by the FHWA (Gettman et al. 2008). The integration of microsimulation and surrogate safety performance measures allows for the assessment of the benefits (safety and operational) in-lieu of observed traffic and crash data. SSAM based indirect safety assessment and the findings provide us with insight on potential conflicts arising from design changes.

Operational Performance Analysis

Output from SIDRA Simulation for Operational Performance

Table F1. SIDRA Output for Operational Performance Analysis of Mini-Roundabout.

Scenarios	ICD (ft)	EA (°)	Major Road Volume (veh/hr/leg)	Minor Road Volume (veh/hr/leg)	Demand Flow (total) (veh/hr)	Average Control Delays (secs)	Average Geometric Delays (secs)	95% Back of Queue -Dist. (Worst Lane) (ft)	LOS	Effective Intersection Capacity (veh/hr)
1	45	50	100	100	421	3.1	2.2	14.44	A	3838
2	45	50	100	200	632	3.5	2.2	31.17	A	2948
3	45	50	100	300	842	3.8	2.2	51.51	A	2648
4	45	50	100	400	1053	4.1	2.2	76.77	A	2488
5	45	50	200	100	632	3.5	2.2	31.17	A	2948
6	45	50	200	200	842	4.3	2.2	36.75	A	3361
7	45	50	200	300	1053	4.9	2.2	62.01	A	2798
8	45	50	200	400	1263	5.5	2.2	92.85	A	2537
9	45	50	300	100	842	3.8	2.2	51.51	A	2648
10	45	50	300	200	1053	4.9	2.2	62.01	A	2798
11	45	50	300	300	1263	5.8	2.2	72.18	A	2940
12	45	50	300	400	1474	7.8	2.2	127.3	A	2544
13	45	50	400	100	1053	4.1	2.2	76.77	A	2488
14	45	50	400	200	1263	5.5	2.2	92.85	A	2537
15	45	50	400	300	1474	7.8	2.2	127.3	A	2544
16	45	50	400	400	1684	11.6	2.2	169.29	B	2542
17	60	50	100	100	421	2.4	1.6	14.11	A	3927
18	60	50	100	200	632	2.8	1.6	30.51	A	3013
19	60	50	100	300	842	3.1	1.6	50.2	A	2705
20	60	50	100	400	1053	3.4	1.6	74.48	A	2541
21	60	50	200	100	632	2.8	1.6	30.51	A	3013
22	60	50	200	200	842	3.6	1.6	35.76	A	3448
23	60	50	200	300	1053	4.2	1.6	60.37	A	2869
24	60	50	200	400	1263	4.7	1.6	89.9	A	2601
25	60	50	300	100	842	3.1	1.6	50.2	A	2705
26	60	50	300	200	1053	4.2	1.6	60.37	A	2869
27	60	50	300	300	1263	5.1	1.6	69.88	A	3025
28	60	50	300	400	1474	6.7	1.6	120.41	A	2617
29	60	50	400	100	1053	3.4	1.6	74.48	A	2541
30	60	50	400	200	1263	4.7	1.6	89.9	A	2601
31	60	50	400	300	1474	6.7	1.6	120.41	A	2617
32	60	50	400	400	1684	10.2	1.6	158.79	B	2623

33	75	50	100	100	421	1.8	1	13.45	A	4051
34	75	50	100	200	632	2.1	1	29.53	A	3105
35	75	50	100	300	842	2.4	1	48.56	A	2785
36	75	50	100	400	1053	2.7	1	71.85	A	2615
37	75	50	200	100	632	2.1	1	29.53	A	3105
38	75	50	200	200	842	2.9	1	34.45	A	3571
39	75	50	200	300	1053	3.4	1	58.07	A	2970
40	75	50	200	400	1263	3.9	1	86.29	A	2690
41	75	50	300	100	842	2.4	1	48.56	A	2785
42	75	50	300	200	1053	3.4	1	58.07	A	2970
43	75	50	300	300	1263	4.2	1	66.93	A	3144
44	75	50	300	400	1474	5.6	1	111.22	A	2719
45	75	50	400	100	1053	2.7	1	71.85	A	2615
46	75	50	400	200	1263	3.9	1	86.29	A	2690
47	75	50	400	300	1474	5.6	1	111.22	A	2719
48	75	50	400	400	1684	8.6	1	146.33	A	2737
49	90	50	100	100	421	1.2	0.5	13.12	A	4176
50	90	50	100	200	632	1.6	0.5	28.54	A	3197
51	90	50	100	300	842	1.8	0.5	46.92	A	2865
52	90	50	100	400	1053	2.1	0.5	69.23	A	2689
53	90	50	200	100	632	1.6	0.5	28.54	A	3197
54	90	50	200	200	842	2.2	0.5	33.46	A	3694
55	90	50	200	300	1053	2.7	0.5	55.77	A	3071
56	90	50	200	400	1263	3.2	0.5	82.68	A	2780
57	90	50	300	100	842	1.8	0.5	46.92	A	2865
58	90	50	300	200	1053	2.7	0.5	55.77	A	3071
59	90	50	300	300	1263	3.5	0.5	64.3	A	3264
60	90	50	300	400	1474	4.5	0.5	103.02	A	2823
61	90	50	400	100	1053	2.2	0.5	69.23	A	2689
62	90	50	400	200	1263	3.2	0.5	82.68	A	2780
63	90	50	400	300	1474	4.5	0.5	103.02	A	2823
64	90	50	400	400	1684	7.2	0.5	135.17	A	2852
65	45	60	100	100	421	3.2	2.2	15.09	A	3656
66	45	60	100	200	632	3.5	2.2	31.17	A	2948
67	45	60	100	300	842	3.9	2.2	54.46	A	2530
68	45	60	100	400	1053	4.3	2.2	81.69	A	2379
69	45	60	200	100	632	3.6	2.2	32.81	A	2813
70	45	60	200	200	842	4.5	2.2	39.04	A	3182

71	45	60	200	300	1053	5.2	2.2	66.27	A	2650
72	45	60	200	400	1263	5.8	2.2	99.74	A	2400
73	45	60	300	100	842	3.9	2.2	54.46	A	2530
74	45	60	300	200	1053	5.2	2.2	66.27	A	2650
75	45	60	300	300	1263	6.3	2.2	77.76	A	2767
76	45	60	300	400	1474	9	2.2	144.36	A	2395
77	45	60	400	100	1053	4.3	2.2	81.69	A	2379
78	45	60	400	200	1263	5.8	2.2	99.74	A	2400
79	45	60	400	300	1474	9	2.2	144.36	A	2395
80	45	60	400	400	1684	13.9	2.2	195.21	B	2377
81	60	60	100	100	421	2.5	1.6	14.76	A	3741
82	60	60	100	200	632	2.9	1.6	32.15	A	2876
83	60	60	100	300	842	3.2	1.6	53.15	A	2585
84	60	60	100	400	1053	3.6	1.6	79.4	A	2430
85	60	60	200	100	632	2.9	1.6	32.15	A	2876
86	60	60	200	200	842	3.8	1.6	38.06	A	3265
87	60	60	200	300	1053	4.4	1.6	64.3	A	2719
88	60	60	200	400	1263	5	1.6	96.46	A	2467
89	60	60	300	100	842	3.2	1.6	53.15	A	2585
90	60	60	300	200	1053	4.4	1.6	64.3	A	2719
91	60	60	300	300	1263	5.4	1.6	74.8	A	2848
92	60	60	300	400	1474	7.8	1.6	136.15	A	2464
93	60	60	400	100	1053	3.6	1.6	79.4	A	2430
94	60	60	400	200	1263	5	1.6	96.46	A	2467
95	60	60	400	300	1474	7.8	1.6	136.15	A	2464
96	60	60	400	400	1684	12.1	1.6	182.09	B	2454
97	75	60	100	100	421	1.9	1	14.11	A	3860
98	75	60	100	200	632	2.3	1	30.84	A	2964
99	75	60	100	300	842	2.6	1	51.18	A	2662
100	75	60	100	400	1053	2.9	1	76.12	A	2501
101	75	60	200	100	632	2.3	1	30.84	A	2964
102	75	60	200	200	842	3.1	1	36.75	A	3382
103	75	60	200	300	1053	3.6	1	61.68	A	2815
104	75	60	200	400	1263	4.2	1	92.19	A	2553
105	75	60	300	100	842	2.6	1	51.18	A	2662
106	75	60	300	200	1053	3.6	1	61.68	A	2815
107	75	60	300	300	1263	4.6	1	71.52	A	2961
108	75	60	300	400	1474	6.5	1	125.66	A	2562

109	75	60	400	100	1053	2.9	1	76.12	A	2501
110	75	60	400	200	1263	4.2	1	92.19	A	2553
111	75	60	400	300	1474	6.5	1	125.66	A	2562
112	75	60	400	400	1684	10.2	1	166.67	B	2562
113	90	60	100	100	421	1.3	0.5	13.78	A	3979
114	90	60	100	200	632	1.7	0.5	29.86	A	3052
115	90	60	100	300	842	1.9	0.5	49.54	A	2739
116	90	60	100	400	1053	2.2	0.5	73.49	A	2572
117	90	60	200	100	632	1.7	0.5	29.86	A	3052
118	90	60	200	200	842	2.4	0.5	35.43	A	3500
119	90	60	200	300	1053	3	0.5	59.38	A	2912
120	90	60	200	400	1263	3.5	0.5	88.25	A	2639
121	90	60	300	100	842	1.9	0.5	49.54	A	2739
122	90	60	300	200	1053	3	0.5	59.38	A	2912
123	90	60	300	300	1263	3.8	0.5	68.57	A	3075
124	90	60	300	400	1474	5.4	0.5	116.47	A	2660
125	90	60	400	100	1053	2.2	0.5	73.49	A	2572
126	90	60	400	200	1263	3.5	0.5	88.25	A	2639
127	90	60	400	300	1474	5.4	0.5	116.47	A	2660
128	90	60	400	400	1684	8.6	0.5	153.22	A	2671
129	45	75	100	100	421	3.3	2.2	16.4	A	3380
130	45	75	100	200	632	3.8	2.2	35.76	A	2608
131	45	75	100	300	842	4.2	2.2	59.71	A	2349
132	45	75	100	400	1053	4.6	2.2	90.55	A	2211
133	45	75	200	100	632	3.8	2.2	35.76	A	2608
134	45	75	200	200	842	4.9	2.2	42.98	A	2911
135	45	75	200	300	1053	5.7	2.2	73.49	A	2427
136	45	75	200	400	1263	6.9	2.2	122.05	A	2201
137	45	75	300	100	842	4.2	2.2	59.71	A	2349
138	45	75	300	200	1053	5.7	2.2	73.49	A	2427
139	45	75	300	300	1263	7.8	2.2	93.83	A	2506
140	45	75	300	400	1474	11.5	2.2	178.81	B	2170
141	45	75	400	100	1053	4.6	2.2	90.55	A	2211
142	45	75	400	200	1263	6.9	2.2	122.05	A	2201
143	45	75	400	300	1474	11.5	2.2	178.81	B	2170
144	45	75	400	400	1684	19.4	2.2	253.61	B	2132
145	60	75	100	100	421	2.7	1.6	15.75	A	3459
146	60	75	100	200	632	3.1	1.6	34.78	A	2666

147	60	75	100	300	842	3.5	1.6	58.07	A	2401
148	60	75	100	400	1053	3.9	1.6	87.6	A	2259
149	60	75	200	100	632	3.1	1.6	34.78	A	2666
150	60	75	200	200	842	4.1	1.6	41.99	A	2988
151	60	75	200	300	1053	4.9	1.6	71.19	A	2491
152	60	75	200	400	1263	6	1.6	115.16	A	2258
153	60	75	300	100	842	3.5	1.6	58.07	A	2401
154	60	75	300	200	1053	4.9	1.6	71.19	A	2491
155	60	75	300	300	1263	6.7	1.6	88.91	A	2581
156	60	75	300	400	1474	10	1.6	167.65	B	2234
157	60	75	400	100	1053	3.9	1.6	87.6	A	2259
158	60	75	400	200	1263	6	1.6	115.16	A	2258
159	60	75	400	300	1474	10	1.6	167.65	B	2234
160	60	75	400	400	1684	16.9	1.6	234.25	B	2199
161	75	75	100	100	421	2	1	15.42	A	3569
162	75	75	100	200	632	2.5	1	33.79	A	2749
163	75	75	100	300	842	2.8	1	56.1	A	2473
164	75	75	100	400	1053	3.2	1	84.32	A	2326
165	75	75	200	100	632	2.5	1	33.79	A	2749
166	75	75	200	200	842	3.4	1	40.35	A	3097
167	75	75	200	300	1053	4.1	1	68.24	A	2580
168	75	75	200	400	1263	4.9	1	106.3	A	2338
169	75	75	300	100	842	2.8	1	56.1	A	2473
170	75	75	300	200	1053	4.1	1	68.24	A	2580
171	75	75	300	300	1263	5.5	1	82.35	A	2685
172	75	75	300	400	1474	8.4	1	153.87	A	2324
173	75	75	400	100	1053	3.2	1	84.32	A	2326
174	75	75	400	200	1263	4.9	1	106.3	A	2338
175	75	75	400	300	1474	8.4	1	153.87	A	2324
176	75	75	400	400	1684	14	1	210.3	B	2299
177	90	75	100	100	421	1.4	0.5	14.76	A	3681
178	90	75	100	200	632	1.9	0.5	32.48	A	2832
179	90	75	100	300	842	2.2	0.5	54.13	A	2546
180	90	75	100	400	1053	2.5	0.5	81.04	A	2394
181	90	75	200	100	632	1.9	0.5	32.48	A	2832
182	90	75	200	200	842	2.7	0.5	38.71	A	3206
183	90	75	200	300	1053	3.4	0.5	65.62	A	2670
184	90	75	200	400	1263	4	0.5	98.75	A	2418

185	90	75	300	100	842	2.2	0.5	54.13	A	2546
186	90	75	300	200	1053	3.4	0.5	65.62	A	2670
187	90	75	300	300	1263	4.4	0.5	76.44	A	2791
188	90	75	300	400	1474	7.1	0.5	142.06	A	2415
189	90	75	400	100	1053	2.5	0.5	81.04	A	2394
190	90	75	400	200	1263	4	0.5	98.75	A	2418
191	90	75	400	300	1474	7.1	0.5	142.06	A	2415
192	90	75	400	400	1684	11.8	0.5	190.94	B	2399
193	45	90	100	100	421	3.5	2.2	17.72	A	3109
194	45	90	100	200	632	4.1	2.2	39.37	A	2396
195	45	90	100	300	842	4.6	2.2	66.27	A	2171
196	45	90	100	400	1053	5.1	2.2	101.38	A	2044
197	45	90	200	100	632	4.1	2.2	39.37	A	2396
198	45	90	200	200	842	5.4	2.2	47.9	A	2647
199	45	90	200	300	1053	6.3	2.2	82.68	A	2209
200	45	90	200	400	1263	8.7	2.2	151.9	A	2006
201	45	90	300	100	842	4.6	2.2	66.27	A	2171
202	45	90	300	200	1053	6.3	2.2	82.68	A	2209
203	45	90	300	300	1263	9.8	2.2	114.83	A	2253
204	45	90	300	400	1474	15.5	2.2	231.96	B	1951
205	45	90	400	100	1053	5.1	2.2	101.38	A	2044
206	45	90	400	200	1263	8.7	2.2	151.9	A	2006
207	45	90	400	300	1474	15.4	2.2	230.97	B	1951
208	45	90	400	400	1684	31.5	2.2	364.17	C	1906
209	60	90	100	100	421	2.9	1.6	17.39	A	3182
210	60	90	100	200	632	3.4	1.6	38.06	A	2460
211	60	90	100	300	842	3.9	1.6	64.3	A	2219
212	60	90	100	400	1053	4.3	1.6	98.1	A	2090
213	60	90	200	100	632	3.4	1.6	38.06	A	2460
214	60	90	200	200	842	4.6	1.6	46.59	A	2718
215	60	90	200	300	1053	5.5	1.6	80.05	A	2268
216	60	90	200	400	1263	7.5	1.6	142.72	A	2059
217	60	90	300	100	842	3.9	1.6	64.3	A	2219
218	60	90	300	200	1053	5.5	1.6	80.05	A	2268
219	60	90	300	300	1263	8.5	1.6	108.6	A	2321
220	60	90	300	400	1474	13.5	1.6	214.24	B	2010
221	60	90	400	100	1053	4.3	1.6	98.1	A	2090
222	60	90	400	200	1263	7.5	1.6	142.72	A	2059

223	60	90	400	300	1474	13.5	1.6	214.24	B	2010
224	60	90	400	400	1684	26.4	1.6	324.48	C	1967
225	75	90	100	100	421	2.2	1	16.73	A	3285
226	75	90	100	200	632	2.7	1	36.75	A	2537
227	75	90	100	300	842	3.1	1	62.01	A	2287
228	75	90	100	400	1053	3.6	1	93.83	A	2153
229	75	90	200	100	632	2.7	1	36.75	A	2537
230	75	90	200	200	842	3.8	1	44.62	A	2819
231	75	90	200	300	1053	4.7	1	76.44	A	2351
232	75	90	200	400	1263	6.2	1	131.56	A	2133
233	75	90	300	100	842	3.1	1	62.01	A	2287
234	75	90	300	200	1053	4.7	1	76.44	A	2351
235	75	90	300	300	1263	7.2	1	100.72	A	2418
236	75	90	300	400	1474	11.4	1	194.23	B	2093
237	75	90	400	100	1053	3.6	1	93.83	A	2153
238	75	90	400	200	1263	6.2	1	131.56	A	2133
239	75	90	400	300	1474	11.4	1	194.23	B	2093
240	75	90	400	400	1684	21.2	1	282.81	C	2053
241	90	90	100	100	421	1.6	0.5	16.08	A	3389
242	90	90	100	200	632	2.1	0.5	35.76	A	2614
243	90	90	100	300	842	2.5	0.5	59.71	A	2355
244	90	90	100	400	1053	2.9	0.5	90.22	A	2216
245	90	90	200	100	632	2.1	0.5	35.76	A	2614
246	90	90	200	200	842	3.1	0.5	42.98	A	2920
247	90	90	200	300	1053	3.9	0.5	73.16	A	2434
248	90	90	200	400	1263	5.2	0.5	121.39	A	2208
249	90	90	300	100	842	2.5	0.5	59.71	A	2355
250	90	90	300	200	1053	3.9	0.5	73.16	A	2434
251	90	90	300	300	1263	6	0.5	93.5	A	2515
252	90	90	300	400	1474	9.6	0.5	177.49	A	2177
253	90	90	400	100	1053	2.9	0.5	90.22	A	2216
254	90	90	400	200	1263	5.2	0.5	121.39	A	2208
255	90	90	400	300	1474	9.6	0.5	177.49	A	2177
256	90	90	400	400	1684	17.5	0.5	251.31	B	2140

Output for TWSC and AWSC Intersections

Table F2. SIDRA Output Table for Operational Performance Analysis of TWSC and AWSC Intersections.

Scenarios	Major Road Volume (veh/hr/leg)	Minor Road Volume (veh/hr/leg)	Demand Flow (total) (veh/hr)	Average Control Delay (secs)	Average Geometric Delay (secs)	95% Back of Queue - Distance (Worst Lane) (ft)	LOS	Effective Intersection Capacity (veh/hr)	Average Travel Speed (mph)
1	100	100	421	3.9	3.2	10.17	B	3736	19.45
2	100	200	632	5.1	4.1	22.64		2754	19.32
3	100	300	842	6	4.6	38.39		2397	19.20
4	100	400	1053	7.3	4.9	79.40		2190	19.01
5	200	100	632	3.3	2.3	12.80		4408	19.51
6	200	200	842	5	3.2	30.18	C	2888	19.32
7	200	300	1053	6.7	3.8	63.65		2352	19.08
8	200	400	1263	8.9	4.1	119.42		2057	18.77
9	300	100	842	3.3	1.9	16.40		4482	19.51
10	300	200	1053	5.5	2.7	44.29		2749	19.20
11	300	300	1263	8.1	3.2	91.21	C	2153	18.83
12	300	400	1474	13.1	3.6	199.48		1827	18.14
13	400	100	1053	3.7	1.6	22.97		4125	19.45
14	400	200	1263	6.7	2.3	63.65		2424	19.01
15	400	300	1474	12.3	2.8	156.82		1842	18.21
16	400	400	1684	64.3	3.2	870.41	E	1538	12.80

Effect of turning volume on Average Control Delay

Lower turn percent seem to produce lower average control delay in all scenarios. Two-way major road volume upto 800 veh/hr with a two-way minor road volume of 400 veh/hr and turn percent of 20% or a two-way major road volume upto 1000 veh/hr with a two-way minor road volume of 400 veh/hr and turn percent of 10% produce moderate average control delay (less than 6 secs) for a mini-roundabout. Higher volume on major road (more than 800 veh/hr) with higher turn percent (more than 10%) should be avoided to minimize the average control delay.

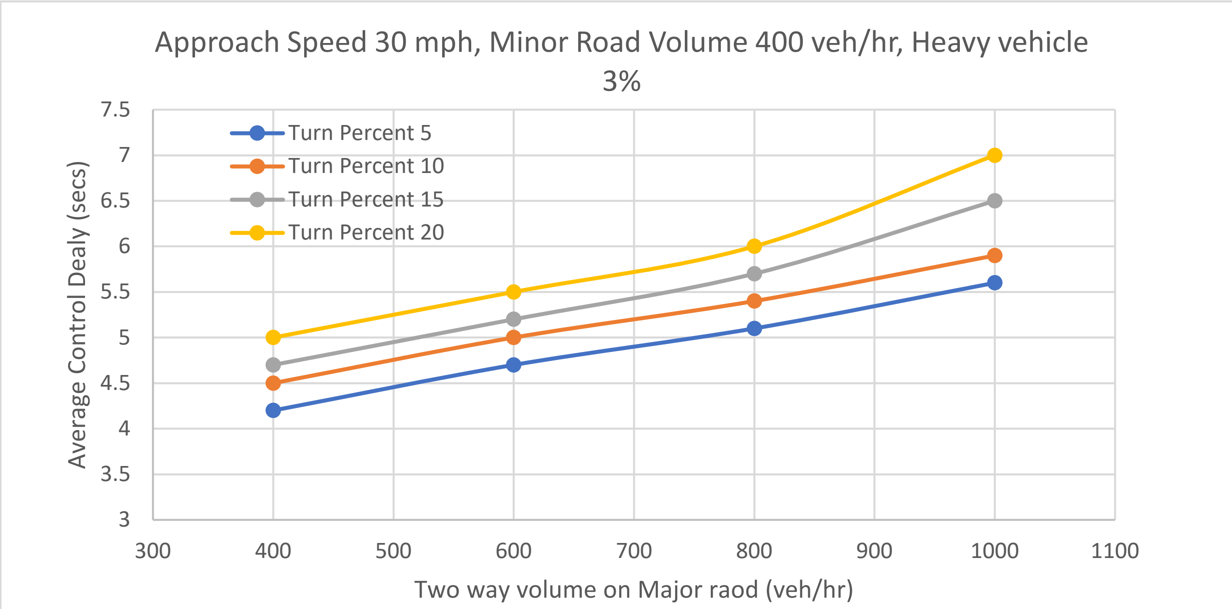


Figure F1. Effect of turn percentages on average control delay.

Average Geometric Delay

Delay due to physical and basic traffic control factors as experienced by a vehicle that negotiates the intersection in the absence of any other vehicles (decelerates from the approach cruise speed down to an approach negotiation speed, travels at that speed, accelerates to an exit negotiation speed, and travels at exit negotiation speed until clearing the intersection negotiation area) is called geometric delay (SIDRA 8.0 Glossary).

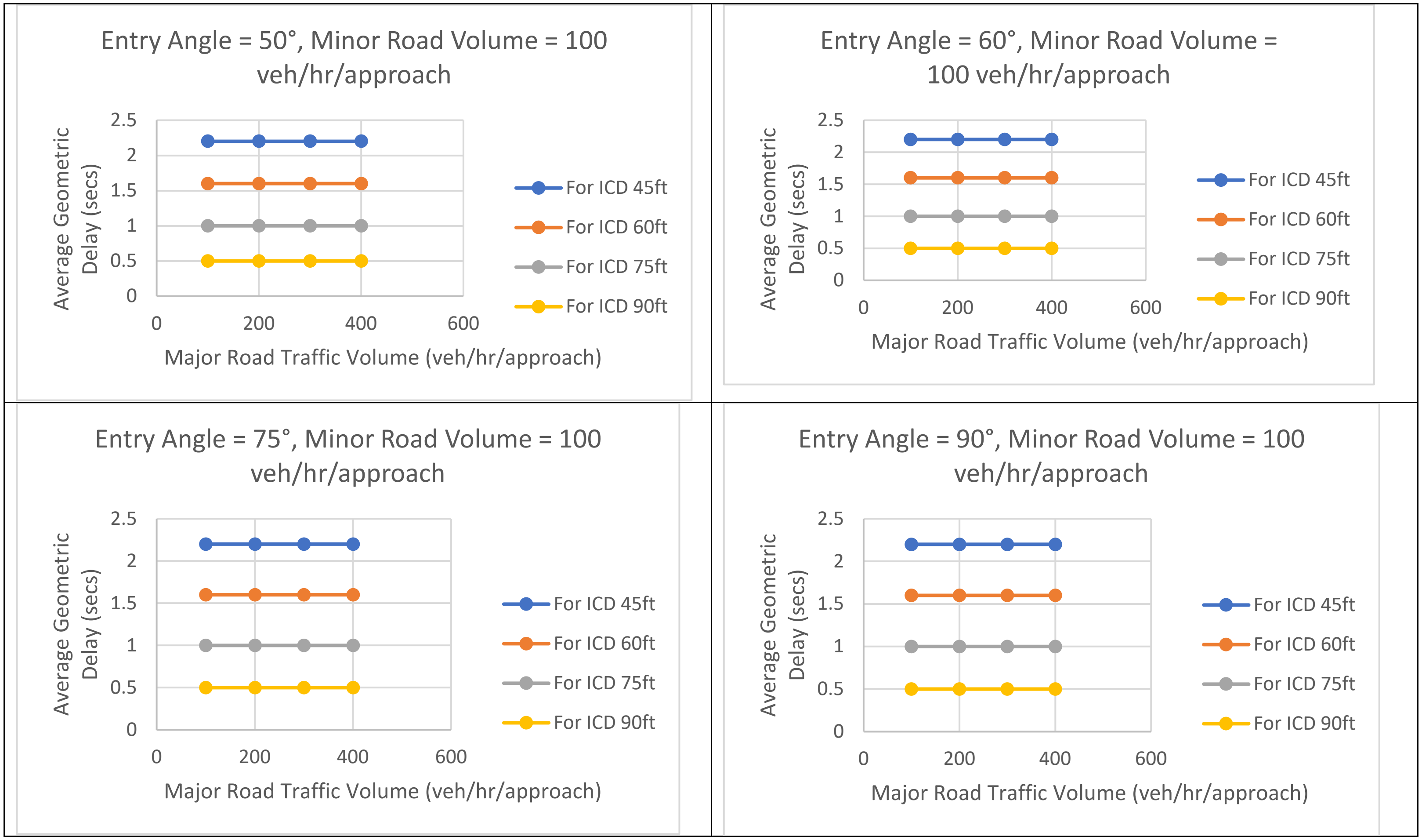


Figure F2. Average geometric delay (secs) based on major road volume, ICD, and EA.
(with minor road volume of 100 veh/hr/approach)

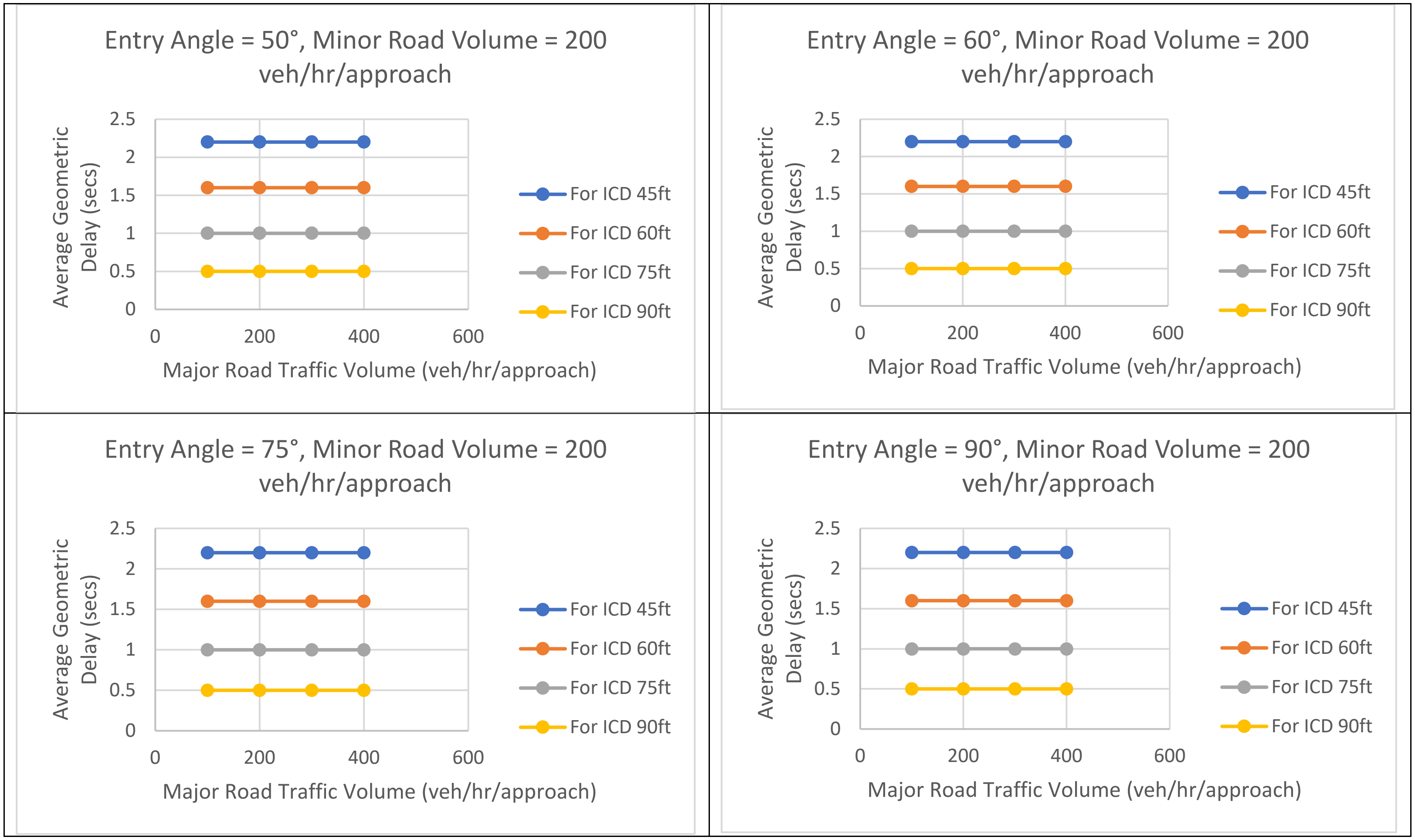


Figure F3. Average geometric delay (secs) based on major road volume, ICD, and EA. (with minor road volume of 200 veh/hr/approach)

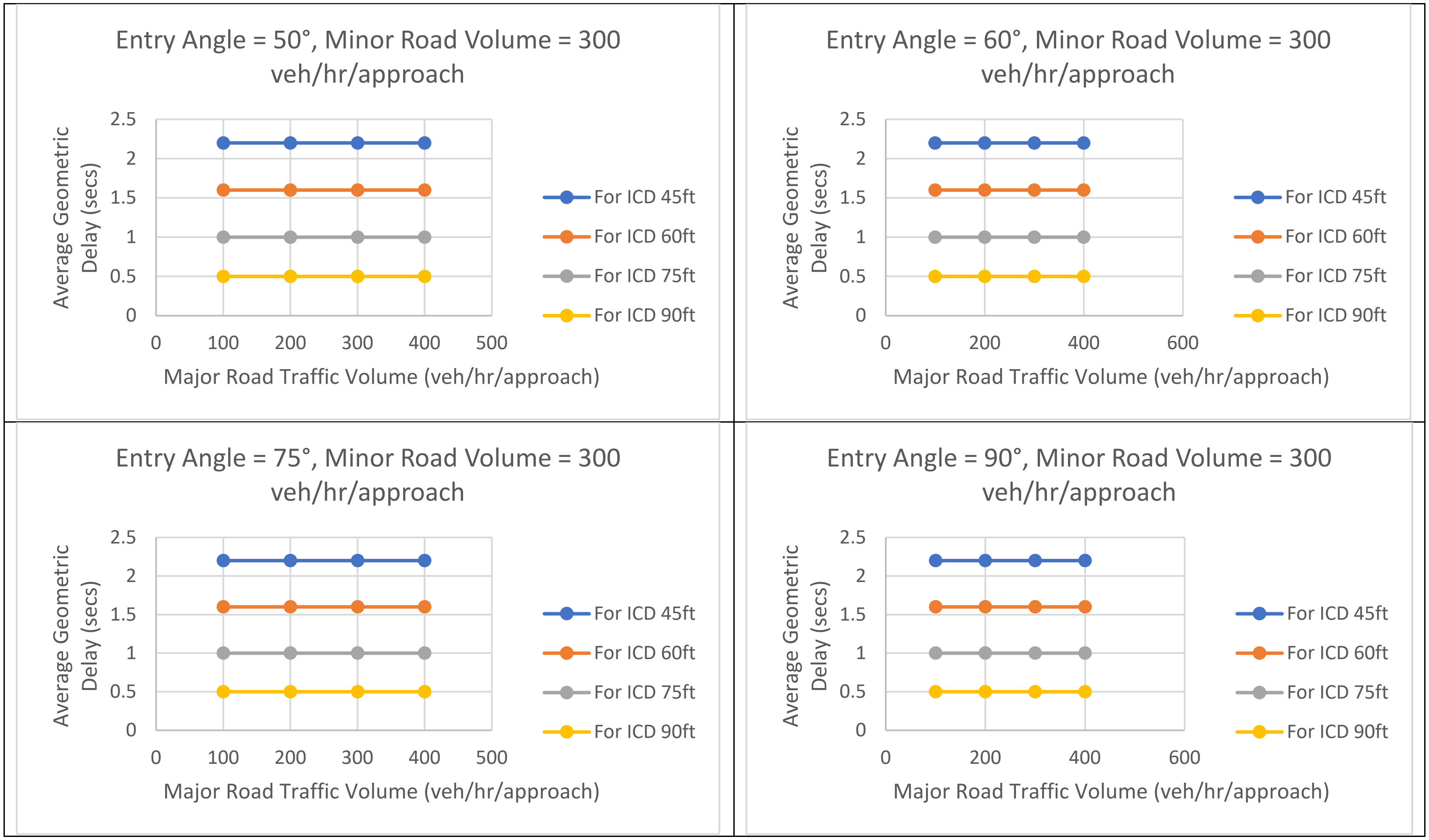


Figure F4. Average geometric delay (secs) based on major road volume, ICD, and EA. (with minor road volume of 300 veh/hr/approach)

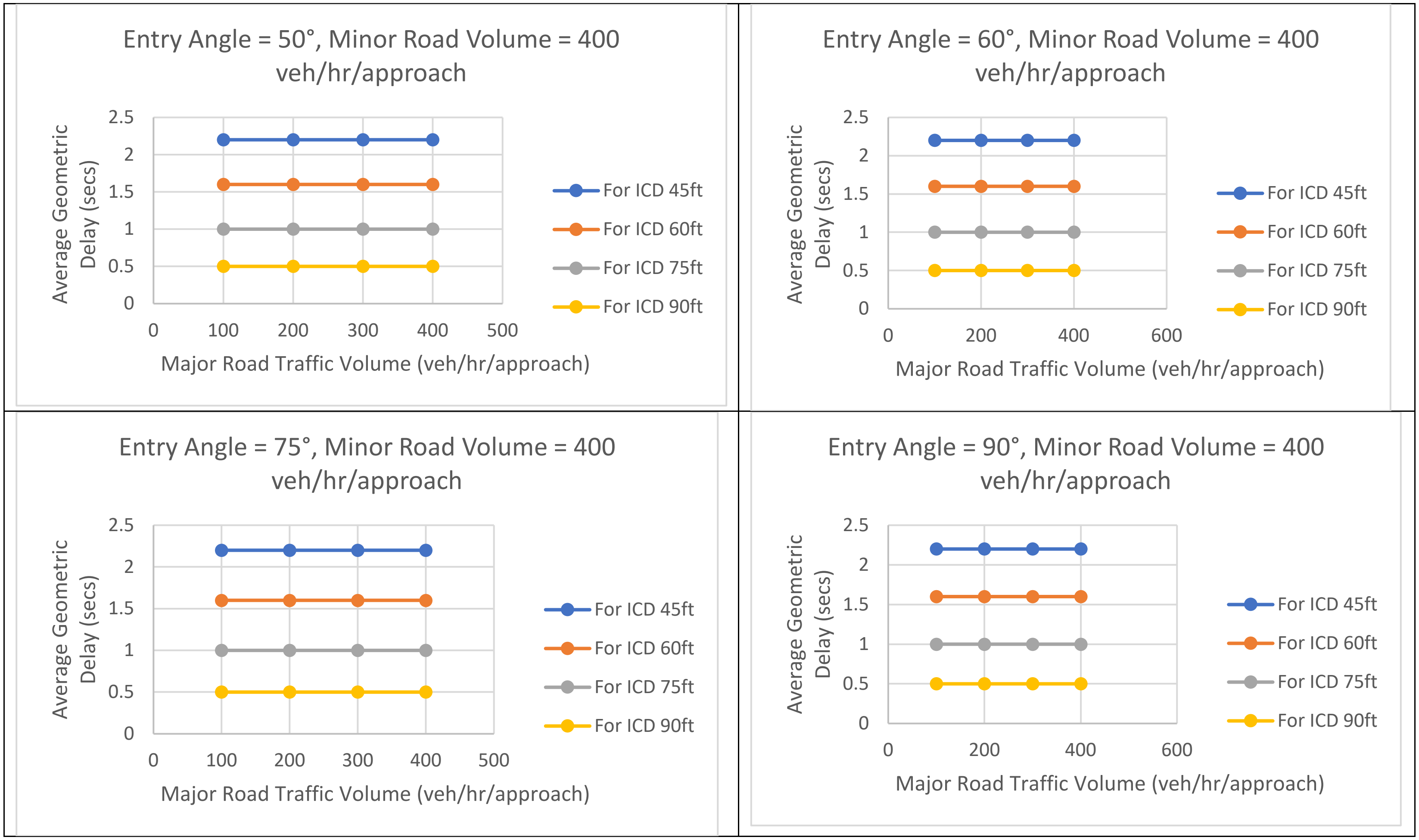


Figure F5, Average geometric delay (secs) based on major road volume, ICD, and EA.
(with minor road volume of 400 veh/hr/approach)

Safety analysis

Scenarios for Safety Analysis

For safety analysis, variable demand volume was considered and geometric parameters was held constant. From the operational performance analysis, ICD- 90 ft, entry angle- 50°, 4- legs, and width of circular way- 24 ft yielded best results. Hence, these parameters were taken as sample of best mini-roundabout in terms of operational performance. Circular way was designed as two lanes for convenience in VISSIM. With these geometric parameters, four scenarios were created with variable demand volume in major and minor approaches as in scenarios (S12-S15) in Table F1 (Table F3).

Table F3. Scenarios for Safety Analysis.

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Heavy Vehicle (%)
	Total Volume (veh/hr)	Dist. (%)	Total Volume (veh/hr)	Dist. (%)	Total Volume (veh/hr)	Dist. (%)	Total Volume (veh/hr)	Dist. (%)	
East Bound (Major)	200	RT = 10	400	RT = 10	200	RT = 10	400	RT = 10	3
		Th = 80		Th = 80		Th = 80		Th = 80	
		LT = 10		LT = 10		LT = 10		LT = 10	
West Bound (Major)	200	RT = 10	400	RT = 10	200	RT = 10	400	RT = 10	
		Th = 80		Th = 80		Th = 80		Th = 80	
		LT = 10		LT = 10		LT = 10		LT = 10	
North Bound (Minor)	50	RT = 30	100	RT = 30	200	RT = 30	400	RT = 30	
		Th = 40		Th = 40		Th = 40		Th = 40	
		LT = 30		LT = 30		LT = 30		LT = 30	
South Bound (Minor)	50	RT = 30	100	RT = 30	200	RT = 30	400	RT = 30	
		Th = 40		Th = 40		Th = 40		Th = 40	
		LT = 30		LT = 30		LT = 30		LT = 30	

* RT = Right Turn, Th = Through, and LT = Left Turn.

Safety Analysis Outputs

The safety analysis results of the four scenarios are presented in the Table F4 below.

Table F4. Output of Safety Analysis from VISSIM and SSAM.

Scenarios	Total number of collisions	Collision Type		
		crossing	rear end	lane change
S1	1	0	1	0
S2	16	1	14	1
S3	8	0	8	0
S4	120	0	118	2
Total	145	1	141	3

2 simulation scenarios mentioned in Table A3 were run for evaluation of safety by VISSIM and SSAM software. Output of this simulation was total number and different types of collisions (i.e., crossing, rear-end and lane change conflicts, etc.) occurred during one hour simulation period. It was observed from the simulation results that number of conflicts increases with the increased demand volume but the relationship is not linear. There is a sudden increase of conflicts after the demand

volume crosses 1000 veh/hr. Optimum demand volume for safe operation is 800 – 1000 veh/hr. Both combination of approaches (i.e. major-minor, and major-major) performs well at this volume range.

APPENDIX G

Life Cycle Cost Analysis

Task 6

TASK 6: LIFE CYCLE COST ANALYSIS.

1. INTRODUCTION

In Task 6, the research team aimed to develop a Life Cycle Cost Assessment Tool that would enable comparison between alternatives over the life-cycle of the specific type of RAB. This task considered factors such as inscribed circle and central island radii, construction materials; and different construction means and methods. Based on information from publications and also ODOT's actual project cost of RABs, the life cycle cost analysis using the Net Present Value (NPV) can be conducted. The comparison would be between modular mini-RABs (with cost data sourced from Vortex, which is funded by the US DOT), mini-RABs with different materials (with cost data sourced from RS Means), and traditional RABs (with cost data sourced from actual RAB projects funded by ODOT). The objective of the Life Cycle Cost Assessment Tool for the Roundabouts (LiCAR) is to compare three different roundabouts options based on user inputs (project data).

2. BACKGROUND

Traditional-roundabouts (RABs) have increasingly become a critical intersection control type providing benefits such as reductions in travel time, crashes, and injury severity; and improving traffic flows/operations (Burris and Sullivan, 2006; Bushell et al. 2013; FHWA, 2010; FHWA, 2018; Korve and Niemeier, 2002; Li and Madanu, 2009; NCHRP 2016; TRB, 2000; Weber and McCullogh, 2016). Moreover, within this class of intersection control, there are a number of alternatives such as single-lane, multi-lane, and mini-RABs. As agencies (DOTs, Consultants, Cities, Counties, etc.) consider to design, build, and maintain RABs of different types; there is a need to identify the least-cost option to meet the regulatory needs and maximize the benefits from the investment.

The most commonly adopted approach to select among options is the Benefit-Cost Analysis (BCA); which in this case would compare estimated benefits and costs of the potential mini-RAB (FHWA, 1998; (Korve and Niemeier, 2002; Li and Madanu, 2009). After Wilde et al. (1999) introduced the BCA for pavement design, previous studies developed cost models using the BCA (Falls and Tighe, 2003; Riegle et al. 2005; Li and Madanu, 2009). The details of the BCA are determined by three fundamental elements, Benefit, Cost, and Time, by comparing the net value which is a difference between Benefits and Costs over the considered Time (Krop et al., 2019). The three critical elements are:

- **Benefits**: Each mini-RAB will produce benefits, such as reduction of travel time, reduction of crashes, reduction of traffic volumes (Burris and Sullivan, 2006; FHWA, 2018; Korve and Niemeier, 2002; Li and Madanu, 2009; NCHRP 2016; TRB, 2000; Weber and McCullogh, 2016). Some of the benefits can be expressed in monetary terms (e.g., reduction of crashes or reduction of traffic volumes) but some of the benefits are difficult to monetize (e.g., cutback of vehicle air emission) (Krop et al., 2019). The BCA only consider benefits that can be expressed in monetary terms (Krop et al., 2019).
- **Costs**: This includes construction costs which are an up-front cost and operations and maintenance (O&M) costs which recur during the life time (Krop et al., 2019). The costs also consider an opportunity costs of the projects which could be generated from other potential opportunity.
- **Time**: Since benefits and costs are incurred over the life of the mini-RABs, the BCA must consider the time value of money (Krop et al., 2019).

Based on the three critical elements, the BCA to compare benefits and costs can be done with several metrics, i.e., the Net Present Value (NPV), the Benefit-Cost Ratio (B/C Ratio), Payback Period, and the Internal Rate of Return (IRR) (Krop et al., 2019). The NPV converts all the benefits and costs to the present value, and calculate the net present value which is a difference between benefits and costs over the life of the mini-RABs. A project with the greatest NPV has the highest value and the project should be selected (Krop et al., 2019). The B/C Ratio is a ratio between the benefits and costs by the present value. The highest B/C ratio are the greatest return on the expenditures, so the project should be selected (Krop et al., 2019). When comparing the length of time to take back the initial investment, the Payback period can be compared. A project with the shortest Payback period should be selected (Krop et al., 2019). The IRR is a discount rate that would make the Net Present Value (NPV) to zero with a consideration of the lifetime of a project. A project with the higher IRR should be selected (Krop et al., 2019). Among the metrics, the Net Present Value (NPV) is the most common and the best metric to compare the overall value of the project value of the mini-RABs. Table 6.1 summarizes a list of benefits and costs of mini-RABs during construction phase and operations and maintenance phases.

Table 6.1. Summary of Benefits and Costs of Mini-Roundabouts.

	Construction Phase	Operations and Maintenance Phase	Reference
Benefit	• Small intersection footprint • Less Right-of-Way (ROW) • Reduction of work-zone accidents • Quicker construction period • Lower initial cost • Aesthetics • No landscaping costs	• Reduction of crashes • Reduction of travel time • Reduction of traffic volume • Cutback of vehicle air emissions • Minimize annual O&M costs • Less through traffic delay • Aesthetics • No landscaping maintenance	• Alberta Government 2018 • Burris and Sullivan 2006 • Fanucci 2020 • FHWA 2010 • FHWA 2018 • Korve and Niemeier 2002 • Li and Madanu, 2009 • NCHRP 2016 • TRB 2000 • TRB 2017 • Weber and McCullogh 2016
Cost	• Material Type • Design (Radius) • Unit rates of construction	• Unit rates of vehicle operating costs • Discount rates	• FHWA 2018 • Li and Madanu, 2009 • NCHRP 2016 • TRB 2000

3. LiCAR TOOL DEVELOPMENT

As mentioned earlier, a Life Cycle Cost Assessment Tool for Roundabouts (LiCAR) was developed using BCA concepts to compare three different RAB alternatives based on user defined inputs (project data). The steps involved during the development process include conceptualization, detailed planning, tool programming, and testing/debugging phases. During the conceptualization phase, the research team determined tool inputs, process, and outputs. The inputs of the tool were determined for the design (planning) phase, the construction phase, and the operations and maintenance (O&M) phases. The detailed tool logic flowchart is presented in Figure 6.1.

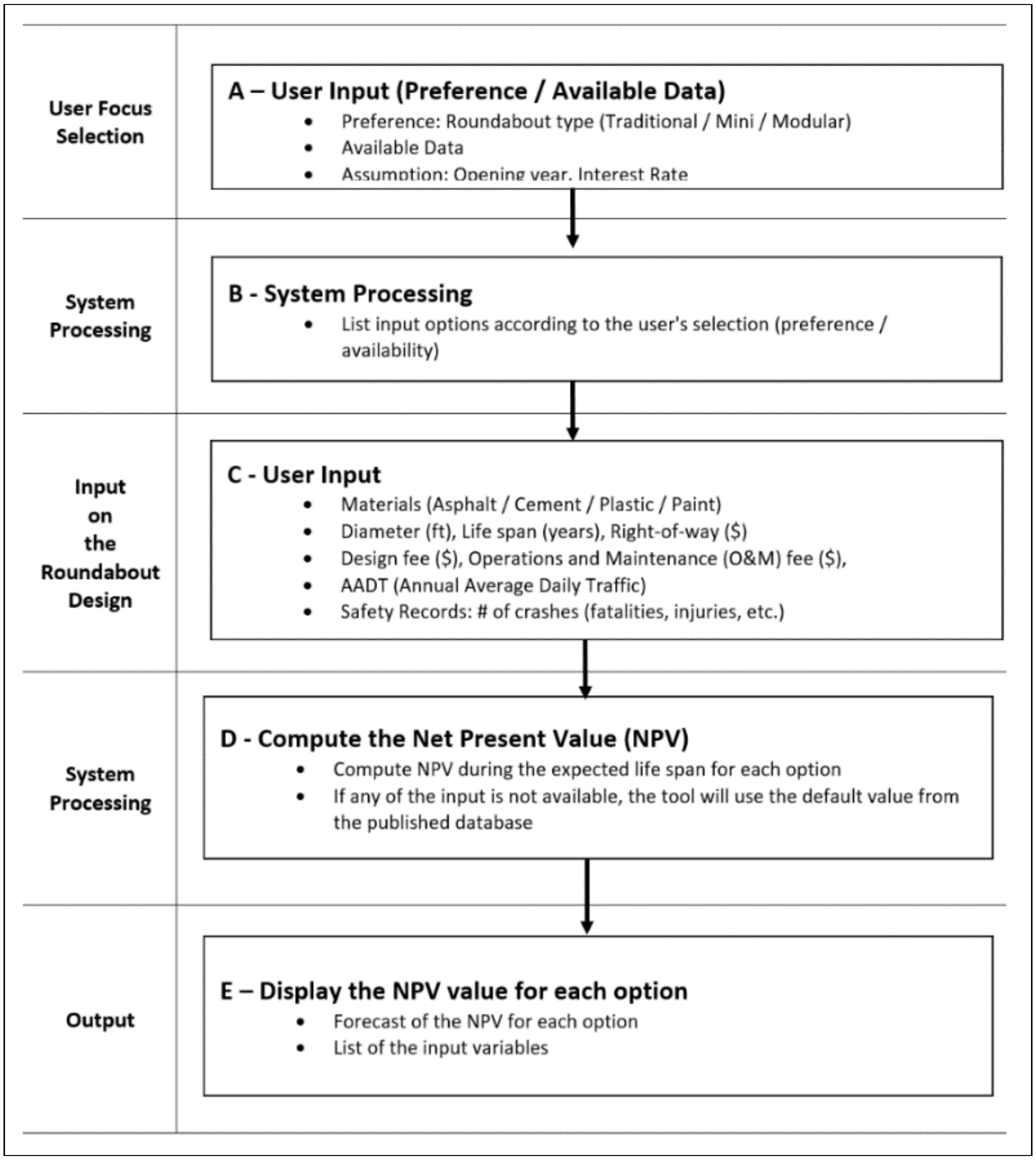


Figure 6.1. LiCAR tool logic flowchart.

During the detailed planning phase, the structure of the tool includes two tabs – a user interface tab and a resident database tab. Interface tabs consist of four different tabs: *Introduction*, *User Guide*, *Input*, and *Outputs*, while the resident database tab includes the cost database and other data for the life cycle cost analysis. The first two interface tabs – *Introduction* and *User Guide* – provide an introduction and guidance on how to use the LiCAR tool. The following tabs – *Inputs* and *Outputs* – allow user input based on the specific project information and compare three different options, a traditional, mini, and modular mini-RABs.

The tool programing was initiated when the tool logic was determined and revised by incorporating the initial feedback from the TAC members. A list of the input variables used are presented on the output tab for user's record. Upon completion of the tool programming, the tool was reviewed by the research team and modified for additional features such as "PRINT" and "SAVE."

3.1 LiCAR Tool Inputs and Outputs.

The LiCAR tool operates in accordance with the user's input of the following information:

1) the *design (planning) phase*: the planned material, traffic flow volume (TFV), and design fee
2) the *construction phase*: the right-of-way
3) the *operations and maintenance (O&M) phase*: landscaping and resurfacing cost.

The LiCAR tool inputs are not limited to one roundabout type, after users provide input, the system will calculate the life cycle cost for each type. The tool then compares life cycle between 1) a traditional vs. mini-RAB, 2) a traditional vs. modular-RAB, and 3) a mini vs. modular-RAB. Based on user's input to the project information, the tool outputs are:

1) the *design (planning) phase*: the cost for the design fee or the layout design (for traditional, mini- and/or modular-RABs).
2) the *construction phase*: the cost for the right-of-way, the excavation, material, installation, labor, marking, embankment, landscaping, and signage.
3) the *operations and maintenance (O&M) phase*: the cost for resurfacing, landscaping, safety (collisions), and any delay.

3.2 LiCAR Tool Computation.

The LiCAR tool analyzes the Benefit and Cost Ratio based on the user's input of the project information and the outputs of each roundabout types. Among the outputs, the safety (collision) reduction and the traffic delays are considered as a benefit, and other outputs are considered as a cost. Then, the benefit cost is divided by the cost (expenditure) to calculate the B/C ratio.

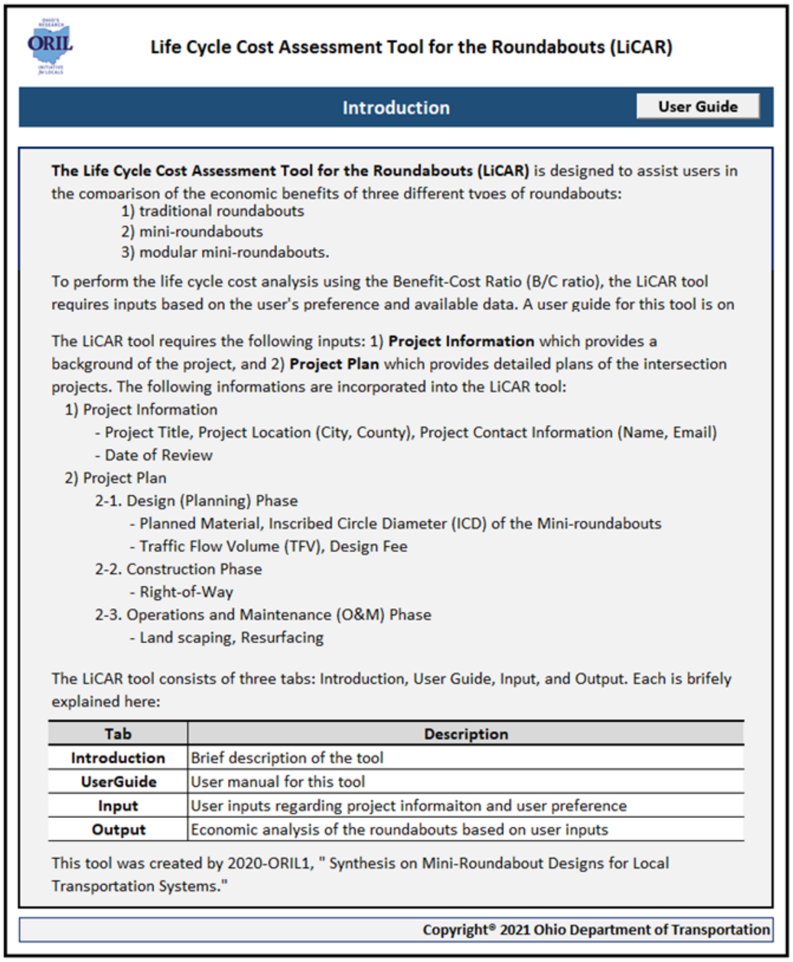
A user guide to the LiCAR tool and the tool itself (excel spreadsheet) are available separately as addendums to this draft report.

LiCAR Tool User Guide

1) Introduction

The introduction tab (see Figure G1) provides an overview of the LiCAR Tool. A user can navigate to the tool's user manual by clicking on the User Guide tab. To correctly operate the tool, a user must use buttons to navigate the following tabs. Specific features of the LiCAR tool include:

- It is a Microsoft® Excel-based (Version 2013 or later) tool;
- It requires user inputs regarding the cost of the design (planning), the construction, and the operations and maintenance (O&M);
- It allows replicability and therefore the analysis process can be repeated for the same project; and
- The utilized inputs are summarized and listed in the output tab.


Life Cycle Cost Assessment Tool for the Roundabouts (LiCAR)

Introduction | User Guide

The Life Cycle Cost Assessment Tool for the Roundabouts (LiCAR) is designed to assist users in the comparison of the economic benefits of three different types of roundabouts:
1) traditional roundabouts
2) mini-roundabouts
3) modular mini-roundabouts.

To perform the life cycle cost analysis using the Benefit-Cost Ratio (B/C ratio), the LiCAR tool requires inputs based on the user's preference and available data. A user guide for this tool is on

The LiCAR tool requires the following inputs: 1) **Project Information** which provides a background of the project, and 2) **Project Plan** which provides detailed plans of the intersection projects. The following informations are incorporated into the LiCAR tool:
1) Project Information
- Project Title, Project Location (City, County), Project Contact Information (Name, Email)
- Date of Review
2) Project Plan
2-1. Design (Planning) Phase
- Planned Material, Inscribed Circle Diameter (ICD) of the Mini-roundabouts
- Traffic Flow Volume (TFV), Design Fee
2-2. Construction Phase
- Right-of-Way
2-3. Operations and Maintenance (O&M) Phase
- Land scaping, Resurfacing

The LiCAR tool consists of three tabs: Introduction, User Guide, Input, and Output. Each is brifely explained here:

Tab	Description
Introduction	Brief description of the tool
UserGuide	User manual for this tool
Input	User inputs regarding project informaiton and user preference
Output	Economic analysis of the roundabouts based on user inputs

This tool was created by 2020-ORIL1, " Synthesis on Mini-Roundabout Designs for Local Transportation Systems."

Figure G1. Screenshot of the Introduction Tab of the LiCAR Tool.

2) User Guide

The User Guide tab (see Figure G2) provides three steps to calculate the Life Cycle Costs of three different roundabouts: 1) a traditional roundabout, 2) a mini-roundabout, and 3) a modular-roundabouts. The tab reminds users to use the button to move to the next tab, and not to over-write the master template file.

Also, the tab illustrates the software requirements, Microsoft® Office Excel 2013 (or later version) and "Macro" must be enabled in order to operate this LiCAR Tool. To enable Macros, users click the "File" tab, then click the "Options" button. In the pop-up window, click the "Trust Center" in the menu and then click "Trust Center Settings" in the window. Under the Macro setting, select "Enable all macros" or "Disable with notifications" if users want to allow some macros.

ORIL

Life Cycle Cost Assessment Tool for the Roundabouts (LiCAR)

Introduction | **User Guide** | **Input**

The LiCAR Tool interface four tabs and the analysis will be automatically calculated with the inputs by the

Steps and Details

Action	Detail
1. Provide Project Information	Before proceeding to the this step ("Input Tab"), it is highly recommended to save the file. Users can change the file name and choose the folder directory. **(Please do not over-write the master template file.)** Starting with the INPUT tab, provide the project information which includes project title, project location (city and county), project contact information (name and email), and date of review.
2. Respond to Project Plans	After providing the project information, the Licar tool will require the project plans for the roundabouts. Each quesiton has two options with data (e.g. "Have Plan" or "Have Data") or without data (e.g. "No Plan" or "No Data"). If user select an option without data, the system default response for each question is the data in the embeded dataset. The defaults A list of default values and their sources are listed in below. 1) Project Information Project Title — User input Project Location — User input Project Contact Information — User input Date of Review — User input 2) Project Plan 2-1. Design (Planning) Phase — **Defaul Value (When a user selects "No Data")** Planned Material — **Asphalt** *(ODOT WOO-199-29.10)* Inscribed Circle Diameter (ICD) — Traditional roundabouts: **130 ft** Mini-round abouts: **60 ft** Modular roundabouts: **40 ft** *(Vortex)* Traffic Flow Volume (TFV) — Major (**400 TFV**) & Minor (**200 TFV**) *(VDOT)* Design Fee — **$30,000** 2-2. Construction Phase Right-of-Way — **$ 0.5/ft²** Excavation — **$45/cy** *(ODOT Database)* Material Cost 8" Con'c Pavement — **$84.7/sy** *(ODOT Database)* Asphalt Con'c Courses — **$154.9/cy** *(ODOT Database)* Asphalt Con'c Base — **$122.2/cy** *(ODOT Database)* Aggregate Base — **$47.4/cy** *(ODOT Database)* Curb — **$28.42/ft** *(ODOT Database)* Non-Tracking Coat — **$3.1/gal** *(ODOT Database)* Marking Edge Line — **$713.36/gal** *(ODOT Database)* Line — **$6.20/ft** *(ODOT Database)* Lane — **$75/ft** *(ODOT Database)* Railroad — **$300/EA** *(ODOT Database)* Ground — **$10.59/ft** *(ODOT Database)* Embankment — **$34/cf** *(RS Means 2020)* Landscaping — **$30/sy** Sign — **$5,622/Set** *(ODOT)* 2-3. Operations and Maintenance (O&M) Phase Land scaping — **$6/sy** *(ODOT, PID 76391)* Resurfacing — **$35/sy** *(ODOT, PID 90834)* By clicking "Defalt All" button, a user can clear all answers and by clicking "Output" button, a user can move to the analysis page.
3. Review the Life Cycle Cost Analysis	Proceeding to the "Output" tab, the tool provides specific insight into the Design Cost, the Construction Cost, and the Operations and Maintenance (O&M) Cost. The tool also presents the analysis of Benefit Cost Ratio with comparision between roundabout options: 1) Traditional vs. Mini Roundabouts 2) Traditional vs. Modular-roundabouts, and 3) Mini vs. Modular-roundabouts. The tool summarizes all the input values to analyze the Benefit/Cost Ratio. Users can print the output to a printer or convert it to a PDF file using the "Print Out This Page" button.

Software Requirements

Microsoft® Office Excel 2013 (or later version) must be installed and "Macro" must be enabled in order to operate this LiCAR Tool. Please note that there could be a short delay while processing, depending on your system.

Figure G2. Screenshot of the User Guide Tab of the LiCAR Tool

3) Input

Before proceeding to the Input tab (see Figure G3), the system will prompt the user to save the file. Users can change the file name and choose the folder directory. (Please do not over-write the master template file.) Starting with the INPUT tab, provide the project information which includes project name, project location (city and county), project contact (name and email), and date of review. This information will be copied to the Output tab for the record.

After providing the project information, the LiCAR tool will require the project plans for the roundabouts. Each question has two options with data (e.g. "Have Plan" or "Have Data") or without data (e.g. "No Plan" or "No Data"). If user select an option without data, the system default response for each question is the data in the embedded dataset. By clicking "Default All" button, a user can clear all answers and by clicking "Output" button, a user can move to the analysis page.

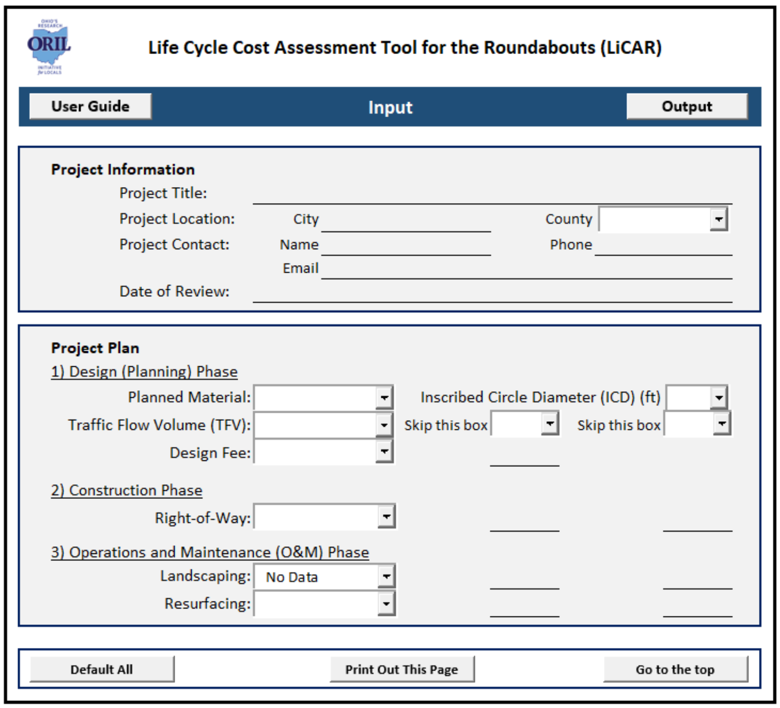


Figure G3. Screenshot of the Input Tab of the LiCAR Tool

4) Output

Proceeding to the "Output" tab (see Figure G4), the tool provides specific insight into the Design Cost, the Construction Cost, and the Operations and Maintenance (O&M) Cost. The tool also presents the analysis of Benefit Cost Ratio with comparison between roundabout options:

1) Traditional vs. Mini Roundabouts
2) Traditional vs. Modular-roundabouts, and
3) Mini vs. Modular-roundabouts.

The tool summarizes all the input values to analyze the Benefit/Cost Ratio. Users can print the output to a printer or convert it to a PDF file using the "Print Out This Page" button.

Life Cycle Cost Assessment Tool for the Roundabouts (LiCAR)

Input | **Output**

Project Information

Project Title:

Project Location:

Project Contact:

Date of Review:

Cost Breakdown

		Item	Traditional Roundabouts ICD: 130 ft	Mini-roundabouts ICD: 60 ft	Modular-roundabouts ICD: 40 ft
Costs	D	Design Fee			
		Lay-out Design			
	C	Right-of-Way			
		Excavation			
		Roundabouts (Mat'l)			
		Installation			
		Labor			
		Marking			
		Embankment			
		Landscaping			
		Sign			
	O	Resurfacing			
		Landscaping			
		Safety (Collisions)			
		Delays			

Note.) D: Design Phase, C: Construction Phase, O: Operations & Maintenance Phase

Benefit/Cost Ratio

1. Traditional Roundabouts vs. Mini-Roundabouts

Benefits		B/C Ratio	
Costs		Suggestion:	

2. Traditional Roundabouts vs. Modular-Roundabouts

Benefits		B/C Ratio	
Costs		Suggestion:	

3. Minil Roundabouts vs. Modular-Roundabouts

Benefits		B/C Ratio	
Costs		Suggestion:	

Print Out This Page | Go to the top

Figure G4. Screenshot of the Output Tab of the LiCAR Tool

APPENDIX H

Multi-Criteria Assessment

Task 7

TASK 7: MULTI-CRITERIA ASSESSMENT.

1. INTRODUCTION

To assist in decision making for location-specific mini-/modular-RAB design selection, a tool that is based on a multi-criteria assessment (MCA) was developed. With a variety of performance measures to consider (operations, safety, capacity etc.), it would become difficult to select a specific RAB design; especially that the performance measures are dynamic with inputs. The MCA tool uses an overall performance score of each design option considering different performance measures with different units. Multi-Criteria Assessment (MCA) tools have been used in many civil engineering and transportation engineering applications (Zavadskas et al., 2015; Yakar and Celik, 2014; Tudela et al., 2006). MCA has been used to rank alternatives from the most preferred option to the least preferred option considering multiple performance measures/criteria (Dodgson et al. 2009).

2. MCA DEVELOPMENT

In developing the MCA tool for this project, an initial step of any MCA is to establish a clear understanding of the decision context and the objectives of the analysis. This is followed by developing a relative quantitative performance scoring scale based on the measured qualitative and quantitative attributes (i.e., performance measures/criteria), known as normalization of the criteria. After normalization of the performance of each mini-RAB design alternative in terms of performance criteria, weights are assigned to each criterion to reflect its relative importance of each performance measure in the decision-making. To calculate an overall cumulative performance score for each alternative, scores for all performance measure/criteria are multiplied by their respective weights based on the following formula:

$$S_i = w_1 S_{i1} + w_2 S_{i2} + \cdots \dots \dots \dots \dots + w_n S_{in} = \sum_{j=1}^{n} w_j S_{ij} \quad (1)$$

Where:

S_i is the overall weighted score for a mini-roundabout design,

i; w_j the weight for each criterion,

S_{ij} is the score of mini-roundabout design *i* on criterion j and n is the number of criteria.

The relative score (i.e., importance) for each performance criterion was calculated based on the survey of local transportation engineers (Task 3) in this research. Then, an MCA was conducted to calculate an overall performance score of each design alternative considered in the simulation portion of the project (i.e. Task 5) to rank different mini-RAB design alternatives. More specifically, and also detailed in the following sub-sections, the steps followed in developing the MCA are:

- Identification of mini/modular-roundabout performance measures/factors,
- Selection of mini/modular-roundabout design alternatives,
- Development of weight(s) for each performance evaluation factor,
- Calculation of total performance score/aggregate score.

2.1. Identification of mini/modular-RAB performance measures/factors.

Overall, in their need to install a mini-RAB, transportation professionals identified (in Task 3) that they considered the following factors (i) safety improvement (i.e., reduce crash severity, reduce crash frequency, reduce speeding, better pedestrian/cyclist facilities), (ii) operational performance improvement, (iii) requirement of right of way for installation, (iv) construction cost, (v) operation and maintenance cost, (vi) construction duration, (vii) improvement of intersection aesthetics, and (viii) reduction of environmental impact. However, for the MCA analysis, only operational performance, right of way requirement, construction cost, operation and maintenance cost, construction duration, and aesthetics were considered; more so due to their importance and availability of qualitative and/or quantitative data. Details regarding these factors and their range of values adopted in the MCA analysis are presented below.

Operational performance: five performance measures from the micro-simulation assessment (Task 5) were considered; including

- Average control delay - divided into five groups (<5 secs, 5 to 10 secs, 10 to 20 secs, 20 to 30 secs, and >30 secs);
- Average geometric delay – used four different values (0.5 sec for 90 ft ICD, 1 sec for 75 ft ICD, 1.6 secs for 60 ft ICD, and 2.2 secs for 45 ft ICD) from simulation results;
- Back of queue distance - divided into four groups (< 50 ft, 50 to 100 ft, 100 to 200 ft, and > 200 ft);
- Effective intersection capacity - divided into four groups (> 4000 veh/hr, 3000 to 4000 veh/hr, 2000 to 3000 veh/hr, and < 2000 veh/hr); and
- Average speed - divided into four groups (< 17 mph, 17 to 18 mph, 18 to 19 mph, and 19 to 20 mph).

Right-Of-Way (ROW): considered a very important factors in decisions regarding installation of a mini-RAB; with larger ICDs requiring larger ROW. Based on this assumption, the ROW factor was categorized as low, medium and high based on ICD. That is, low ROW for 45 ft ICD, medium for 60 and 75 ft ICDs, and high for 90 ft ICD.

Construction and Maintenance costs: survey respondents mentioned costs of mini-RABs ranging from \$150K to 300K. Therefore, \$150K was taken for the lowest ICD (45 ft). Then a linear increase in cost was assumed for higher ICDs (i.e., \$200K for 60 ft, 250K for 75 ft, and 300K for 90 ft).

Construction Duration: categorized as low, medium, and high based on ICD (i.e., low for 45 ft ICD, medium for 60 and 75 ft ICD, and high for 90 ft ICD).

Improvement of Aesthetics: was considered same for all alternatives.

With the factors above and their assumed values, a performance matrix (Table H1) with 256 combinations was developed.

2.2. Selection of mini/modular-RAB design alternatives.

Two geometric properties (ICD and EA) were considered as the key design factors for MCA. More specifically, four ICDs (i.e., 45, 60, 75, and 90-ft) and four EAs (50°, 60°, 75°, and 90°). Traffic volumes on major and minor road were varied between 100 to 400 vehs/hr on each approach (i.e., 100, 200, 300, and 400 vehs/hr/approach). Table H1 presents mini-RAB intersection performance matrix based on simulation results (task 5) and range of the performance measures/factors mentioned in sub-section 2.1 for all possible scenarios based on Section 2.2.

2.3. Development of weight(s) for each performance evaluation factor.

A total of 100% weight were distributed to five evaluation criteria (i.e., operational performance, ROW, construction and maintenance cost, construction duration, and aesthetics). Based on the survey responses, the average importance score given to these five criteria before installation of a mini-RAB on a scale of 5 was found to be 4.2, 3.6, 3.0, 2.4, and 2.3, respectively. From these scores, the relative importance scores or weights were calculated for each factor (out of 100%). According the relative score of each factor, the calculated weight for operational performance was 30%. Similarly, the weights for ROW, construction and maintenance cost, construction duration, and aesthetics were calculated as 20%, 20%, 15%, and 15% respectively. Weight of operational performance (30%) was assigned evenly to the five operational performances criteria (i.e., each operational performance criteria was assigned 6% weight). *Note, these weights can be modified by practitioners when calculating the overall performance score for each design alternative depending on their personal/agency specific importance of each factor.* As well, practitioners can modify the weights and calculate performance score of each design alternatives using the accompanying spreadsheet-based MCA tool.

Before calculating the overall performance score of design alternatives, a maximum non-weighted score for each performance criterion was 100 before applying weight percentage of each criterion. Maximum score was assigned to the most desirable value of a performance criterion. For example, lowest average control delay (i.e., <5 secs) was assigned a non-weighted score of 100. The score for average control delay decreased with increase in average control delay. For cost, lowest cost was assigned 100 and the score decrease with increased cost. Non-weighted scores for all evaluation criteria are presented in Table 7.2.

2.4. Calculation of overall performance score (i.e., weighted score)

In sub-section 2.3, the individual weights (i.e., w_n in Equation 1) were calculated for five evaluation criteria (i.e., operational performance - 30%, ROW – 20%, construction and maintenance cost – 20%, construction duration 15%, and aesthetics – 15%). The non-weighted scores (i.e., S_{in} in Equation 1) are presented in Table H2. Following the Equation 1, the aggregated/overall performance score for each mini-RAB was calculated as presented in Table H3 (last column). Using these performance scores/aggregate scores, different mini-RAB design alternatives can be compared and ranked. In the accompanied MCA tool, these performance scores are displayed as the final output to compare different mini-RAB design alternatives. Higher score of a mini-RAB design alternative indicates better performance of an alternative based on the evaluation criteria (e.g., operational performance, construction and maintenance cost, construction duration, and aesthetics).

Table H1: Mini-roundabout intersection performance matrix based on simulation results (task 5) and range of the performance measures/factors mentioned in section 2.1 for all possible scenarios based on section 2.2.

Design Inputs					Simulation results					Adopted values based on the survey			
					Operational Performance								
Alternatives	ICD (ft)	EA (°)	Major Road Volume (veh/hr/leg)	Minor Road Volume (veh/hr/leg)	Avg. Control Delay (secs)	Avg. Geometric Delay (secs)	Queue Dist. (ft)	EIC (veh/hr)	Average Travel Speed (mph)	Right of way	Construction Cost	Construction duration	Aesthetics
1	45	50	100	100	< 5	2.2	< 50	3K – 4K	19 - 20	Low	150K	Low	Good
2	45	50	100	200	< 5	2.2	< 50	2K – 3K	19 - 20	Low	150K	Low	Good
3	45	50	100	300	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
4	45	50	100	400	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
5	45	50	200	100	< 5	2.2	< 50	2K – 3K	19 - 20	Low	150K	Low	Good
6	45	50	200	200	< 5	2.2	< 50	3K – 4K	19 - 20	Low	150K	Low	Good
7	45	50	200	300	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
8	45	50	200	400	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
9	45	50	300	100	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
10	45	50	300	200	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
11	45	50	300	300	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
12	45	50	300	400	5 - 10	2.2	100 -200	2K – 3K	18 - 19	Low	150K	Low	Good
13	45	50	400	100	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
14	45	50	400	200	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
15	45	50	400	300	5 - 10	2.2	100 -200	2K – 3K	18 - 19	Low	150K	Low	Good
16	45	50	400	400	10 - 20	2.2	100 - 200	2K – 3K	18 - 19	Low	150K	Low	Good
17	60	50	100	100	< 5	1.6	< 50	3K – 4K	19 - 20	Medium	200K	Medium	Good
18	60	50	100	200	< 5	1.6	< 50	3K – 4K	19 - 20	Medium	200K	Medium	Good
19	60	50	100	300	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
20	60	50	100	400	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
21	60	50	200	100	< 5	1.6	< 50	3K – 4K	19 - 20	Medium	200K	Medium	Good
22	60	50	200	200	< 5	1.6	< 50	3K – 4K	19 - 20	Medium	200K	Medium	Good
23	60	50	200	300	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
24	60	50	200	400	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
25	60	50	300	100	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
26	60	50	300	200	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
27	60	50	300	300	5 - 10	1.6	50 - 100	3K – 4K	19 - 20	Medium	200K	Medium	Good
28	60	50	300	400	5 - 10	1.6	100 - 200	2K – 3K	19 - 20	Medium	200K	Medium	Good
29	60	50	400	100	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
30	60	50	400	200	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
31	60	50	400	300	5 - 10	1.6	100 - 200	2K – 3K	19 - 20	Medium	200K	Medium	Good

32	60	50	400	400	10 - 20	1.6	100 - 200	2K – 3K	18 - 19	Medium	200K	Medium	Good
33	75	50	100	100	< 5	1	< 50	> 4K	19 - 20	Medium	250K	Medium	Good
34	75	50	100	200	< 5	1	< 50	3K – 4K	19 - 20	Medium	250K	Medium	Good
35	75	50	100	300	< 5	1	< 50	2K – 3K	19 - 20	Medium	250K	Medium	Good
36	75	50	100	400	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
37	75	50	200	100	< 5	1	< 50	3K – 4K	19 - 20	Medium	250K	Medium	Good
38	75	50	200	200	< 5	1	< 50	3K – 4K	19 - 20	Medium	250K	Medium	Good
39	75	50	200	300	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
40	75	50	200	400	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
41	75	50	300	100	< 5	1	< 50	2K – 3K	19 - 20	Medium	250K	Medium	Good
42	75	50	300	200	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
43	75	50	300	300	< 5	1	50 - 100	3K – 4K	19 - 20	Medium	250K	Medium	Good
44	75	50	300	400	5 - 10	1	100 - 200	2K – 3K	19 - 20	Medium	250K	Medium	Good
45	75	50	400	100	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
46	75	50	400	200	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
47	75	50	400	300	5 - 10	1	100 - 200	2K – 3K	19 - 20	Medium	250K	Medium	Good
48	75	50	400	400	5 - 10	1	100 - 200	2K – 3K	18 - 19	Medium	250K	Medium	Good
49	90	50	100	100	< 5	0.5	< 50	> 4K	19 - 20	High	300K	High	Good
50	90	50	100	200	< 5	0.5	< 50	3K – 4K	19 - 20	High	300K	High	Good
51	90	50	100	300	< 5	0.5	< 50	2K – 3K	19 - 20	High	300K	High	Good
52	90	50	100	400	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
53	90	50	200	100	< 5	0.5	< 50	3K – 4K	19 - 20	High	300K	High	Good
54	90	50	200	200	< 5	0.5	< 50	3K – 4K	19 - 20	High	300K	High	Good
55	90	50	200	300	< 5	0.5	50 - 100	3K – 4K	19 - 20	High	300K	High	Good
56	90	50	200	400	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
57	90	50	300	100	< 5	0.5	< 50	2K – 3K	19 - 20	High	300K	High	Good
58	90	50	300	200	< 5	0.5	50 - 100	3K – 4K	19 - 20	High	300K	High	Good
59	90	50	300	300	< 5	0.5	50 - 100	3K – 4K	19 - 20	High	300K	High	Good
60	90	50	300	400	< 5	0.5	100 - 200	2K – 3K	19 - 20	High	300K	High	Good
61	90	50	400	100	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
62	90	50	400	200	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
63	90	50	400	300	< 5	0.5	100 - 200	2K – 3K	19 - 20	High	300K	High	Good
64	90	50	400	400	5 - 10	0.5	100 - 200	2K – 3K	18 - 19	High	300K	High	Good
65	45	60	100	100	< 5	2.2	< 50	3K – 4K	19 - 20	Low	150K	Low	Good
66	45	60	100	200	< 5	2.2	< 50	2K – 3K	19 - 20	Low	150K	Low	Good
67	45	60	100	300	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
68	45	60	100	400	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
69	45	60	200	100	< 5	2.2	< 50	2K – 3K	19 - 20	Low	150K	Low	Good
70	45	60	200	200	< 5	2.2	< 50	3K – 4K	19 - 20	Low	150K	Low	Good
71	45	60	200	300	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
72	45	60	200	400	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
73	45	60	300	100	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
74	45	60	300	200	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good

75	45	60	300	300	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
76	45	60	300	400	5 - 10	2.2	100 - 200	2K – 3K	18 - 19	Low	150K	Low	Good
77	45	60	400	100	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
78	45	60	400	200	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
79	45	60	400	300	5 - 10	2.2	100 - 200	2K – 3K	18 - 19	Low	150K	Low	Good
80	45	60	400	400	10 - 20	2.2	100 - 200	2K – 3K	17 - 18	Low	150K	Low	Good
81	60	60	100	100	< 5	1.6	< 50	3K – 4K	19 - 20	Medium	200K	Medium	Good
82	60	60	100	200	< 5	1.6	< 50	2K – 3K	19 - 20	Medium	200K	Medium	Good
83	60	60	100	300	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
84	60	60	100	400	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
85	60	60	200	100	< 5	1.6	< 50	2K – 3K	19 - 20	Medium	200K	Medium	Good
86	60	60	200	200	< 5	1.6	< 50	3K – 4K	19 - 20	Medium	200K	Medium	Good
87	60	60	200	300	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
88	60	60	200	400	5 - 10	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
89	60	60	300	100	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
90	60	60	300	200	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
91	60	60	300	300	5 - 10	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
92	60	60	300	400	5 - 10	1.6	100 - 200	2K – 3K	18 - 19	Medium	200K	Medium	Good
93	60	60	400	100	5 - 10	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
94	60	60	400	200	5 - 10	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
95	60	60	400	300	5 - 10	1.6	100 - 200	2K – 3K	18 - 19	Medium	200K	Medium	Good
96	60	60	400	400	10 - 20	1.6	100 - 200	2K – 3K	18 - 19	Medium	200K	Medium	Good
97	75	60	100	100	< 5	1	< 50	3K – 4K	19 - 20	Medium	250K	Medium	Good
98	75	60	100	200	< 5	1	< 50	2K – 3K	19 - 20	Medium	250K	Medium	Good
99	75	60	100	300	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
100	75	60	100	400	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
101	75	60	200	100	< 5	1	< 50	2K – 3K	19 - 20	Medium	250K	Medium	Good
102	75	60	200	200	< 5	1	< 50	3K – 4K	19 - 20	Medium	250K	Medium	Good
103	75	60	200	300	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
104	75	60	200	400	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
105	75	60	300	100	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
106	75	60	300	200	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
107	75	60	300	300	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
108	75	60	300	400	5 - 10	1	100 - 200	2K – 3K	19 - 20	Medium	250K	Medium	Good
109	75	60	400	100	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
110	75	60	400	200	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
111	75	60	400	300	5 - 10	1	100 - 200	2K – 3K	19 - 20	Medium	250K	Medium	Good
112	75	60	400	400	10 - 20	1	100 - 200	2K – 3K	18 - 19	Medium	250K	Medium	Good
113	90	60	100	100	< 5	0.5	< 50	3K – 4K	19 - 20	High	300K	High	Good
114	90	60	100	200	< 5	0.5	< 50	3K – 4K	19 - 20	High	300K	High	Good
115	90	60	100	300	< 5	0.5	< 50	2K – 3K	19 - 20	High	300K	High	Good
116	90	60	100	400	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
117	90	60	200	100	< 5	0.5	< 50	3K – 4K	19 - 20	High	300K	High	Good

118	90	60	200	200	< 5	0.5	< 50	3K – 4K	19 - 20	High	300K	High	Good
119	90	60	200	300	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
120	90	60	200	400	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
121	90	60	300	100	< 5	0.5	< 50	2K – 3K	19 - 20	High	300K	High	Good
122	90	60	300	200	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
123	90	60	300	300	< 5	0.5	50 - 100	3K – 4K	19 - 20	High	300K	High	Good
124	90	60	300	400	5 - 10	0.5	100 - 200	2K – 3K	19 - 20	High	300K	High	Good
125	90	60	400	100	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
126	90	60	400	200	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
127	90	60	400	300	5 - 10	0.5	100 - 200	2K – 3K	19 - 20	High	300K	High	Good
128	90	60	400	400	5 - 10	0.5	100 - 200	2K – 3K	18 - 19	High	300K	High	Good
129	45	75	100	100	< 5	2.2	< 50	3K – 4K	19 - 20	Low	150K	Low	Good
130	45	75	100	200	< 5	2.2	< 50	2K – 3K	19 - 20	Low	150K	Low	Good
131	45	75	100	300	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
132	45	75	100	400	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
133	45	75	200	100	< 5	2.2	< 50	2K – 3K	19 - 20	Low	150K	Low	Good
134	45	75	200	200	< 5	2.2	< 50	2K – 3K	19 - 20	Low	150K	Low	Good
135	45	75	200	300	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
136	45	75	200	400	5 - 10	2.2	100 - 200	2K – 3K	18 - 19	Low	150K	Low	Good
137	45	75	300	100	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
138	45	75	300	200	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
139	45	75	300	300	5 - 10	2.2	50 - 100	2K – 3K	18 - 19	Low	150K	Low	Good
140	45	75	300	400	10 - 20	2.2	100 - 200	2K – 3K	18 - 19	Low	150K	Low	Good
141	45	75	400	100	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
142	45	75	400	200	5 - 10	2.2	100 - 200	2K – 3K	18 - 19	Low	150K	Low	Good
143	45	75	400	300	10 - 20	2.2	100 - 200	2K – 3K	18 - 19	Low	150K	Low	Good
144	45	75	400	400	10 - 20	2.2	200 - 400	2K – 3K	17 - 18	Low	150K	Low	Good
145	60	75	100	100	< 5	1.6	< 50	3K – 4K	19 - 20	Medium	200K	Medium	Good
146	60	75	100	200	< 5	1.6	< 50	2K – 3K	19 - 20	Medium	200K	Medium	Good
147	60	75	100	300	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
148	60	75	100	400	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
149	60	75	200	100	< 5	1.6	< 50	2K – 3K	19 - 20	Medium	200K	Medium	Good
150	60	75	200	200	< 5	1.6	< 50	2K – 3K	19 - 20	Medium	200K	Medium	Good
151	60	75	200	300	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
152	60	75	200	400	5 - 10	1.6	100 - 200	2K – 3K	19 - 20	Medium	200K	Medium	Good
153	60	75	300	100	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
154	60	75	300	200	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
155	60	75	300	300	5 - 10	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
156	60	75	300	400	5 - 10	1.6	100 - 200	2K – 3K	18 - 19	Medium	200K	Medium	Good
157	60	75	400	100	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
158	60	75	400	200	5 - 10	1.6	100 - 200	2K – 3K	19 - 20	Medium	200K	Medium	Good
159	60	75	400	300	5 - 10	1.6	100 - 200	2K – 3K	18 - 19	Medium	200K	Medium	Good
160	60	75	400	400	10 - 20	1.6	200 - 400	2K – 3K	17 - 18	Medium	200K	Medium	Good

161	75	75	100	100	< 5	1	< 50	3K – 4K	19 - 20	Medium	250K	Medium	Good
162	75	75	100	200	< 5	1	< 50	2K – 3K	19 - 20	Medium	250K	Medium	Good
163	75	75	100	300	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
164	75	75	100	400	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
165	75	75	200	100	< 5	1	< 50	2K – 3K	19 - 20	Medium	250K	Medium	Good
166	75	75	200	200	< 5	1	< 50	3K – 4K	19 - 20	Medium	250K	Medium	Good
167	75	75	200	300	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
168	75	75	200	400	< 5	1	100 - 200	2K – 3K	19 - 20	Medium	250K	Medium	Good
169	75	75	300	100	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
170	75	75	300	200	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
171	75	75	300	300	5 - 10	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
172	75	75	300	400	5 - 10	1	100 - 200	2K – 3K	18 - 19	Medium	250K	Medium	Good
173	75	75	400	100	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
174	75	75	400	200	< 5	1	100 - 200	2K – 3K	19 - 20	Medium	250K	Medium	Good
175	75	75	400	300	5 - 10	1	100 - 200	2K – 3K	18 - 19	Medium	250K	Medium	Good
176	75	75	400	400	14	1	200 - 400	2K – 3K	18 - 19	Medium	250K	Medium	Good
177	90	75	100	100	< 5	0.5	< 50	2K – 3K	19 - 20	High	300K	High	Good
178	90	75	100	200	< 5	0.5	< 50	2K – 3K	19 - 20	High	300K	High	Good
179	90	75	100	300	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
180	90	75	100	400	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
181	90	75	200	100	< 5	0.5	< 50	2K – 3K	19 - 20	High	300K	High	Good
182	90	75	200	200	< 5	0.5	< 50	3K – 4K	19 - 20	High	300K	High	Good
183	90	75	200	300	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
184	90	75	200	400	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
185	90	75	300	100	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
186	90	75	300	200	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
187	90	75	300	300	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
188	90	75	300	400	5 - 10	0.5	100 - 200	2K – 3K	18 - 19	High	300K	High	Good
189	90	75	400	100	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
190	90	75	400	200	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
191	90	75	400	300	5 - 10	0.5	100 - 200	2K – 3K	18 - 19	High	300K	High	Good
192	90	75	400	400	10 - 20	0.5	100 - 200	2K – 3K	18 - 19	High	300K	High	Good
193	45	90	100	100	< 5	2.2	< 50	3K – 4K	19 - 20	Low	150K	Low	Good
194	45	90	100	200	< 5	2.2	< 50	2K – 3K	19 - 20	Low	150K	Low	Good
195	45	90	100	300	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
196	45	90	100	400	5 - 10	2.2	100 - 200	2K – 3K	19 - 20	Low	150K	Low	Good
197	45	90	200	100	< 5	2.2	< 50	2K – 3K	19 - 20	Low	150K	Low	Good
198	45	90	200	200	5 - 10	2.2	< 50	2K – 3K	19 - 20	Low	150K	Low	Good
199	45	90	200	300	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
200	45	90	200	400	5 - 10	2.2	100 - 200	2K – 3K	18 - 19	Low	150K	Low	Good
201	45	90	300	100	< 5	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
202	45	90	300	200	5 - 10	2.2	50 - 100	2K – 3K	19 - 20	Low	150K	Low	Good
203	45	90	300	300	5 - 10	2.2	100 - 200	2K – 3K	18 - 19	Low	150K	Low	Good

204	45	90	300	400	10 - 20	2.2	200 - 400	2K – 3K	17 - 18	Low	150K	Low	Good
205	45	90	400	100	5 - 10	2.2	100 - 200	2K – 3K	19 - 20	Low	150K	Low	Good
206	45	90	400	200	5 - 10	2.2	100 - 200	2K – 3K	18 - 19	Low	150K	Low	Good
207	45	90	400	300	10 - 20	2.2	200 - 400	2K – 3K	17 - 18	Low	150K	Low	Good
208	45	90	400	400	> 30	2.2	200 - 400	2K – 3K	< 17	Low	150K	Low	Good
209	60	90	100	100	< 5	1.6	< 50	3K – 4K	19 - 20	Medium	200K	Medium	Good
210	60	90	100	200	< 5	1.6	< 50	2K – 3K	19 - 20	Medium	200K	Medium	Good
211	60	90	100	300	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
212	60	90	100	400	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
213	60	90	200	100	< 5	1.6	< 50	2K – 3K	19 - 20	Medium	200K	Medium	Good
214	60	90	200	200	< 5	1.6	< 50	2K – 3K	19 - 20	Medium	200K	Medium	Good
215	60	90	200	300	5 - 10	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
216	60	90	200	400	5 - 10	1.6	100 - 200	2K – 3K	19 - 20	Medium	200K	Medium	Good
217	60	90	300	100	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
218	60	90	300	200	5 - 10	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
219	60	90	300	300	5 - 10	1.6	100 - 200	2K – 3K	18 - 19	Medium	200K	Medium	Good
220	60	90	300	400	13.5	1.6	200 - 400	2K – 3K	18 - 19	Medium	200K	Medium	Good
221	60	90	400	100	< 5	1.6	50 - 100	2K – 3K	19 - 20	Medium	200K	Medium	Good
222	60	90	400	200	5 - 10	1.6	100 - 200	2K – 3K	19 - 20	Medium	200K	Medium	Good
223	60	90	400	300	10 - 20	1.6	200 - 400	2K – 3K	18 - 19	Medium	200K	Medium	Good
224	60	90	400	400	20 - 30	1.6	200 - 400	2K – 3K	< 17	Medium	200K	Medium	Good
225	75	90	100	100	< 5	1	< 50	3K – 4K	19 - 20	Medium	250K	Medium	Good
226	75	90	100	200	< 5	1	< 50	2K – 3K	19 - 20	Medium	250K	Medium	Good
227	75	90	100	300	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
228	75	90	100	400	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
229	75	90	200	100	< 5	1	< 50	2K – 3K	19 - 20	Medium	250K	Medium	Good
230	75	90	200	200	< 5	1	< 50	2K – 3K	19 - 20	Medium	250K	Medium	Good
231	75	90	200	300	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
232	75	90	200	400	5 - 10	1	100 - 200	2K – 3K	19 - 20	Medium	250K	Medium	Good
233	75	90	300	100	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
234	75	90	300	200	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
235	75	90	300	300	5 - 10	1	100 - 200	2K – 3K	19 - 20	Medium	250K	Medium	Good
236	75	90	300	400	10 - 20	1	100 - 200	2K – 3K	18 - 19	Medium	250K	Medium	Good
237	75	90	400	100	< 5	1	50 - 100	2K – 3K	19 - 20	Medium	250K	Medium	Good
238	75	90	400	200	5 - 10	1	100 - 200	2K – 3K	19 - 20	Medium	250K	Medium	Good
239	75	90	400	300	10 - 20	1	100 - 200	2K – 3K	18 - 19	Medium	250K	Medium	Good
240	75	90	400	400	20 - 30	1	200 - 400	2K – 3K	17.15	Medium	250K	Medium	Good
241	90	90	100	100	< 5	0.5	< 50	3K – 4K	19 - 20	High	300K	High	Good
242	90	90	100	200	< 5	0.5	< 50	2K – 3K	19 - 20	High	300K	High	Good
243	90	90	100	300	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
244	90	90	100	400	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
245	90	90	200	100	< 5	0.5	< 50	2K – 3K	19 - 20	High	300K	High	Good
246	90	90	200	200	< 5	0.5	< 50	2K – 3K	19 - 20	High	300K	High	Good

247	90	90	200	300	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
248	90	90	200	400	5 - 10	0.5	100 - 200	2K – 3K	19 - 20	High	300K	High	Good
249	90	90	300	100	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
250	90	90	300	200	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
251	90	90	300	300	5 - 10	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
252	90	90	300	400	5 - 10	0.5	100 - 200	2K – 3K	18 - 19	High	300K	High	Good
253	90	90	400	100	< 5	0.5	50 - 100	2K – 3K	19 - 20	High	300K	High	Good
254	90	90	400	200	5 - 10	0.5	100 - 200	2K – 3K	19 - 20	High	300K	High	Good
255	90	90	400	300	5 - 10	0.5	100 - 200	2K – 3K	18 - 19	High	300K	High	Good
256	90	90	400	400	10 - 20	0.5	200 - 400	2K – 3K	17 - 18	High	300K	High	Good

Table H2: Non-weighted scores for each mini-roundabout intersection alternatives

Alternatives	ICD (ft)	EA (°)	Major Road Volume (veh/hr/leg)	Minor Road Volume (veh/hr/leg)	Operational Performance					Right of way	Construction Cost	Construction duration	Aesthetics
					Avg. Control Delay (secs)	Avg. Geometric Delay (secs)	Queue Dist. (ft)	EIC (veh/hr)	Average Travel Speed (mph)				
1	45	50	100	100	100	40	100	80	100	100	100	100	100
2	45	50	100	200	100	40	100	60	100	100	100	100	100
3	45	50	100	300	100	40	80	60	100	100	100	100	100
4	45	50	100	400	100	40	80	60	100	100	100	100	100
5	45	50	200	100	100	40	100	60	100	100	100	100	100
6	45	50	200	200	100	40	100	80	100	100	100	100	100
7	45	50	200	300	100	40	80	60	100	100	100	100	100
8	45	50	200	400	80	40	80	60	100	100	100	100	100
9	45	50	300	100	100	40	80	60	100	100	100	100	100
10	45	50	300	200	100	40	80	60	100	100	100	100	100
11	45	50	300	300	80	40	80	60	100	100	100	100	100
12	45	50	300	400	80	40	60	60	80	100	100	100	100
13	45	50	400	100	100	40	80	60	100	100	100	100	100
14	45	50	400	200	80	40	80	60	100	100	100	100	100
15	45	50	400	300	80	40	60	60	80	100	100	100	100
16	45	50	400	400	60	40	60	60	80	100	100	100	100
17	60	50	100	100	100	60	100	80	100	80	80	80	100
18	60	50	100	200	100	60	100	80	100	80	80	80	100
19	60	50	100	300	100	60	80	60	100	80	80	80	100
20	60	50	100	400	100	60	80	60	100	80	80	80	100
21	60	50	200	100	100	60	100	80	100	80	80	80	100
22	60	50	200	200	100	60	100	80	100	80	80	80	100
23	60	50	200	300	100	60	80	60	100	80	80	80	100
24	60	50	200	400	100	60	80	60	100	80	80	80	100

25	60	50	300	100	100	60	80	60	100	80	80	80	100
26	60	50	300	200	100	60	80	60	100	80	80	80	100
27	60	50	300	300	80	60	80	80	100	80	80	80	100
28	60	50	300	400	80	60	60	60	100	80	80	80	100
29	60	50	400	100	100	60	80	60	100	80	80	80	100
30	60	50	400	200	100	60	80	60	100	80	80	80	100
31	60	50	400	300	80	60	60	60	100	80	80	80	100
32	60	50	400	400	60	60	60	60	80	80	80	80	100
33	75	50	100	100	100	80	100	100	100	80	60	80	100
34	75	50	100	200	100	80	100	80	100	80	60	80	100
35	75	50	100	300	100	80	100	60	100	80	60	80	100
36	75	50	100	400	100	80	80	60	100	80	60	80	100
37	75	50	200	100	100	80	100	80	100	80	60	80	100
38	75	50	200	200	100	80	100	80	100	80	60	80	100
39	75	50	200	300	100	80	80	60	100	80	60	80	100
40	75	50	200	400	100	80	80	60	100	80	60	80	100
41	75	50	300	100	100	80	100	60	100	80	60	80	100
42	75	50	300	200	100	80	80	60	100	80	60	80	100
43	75	50	300	300	100	80	80	80	100	80	60	80	100
44	75	50	300	400	80	80	60	60	100	80	60	80	100
45	75	50	400	100	100	80	80	60	100	80	60	80	100
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48	75	50	400	400	80	80	60	60	80	80	60	80	100
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51	90	50	100	300	100	100	100	60	100	60	40	60	100
52	90	50	100	400	100	100	80	60	100	60	40	60	100
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57	90	50	300	100	100	100	100	60	100	60	40	60	100
58	90	50	300	200	100	100	80	80	100	60	40	60	100
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60	90	50	300	400	100	100	60	60	100	60	40	60	100
61	90	50	400	100	100	100	80	60	100	60	40	60	100
62	90	50	400	200	100	100	80	60	100	60	40	60	100
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64	90	50	400	400	80	100	60	60	80	60	40	60	100
65	45	60	100	100	100	40	100	80	100	100	100	100	100
66	45	60	100	200	100	40	100	60	100	100	100	100	100
67	45	60	100	300	100	40	80	60	100	100	100	100	100

68	45	60	100	400	100	40	80	60	100	100	100	100	100
69	45	60	200	100	100	40	100	60	100	100	100	100	100
70	45	60	200	200	100	40	100	80	100	100	100	100	100
71	45	60	200	300	80	40	80	60	100	100	100	100	100
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78	45	60	400	200	80	40	80	60	100	100	100	100	100
79	45	60	400	300	80	40	60	60	80	100	100	100	100
80	45	60	400	400	60	40	60	60	60	100	100	100	100
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84	60	60	100	400	100	60	80	60	100	80	80	80	100
85	60	60	200	100	100	60	100	60	100	80	80	80	100
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87	60	60	200	300	100	60	80	60	100	80	80	80	100
88	60	60	200	400	80	60	80	60	100	80	80	80	100
89	60	60	300	100	100	60	80	60	100	80	80	80	100
90	60	60	300	200	100	60	80	60	100	80	80	80	100
91	60	60	300	300	80	60	80	60	100	80	80	80	100
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94	60	60	400	200	80	60	80	60	100	80	80	80	100
95	60	60	400	300	80	60	60	60	80	80	80	80	100
96	60	60	400	400	60	60	60	60	80	80	80	80	100
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98	75	60	100	200	100	80	100	60	100	80	60	80	100
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100	75	60	100	400	100	80	80	60	100	80	60	80	100
101	75	60	200	100	100	80	100	60	100	80	60	80	100
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103	75	60	200	300	100	80	80	60	100	80	60	80	100
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105	75	60	300	100	100	80	80	60	100	80	60	80	100
106	75	60	300	200	100	80	80	60	100	80	60	80	100
107	75	60	300	300	100	80	80	60	100	80	60	80	100
108	75	60	300	400	80	80	60	60	100	80	60	80	100
109	75	60	400	100	100	80	80	60	100	80	60	80	100
110	75	60	400	200	100	80	80	60	100	80	60	80	100

111	75	60	400	300	80	80	60	60	100	80	60	80	100
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128	90	60	400	400	80	100	60	60	80	60	40	60	100
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140	45	75	300	400	60	40	60	60	80	100	100	100	100
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143	45	75	400	300	60	40	60	60	80	100	100	100	100
144	45	75	400	400	60	40	40	60	60	100	100	100	100
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146	60	75	100	200	100	60	100	60	100	80	80	80	100
147	60	75	100	300	100	60	80	60	100	80	80	80	100
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151	60	75	200	300	100	60	80	60	100	80	80	80	100
152	60	75	200	400	80	60	60	60	100	80	80	80	100
153	60	75	300	100	100	60	80	60	100	80	80	80	100

154	60	75	300	200	100	60	80	60	100	80	80	80	100
155	60	75	300	300	80	60	80	60	100	80	80	80	100
156	60	75	300	400	80	60	60	60	80	80	80	80	100
157	60	75	400	100	100	60	80	60	100	80	80	80	100
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159	60	75	400	300	80	60	60	60	80	80	80	80	100
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169	75	75	300	100	100	80	80	60	100	80	60	80	100
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171	75	75	300	300	80	80	80	60	100	80	60	80	100
172	75	75	300	400	80	80	60	60	80	80	60	80	100
173	75	75	400	100	100	80	80	60	100	80	60	80	100
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175	75	75	400	300	80	80	60	60	80	80	60	80	100
176	75	75	400	400	14	80	40	60	80	80	60	80	100
177	90	75	100	100	100	100	100	60	100	60	40	60	100
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179	90	75	100	300	100	100	80	60	100	60	40	60	100
180	90	75	100	400	100	100	80	60	100	60	40	60	100
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182	90	75	200	200	100	100	100	80	100	60	40	60	100
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184	90	75	200	400	100	100	80	60	100	60	40	60	100
185	90	75	300	100	100	100	80	60	100	60	40	60	100
186	90	75	300	200	100	100	80	60	100	60	40	60	100
187	90	75	300	300	100	100	80	60	100	60	40	60	100
188	90	75	300	400	80	100	60	60	80	60	40	60	100
189	90	75	400	100	100	100	80	60	100	60	40	60	100
190	90	75	400	200	100	100	80	60	100	60	40	60	100
191	90	75	400	300	80	100	60	60	80	60	40	60	100
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195	45	90	100	300	100	40	80	60	100	100	100	100	100
196	45	90	100	400	80	40	60	60	100	100	100	100	100

197	45	90	200	100	100	40	100	60	100	100	100	100	100
198	45	90	200	200	80	40	100	60	100	100	100	100	100
199	45	90	200	300	80	40	80	60	100	100	100	100	100
200	45	90	200	400	80	40	60	60	80	100	100	100	100
201	45	90	300	100	100	40	80	60	100	100	100	100	100
202	45	90	300	200	80	40	80	60	100	100	100	100	100
203	45	90	300	300	80	40	60	60	80	100	100	100	100
204	45	90	300	400	60	40	40	60	60	100	100	100	100
205	45	90	400	100	80	40	60	60	100	100	100	100	100
206	45	90	400	200	80	40	60	60	80	100	100	100	100
207	45	90	400	300	60	40	40	60	60	100	100	100	100
208	45	90	400	400	20	40	40	60	40	100	100	100	100
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212	60	90	100	400	100	60	80	60	100	80	80	80	100
213	60	90	200	100	100	60	100	60	100	80	80	80	100
214	60	90	200	200	100	60	100	60	100	80	80	80	100
215	60	90	200	300	80	60	80	60	100	80	80	80	100
216	60	90	200	400	80	60	60	60	100	80	80	80	100
217	60	90	300	100	100	60	80	60	100	80	80	80	100
218	60	90	300	200	80	60	80	60	100	80	80	80	100
219	60	90	300	300	80	60	60	60	80	80	80	80	100
220	60	90	300	400	13.5	60	40	60	80	80	80	80	100
221	60	90	400	100	100	60	80	60	100	80	80	80	100
222	60	90	400	200	80	60	60	60	100	80	80	80	100
223	60	90	400	300	60	60	40	60	80	80	80	80	100
224	60	90	400	400	40	60	40	60	40	80	80	80	100
225	75	90	100	100	100	80	100	80	100	80	60	80	100
226	75	90	100	200	100	80	100	60	100	80	60	80	100
227	75	90	100	300	100	80	80	60	100	80	60	80	100
228	75	90	100	400	100	80	80	60	100	80	60	80	100
229	75	90	200	100	100	80	100	60	100	80	60	80	100
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231	75	90	200	300	100	80	80	60	100	80	60	80	100
232	75	90	200	400	80	80	60	60	100	80	60	80	100
233	75	90	300	100	100	80	80	60	100	80	60	80	100
234	75	90	300	200	100	80	80	60	100	80	60	80	100
235	75	90	300	300	80	80	60	60	100	80	60	80	100
236	75	90	300	400	60	80	60	60	80	80	60	80	100
237	75	90	400	100	100	80	80	60	100	80	60	80	100
238	75	90	400	200	80	80	60	60	100	80	60	80	100
239	75	90	400	300	60	80	60	60	80	80	60	80	100

240	75	90	400	400	40	80	40	60	60	80	60	80	100
241	90	90	100	100	100	100	100	80	100	60	40	60	100
242	90	90	100	200	100	100	100	60	100	60	40	60	100
243	90	90	100	300	100	100	80	60	100	60	40	60	100
244	90	90	100	400	100	100	80	60	100	60	40	60	100
245	90	90	200	100	100	100	100	60	100	60	40	60	100
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250	90	90	300	200	100	100	80	60	100	60	40	60	100
251	90	90	300	300	80	100	80	60	100	60	40	60	100
252	90	90	300	400	80	100	60	60	80	60	40	60	100
253	90	90	400	100	100	100	80	60	100	60	40	60	100
254	90	90	400	200	80	100	60	60	100	60	40	60	100
255	90	90	400	300	80	100	60	60	80	60	40	60	100
256	90	90	400	400	60	100	40	60	60	60	40	60	100

Table H3: Ranking of mini-roundabout alternatives based on Multi-Criteria Assessment

Alternatives	ICD (ft)	EA (°)	Major Road Volume (veh/hr/leg)	Minor Road Volume (veh/hr/leg)	Operational Performance					Right of way	Construction Cost	Construction duration	Aesthetics	Performance score
					Avg. Control Delay (secs)	Avg. Geometric Delay (secs)	Queue Dist. (ft)	EIC (veh/hr)	Average Travel Speed (mph)					
1	45	50	100	100	6	2.4	6	4.8	6	20	20	15	15	95.20
2	45	50	100	200	6	2.4	6	3.6	6	20	20	15	15	94.00
3	45	50	100	300	6	2.4	4.8	3.6	6	20	20	15	15	92.80
4	45	50	100	400	6	2.4	4.8	3.6	6	20	20	15	15	92.80
5	45	50	200	100	6	2.4	6	3.6	6	20	20	15	15	94.00
6	45	50	200	200	6	2.4	6	4.8	6	20	20	15	15	95.20
7	45	50	200	300	6	2.4	4.8	3.6	6	20	20	15	15	92.80
8	45	50	200	400	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
9	45	50	300	100	6	2.4	4.8	3.6	6	20	20	15	15	92.80
10	45	50	300	200	6	2.4	4.8	3.6	6	20	20	15	15	92.80
11	45	50	300	300	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
12	45	50	300	400	4.8	2.4	3.6	3.6	4.8	20	20	15	15	89.20
13	45	50	400	100	6	2.4	4.8	3.6	6	20	20	15	15	92.80
14	45	50	400	200	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
15	45	50	400	300	4.8	2.4	3.6	3.6	4.8	20	20	15	15	89.20
16	45	50	400	400	3.6	2.4	3.6	3.6	4.8	20	20	15	15	88.00
17	60	50	100	100	6	3.6	6	4.8	6	16	16	12	15	85.40

18	60	50	100	200	6	3.6	6	4.8	6	16	16	12	15	85.40
19	60	50	100	300	6	3.6	4.8	3.6	6	16	16	12	15	83.00
20	60	50	100	400	6	3.6	4.8	3.6	6	16	16	12	15	83.00
21	60	50	200	100	6	3.6	6	4.8	6	16	16	12	15	85.40
22	60	50	200	200	6	3.6	6	4.8	6	16	16	12	15	85.40
23	60	50	200	300	6	3.6	4.8	3.6	6	16	16	12	15	83.00
24	60	50	200	400	6	3.6	4.8	3.6	6	16	16	12	15	83.00
25	60	50	300	100	6	3.6	4.8	3.6	6	16	16	12	15	83.00
26	60	50	300	200	6	3.6	4.8	3.6	6	16	16	12	15	83.00
27	60	50	300	300	4.8	3.6	4.8	4.8	6	16	16	12	15	83.00
28	60	50	300	400	4.8	3.6	3.6	3.6	6	16	16	12	15	80.60
29	60	50	400	100	6	3.6	4.8	3.6	6	16	16	12	15	83.00
30	60	50	400	200	6	3.6	4.8	3.6	6	16	16	12	15	83.00
31	60	50	400	300	4.8	3.6	3.6	3.6	6	16	16	12	15	80.60
32	60	50	400	400	3.6	3.6	3.6	3.6	4.8	16	16	12	15	78.20
33	75	50	100	100	6	4.8	6	6	6	16	12	12	15	83.80
34	75	50	100	200	6	4.8	6	4.8	6	16	12	12	15	82.60
35	75	50	100	300	6	4.8	6	3.6	6	16	12	12	15	81.40
36	75	50	100	400	6	4.8	4.8	3.6	6	16	12	12	15	80.20
37	75	50	200	100	6	4.8	6	4.8	6	16	12	12	15	82.60
38	75	50	200	200	6	4.8	6	4.8	6	16	12	12	15	82.60
39	75	50	200	300	6	4.8	4.8	3.6	6	16	12	12	15	80.20
40	75	50	200	400	6	4.8	4.8	3.6	6	16	12	12	15	80.20
41	75	50	300	100	6	4.8	6	3.6	6	16	12	12	15	81.40
42	75	50	300	200	6	4.8	4.8	3.6	6	16	12	12	15	80.20
43	75	50	300	300	6	4.8	4.8	4.8	6	16	12	12	15	81.40
44	75	50	300	400	4.8	4.8	3.6	3.6	6	16	12	12	15	77.80
45	75	50	400	100	6	4.8	4.8	3.6	6	16	12	12	15	80.20
46	75	50	400	200	6	4.8	4.8	3.6	6	16	12	12	15	80.20
47	75	50	400	300	4.8	4.8	3.6	3.6	6	16	12	12	15	77.80
48	75	50	400	400	4.8	4.8	3.6	3.6	4.8	16	12	12	15	76.60
49	90	50	100	100	6	6	6	6	6	12	8	9	15	74.00
50	90	50	100	200	6	6	6	4.8	6	12	8	9	15	72.80
51	90	50	100	300	6	6	6	3.6	6	12	8	9	15	71.60
52	90	50	100	400	6	6	4.8	3.6	6	12	8	9	15	70.40
53	90	50	200	100	6	6	6	4.8	6	12	8	9	15	72.80
54	90	50	200	200	6	6	6	4.8	6	12	8	9	15	72.80
55	90	50	200	300	6	6	4.8	4.8	6	12	8	9	15	71.60
56	90	50	200	400	6	6	4.8	3.6	6	12	8	9	15	70.40
57	90	50	300	100	6	6	6	3.6	6	12	8	9	15	71.60
58	90	50	300	200	6	6	4.8	4.8	6	12	8	9	15	71.60
59	90	50	300	300	6	6	4.8	4.8	6	12	8	9	15	71.60
60	90	50	300	400	6	6	3.6	3.6	6	12	8	9	15	69.20

61	90	50	400	100	6	6	4.8	3.6	6	12	8	9	15	70.40
62	90	50	400	200	6	6	4.8	3.6	6	12	8	9	15	70.40
63	90	50	400	300	6	6	3.6	3.6	6	12	8	9	15	69.20
64	90	50	400	400	4.8	6	3.6	3.6	4.8	12	8	9	15	66.80
65	45	60	100	100	6	2.4	6	4.8	6	20	20	15	15	95.20
66	45	60	100	200	6	2.4	6	3.6	6	20	20	15	15	94.00
67	45	60	100	300	6	2.4	4.8	3.6	6	20	20	15	15	92.80
68	45	60	100	400	6	2.4	4.8	3.6	6	20	20	15	15	92.80
69	45	60	200	100	6	2.4	6	3.6	6	20	20	15	15	94.00
70	45	60	200	200	6	2.4	6	4.8	6	20	20	15	15	95.20
71	45	60	200	300	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
72	45	60	200	400	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
73	45	60	300	100	6	2.4	4.8	3.6	6	20	20	15	15	92.80
74	45	60	300	200	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
75	45	60	300	300	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
76	45	60	300	400	4.8	2.4	3.6	3.6	4.8	20	20	15	15	89.20
77	45	60	400	100	6	2.4	4.8	3.6	6	20	20	15	15	92.80
78	45	60	400	200	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
79	45	60	400	300	4.8	2.4	3.6	3.6	4.8	20	20	15	15	89.20
80	45	60	400	400	3.6	2.4	3.6	3.6	3.6	20	20	15	15	86.80
81	60	60	100	100	6	3.6	6	4.8	6	16	16	12	15	85.40
82	60	60	100	200	6	3.6	6	3.6	6	16	16	12	15	84.20
83	60	60	100	300	6	3.6	4.8	3.6	6	16	16	12	15	83.00
84	60	60	100	400	6	3.6	4.8	3.6	6	16	16	12	15	83.00
85	60	60	200	100	6	3.6	6	3.6	6	16	16	12	15	84.20
86	60	60	200	200	6	3.6	6	4.8	6	16	16	12	15	85.40
87	60	60	200	300	6	3.6	4.8	3.6	6	16	16	12	15	83.00
88	60	60	200	400	4.8	3.6	4.8	3.6	6	16	16	12	15	81.80
89	60	60	300	100	6	3.6	4.8	3.6	6	16	16	12	15	83.00
90	60	60	300	200	6	3.6	4.8	3.6	6	16	16	12	15	83.00
91	60	60	300	300	4.8	3.6	4.8	3.6	6	16	16	12	15	81.80
92	60	60	300	400	4.8	3.6	3.6	3.6	4.8	16	16	12	15	79.40
93	60	60	400	100	4.8	3.6	4.8	3.6	6	16	16	12	15	81.80
94	60	60	400	200	4.8	3.6	4.8	3.6	6	16	16	12	15	81.80
95	60	60	400	300	4.8	3.6	3.6	3.6	4.8	16	16	12	15	79.40
96	60	60	400	400	3.6	3.6	3.6	3.6	4.8	16	16	12	15	78.20
97	75	60	100	100	6	4.8	6	4.8	6	16	12	12	15	82.60
98	75	60	100	200	6	4.8	6	3.6	6	16	12	12	15	81.40
99	75	60	100	300	6	4.8	4.8	3.6	6	16	12	12	15	80.20
100	75	60	100	400	6	4.8	4.8	3.6	6	16	12	12	15	80.20
101	75	60	200	100	6	4.8	6	3.6	6	16	12	12	15	81.40
102	75	60	200	200	6	4.8	6	4.8	6	16	12	12	15	82.60
103	75	60	200	300	6	4.8	4.8	3.6	6	16	12	12	15	80.20

104	75	60	200	400	6	4.8	4.8	3.6	6	16	12	12	15	80.20
105	75	60	300	100	6	4.8	4.8	3.6	6	16	12	12	15	80.20
106	75	60	300	200	6	4.8	4.8	3.6	6	16	12	12	15	80.20
107	75	60	300	300	6	4.8	4.8	3.6	6	16	12	12	15	80.20
108	75	60	300	400	4.8	4.8	3.6	3.6	6	16	12	12	15	77.80
109	75	60	400	100	6	4.8	4.8	3.6	6	16	12	12	15	80.20
110	75	60	400	200	6	4.8	4.8	3.6	6	16	12	12	15	80.20
111	75	60	400	300	4.8	4.8	3.6	3.6	6	16	12	12	15	77.80
112	75	60	400	400	3.6	4.8	3.6	3.6	4.8	16	12	12	15	75.40
113	90	60	100	100	6	6	6	4.8	6	12	8	9	15	72.80
114	90	60	100	200	6	6	6	4.8	6	12	8	9	15	72.80
115	90	60	100	300	6	6	6	3.6	6	12	8	9	15	71.60
116	90	60	100	400	6	6	4.8	3.6	6	12	8	9	15	70.40
117	90	60	200	100	6	6	6	4.8	6	12	8	9	15	72.80
118	90	60	200	200	6	6	6	4.8	6	12	8	9	15	72.80
119	90	60	200	300	6	6	4.8	3.6	6	12	8	9	15	70.40
120	90	60	200	400	6	6	4.8	3.6	6	12	8	9	15	70.40
121	90	60	300	100	6	6	6	3.6	6	12	8	9	15	71.60
122	90	60	300	200	6	6	4.8	3.6	6	12	8	9	15	70.40
123	90	60	300	300	6	6	4.8	4.8	6	12	8	9	15	71.60
124	90	60	300	400	4.8	6	3.6	3.6	6	12	8	9	15	68.00
125	90	60	400	100	6	6	4.8	3.6	6	12	8	9	15	70.40
126	90	60	400	200	6	6	4.8	3.6	6	12	8	9	15	70.40
127	90	60	400	300	4.8	6	3.6	3.6	6	12	8	9	15	68.00
128	90	60	400	400	4.8	6	3.6	3.6	4.8	12	8	9	15	66.80
129	45	75	100	100	6	2.4	6	4.8	6	20	20	15	15	95.20
130	45	75	100	200	6	2.4	6	3.6	6	20	20	15	15	94.00
131	45	75	100	300	6	2.4	4.8	3.6	6	20	20	15	15	92.80
132	45	75	100	400	6	2.4	4.8	3.6	6	20	20	15	15	92.80
133	45	75	200	100	6	2.4	6	3.6	6	20	20	15	15	94.00
134	45	75	200	200	6	2.4	6	3.6	6	20	20	15	15	94.00
135	45	75	200	300	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
136	45	75	200	400	4.8	2.4	3.6	3.6	4.8	20	20	15	15	89.20
137	45	75	300	100	6	2.4	4.8	3.6	6	20	20	15	15	92.80
138	45	75	300	200	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
139	45	75	300	300	4.8	2.4	4.8	3.6	4.8	20	20	15	15	90.40
140	45	75	300	400	3.6	2.4	3.6	3.6	4.8	20	20	15	15	88.00
141	45	75	400	100	6	2.4	4.8	3.6	6	20	20	15	15	92.80
142	45	75	400	200	4.8	2.4	3.6	3.6	4.8	20	20	15	15	89.20
143	45	75	400	300	3.6	2.4	3.6	3.6	4.8	20	20	15	15	88.00
144	45	75	400	400	3.6	2.4	2.4	3.6	3.6	20	20	15	15	85.60
145	60	75	100	100	6	3.6	6	4.8	6	16	16	12	15	85.40
146	60	75	100	200	6	3.6	6	3.6	6	16	16	12	15	84.20

147	60	75	100	300	6	3.6	4.8	3.6	6	16	16	12	15	83.00
148	60	75	100	400	6	3.6	4.8	3.6	6	16	16	12	15	83.00
149	60	75	200	100	6	3.6	6	3.6	6	16	16	12	15	84.20
150	60	75	200	200	6	3.6	6	3.6	6	16	16	12	15	84.20
151	60	75	200	300	6	3.6	4.8	3.6	6	16	16	12	15	83.00
152	60	75	200	400	4.8	3.6	3.6	3.6	6	16	16	12	15	80.60
153	60	75	300	100	6	3.6	4.8	3.6	6	16	16	12	15	83.00
154	60	75	300	200	6	3.6	4.8	3.6	6	16	16	12	15	83.00
155	60	75	300	300	4.8	3.6	4.8	3.6	6	16	16	12	15	81.80
156	60	75	300	400	4.8	3.6	3.6	3.6	4.8	16	16	12	15	79.40
157	60	75	400	100	6	3.6	4.8	3.6	6	16	16	12	15	83.00
158	60	75	400	200	4.8	3.6	3.6	3.6	6	16	16	12	15	80.60
159	60	75	400	300	4.8	3.6	3.6	3.6	4.8	16	16	12	15	79.40
160	60	75	400	400	3.6	3.6	2.4	3.6	3.6	16	16	12	15	75.80
161	75	75	100	100	6	4.8	6	4.8	6	16	12	12	15	82.60
162	75	75	100	200	6	4.8	6	3.6	6	16	12	12	15	81.40
163	75	75	100	300	6	4.8	4.8	3.6	6	16	12	12	15	80.20
164	75	75	100	400	6	4.8	4.8	3.6	6	16	12	12	15	80.20
165	75	75	200	100	6	4.8	6	3.6	6	16	12	12	15	81.40
166	75	75	200	200	6	4.8	6	4.8	6	16	12	12	15	82.60
167	75	75	200	300	6	4.8	4.8	3.6	6	16	12	12	15	80.20
168	75	75	200	400	6	4.8	3.6	3.6	6	16	12	12	15	79.00
169	75	75	300	100	6	4.8	4.8	3.6	6	16	12	12	15	80.20
170	75	75	300	200	6	4.8	4.8	3.6	6	16	12	12	15	80.20
171	75	75	300	300	4.8	4.8	4.8	3.6	6	16	12	12	15	79.00
172	75	75	300	400	4.8	4.8	3.6	3.6	4.8	16	12	12	15	76.60
173	75	75	400	100	6	4.8	4.8	3.6	6	16	12	12	15	80.20
174	75	75	400	200	6	4.8	3.6	3.6	6	16	12	12	15	79.00
175	75	75	400	300	4.8	4.8	3.6	3.6	4.8	16	12	12	15	76.60
176	75	75	400	400	0.84	4.8	2.4	3.6	4.8	16	12	12	15	71.44
177	90	75	100	100	6	6	6	3.6	6	12	8	9	15	71.60
178	90	75	100	200	6	6	6	3.6	6	12	8	9	15	71.60
179	90	75	100	300	6	6	4.8	3.6	6	12	8	9	15	70.40
180	90	75	100	400	6	6	4.8	3.6	6	12	8	9	15	70.40
181	90	75	200	100	6	6	6	3.6	6	12	8	9	15	71.60
182	90	75	200	200	6	6	6	4.8	6	12	8	9	15	72.80
183	90	75	200	300	6	6	4.8	3.6	6	12	8	9	15	70.40
184	90	75	200	400	6	6	4.8	3.6	6	12	8	9	15	70.40
185	90	75	300	100	6	6	4.8	3.6	6	12	8	9	15	70.40
186	90	75	300	200	6	6	4.8	3.6	6	12	8	9	15	70.40
187	90	75	300	300	6	6	4.8	3.6	6	12	8	9	15	70.40
188	90	75	300	400	4.8	6	3.6	3.6	4.8	12	8	9	15	66.80
189	90	75	400	100	6	6	4.8	3.6	6	12	8	9	15	70.40

190	90	75	400	200	6	6	4.8	3.6	6	12	8	9	15	70.40
191	90	75	400	300	4.8	6	3.6	3.6	4.8	12	8	9	15	66.80
192	90	75	400	400	3.6	6	3.6	3.6	4.8	12	8	9	15	65.60
193	45	90	100	100	6	2.4	6	4.8	6	20	20	15	15	95.20
194	45	90	100	200	6	2.4	6	3.6	6	20	20	15	15	94.00
195	45	90	100	300	6	2.4	4.8	3.6	6	20	20	15	15	92.80
196	45	90	100	400	4.8	2.4	3.6	3.6	6	20	20	15	15	90.40
197	45	90	200	100	6	2.4	6	3.6	6	20	20	15	15	94.00
198	45	90	200	200	4.8	2.4	6	3.6	6	20	20	15	15	92.80
199	45	90	200	300	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
200	45	90	200	400	4.8	2.4	3.6	3.6	4.8	20	20	15	15	89.20
201	45	90	300	100	6	2.4	4.8	3.6	6	20	20	15	15	92.80
202	45	90	300	200	4.8	2.4	4.8	3.6	6	20	20	15	15	91.60
203	45	90	300	300	4.8	2.4	3.6	3.6	4.8	20	20	15	15	89.20
204	45	90	300	400	3.6	2.4	2.4	3.6	3.6	20	20	15	15	85.60
205	45	90	400	100	4.8	2.4	3.6	3.6	6	20	20	15	15	90.40
206	45	90	400	200	4.8	2.4	3.6	3.6	4.8	20	20	15	15	89.20
207	45	90	400	300	3.6	2.4	2.4	3.6	3.6	20	20	15	15	85.60
208	45	90	400	400	1.2	2.4	2.4	3.6	2.4	20	20	15	15	82.00
209	60	90	100	100	6	3.6	6	4.8	6	16	16	12	15	85.40
210	60	90	100	200	6	3.6	6	3.6	6	16	16	12	15	84.20
211	60	90	100	300	6	3.6	4.8	3.6	6	16	16	12	15	83.00
212	60	90	100	400	6	3.6	4.8	3.6	6	16	16	12	15	83.00
213	60	90	200	100	6	3.6	6	3.6	6	16	16	12	15	84.20
214	60	90	200	200	6	3.6	6	3.6	6	16	16	12	15	84.20
215	60	90	200	300	4.8	3.6	4.8	3.6	6	16	16	12	15	81.80
216	60	90	200	400	4.8	3.6	3.6	3.6	6	16	16	12	15	80.60
217	60	90	300	100	6	3.6	4.8	3.6	6	16	16	12	15	83.00
218	60	90	300	200	4.8	3.6	4.8	3.6	6	16	16	12	15	81.80
219	60	90	300	300	4.8	3.6	3.6	3.6	4.8	16	16	12	15	79.40
220	60	90	300	400	0.81	3.6	2.4	3.6	4.8	16	16	12	15	74.21
221	60	90	400	100	6	3.6	4.8	3.6	6	16	16	12	15	83.00
222	60	90	400	200	4.8	3.6	3.6	3.6	6	16	16	12	15	80.60
223	60	90	400	300	3.6	3.6	2.4	3.6	4.8	16	16	12	15	77.00
224	60	90	400	400	2.4	3.6	2.4	3.6	2.4	16	16	12	15	73.40
225	75	90	100	100	6	4.8	6	4.8	6	16	12	12	15	82.60
226	75	90	100	200	6	4.8	6	3.6	6	16	12	12	15	81.40
227	75	90	100	300	6	4.8	4.8	3.6	6	16	12	12	15	80.20
228	75	90	100	400	6	4.8	4.8	3.6	6	16	12	12	15	80.20
229	75	90	200	100	6	4.8	6	3.6	6	16	12	12	15	81.40
230	75	90	200	200	6	4.8	6	3.6	6	16	12	12	15	81.40
231	75	90	200	300	6	4.8	4.8	3.6	6	16	12	12	15	80.20
232	75	90	200	400	4.8	4.8	3.6	3.6	6	16	12	12	15	77.80

233	75	90	300	100	6	4.8	4.8	3.6	6	16	12	12	15	80.20
234	75	90	300	200	6	4.8	4.8	3.6	6	16	12	12	15	80.20
235	75	90	300	300	4.8	4.8	3.6	3.6	6	16	12	12	15	77.80
236	75	90	300	400	3.6	4.8	3.6	3.6	4.8	16	12	12	15	75.40
237	75	90	400	100	6	4.8	4.8	3.6	6	16	12	12	15	80.20
238	75	90	400	200	4.8	4.8	3.6	3.6	6	16	12	12	15	77.80
239	75	90	400	300	3.6	4.8	3.6	3.6	4.8	16	12	12	15	75.40
240	75	90	400	400	2.4	4.8	2.4	3.6	3.6	16	12	12	15	71.80
241	90	90	100	100	6	6	6	4.8	6	12	8	9	15	72.80
242	90	90	100	200	6	6	6	3.6	6	12	8	9	15	71.60
243	90	90	100	300	6	6	4.8	3.6	6	12	8	9	15	70.40
244	90	90	100	400	6	6	4.8	3.6	6	12	8	9	15	70.40
245	90	90	200	100	6	6	6	3.6	6	12	8	9	15	71.60
246	90	90	200	200	6	6	6	3.6	6	12	8	9	15	71.60
247	90	90	200	300	6	6	4.8	3.6	6	12	8	9	15	70.40
248	90	90	200	400	4.8	6	3.6	3.6	6	12	8	9	15	68.00
249	90	90	300	100	6	6	4.8	3.6	6	12	8	9	15	70.40
250	90	90	300	200	6	6	4.8	3.6	6	12	8	9	15	70.40
251	90	90	300	300	4.8	6	4.8	3.6	6	12	8	9	15	69.20
252	90	90	300	400	4.8	6	3.6	3.6	4.8	12	8	9	15	66.80
253	90	90	400	100	6	6	4.8	3.6	6	12	8	9	15	70.40
254	90	90	400	200	4.8	6	3.6	3.6	6	12	8	9	15	68.00
255	90	90	400	300	4.8	6	3.6	3.6	4.8	12	8	9	15	66.80
256	90	90	400	400	3.6	6	2.4	3.6	3.6	12	8	9	15	63.20