TRUCK ACCESS INTO ROUNDABOUTS

Draft Full Report:
Field Observations of Gap Acceptance;
VISSIM Simulation for Best Modeling Practices; and
Heavy Vehicle Driving Simulation for Trucks at Roundabouts

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TRUCK ACCESS INTO ROUNDABOUTS

Final Report

by

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16. Abstract

This study evaluated the operational efficiency and ability for heavy trucks to enter and traverse congested roundabouts. The use of field work observations allowed for critical gap values to be defined. These values described heavy truck driver behavior and highlighted the large magnitude of difference in gap acceptance tendencies which ranged from 5.4 seconds to 6.4 seconds based on the type of vehicle being operated. VISSIM simulation modeling revealed that the larger classifications of heavy trucks are underrepresented in the current North American Default Fleet, and that priority rules yield the most representative modeling results in terms of heavy truck gap acceptance and behavior. The driving simulator study assessed proposed geometric and traffic control device modifications with heavy truck drivers. It was revealed that roundabout geometry impacts driver behavior and modifications are dependent on the objectives at specific locations. The elliptical design was associated with decreased stress but may not be suitable at locations where higher speeds are already an initial concern. Placement of roundabout metering influences driver's approach behavior, and additional concern should be placed on the relative distance from the roundabout.

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EXECUTIVE SUMMARY

This report presents findings from the evaluation of field observations, VISSIM modeling, and heavy vehicle driving simulator studies to assess the ability of heavy trucks to enter congested roundabouts. The overall findings from these three studies identify how entering requirements differ across heavy truck classifications, how these differences can be modeled more effectively in a microsimulation environment, and how geometric and operation modifications might be implemented to make roundabouts more accessible for larger vehicles.

The field assessment study evaluated 164 hours of video data to transcribe 2,626 heavy truck movements at single-lane roundabout sites in the states of Oregon and Washington that met pre-established criteria. A variety of heavy truck classifications were observed and transcribed with the most common being the WB-40, WB-50, WB-62, WB-67, WB-67D, and WB-92D. Within each of these heavy truck classifications, gap acceptance behavior was found to differ. A total of 400 heavy trucks had to stop and wait at the roundabout entrance in response to circulating traffic before finding an acceptable gap length to enter the intersection. An analysis of observed gap rejections determined that 52.5% of heavy trucks rejected one gap before entering the roundabout, 35.5% rejected two-or-three gaps, and 12% of the observations rejected four-or-more gaps before entering the roundabout. It was found that average rejected gap lengths were 3.84 seconds while average accepted gap lengths were 8.69 seconds, indicating heavy trucks often accepted gaps that were more than two-times larger than the prior gaps.

Critical gap length was assessed on an individual-classification basis to compare critical gaps across heavy truck types observed in the field. Critical gap length for heavy trucks ranged from 5.4 seconds to 6.4 seconds, approximately 2 to 3 times larger than that of a passenger car and increased proportionately with the size of the heavy truck. WB-40 and WB-50 trucks were the smallest heavy truck assessed and were found to have the lowest critical gap length of 5.4 seconds. Conversely, the WB-92D was the largest heavy truck and was associated with a critical gap length of 6.4 seconds. This finding indicates that assessment of roundabout implementation should include analysis of the heavy truck types using these facilities as well as the existing and anticipated demand.

The VISSIM simulation study evaluated base model performance using varying configurations of vehicle fleets and yield controls. Comparison of VISSIM default heavy truck fleets versus heavy truck fleets developed from the field observations was a primary consideration as was the method used to control vehicular traffic (priority rules versus conflict areas). Using a reference roundabout from the initial field study, models were developed to assess differences in the variable levels. It was found that the default fleet included in VISSIM may not be an accurate representation of the heavy truck fleets using roundabouts across Oregon. The default fleet in VISSIM is composed of smaller heavy trucks with 91% being smaller than a WB-50, 32.5% of which are smaller than the WB-40, the smallest observed heavy truck in the field. This suggests that additional heavy truck models should be developed to accurately predict movement patterns at roundabouts using VISSIM simulation. Additionally, priority rules yield higher accuracy

and flexibility as compared to conflict areas when modeling heavy trucks at roundabouts. As evidenced by the gap rejection tendencies across simulations, the models which used priority rules better represented observations from the field.

The heavy truck driving simulator experiment was conducted to assess the response of 41 truck drivers possessing a Commercial Driver's License (CDL) to a variety of simulated roundabout scenarios including geometric modifications (traditional, tapered, and elliptical) as well as roundabout metering which included a near (115-ft) and far (230-ft) distance from the roundabout entrance. Observed lateral positioning suggested that drivers were better able to center themselves in the circulatory lane when traversing the elliptical configuration, likely due to the reduced deflection and available sight distance. Deviation from lane center in the traditional and tapered configurations reached peaks of 4.31-ft and 3.55-ft further offset from center-of-lane as compared to the elliptical configuration. These comparisons are one indication of improved performance as position near the lane center (i.e., elliptical traversal) provides increased predictability of the heavy truck movement which can contribute to easier negotiation with other roadway users. Velocity results revealed that circulating speed and approach speed profiles vary significantly when drivers traversed the different geometric configurations and roundabout metering locations, respectively. Evaluation of the circulating velocity revealed that the traditional and tapered configurations yielded similar behavior, with average heavy truck operating speeds of 16-mph. The elliptical configuration functioned differently and was associated with speeds of over 4.0 mph faster. This differential may create operational concerns associated with the elliptical design when considering the entering capacity at adjacent legs, and safety concerns at pedestrian crossings.

When roundabout metering was placed at a far distance (i.e., 230-ft) from the roundabout entrance, larger variations of heavy truck acceleration and deceleration were observed. Conversely, the near meter position (i.e., 115-ft) resulted in driver velocity that was relatively constant and allowed drivers to better judge available gap lengths without requiring large acceleration to enter the roundabout. Due to more predictable speeds and decreased variation in driver response, the near meter (115-ft) position operated more efficiently as compared to the far meter (230-ft) position.

Galvanic skin response (GSR) measurements highlighted how driver stress changes on the approach, when they are entering the roundabout, and when they are on the circulating roadway. These zones become sequentially more concerning as the GSR results revealed an increase in stress response throughout traversal. Approach stress elicited the lowest measure of 5.58 peaks/min, followed by an entering stress of 6.91 peaks/min, and reaching values of 10.20 peaks/min once within the circulating roadway. Implementing different geometric configurations can serve to reduce stress by as much as 3.08 peaks/min within the circulating roadway. This reduction was observed for drivers traversing the elliptical configuration as compared to the traditional design.

The findings from these studies document roundabout entering behavior across heavy truck classifications, how these behaviors can be accurately modeled using microsimulation, and provide preliminary analysis of potential geometric and operational mitigations. As heavy trucks size increases, their requirements to enter roundabouts also increase, requiring critical gap lengths of up-to 6.4 seconds for double trailer classifications. This was consistent with VISSIM simulation modeling, where vehicle fleet composition should be an important consideration for accurately modeling heavy truck movements through roundabouts. Additionally, the gap acceptance decision making of heavy trucks may be improved by providing geometric modifications or well-place roundabout metering devices on the approach to the roundabout. These findings can be used when implementing new roundabouts to better accommodate heavy trucks of varying volumes and sizes, particularly in the presence of congestion.

1.0 INTRODUCTION

The following report describes three coordinated research studies that were conducted to understand heavy truck access into congested roundabouts and to develop recommendations for improvements. Heavy trucks can be described as those that feature a gross-vehicle weight of over 26,000 pounds (FHWA, 2012). In addition to being heavier, these vehicles feature a longer footprint, larger turning radii with more significant offtracking, and greater required distances to achieve desired acceleration and deceleration. These innate characteristics influence the ways in which heavy trucks enter and traverse roundabouts. Roundabouts are often designed with these difficulties in mind, but under congested conditions the limitations are confounded by a more restrictive profile of available gaps. Gap length is the time or distance between adjacent vehicles operating within the circulatory roadway of the roundabout. As roundabouts use yield-control upon entry, it is the responsibility of the driver to find an acceptably sized gap to safely enter without relying on the circulating traffic to stop. One useful measure of gap acceptance is the critical gap, which describes the threshold where 50% of vehicles will accept a gap of a specified length, while 50% will reject the same gap.

Accepted, rejected, and critical gap lengths were the performance measures evaluated when assessing heavy truck movements in the field, described in Chapter 2.0. The field study was conducted to develop a dataset comprised of 2,626 heavy truck observations at highly congested roundabout sites across the States of Oregon and Washington. The transcribed data described throughout Chapter 2.0 emphasizes heavy truck driver tendencies and behavior when entering a roundabout and provides analytical techniques that identify variations based on heavy truck classifications. This data was used to understand gap acceptance tendencies on a per-vehicle class basis and provide considerations for roundabouts located along roadways with high heavy truck volumes.

Using microsimulation modeling to understand the operational efficiency of certain roadway environments is a common step in assessing the feasibility of new designs. The second study in this report, described throughout Chapter 3.0, leveraged VISSIM simulation to assess the Oregon Department of Transportation's (ODOT) current best practice for VISSIM modeling in the context of heavy truck entrance into congested roundabouts. Multiple simulation models were developed that use varying degrees of priority controls in conjunction with different heavy truck fleets. Recommendations for possible modification to existing ODOT methodology specifically aimed at more accurate modeling of heavy trucks at roundabouts are a key output from this study.

A Heavy Truck Driving Simulator study was carried out to test heavy truck driver response to various roundabout designs to provide recommendations for improving their ability to enter congested roundabouts. Distinct roundabout geometries and traffic control devices were developed and testing procedures were performed with licensed and experienced heavy truck drivers, while performance measures were evaluated to provide recommendations for improvements. The recommendations described in Chapter 4.0 provide opportunities for roundabout modifications that may improve roundabout functionality through geometric changes and implementation of traffic control devices.

2.0 FIELD OBSERVATIONS MEASURING HEAVY TRUCK ENTERING CAPACITY ON A PER VEHICLE CLASS BASIS

2.1 FIELD STUDY SITE SELECTION

The primary purpose of this field study was to develop a robust dataset comprised of heavy truck observations that allow for the documentation of heavy truck driver behavior when entering into congested roundabouts. Selection of the field study sites for data collection was a primary consideration in developing this dataset and required various forms of assessment to determine the most optimal locations. This Section describes the steps that were involved as well as the final site list used in the field study.

2.1.1 Site Selection Criteria

Adequate site selection criteria were developed as a first step to ensure the data collected sufficiently helps to accomplish study goals in the most efficient manner. Sites were selected that ***featured relatively high proportions of heavy truck traffic*** in tandem with ***congested or near-capacity conditions***. By filtering out sites that do not meet these criteria, the resulting dataset featured a) a sufficiently large count of heavy truck observations that was necessary to develop accurate recommendations; and b) a large count of gap rejection observations due to negotiations between heavy trucks and circulating passenger cars. Additionally, roundabouts must be sufficiently well-established to provide valid data, as new intersection designs require time for drivers to adjust, and the long-term impacts of roundabouts on traffic flow are of greater interest for this study than the effects in the short term. For this reason, ***sites were ruled out if they had been in operation for less than one-year.*** This requirement filtered out potential sites that were relatively new to ensure representative driver behavior is being captured. This coincides with previous literature, as large modifications such as adjustments to intersection geometry or implementation of a roundabout has a dramatic impact and the effect of this treatment may take years to observe representative results (Hauer, 1997).

Potential sites were identified throughout Oregon and individually assessed to ensure that these three criteria were met. A description of the potential sites that were reviewed, as well as the sites selected from this list are described in Sections 2.1.2 and 2.1.3, respectively. While no roundabouts are identical, unique features may provide unusual results and therefore site selection was guided by the intent to observe locations with similar geometric traits. Although multi-lane roundabouts may still pose a problem, it has been expressed that single-lane designs are of utmost concern at the time of this study. Single-lane designs were thus a primary focus.

2.1.2 Potential Sites Reviewed

Nine roundabouts were reviewed in the initial investigation for potential data collection sites. Roundabout sites were reviewed beginning as far South as Klamath Falls, OR at the intersection of OR 140 and Homedale Rd, and spanned as far north as Astoria, OR at the intersection of US 101 and W Marine Dr. Upon further inspection, these two locations did not meet the exclusionary criteria for the purposes of this study due to either having multilane/unique configurations or not having been in operation for at least one-year at the time the field study was conducted. Locations in Eastern Oregon were also assessed, with the intersection at OR 126 and Tom McCall Rd in Prineville, OR and OR 140 and Foothill Rd/Atlantic Ave in White City, OR evaluated as potential sites for data collection efforts. Although heavy truck volumes at these locations were high, they lacked the gap rejection and delay due to congestion. Preliminary assessment of these locations showed that during two-hour periods at both sites, only 12 heavy trucks collectively had to reject a gap before entering the roundabout.

A similar process was repeated for the remaining roundabout sites selected as potential locations that met the ideal study parameters. The finalized site list is described in further detail in Section 2.1.3.

2.1.3 Sites Selected

A total of six roundabout sites were selected for field data collection efforts, which consisted of three locations in Oregon and three in Washington. The three locations in Washington were added as supplemental sites for data collection efforts to develop a more robust dataset, as the data obtained from Oregon roundabouts provided many heavy truck counts and various classification types, but lacked the desired amount of congestion. The addition of the Washington field sites was found to be a practical supplement as they provided observations under highly congested conditions. All locations featured a central island apron, while Oregon sites included an outer truck apron along the entering approach legs as shown at the Southbound approach leg to the Forest Grove site in Figure 1. The final roundabout sites where data collection was performed to generate the dataset for this study are listed in Table 1, along with key geometric characteristics.

Figure 1: Southbound Roundabout Approach in Forest Grove, OR

It was determined that the roundabout in Sisters, OR was a viable baseline condition and could be used in additional modeling tasks (e.g., VISSIM Modeling and Heavy Vehicle Driving Simulation, Chapters 3.0 and 4.0, respectively). This decision was based on observations and knowledge regarding the adequate functionality of this roundabout design despite the large heavy truck volumes and congestion at this site. Additionally, there are no extremities in terms of design parameters associated with this roundabout but instead it uses well designed deflection angles and operational space to accomplish the goals described.

Table 1: Field Study Sites and Geometric Characteristics

City	Intersection	# of Approach Legs	# of Circulating Lanes	Lane Width (ft)	ICD (ft)	Truck Apron Width (ft)
Fife, WA	Hwy 99 & Wapato Way	3	2	15	146-151	Varies
Lakewood, WA	Murray Rd & 150th St	3	1	15	140	11
Lakewood, WA	Murray Rd & Thorne Ln	4	1	15	110	20
Forest Grove, OR	Hwy 47 & Verboort Rd	4	1	21	180	20
Forest Grove, OR	Hwy 47 & David Hill Rd	3	1	20	180	19
Sisters, OR	Hwy 20 & Barclay Dr	4	1	21	150	14

2.2 FIELD DATA COLLECTION

The field data was collected during the time period beginning at the end of June and wrapping up at the beginning of September, 2022. This window for data collection was selected due to truck volumes and weather conditions being optimal in the summer months across the Pacific Northwest for conducting and making field observations. Data collection efforts consisted of site visits spanning two- or three-night stays based on the commute distances required.

2.2.1 Observation Periods

On average, 48-hours of video data was collected at each site for all approach legs of the roundabout. Table 2 describes the total amount of video data collected at each location and how much of this data was transcribed. As shown, the entirety of video data was not transcribed due to factors such as lower truck volumes than anticipated, unexpected traffic characteristics, and time/resources. The roundabouts in Lakewood, WA were found to have high heavy truck volumes but lacked additional traffic congestion – Thus limiting the ability to make the desired observations for critical gap measurements. It was discovered during the data collection process that the Northbound approach of the Lakewood, WA roundabout at the intersection of Murray Rd and 150th St. was closed due to construction. This was an unforeseen issue at this site, and it is expected that this influenced the lower number of gap rejection observations. Additionally, the roundabout in Sisters, OR features less available data due to unexpected equipment issues. Provided this location was the first site in this data collection series, equipment was adjusted and calibrated for future sites to ensure problems were resolved.

The data collection period was continuous and spanned the weekdays of Tuesday – Thursday, allowing for two full days of data collection which were kept constant across sites to ensure consistent observation windows. In addition, it was expected that truck volumes on these days of the week would be most consistent and representative of the usage at the roundabout locations. To accommodate uncertainties about when trucks access these sites, capturing continuous video allowed researchers to make observations throughout the day and night. It was found that the peak-period for heavy truck operations most often occurred in the late-morning to early-afternoon and these time intervals were found to be when gap rejections most frequently occurred.

Table 2: Field Data Observation and Transcription Information

City	Intersection	Dates Observed	Hours Transcribed	Hours Available	Percent Transcribed
Fife, WA	Hwy 99 & Wapato Way	08/30/2022 – 09/01/2022	4.5	45	10
Lakewood, WA	Murray Rd & 150th St	08/16/2022 – 08/18/2022	24.5	48	51
Lakewood, WA	Murray Rd & Thorne Ln	08/16/2022 – 08/18/2022	22	47.5	46
Forest Grove, OR	Hwy 47 & Verboort Rd	07/11/2022 – 07/13/2022	48	48	100
Forest Grove, OR	Hwy 47 & David Hill Rd	07/11/2022 – 07/13/2022	26	48	54
Sisters, OR	Hwy 20 & Barclay Dr	06/27/2022 – 06/29/2022	39	39	100
Total	----	----	**164**	**275.5**	**60%**

2.2.2 Equipment Setup and Calibration

Data collection efforts consisted of the installation of high-resolution cameras affixed to telescoping poles mounted to roadside infrastructure surrounding the roundabouts and the periodic monitoring of these cameras to ensure accurate recording. The equipment included ten cameras - six CountCam2 and four CountCam3+ units; Both of which are developed by Spack Solutions.

Devices were installed on all approach legs and were oriented towards the circulatory roadway of the roundabout. This configuration allowed for the observation of entering trucks on each leg to accurately measure gap rejection timings. One restriction with implementation is that the cameras required a stable pole or other roadside object by which the telescoping poles could be secured to. Most often, the Non-Vehicular Warning Sign W11-2 was used as a mounting location due to its position in relation to the entering lane and ability to capture a wide field-of-view (FOV) to make necessary observations. The unobtrusive nature of these cameras permitted mounting in this location without creating distraction for drivers, as shown in Figure 2 at the entering approach of Hwy 47 and David Hill Rd in Forest Grove, OR on the Northbound approach. Depending on the approach characteristics, select cameras were installed at locations other than the W11-2 sign when necessary. Figure 3a shows an example of an OSU researcher installing a camera in the field along the Southbound approach at the site in Sisters, OR while Figure 3b provides a view of a camera that was mounted to an R4-7c sign on the Westbound approach at the roundabout in Lakewood, WA.

Figure 2: Hwy 47 and David Hill Rd Camera Mounted on W11-2 Sign

Figure 3: Equipment Installation on (a) Southbound Approach in Sisters, OR and (b) Camera in Field on Westbound Approach in Lakewood, WA

The CountCam recording systems allowed for the monitoring of the field of view prior to beginning any of the video recordings. Slight adjustments to the downward angle, vertical height, position, and orientation of the unit were made to determine the optimal view. Notable considerations made during the height and angle adjustments included that heavy trucks were classifiable as were gaps in circulating traffic. For these reasons, telescoping poles were elongated to a sufficient height to capture a view above the heavy trucks, and angled downward to ensures the circulating traffic was being captured as well. Figure 4 shows one example of the view captured in Sisters, OR along the Southbound approach leg. This image describes the various aspects in the collected video data that were considered throughout the transcription process with the date, time, gap in traffic, and entering vehicle highlighted as key considerations.

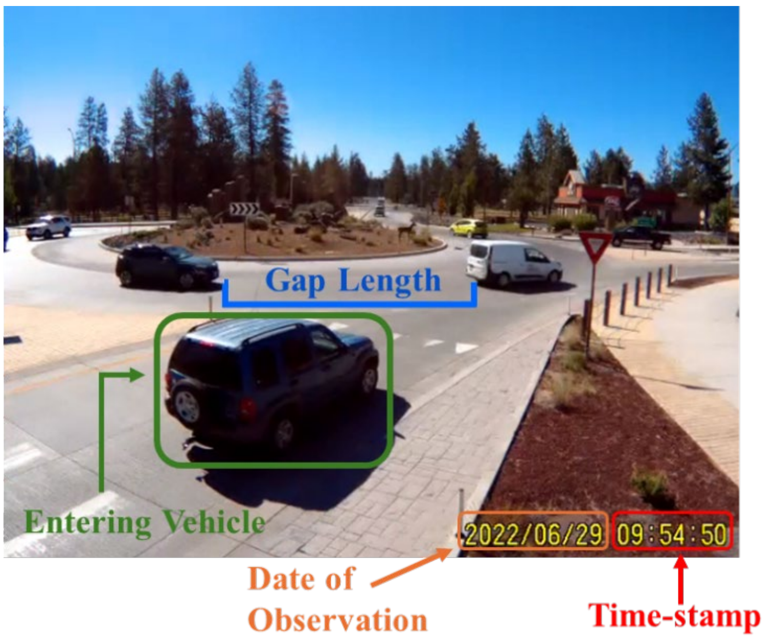


Figure 4: Video Data Capture from Sisters, OR with Parameters of Interest

2.3 DATASET

A dataset comprised of heavy truck observations at all six roundabout sites was developed using the recorded field video data. From the 164 hours of reviewed video data, there were 2,626 heavy truck observations. The heavy truck counts at each location, as well as a percentage breakdown of the vehicle classifications observed are described throughout this Section.

2.3.1 Observed Heavy Truck Volumes

Heavy truck movements were transcribed at the various field sites to generate a dataset identifying driver behavior and tendencies when looking to enter congested roundabouts. Additionally, the vehicle counts and vehicle classifications using these facilities were compared across locations. The largest heavy truck count was observed at the roundabout in Fife, WA – where data for 865 heavy trucks was transcribed. A breakdown on a per-site basis is described in Table 3.

Table 3: Heavy Truck Counts by Location

City	Intersection	# of Heavy Trucks	Heavy Truck Percent of Total Volume
Fife, WA	Hwy 99 & Wapato Way	872	11.5
Lakewood, WA	Murray Rd & 150th St	434	8.4
Lakewood, WA	Murray Rd & Thorne Ln	124	2.4
Forest Grove, OR	Hwy 47 & Verboort Rd	298	2.6
Forest Grove, OR	Hwy 47 & David Hill Rd	181	2.9
Sisters, OR	Hwy 20 & Barclay Dr	717	3.3
Total	----	**2,626**	**----**

Although the location in Fife, WA only has a portion of the data transcribed, it makes up the largest heavy truck count in the dataset. Figure 5a illustrates the large truck volumes at this location which comprised 11.5 percent of the total loading volume. In this Figure, a WB-67 truck is shown entering from the South approach, while another WB-67 is exiting the roundabout on the Southbound leg. In the background, a WB-62 can be seen taking the Westbound exit. It was discovered that this site experiences additional delays when heavy trucks find difficulty entering the roundabout thus resulting in additional congestion for all drivers. One of the many camera views collected at this site is shown in Figure 5b, which provides an example of vehicular ques extending onto the Northbound approach leg of the Fife, WA site. From this angle, the vehicles are backed up to the point where they are outside of the observable filed of view, due to three heavy trucks looking to enter the roundabout.

Figure 5: (a) Congested Conditions at Fife, WA (b) Backup Created During Heavy Truck Entrance Extending beyond FOV

2.3.2 Heavy Truck Classification

Transcription of heavy truck classifications followed AASHTO standards and were used to better understand the type of vehicles using these facilities. The count of each heavy truck classification type at the field study locations can be found in Table 4. Vehicle classifications were transcribed using characteristics that are easily identifiable from the video data such as trailer length and number of axles. The WB-40, WB-50, WB-62, and WB-67 classifications are all single-trailer designs but feature different overall lengths, with the shortest being the WB-40 and the largest being the WB-67. The WB-67D and WB-92D are double-trailer designs that feature varying axle counts which made them easily distinguishable from each other in the transcription process. This data was used to further understand the distribution of heavy truck types that traverse these roundabouts and was also used in the gap acceptance assessment discussed in Section 2.4.2, where gap length was measured on a per-vehicle class basis. The data described in Table 4 was also used to calculate the percentage of each heavy truck classification observed. The percentage breakdown by vehicle classification is described in Figure 6.

Table 4: Heavy Truck Count by Classification at Study Sites

Intersection	*WB-40*	*WB-50*	*WB-62*	*WB-67*	*WB-67D*	*WB-92D*
Hwy 99 & Wapato Way	38	85	421	313	6	9
Murray Rd & 150th St	11	22	98	297	4	2
Murray Rd & Thorne Ln	5	4	33	82	0	0
Hwy 47 & Verboort Rd	5	19	72	175	8	19
Hwy 47 & David Hill Rd	0	13	53	98	7	10
Hwy 20 & Barclay Dr	18	43	64	505	40	47

Figure 6 visualizes the vehicle counts but has grouped the data by city to describe the percentage breakdown of each classification. Due to the relatively close proximity of study sites in Forest Grove, OR and Lakewood, WA the data for these sites were grouped together. From these visualizations, similarities exist across cities with a large percent of WB-67 heavy trucks using these facilities while there is a comparatively small percentage of WB-67D and WB-92D vehicles. Fife, WA is the exception where the most common heavy truck classification observed was the WB-62.

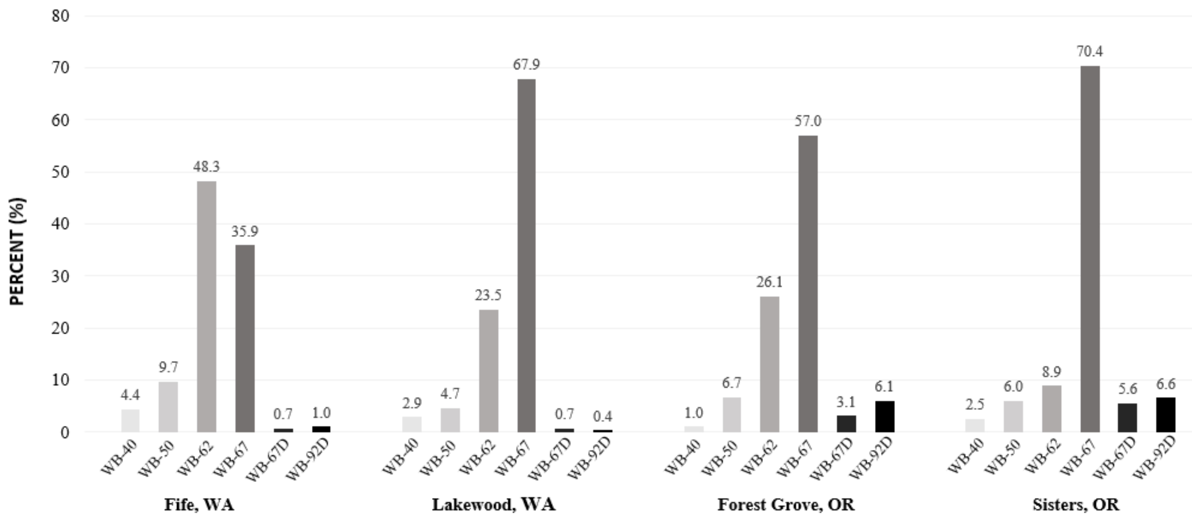


Figure 6: Heavy Truck Loading Percentage at Field Locations

2.4 GAP ACCEPTANCE

The collected field data was analyzed to better understand the tendency for trucks to accept or reject gaps in the circulating flow. The decision of drivers to accept a gap is based on whether the time and space between circulating vehicles is sufficient to safely enter the roundabout (Kay et al., 2006). The gap length required for vehicle operators to accept and enter the roundabout will vary depending on a variety of factors (e.g., geometry of the location, vehicle types in the circulating flow, risk tolerance, and visibility of oncoming vehicles), and the decision making is different from person to person and can vary for an individual given a variety of factors (e.g., how long they are forced to wait, time of day, previous experience, and acceleration of vehicle being operated). Alternatively, if the gap is not a sufficient size, the entering vehicle operator will decide not to enter the roundabout thus denoting a gap rejection. Gap acceptance and rejection tendencies are evaluated throughout this Section as a measure of performance in the context of heavy trucks entering the roundabout at field study sites.

2.4.1 Measuring Gap Rejection and Gap Acceptance

Evaluation of accepted and rejected gap lengths on a per vehicle basis was one method used to assess the operational performance of the roundabout sites. Figure 7 shows a visual representation of a gap opportunity in circulating traffic, where three vehicles are of primary interest: circulating vehicle 1, circulating vehicle 2, and the entering vehicle. In this context, the gap opens when the rear-end of circulating vehicle 1 reaches a point that allows for the entering vehicle to begin their movement. Alternatively, the gap is closed when the front-end of circulating vehicle 2 enters a zone that presents a risk of collision with the entering vehicle. This reference was developed by Shaaban & Hamad (Shaaban & Hamad, 2018).

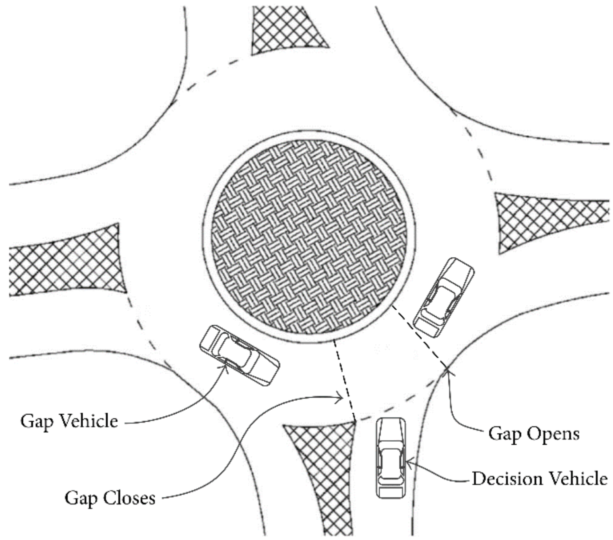


Figure 7: Example Gap in Traffic Flow (From: Shaaban & Hamad, 2018)

Identifying the precise locations of the gap open/close points in the video data required a preliminary assessment of multiple heavy truck observations at the roundabout. All the while, evaluating and developing a baseline of when the heavy trucks would begin their entering movement. Figure 8 provides a visual representation of when these instances occur using direct observations from the field data at the Sisters, OR site with the addition of markers denoting the opening and closing points in the video data reduction process. Figure 8a denotes where the gap was determined to "open" as it was at this point when heavy trucks were found to begin their entering maneuver, while Figure 8b shows how a second circulating vehicle "closes" the gap.

The length of every rejected/accepted gap was timed using the video timestamps linked to the associated observation. This length was then transcribed along with the entering vehicles decision to either accept or reject the presented gap for each heavy truck observation. A gap rejection was recorded if the heavy truck looking to enter the roundabout reduced their speed or stopped on approach in response to the circulating traffic. Of the 2,626 heavy truck observations, a total of 400 of these represented a heavy truck that rejected at least one gap before entering the circulatory roadway. These 400 observations make up the sample size used for assessment of gap acceptance and rejection tendencies described in the following Sections. Accepted gap lengths greater than 20 seconds was excluded from the analysis as it was found that gaps of this magnitude were commonly accepted by heavy truck operators. This process is consistent with work done by Azhari et. al., where gap lengths of 13 seconds were excluded when assessing passenger cars entrance into roundabouts (Azhari et. al., 2019).

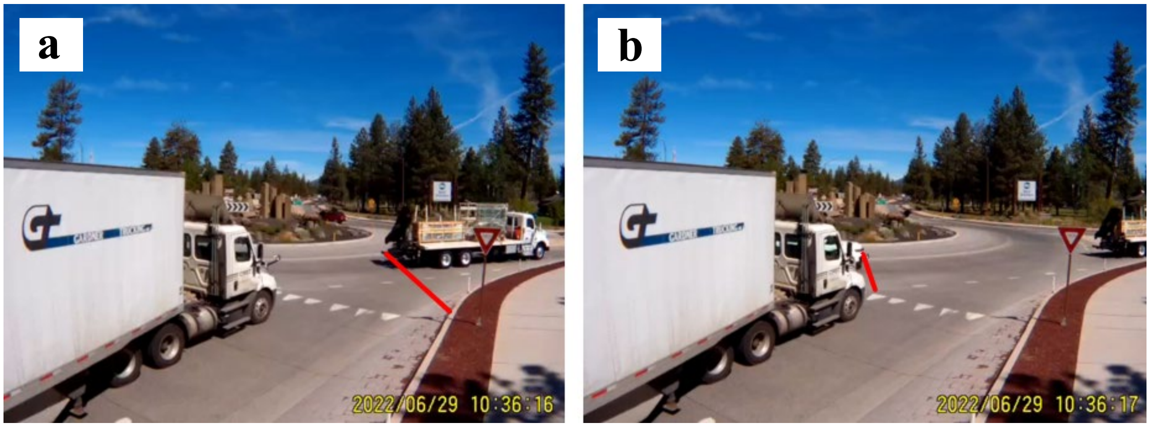


Figure 8: (a) Gap Opens and (b) Gap Closes from Video Data

2.4.2 Gap Acceptance Results

The data reduction process resulted in the observation of 598 individual gap rejections. Each gap was timed and recorded by researchers. The field data revealed that ***the majority of heavy trucks had to reject one gap before finding an acceptable gap length, making up 52.5% of the observations***. In addition, 24.7% and 10.8% of heavy trucks rejected two and three gaps, respectively. The remaining 12% of heavy trucks had to reject at least four gaps before finding an acceptable length to enter the roundabout. To better understand the impact of the number of gaps rejected on the delay of the heavy trucks, the difference in the arrival and departure time was used. In the context of the percentage breakdown stated previously, vehicles that rejected one gap only had an average intersection delay of 7 seconds. Alternatively, when vehicles were forced to reject two or three gaps, the delay increased to 10 and 14 seconds, respectively. The largest increase in intersection delay was recognized when heavy trucks had to reject 4 or more gaps as the average delay increased to larger than 20 seconds.

On average, rejected gap lengths were 3.84 seconds while accepted gap lengths were 8.69 seconds. This indicates that heavy trucks looking to enter the roundabout often accepted gaps that were over two-times larger than the prior gaps. Using the AASHTO classifications, gap timings were analyzed based on the type of heavy truck. Table 5 describes the average gap rejection and acceptance values across different heavy truck classifications. From this table, it can be seen that WB-40 and WB-50 heavy trucks had gap acceptance values on the lower end of the different heavy truck classifications. Additionally, WB-67D and WB-62D heavy trucks required the longest gap to enter the roundabout. It should be noted that the sample size for WB-67D vehicles was smaller than the other classifications, as described in Figure 6, with only three separate WB-67D vehicles rejecting a gap in the reduced data. Figure 9 presents a boxplot of the information displayed in Table 5, where rejected (Figure 9a) and accepted (Figure 9b) gap lengths are presented across the different heavy truck classifications.

Table 5: Average Gap Accept/Reject duration by Classification

Heavy Truck Classification	Heavy Truck Count	Average Gap Rejection (s)	Average Gap Acceptance (s)
WB-40	17	3.81	8.63
WB-50	29	3.48	8.51
WB-62	90	3.37	9.06
WB-67	130	3.31	8.77
WB-67D	3	1.51	9.15
WB-92D	10	2.89	9.26

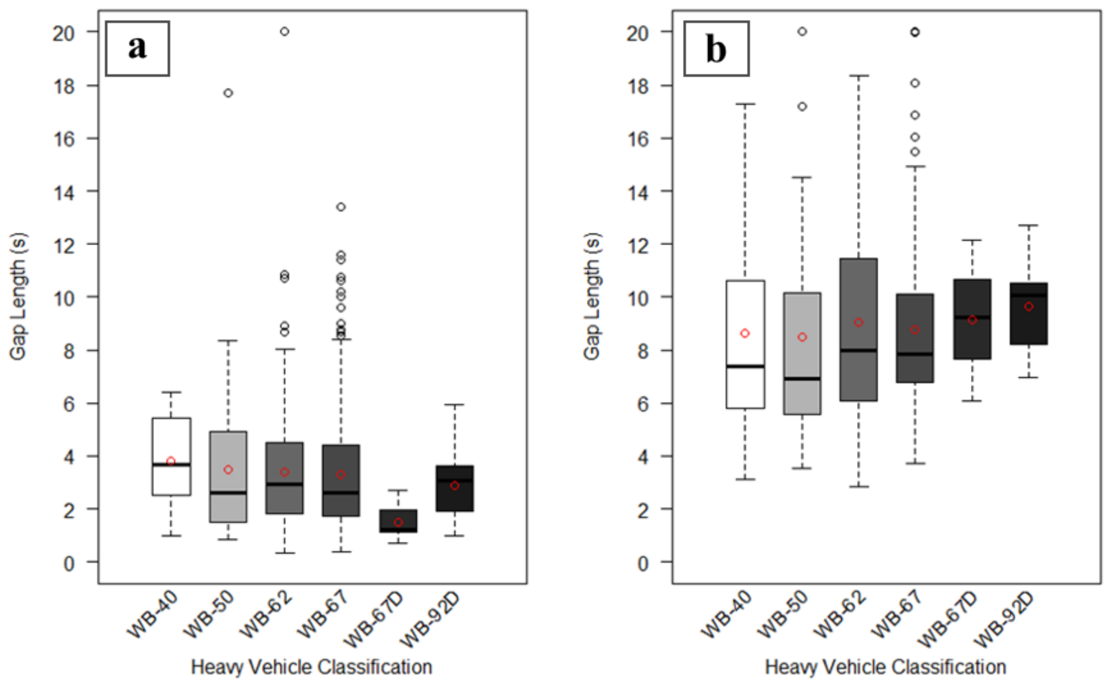


Figure 9: (a) Gap Rejection and (b) Gap Acceptance by Vehicle Classification

2.4.3 Critical Gap Results

The accessibility of the roundabouts for each heavy truck classification was assessed using the critical gap, which can be defined as the minimum time interval between successive vehicles in the major stream that allows for entry by a minor street vehicle (HCM, 2010). Critical gap lengths were evaluated on a per-vehicle classification basis to further understand if there are differences across the size of the vehicle. The results of this analysis showed a direct relationship between the heavy truck size and critical gap, where an increase in the vehicle size was correlated with a larger critical gap. One exception being between the WB-40 and WB-50 trucks, which were found to have the same critical gap length.

The procedure used in this analysis process followed Raff's Method, which plots cumulative probabilities for rejected and accepted gaps to find where these curves intersect (Raff & Hart, 1950; Azhari et. al., 2019). The interaction point describes the time in seconds where entering vehicles have an equally likely probability of rejecting or accepting the gap of a specific length. The total number of rejected and accepted gaps used in this analysis was 598 and 279, respectively. A breakdown of the number of observations for each heavy truck type is shown in Table 6. Additionally, the critical gap values listed in Table 6 were taken directly from Figure 10, which visualized the time in seconds where vehicles are less likely to reject a gap and more likely to accept the gap. Figure 10a-e shows the critical gap curves for five of the six heavy truck classifications in this study: WB-40, WB-50, WB-62, WB-67, and WB-92D. The WB-67D class is not displayed in this Figure because there was insufficient data to generate a critical gap curve as the available data only contained three observations, as shown in Table 6.

Table 6: Critical Gap Values

Heavy Truck Classification	Total Gaps Rejected	Total Gaps Accepted	Critical Gap by Raff's Method
WB-40	48	17	5.4s
WB-50	65	29	5.4s
WB-62	207	90	5.8s
WB-67	254	130	6.2s
WB-67D	8	3	N/A
WB-92	16	10	6.4s
Total	598	279	--

The critical gap across all vehicles spanned a range of 1.0 seconds, where the smaller vehicle classes (WB-40 and WB-50) had the same critical gap length of 5.4 seconds. The charts describing the larger vehicle classes show an interesting observation, where a positive correlation can be observed between the vehicle size and the critical gap. Figure 10 shows that as the vehicle size increases, the critical gap length also increases. Furthermore, the magnitude of this increase is relatively consistent; The difference between a WB-50 and WB-62 was found to increase by 0.4 seconds; While a similar finding was observed comparing a WB-62 to a WB-67, which also resulted in a 0.4 second increase in critical gap length. The WB-92D required the largest gap length for the vehicle to enter the roundabout and the resulting length was found to be 6.4 seconds.

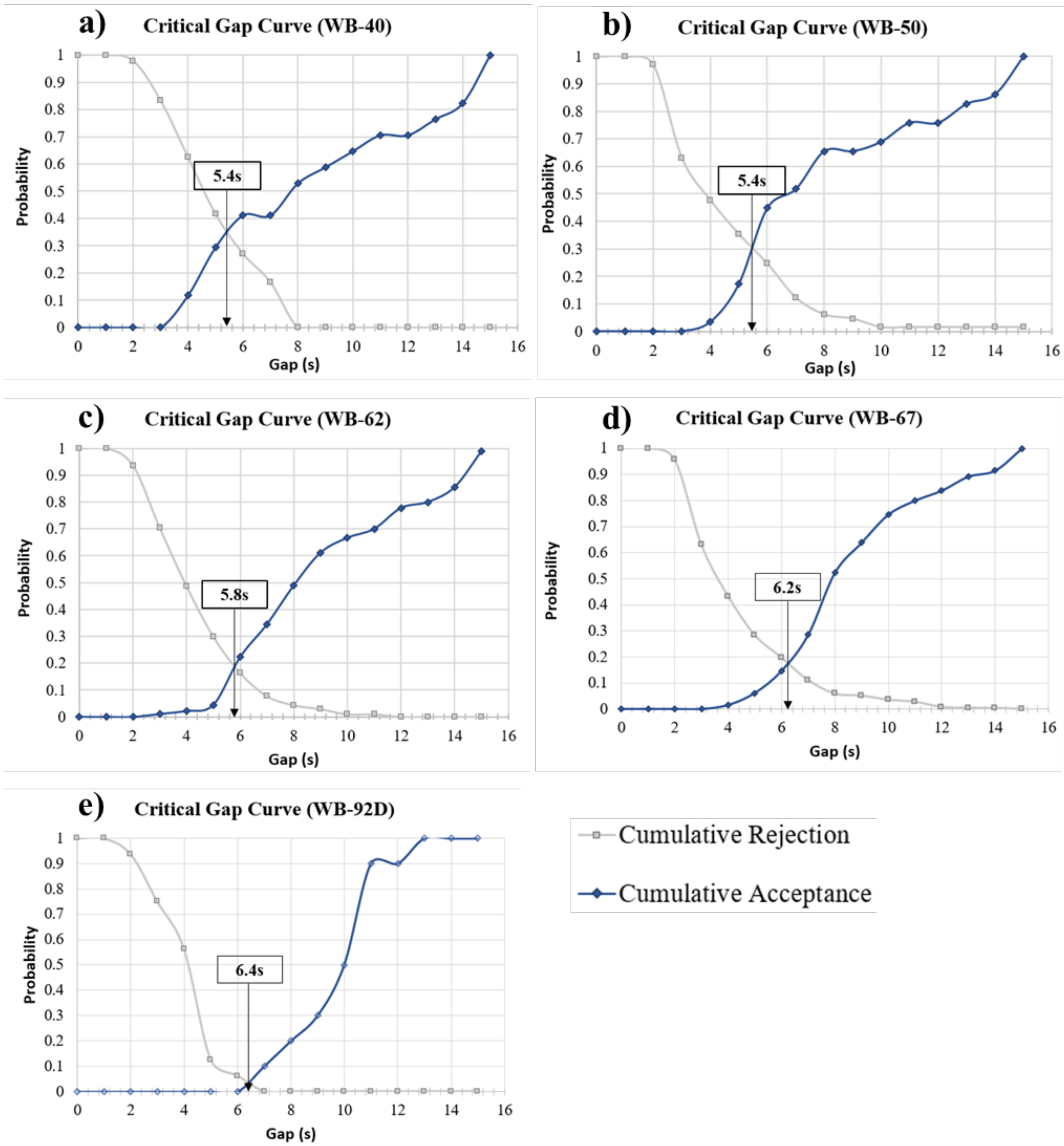


Figure 10: Critical Gap by Vehicle Classification Using Raff's Method

2.5 FIELD STUDY CONCLUSIONS

Assessing the gap acceptance of heavy trucks at roundabouts will expand the understanding of operational characteristics under congested conditions. This deeper knowledge regarding heavy trucks gap acceptance may provide direction for proposed design adjustments at future roundabout sites to improve passenger car and heavy truck negotiations, and address loading volumes comprised of various heavy truck classifications. The results showed that WB-67 trucks were the most common vehicle type observed in this field study and demonstrated acceptance of gap lengths relatively in the middle of the distribution of heavy trucks such as the WB-50, WB-62, WB-67D, and WB-92D classifications.

The findings from the critical gap assessment emphasized how larger vehicles require a longer critical gap to enter the roundabouts as compared to passenger cars, and provide insight to the magnitude of the difference. The critical gap lengths determined in this study range from 5.4 seconds to 6.4 seconds, this is much larger than the critical gap length for passenger cars which was established to be between two to three seconds in length (Mensah et. al., 2010; Fitzpatrick et. al., 2013). Intuitively it would be expected that heavy trucks require a larger gap length than passenger cars, but the range of the gap differential across vehicle types is an interesting outcome from this data. ***To expand, the critical gap of a WB-40 vehicle is about two times larger than a passenger car, whereas the critical gap for a WB-92D is nearly three times larger than that of a passenger car.*** These differences emphasize how heavy truck classification may impact roundabout operations and that the percentage breakdown of heavy truck classifications should be considered. Additionally, roundabouts that are anticipated to experience more significant heavy truck volumes of larger classifications (e.g., double trailers such as WB-67D or WB-92D) may require additional considerations.

3.0 VISSIM SIMULATION IMPROVEMENTS FOR MODELING HEAVY TRUCKS AT ROUNDABOUTS

3.1 VISSIM MODEL DEVELOPMENT

Base VISSIM roundabout models were developed in reference to the roundabout intersection of US 20 and Barclay Drive in Sisters, Oregon, using the current Oregon Department of Transportation (ODOT) Protocol for VISSIM Simulation (ODOT, 2011). This roundabout was selected as one of several sites for the field data collection associated with Chapter 2.0. This location was identified as an adequate site for modeling in VISSIM due to desirable features including its relatively standard configuration (e.g., four approach legs, one circulating lane, 150-ft inscribed diameter), its total heavy truck throughput during the peak period, and its overall vehicular volume during the peak period. The peak hour heavy truck observations occurred from 9:00 am to 10:00 am on Tuesday, June 28, 2022. Forty heavy trucks and 1,182 passenger cars were observed, with the heavy truck volume being the highest at any point in the 48 hours of data.

Four base models of the roundabout were developed for analysis and comparison as means to evaluate the overall methodology ODOT employs when modeling roundabouts in VISSIM. Within ODOT's existing methodology, two elements of VISSIM roundabout models were identified as warranting additional consideration. The first element was the heavy truck fleet composition, which would typically be VISSIM's default North American fleet according to ODOT's VISSIM protocol. The second element was the method of unsignalized control. The ODOT methodology recommends using the "conflict area" function in VISSIM, though the "priority rule" function is another available means of simulating yielding behavior (ODOT, 2011). The four base models were developed to form distinct combinations of the heavy truck fleet and unsignalized control configurations:

1. Existing traffic conditions with the VISSIM default heavy truck fleet and "conflict area" yielding behavior
2. Existing traffic conditions with the VISSIM default heavy truck fleet and "priority rule" yielding behavior
3. Existing traffic conditions with the heavy truck fleet observed in the field and "conflict area" yielding behavior
4. Existing traffic conditions with the heavy truck fleet observed in the field and "priority rule" yielding behavior

This Section of the report will outline the overall approach to developing the four base models. All inputs are reported, but greater depth will be dedicated to the methods applied to developing the different heavy truck fleets and unsignalized controls.

3.1.1 General Modeling Inputs

The model was developed using English units. An ortho-rectified aerial photo of the roundabout was obtained from Google Maps, scaled, and inserted as a background image. Links and connectors pertaining to the roundabout are shown overlaid on the Google Maps image in Figure 11. The passenger car fleet was built using the North American Default fleet, as an in-depth passenger car fleet was not necessary for the goals of this study. Buses, cyclists, and pedestrians were not coded into the model. The car following models were not edited from the VISSIM defaults. Simulations were run at a rate of ten time steps per second, meaning simulations ran ten times faster than real time.

Figure 11: Roundabout VISSIM Model

Speed control coding was applied based on the speed limits for the approach legs and the anticipated speed decreases resulting from roundabout geometry. The speed limits on the US 20 approaches to the North and South are 35 mph while the McKinney Butte Rd to the West and W Barclay Dr approach to the East has a speed limit of 30 mph in the field. Speed decisions were applied where road geometry begins to curve in preparation for roundabout entry. According to the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA), for a roundabout with a 150-ft inscribed diameter, circulating speeds for passenger cars would be estimated around 18.4 mph (NCHRP, 2010). This speed is lower for heavy trucks. Speeds were estimated by timing video recordings of heavy trucks while they travelled the circulating roadway and were verified with data provided by the freight telematics company EROAD. Heavy truck circulating speed was estimated at around 12.6 mph. All speed profiles were linearly distributed in the VISSIM models. Vehicle inputs and routing were developed based on turning movements during the peak hour for the observed vehicles. In accordance with the ODOT VISSIM protocol, the inputs were coded for 15-minute increments (ODOT, 2011). Table 7 shows the vehicle inputs, while Table 8 shows the static vehicle routes. Northbound and Southbound thru movements are the major vehicle movements for both passenger cars and heavy trucks, listed in vehicles per hour. 0.001 was used for static passenger car routes with no observed vehicles. The relative proportion of observed turning movements was entered for static heavy truck routes with no observed vehicles during the peak period.

Table 7: Vehicular Volume Inputs Based on Field Data

Approach	Passenger Car Flow	Heavy Truck Flow	First Quarter Flow	Second Quarter Flow	Third Quarter Flow	Fourth Quarter Flow
NB	393	16	388	452	396	400
WB	192	6	200	192	156	244
SB	395	18	424	388	380	460
EB	202	0.001	224	220	192	172

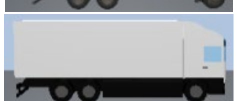
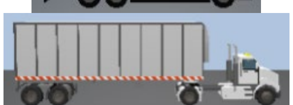
Table 8: Static Vehicle Routes

Routing Decision	Movement	Flow 9:00-9:15	Flow 9:15-9:30	Flow 9:30-9:45	Flow 9:45-10:00
Northbound Passenger Cars	Right Turn	16	16	12	16
	Thru	288	340	296	304
	Left Turn	60	80	60	60
	U Turn	4	4	8	8
Westbound Passenger Cars	Right Turn	60	88	48	92
	Thru	88	76	68	108
	Left Turn	44	24	36	36
	U Turn	0.001	0.001	0.001	0.001
Southbound Passenger Cars	Right Turn	12	4	8	28
	Thru	280	284	288	320
	Left Turn	88	20	44	48
	U Turn	28	48	24	56
Eastbound Passenger Cars	Right Turn	104	84	96	72
	Thru	44	64	48	40
	Left Turn	76	72	48	60
	U Turn	0.001	0.001	0.001	0.001
Northbound Heavy Trucks	Right Turn	0.014	0.014	0.014	0.014
	Thru	20	12	20	12
	Left Turn	0.037	0.037	0.037	0.037
	U Turn	0.006	0.006	0.006	0.006
Westbound Heavy Trucks	Right Turn	4	4	0.316	0.316
	Thru	0.053	0.053	0.053	0.053
	Left Turn	4	0.632	4	8
	U Turn	0.001	0.001	0.001	0.001
Southbound Heavy Trucks	Right Turn	0.003	0.003	0.003	0.003
	Thru	16	28	16	8
	Left Turn	0.046	4	0.046	0.046
	U Turn	0.009	0.009	0.009	0.009
Eastbound Heavy Trucks	Right Turn	0.5	0.5	0.5	0.5
	Thru	0.1	0.1	0.1	0.1
	Left Turn	0.3	0.3	0.3	0.3
	U Turn	0.1	0.1	0.1	0.1

3.1.2 Heavy Truck Fleet Development

As previously mentioned, two heavy truck fleet compositions were compared in VISSIM. The first was the default North American fleet included with VISSIM, while the second heavy truck fleet composition is derived from the observed heavy truck fleet at the study roundabout. These heavy truck fleets are composed as described in Table 9, which includes the VISSIM models for each vehicle class. VISSIM does not have built-in models for the WB-62 and WB-67 AASHTO classifications of heavy trucks. As such, the dimensions of the WB-65 was the closest substitute that could be provided. The North American default distribution does not include vehicle classifications larger than the WB-67D configuration. European EU-04 trucks and flatbed trucks are also included as part of the heavy truck fleet, likely a consequence of PTV's European origination. Models were developed for the WB-92D and WB-100T AASHTO configurations using the instructions provided in the ODOT VISSIM Protocol (ODOT, 2011). Additionally, the steps described in Appendix A are provided as a reference for the parameters used to create the larger configurations (WB-92D and WB-100T) used in this study.

Table 9: Heavy Truck Fleet VISSIM Models

VISSIM Model	Classification	Proportion of Fleet in NA Default Fleet	Proportion of Fleet from Field Observation
	Flatbed Truck	0.050	0
	EU-04	0.275	0
	WB-40	0.105	0.025
	WB-50	0.480	0.059
	WB-65	0.045	0.786
	WB-67D	0.045	0.055
	WB-92D	0	0.010
	WB-100T	0	0.065

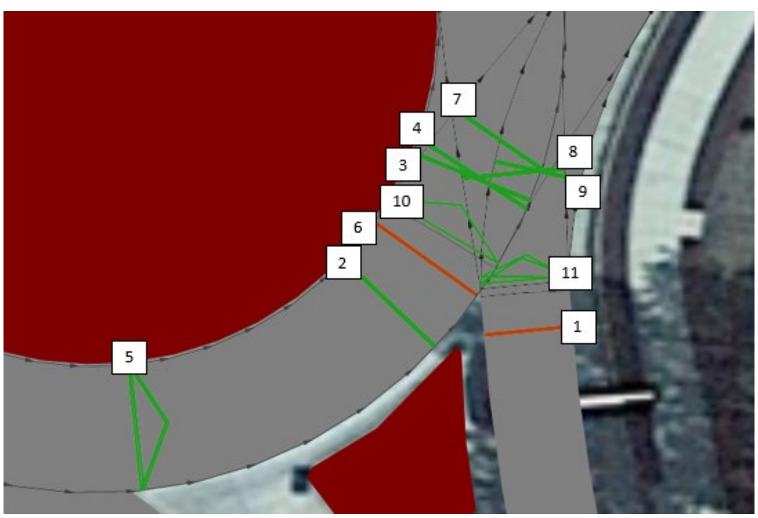
The heavy truck type distributions as well as the fleet compositions are different in the models assessed. The North American default fleet is composed primarily of the smaller WB-50 and EU-04 heavy trucks, while the observed fleet at the study roundabout was composed primarily of WB-62 and WB-67 heavy trucks, modeled together in VISSIM as WB-65 trucks (the closest available representation). Additionally, only 9% of the North American default fleet is longer than 60 ft, compared with 91.6% in the observed heavy truck fleet. This suggests that the current ODOT methodology does not typically account for the true spatial demands imposed on roundabout traffic by heavy trucks, as heavy trucks are typically modeled as being over 20 feet shorter than those observed in Oregon at the study location.

At the field study roundabouts in Oregon where data collection was conducted, heavy trucks fitting the WB-67 classification made up over 50% of heavy truck traffic. The WB-62 classification was the next most observed vehicle at each site, followed by larger articulated vehicles such as the WB-67D, WB-92D, and WB-100T. The smaller WB-40 and WB-50 vehicles were the least common. These three roundabouts, which are expected to include the highest heavy truck traffic at roundabouts in Oregon, provide a consistent heavy truck fleet. It is recommended that ODOT develop heavy truck fleets closely resembling the composition in the "Field Observation" column of Table 9, including building the larger WB-92D and WB-100T models using the files available through VISSIM. While data is not present to confirm that all roundabouts in Oregon would use this exact fleet, the present sample indicates that this fleet is a reasonable baseline for heavy truck fleets at the roundabout modeled in this investigation.

3.1.3 Methods of Simulating Vehicle Yielding Behavior

VISSIM has two means of determining vehicular yielding behavior- conflict areas and priority rules. The two methods have different attributes which directly affect how vehicles in a given model will yield. As a result, analysis of both types of yield controls is valuable to developing models of roundabout conditions. ODOT's VISSIM protocol recommends using conflict areas, which allow the user to determine which movements yield wherever conflicting vehicle flows are present. In the case of roundabouts, approach vehicles yield to conflicting vehicles travelling or exiting the circular roadway. Gap qualifications are used to determine whether a vehicle can safely enter the roundabout. The "front gap" is the amount of time an approaching vehicle waits until the conflict area has been cleared before entering. The "rear gap" is the minimum amount of time the approaching vehicle needs to anticipate being in the roundabout before another circulating vehicle reaches the area conflicting with the approach. The "safety distance factor" is a multiplier for an individual vehicle's safe following distance to ensure smooth entry into the circulating roadway (PTV Group, 2018). The base models which were configured with conflict areas had approaching vehicles yield to circulating vehicles in all possible conflicts except for the conflicts between right-turning approaching vehicles and the continued progression of circulating vehicles. In some simulations, setting the approach vehicle to yield in that conflict led to both the circulating and approach vehicles waiting for each other, which would eventually form an unrealistic gridlock at all entrances. The VISSIM default values of a 0.5-second "front gap," a 0.5-second "rear gap," and a "safety distance factor" of 1.5 were not adjusted. ODOT recommends using "front gap" and "rear gap" lengths from 0 to 1 seconds and a "safety distance factor" of at least 1, with adjustments from the default values being made according to engineering judgment.

For simulations using priority rules instead of conflict areas, separate priority rules for passenger cars and heavy trucks were positioned at the yield line for each approach. The passenger car priority rules were coded to allow passenger cars entry if circulating vehicles were at least three seconds from the start of the merge area and if the approach vehicle could enter the merge area with at least 25 feet of clearance from the end of the merge area. The heavy truck priority rules were coded for heavy trucks to enter the roundabout if circulating vehicles were at least 5.5 seconds from the start of the merge area and if the heavy truck could enter the merge area with at least 70 feet of clearance from the end of the merge area. Additional priority rules were added for circulating vehicles, which would sometimes fail to decelerate for larger entering heavy trucks, leading to collisions. Clear distances between 15 ft and 18 ft were applied to prevent passenger cars from colliding with heavy trucks. As an example, the priority rules at the south approach leg are shown in Figure 12. The red marker labeled “1” indicates where the yielding rules are applied for entering vehicles. The green markers labeled “2,” “3,” “4,” and “5” are the corresponding rules. The marker labeled “2” applies the gap time rule, while the markers labeled “3” and “4” mark the ends of the clearance areas. The green triangle labeled “5” marks the start of the clearance area. The red marker labeled “6” is the priority rule applied to circulating passenger cars. The green markers numbered “7,” “8,” and “9” indicate the ends of the corresponding clearance areas. The green triangle labeled “10” indicates the start of the clearance area ending at marker “7,” while the green triangle labeled “11” indicates the start of the clearance areas ending at markers “8” and “9.”



1. Priority rule for entering heavy vehicles
2. Gap time rule for entering heavy vehicles
3. End of clearance area for entering heavy vehicles
4. End of clearance area for entering heavy vehicles
5. Start of clearance area ending at 3 and 4
6. Priority rule for circulating passenger cars
7. End of clearance area for circulating passenger cars
8. End of clearance area for circulating passenger cars
9. End of clearance area for circulating passenger cars
10. Start of clearance area ending at 7
11. Start of clearance area ending at 8 and 9

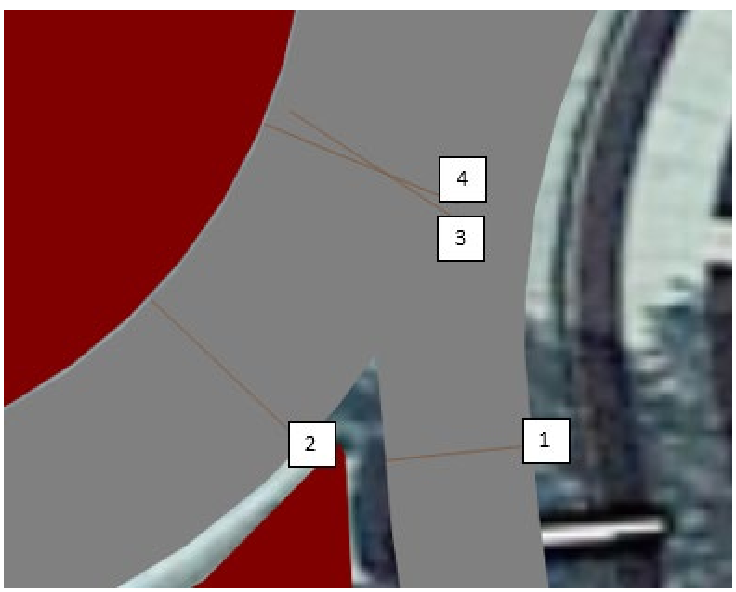
Figure 12: Priority Rules for South Approach

3.2 VISSIM CALIBRATION

The calibration process for the study roundabout involved comparing the performance measures of the four base scenarios. This Section will first discuss the process used to obtain values for calibration, after which model accuracy will be evaluated in comparison with the field observations. Due to the nature of the roundabout models as standalone intersections, the volume and speed data were the primary values which were necessary to ensure that the roundabout was operating realistically. Due to its nature as one of the primary research questions, heavy truck gap acceptance behavior was also considered in the calibration process. Additional factors to consider in the model calibration process will also be discussed.

3.2.1 VISSIM Data Collection

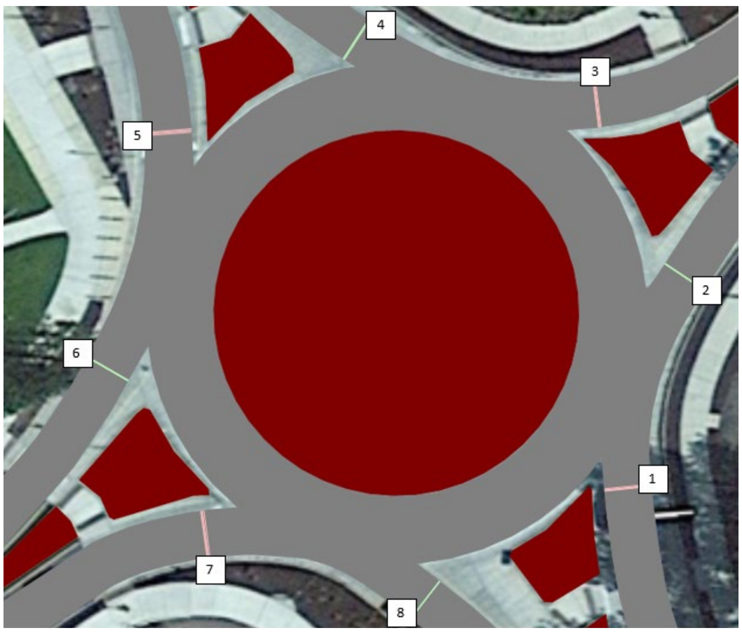
Data collection points and travel time measurements were the two primary methods of gathering the necessary data for model calibration. Data collection points record events whenever the front or rear of a vehicle crosses the data collection point. Each event includes the vehicle classification, the time of the event, the velocity and acceleration of the vehicle, the vehicle length, and a numeric identifier to differentiate each vehicle from all other vehicles in the same simulation (PTV Group, 2018). The data provided by the data collection points allowed for the calibration of volumes and calculation of critical gap lengths. Figure 13 shows the positioning of data collection points around the South approach leg. The data collection point labeled “1” is positioned slightly upstream of where conflict areas and priority rules begin to ensure that yielding approach vehicles are identified while they are waiting. The other three data collection points labeled “2,” “3,” and “4” capture information for vehicles using or exiting the circular roadway. This configuration closely matches the positioning used during the field data reduction to determine heavy truck critical gap lengths.



1. Data collection point tracking when approach vehicles reach the yield line
2. Data collection point tracking when circulating and exiting vehicles enter the conflict area
3. Data collection point tracking when exiting vehicles leave the conflict area
4. Data collection point tracking when circulating vehicles leave the conflict area

Figure 13: Data Collection Point Positioning

Travel time measurements record vehicle type, travel time, delay time, travel distance, and route completion time, as well as the numeric identifiers mentioned previously (PTV Group, 2018). Individual vehicle speeds can be calculated from the travel time, delay time, and travel distance. Figure 14 shows the positioning of the travel time measurement markers. Travel time starts when a vehicle reaches a red marker, which is positioned near the yield bar. Travel time measurement ends when the vehicle reaches a green marker, which is positioned slightly downstream of the roundabout exit. Travel distance is measured from the red bar to the green bar. Delay is measured only after a vehicle reaches the red bar; delay from queueing at the roundabout entry was not calculated as part of the calibration process. A total of 16 travel time measurements were placed around the roundabout, with each approach having measurements for the right turn, thru, left turn, and U turn movements. Marker start and end positions were placed in the same positions for consistency.



1. Travel time measurement start point for NB approach
2. Travel time measurement end point for EB exit
3. Travel time measurement start point for WB approach
4. Travel time measurement end point for NB exit
5. Travel time measurement start point for SB approach
6. Travel time measurement end point for WB exit
7. Travel time measurement start point for EB approach
8. Travel time measurement end point for SB exit

Figure 14: Vehicle Travel Time Measurement Setup

3.2.2 Volume Calibration

Pertinent volumes for calibration according to the ODOT VISSIM protocol included the entry and exit points at the roundabout legs, the Northbound and Southbound thru movements, and the total volume. In addition to calibrating those volumes for total vehicles, these volumes were also calibrated specifically for heavy truck flows. Calibration was conducted using the Geoffrey E Havers (GEH) equation, defined as

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

where m is the output volume from the model and c is the input volume (ODOT, 2011). According to the ODOT VISSIM Protocol, volume data is considered valid if the GEH value is less than five. The more stringent Washington State DOT VISSIM guidance uses a maximum GEH value of three. The relevant GEH values are tabulated below in Table 10. All GEH values are within the accepted range, with the highest GEH being 0.577. This indicates that the models closely resemble observed field conditions with respect to volumes and turning movements, as would be expected given the nature of the model network and the quality of the input data.

Table 10: GEH Values

Criteria	Default Fleet *Conflict Areas*	Default Fleet *Priority Rules*	Observed Fleet *Conflict Areas*	Observed Fleet *Priority Rules*
NB Entry Volume	0.173	0.164	0.168	0.168
NB Exit Volume	0.153	0.163	0.167	0.167
WB Entry Volume	0.085	0.078	0.085	0.085
WB Exit Volume	0.263	0.253	0.253	0.253
SB Entry Volume	0.252	0.237	0.237	0.237
SB Exit Volume	0.318	0.318	0.318	0.318
EB Entry Volume	0.113	0.099	0.092	0.092
EB Exit Volume	0.234	0.249	0.234	0.234
NB Thru Movement Volume	0.195	0.190	0.190	0.190
SB Thru Movement Volume	0.108	0.102	0.097	0.097
Total Volume	0.189	0.178	0.180	0.172
NB Entry HV Volume	0.532	0.532	0.532	0.532
NB Exit HV Volume	0.065	0.065	0.065	0.065
WB Entry HV Volume	0.166	0.166	0.166	0.166
WB Exit HV Volume	0.577	0.577	0.577	0.577
SB Entry HV Volume	0	0	0	0
SB Exit HV Volume	0.436	0.436	0.436	0.436
EB Entry HV Volume	0	0	0	0
EB Exit HV Volume	0.447	0.447	0.447	0.447
NB HV Thru Volume	0.532	0.532	0.532	0.532
SB HV Thru Volume	0.120	0.120	0.120	0.120
HV Volume	0.266	0.266	0.266	0.266

3.2.3 Speed Calibration

As mentioned in Section 3.1.1, passenger cars are expected to travel through the circulating roadway at about 18.4 mph, while heavy trucks are expected to travel through the circulating roadway at about 12.6 mph. Average passenger car and heavy truck speeds were computed for the four base models using the travel time data for the thru, left turn, and U turn movements. Right turn movements were not included due to speeds taken in right turn movements being less affected by roundabout geometry (AASHTO, 2001). As shown in Table 11, passenger car and heavy truck speeds were within acceptable ranges, with percent differences hovering around 5%. Simulated speeds were consistently slightly lower than the expected values.

Table 11: Speed Comparisons

Category	Default Fleet *Conflict Areas*	Default Fleet *Priority Rules*	Observed Fleet *Conflict Areas*	Observed Fleet *Priority Rules*
Expected PC Speed	18.40	18.40	18.40	18.40
Percent Difference	5.49%	5.00%	5.00%	4.78%
Average HV Speed in VISSIM	11.90	12.01	12.02	12.18
Expected HV Speed	12.62	12.62	12.62	12.62
Percent Difference	5.71%	4.83%	4.75%	3.49%

3.2.4 Gap Acceptance Behavior

Heavy truck gap acceptance behavior was studied using information obtained from the data collection points. As with the field data for gap acceptance, gaps 20 seconds or longer were filtered from the data before analysis. It should be noted that nearly 50% of all accepted gaps were at least 20 seconds long, while no rejected gap exceeded 15 seconds. Gap acceptance behavior for individual heavy truck classifications in VISSIM were not determined due to the simulation producing low volumes for all classifications except the WB-65.

The rate of rejecting gaps was compared between the four base scenario models and the field data. The results are summarized in Table 12. None of the VISSIM models matched the observed rate of entering roundabouts without rejecting gaps, but the models using priority rules produced the highest rate of gap acceptance. This suggests that conflict areas portray heavy trucks as being too cautious if the default settings are not adjusted. Visual inspection indicated more cautious behavior for both heavy trucks and passenger cars when conflict areas were in use. Neither priority rules nor conflict areas are completely accurate in portraying queueing behavior, but priority rules more closely approximated observed queueing patterns and allow for greater fine-tuning of vehicle behaviors. It should be noted that during the sensitivity analysis, breakdowns occurred at lower volumes for conflict areas than priority rules, though according to HCM calculations the roundabout was still functioning below capacity.

Table 12: Distribution of Number of Gaps Rejected

Number of Rejected Gaps	Field Data	Default Fleet *Conflict Areas*	Default Fleet *Priority Rules*	Observed Fleet *Conflict Areas*	Observed Fleet *Priority Rules*
0	84.8%	72.7%	80.8%	64.8%	82.0%
1	8.0%	15.2%	11.1%	18.5%	9.5%
2	3.8%	6.1%	3.6%	7.6%	3.6%
3	1.6%	3.3%	2.6%	4.3%	2.4%
4+	1.8%	2.8%	1.9%	4.8%	2.6%

The distribution of gaps accepted and rejected by heavy trucks in the four base simulation scenarios is summarized in Figure 15. The boxplots in Figure 15a show the distribution of the accepted gaps, while the boxplots in Figure 15b show the distribution of rejected gaps. Overall, accepted gap lengths modeled in VISSIM are longer than those observed in the field, while modeled rejected gap lengths were shorter than those in the field. Priority rules generally result in shorter accepted and rejected gaps. It is possible that gap lengths would be closer to the observed values if car following parameters were adjusted and gap acceptance values were modified accordingly.

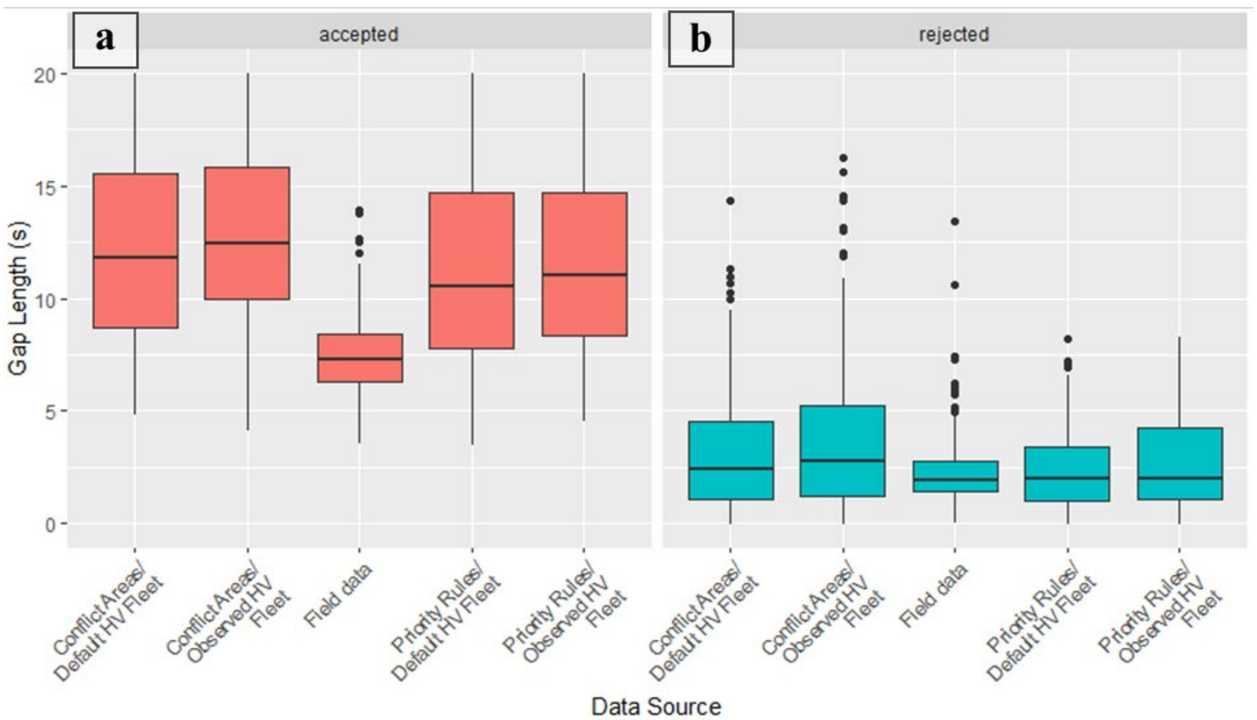


Figure 15: Heavy Truck (a) Accepted and (b) Rejected Gap Length Distributions

For consistency with the field observations, Raff's Critical Gap Method was used to determine critical gaps for simulated heavy trucks (Raff, 1950, Fitzpatrick et al, 2013).

Data from all ten simulations of each scenario were combined to determine the critical gaps shown in Figure 16a through Figure 16d. The blue lines plot the probability of rejecting a gap of a certain length and the orange lines plot the probability of accepting a gap of a certain length. The combination of using the observed heavy truck fleet with priority rules (Figure 16d) yielded a critical gap of 6.26 seconds, similar to the WB-67 critical gap of 6.2 seconds observed in the field. Comparison with the WB-67 critical gap is most suitable considering that most of the observed heavy trucks fell in the WB-67 classification, so most of the simulated heavy trucks were likewise of that configuration. Additionally, the configuration of the WB-67 makes it the ideal design vehicle, as it is the largest single-trailer heavy truck and is most subject to geometric constraints in a roundabout (NCHRP, 2010). The observed heavy truck fleet had a critical gap of 7.38 seconds when conflict areas were in use (Figure 16c), a critical gap exceeding those calculated for WB-92D vehicles in the field data (6.4 seconds). Likewise, the default heavy truck fleet with conflict areas had a critical gap of 6.86 seconds (Figure 16a). The default heavy truck fleet had a critical gap of only 5.33 seconds with priority rules (Figure 16b), a value lower than the critical gap lengths identified for any individual class of heavy truck in the field study. If heavy trucks have consistent gap acceptance behavior regardless of roundabout geometry and traffic volumes, the combination of the observed heavy truck fleet and priority rules is the most accurate reflection of heavy truck gap acceptance. It is recommended that priority rules, rather than conflict areas, be used to model yielding at roundabouts.

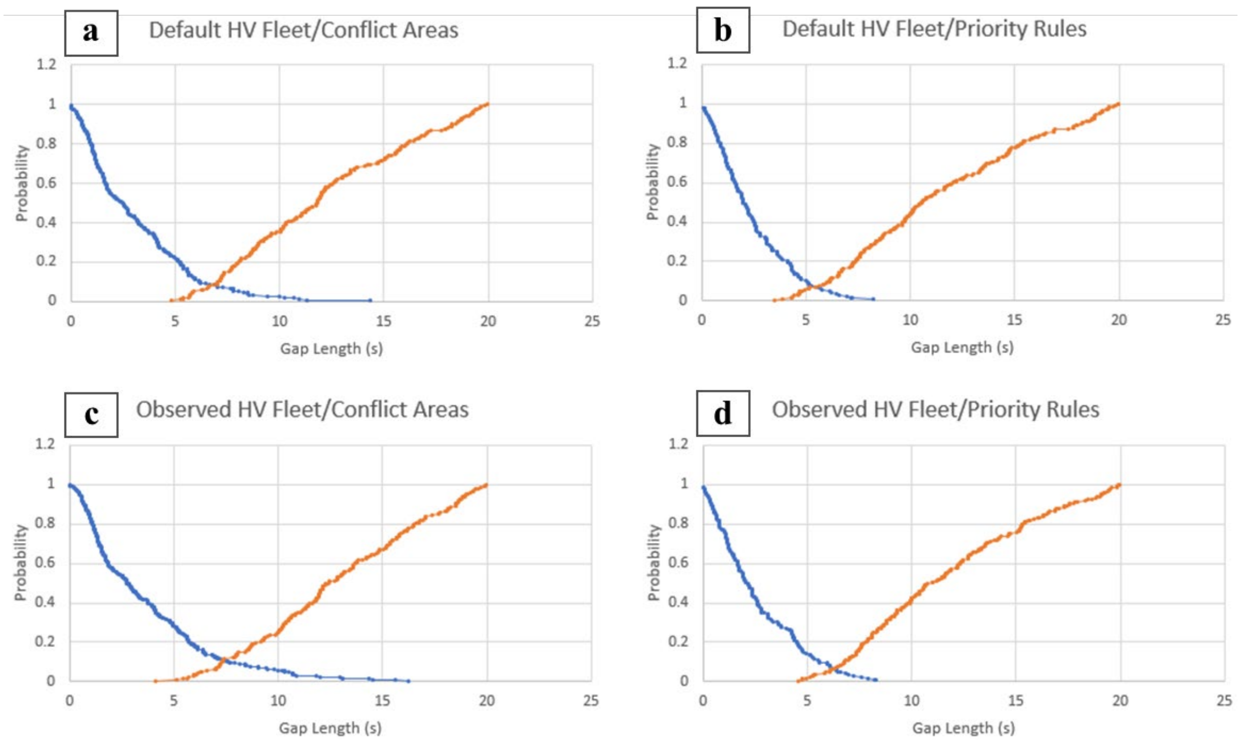


Figure 16: Critical Gap Lengths for Various Base Scenarios

3.2.5 Preferred Model Selection

According to the calibration criteria for vehicle volumes and speeds, all four models could serve as acceptable approximations of real-world conditions at a roundabout. To determine which model configurations, if any, are preferable, t-tests were used to compare the distributions of the heavy truck critical gaps. The heavy truck critical gap provides valuable insight into overall roundabout performance. Similar to how a design vehicle presents constraints to roundabout geometry, heavy truck gap acceptance behavior can impact roundabout operations. The critical gaps in Section 3.2.4 were determined by aggregating all heavy truck gap acceptance data across ten simulations. To increase the available data for the t-test, new critical gaps were developed by aggregating heavy truck gap acceptance from groups of five simulations. This process was repeated 20 times for each combination of heavy truck fleet compositions and yielding behaviors to produce a larger sample size. Table 13 provides summary statistics and the results of the t-test, while Figure 17 illustrates the various distributions.

Table 13: Simulation t-test Results

Category	Default Fleet *Conflict Areas*	Default Fleet *Priority Rules*	Observed Fleet *Conflict Areas*	Observed Fleet *Priority Rules*
Minimum	6.53	5.18	7.06	5.53
Mean	6.87	5.86	7.77	6.37
Maximum	7.61	6.36	8.51	6.96
Standard Deviation	0.29	0.36	0.35	0.35
t-statistic	10.36	-4.32	19.95	2.25
p-value	2.98e-09	3.72e-04	3.33e-14	0.036

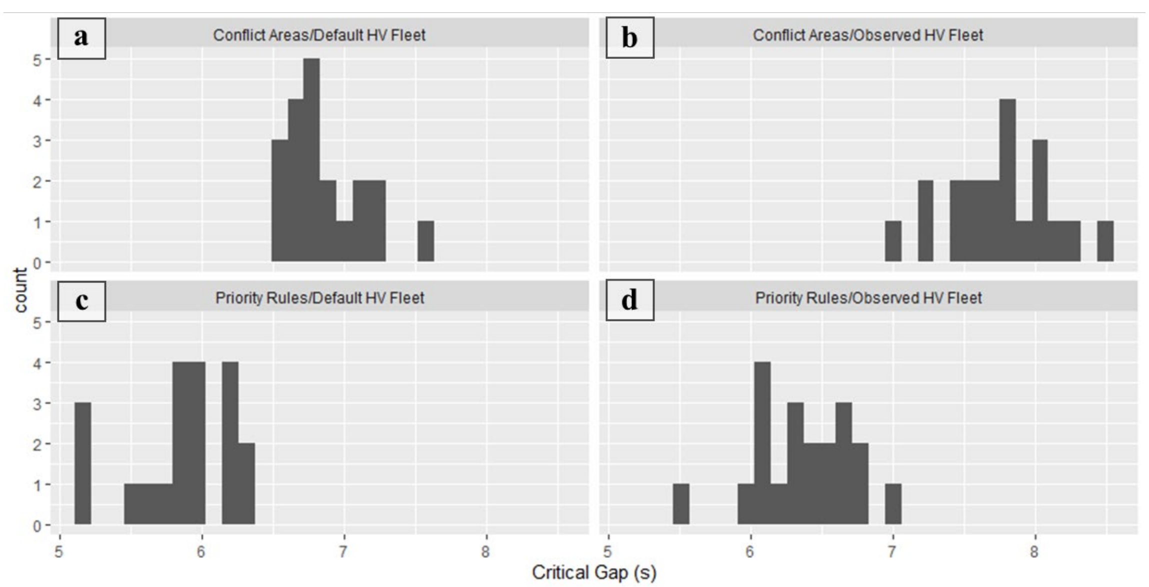


Figure 17: Simulated Critical Gap Distributions

Overall, it does appear that critical gaps estimated in VISSIM are reliable and repeatable, with each method maintaining a range of about 1 second. The critical gaps in Figure 16 appear generally representative, though the critical gap for priority rules and the default heavy truck fleet was slightly lower than would be expected, based on field observations. The t-tests conducted on the four distributions show that at a 95% confidence level, none of the four methods would be expected to include the WB-67 critical gap length of 6.2 seconds. The method which comes closest to approximating that critical gap length is the combination of priority rules and the observed heavy truck fleet (Figure 17d). The conflict area models were the least accurate models, as both estimated critical gaps to be longer than expected.

To compare goodness of fit, the Wilcoxon Rank Sum test and Kolmogorov-Smirnov test were used to compare the median and distribution, respectively, of heavy truck gap acceptance behaviors across the different models. This included accepted and rejected gap lengths as well as the number of rejected gaps. The results are tabulated in Table 14, with p-values listed in parentheses below the corresponding test statistics.

Table 14: Gap Acceptance Goodness of Fit

Value	**Statistical Test**	**Default Fleet** *Conflict Areas*	**Default Fleet** *Priority Rules*	**Observed Fleet** *Conflict Areas*	**Observed Fleet** *Priority Rules*
Number of Gaps Rejected	Wilcoxon Rank Sum	174344 (2.88e-09)	162217 (0.0053)	186722 (2.20e-16)	143732 (0.0071)
	Kolmogorov-Smirnov	0.139 (6.79e-05)	0.061 (0.2792)	0.220 (1.19e-11)	0.059 (0.3649)
Rejected Gap Length	Wilcoxon Rank Sum	18369 (0.4887)	11036 (0.3895)	25956 (0.0194)	10919 (0.5097)
	Kolmogorov-Smirnov	0.206 (0.0009)	0.188 (0.0089)	0.258 (4.37e-06)	0.206 (0.0034)
Accepted Gap Length	Wilcoxon Rank Sum	14147 (2.2e-16)	14760 (1.37e-12)	15500 (2.2e-16)	13894 (8.14e-16)
	Kolmogorov-Smirnov	0.532 (6.11e-15)	0.461 (1.15e-11)	0.620 (2.20e-16)	0.500 (3.18e-13)

The p-values for the Wilcoxon Rank Sum tests indicate the probability that a specific distribution from a simulation has the same median as the distribution from the observed field data. As was clearly visualized in Figure 15, all four models clearly do not have the same median accepted gap length. However, only the model using conflict areas and the observed heavy truck fleet is likely to not have the same median rejected gap length as was recorded in the field data. At a 95% confidence level, each of the four models do not have the same median number of rejected gaps as the field data, but the two models using priority rules are more accurate to field observed conditions than the two models using conflict areas. The test statistics for the Kolmogorov-Smirnov tests show the largest gap between the simulated cumulative distribution and the observed cumulative distribution. For instance, the Kolmogorov-Smirnov statistic for the number of gaps rejected by heavy trucks in the simulation with priority rules and the default heavy truck fleet indicates that while about 87% of observed heavy trucks rejected no gaps, in the simulation only about 81% of heavy trucks rejected no gaps. As the number of rejected gaps increases, that discrepancy decreases. The p-values can be roughly interpreted as the probability that the two distributions are the same. For the number of gaps rejected, the rejected gap lengths, and the accepted gap lengths, both conflict area models had different distributions from the observed field data. The accepted and rejected gap length distributions for the priority rule models were also likely to have a different distribution from the observed data, though these models performed marginally better in measuring rejected gap length. In terms of the number of rejected gaps, the priority rule models likely had the same distribution as the field data.

Figure 18 visualizes the cumulative distributions of the number of rejected gaps (Figure 18a) and the rejected gap lengths (Figure 18b) for all four models. In both cases, the models using priority rules outperform the models with conflict areas, with the model using the default heavy truck fleet being slightly more accurate than the model with the observed heavy truck fleet. The priority rule models do not allow for rejected gaps to be as long as they can be in the field, while the conflict area models allow for even longer rejected gaps. Conversely, the conflict area models allow heavy trucks to reject far more gaps than any heavy truck was observed doing in the field, while the priority rule models show heavy trucks not rejecting more gaps than observed in the field.

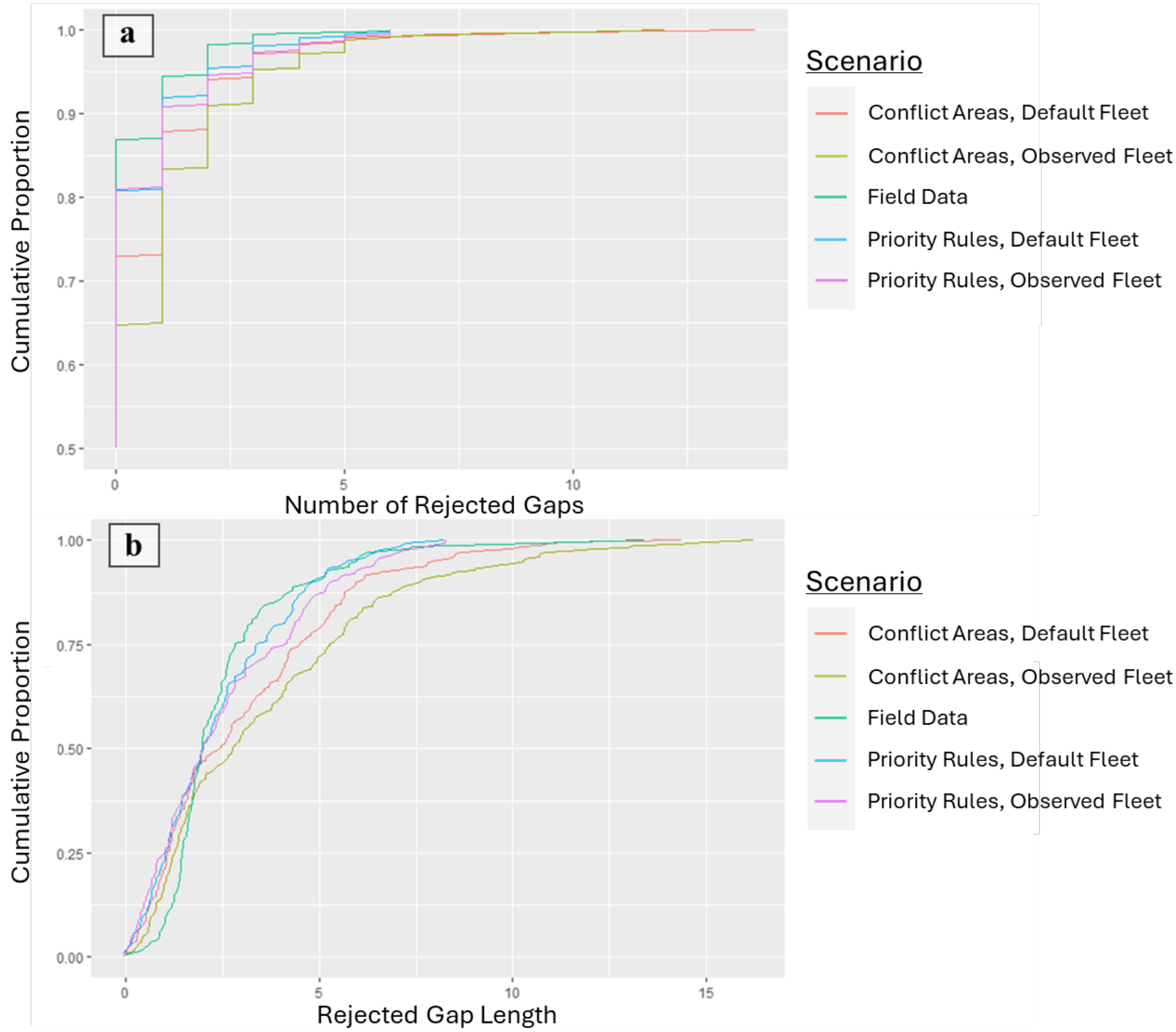


Figure 18: Cumulative Distribution of (a) Number and (b) Length of Rejected Gaps

Overall, heavy truck gap acceptance behavior appears to be an informative indicator of model accuracy for roundabout microsimulations. Within the calibration guidelines set forth by ODOT, a variety of heavy truck fleet compositions and yielding behaviors can produce models with acceptable outputs. However, heavy truck gap acceptance measures such as the critical gap, number of rejected gaps, and length of rejected gaps appear more sensitive to settings within VISSIM. The critical gap was of particular interest given it provides concise information about heavy truck requirements for entering a roundabout. However, the critical gap length is a relatively time-consuming value to produce, as it requires the collection of large volumes of accepted and rejected gaps, which must then be plotted graphically. In contrast, a lower volume of data is required to conduct a Kolmogorov-Smirnov test of the number of gaps rejected or the length of gaps rejected, and high volumes of plots would not need to be developed. However, it must be noted that calibrating VISSIM models for heavy truck gap acceptance behavior will require that field data of that gap acceptance behavior be collected at that roundabout. In the case of conducting a Kolmogorov-Smirnov test, that would require timing rejected gap lengths in the field for heavy trucks at the roundabout being modeled.

3.3 ADDITIONAL SCENARIOS

For each of the four base scenarios, 19 no-build scenarios were developed to perform sensitivity analyses of roundabout conditions under increased heavy truck and total vehicle flows. This Section will discuss the process used to develop the additional scenarios, the results of the simulated additional scenarios, and the implications of these results. A matrix describing all 80 modeled scenarios is included in Appendix A.

3.3.1 Model Configuration

The vehicle compositions and vehicle inputs were the two adjustments made within VISSIM to run scenarios for the sensitivity analysis. The former was used to increase the proportion of heavy trucks while maintaining a constant total volume, while the latter was used to increase total volume. Table 15 and Table 16 list the combinations of inputs for the sensitivity analysis. The same inputs were used for all combinations of yield control and heavy truck fleet compositions.

Table 15: Additional Scenario Relative Flows

Percent Truck Vehicles	PC Flow *NB*	PC Flow *WB*	PC Flow *SB*	PC Flow *EB*	HV Flow *NB*	HV Flow *WB*	HV Flow *SB*	HV Flow *EB*
3.3%	393	192	395	202	16	6	18	0
4.4%	388	190	389	202	21	8	24	0
5.5%	382	188	383	202	27	10	30	0
6.6%	377	186	377	202	32	12	36	0

The heavy truck relative flows were increased proportionately to produce the expected heavy truck flows. Other inputs such as gap acceptance parameters and car following distances were not edited, with the assumption being made that the changes in traffic for the sensitivity analysis were not sufficient to cause quantifiable changes in driving behavior.

Table 16: Additional Scenario Vehicle Flows

Hourly Volume (Percent Increase)	NB	WB	SB	EB	Start Time
1,222 (0%)	388	200	424	224	9:00
	452	192	388	220	9:15
	396	156	380	192	9:30
	400	244	460	172	9:45
1,253 (2.5%)	397.7	205	434.6	229.6	9:00
	463.3	196.8	397.7	225.5	9:15
	405.9	159.9	389.5	196.8	9:30
	410	250.1	471.5	176.3	9:45
1,283 (5%)	407.4	210	445.2	235.2	9:00
	474.6	201.6	407.4	231	9:15
	415.8	163.8	399	201.6	9:30
	420	256.2	483	180.6	9:45
1,314 (7.5%)	417.1	215	455.8	240.8	9:00
	485.9	206.4	417.1	236.5	9:15
	425.7	167.7	408.5	206.4	9:30
	430	262.3	494.5	184.9	9:45
1,344 (10%)	426.8	220	466.4	246.4	9:00
	497.2	211.2	426.8	242	9:15
	435.6	171.6	418	211.2	9:30
	440	268.4	506	189.2	9:45

3.3.2 Performance Measures

Roundabout performance under simulated conditions in the sensitivity analysis was measured using currently accepted roundabout performance measures outlined in the Highway Capacity Manual (HCM). Measures include the volume-capacity ratio, control delay, and 95th percentile queue length (HCM, 2016). In addition, gap acceptance behaviors for heavy trucks were monitored to identify how heavy truck drivers might react to increased volumes and heavy truck flows at roundabouts. All of these performance measures were calculated using approach volumes and the corresponding conflicting volumes, where the conflicting volume is defined as the volume on the circulating roadway which crosses in front of the approach leg. The entry capacity for a single-lane approach at a single-lane roundabout in passenger cars per hour is

$$c_{i,pce} = 1130 \cdot e^{-1 \cdot 10^{-3} \cdot v_{i,pce}}$$

where $v_{i,pce}$ is the volume at approach "i" in passenger car equivalents. A heavy truck is the equivalent of two passenger cars. The volume-capacity ratio for an approach is

$$x = \frac{v}{c}$$

where the volume and capacities previously defined can be inserted into the equation. The control delay for an approach in seconds per vehicle can be calculated as

$$d = \frac{3600}{c} + 900T\left[x - 1 + \sqrt{(x-1)^2 + \frac{3600x}{450cT}}\right] + 5 \cdot \min(x, 1)$$

The volume-capacity ratio and capacity are as defined previously, and time period "T" is 1 for one hour, or 0.25 for 15 minutes. The average control delay at the intersection is computed as

$$d_{int} = \frac{\Sigma d_i v_i}{\Sigma v_i}$$

which is a weighted average of the delay from each approach "i" weighted by the volume at each approach. The 95th percentile queue in vehicles is calculated as

$$Q_{95} = 900T\left[x - 1 + \sqrt{(x-1)^2 + \frac{3600x}{150cT}}\right] \cdot \frac{c}{3600}$$

with all variables as described previously.

3.3.3 VISSIM Model Analysis

Performance measures were calculated for all simulated scenarios. Although 80 total scenarios were simulated in the sensitivity analysis process, the currently accepted calculation procedures of the HCM performance measures are such that they are almost completely unaffected by changes in yield control and heavy truck fleet composition. These performance measures are governed by volumes and turning movements, and a cross-sectional comparison when yield controls and heavy truck fleet compositions are compared with matching volumes and turning proportions is not informative. The difference in the 95th percentile queue roundabout performance measure is typically as little as several hundredths of a vehicle, and the difference in average delay is a small fraction of a second between models using different yield controls and heavy truck fleets. Only the gap acceptance behavior shows significant measurable differences. As a result, the data discussed in this Section will focus on the models using the observed heavy truck fleet.

Table 17 outlines changes in the performance measures for the North approach, which experienced the highest expected delay of the four approaches. The figures are produced by the models using priority rules. As mentioned previously, there are no major differences between these values and the values produced for models using conflict areas.

Table 17: Sensitivity Analysis Performance Measures

Hourly Volume (% Increase)	Percent Heavy Trucks	Capacity	V/C Ratio	Average Delay	95th Percentile Queue
1,222 (0%)	3.3%	923.3	0.443	9.189	2.360
	4.4%	923.3	0.443	9.189	2.360
	5.5%	923.5	0.443	9.194	2.362
	6.6%	923.8	0.443	9.192	2.361
1,253 (2.5%)	3.3%	918.6	0.453	9.392	2.456
	4.4%	918.6	0.453	9.394	2.456
	5.5%	918.9	0.453	9.399	2.460
	6.6%	919.1	0.453	9.399	2.460
1,283 (5%)	3.3%	914.3	0.467	9.690	2.596
	4.4%	914.3	0.467	9.691	2.597
	5.5%	914.2	0.467	9.692	2.597
	6.6%	914.2	0.467	9.694	2.598
1,314 (7.5%)	3.3%	909.8	0.481	10.01	2.751
	4.4%	909.8	0.481	10.01	2.751
	5.5%	909.8	0.481	10.01	2.751
	6.6%	909.8	0.481	10.00	2.745
1,344 (10%)	3.3%	906.2	0.495	10.34	2.904
	4.4%	906.2	0.495	10.34	2.904
	5.5%	906.1	0.495	10.34	2.904
	6.6%	906.1	0.495	10.34	2.904

Changes in performance measures are roughly linear with increases in total volume. Changes caused by changes in heavy truck volume are less predictable, though they are also smaller in magnitude. Overall, roundabout performance was not dramatically impacted by the volumes and vehicle fleets applied in the sensitivity analysis. Roundabout operations continue relatively uninterrupted with a 10% volume increase and doubled heavy truck loads, and none of the approaches exceeded a volume-capacity ratio of 0.5 under the heaviest tested loadings. The average delay was low, ranging from about 9 to

10 seconds. This corresponds with levels of service A and B, respectively, indicating good overall service. It should be noted that the HCM performance measures are not sensitive to heavy truck traffic. This is in part because the HCM performance measures are governed entirely by the approach and conflicting volumes, making them insensitive to other conditions. Furthermore, since a heavy truck essentially counts as two passenger cars in the HCM equations, significantly increasing heavy truck volumes only results in marginal changes in HCM performance measures. While these performance measures provide valuable information about overall roundabout performance, they provide little indication of the individual experiences of heavy trucks at roundabouts. Under the data collection configuration outlined in Section 3.2.1, heavy truck delays collected by VISSIM could be compared with the overall expected delay from the HCM equations.

Figure 19 illustrates the critical gap length across all twenty scenarios for both the priority rule and conflict area models. The results from the models using priority rules cluster to the lower left portion of the graph, while the results from the models using conflict areas are spread toward the upper right region. The points with lighter shades of blue indicate higher vehicular volumes, while the darker points indicate simulations with lower volumes. The critical gap lengths were plotted against the average number of gaps rejected per heavy truck to further illustrate possible differences in gap acceptance behavior between the two methodologies.

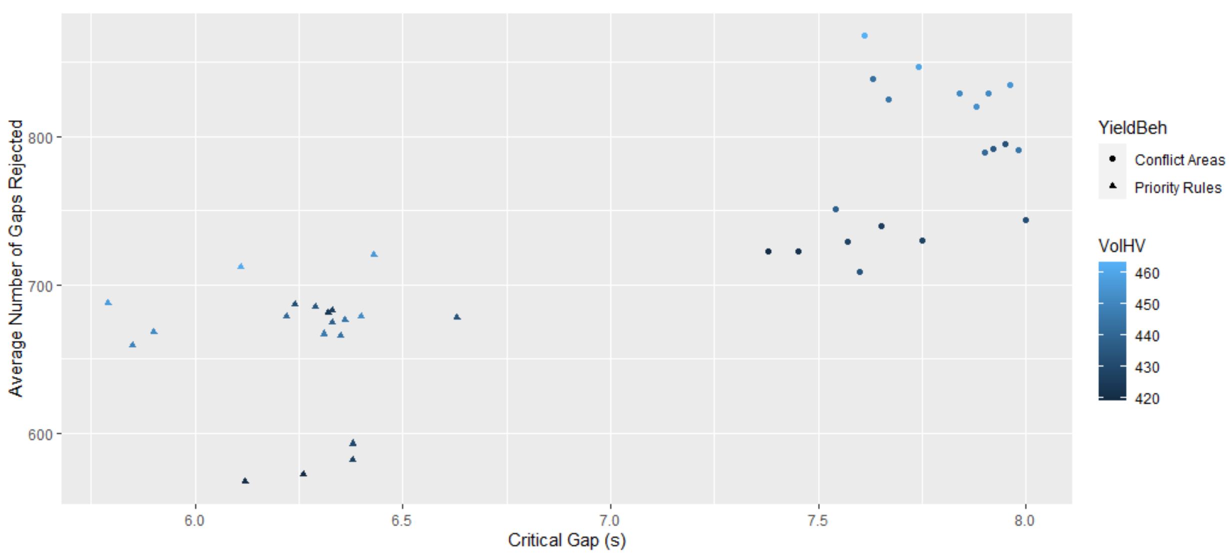


Figure 19: Distribution of Critical Gap Lengths

In addition to having higher critical gap lengths, models using conflict areas seem to show heavy trucks as being more conservative, with heavy trucks rejecting gaps at a higher rate. As may be expected, the average number of gaps rejected rises with increasing volumes. The critical gap does not follow a clear pattern, and the magnitude of the change is fairly low within the volume ranges applied.

Interestingly, the lowest critical gap lengths for the models with priority rules were obtained from the highest total volumes. Most of the other models had critical gaps around 6.3 seconds. There is not a clear pattern with tendencies to reject or accept gaps, as most of the models exceeding the base case scenario's 1,222 vehicles per hour show an average of 0.5 to 0.6 gaps rejected per heavy truck, while the models with 1,222 vehicles per hour averaged less than 0.4 gaps rejected.

Figure 20 further illustrates the difference in gap acceptance behavior. The proportion of the number of gaps rejected by heavy trucks is portrayed under the heaviest loading, with an increase of about 120 vehicles per hour accessing the roundabout and doubled heavy truck volumes. Though both models are similarly skewed, the model with conflict areas (Figure 20a) has a higher proportion of heavy trucks rejecting between one and five gaps, as well as a longer tail. Meanwhile, the model using priority rules (Figure 20b) has a larger proportion of vehicles not rejecting any gaps. This parallels the boxplots from Figure 15, which showed conflict areas rejecting a wider range of gap lengths as compared to priority rules.

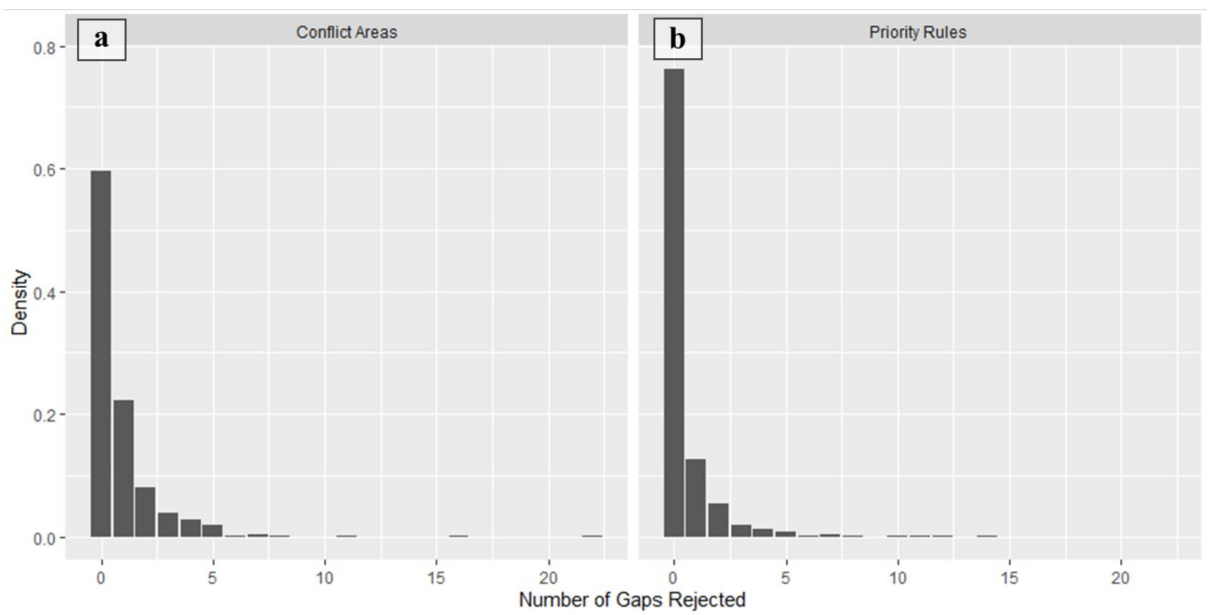


Figure 20: Frequency of Number of Gaps Rejected in (a) Conflict Areas and (b) Priority Rules

3.4 VISSIM SIMULATION CONCLUSIONS

The primary purposes of modeling the US 20-Barclay Dr roundabout in VISSIM were to evaluate ODOT's current methodology for modeling roundabouts and to study possible future roundabout conditions. Several aspects of the ODOT methodology were identified as potential opportunities for improvement which could enhance the representation of roundabouts and heavy truck operations at roundabouts.

First, the North America default heavy truck fleet included in VISSIM is not an accurate representation of the heavy truck fleets using roundabouts in Oregon. The North America default heavy truck fleet is comprised of smaller heavy trucks, with 91% of heavy trucks being WB-50 trucks or smaller and 32.5% of heavy trucks being smaller than a WB-40 truck. In contrast, 8.4% of observed heavy trucks at the study roundabout were WB-40 or WB-50 trucks, while the remaining 91.6% of observed heavy trucks were classified as WB-62, WB-67, WB-67D, WB-92D, or WB-100T trucks. It was further determined that while the largest classifications of heavy truck (WB-92D and WB-100T) are not included in the default heavy truck fleet, these models can be built in VISSIM and included in the heavy truck fleet. ODOT should consider using observed heavy truck fleet compositions in the place of the North America default heavy truck fleet due to the sharp contrast in vehicle classifications. The heavy truck fleet proportions used in the model discussed is reasonable for the location modeled and the process used to produce the distributions is transferable to other roundabouts in the state, however the exact distribution may require additional calibration before implementation at other roundabouts.

Second, priority rules yield higher accuracy and flexibility when modeling heavy truck gap acceptance behavior at roundabouts relative to conflict areas. Conflict areas tend to model overly conservative gap acceptance behavior for heavy trucks which was not representative of most heavy trucks observed at roundabouts. This was evidenced by heavy trucks rejecting gaps at a higher rate than observed in the field, heavy trucks rejecting longer gaps than they were observed to in the field, longer queues, and heavy trucks having longer critical gaps. This is contrasted by lower gap rejection rates, less rejection of long gaps, and lower critical gaps when priority rules were used. ODOT should consider that priority rules be implemented to control yielding for roundabout approach vehicles as recommended in the VISSIM user manual, with separate priority rules for spatial and temporal gaps. Additional rules should also be applied to prevent circulating vehicles from colliding with larger heavy trucks.

Third, heavy truck gap acceptance behavior can serve as a criterion during calibration for roundabouts where heavy truck access is a primary concern. Though the critical gap is consistent across models using the same coding, its higher data requirements (multiple simulation runs) and its visual nature make it a time-consuming value to produce. The cumulative distributions of the number of gaps rejected by heavy trucks or the lengths of gaps rejected by heavy trucks can be computed more efficiently while providing practical data which can be easily interpreted in terms of the effect had on heavy truck operations, though it, too, has heightened data requirements relative to the current methodology. Using one or both values for calibration is worth consideration by ODOT to ensure that heavy truck operations are accounted for and accurately portrayed, particularly if roundabouts become more common along major truck routes. It appears that properly developed priority rules are currently adequate to represent heavy truck roundabout entry behavior for existing roundabout heavy truck traffic in Oregon. Positioning data collection points around roundabout entries as described in Section 3.2.1 enables collection of the necessary data in VISSIM. It should be noted that such calibration would require collecting gap acceptance data, including the number of gaps encountered and the length of each gap presented to a heavy truck. These data can be collected and transcribed through video observation.

Finally, HCM roundabout performance measures including the volume-capacity ratio, average delay, and 95th percentile queue can be determined from model outputs. However, these performance measures are not sensitive to the presence of heavy trucks. Since a heavy truck is treated as the equivalent of two passenger cars by the HCM equations, and all performance measures are based on approach volumes and conflicting volumes, these performance measures only capture overall roundabout conditions without providing useful details about the operation of individual heavy trucks. Identifying the critical gap length, measuring the rate of gap rejection per heavy truck, or measuring heavy truck delay could be considered to better visual changes in heavy truck operation conditions at roundabouts. The relation of these four recommendations to the existing ODOT VISSIM modeling approach is summarized in Figure 21.

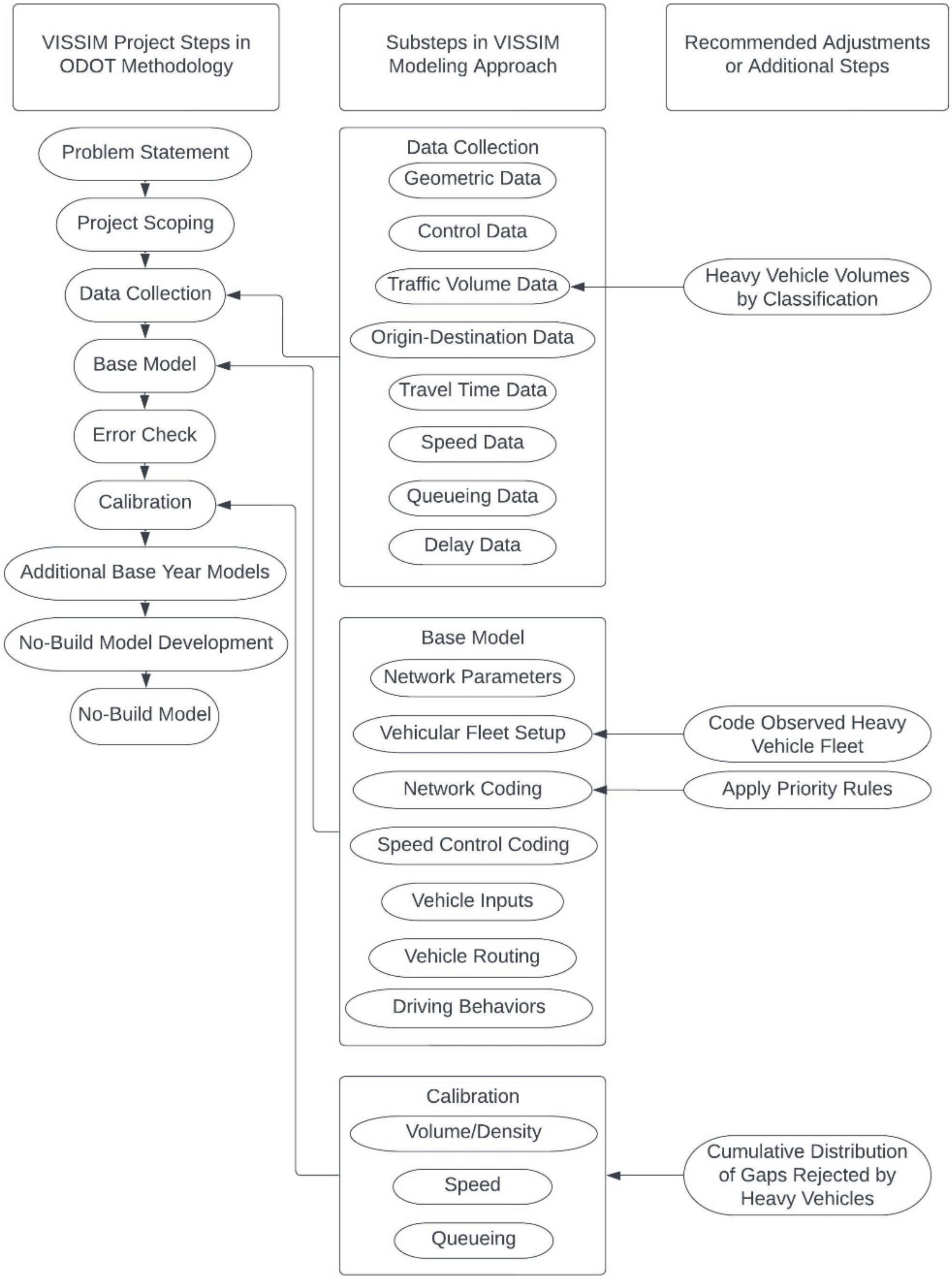


Figure 21: Recommended Adjustments to ODOT VISSIM Protocol

4.0 HEAVY VEHICLE DRIVING SIMULATOR GEOMETRIC DESIGN AND TRAFFIC CONTROL DEVICE ALTERNATIVES

4.1 DRIVING SIMULATOR STUDY OVERVIEW

To address problems observed in the field regarding the maneuverability of heavy trucks at congested roundabouts, a driving simulator study was designed to place heavy truck drivers in representative scenarios. The Oregon State University (OSU) Heavy Vehicle Simulator was leveraged as a tool to study the maneuverability of heavy trucks in a simulated environment using human-subjects research and a within-groups study design to expose Commercial Motor Vehicle (CMV) drivers to all variables of interest. Variables included unique roundabout geometries less common in the as-built environment, as well as Traffic Control Devices (TCD) intended to enhance the fluidity when roundabouts are experiencing congested conditions. Exploration of the impact of these designs in a controlled environment allowed for examination of the effectiveness of various roundabout geometries and TCD implementation. Additionally, data collected using this method provides direct measurements from CMV operators while providing an accessible alternative due to the limited field sites available. Individuals who: possessed a valid Commercial Driver's License (CDL), were at least 18 years of age, and had over one year of driving experience were recruited as study participants.

The purpose of this study was to understand whether implementation of roundabouts featuring slight geometric modifications, or the inclusion of TCDs are a viable solution to address the concerns previously highlighted. This simulation study allowed for preliminary assessments to be made regarding the efficacy of these alternatives. The field work conducted in Chapter 2.0 was used to calibrate roadway characteristics, traffic operations, and heavy truck classes to align with representative conditions observed at roundabout sites across the states of Oregon and Washington. Particular attention was paid to the most common heavy truck classification observed in the field, the WB-67. For this reason, all simulated controls (turning radii, steering calibration, trailer length and vehicle configuration) were calibrated to provide the same look and feel as that of a WB-67.

4.1.1 Problem Description and Proposed Solution

Chapter 2.0 included field data evaluation to derive a critical gap value for multiple heavy truck classifications, which was found to have a relatively large variation across vehicle classes; Results revealed that the critical gap for heavy trucks tends to be between 5.4s and 6.4s. A more common practice is to assess the critical gap for passenger cars, in which many previous studies have evaluated the entering ability for these smaller vehicles and deemed average critical gap values to lie between 2 and 3 seconds. The comparison between these two vehicle types emphasizes the operational struggles associated with heavy trucks that tend to be longer, heavier, and slower than that of a passenger car. The present study utilized the gap length values derived from the field work across Oregon and Washington to calibrate a driving simulation study and further examine potential solutions to these entering concerns.

4.1.2 Participant Sample

Provided this study aimed at addressing concerns for heavy trucks, it was imperative that participants represented the portion of the population that operates these larger vehicles. For this reason, individuals were invited to participate provided they met the three exclusionary criteria:

1. At least 18 years of age;
2. Possessed a valid CDL;
3. At least one year of commercial driving experience.

These criteria were put in place to collect a sample of participants that were representative of heavy truck operators on the roadway. The third criteria was included in the selection of drivers to ensure that any driving behavior was true to CMV operators as opposed to a lack of experience. Participants were instructed to bring their CDL license prior to beginning the experiment and researchers performed a brief inspection to ensure all participants met the exclusionary criteria.

All CDL classes were accepted and a total of 41 individuals participated in the study. Due to the experiencing of simulator sickness, a phenomenon that results in feelings of nausea and discomfort, the data for certain subjects were invalidated and thus the final sample size was 31 complete datasets. The data from individuals that experienced simulator sickness were not included in the analysis because it may influence unrepresentative driving behavior as well as impact the response time of drivers.

4.2 DRIVING SIMULATOR STUDY DESIGN

Guided by study objectives, the independent variables and performance measures were carefully selected to produce findings that could support decision making related to the geometrics and operations of roundabouts in Oregon. The following Sections describe the considerations made and process followed for selecting and designing independent variables, evaluating performance measures of interest, and calibrating the equipment used in the heavy truck driving simulator.

4.2.1 Independent Variables

The influence of traffic characteristics, geometric design alternatives, and TCDs were deemed most notable for the purposes of this study. Manipulation of four independent variables: volumetric loading of the circulating traffic, gap lengths presented by circulating traffic, variations in roundabout geometry, and the implementation of roundabout metering resulted in a fully counterbalanced, partially randomized, factorial design with 24 unique scenarios requiring participants to traverse 24 different roundabouts in the simulated environment. Table 18 describes the categorical levels of each independent variable. A detailed description of the independent variable levels and other experimental design parameters are described throughout this Section.

Table 18: Independent Variable Levels and Description

Variable	# of Levels	Level Names	Description
Gap Length	2	5.4 s	Gap length presented by circulating traffic within roundabout
		6.4 s	
Volumetric Loading	2	High	Level of congestion
		Low	
Geometry	3	Traditional	Variations in geometric shape of roundabout
		Elliptical	
		Tapered	
Roundabout Metering	3	Meter Near (MN)	Signalization at various points along approach
		Meter Far (MF)	
		No Meter (NM)	

4.2.1.1 Traffic Characteristics

As noted in the field work, drivers looking to enter a roundabout under congested conditions must coordinate their movement to safely blend into the circulating traffic flow. This task becomes more difficult when operating a longer or heavier vehicle, and as circulating traffic congestion increases. Therefore, the level of traffic congestion and the profile of the presented gap lengths within the roundabout were carefully selected. These traffic parameters were designed to resemble field-observed conditions consisting of vehicles entering from various legs of the roundabout while displaying similar yielding behavior and compliance with traffic regulations. Additionally, two variables: *volumetric loading* and *critical gap length* were of particular interest and as such were adjusted to several levels within the experiment.

The volumetric loading at the roundabout corresponds to the number of circulating vehicles at any given time. Presenting two levels, high and low, participants were exposed to scenarios that had consistent traffic at the intersection (high) as compared to instances where there was half as much of this traffic congestion (low). Inclusion of this variable helps to understand how driver decision making differs when there does not seem to be a clear delineated end in the conflicting traffic flow – And the impact on a heavy truck drivers' decision when entering the roundabout. Design of this variable level was conducted within the simulation software, SimVista, which allowed for Javascript code to control traffic movements, speed, and timing parameters. Vehicle movements were coded on a per vehicle basis, and scripts were transferable across scenarios to ensure no unintended discrepancies were present. Figure 22a displays a "low" level of congestion, e.g., 2 vehicles visible in the driver's field of view, as compared to the "high" level of congestion displayed in Figure 22b, e.g., 4 vehicles visible in the driver's field of view. Vehicle volumes displayed in Figure 22 are represented as a static image, not detectable in the high traffic condition are audio-cues from increased traffic, higher frequency of entering vehicles, and increased queue lengths on adjacent approach legs.

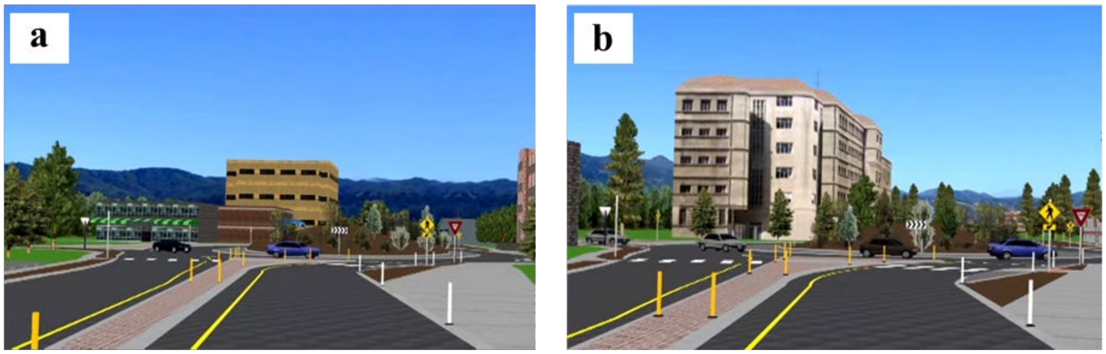


Figure 22: Loading Variable with (a) Low and (b) High Traffic

The critical gap length(s) as defined in the field work was used as a reference for the gap length variable in this driving simulator study. To reiterate what was discussed in Chapter 2.0, critical gap is one performance measure that can be assessed at intersections which feature stop, yield, or permitted movements, which can be described as the value where 50% of traffic will reject a gap of a particular length while 50% will accept it. Field observed values of this performance measure revealed noticeably different results with heavy trucks requiring a 2.5 times larger gap as compared to passenger cars, likely due to their longer footprint, increased weight, and more restrictive maneuverability. For this reason, the inclusion of gap length as a variable in the driving simulation study was imperative. Similar to the volumetric loading variable, manipulation of circulating traffic used JavaScript code to achieve gap lengths representative of field observed critical gap values (5.4 seconds and 6.4 seconds). Timing parameters were established through trial and error to achieve the desired gap lengths, and measurement of these gaps used the same reference points as that of the data transcription from the field work.

4.2.1.2 Geometric Design Alternatives

Roundabout geometry was a focal point in the variable selection process. Three different roundabout configurations were modeled which will be referred to throughout this report as: traditional, tapered, and elliptical. The "Traditional" roundabout was assigned this designation as it features a common circular shape and was geocoded to specifications and design drawings of the as-built roundabout in Sisters, OR at the intersection of W Barclay Dr and Highway 20. Figure 23 provides a visualization of the translation from the design drawings of the as-built roundabout (Figure 23a) to the 3-D model constructed using Blender Version 2.71 (Figure 23b). This variable level features a circular shape with geometric features and traffic control device configurations that align with standards in Oregon, with the inclusion of a truck apron and entrance truck apron along two approach legs. Key geometric measurements are described in Table 19 which were discerned from the design plans, and subsequently verified with field measurements, for this roundabout configuration and include aspects such as the Inscribed Circle Diameter (ICD), lane widths, and truck apron layout. Selection of the traditional shape as the control configuration followed recommendations from the Technical Advisory Committee (TAC) which recognized this location as a good example of a prototypical roundabout in Oregon with high vehicular volumes and a good proportion of heavy truck traffic. Additional design alternatives were generated through manipulation of this configuration to ensure approach legs, entering geometry, and overall feel while driving was consistent across variable levels. Figure 24 presents an aerial perspective of each design alternative included in this study: (a) Traditional, (b) Tapered, (c) Elliptical.

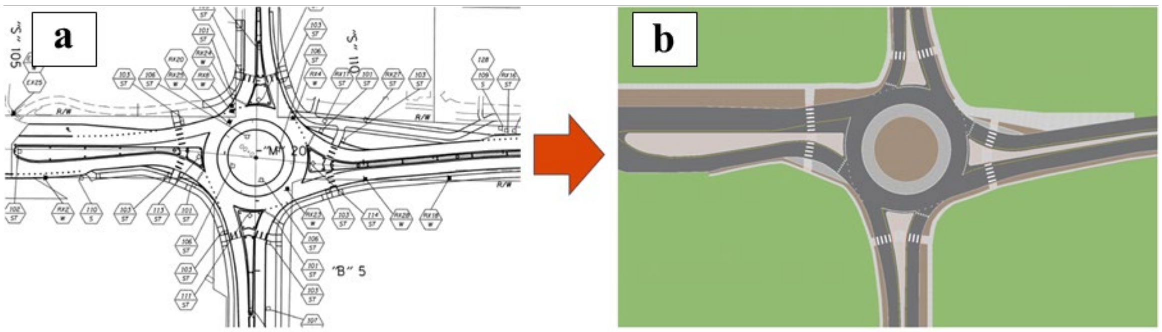


Figure 23: (a) Design Drawing from Sisters, OR and (b) 3-D Rendered Roundabout

Table 19: Key Geometric Characteristics

Geometry	ICD	Lane Width	Truck Apron Width
Traditional	155 ft	21 ft	14 ft
Tapered	155 ft	21 ft	Varies
Elliptical	Varies	21 ft	14 ft

The notable difference with the "Tapered" configuration displayed in Figure 24b is the modification made to the central island portion of the roundabout. This descriptor refers to the cut-off nature of the landscaping area within the central island. Upon initial inspection, sight-distance is notably influenced as the increased visibility towards the path-of-travel contradicts how landscaping is typically used to limit excess sight distance and to encourage slower speeds (NCHRP, 2010). In return, heavy trucks are provided with a larger truck apron at critical points and thus more operating space during traversal. This consideration is important given the context of the Oregon Department of Transportation (ODOT) Highway Design Manual which states, "*Widening the truck apron will decrease the remaining raised center area. One important reason for the raised center area is to provide a visual screen using vegetation to restrict visibility from one side of the roundabout to the other*" (ODOT, 2023). In consideration of this design parameter, and despite the increased visibility associated with the tapered configuration, the raised center area was still present to provide a visual cue to drivers of the presence of the roundabout and present visual restrictions to limit sight distance to the other side of the intersection. Additionally, the landscaping area still met idealized design parameters described in additional design manuals where the domed shape within the central island featured elevations between 3.5 ft and 6 ft as specified by the Wisconsin Department of Transportation's Facilities Development Manual and NCHRP Report 672 (WisDOT, 2013; NCHRP, 2010). All other design aspects outside of the central island modifications were kept consistent with the traditional roundabout configuration.

Unlike the tapered configuration which featured modifications solely to the central island, the "Elliptical" configuration required more significant manipulation of the roundabout. Lengthening of the roundabout along one-axis creates the distinct characteristic of its prolonged or oval shape, resulting in a configuration that features differing radii at various points of the circulatory roadway. Inclusion of this design alternative in the study provided a better understanding of the operational impacts during congested conditions involving heavy trucks. The modeling task for this configuration required an iterative process through manipulation of the traditional roundabout design until the elliptical shape could be discerned from the driver's perspective in the simulation environment. Steps involved translation of the entering approach legs combined with the extension of the circulatory roadway along the axis of interest. The final design features a radius that is two times longer in one direction, with the shorter radius remaining the same as the traditional roundabout configuration. Figure 24c provides a plan view of the elliptical roundabout used in the driving simulator experiment.

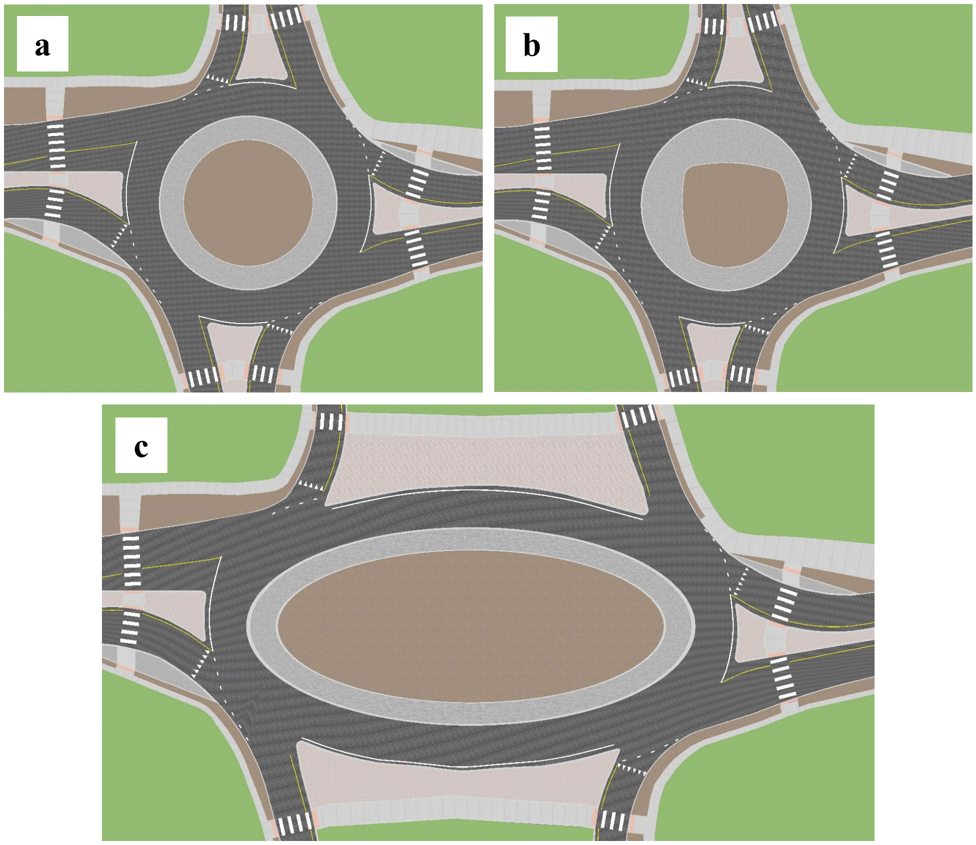


Figure 24: Geometric Variable Levels (a) Traditional (b) Taper (c) Elliptical

4.2.1.3 Traffic Control Devices

Traffic Control Devices are "… all signs, signals, markings, and other devices used to regulate, warn, or guide traffic, placed on, over, or adjacent to a street, highway, pedestrian facility, bikeway, or private road open to public travel by authority of a public agency…" (FHWA, 2009). Roundabouts inherently utilize a yield-control method for managing traffic operations as indicated by the yield signs and markings on entering approaches. Without removing the yield control functionality, the addition of signalization was investigated as a TCD variable termed "Roundabout Metering." The terminology, design, and functionality for this TCD was adopted from ramp metering, a well-established method for controlling the frequency and entering capacity of vehicles onto highways during congested hours. Blender Version 2.71 was leveraged for creating the roundabout metering unit and was modeled in accordance with parameters for ramp-metering designs as specified by the California Department of Transportation (CalTrans) design manual (CalTrans, 2016). This design features two signal heads, a 12-inch 3-section upper and an 8-inch 3-section lower supplemented by an R10-6a "Stop Here on Red" sign. This same design is being used at a roundabout site in Richland, WA along Columbia Park Trail which was referenced as one place where this TCD is currently in operation. Figure 25 shows the Roundabout Metering device developed for the simulation environment.

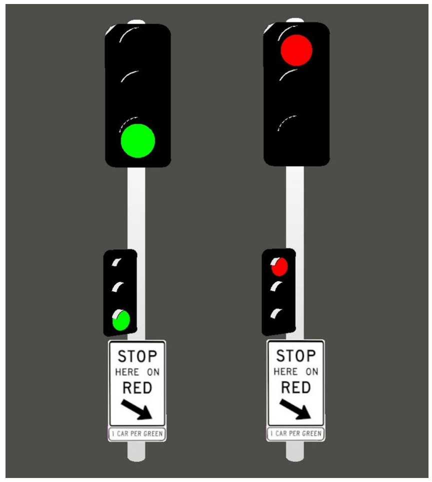


Figure 25: Roundabout Metering Device 3-D Model

Functionality of this TCD places an emphasis on breaking-up of large vehicle platoons to improve the entering capacity at adjacent legs of the roundabout. This is one method for managing traffic to present more consistent gaps in circulating traffic for heavy trucks looking to enter congested roundabouts. The functionality of the roundabout metering device was coded in the simulated environment, so signal phasing parameters aligned with the gap timing variable of interest and leveraged Javascript coding to control entering frequency. The result was circulating traffic that entered the roundabout at specified intervals to present consistent gap lengths of 5.4 seconds or 6.4 seconds, depending on the scenario presented. Participants were not informed of the presence of this design alternative, although the adjacent meters and queued vehicles were visible to drivers as they approached the roundabout entrance.

In addition to managing the rate of entering vehicles to meet gap length parameters, the location of the roundabout meter was also manipulated. Figure 26 provides an example within the driving simulator environment of scenarios where the roundabout meter was placed as a “near” variable level (Figure 26a) as well as the opposing “far” variable level (Figure 26b), which were 115-ft and 230-ft from the roundabout entrance, respectively. These distances were specified based on as-built conditions at locations where roundabout meters have been implemented.

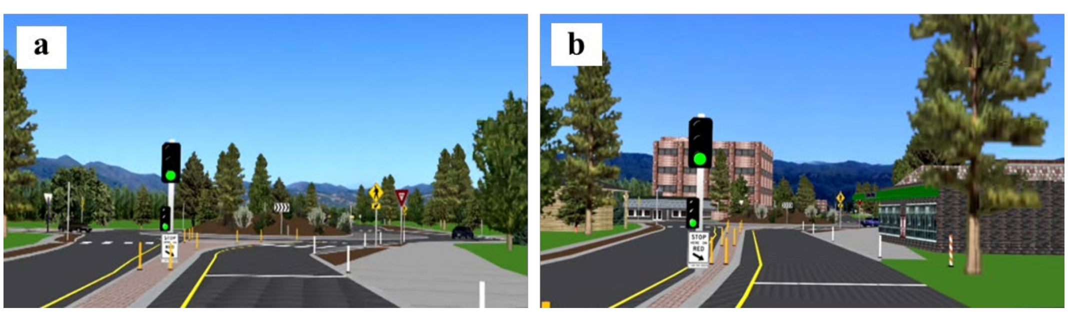


Figure 26: (a) Near and (b) Far Roundabout Metering

4.2.2 Dependent Variables

The impact of the variables of interest on driver performance was assessed using various dependent measurements. Data was recorded throughout the duration of the study using a variety of platforms, with each method being described in their respective section. Javascript coding was implemented in advance of testing to automate the parsing of scenarios to ensure uniformity across the observation windows and save time in the data reduction process. The performance measures of interest include: vehicle position and velocity throughout roundabout traversal, stress response, and visual attention.

4.2.2.1 Vehicle Position

One output from the OSU Heavy Vehicle Driving Simulator is the coordinates of the subject vehicle throughout the duration of the experiment. The position of the heavy truck across each roundabout traversal was segmented to understand driver tendencies across the different geometric configurations. This positioning data was measured from the centroid of the simulated vehicle and was recorded at 60 Hz, allowing assessment of the vehicle position 60 times every second. For simplification and conservation of computing power, coding was leveraged to automate the segmentation of the vehicles position at 10-ft intervals. Extraction of this data allows for visualization of how drivers position the heavy truck throughout traversal, as well as highlight whether they are using the provided truck aprons. Statistical analysis on the position dataset was conducted to understand deviations of the vehicles centroid from the center of lane, one method described by the Society of Automotive Engineers (SAE) standards for understanding variations in this performance measure (SAE, 2015).

4.2.2.2 Velocity

Similar to the position coordinates within the simulated environment, instantaneous velocity measurements were recorded for the subject vehicle throughout the duration of the experiment. Velocity is an important consideration as it plays a pivotal role in crash causality and intersection efficiency. Researchers correlated if other variable levels are associated with extreme velocity measurements throughout traversal and identified entering velocities when a heavy truck driver accepted a gap in circulating traffic. Javascript coding was implemented prior to the data collection process to automate the process for segmenting scenarios when drivers were approaching and traversing a roundabout. To fully understand the impact of the independent variables, circulating velocity inside the roundabout as well as approach velocity were assessed, with the latter being noted as a prevalent safety concern (Mahdalova et. al., 2016). Circulating and approach velocity will both be discussed on an individual level in Section 4.4.2.

4.2.2.3 Stress Response

Participants were fitted with electrode sensors that measure changes in electrical current of the wearer as their sweat glands respond to the presented stimuli or scenarios during the entirety of their experimental drive (Shimmer, 2018). This measurement identifies whether any specific scenarios, variables, or points in the drive were associated with an increase in driver stress response. Although certain performance measures (position and/or velocity) can be indicative of a better driver response, consideration regarding the level of comfort during traversal should also be kept at a high priority. This performance measure of driver stress response will be used in conjunction with additional analysis techniques to understand whether any scenarios resulted in unreasonably large discomfort experienced by drivers and indicate if something can be done to help mitigate those impacts.

4.2.2.4 Visual Attention

Visual attention was measured using advanced glasses fitted with cameras and infrared sensors that participants wore throughout the duration of the experiment. After completion of the calibration procedure described in Section 4.3.2, data from various camera inputs was collected and simultaneously synced to generate a visual field and quantitative measurements for fixation and saccade sequences viewed by participants. Fixations are the visual attention allocated to a particular point within the wearer's field of view, while saccades are movement of the eye between fixations (citation). This data was evaluated to understand where drivers focused their visual attention before entering the roundabout and the total time fixating at specific points before making this decision.

4.2.3 Experimental Equipment

Multiple pieces of equipment were calibrated to function simultaneously during the experimental trial to collect data for the various dependent measurements. Each of the data collection devices described in detail throughout this Section were used to collect a specific type of data that relates to the performance measures described.

4.2.3.1 Heavy Vehicle Driving Simulator

The OSU Heavy Vehicle Driving Simulator seats the driver within a quarter-cab steering and operation station and presents the opportunity to operate the heavy truck within the simulated environment. This piece of equipment also features an adjustable seat that faces three 60-inch high-definition screens to provide an expansive 210° field-of-view. Additionally, side mirrors are embedded in the screens to provide accurate visualizations of the trailer configuration and traffic following the simulated vehicle. Dashboard configuration is representative of a heavy truck on the roadway. This entire setup is shown in Figure 27.

Figure 27: OSU Heavy Vehicle Driving Simulator

4.2.3.2 Shimmer3 GSR+

GSR measurements were collected using the device displayed in Figure 28, the Shimmer3 GSR+ unit. This portable device utilizes Bluetooth to connect to an external laptop which runs the program, iMotions, used for data collection. The wearer of this device has the electrode sensors secured and calibrated at the base of their fingers (see Section 4.3.2), and the platform collects data pertaining to the electrodermal activity of the wearer's skin. This is one method for measuring stress response to various scenarios and was the piece of equipment used to evaluate this performance measure.

Figure 28: Shimmer3 GSR+ Device

4.2.3.3 Tobii Pro Glasses 3

These glasses feature four cameras seamlessly implemented into the lenses side-by-side 16 illuminators, along with a front facing scene camera to capture a 106º field-of-view (Tobii, 2023). Inclusion of prescription lenses were available on-site that could attach to the device and permitted those that typically wear prescription glasses to participate in the study without having to limit their visual acuity. Figure 29 shows the Tobii Pro device and the associated data collection unit that connects via Wi-Fi to an external laptop used to calibrate and collect the data. The system was integrated to be synced to this external platform, iMotions, the software that allowed data to be collected and assessed in real-time.

Figure 29: Tobii Pro Glasses 3 Unit

4.3 METHODOLOGY

The process that was used for recruiting subjects, calibrating the equipment, and performing data collection procedures is described in this Chapter. Participation involved meeting with individuals at the OSU Driving and Bicycling Simulator Laboratory, where study activities were carried out. Participants were compensated $80 in cash following completion of the hour-long experiment as specified by the research protocols for this study.

4.3.1 Participant Recruitment

41 individuals were recruited that met the pre-established requirements for participation in this heavy truck study. These requirements were strictly followed, with the CDL of all participants being checked prior to beginning the experiment. The recruiting process for this study utilized all resources available to generate the sample size obtained. Printed flyers were posted at various trucking organizations, common rest stops, and bulletin

boards along the I-5 corridor spanning from Portland to Corvallis, OR. Social media posts on Facebook, LinkedIn, and various OSU campus list-servs were leveraged to spread information of the study. Lastly, many agencies provided the information of the study to those within their network to generate a larger sample of drivers.

Upon arrival, participants were asked to read and acknowledge the informed consent documentation outlining the potential risks associated with participation in this study (IRB Study Number: IRB-2021-1242). This document does not provide any specific details of the study to avoid bias in driver response to the scenarios of interest, but offers information pertaining to reason, overview, and objectives of the study.

4.3.2 Equipment Calibration

The three primary pieces of equipment used throughout this study's duration had to be calibrated to each participant individually prior to beginning the data collection procedure. The eye-tracking glasses, GSR device, and OSU Heavy Vehicle Driving Simulator required slight adjustments across individuals to ensure the most comfortable environment and most accurate data collection.

Participants were fitted with the Tobii Pro 3 eye-tracking glasses and asked to secure them to their head using the provided adjustment strap. The calibration process required participants to focus their visual attention on the calibration card included with the glasses while a calibration procedure on the synchronized software was conducted. The calibration procedure ensures the syncing of the 106º field-of-view front facing camera with the four cameras located in the lenses of the glasses aimed at the eye of the wearer. The result is a live video produced leveraging both camera angles to generate a video feed that features a red indicator to display where the wearer is focusing their visual attention, which was monitored in real-time to assess whether recalibration is necessary. This video feed was monitored throughout the duration of the experiment to ensure the most accurate data collection. The successful calibration of the glasses and associated indicator is shown in Figure 30.

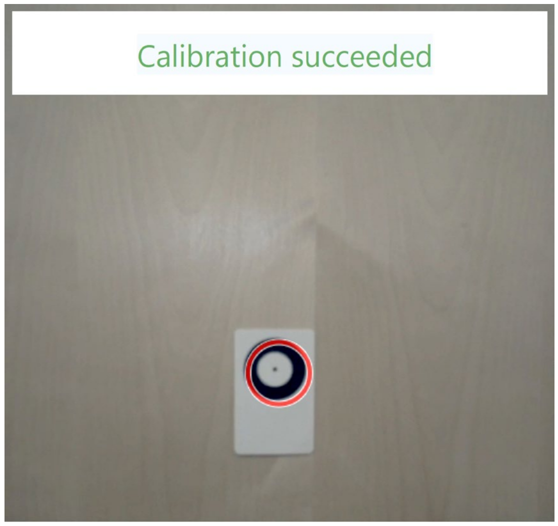


Figure 30: Successful Calibration Procedure

The GSR device shown in Figure 31 was also fitted to the participant with the electrode sensors being secured and calibrated at the base of their fingers. The straps used to secure the sensors to the participant were tightened and fit was assessed while monitoring the signal strength using the synced iMotions platform, at which point data could be captured (Cobb et. al., 2021). The Shimmer3 GSR+ unit leverages the ability to create a baseline response for each individual participant throughout the recording process and emphasizes the necessity of an accurate calibration procedure. This baseline is required for assessments to be carried out related to observed counts of peak stress response of the drivers. Automating this procedure within the device reduces the chance of a user-error and ensures consistency across participants. Additionally, it provides automated output for participants stress levels in Peaks Per Minute (PPM), which will be the unit of measurement used throughout this report.

Figure 31: Calibration of Shimmer3 GSR

Following the fitting of the external data collection devices, the OSU Heavy Vehicle Driving Simulator required slight adjustments to enhance the comfort and visual field for each participant. Adjustments made to the seat position, steering wheel angle, and side mirror angles were completed. Following these adjustments, a steering calibration executable file was run to synchronize the physical position of the steering wheel with the computerized model to accurately align and present the most authentic driving experience. Visualizations of these different calibration procedures are shown in Figure 32. In addition to the physical calibrations made to the simulator, participants were also provided a calibration drive, which was always the first simulated drive they encountered. Although no data was collected during this portion, it allowed participants the opportunity to get acclimated to the simulated environment by driving on a roadway section similar to what they will experience in the experimental drive, but without any of the experimental variables of interest. This part of the procedure allowed the driver to get familiar with aspects such as the turning and speed of the vehicle, while providing the opportunity to assess the risk of experiencing simulator sickness.

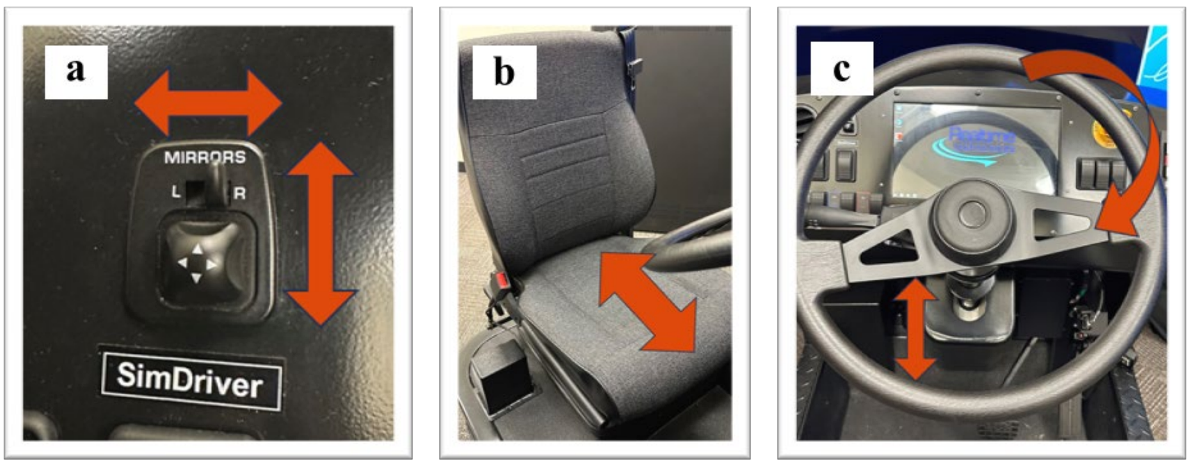


Figure 32: Calibration of Shimmer3 GSR

4.3.3 Experimental Drive

Participants were exposed to 24 intersections of interest, across which they experienced all variable levels. These experimental scenarios were spread across four different drives or "grids" with each grid having six intersections. This allowed for randomization of the experiment for each participant and present variables in differing orders, helping to mitigate the possibility of learning effects from occurring. Each track was designed to take five minutes to complete. Due to the delay in waiting for gaps at the congested roundabouts and the slower nature of heavy trucks, each track took participants between seven to ten minutes to complete. Directions were provided for turning maneuvers and navigation along the roadway. Notably, the heavy truck drivers were instructed to proceed straight at roundabout intersections; This aligns with the most common turning movement observed in the field data collected.

Prior to beginning the experimental drive, participants were provided with a diagram of the WB-67 truck that was modeled and calibrated for the simulated environment and were instructed to operate the vehicle the same as if they were driving it in the as-built environment. This diagram provided the length of the vehicle cab and trailer as well as the axle configuration to help participants visualize their vehicle before beginning the simulated drive.

4.3.4 Data Extraction and Assessment

A combination of Javascript and RStudio coding provided efficient and reliable extraction of the data generated while ensuring observation windows were kept consistent throughout experimental scenarios. The OSU Heavy Vehicle Driving Simulator collects data at 60 Hz, which results in instantaneous measurements being exported 60 times per second. The resulting output from each drive necessitated computing power to extract, visualize, and analyze the results provided the large file size for each drive. RStudio and Microsoft Excel were used to format the data, perform in-depth assessment, and conduct statistical testing procedures segmented by the variable types that were studied. The steps include extraction and formatting of data, visualization across variable levels, statistical analysis for differences, and assessment of the results. Two performance measures of interest were extracted from this data: The coordinates of drivers to generate positioning data, and the velocity both on approach to, and while traversing the roundabouts.

The linear distance upon entering the roundabout to the exit of the roundabout was approximately 177-ft in the traditional and taper variable levels, while it was 324-ft in the elliptical configuration. These distances were kept in mind when generating the data used for the positioning charts displayed in Section 4.4.1, as the location of participants throughout traversal was marked every 10 feet. After identifying the position at 10-ft increments, distance from the center of the roundabout was calculated to generate a universal method for assessing lateral position in the lane. Participant offset from the roundabout centerline was averaged for *each* individual participant. A trendline was generated for each participant which displays their average position throughout the roundabout traversal separated by the geometric configuration to develop and understand how driver tendency may change depending on the configuration presented.

A similar process was used to assess approach velocity, where the instantaneous velocity of participants was extracted at 30-ft increments. Data was assessed at each incremental observation to generate trendlines formulated by boxplot descriptors and average velocity at each point along the traversal. This allowed for a better understanding of how velocity varies as a function of distance during approach. Figure 33a provides a visualization of how the data was segmented to assess participants variations in velocity while approaching the intersections, while Figure 33b describes the point where their circulating velocity was assessed. This segmentation allowed for separate evaluations to be made, where the impact of roundabout metering can be assessed using approach velocities, while evaluation of participants circulating velocity will highlight any notable differences when traversing roundabouts with varying geometric configurations.

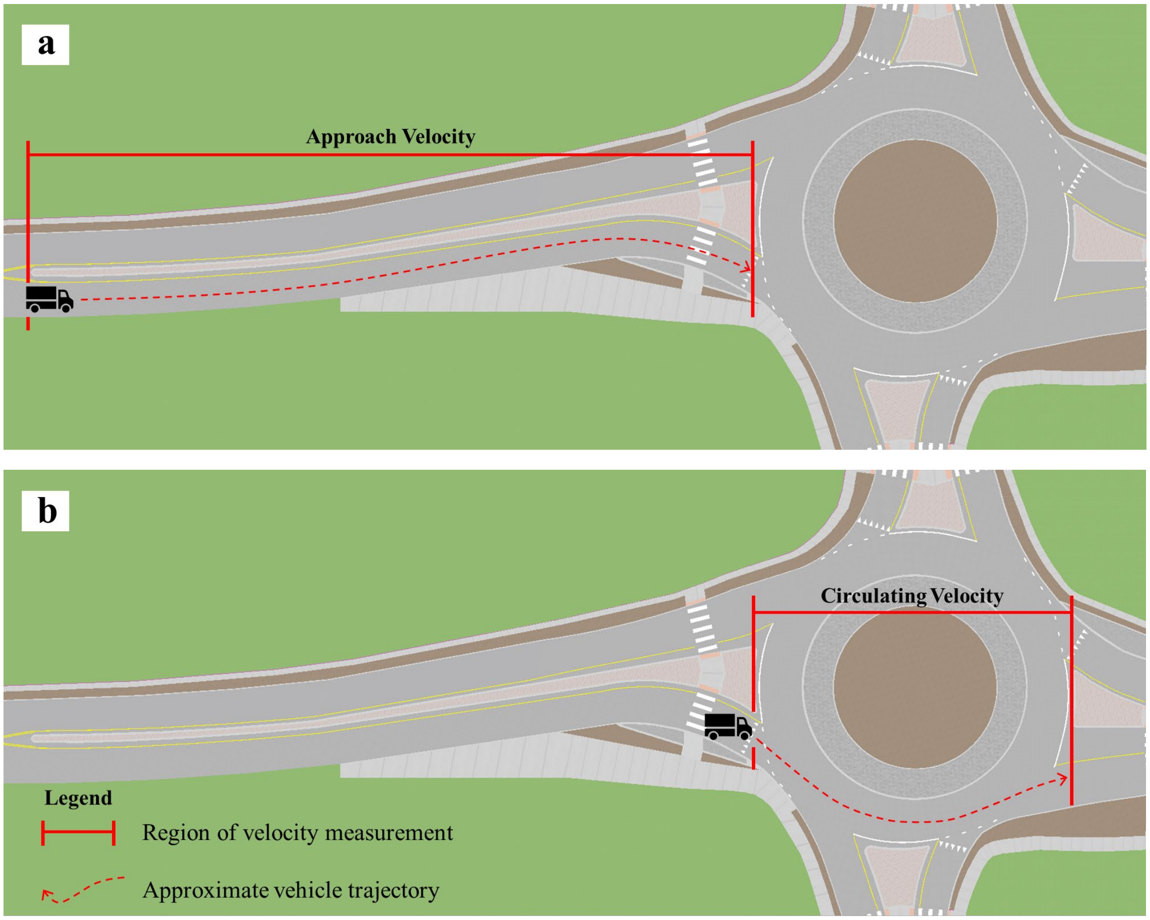


Figure 33: (a) Approach Velocity and (b) Circulating Velocity Zones

Unlike the datasets generated from the driving simulator, the eye-tracking and GSR data required the use of the specific software, iMotions, to perform the data reduction process. As mentioned, Javascript coding was utilized to automatically parse scenarios of interest, so each observation window was kept consistent across scenarios. Figure 34 shows how this marking of scenarios appeared in the reduction process, where the bottom axis displays the time and scenario number being observed. The reduction process for eye-tracking fixations required generation of Areas of Interest (AOI), which were coded and manipulated within the iMotions platform to define specific objects in the participants field-of-view that may be of interest. This process evaluated common AOI's at the roundabout by which participants fixated their visual attention while deciding on when best to enter. Adjustments to the position of each AOI were made incrementally, modifying their exact position in the field-of-view by re-evaluating the video every 50ms. Review of this rate of adjustment was found to be a good balance that allowed for the accurate capture of glances by participants as they searched for gaps in circulating traffic. More finite adjustments for visual attention assessment can be used but diminishing returns will be observed at the expense of additional time required. Figure 34 shows how AOIs are coded into the video data collected within the iMotions platform while incremental adjustments to the locations within the visual scene of these AOIs were conducted to develop the visual attention dataset.

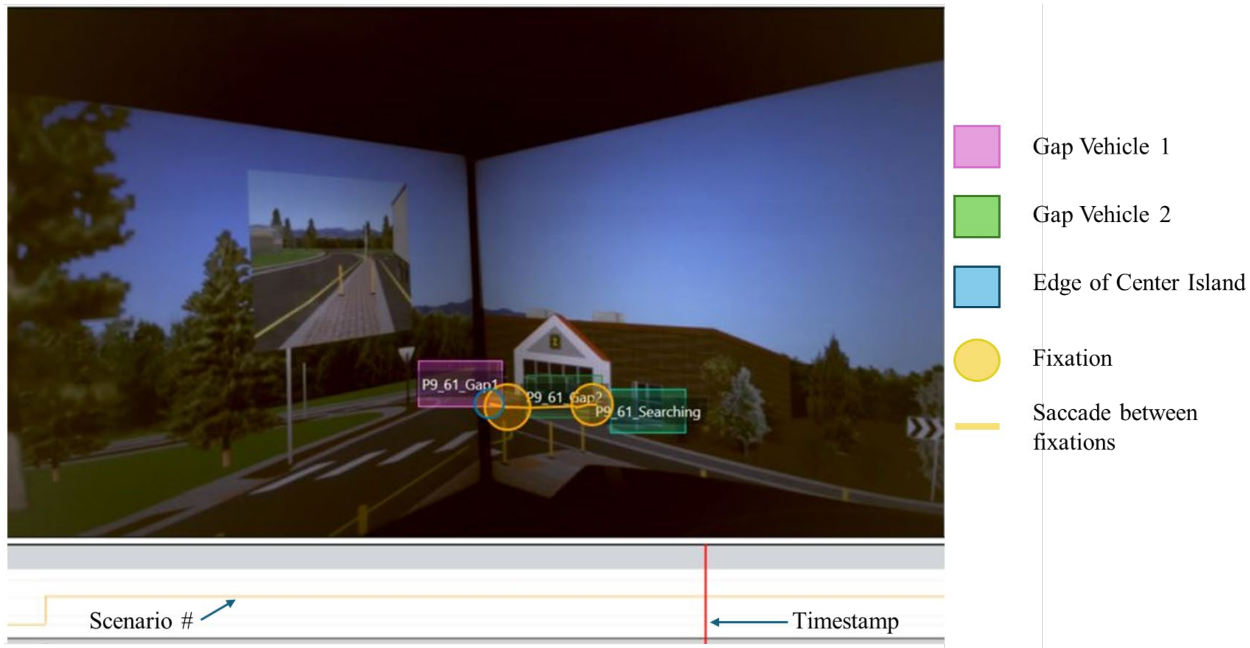


Figure 34: AOI Reduction Process

GSR response was assessed using a Peaks Per Minute (PPM) measurement. This unit of measurement provides a frequency count of the number of times the wearers stress response "peaked" above their baseline skin conductance levels during a particular interval of time. Figure 35 describes the stress response of participants disaggregated into three segments: on approach to the roundabout, while searching for a gap to enter the roundabout, and while circulating within the roundabout. It should be noted that although the distance traveled in each zone varies, using PPM balances stress levels based on the duration of the observation window; Therefore, this unit of measurement accounts for variations in time allowing for consistent comparisons to be made.

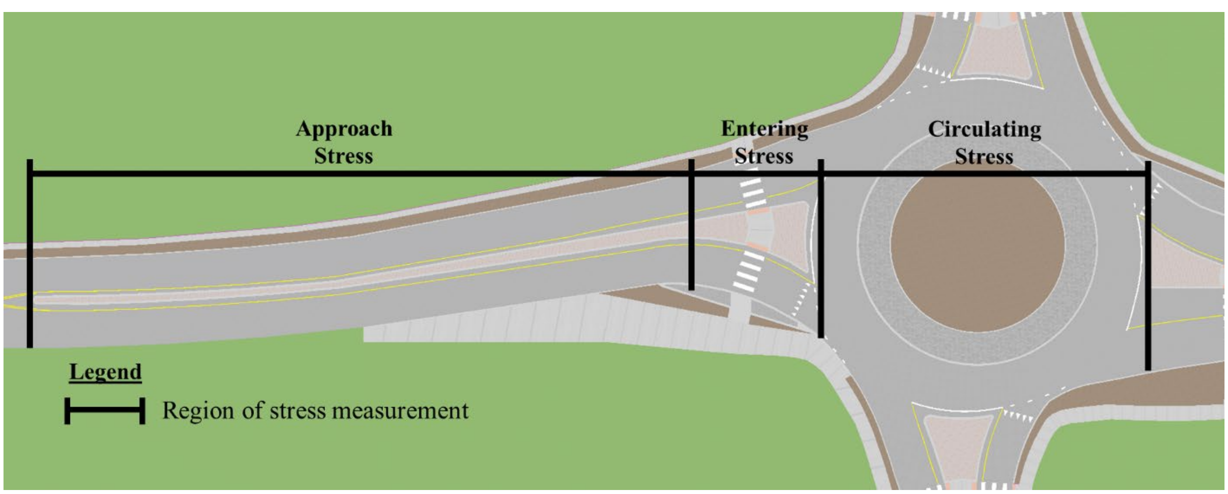


Figure 35: Stress Measurement Zones

4.4 RESULTS

Findings regarding vehicle position, approach and circulating velocity, visual attention, and stress response are reported in the following Chapter. Visualization and statistical comparisons were performed on the data as described in the following sections. The results described were taken from the sample of participants that did not experience simulator sickness, so as to include only responses that are representative of more authentic behavioral responses to the various experimental scenarios.

4.4.1 Position Results

The lateral position of the centroid of the heavy truck as participants traversed the various roundabout geometries is displayed in Figure 36. Each trendline describes the average position of each individual participant measured from the offset of the centerline every 10 feet for each geometric configuration. The resulting charts demonstrate how drivers tend to position themselves throughout traversal. It is notable that when participants traversed the elliptical design (Figure 36c), they tended to position themselves in the middle of the lane, whereas use of the truck-apron within the roundabout is more prevalent while traversing the traditional and tapered roundabout configurations (Figure 36a and Figure 36b, respectively).

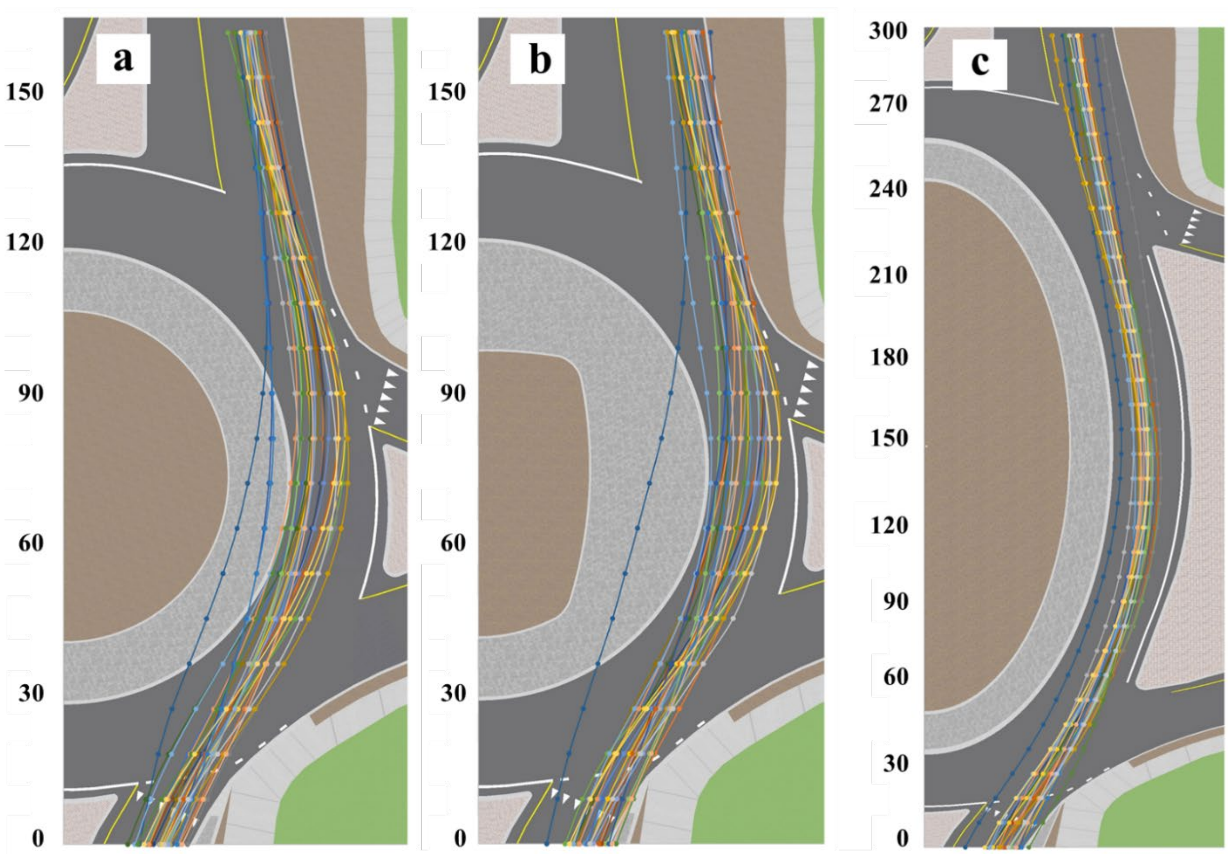


Figure 36: Position During Roundabout Traversal in (a) Traditional (b) Taper (c) Elliptical Configurations

One method for assessing lateral position in a driving simulator setting is evaluation of the drivers center of gravity in relation to the lane centerline (SAE, 2015). This technique was followed to better understand deviation from lane and perform statistical analysis on the position of drivers throughout traversal of roundabout configurations. The trendline data developed to visualize trajectories of each participant on an individual level was reduced to discern the lateral offset from the circulatory roadway centerline, resulting in a singular point describing the average centroid position of all participants across the geometric variables of interest. The center of lane, average centroid position, and lateral distance between the two are displayed for the traditional, tapered, and elliptical roundabout configurations in Figure 37a, 37b, and 37c, respectively. Inspection of these plots highlights how driver trajectories followed a similar path to the lane centerline when traversing the elliptical configuration, whereas larger deviations are observed in the traditional and tapered configurations. Additionally, the max average offset occurs at different points along each configuration, indicating that variations and driver tendencies exist as they move throughout the roundabout depending on the configuration being presented. The max average offset value was also approximately 2.75 and 2.45 times larger in the traditional and tapered configurations (6.76-ft and 6.00-ft) as compared to the elliptical configuration (2.45-ft).

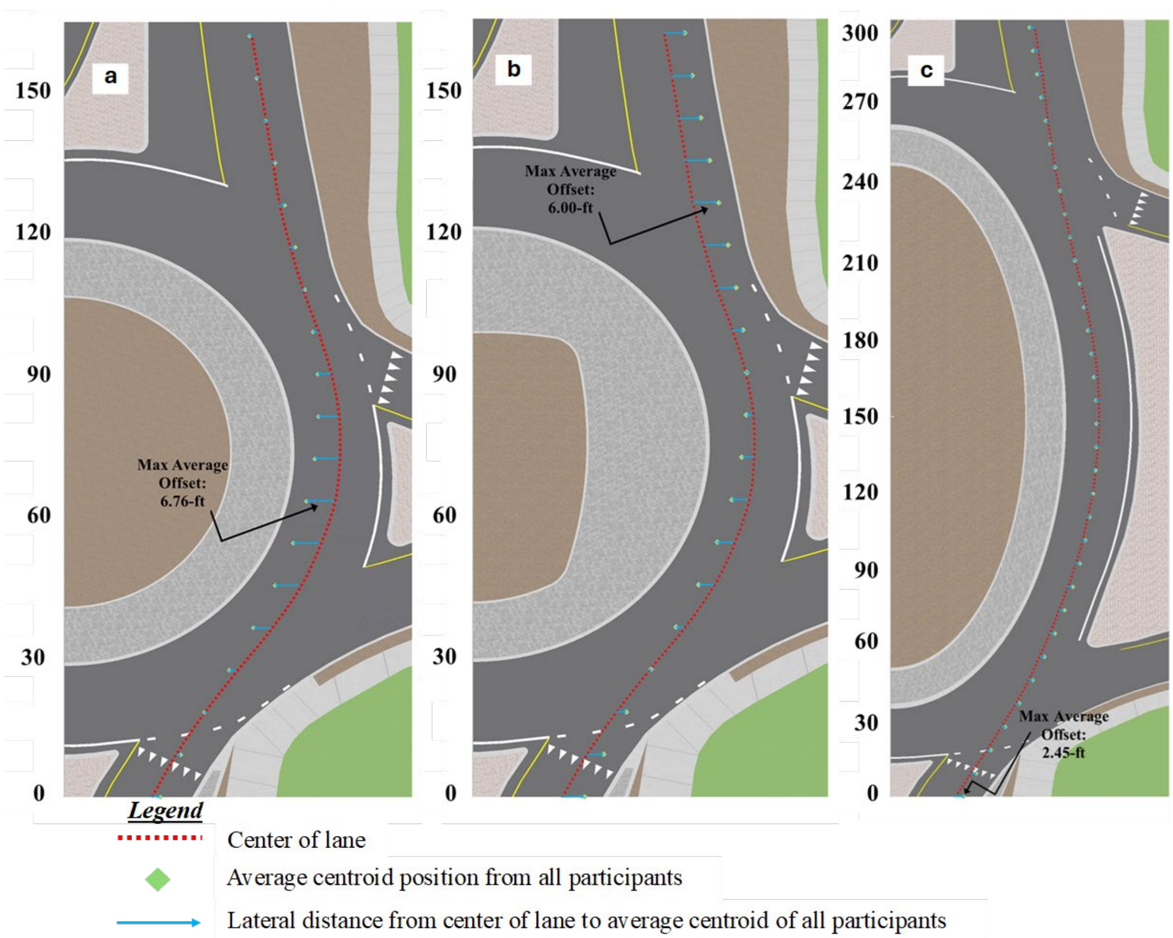


Figure 37: Average Offset from Lane Center in (a) Traditional (b) Tapered and (c) Elliptical Configurations

Using the data related to the offset from lane centerline, statistical analysis was conducted to generate a deeper understanding of the magnitude of differences observed across geometric configurations. Analysis of Variance (ANOVA) was selected as the statistical test given the study design, while Tukey's Honestly Significant Difference (HSD) was also implemented to compare the three configurations and assess for differences in lateral position (Ramsey & Shafer, 2013; Fleskes & Hurwitz, 2018). The results of the ANOVA test revealed a statistically significant result, with a **p-value < 0.001**. Due to the low p-value observed, Tukey's HSD was conducted as a post-hoc test to better understand the magnitudes of differences that exist across the configurations. This testing method was selected due to the ability to compare the differences in means of values between two-selected variable levels (Nanda et. al., 2021). The results of Tukey's HSD comparing the refined differences in configurations are displayed in Table 20. From this test, all comparisons across geometric configurations have a statistically significant difference when assessing distance from center of lane.

The method used for assessing offset from center of lane, which followed SAE standards, indicates that negative differences are associated with positions further to the left of lane center, while positive difference are associated with distances further to the right of lane center. Table 20 describes that participants tended to maintain a lateral position situated further to the left side of the travel lane while traversing the traditional roundabout configuration, driving approximately 1.1-ft and 0.6-ft further to the left as compared to the tapered and elliptical configurations, respectively. Alternatively, when traversing the tapered roundabout configuration, drivers had the tendency to position themselves further to the right side of the travel lane, maintaining a position 0.5-ft further from lane center as compared to the elliptical configuration.

Table 20: Results of Tukey's HSD on Lateral Offset from Lane Center

Geometry (i)	Compared to (j)	Difference (ft)	p-value	Significance
Traditional	Tapered	-1.092	<0.001	***
	Elliptical	-0.626	<0.001	***
Tapered	Traditional	1.092	<0.001	***
	Elliptical	0.466	<0.001	***
Elliptical	Traditional	0.626	<0.001	***
	Tapered	-0.466	<0.001	***

***Significance < 0.01; **Significance < 0.05; *Significance < 0.1; n.s. Not Significant.

4.4.2 Velocity Results

As mentioned, velocity was assessed in two parts, approach and circulating velocity, to better understand variations in these two zones. These results are described in the following subsections.

4.4.2.1 *Approach Velocity*

Provided that one aspect of the roundabout metering variable was the location of the signal head being placed near (115-ft) and far (230-ft) in relation to the roundabout entrance (yield-markings at circulatory roadway), boxplots describing the incremental velocity observed on approach to the roundabout entrance was visualized in Figure 38 for a) Near Meter, b) Far Meter, and c) No Meter scenarios. The chart displayed in Figure 38a describes driver velocity on approach to the Near Meter signalization (115-ft from roundabout entrance), where drivers tended to reduce their velocity in advance of the roundabout meter. Similarly, the same trend is observed for Far Meter scenarios (230-ft from roundabout entrance), with a slowing in velocity observed that begins shortly after entering the zone where these observations are being made. The maximum values observed in these charts highlight that certain scenarios may have featured non-compliance from drivers in response to the Near and Far meters, as speeds approaching 25mph can be observed at locations just 5-ft in advance of the signalization. Similarly, the opposite may also be observed where drivers began reducing their speeds as far as 40-ft in advance of the Far Meter scenarios.

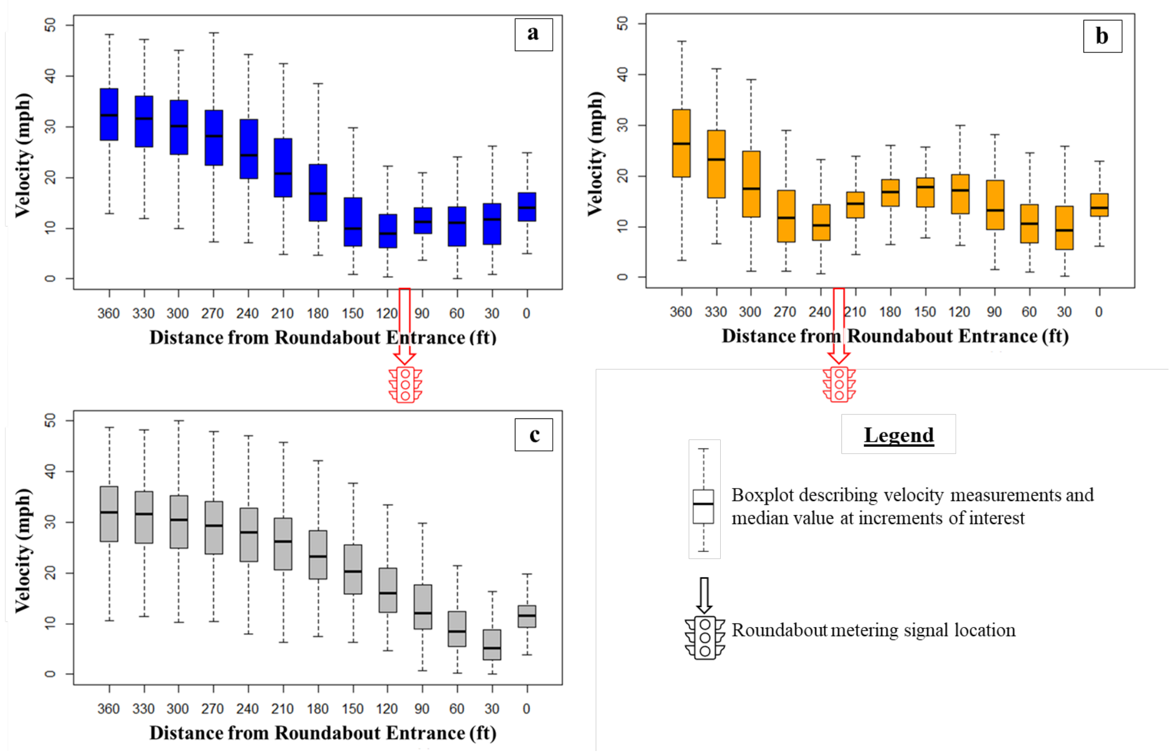


Figure 38: Boxplot of Incremental Velocities on Approach to Roundabout when Traversing (a) Near Meter (b) Far Meter and (c) No Meter Variable Levels

After development of the charts displayed in Figure 38, the average velocity at each incremental measurement was extracted and a trendline was developed to visualize velocity differences based on the roundabout meter location. Figure 39 shows the average velocity at 30-ft increments beginning 360 ft upstream of the yield marking in the various roundabout metering scenarios. Although not included in this Figure, the near (115-ft) and far (230-ft) roundabout meters were present in these variable levels, which allows for an interpretation of the driver's velocity response at different locations. Decelerations can be observed proximate to the near and far roundabout meters as stops were required here as well as a consistent reduction in velocity when drivers were approximately 30-ft from the roundabout entrance. An acceleration is observed starting 30 ft upstream of the yield markings as vehicles prepare to enter the roundabout in all scenarios. This acceleration allowed participants to enter the roundabout at an increased speed to merge with the circulating traffic. Scenarios that featured a "Far" roundabout meter had demonstrated more variability as compared to the near or no meter scenarios. Due to the distance from the entrance in the Far Meter condition, participants tended to increase their speed after the meter to approximately 18 mph, before decelerating again just before entering the roundabout. A similar evaluation was conducted to assess the impact of the roundabout geometric configuration on average approach velocity in the presence of metering and non-metering scenarios, but the analysis produced no significant variations in approach velocity profiles. Figure 39 visualizes the average velocity throughout the approach for each geometric variable level and can be found in Appendix B, Section 6.2.

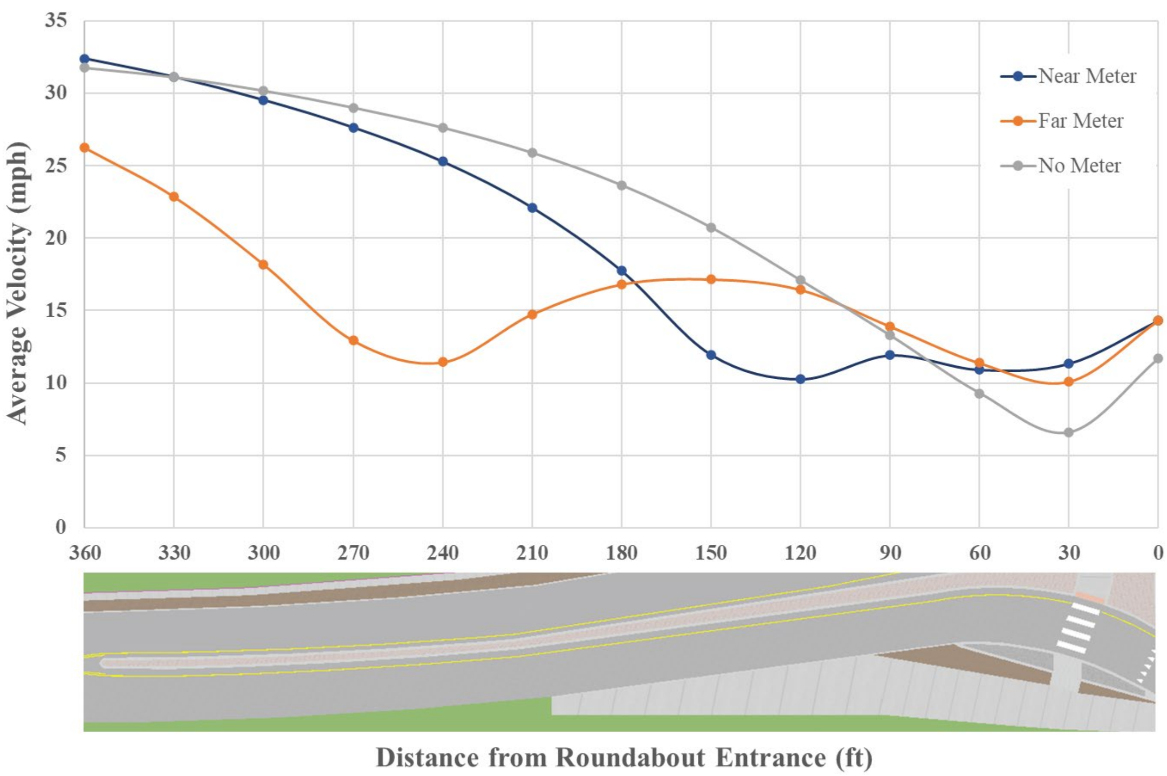


Figure 39: Approach Velocity by Metering Variable

4.4.2.2 *Circulating Velocity*

The velocity plots in Figure 39 show that drivers tended to enter roundabouts with a velocity between 10-15 mph, thus assessing the circulating velocity is necessary to understand behavior beyond this point. Figure 40 provides boxplot visualizations of participants velocity once inside the roundabout, separated by the geometric configuration they were traversing. The average velocity while participants traversed the traditional and tapered configurations were similar to the entering velocity at approximately 16 mph, and no statistical significance was observed upon performing an ANOVA paired with Tukey's HSD test. Alternatively, driver velocity in the elliptical configuration was higher, featuring a mean value of 20.4 mph. The same statistical test was conducted to compare this variable level with the traditional and tapered designs and a statistically significant result was found with a p-value of < 0.001, indicating velocities in the elliptical design were larger than the other geometries by 4.5 mph and 4.0 mph when compared to the traditional and tapered designs, respectively. These values are listed in Table 21, which describes the results of Tukey's HSD which compares all geometric configurations.

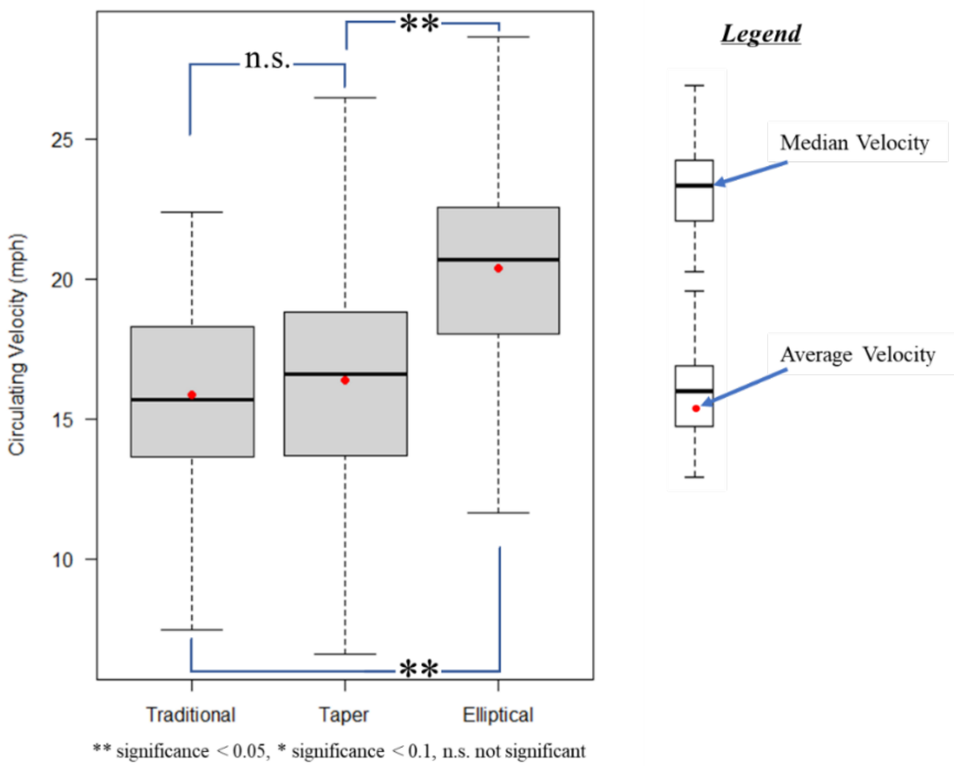


Figure 40: Box Plots of Circulating Velocity for Three Geometric Configurations

Table 21: Results of Tukey's HSD on Circulating Velocity by Geometric Configuration

Geometry (i)	Compared to (j)	Difference (mph)	p-value	Significance
Traditional	Tapered	-0.542	0.673	n.s
	Elliptical	-4.542	<0.001	***
Tapered	Traditional	0.542	0.673	n.s
	Elliptical	-4.00	<0.001	***
Elliptical	Traditional	4.542	<0.001	***
	Tapered	4.00	<0.001	***

***Significance < 0.01; **Significance < 0.05; *Significance < 0.1; n.s Not Significant.

4.4.3 Visual Attention Results

While entering the roundabout, participants encountered multiple (two or four) circulating vehicles. To safely merge into this conflicting traffic, participants had to focus their visual attention on the vehicles to identify an acceptable gap length. This portion of the driving task was segmented and extracted to analyze how the visual attention was allocated to the circulating traffic. Specifically, how long did participants glance at the critical gap vehicles when separating based on this variable level (5.4 seconds versus 6.4 seconds). Figure 41 provides a reference for the two gap vehicles (termed Gap 1 and Gap 2) and the measurement of gap length between these adjacent vehicles in the circulating roadway. The vehicles represented in this image do not display the critical gap length, instead they are used to demonstrate more clearly how the Gap vehicles were defined as well as the gap length between them.

Figure 41: Example of Gap Vehicles and Gap Length Measurement in Driving Simulator

Figure 42 plots the Total Fixation Duration (TFD), which can be defined as the total time participants spent fixating on the Gap 2 vehicle (as shown in Figure 41) before entering the roundabout. This chart indicates that when the critical gap length is 5.4s, participants spent longer looking at the vehicle, whereas a critical gap length of 6.4s was associated with lower visual attention being allocated to this vehicle. The results suggest that when a larger gap is present (i.e., critical gap of 6.4 s), participants made the decision to enter the roundabout quicker and therefore focus less visual attention to judge the gap. This lower TFD value emphasizes that when a larger gap length is provided, drivers make the decision to enter more quickly and do not allocate as much visual attention judging whether the gap length is adequate.

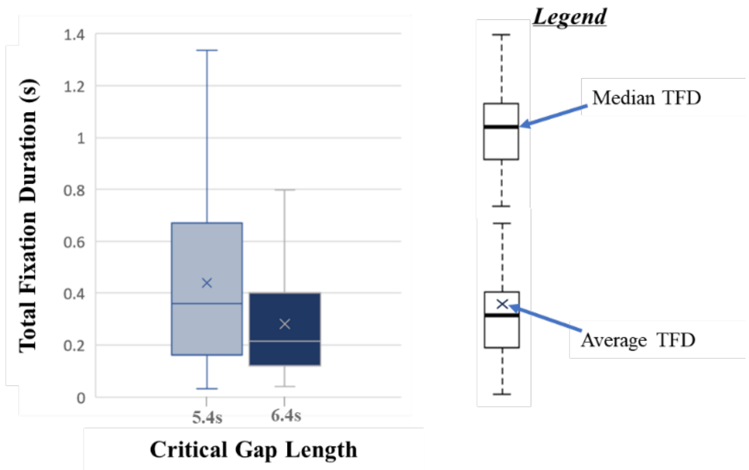


Figure 42: TFD on Critical Gap Vehicle(s)

4.4.4 GSR Results

The GSR measurements for participants were evaluated in three segments to fully understand stress levels across the approach, entrance and circulating elements of the roundabout. Figure 43 emphasizes the increase in stress response as drivers traversed the different zones of interest, with driver peaks/min being most frequent once they were within the circulating roadway of the roundabout. One notable result observed in this chart is the large count of observations during the “entering” zone of the roundabout traversal outside of the upper quartile. This finding indicates that there are a portion of drivers that experienced the greatest stress response in this zone.

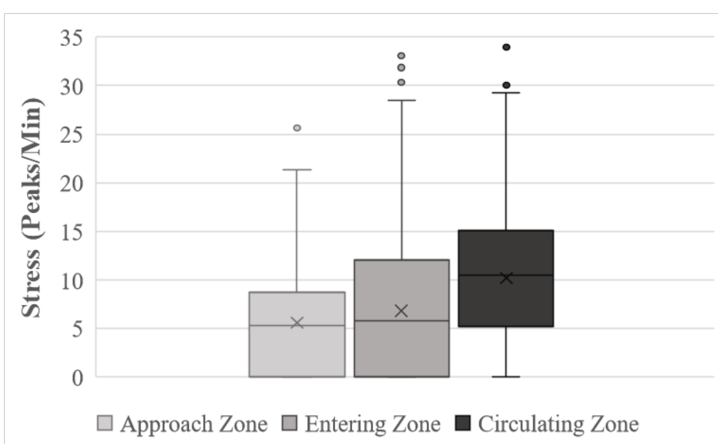


Figure 43: GSR Response in Various Zones of Interest

Provided that driver discomfort was greatest once they were within the circulating roadway, additional plots were developed to understand if this was correlated with the geometric variables of interest. Comparison of the stress response while circulating the different geometric configurations is displayed in Figure 44. Visual inspection suggests that driver stress was greatest while maneuvering through the traditional roundabout configuration, with a mean and median of approximately 12 peaks/min. Conversely, drivers experienced lower stress while traversing the elliptical design with an average of approximately 9 peaks/min.

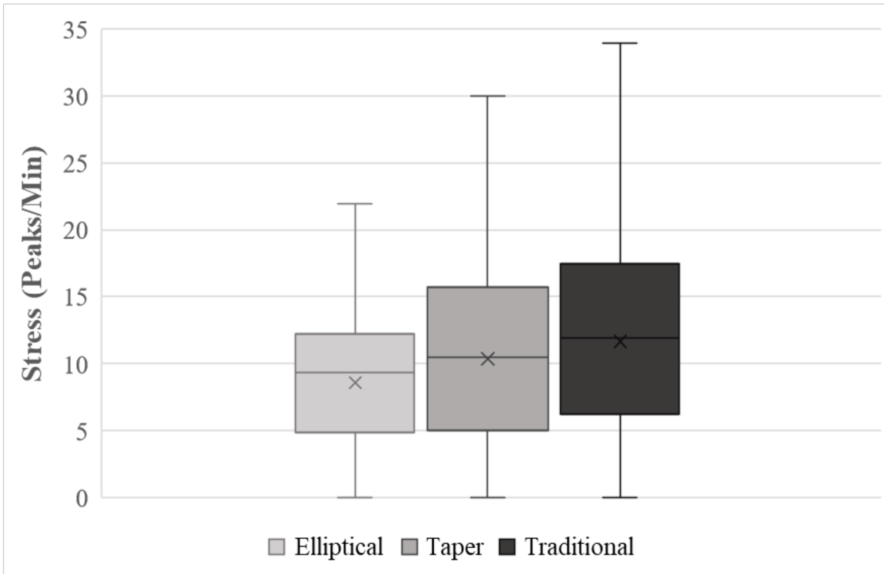


Figure 44: GSR Response to Geometric Alternatives while Circulating Roundabout

Further assessment was conducted to better understand the lower stress experienced by drivers when traversing the elliptical design as compared to the traditional and taper configurations. Statistical tests revealed significantly lower stress response (measured in peaks/min) in the elliptical scenarios, while participant stress responses increased in the traditional and taper configurations. Figure 45 highlights how the data may be associated with a slight skew in normality when assessing the elliptical box and whiskers plot, with the mean value being slightly lower than the median – This suggests there were more observations where participants experienced a greater stress response and the scenarios associated with this stress increase should be considered. In addition to these plots, the variations across geometric configurations are described in Table 22, which shows the results of Tukey's HSD test.

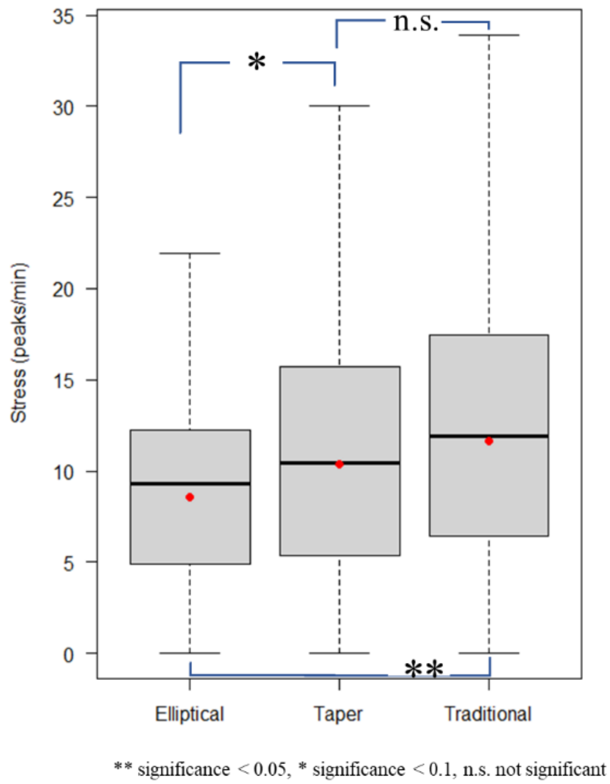


Figure 45: Significance Results on Circulating Stress Response across Geometric Alternatives

Table 22: Results of Tukey's HSD on Stress Response

Geometry (i)	Compared to (j)	Difference (ppm)	p-value	Significance
Traditional	Tapered	1.305	0.291	n.s
	Elliptical	3.080	0.01	**
Tapered	Traditional	-1.305	0.291	n.s
	Elliptical	1.775	0.10	*
Elliptical	Traditional	-3.080	0.01	**
	Tapered	-1.775	0.10	*

***Significance < 0.01; **Significance < 0.05; *Significance < 0.1; n.s Not Significant.

4.5 HEAVY VEHICLE SIMULATION CONCLUSIONS

The present study leveraged the OSU Heavy Vehicle Driving Simulator to assess the impact of different roundabout geometries and traffic control devices on the maneuverability of a simulated WB-67 truck. This process included the recruitment of licensed heavy truck drivers to gather data pertaining to position, velocity, visual attention, and stress when traversing different roundabout scenarios in a consistent and controlled environment. The resulting evaluation of these performance measures indicates that discrepancies are present when comparing various geometries and the presence of roundabout metering.

Vehicle trajectories generated from the position data indicate that the use of the inner truck apron is most frequent when traversing the traditional configuration, where six of the drivers encroached this zone on average. Use of the inner truck apron was less prominent when drivers maneuvered through the elliptical design, with none of the drivers encroaching this zone upon evaluation of their average position. Further evaluation of the lateral offset indicated that participants maintained a position significantly closer to the center of lane while traversing the elliptical configuration, where the largest deviation from lane center was 2.45 to 2.75 times less than the traditional and tapered configurations. Statistical analysis revealed that lane position variability across the elliptical configuration was minimal (2.45-ft maximum), and drivers consistently maintained a position near the center of lane throughout traversal. Responses to the tapered roundabout configuration featured the most inconsistent position, with the average offset from lane center being further to the left within the circulatory roadway, then transitioning to be further to the right when exiting the circulatory roadway. The traditional roundabout configuration showed improvements over the tapered design, as drivers tended to maintain a position to the left of lane center throughout their traversal, but it should be considered that this configuration was associated with the largest deviation from lane center (6.76-ft).

The position charts show that in the tapered roundabout scenarios, there was a tendency for heavy truck drivers to maneuver their vehicle so it was closer to the outer edge when exiting the roundabout, which may be a result of the visual acuity of the design, where the path of travel is more direct due to the nature of the central island. Keeping this in mind, if this design were to be implemented, it may be necessary to include an exit apron to accommodate the lack of turning at the end of traversal. Although less common, implementation of this design configuration is only warranted if, “Entrance and exit aprons should only be used when all other design options have been evaluated and they are the only reasonable alternative to provide accommodation for large vehicles through the roundabout” (ODOT, 2023).

Assessment of additional performance measures revealed that the elliptical design was associated with significantly higher circulating velocities, as well as significantly lower stress when evaluating the statistical comparisons across the geometric variable levels. This indicates that drivers were able to progress through the roundabout at increased operating speeds (4.00 to 4.52 mph greater), while also experiencing significantly lower stress measurements throughout the traversal. Stress responses in the elliptical configuration featured peaks/min of approximately 3.0 and 1.7 less than the traditional and tapered designs, respectively. Driver response across the traditional roundabout and the tapered roundabout configurations were not as distinct and featured similar responses in terms of circulating velocity and stress response, both of which were statistically insignificant when compared. These findings suggest that geometric modifications made solely to the center island of a roundabout do not elicit large changes in velocity or stress response.

The location of the roundabout meter in relation to the roundabout entrance shifted participant approach velocity. Assessment of the average approach velocity trendlines during the Far Meter scenarios indicate that participants had varying speeds throughout the traversal, requiring constant acceleration and deceleration throughout the approach. This fluctuation can create additional difficulties for drivers, other roadway users, as well as influence unpredictable driving behavior along the approach. Therefore, it may be best to avoid using the Far Meter position (230-ft) from the roundabout entrance at locations that feature high heavy truck volumes. The Near Meter scenarios performed better, with a consistent velocity being maintained after stopping in response to the signalization 115-ft from the roundabout entrance. When comparing both metering locations to the No Meter scenarios, they all feature a velocity decrease 30-ft in advance of the roundabout entrance. This indicates that regardless of the roundabout meter position, behavior in this zone is relatively consistent.

Considering all performance measures evaluated, the geometric configuration of the roundabout appears to influence heavy truck driver position, circulating velocity, and stress response. These impacts are more prominent when evaluating configurations that have modification made to the overall roundabout shape (i.e., elliptical), while geometric modifications to the central island (i.e., tapered) did not generate as significant of response. The elliptical configuration was associated with improved responses from drivers when considering position and stress levels, as well as a higher circulating velocity. The consistent positioning and predictability of the heavy truck driver in the center of lane can also make it easier for other road users at the roundabout, while the lowered stress response may indicate the potential for increased comfort for heavy truck drivers on the roadway. This design may be preferred at locations with high through-moving truck volumes given these operating improvements. This configuration could result in higher speeds for *all* vehicles (especially for familiar drivers) on the mainline. As evidenced by the circulating speeds of over 20 mph. The characteristics of the elliptical roundabout (less deflection and different radii) may present additional challenges for users entering from the different approaches. These challenges may include increased difficulty for vehicles entering the roundabout from side-street approaches, as well as increased safety risks at pedestrian crossings.

One advantage of the traditional roundabout is the uniformity in design aspects within the circulatory roadway. This promotes consistent speeds throughout the circulatory roadway and across all users when negotiating entrance regardless of the entering leg. The traditional roundabout configuration and the tapered roundabout configuration did not have much differentiation, although the positioning results reveal that the traditional roundabout may have a slightly better performance given the ability to maintain a position closely resembling the center of lane, relative to the tapered design. The traditional design was associated with a slightly increased stress response, but not a significant amount as compared to the tapered design.

Implementation of roundabout metering was found to impact driver approach velocity and behavior. In the metering scenarios, the entering velocity at the roundabout was higher than the No Meter scenarios and indicates that heavy truck drivers were better able to judge the acceptable gap in circulating traffic and make more accurate predictions on when best to enter the roundabout. Therefore, implementation of this design may result in better gap recognition for heavy trucks and improved efficiency. Despite this outcome, the approach velocity results revealed that the Far Meter (230-ft) may be too distant from the roundabout entrance and results in velocity behavior that tends to change and vary greatly during the approach. Therefore, this position is not recommended given the unpredictability of this behavior. The Near Meter scenario was associated with a steady increase in velocity and resulted in heavy truck drivers being able to predict the entering capacity between adjacent legs of the roundabout. This location, 115-ft, has the potential to function well and improve operational efficiency during highly congested periods. This may be a viable option to provide better opportunities for heavy truck drivers to enter congested roundabouts.

5.0 CONCLUSIONS

The three studies described throughout this report emphasize the entering ability of various heavy truck classifications at congested roundabouts, how to best model heavy truck access using VISSIM, and evaluation of potential improvements. The conclusions made regarding consideration for practice are as follows.

The field results showed that WB-67 trucks were the most common vehicle type observed and aligns with use of this classification as a design vehicle. The findings from the critical gap analysis emphasized how larger vehicles require a longer critical gap to enter the roundabouts as compared to passenger cars and provide insight to the magnitude of the difference. Observed critical gap lengths were between 5.4 seconds and 6.4 seconds for heavy truck classifications ranging from the WB-40 to the WB-92D. Additionally, the critical gap of a WB-40 vehicle is about two times larger than a passenger car, whereas the critical gap for a WB-92D is nearly three times larger than that of a passenger car. These differences emphasize how heavy truck classification impacts entering ability and that the percentage breakdown of heavy truck classifications should be considered when assessing field sites of interest.

Microsimulation analysis using VISSIM revealed that the North America default heavy truck fleet is not an accurate representation of the heavy truck proportions using roundabouts in Oregon. The North America default heavy truck fleet is comprised of smaller heavy trucks, with 91% of heavy trucks being WB-50 or smaller. This underrepresents the larger classifications and neglects the double-trailer designs such as the WB-67D and WB-92D observed in the field. Additionally, VISSIM simulation revealed that the yielding method that is used within the model impacts gap acceptance tendencies and behavior. In scenarios where fidelity is of utmost importance, priority rules were found to be the best modeling technique in terms of gap acceptance modeling as compared to conflict area control techniques. It should be noted that priority rules require more time and computing power to achieve the improved model of heavy truck behavior described.

The heavy truck driving simulation study compared three geometric configurations to assess the performance of each design. It was revealed that roundabout geometry impacts driver behavior and that preferred modifications are dependent on the objectives at specific locations. The elliptical design was associated with decreased stress for drivers but may not be suitable at locations where higher speeds are already an initial concern. Additionally, use of the inner truck apron was shown to be more common in the traditional and tapered designs. This knowledge could be utilized when locations have abnormally high influxes of larger heavy truck classifications. Placement of the roundabout metering was found to influence driver's approach velocity, with the far (230-ft) meter resulting in various acceleration and deceleration as compared to the near (115-ft) meter position. Consideration should be given to the placement of a roundabout meter, especially on the roundabout legs with large heavy truck volumes. At locations where this TCD is implemented, all approach legs should include a roundabout meter, or it should be limited to the approaches that do not have large heavy truck volumes.

These considerations for practice can be used in consideration of the types of heavy trucks using these facilities, and how to best model future operations using simulation. Additionally, best options for improvements may depend on the objectives at specific locations and require different geometric or TCD implementation to achieve the desired results.

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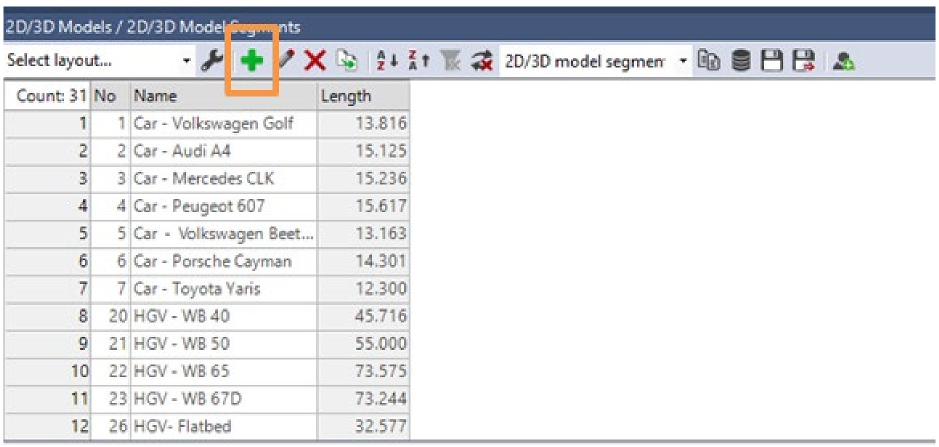
7.0 APPENDIX

7.1 APPENDIX A

7.1.1 Parameters used for Larger Vehicle Models in VISSIM

To create the WB-92D and WB-100T heavy truck configurations within VISSIM, the following steps can be used:

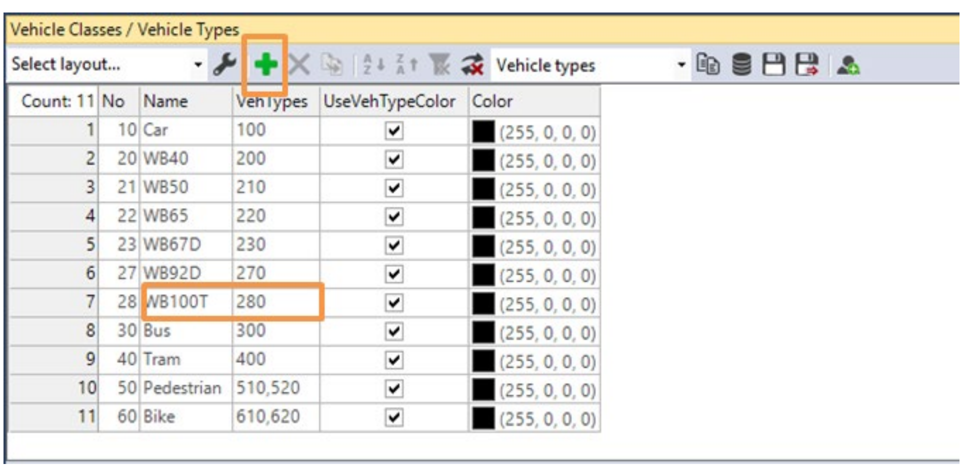
- *Step 1:* Base Data → 2D/3D Models → Add


2D/3D Models / 2D/3D Model Segments

Select layout... 2D/3D model segments

Count: 31	No	Name	Length
1	1	Car - Volkswagen Golf	13.816
2	2	Car - Audi A4	15.125
3	3	Car - Mercedes CLK	15.236
4	4	Car - Peugeot 607	15.617
5	5	Car - Volkswagen Beet...	13.163
6	6	Car - Porsche Cayman	14.301
7	7	Car - Toyota Yaris	12.300
8	20	HGV - WB 40	45.716
9	21	HGV - WB 50	55.000
10	22	HGV - WB 65	73.575
11	23	HGV - WB 67D	73.244
12	26	HGV- Flatbed	32.577

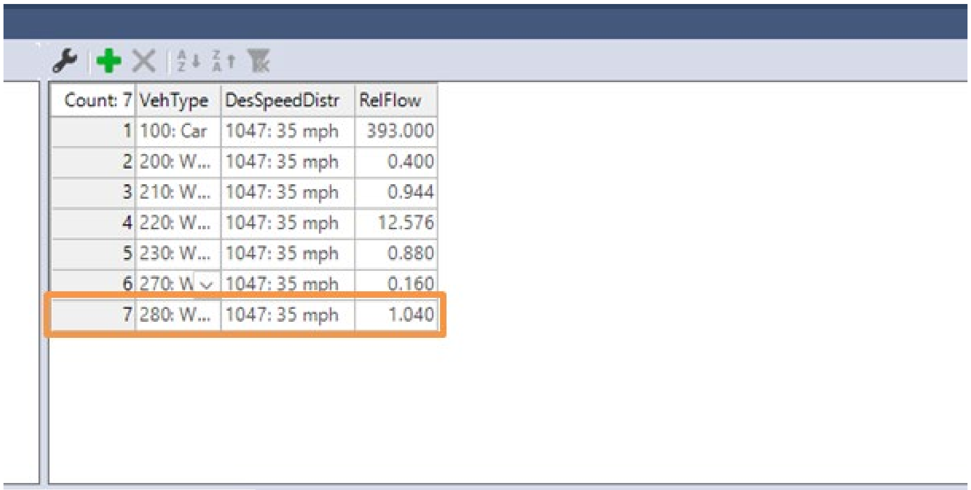
- *Step 2:* Create unique heavy truck configurations by combining tractor/trailers already present within VISSIM:
  - *2a)* WB-92D = WB-50 tractor + WB-50 trailer + WB-67D trailer connector + WB-50 trailer
  - *2b)* WB-100T = WB-50 tractor + WB-67D trailer + WB-67 trailer connector + WB-67D trailer + WB-67 trailer connector + WB-67D trailer
- *Step 3:* Base Data → Vehicle Classes → Add


Vehicle Classes / Vehicle Types

Select layout... Vehicle types

Count: 11	No	Name	VehTypes	UseVehTypeColor	Color
1	10	Car	100	✓	(255, 0, 0, 0)
2	20	WB40	200	✓	(255, 0, 0, 0)
3	21	WB50	210	✓	(255, 0, 0, 0)
4	22	WB65	220	✓	(255, 0, 0, 0)
5	23	WB67D	230	✓	(255, 0, 0, 0)
6	27	WB92D	270	✓	(255, 0, 0, 0)
7	28	WB100T	280	✓	(255, 0, 0, 0)
8	30	Bus	300	✓	(255, 0, 0, 0)
9	40	Tram	400	✓	(255, 0, 0, 0)
10	50	Pedestrian	510,520	✓	(255, 0, 0, 0)
11	60	Bike	610,620	✓	(255, 0, 0, 0)

- *Step 4:* Name the classification according to the corresponding AASHTO classification within the VISSIM model
- *Step 5:* Add **ONLY** that vehicle type
- *Step 6:* Traffic → Vehicle Compositions



- *Step 7:* Add each individual heavy truck classification
  - *Note:* Relative flow (RelFlow) is the total number of heavy vehicles multiplied by the proportion of heavy vehicles of the corresponding classification

7.1.2 EROAD Data

Stopping Time

Number of Heavy Vehicles	125
Number Stopped	28
Mean Stop Time (s)	7.467
Stop Time Standard Deviation	4.447
Minimum Stop Time (s)	1
Median Stop Time (s)	7.5
Maximum Stop Time (s)	18

Turning Movements

Movement	Count
NB Right	1
NB Thru	60
NB Left	0
NB U-Turn	0
WB Right	2

WB Thru	1
WB Left	0
WB U-Turn	0
SB Right	1
SB Thru	53
SB Left	1
SB U-Turn	3
EB Right	1
EB Thru	0
EB Left	2
EB U-Turn	0

7.1.3 Testing Matrix

Yielding Behavior	HV Fleet	Hourly Volume	Percent HV	NB	NB	WB	WB	SB	SB	EB	EB
				PC	*HV*	*PC*	*HV*	*PC*	*HV*	*PC*	*HV*
Conflict Areas	VISSIM Default	1222	3.3%	393	16	192	6	395	18	202	0
Conflict Areas	VISSIM Default	1222	4.4%	388	21	190	8	389	24	202	0
Conflict Areas	VISSIM Default	1222	5.5%	382	27	188	10	383	30	202	0
Conflict Areas	VISSIM Default	1222	6.6%	377	32	186	12	377	36	202	0
Conflict Areas	VISSIM Default	1253	3.3%	393	16	192	6	395	18	202	0
Conflict Areas	VISSIM Default	1253	4.4%	388	21	190	8	389	24	202	0
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Conflict Areas	VISSIM Default	1314	3.3%	393	16	192	6	395	18	202	0
Conflict Areas	VISSIM Default	1314	4.4%	388	21	190	8	389	24	202	0
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Conflict Areas	VISSIM Default	1314	6.6%	377	32	186	12	377	36	202	0
Conflict Areas	VISSIM Default	1344	3.3%	393	16	192	6	395	18	202	0

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Conflict Areas	VISSIM Default	1344	5.5%	382	27	188	10	383	30	202	0
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Priority Rules	VISSIM Default	1222	3.3%	393	16	192	6	395	18	202	0
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Conflict Areas	Observed	1222	5.5%	382	27	188	10	383	30	202	0
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7.2 APPENDIX B