NETWORK AND DESIGN CONCEPTS FOR ACCOMMODATING LARGE TRUCKS AT ROUNDABOUTS

by

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Abstract

It has been well documented that roundabouts can offer several safety and operational benefits over signalized and stop controlled intersection alternatives. However the growing use of roundabouts and their benefits could be greatly diminished because they may not be well designed for large trucks, or to accommodate oversize/overweight (OSOW) vehicles which may be essential to a state's industry and economy. This dissertation addresses concepts to better design roundabouts for use by owners/operators of typical large trucks, and that will also accommodate OSOW vehicles where appropriate. Roundabout safety generally decreases with increased roundabout size, wider lanes and larger radii, the geometric parameters that benefit large trucks and OSOW, thus a better balance is needed.

This study accomplishes this balance by initially reviewing and incorporating those portions of the study "Accommodating Oversize Overweight Vehicles at Roundabouts" that were researched, completed and written by the author of this dissertation, and which compiled current practice, research and concerns by various U.S. states and concerns of the trucking industry, by conducting four different surveys. Then to meet these concerns expressed by survey respondents, a great number of possible accommodation, strategies and design templates were developed by using existing design software. An evaluation method was also developed.

Two additional, needed studies, not previously reported in any published literature, addressed : 1. a vertical, ground clearance analysis, and 2. a study of the use of roundabouts in urban freight networks to incorporate their inherent benefits ,such as, reducing congestion, delay and pollution.

The first analysis described above was conducted by using software with 3D analysis capabilities to check and recommend critical vertical grades and maximum dimensions for a range of large truck types and OSOW vehicle configurations. Guidelines were developed to avoid problems of low, ground clearance vehicles scraping roundabout surfaces ("hanging up").

The second study used existing software that relates intersection types to intersection traffic flow efficiency and related pollution, on a number of routing scenarios to test the hypothesis that integration of roundabouts in these freight networks improves traffic flow, and decreases delay, congestion and pollution. The results were mixed but the procedure is sound and should be beneficial for future use by researchers and decision makers.

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Major Professor

Dr. Eugene Russell

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Dedication

I would like to dedicate this doctoral dissertation to my grandmother Leelavathi who always wanted to see me as a successful Civil Engineer.

I would also like to dedicate this doctoral dissertation to my parents.

Chapter 1 - Introduction, Problem Statement, and Study Objectives

Roundabouts can offer several advantages over signalized and stop controlled intersection alternatives, including better overall safety performance, greatly reduced intersection injury crashes and fatalities, lower delays, shorter queues, better management of speed and opportunities for community enhancement (*1*). The safety and traffic operational benefits of roundabouts for the typical vehicle fleet (automobiles. and small trucks) have been well documented and are presented in Chapter 2. Although roundabouts have been in widespread use in other countries for many years, their general use in the United States (US) began only in the recent past (1990 is generally accepted as the year the first modern roundabouts were built in the US), but their use is growing at an ever increasing rate (*1*). In some cases roundabouts can avoid or delay the need for expensive widening of an intersection approach that would be necessary for signalization.

However the growing potential use of roundabouts with all their benefits could be greatly diminished because they may not be well designed for large trucks or to accommodate oversize/overweight vehicles. For example, due to complaints from truckers, legislation was introduced in the state legislature in Oregon restricting roundabouts, leading to the Oregon Department of Transportation to impose a moratorium on designing and building roundabouts in the state (*2*).

Figure 1.1 shows some pictures of oversize/overweight vehicles. The design vehicle for a roundabout, as in any design, should be the largest vehicle that can reasonably be anticipated for normal use. Better guidelines for determining where and what vehicle size should be designed are needed, particularly on routes used by large trucks. Also, Oversize Overweight vehicles (OSOW) are vehicles that use the roadway by special permit and travel on a random basis. They may be essential to a state's industry and economy but may need special designs or accommodations at roundabouts on designated routes. Their physical characteristics and turning requirements, which may be unique to certain types of loads, usually exceed the dimensions given for standard, recommended design vehicles recommended in "*A Policy on Geometric Design of Highways and Streets*", commonly known as "The Green Book", the book of standards followed by all states (*3*). There is also a question of policy regarding which roundabouts in a state need to accommodate what type of OSOW, leading to a need for planning designated networks.

Figure 1.1: Pictures of Oversize/Overweight Vehicles

Source: Dr. Eugene Russell photo collection (*4*).

In the US, trucks carry a share of 60 percent of freight volume and 67 percent of freight value according to the Office of Freight Management and Operations (HOFM) and the Freight Analysis Framework (FAF) (*5*). It is also estimated by the HOFM's Freight Analysis, Framework (FAF), that the freight tonnage will increase by 48 percent between 2002 and 2035 and shows truck Vehicle Miles Travelled (VMT) growing faster than the automobile VMT. This projected increase in freight truck tonnage, without increased capacity and operation changes, will amount to an increase in congestion. Congestion increases travel time and costs, and leads to a less reliable pickup and delivery time for truck operators. This congestion increases the cost of transportation, which over time is passed along to customers, as well as having negative impacts on urban areas and their environments, such as increased pollution. It is estimated by FHWA that increase in travel time costs shippers and carriers an additional $25 to $200 per hour depending on the product. Pollution can decrease an areas quality of life (*5*).

An FHWA report, *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation* (*6*), has estimated about 40 percent of traffic congestion in general, as opposed to freight congestion specifically, is caused by bottlenecks, resulting in stop-and-go traffic flow and long backups. Bottlenecks on highways that serve high volumes of trucks are “freight bottlenecks" (*7*). A recent study conducted by FHWA, *An Initial Assessment of Freight Bottlenecks on Highways* (*7*) have shown that freight bottlenecks cause upwards of 243 million truck hours of delay and the direct user cost from this delay is about $7.8 billion per year. It is also observed that highway interchange bottlenecks accounted for more than 50 percent of the delay, or about 124 million hours of delay (*7*). Simultaneously, signalized, arterial intersections account for a total of 18 percent of the delay, or about 43 million hours of delay, for different freight routes comprised of urban freight corridors, intercity freight corridors, truck access routes and intermodal connectors (*7*).

There are also air pollution concerns from heavy congestion in urban areas. According to the 2009 *Freight Fact and Figures - Office of Freight Management and Operations Report* (*8*), diesel-fueled, heavy trucks emit small amounts of carbon monoxide (CO) but large amounts of nitrogen oxides (NO_x) when compared to gasoline-fueled cars affecting the air quality. Freight transportation contributes 27 percent of the total NO_x emissions and one-third of emissions of particulate matter 10 microns in diameter (PM-10) from mobile sources in the US. Among various modes of transportation in the freight sector, like heavy-duty trucks, freight rail, commercial marine, and air freight, heavy-duty trucks contribute a two-thirds share of the NO_x emissions from the freight sector (*8*).

Apart from the above emissions, the transportation sector releases large quantities of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane, nitrous oxide, and hydro fluorocarbons and these gases trap heat in the atmosphere which affects the earth's temperature (*8*). Therefore, the increase in the congestion of the trucks at urban intersections can affect the quality of air by emissions which can be mitigated by better traffic flow techniques such as less delay at urban intersections (*8*).

The above challenges clearly show that there is a need for improving traffic flow at interchanges, intersections and other transportation facilities to better accommodate vehicles and trucks with less congestion, thus decreasing the overall delay time and saving many dollars.

The National Cooperative Highway Research Program (NCHRP) report, *Synthesis 320 Integrating Freight Facilities and Operations with Community Goals* has studied the issues and concerns of the growing amount of freight traffic during freight operations (*9*). It has been concluded that balancing freight transportation facilities and operations with community goals can be complex and there is "no one size fits all" solution. However, the report concludes that solutions have to be developed through a common understanding of issues, working together to craft the solutions, and continuously checking to see if the solution remains effective (*9*).

1.1 Problem Statement

Most US roundabouts are intentionally designed to operate at slow speeds by using narrow curb to curb widths and relatively tight turning radii. However, if the design geometrics are too restrictive, roundabout use by OSOW vehicles, and in some cases even typical, large trucks, commonly called tractor-trailers, “semis” or “18-wheelers”, may be difficult or even impossible. In some cases in the US this has led to opposition to roundabouts by the trucking industry and to the possibility of lobbying their state legislatures for laws detrimental to roundabout use, as occurred in Oregon (*2*). There is a pressing need to address and mitigate their concerns in order to not diminish the growth of roundabouts and thus their safety and operational benefits to other vehicles and the general traveling public. Therefore, the central issue is how to design roundabouts that are not difficult to use by typical large trucks and also accommodate OSOW vehicles where appropriate. They need to be accommodated on designated routes, networks or certain areas where their transport is necessary, without sacrificing the safety and operational efficiency of the roundabouts, which generally decreases with increased roundabout size, wider lanes and longer radii. Thus there are safety, cost and other benefits in keeping roundabouts small but still capable of being acceptable to truckers and able to accommodate OSOW vehicles as appropriate to their essential travel. OSOW are generally routed around roadway restrictions such as certain bridges, narrow roadways, etc.; however, with the popularity of roundabouts and the benefits they provide, such routing could become more difficult and could potentially lead to reduced or prohibited roundabout use if OSOW cannot be accommodated.

With the rapid increase in construction of roundabouts in and around urban areas in the US there are many instances where these roundabouts impact freight movement routes. Roundabouts in the US have proven to have many advantages (*1*). Among the many advantages roundabouts have is less delay and decreased congestion which should help freight flows, thereby saving many dollars while reducing delay and negative environmental impacts such as air pollution. Roundabouts, as a part of freight networks, should be able to better handle the increasing freight demand, and reduce congestion and negative environmental issues and concerns in and around urban communities.

There have been no published studies in the area of optimizing the use of roundabouts to incorporate their inherent benefits into freight networks to better serve trucking and community needs, i.e. reducing congestion, delay, pollution and other negative impacts while accommodating increased freight demand.

1.2 Study Objectives

The objectives of the study included:

1. Compile current practice and research by various US states related to the effects that OSOW have on roundabout location, design, and accommodation. This will be achieved by participating in developing, and then analyzing surveys to 50 US State agencies, and OSOW haulers, concurrently conducted for the study "*Accommodating Oversize/Overweight Vehicles at Roundabouts*" (*2*).
2. Investigate strategies, recommendations and guidelines to build statewide freight networks for large trucks and necessary OSOW needs, and recommend state policy.
3. Build designs for typical roundabout intersection types to accommodate all reported types of large trucks and representative OSOW configurations/combinations which may need to be accommodated.
4. Perform 3-D vehicle simulations and develop guidelines for a vertical ground clearance analysis, by adapting 3-D swept path analysis software and recommending maximum vertical dimensions for roundabout geometric features.
5. Investigate integrating the greater use of roundabouts in freight networks in and around urban areas to optimize goods movement while decreasing air pollution due to trucks in and around the communities.

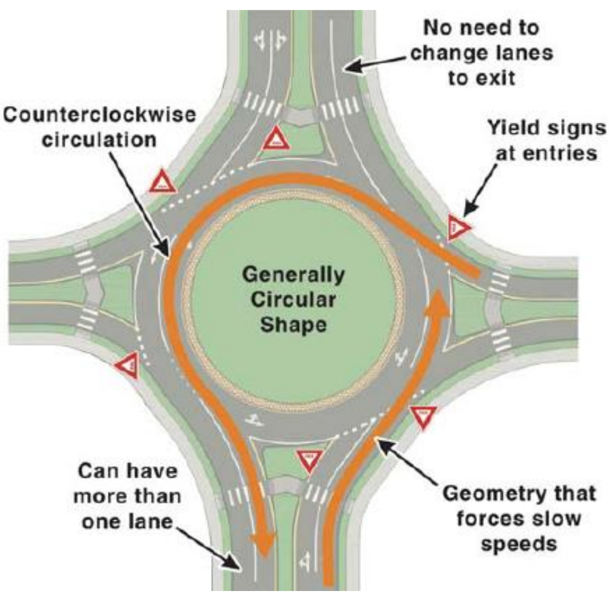
Chapter 2 - Literature Review

2.1 Origin of Roundabouts

Use of traffic circles in the US started from 1905 when William Phelps Eno designed the Columbus Circle in New York City (*1*). These traffic *circles* gave priority to entering vehicles leading to high speed entries. However, due to high crash experience and congestion in the circles, they became out of favor in the US after the mid-1950s (*1*).

The United Kingdom developed the concept of modern roundabouts to address the problems with traffic circles by adapting a rule that for all circular intersections, the entering traffic should give the way, yield, to the circulating traffic. It was observed that these changes improved the operational and safety characteristics of the circular intersections and thereafter, many countries then adapted what can be now referred to as a *modern* roundabout, as a common intersection form. Figure 2.1 shows the key characteristics of a typical roundabout and Table 2.1 describes the key roundabout features (*1*).

Figure 2.1: Key Roundabout Characteristics



Source: Roundabouts: An Informational Guide, Second Edition (*1*)

Table 2.1: Key Roundabout Features

Feature	Description
Central island	The central island is the raised area in the center of a roundabout around which traffic circulates. The central island does not necessarily need to be circular in shape. In the case of mini-roundabouts the central island is traversable.
Splitter island	A splitter island is a raised or painted area on an approach used to separate entering from exiting traffic, deflect and slow entering traffic, and allow pedestrians to cross the road in two stages. Circulatory roadway The circulatory roadway is the curved path used by vehicles to travel in a counterclockwise fashion around the central island.
Circulatory Roadway	The circulatory roadway is the curved path used by vehicles to travel in a counterclockwise fashion around the central island.
Apron	An apron is the traversable portion of the central island adjacent to the circulatory roadway that may be needed to accommodate the wheel tracking of large vehicles. An apron is sometimes provided on the outside of the circulatory roadway.
Entrance line	The entrance line marks the point of entry into the circulatory roadway. This line is physically an extension of the circulatory roadway edge line but functions as a yield or give-way line in the absence of a separate yield line. Entering vehicles must yield to any circulating traffic coming from the left before crossing this line into the circulatory roadway.
Accessible pedestrian crossings	For roundabouts designed with pedestrian pathways, the crossing location is typically set back from the entrance line, and the splitter island is typically cut to allow pedestrians, wheelchairs, strollers, and bicycles to pass through. The pedestrian crossings must be accessible with detectable warnings and appropriate slopes in accordance with ADA requirements.
Landscape strip	Landscape strips separate vehicular and pedestrian traffic and assist with guiding pedestrians to the designated crossing locations. This feature is particularly important as a way finding cue for individuals who are visually impaired. Landscape strips can also significantly improve the aesthetics of the intersection.

Source: Roundabouts: An Informational Guide, Second Edition (*1*)

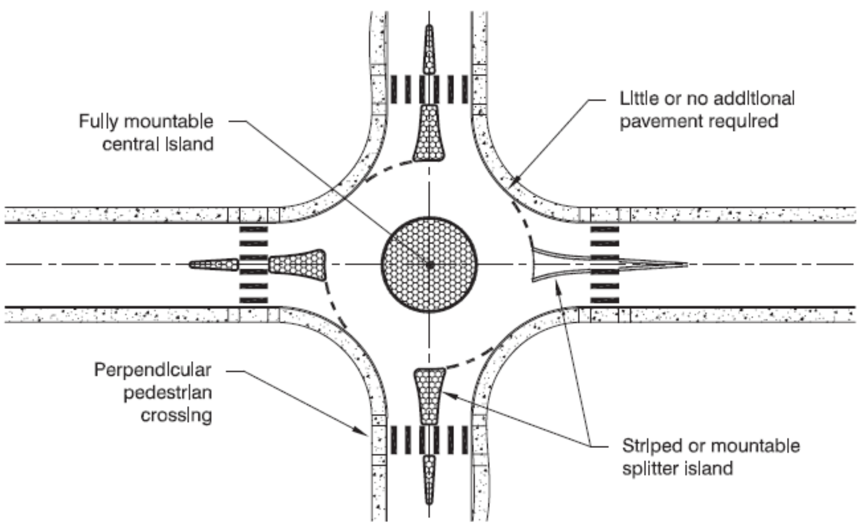
2.2 Roundabout Categories

Roundabouts can be categorized into three basic types based on the size and number of lanes (*1*). They are discussed below.

2.2.1 Mini Roundabouts

These are small roundabouts with fully traversable center island, commonly used in low speed urban environments with an average operating speed of 30 mph or less in Europe (*1*). A fully traversable center island helps in better accommodating larger vehicles at a mini-roundabout and therefore they are mostly recommended when a traditional single-lane roundabout has insufficient right of way to accommodate the design vehicle. However, the mini-roundabout is designed in such a way that the passenger cars generally do not traverse over the center island (*1*). To date, their use has not caught on in the US.

Figure 2.2: Features of Typical Mini-Roundabout



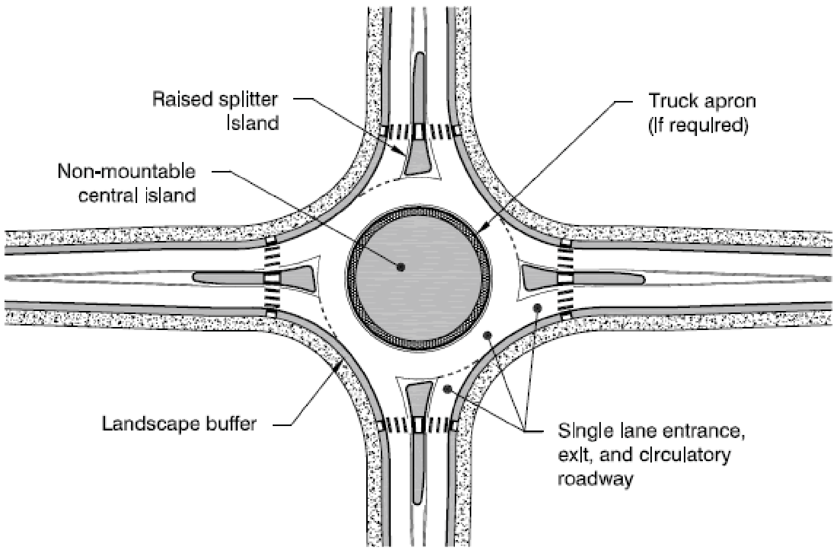
Source: Roundabouts: An Informational Guide, Second Edition (*1*)

2.2.2 Single- lane Roundabout

This type of roundabout has a single-lane entry for all the legs and one circulating lane. Their geometric design typically includes features such as a raised splitter island, a non-traversable center island, crosswalks and a truck apron (*1*). They generally have larger inscribed circle diameter when compared to mini-roundabouts. However, the size of the roundabout is largely influenced by the design vehicle and right of way constraints (*1*).

Figure 2.3 shows the features of a typical single-lane roundabout.

Figure 2.3: Features of Typical Single-Lane Roundabout



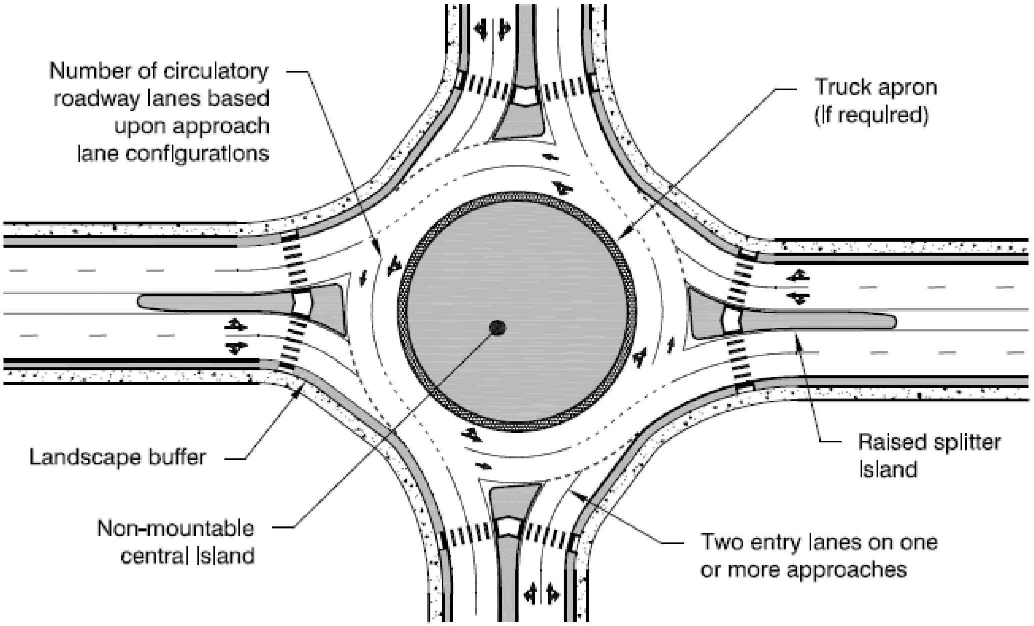
Source: Roundabouts: An Informational Guide, Second Edition (*1*)

2.2.3 Multilane Roundabouts

This type of roundabout has at least one entry with two or more lanes and in some cases they might have different number of lanes on one or more approaches (*1*). The geometric design typically includes a raised splitter islands, a truck apron, a non-traversable center island, and appropriate entry path deflection. These types of roundabouts have wider circulatory roadways, so that more than one vehicle can travel side by side. The speed of the vehicles at the entry, on the circulatory roadway, and at the exit, are generally similar or may be slightly higher than the single-lane roundabouts (*1*).

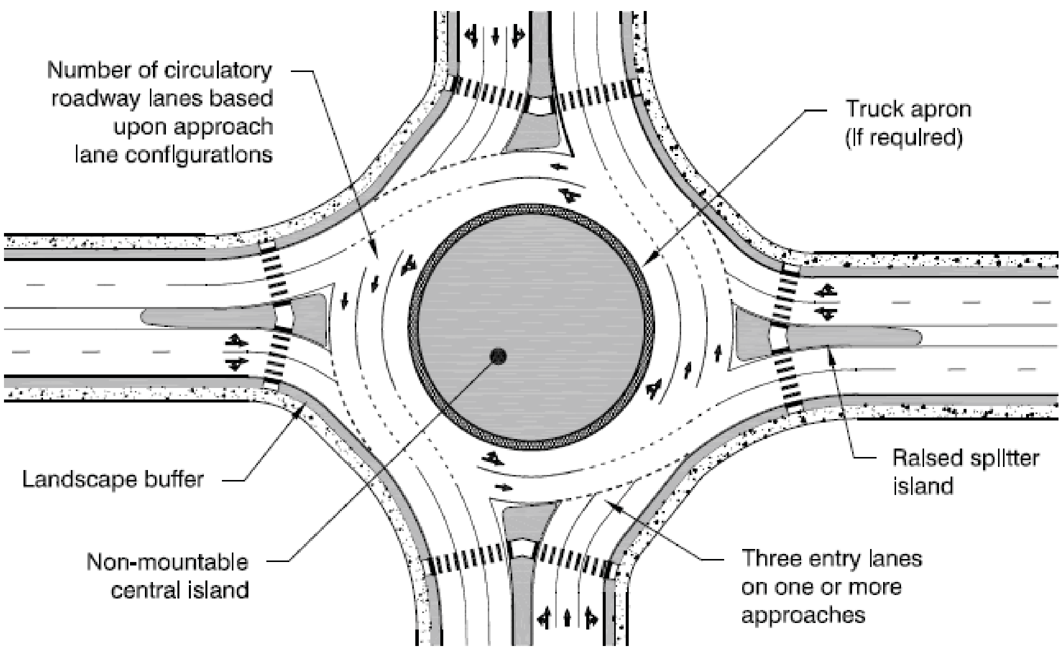
Figure 2.4 shows the features of a typical two-lane roundabout and Figure 2.5 shows the features of a three-lane roundabout. Table 2.2 shows the summary of design and operational elements for each of these three roundabout categories.

Figure 2.4: Features of Two-Lane Roundabout



Source: Roundabouts: An Informational Guide, Second Edition (*1*)

Figure 2.5: Features of Three-Lane Roundabout



Source: Roundabouts: An Informational Guide, Second Edition (*1*)

Table 2.2: Design Characteristics of three Roundabout Categories

Design Element	Mini-Roundabout	Single-Lane Roundabout	Multilane Roundabout
Desirable maximum entry design speed	15 to 20 mph (25 to 30 km/h)	20 to 25 mph (30 to 40 km/h)	25 to 30 mph (40 to 50 km/h)
Maximum number of entering lanes per approach	1	1	2+
Typical inscribed circle diameter	45 to 90 ft (13 to 27 m)	90 to 180 ft (27 to 55 m)	150 to 300 ft (46 to 91 m)
Central island treatment	Fully traversable	Raised (may have traversable apron)	Raised (may have traversable apron)
Typical daily service volumes on 4-leg roundabout below which may be expected to operate without requiring a detailed capacity analysis (veh/day)*	Up to approximately 15,000	Up to approximately 25,000	Up to approximately 45,000 for two-lane roundabout

*Operational analysis needed to verify upper limit for specific applications or for roundabouts with more than two lanes or four legs.

Source: Roundabouts: An Informational Guide, Second Edition (*1*)

2.3 Advantages of Roundabouts

2.3.1 Safety Features

NCHRP *Report 572, Roundabouts in the United States* conducted a before-after safety study by considering 55 locations that used to have different previous intersection treatments such as two-way stop, all way stop, or signal control and are changed to a roundabout treatment (*10*). On a whole, it was observed that there was a 35% reduction in total crashes and 76% reduction in injury crashes by converting the intersection treatment (signalized, all-way stop, or two-way stop) to a roundabout (*10*).

Table 2.3 shows the percentage crash reduction obtained for both total and injury accidents, categorized by intersection control, type of setting and number of lanes (*10*). Table 2.4 presents a comparison of mean crash reduction for various countries which shows that roundabouts are safer than comparable intersection alternatives (*1*). It was observed that converting intersections with signals and two-way stop control to roundabout has produced significant safety benefits, and especially for injury accidents (*10*).

Roundabouts generally operate with lower delays, less stopping and less idling, when compared to other intersection forms when operating within their capacity (*1, 11*). Therefore, with the reduction of vehicle delays, roundabouts can provide environmental benefits. Though there may be heavy volumes of vehicles, they continue to move slowly rather than completely stopping, and therefore, noise and air quality impacts are reduced (*1*). Mandavilli et al. have studied the impact of modern roundabouts in decreasing the vehicular emissions at four sites in Kansas where modern roundabout had replaced a stop controlled intersection (*12*). Analyzing four measures of effectiveness, i.e., emissions of HC, CO, NOx, and CO_2, at roundabouts vs other intersection control, it was found that the modern roundabout performed better than the stop controlled intersections (*12*). A 38%-45% decrease in CO emissions (in Kg/hr) was observed with the installation of a roundabout for AM and PM periods. A 55%-61% decrease in CO_2 emissions (in Kg/hr) was observed with the installation of a roundabout for AM and PM periods. A 44%-51% decrease in NO_x emissions (in Kg/hr) was observed with the installation of a roundabout for AM and PM periods. A 62%-68% decrease in HC emissions (in Kg/hr) was observed with the installation of a roundabout for AM and PM periods (*12*).

Table 2.3: Crash Reduction by Implementing a Roundabout

Control Before	Sites	Setting	Lanes	Estimate of the Percent Reduction in Crashes (and Standard Error)	
				All	Injury + Fatal
All Sites	55	All	All	35.4% (3.4)	75.8% (3.2)
Signalized	9	All	All	47.8% (4.9)	77.7% (6.0)
	4	Suburban	2	66.7% (4.4)	Sample too small to analyze
	5	Urban	All	Effects insignificant	60.1% (11.6)
All-way stop	10	All	All	Effects insignificant	Effects insignificant
Two-way stop	36	All	All	44.2% (3.8)	81.8% (3.2)
	9	Rural	1	71.5% (4.0)	87.3% (3.4)
	17	Urban	All	29.0% (9.0)	81.2% (7.9)
	12		1	39.8% (10.1)	80.3% (10.0)
	5		2	Sample too small to analyze	Sample too small to analyze
	10	Suburban	All	31.8% (6.7)	71.0% (8.3)
	4		1	78.2% (5.7)	77.6% (10.4)
	6		2	19.3% (9.1)	68.0% (11.6)
	27	Urban/ Suburban	All	30.8% (5.5)	74.4% (6.0)
	16		1	56.3% (6.0)	77.7% (7.4)
	11		2	17.9% (8.2)	71.8% (9.3)

Source: Roundabouts in the United States, NCHRP Report 572 (*10*)

Table 2.4: Mean Crash Reduction in various Countries

Country	Mean Reduction (%)	
	All Crashes	Injury Crashes
Australia	41–61%	45–87%
France	-	57–78%
Germany	36%	-
Netherlands	47%	-
United Kingdom	-	25–39%
United States	35%	76%

Source: Roundabouts: An Informational Guide, Second Edition (*1*)

2.4 Geometric Features

2.4.1 Inscribed Circle Diameter

The Inscribed Circle Diameter (ICD) is the distance across the circle that is inscribed by the outer curbs and is the sum of center island diameter and twice the circulatory roadway width (*1*). The ICD design is based on an iterative process and is based upon design objectives such as accommodating the design vehicle and providing speed control (*1*).

For a single-lane roundabout the turning requirements of a design vehicle plays a prominent role in deciding the size of the ICD. To accommodate an AASHTO designated WB-50 design vehicle, at least a 105 ft. inscribed circle diameter is needed, and to accommodate a WB-67 design vehicle, a larger inscribed circle diameter, in the range 130 to 150 ft., will be required. The dimensions and turning path requirements for different common highway vehicles can be found in the Appendix A.

For a multilane roundabout, the size of the roundabout is based on balancing the need to achieve deflection, speed control and good alignment for normal small vehicles. The inscribed circle diameter of a multilane roundabout ranges from 150 to 250 ft. Table 2.5 shows the inscribed circle diameter ranges for different categories of roundabouts. These inscribed circle diameter ranges have to be considered an initial selection as modifications are often necessary based on the context of the location (*1*).

Table 2.5: Inscribed Circle Diameter Ranges for different Categories of Roundabouts

Roundabout Configuration	Typical Design Vehicle	Common Inscribed Circle Diameter Range*	
Mini-Roundabout	SU-30 (SU-9)	45 to 90 ft	(14 to 27 m)
Single-Lane Roundabout	B-40 (B-12)	90 to 150 ft	(27 to 46 m)
	WB-50 (WB-15)	105 to 150 ft	(32 to 46 m)
	WB-67 (WB-20)	130 to 180 ft	(40 to 55 m)
Multilane Roundabout (2 lanes)	WB-50 (WB-15)	150 to 220 ft	(46 to 67 m)
	WB-67 (WB-20)	165 to 220 ft	(50 to 67 m)
Multilane Roundabout (3 lanes)	WB-50 (WB-15)	200 to 250 ft	(61 to 76 m)
	WB-67 (WB-20)	220 to 300 ft	(67 to 91 m)

* Assumes 90° angles between entries and no more than four legs. List of possible design vehicles is not all-inclusive.

Source: Roundabouts: An Informational Guide, Second Edition (*1*)

2.4.2 Truck Apron

A truck apron is usually provided within the center island on the outer edge to keep the inscribed circle diameter reasonably small, while providing additional paved area to accommodate off-tracking of the rear wheels of larger design vehicles while maintaining the deflection for smaller vehicles (*1*). Roundabouts truck aprons should be designed in such a way that they are traversable by trucks but discourage passenger vehicles from using them, usually by being elevated. Therefore the outer edge of the truck apron should by approximately 2 to 3 in. above the surface of circulatory roadway (*1*). The actual height and curb type is somewhat controversial and there is currently no consensus among designers or in states' guidelines (this will be covered in detail in later sections).

The swept path of the design vehicle dictates the clearance needed (*1*). Swept path is the calculation and analysis of the movement and path of different parts of the vehicle as it maneuvers a turning movement (*13*). The wheel paths of the design vehicle dictates the width of the truck apron which typically varies from 3 to 15 ft. wide with a cross slope of 1% to 2% away from the center island (*1*). Computer Aided Design (CAD) based vehicle turning, simulation software, is generally used to simulate a tracking template of the design vehicle in order to decide upon the minimum truck apron width needed. A truck apron should be constructed with material which is visually different from the circulatory roadway and sidewalks so that they can be easily differentiated, and also, so pedestrians are not encouraged to cross the circulatory roadway thinking it is a sidewalk. It can be understood from Figure 2.6 that roundabouts with a smaller inscribed circle diameter requires a wider truck apron to accommodate a left-turning vehicle (*1*).

2.4.3 Design Vehicle

The largest vehicle that is likely to regularly use the intersection is termed the 'design vehicle', and the accommodation of this vehicle at the intersection dictates many of the roundabouts' dimensions (*1*). Roundabouts are intentionally designed to slow traffic by different techniques such as narrow curb-to-curb widths and relatively tight turning radii, and this concept could create difficulties for large vehicles if they are not considered during the design process(*1*).

The approaching roadway type and surrounding land use characteristics help decide the choice of the design vehicle, but the local or state agency with jurisdiction of the roadways, and all stakeholders, e.g. large industrial shippers, should be consulted to assist in determining the appropriate design vehicle and possible need for OSOW accommodation (*1*). The dimensions and turning path requirements for different common highway vehicles can be found in the Appendix A.

Fire engines, transit vehicles, and single-unit delivery vehicles should also be considered to be accommodated in urban areas without the use of the truck apron. Generally, WB-50 vehicles are the largest vehicle needed on urban collectors and arterials; however, larger trucks such as WB-67 may need to be considered at intersections on Interstate or primary state highway systems (*1*). Accommodating WB-67 vehicles at roundabouts designed using the WB-50 design vehicle are discussed in later sections of this study.

Some locations in rural areas and freeway interchanges may expect OSOW which travel on the roadways infrequently and require a special permit. These oversized vehicles should not be used as a design vehicle for a roundabout design since their passage is usually infrequent, and excessive dimensions would lead to higher speeds and lessened safety for the majority of the users. Therefore, the challenge is to design roundabouts on roadways where an OSOW vehicle can be anticipated and needs to be accommodated, without diminishing the safety benefits for the majority of users (*1*).

Figure 2.6: Swept Path Analysis of WB-67 Vehicle for Different Diameters

(a) Inscribed circle diameter of 125 ft (38 m)

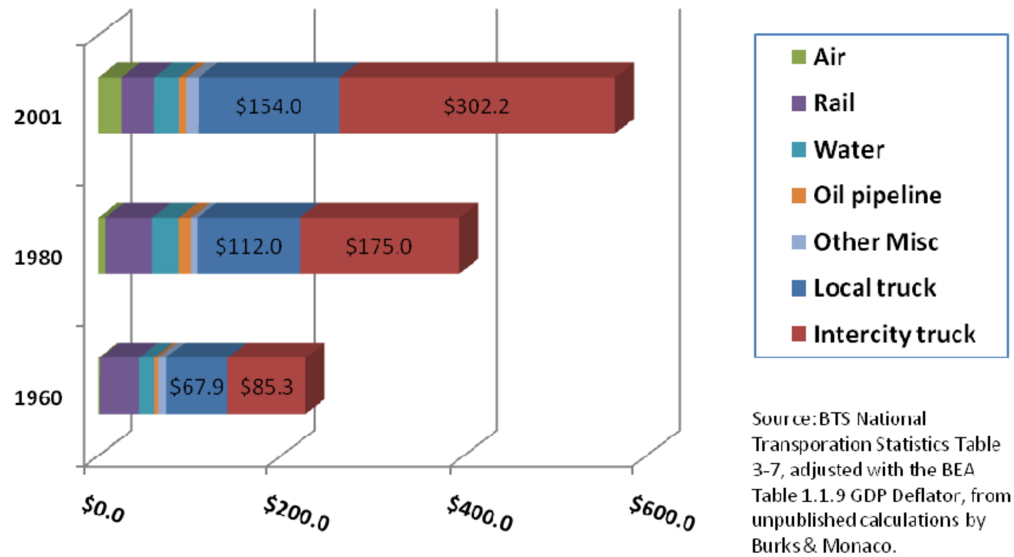
(b) Inscribed circle diameter of 140 ft (43 m)

Source: Roundabouts: An Informational Guide, Second Edition (*1*)

2.5 Trucking

The use of motor vehicles for freight transportation accelerated in the US during World War I (1914-1918) (*14*). It was estimated that commercial trucks have increased by 56 percent between 1980 and 2007 (*8*). From Figure 7, it can be observed that freight expenditure, the combining local and intercity trucking shares, are a major portion of US freight expenditures and it has increased over time (*14*).

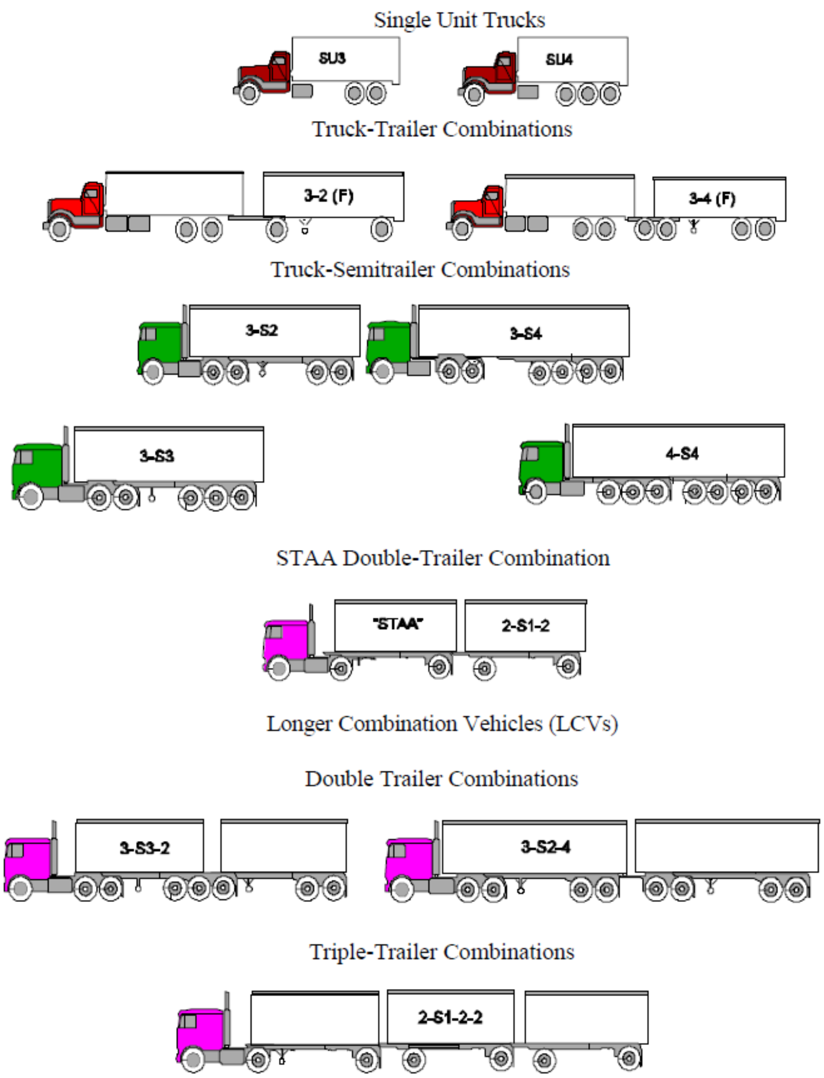
Figure 2.7: U.S. Freight Expenditures by Mode (in billions of 2000 US$)



Source: Trucking 101: An Industry Primer (*14*)

According to an estimate by the American Trucking Association (ATA), in 2009 the trucking industry had a revenue share of 81.9% ($544.4 billion) of the total spent on all modes of freight transportation in US (*15*). Trucking also plays a prominent role in international trade. Freight movement between US and other continents primarily taking place by a ship or an airplane; however, trucks make shipments to ports and airports and are used when freight has to travel between the US, Mexico, and Canada (*15*). According to an estimate of the Bureau of Transportation Statistics (BTS) in 2006, goods transported between the US, Canada, and Mexico by truck had a share of 61.6% of the value of cargo, and this share accounts for 26.3% of the tons of cargo moved between these countries (*16*). Figure 2.8 illustrates different types of large trucks that operate in US.

Figure 2.8: FHWA Truck Classifications



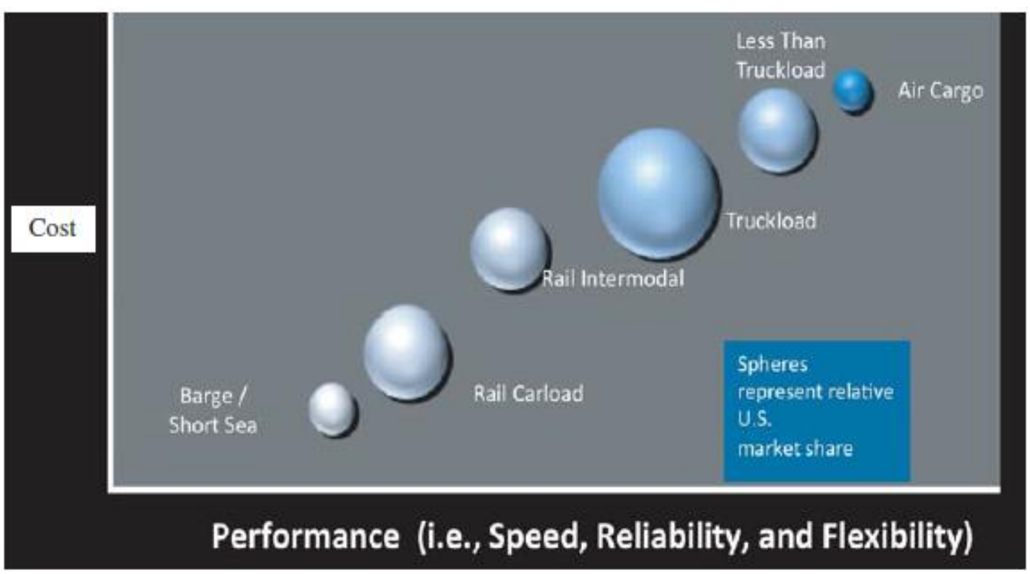
Source: FHWA Comprehensive Truck Size and Weight Study, Volume 2 (*17*)

The legal, maximum gross vehicle weight (GVW) of a truck is 80,*000* lbs (*14*) based on the current federal regulations. These regulations are enforced by a combination of weigh-in-motion (WIM) sites and roadside weigh and inspection stations (*14*). About 200 million weighs were made in 2008 with WIM sites sharing 60% and the remaining 40% were static (*8*). Heavy trucks exceeding the GVW limit can do damage to roads and bridges (*8*). Single-unit trucks and combination vehicles are two different categories of truck types. As can be seen in Figure 2.8, single-unit trucks have short wheel bases and they do not have trailers. Combination vehicles can be further categorized into conventional combination vehicles and longer combination vehicles (LCVs) as shown in Figure 2.8. (*17*). Congress has defined an LCV as "any combination of a truck tractor and two or more trailers or semi-trailers which operates on interstate system at a gross vehicle weight (GVW) greater than 80,000 lbs." (*18*).

2.6 Freight Transportation and Logistics

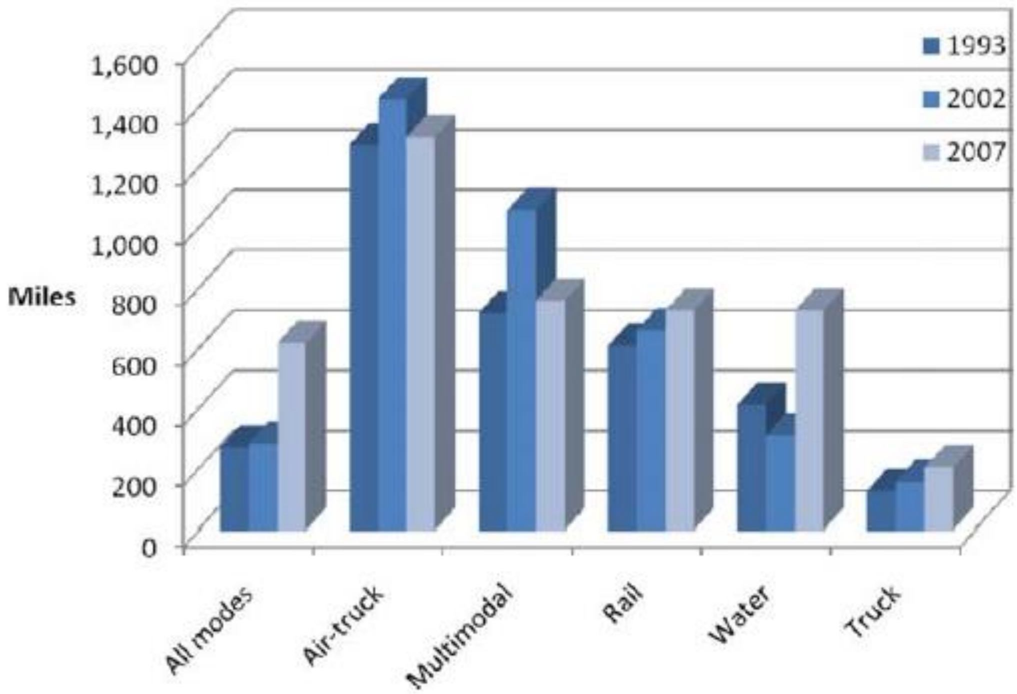
Freight transportation and logistics management are an integral part of supply chain management which basically involves transportation services to deliver raw materials, intermediate goods, and finished goods between origin and destination (*19*). There are various modes of transportation available in logistics management such as rail, truck, water, and air. Among the various modes of transportation available, motor carriers (trucks) are used for the 'last' mile of journey in the usual supply chain process because of their greater flexibility and universal access to industrial and commercial locations (*20*). As a result of the last mile truck travel, urban truck traffic is growing in the urban areas resulting in congestion problems which are seen in many American cities today (*20*). Figure 2.9 explains the relationship between cost and modal service associated with various available freight transportation modes. Figure 2.10 illustrates the trend in average length of haul by mode from three recent commodity flow survey (CFS). It can be noted that from the 2007 CFS, the average truck shipment moves 206 miles, and the average length of hauling in trucking mode has increased 24 percent over 2002 (*20*).

Figure 2.9: Relationship between Cost and Modal Service Associated with various available Freight Transportation Modes



Source: Preserving and Protecting Freight Infrastructure and Routes (*19*)

Figure 2.10: Trend in Average Length of Haul by Mode



Source: Preserving and Protecting Freight Infrastructure and Routes (*19*)

Transportation and warehousing industries employed 4.5 million people in 2008 which was more than 3 percent of the total U.S. employment. Also trucking was the largest employer with 1.4 million employees within the for-hire transportation section (*19*).

Three quarters of people in America were reported to be living in urban locations by 1990. Currently, over 83 percent of the U.S. population is reported living and working in urbanized areas (*20*). By considering the 20 largest U.S. metropolitan areas, it was determined that 41 percent of population lives in the city and the rest 59 percent live in the surrounding suburbs (*20*). Urbanized area is defined by the Census Bureau as:

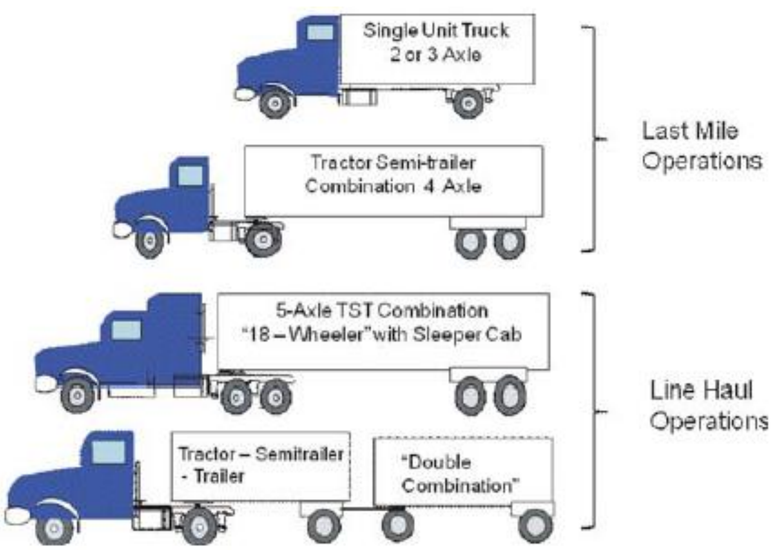
> "An area consisting of a central place (s) and adjacent territory with a general population density of at least 1,000 people per square mile of land area that together have a minimum residential population of at least 50,000 people. The U.S. Census Bureau uses published criteria to determine the qualification and boundaries of urban areas." (*20*)

Urban delivery service has many operational challenges while making just-in-time (JIT) deliveries travelling through congested highways, parking restrictions, and route restrictions (*20*). Warehouses and distribution facilities are constructed in or near urban areas to overcome these challenges and meet the delivery times by transporting the goods in smaller vehicles that can negotiate the road geometrics in dense urban areas (*20*). The truck configuration that is most commonly used in US is a 5-axle tractor-semi-trailer (TST) combination vehicle which is commonly called an '18 wheeler' or just "semi". However, this 5-axle TST is commonly used to transport goods from origin to warehousing facility near urban areas (*20*). The last mile deliveries were generally made in smaller trucks which are shown in Figure 2.11.

Various movements involving urban truck traffic include (*20*):

1) long haul trucks passing through the urban area on the urban highway network which has both the origin and destination outside the urban area,
2) long haul trucks having either pick-up or delivery in the urban region,
3) truck drayage,
4) local trucks moving goods among facilities,
5) construction vehicles,
6) utility and other residential service vehicles,
7) van lines delivering goods with special requirement, and
8) package services.

Figure 2.11: Trucks used for Last Mile and Line Haul Operations



Source: Preserving and Protecting Freight Infrastructure and Routes (*19*)

2.7 Conflicting Land Uses for Freight Transportation

Residential, educational, and medical related land uses were generally considered incompatible with freight transportation activities (*19*). Some of the major conflicts that non-freight interests face with freight transportation facilities are air and water pollution, light pollution, noise pollution, effects of vibration, safety issues, congestion, and environmental justice issues (*19*). However, these conflicts lead to building of barriers for the development of efficient freight transportation operation from the freight perspective of interest. On the other hand, potential barriers for freight services are speed restrictions, limitations on hours of operation, height and clearance impacts, size and weight limitations, corridor design impacts, environmental permitting, limitations on dredging operations and/or the depositing of dredging material, backlog of waterway lock or channel maintenance, hazardous material routing restrictions, and gentrification that displaces, impedes, or increases the cost of freight transportation. Barriers for freight facilities not only affect the freight transportation facilities, but also the route choice and accessibility to their destination points (*19*).

Freight facilities and corridors are very important and have to be preserved. Lack of preserving freight facilities, yards, and other ancillary facilities in the transportation network can create bottlenecks, increase in cost of goods, and ultimately effects the customers by increased prices. Various practices such as long range planning activities, delineation of corridors, freight support and preservation initiatives, maintenance activities, and purchase of corridors for freight future use have to be conducted for preserving the freight facilities and corridors (*19*).

2.8 Large Trucks and Roundabouts

A study *Accommodating Trucks in Single and Multilane Roundabouts* discusses various issues and a design measure related to trucks and oversize vehicles at roundabouts and describes the treatments used when the truck percentages are high and the trade-offs in terms of safety and speed control when using these techniques (*21*).

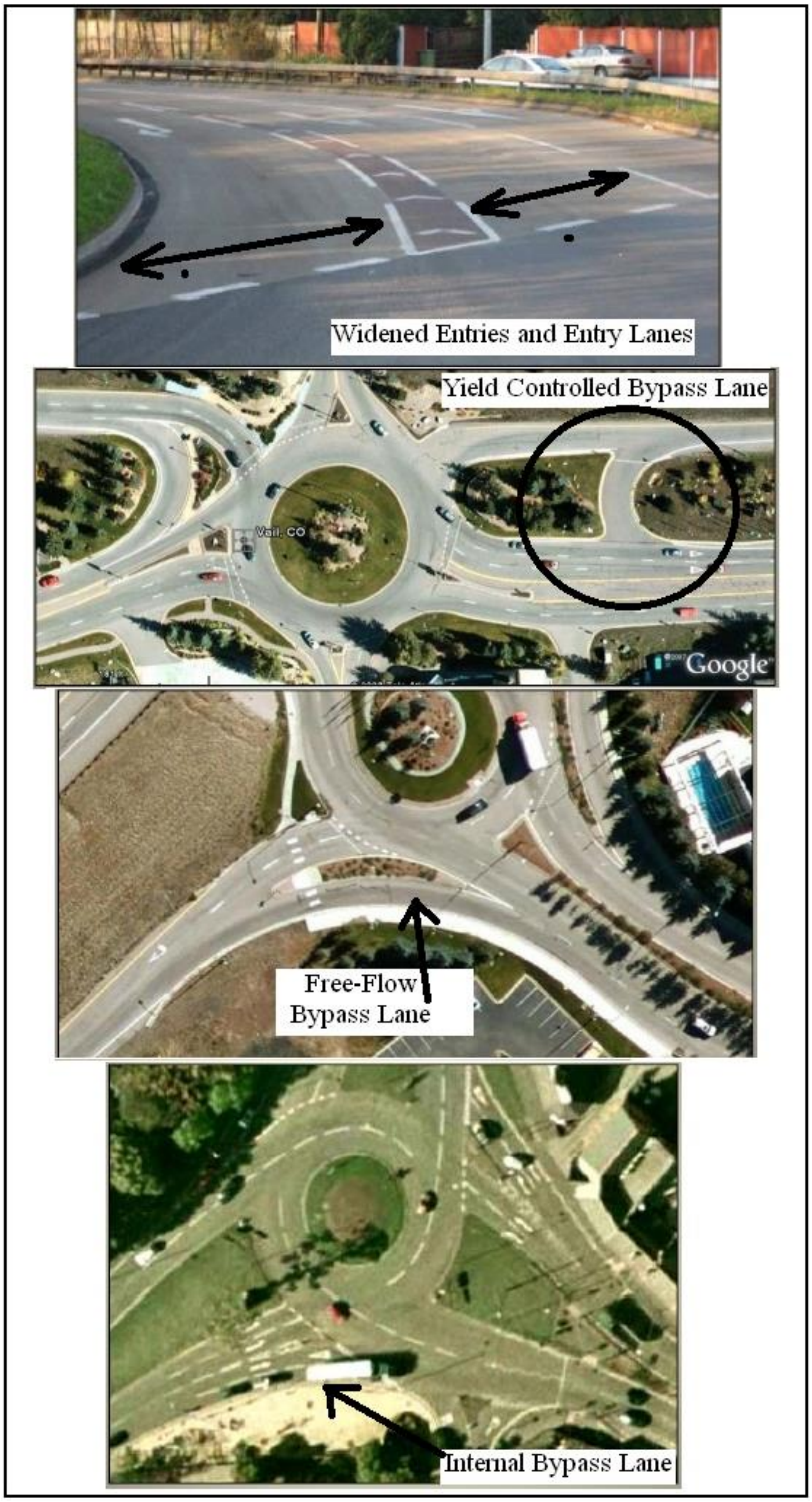
An optimal roundabout design is a design which safely accommodates a large portion of road users with minimal delay. Therefore frequencies of use by various users are considered for an optimal roundabout. Accommodating larger vehicles at roundabouts is a relatively a new and growing practical challenge. Many practical measures have been developed worldwide to accommodate larger trucks at roundabouts such as: fully traversable center islands (similar to mini-roundabouts), widened entry and exit lanes, right turn bypass lanes, partially traversable central islands (truck aprons), gated pass-through lanes, lane striping, and others. Each of these methods carry design trade-offs in terms of safety and speed control of cars and small trucks, and so each should be considered for site specific conditions (*21*).

Truck right turns can be accommodated at larger roundabouts by different means, such as, use of an adjacent lane, providing widened entries and entry lanes, providing right turn bypass lanes, free flow bypass lanes, yield controlled bypass lanes, and an internal bypass lane (*21*). Figure 2.12 shows pictures of few of the treatments to accommodate truck right turns.

Truck aprons are generally designed to provide maneuvering space for large vehicles in a roundabout while still providing deflection for smaller vehicles. However, an apron may not be necessary if speed control and truck maneuvering space can be provided without an apron. A fully raised island provides an effective lateral deflection when compared to aprons. Sometimes, the height and slope of the apron can create under clearance and stability problems for trucks (*21*).

A truck apron field study (not OSOW) was conducted at I-17/Happy Valley Road, Phoenix in July 2007. Peak hour apron use by semis and large single-unit trucks was observed. Data showed that out of 624 trucks observed, 77% of them did not use the apron. Among the trucks that did use the apron, most (67%) of them used it because a car was in the adjacent lane. It was also observed that when a car and truck were side-by-side, the smaller vehicle usually accelerated ahead of the truck or applied brakes to get behind the truck (*21*).

Figure 2.12: Treatments for Accommodating Truck Right Turns



Source: Accommodating Trucks in Single and Multilane Roundabouts (*21*)

2.9 Joint Roundabout Truck Study

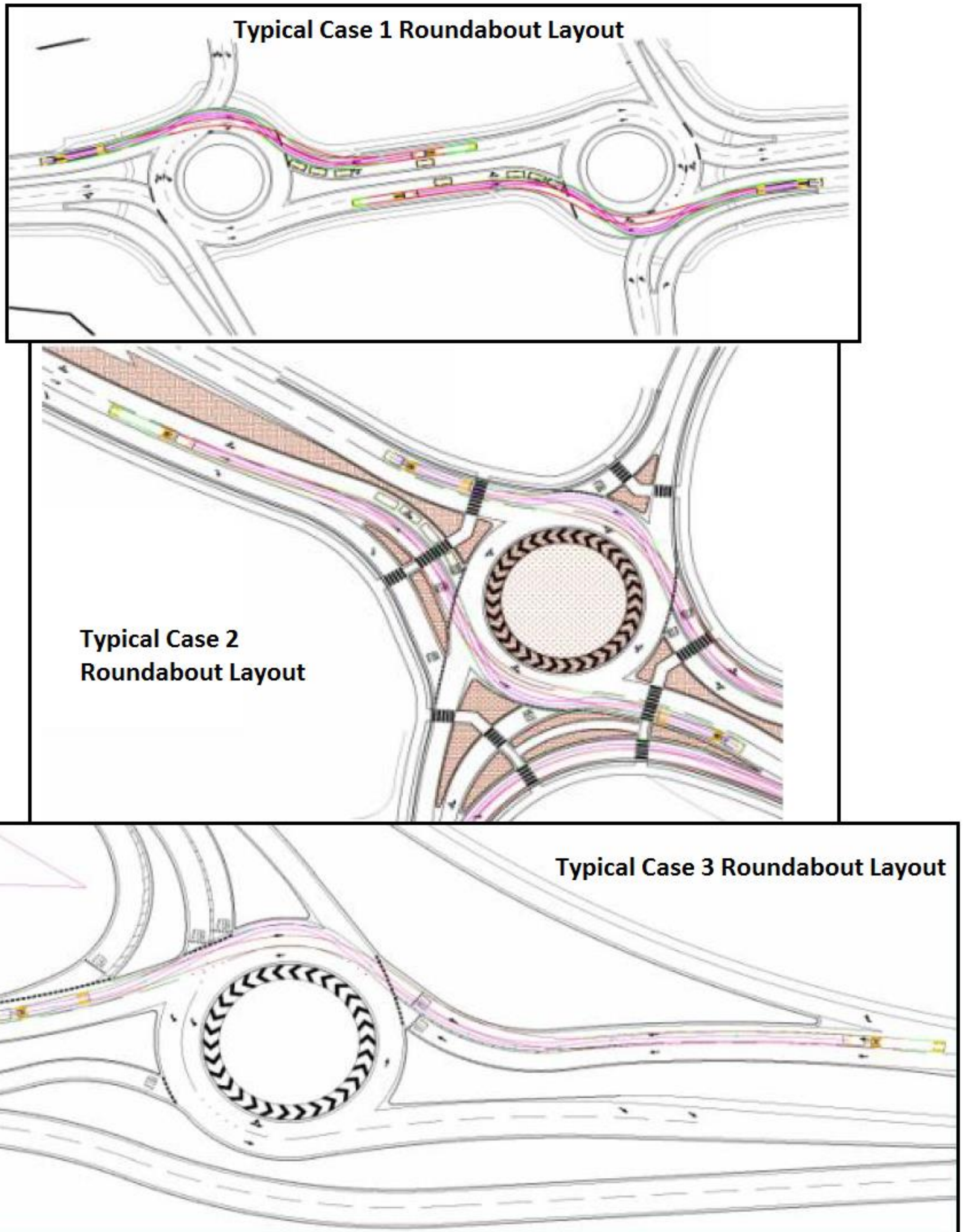
A "Joint roundabout truck study" conducted by Wisconsin DOT (WisDOT) and Minnesota DOT (MnDOT) and their consultants team (*22*) have studied better ways to understand and improve the accommodation of trucks at multilane roundabouts. This study was a four - phase study and the available report provides a summary for the first three phases. Phase 1 studied the current design practices, and obtained inputs from trucking industry via a survey to develop design guidelines for accommodating trucks in multilane roundabouts. A truck in this study is defined as the design vehicle used on state, trunk highways, WB-62 is considered a design vehicle for MnDOT and WB-65 considered as a design vehicle for WisDOT (*22*).

Multilane roundabout designs in the US were categorized into case 1 roundabouts, case 2 roundabouts, and case 3 roundabouts based on the data collected for 18 representative roundabouts located in Wisconsin, Minnesota, Michigan, and Arizona. Figure 2.13 illustrates the example layout of case 1, case 2, and case 3 roundabouts. Case 1 roundabouts are designed such that the trucks encroach into adjacent lanes as they enter, circulate and exit the roundabout. Case 2 roundabouts are designed such that the trucks are accommodated in the lane as they enter, but may encroach the adjacent lanes while circulating and exiting the roundabout. Case 3 roundabouts are designed such that the trucks are accommodated in lane as they enter, circulate, and exit the roundabout. Investigation of the geometric characteristics of the 18 study roundabouts has showed that each roundabout case type has its unique geometric characteristics relative to the other case types (*22*).

Table 2.6 shows the observed design characteristics of the 18 study roundabouts based on case types. Heavy vehicle percentages for the 18 study roundabouts ranged from 5.5% to 18.6%. It was observed that case 2 and case 3 roundabouts were in the higher end of the heavy vehicle percentage range. Case 1 roundabouts in this study were observed to have slightly more truck related crashes and caused delays at entries due to truck encroachment (*22*).

This study also sent out questionnaires to truck companies/drivers to determine their potential concerns about navigating roundabouts. The responses indicated that more information should be conveyed before a roundabout entry to better understand if the truck should stay in the lane or use both lanes. Several responses indicated that the actions of the passenger car drivers may cause conflicts with the trucks and the truck drivers preferred to stay in the lane at roundabout and therefore recommended wider lanes and/or better signage (*22*).

Figure 2.13: Example Layouts of Case 1, Case 2, and Case 3 Roundabouts



Source: Joint Roundabout Truck Study (*22*)

Table 2.6: Observed Design Characteristics of 18 Study Roundabouts

Item	Case 1	Case 2	Case 3
Entry Radii	64 to 75 feet	63 to 138 feet	120 to 130 feet
Entry Radius Length	less than 50 feet	50 to 100 feet	100 feet or more
Entry Widths	24 to 28 feet	32 to 34 feet	32 to 34 feet
Transitional Widening	limited or no use of widening	was implemented	was implemented
ICD	162 to 200 feet	160 to 194 feet	190 to 220 feet
Approach Alignment	Varies	Typically offset left	Typically offset left

Source: Joint Roundabout Truck Study (*22*)

Table 2.7: Apron Width Range and Average by Roundabout Case Type

Roundabout Case Type Selected	Apron Width Ranges	Average Apron Width
Case 1 (4 roundabouts)	5.0 ft to 14.5 ft	10.88 ft
Case 2 (6 roundabouts)	8.0 ft to 15.0 ft	11.33 ft
Case 3 (3 roundabouts)	10.0 ft to 21.5 ft	15.50 ft

Source: Joint Roundabout Truck Study (*22*)

Twelve of the 18 roundabouts had data on the truck apron width. From Table 2.7, it can be concluded that as the case number increased, the apron width required also increased. It was concluded from phase 1 of the study, that each case has advantages and disadvantages, and these tradeoffs needs to be considered for planning and design process (*22*).

The objective of Phase 2 of the "Joint roundabout truck study" was to collect video data for the selected roundabouts in phase 1 and observe the truck operations. Trucks at case 1 roundabouts were observed to be navigating as expected using both lanes, and at rare occasions rode over the outside entry curbs. For case 2 and case 3 roundabouts, when potential conflicting traffic was present, trucks stayed in their lane on the approach 91% of the time and stayed in their lane while circulating 83% of time. When potential conflicting traffic was not present, trucks stayed in their lane on the approach 71% of the time and stayed in their lane while circulating 37% of time. It was concluded, from phase 2 of the study, that trucks mostly operated as expected at these three design case. However, the presence of adjacent traffic influenced the truck 'driving in-lane behavior' when trucks were entering and circulating. One of the limitations of the study was that, small sample sizes of case 2 and case 3 roundabouts were available for phase 1 and phase 2 investigations (*22*).

Table 2.8: Typical Design Parameters for Two-Lane Roundabouts

Item	Case 1	Case 2	Case 3
Inscribed Circle Diameter[a]	150' to 190'	160' to 210'	180' to 220'
Inner Circulatory Lane Width[b]	11' to 13'	11' to 13'	13' to 15'
Outer Circulatory Lane Width[b]	13' to 15'	13' to 15'	15' to 18'
Approach Gore Widths	Not used	2' to 6'	2' to 6'
Entry Width[a]	28' to 32'	32' to 34'	32' to 34'
Entry Radius	65' or greater	65' or greater	65' or greater
Controlling Radius	65' or greater	65' or greater, 100' to 130' typical	65' or greater, 100' to 130' typical
Controlling Radius Length	No max, typically 70' or less	No max, typically 80' +	No max, typically 80' +
Entry Angle	16 to 30 degrees	16 to 30 degrees	16 to 30 degrees
Length of Two Full Lanes for Lane Add[c]	Low V/C – Short length Medium V/C – Medium length High V/C – Long length	Low V/C – Short length Medium V/C – Medium length High V/C – Long length	Low V/C – Short length Medium V/C – Medium length High V/C – Long length
Exit Widths[a]	28' to 32'	28' to 32'	28' to 32' (where large radius or tangential exit used)

* - Based on site conditions, ROW constraints, specific design vehicle, and other factors, designers may choose to implement geometrics outside these recommended ranges; however the overall design should comply with FHWA and WisDOT or MnDOT guidance documents
a - Measurements are from face of curb to face of curb (includes 2' gutter pans on each side)
b - Measurements are from edge gutter flange line to lane line
c - In addition to the segment with two full lanes, a taper following FDM guidance is needed to transition from one to two lanes

Source: Joint Roundabout Truck Study (*22*)

Phase 3 of the "Joint roundabout truck study" provided design guidance for accommodating trucks at roundabouts on state, trunk highways that were generated by the study team based on the designs for more than 700 roundabouts. These design guidelines in phase 3 were provided for accommodating trucks that are in addition to the higher priority requirements from established design guidance documents from FHWA, WisDOT, and MnDOT. It was concluded that a well designed, case 3 roundabout, which meets the applicable geometric design requirements, provides safe and efficient operations, and also provides better truck accommodation (*22*).

Certain specific locations, such as where designated OSOW routes exist, multilane approaches on arterials, interchange ramps, truck stops, and industrial/warehouse districts, warrant additional consideration for a case 3 design. Case 2 designs should be considered as the next most desirable options if case a 3 design is not practical. Case 1 designs should be considered when truck volumes are low and/or if a case 3 or case 2 design has undesirable impacts. Table 2.8 shows the typical design parameters for two-lane roundabouts (*22*).

2.10 Accommodating OSOW Vehicles at Roundabouts

A pooled fund study sponsored by eight states and three non-state sponsors was conducted by Kansas State University, with this dissertation author providing survey input and analyses and all key OSOW accommodation designs and their analyses (incorporated herein) and with Kansas being the lead State (*2*). The objectives were to compile current practice and research by various US states and foreign countries, related to the effects that OSOW have on roundabout location, design, and accommodation. This study also filled information gaps with respect to roundabout design and operations for OSOW vehicles. This study conducted four different surveys to obtain valuable information regarding OSOW vehicles and their accommodation at roundabouts from 50 US state agencies and OSOW haulers (*2*).

Survey 1 was conducted with 50 US states through American Association of State Highway and Transportation Officials (AASHTO) contacts and a total of 37 US states responded to the complete survey. The main objective of the first survey was not on roundabout related issues, but rather to focus on permits that are required to transport OSOW loads and to determine the bottlenecks for OSOW on their roads and to determine which states had roundabouts on state highways. Thirty-one (31) responding states (83.8% of the respondents) had a category for different types of oversize/overweight (OSOW) loads. Thirty-five (35) responding states (94.6% of the respondents) require a permit for transporters to use states highway system that exceeds states' statutes. Of the respondents, only Montana and Nebraska don't require a permit. Only eight (8) states (21.6% of the respondents) reported having a typical design vehicle to aid in determining needed roadway geometry for OSOW vehicles and twenty eight states (75.7% of the respondents) do not. Twenty-five (25) states (67.6% of the respondents) responded that they have designated truck routes and nine (9) states (24.3% of the respondents) responded that they have designated OSOW routes. The list of reported restrictions, with the percentage of respondents reporting the restriction as a known problem to OSOW, is shown below (*2*).

1. Bridges 100%
2. Overhead structures 89.2%
3. Signs and signals 70.3%
4. Intersections 64.9%
5. Interchanges 56.8%
6. Rail-highway grade crossings 48.6%
7. Utilities 48.6%
8. Overhead wires 40.5%
9. **Roundabouts 35.1% (13 States)**
10. Curbs 18.9%
11. Raised channelization 18.9%

The above restrictions were arranged in the order of the percentage reporting the restriction as a problem for OSOW loads. For example, bridges were stated as a known restriction for OSOW loads by 100% of all responding states. It has to be observed that roundabouts were the 9th most reported for OSOW loads among 11 possible restrictions (*2*).

The states replying that roundabouts are a known problem were Connecticut, Idaho, Iowa, Kansas, Louisiana, Minnesota, Missouri, Nebraska, New York, Nevada, Ohio, Virginia, and Wisconsin (*2*).

Survey 2 had more questions related specifically relate to roundabouts and was conducted with the same 50 US states through AASHTO contacts and, after follow up e-mails and phone calls, all the 50 states responded to this survey yielding a 100% survey response rate. All states except Alabama, Hawaii, Idaho, North Dakota, Oklahoma, Texas, Utah, and West Virginia reported having modern roundabouts on their state highways. All states except Delaware, Nebraska, and Rhode Island reported having modern roundabouts on non-state roadways. Results of survey 2 were summarized in section 3.1 of this dissertation (*2*).

Survey 3 was prepared to obtain information on roundabout concerns directly from trucking companies and/or truck drivers. Company names were obtained from searching the internet for companies that hauled oversized loads, calls were made to the company offices asking if they would consider answering a survey, and the surveys were sent out to those who indicated they would. However, there were zero responses returned. A vice president with the Specialized Carriers & Rigging Association (SC&RA) offered to take the survey to a meeting of 13 SC&RA regional managers and they provided one good survey response which was a composite of the vice president and the 13 other regional managers of SC&RA. This response provided some of the best insight available from experienced experts in OSOW hauling. Some of the important responses from survey 3 are summarized below (*2*).

There are unique problems with roundabouts as regular roundabout design does not consider permit loads that exceed normal parameters of length, widths, and weights. Some of the suggested solutions from survey 3 were that roundabouts should be well designed for normal vehicles as well as for expected permit loads by implementing various features such as widening the roundabout access, removing the barriers to OSOW movement, and designing more traversable curbs. Also, it was the respondents opinion that design engineers should consider broader use of OSOW user groups rather than just smaller vehicles and legal loads when designing roundabouts (*2*).

Some of the specific concerns with roundabouts mentioned by the survey 3 respondents as major disruptions of traffic flow that create problems for permit loads while negotiating a roundabout are listed below (*2*):

1. Lowboy (low clearance) vehicles have problems with curbs more than 3 inches in height.
2. There are issues with OSOW riding up on the curb on the exterior of the roundabout.
3. OSOW vehicles don't like hauling their long loads through roundabouts with tight radii.
4. Fixed objects within the center of the roundabout cause problems.
5. Slopes of circular roadway and/truck aprons cause risk of overturning.
6. Drivers not understand what the truck apron is for and need education.

Some of mitigation strategies mentioned by the survey 3 respondents summarized below offer some general solutions but do not provide complete or specific solutions. Better solutions can be provided with a combination of these mitigation strategies and the capability of modifying the roundabout, or various components (if needed), or, in some cases, modifying flow patterns, depending on the size and configuration of the load (*2*). (These will be covered in detail in later sections of this dissertation)

The mitigation strategies from the survey 3 respondents are (*2*):

1. wide truck aprons (12 feet or more) with a minimum slope and mountable curb,
2. custom center islands to address known left turns,
3. tapered center island to support through movements,
4. paved areas behind curbs (right side for off-tracking),
5. installing removable signs and setbacks for permanent fixtures (light poles),
6. allow trucks to cross over the median (stamped, depressed, or corrugated), in a counter flow direction, before entering the roundabout to make a left turn in the opposing lane and then cross back over after the turn, and
7. right-turn lanes (sometimes gated).

It was also mentioned by the survey 3 respondents that it would be beneficial if loads could go straight through the roundabout considering that a removable barrier would have to be in place to prevent small vehicles from doing so, or the pathway would have to be offset so the entrance would lineup with the left approach where the driver would have to move to the left lane of the approach, which would be illegal in all or most states. However, OSOW are usually escorted, so traffic control should be no problem. There were also instances where signs, lights, and other stationary objects were removed for an OSOW movement and later replaced (*2*).

As there was only one, but a very insightful response from survey 3, the researchers partnered with the American Transportation Research Institute (ATRI) for conducting survey 4. It was agreed to let ATRI add several questions of interest to them, and then they distributed the survey to their members. The surveys came back to the K-State researchers for analysis (*2*).

A total of 60 responses were obtained from survey 4; however, only 18 respondents answered that they use OSOW permits. Each question was summarized in three different categories, i.e., one based on the total 60 respondents, one based on the 18 respondents who answered they use OSOW permits, and the third based on the 37 respondents who answered they do not use OSOW permits. Most of the OSOW haulers (15 OSOW haulers, 83.3% of the total

OSOW haulers responded) operate in the for-hire sector of trucking industry and Table 2.9 summarizes all the responses based on sector of trucking industry being operated. Most of the OSOW haulers operate in truckload carrier type (7 OSOW haulers, 38.9% of the OSOW haulers responded) and Specialized (flatbed) carrier type (7 OSOW haulers, 38.9% of the OSOW haulers responded). Table 2.10 summarized the survey responses based on carrier type that best described the company. Most of the OSOW haulers haul either heavy machinery/equipment (6 OSOW haulers, 33.3% of the total OSOW haulers responded) or general freight/truckload (4 OSOW haulers, 22.2% of the total OSOW haulers responded). Some other commodities were oilfield equipment, production buildings, dry bulk commodities, coil steel, grain, and bulk liquids. Table 2.11 categorizes the respondents based on the type of commodity trucks typically haul (*2*). More results from survey 4 are presented in section 3.2 of this dissertation.

Table 2.9: Sector of Trucking Industry Being Operated

Sector of Trucking Industry being Operated	All Respondents *Responses (%)*	Respondents who use OSOW Permits *Responses (%)*	Respondents without OSOW Permits *Responses (%)*
For-hire	45 (75%)	15 (83.3%)	25 (67.6%)
Private Fleet	13 (21.7%)	2 (11.1%)	11 (29.7%)
Mail/Parcel	0	0	0
Other	2 (3.3%)	1 (5.6%)	1 (2.7%)

Source: Accommodating Oversize Overweight Loads at Roundabouts (*2*)

Table 2.10: Carrier type that Best Describes the Company

Carrier type that best describes the Company	All Respondents *Responses (%)*	Respondents who use OSOW Permits *Responses (%)*	Respondents without OSOW Permits *Responses (%)*
Truckload	23 (38.3%)	7 (38.9%)	14 (37.8%)
Less-Than-Truckload	8 (13.3%)	1 (5.6%)	6 (16.2%)
Private Fleet/Shipper	8 (13.3%)	2 (11.1%)	6 (16.2%)
Specialized (Flatbed)	9 (15%)	7 (38.9%)	2 (5.4%)
Specialized (Tanker)	5 (8.3%)	0	4 (10.8%)
Express/Parcel	0	0	0
Other	5 (8.3%)	1 (5.6%)	4 (10.8%)

Source: Accommodating Oversize Overweight Loads at Roundabouts (*2*)

Table 2.11: Type of Commodity Drivers or Contractors Typically Haul

Type of Commodity Drivers or Contractors Typically Haul	All Respondents *Responses (%)*	Respondents who use OSOW Permits *Responses (%)*	Respondents without OSOW Permits *Responses (%)*
Consumer/Retail Products	3 (5%)	0	3 (8.1%)
Household Goods	2 (3.3%)	0	2 (5.4%)
Truck/Auto Transport	1 (1.7%)	0	0
Modular/Mobile Homes	0	0	0
Heavy Machinery/Equipment	6 (10%)	6 (33.3%)	0
US Mail/Parcel	0	0	0
General Freight/Less-than-Truckload	1 (1.7%)	0	1 (2.7%)
Petroleum Products	7 (11.7%)	0	6 (16.2%)
Mine Ores	0	0	0
Forest Products/Building Materials	1 (1.7%)	1 (5.6%)	0
Agricultural Products/Livestock	4 (6.7%)	1 (5.6%)	3 (8.1%)
Processes Foods	3 (5%)	0	3 (8.1%)
General Freight/Truckload	14 (23.3%)	4 (22.2%)	8 (21.6%)
Other	17 (28.3%)	6 (33.3%)	11 (29.7%)

Source: Accommodating Oversize Overweight Loads at Roundabouts (*2*)

2.10.1 Wisconsin DOT OSOW Freight Network Guidelines for Roundabouts

Wisconsin DOT has designed a procedure to check the low ground clearance vehicles' clearance problems at roundabouts that are present on some segments of their OSOW freight network. The procedure to narrow which roundabouts needs this ground clearance analysis is described below:

"

Evaluating Roundabouts to be considered for AutoTurn Pro Analysis:

1) *Is the roundabout located on the OSOW Freight Network, primary and secondary routes? (The location of the regional OSOW Freight Network maps are located: http://dotnet/dtid_bho/extranet/maps/docs/freightnetwork.pdf)*
    a. *Yes: Continue to next step.*
    b. *No: Analysis is not required but is recommended on routes that are known or anticipated to experience standard legal size lowboys.*
2) *Was the roundabout built in 2011, or programmed for construction in 2012 and after?*
    a. *Yes: If it is located on the OSOW Freight Network, AutoTurn Pro is required to complete an analysis to determine if conflict points are present.*

b. *Clearance issue found?*
c. *If yes: Reconfigure the slopes within the conflict areas and check the surrounding area (i.e. approaches) for additional conflict points. If the truck is tracking outside of roundabout, reconfigure as necessary.*

3) *Roundabouts constructed in 2010 and prior years, it is not necessary at this time to analyze for OSOW lowboy clearance." (2)*

Some general design guidelines to design roundabouts on the OSOW freight network are (*2*):

- use truck apron slope of 1% towards the roadway on all roundabouts,
- use pill shaped center island or other shape center island where appropriate to accommodate anticipated OSOW movements,
- a circulatory roadway crown must be installed for roundabouts with 2/3 sloped inward and 1/3 sloped outward on all roundabouts,
- a 4-inch type G/J curb and gutter should be installed on outside of the approach when off-tracking of large vehicles is expected, and
- an 8-inch thickness concrete pad should be installed behind the back of the curb along the outside entrance area where the off-tracking is anticipated. A maximum of 1% slope can be used.

Chapter 3 - Surveys with 50 US States and Trucking Agencies and Guidelines to Build Statewide Freight Networks

Responses for survey 1, survey 3, and some questions in survey 2 and survey 4 were summarized in section 2.10 of this dissertation. Details relevant to the accommodation strategies developed are presented in this chapter. Many questions in survey 2 and survey 4 were included in the survey for the results to be used for developing the accommodation strategies for this dissertation. Therefore the specific questions and their responses in the survey 2 and survey 4 are analyzed and presented in detail in this chapter.

3.1 Survey 2

Survey 2 was then conducted with the AASHTO member contacts from the 50 US states to obtain detailed information regarding roundabouts and their issues with OSOW vehicles. A total of 32 questions were included in Survey 2. However, only nine questions included in the survey were intended to be used in this dissertation for developing accommodation strategies and therefore the responses for these nine questions from survey 2 were analyzed with the accommodation strategies in mind and are presented in this chapter. These selected nine questions from survey 2 were presented in Appendix B.

3.1.1 Concerns about Roundabouts from the Companies that deal with Vehicles Requiring a Permit

One of the most informative questions on survey 2 was the question asking respondents, "Have you heard any concerns about your roundabouts from companies that deal with a vehicle requiring a permit?" Answers that are considered to have information pertinent to accommodation strategies are paraphrased below. Detailed responses can be found in Appendix C. There were concerns about:

- long trailers, 53 feet plus, and long doubles >100 and 120 feet,
- trucks required to stay in lanes on the approaches,
- lowboy vehicles built to limit vertical roundabout clearance to approximately 3 inches hanging up,

- no identifying roadway network based on geometric design limitations,
- roundabouts with tight radii; also clearance issues.
- oversize loads riding up on the exterior curb and high curbs,,
- high-profile curbs on truck apron,
- too narrow lanes,
- drivers not understanding truck aprons are designed to be mounted by tractor-trailer combination vehicles,
- placement of signs and landscaping,
- objects in the center island, and
- roundabouts built too close together.

It is of great importance that the most mentioned concern was vertical clearance, which was mentioned six times – seven if the concern over the outside curb was mentioned. (To date, this has been a neglected issue, except for one other study). Long loads were mentioned three times. The state of Washington indicated they have all sorts of problems with standard intersections but have not had any issues with roundabouts.

However, Washington responded with the suggestions that would tend to help mitigate that states's concerns and are listed below:

- mountable curbing,
- removable signage,
- addressing stationary landscape features, and
- larger radius design to accommodate longer vehicles.

3.1.2 Problems with OSOW Vehicles Navigating Roundabouts

A related question was the question which asked, "Have you heard of any problems with OSOW vehicles navigating roundabouts?" The problems with roundabouts, sent by some respondents, are paraphrased below:

- Alaska's response was very informative. They wrote that meetings with the trucking company led to better design templates and larger diameter roundabouts overall; also, in heavy trucking areas, full use of individual lanes and truck aprons would be beneficial.

- One state reported the permits department issued a permit which allowed OSOW through a roundabout not designed to accommodate a large vehicle. However, other states reported they did coordinate with the OSOW permit section to determine vehicle sizes and geometric requirements on permitted routes.
- Getting long loads through roundabouts required removal of permanent signing, special law enforcement action, and rerouting of some loads.
- One state reported placement of a roundabout eliminated its use for OSOW transport.
- Washington [state of] reported a unique problem with a roundabout in a local agency where the local agencies did not want OSOW going through the location because they did not want their landscaping injured.

It is apparent that the above comments lead to an understanding that communication is very important. This includes internal communication between permitting sections and designers, between designers and trucking associations, and also between states and local agencies where local agency roundabouts might be important on some OSOW permitted routes.

3.1.3 Studies/Information of how OSOW Vehicles or Trucking Associations Accept Roundabouts in a State

Another question in this study is, "Do you know of any studies in your state or have any information or insight into how OSOW vehicles or trucking associations accept roundabouts in your state?" The Wisconsin/Minnesota study mentioned in section 2.9 appeared to be the most relevant, although it was not specifically directed toward OSOW. It is notable also that they have developed a freight network, with designated OSOW sections. It seems that all states could benefit from a freight network in general and some study of developing OSOW routes.

The following is a quote from Oregon's response to the question regarding do they know of problems with OSOW vehicles navigating roundabouts:

> "We have had some minor issues with the only roundabout on the state highway system in Oregon. It is a multi-lane, so not as much problem for OSOW. From what we have heard, most of the problems have been on roundabouts on city streets. We hear they are too small. Unfortunately, due to misunderstanding about roundabouts, the freight

haulers assume we would build the small diameter roundabouts on state highways. We are working to educate the industry. There have been a few cases where heavy haulers had to rebuild curbs/landscaping, but much of the complaints seem to be more anecdotal in nature with few specifics".

Washington [state of] reported that one roundabout project in particular had an overwhelming opposition from a local trucking company and a 130-foot articulated load was used as the design vehicle and the central island was designed to be mountable. Again, as indicated above in other survey question responses and comments, clearances and mountable curbs appear to be one of the most, if not the most, reported concerns in OSOW transport through roundabouts.

Wisconsin responded that mega high (16'+) and wide (16'+) and long (225'+) and/or heavy (350K+) vehicles on occasion, needed to be rerouted. However, they stated that most of the OSOW fleet can get through either in the direction of traffic or counter-flow (traveling the wrong way through the roundabout) , depending on the roundabout design and year built. They do suggest that removable signs, wide truck aprons, and tapered or custom center islands are modifications that make roundabouts more friendly for OSOW. Their suggestions correspond to concerns and problems in other states that have been reported on the second survey, i.e. low vertical clearance, lack of obstructions in the center island, and placement for removable signs are important potential countermeasures.

Maine mitigated similar problems to ones mentioned in the paragraph above (vertical and horizontal clearance) by providing an overlay at a roundabout which reduced the truck apron curb height from 4 inches to 3 inches. They also modified the geometry to remove the vertical exterior curb and replaced it with a sloped, mountable curb.

North Carolina responded that they have modified their curbing around the apron so it is not an abrupt change in elevation. Their latest roundabout has experienced issues with trucks not using the apron and damaging outside curbs, etc.

3.1.4 Input of OSOW Companies/Organizations in Highway Design

Input of OSOW companies/organizations that deal with OSOW vehicles on highways include the following concerns: (refer to Appendix D for detailed responses):

- curb height and shape of curbs,

- lack of OSOW companies' input; only sought for project meetings, special design meetings, and during public hearings,
- rolled curbs and understanding OSOW routes , and
- central island landscaping.

3.1.5 State Agencies Interaction with OSOW Vehicle Owners/Operators or Trucking Association

Fifteen (15) states (Alaska, Arizona, California, Iowa, Kansas, Maine, Montana, Nebraska, Nevada, New York, Oregon, South Carolina, Tennessee, Washington, and Wisconsin) responded that they interact with OSOW vehicle owners/operators or trucking associations on designs such as roundabouts. The author believes interaction of this nature should be universal.

3.1.6 Roundabouts on State or Non-State Routes on which OSOW Vehicles might be Routed

Thirty (30) states (60% of the responding states) replied they have roundabouts on state or non-state routes on which OSOW vehicles might be routed. They are Alaska, Arizona, Arkansas, California, Colorado, Connecticut, Georgia, Illinois, Iowa, Kansas, Kentucky, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, Oregon, Pennsylvania, South Carolina, Washington, Wisconsin, and Wyoming. Nine (9) states (18% of the responding states) replied they do not have roundabouts on state or non-state routes on which OSOW vehicles might be routed and they are Delaware, Florida, Indiana, Louisiana, Montana, Ohio, Rhode Island, South Dakota, Tennessee, and Virginia.

Twenty-four (24) states (48% of the responding states) take OSOW routes into consideration when planning or designing a roundabout. Seventeen (17) states (34% of the responding states) do not take OSOW routes into consideration when planning or designing a roundabout. More details can be found in Appendix E.

3.2 Survey 4

A total of 47 questions were included in Survey 4. However, only 22 questions included in the survey were relevant to developing the accommodations developed in this dissertation and therefore the responses for these 22 questions will be presented and analyzed in this chapter. These 22 questions from survey 4 used for analysis in this chapter were presented in Appendix B.

KSU's, AXIO online survey was used for ATRI to distribute a link from the prepared survey to ATRI members. A total of 60 responses were returned and the results from these responses are summarized below. Of the 60 responses, only 18 of the respondents answered that they use OSOW permits, i.e., from the survey answer to a question asking if they use permits for loads 37 of the respondents answered "no" and therefore, it was assumed they do not haul OSOW loads *(the basic definition of OSOW is a load requiring a permit, a legal requirement in most states)* and five did not answer that question. Thus, several questions designed to specifically address OSOW haulers would not apply to them.

3.2.1 Details of Presenting Respondents' Answers

In the summary tables and charts below, whenever the total number of responses for a particular question are not equal to the total number of returned responses or 100%, it has to be understood that a few of the respondents did not provide replies to that particular question.

Question 30 of survey 4 was designed to find out if the responding trucking agencies use OSOW permits. Only 18 respondents answered they were using vehicles requiring OSOW permits and 37 respondents replied that they do not use OSOW permits. In this case, the sum of the respondents using OSOW permits (18) and respondents not using OSOW permits (37) is 55 and it does not add up to 60. This situation means that five respondents did not answer this particular question.

Each question was summarized in three different categories, i.e., one based on the total 60 respondents, one based on the 18 respondents who answered they use OSOW permits, and the third based on the 37 respondents who answered they do not use OSOW permits. However, a few questions in the survey were exclusively designed to be answered by OSOW haulers and therefore, only the 18 responses that mentioned using OSOW permits were considered in summarizing and analyzing these questions.

3.3 Summary of Survey 4 Responses

3.3.1 Are Roundabouts any more of a Problem Compared to Intersection and Other Highway Features?

Figure 3.1 summarizes results of the Question "Are roundabouts any more of a problem compared with other intersections?" for different category of respondents. It can be observed that 88.9% (16 respondents) of the OSOW haulers felt roundabouts are a problem compared to other intersections. The comments from the OSOW haulers for this question were summarized in Table 3.1. From Table 3.1, it was almost unanimous that roundabouts are more of a problem than other types of intersections. However, the one 'No' in the table with comment 'not if build right' is very insightful.

Figure 3.2 summarizes results of the Question "Are roundabouts any more of a problem than other highway features which may be a concern to oversize/overweight loads such as narrow bridges, wires, curbs, ramps, and so forth?", for different categories of respondents. It can be observed that 83.3% (15 respondents) of the OSOW haulers felt that roundabouts are more of a problem than other highway features, which may be a concern to oversize/overweight loads such as narrow bridges, wires, curbs, ramps, and so forth. Comments from the OSOW haulers for this question were summarized in Table 3.2. From Table 3.2, it was almost unanimous that roundabouts are more of a problem than highway features which may be of concern to oversize/overweight loads such as narrow bridges, wires, curbs, ramps, and so forth. This is contrary to results from OSOW survey 1 in section 2.10 of this dissertation which listed 11 obstructions to OSOW, and roundabouts were 9th of 11. This may be because the survey 1 was conducted with state officials and survey 4 was conducted with OSOW haulers. It has to be understood that if specific OSOW movements that are expected at an intersection known, the roundabout can be built to accommodate the expected OSOW movements. Chapter 4 of this dissertation specifically addresses how to design roundabouts when OSOW movements are expected.

Figure 3.1 Summary of the Question "Are Roundabouts any more of a Problem compared with Other Intersections?"

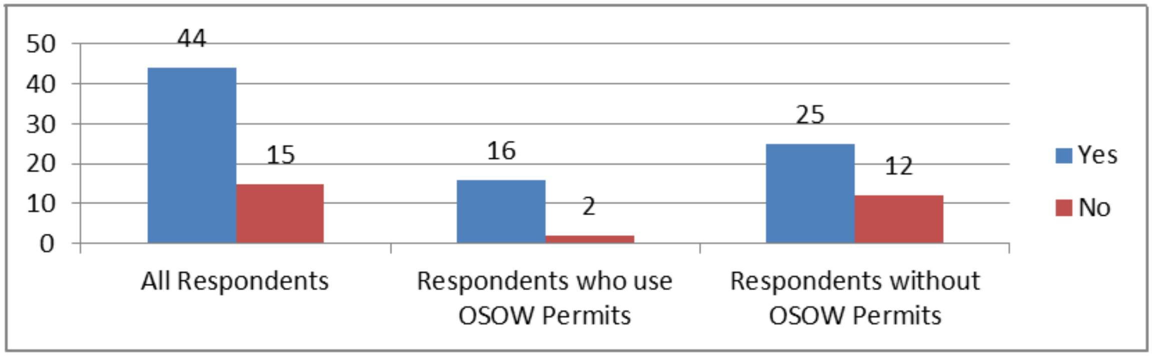
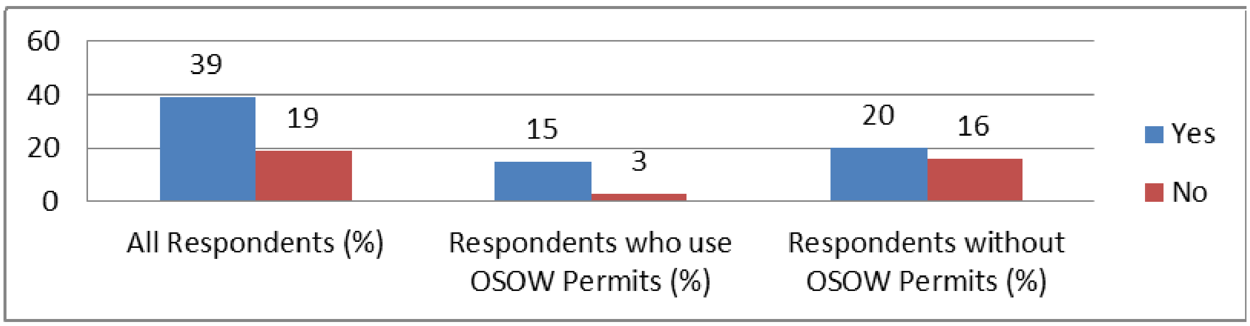


Figure 3.2 Summary of the Question "Are Roundabouts any more of a Problem than Highway Features which may be of a Concern to Oversize/Overweight Loads such as Narrow Bridges, Wires, Curbs, Ramps, and so Forth?"



3.3.2 Unique Problems with Roundabouts

Table 3.3 summarizes results of the Question "Do you have any unique problems with roundabouts, and if so, please explain?", asked of respondents who use OSOW permits Most of the problems are addressed in this dissertation. From Table 3.3, the comment about clearance issues (ground clearance) is definitely considered a problem and is addresses in detain in chapter 5. Also problems such as trailer " hangups" at curbs, loads unable to get through the roundabout can be mitigated by better designing the roundabout for expected vehicles which is addresses in chapter 4.

3.3.3 Solutions to Mitigate Problems at Roundabouts

Table 3.4 summarizes the responses for Question 17 for OSOW haulers, "If the answer to question 15 and/or 16 is "yes", what possible solutions do you think might mitigate the problem(s) without compromising their safety benefits to passenger vehicles, or requiring excessive right of way and cost?". It can be observed form Table 3.4 that the most mentioned solution is by providing larger roundabout which can be agreed as better way of accommodating trucks. However, the roundabout should not be bigger than necessary so as not to diminish safety benefits of roundabouts.

Table 3.1 Comments for the Question "Are Roundabouts any more of a Problem Compared with Other Intersections?"

Survey Respondent Number (OSOW Hauler)	Are roundabouts any more of a problem compared with other intersections?	Comments
1	Yes	To narrow a radius for trucks, especially if there is a curb in the middle, and also trailers track in the other lane if not built right
2	Yes	Clearance issues, liability issues, driver education challenges (not ours but the traveling public)
3	Yes	We have several roundabouts in town and they are a substantial problem for large trucks as vehicles encroach in adjacent lanes. If lanes are wider than the normal, they can be ok.
4	Yes	Depends on if they have round or square corners [curb radius?] - and the height of them
5	Yes	Here in Billings, MT, the roundabouts are very difficult to maneuver with the rocky mountain doubles.
6	Yes	Difficult to move oversize loads. Should never be in middle of major highways.
7	Yes	Double-drop trailers and 53-foot-spread axle trailers, as well as any stretch trailers have issues with roundabouts.
8	Yes	Too many drivers feel it is an automatic green light and no [do not] yield.
9	Yes	We haul many oversized loads and they are limiting the routes we can use.
10	Yes	Yes, the trailers drift into the second lane causing the potential for a collision.
11	Yes	The concept is posing an extreme threat to the movement of oversize cargoes and results in routing headaches and unnecessary out-of-route costs to our shippers. It is imperative that roundabouts not be allowed on state or federal highways.
12	No	Not if built right. Note that large trucks are not allowed on residential streets except for deliveries and moves.

Note: Only minor editing for grammar and spelling was performed for responses for clarification.

Table 3.2 Comments for the Question "Are Roundabouts any more of a Problem than Highway Features which may be of a Concern to Oversize/Overweight Loads such as Narrow Bridges, Wires, Curbs, Ramps, and so Forth?"

Survey Respondent Number (OSOW Hauler)	Are roundabouts any more of a problem than other highway features which may be a concern to oversize overweight loads such as narrow bridges, wires, curbs, ramps, and so forth?	Comments
1	Yes	The traveling public is interacting on three or four points as well as not truly educated on how to traverse a roundabout.
2	Yes	Yes, they can be a problem for heavy haul and car haulers due to height of trailer from ground.
3	Yes	States will not route you through them.
4	Yes	Yes, the width of the lanes do not compensate for articulating CMV or OW / OS [OSOW]load.
5	Yes	They are, and will continue to be a major operational and safety issue for O D [OSOW]carriers.
6	Yes	There are more and more of them and unlike narrow bridges, they are not as well documented for routing purposes.
7	No	If the road is for long vehicles, it needs a bigger radius.

Note: Only minor editing for grammar and spelling was performed for clarification in a few cases when felt necessary.

Table 3.3 Summary of Responses for the Question “Do you have any Unique Problems with Roundabouts, and if so, please Explain?”

Do you have any unique problems with roundabouts, and if so, please explain?	Comments
Yes	The traffic volumes in and around them make it hard for trucks to enter safely. It takes a long time especially in multilane roundabouts to have an opportunity to enter safely.
Yes	Clearance issues, sight distance, bike and pedestrian islands, size and radius.
Yes	Roundabouts are too small and the trucks can't stay in the proper lane and smaller traffic doesn't pay attention to signs saying trucks need both lanes. Poor or no directional signage for which lane to be in to get off of the roundabout where you want to and where that street or road goes.
Yes	Both construction and maintenance cost are high especially in snow country
Yes	Elevated and sloped curbs cause trailers to hang up on any turns more than 90degrees
Yes	Loads cannot get through them.
Yes	Yes, the trailer will track from lane 1 to lane 2 or the trailer will run up on the curb/island if lane 2 is being used.
Yes	Continued expansion of roundabouts will force O D cargoes [OSOW] to use only Interstates and inappropriate secondary routes and add needless costs and exposure to accidents. We can foresee tonnage being forced back onto the inefficient rails.
Yes	Typical roundabout design is too small in scale to accommodate large trucks effectively and doesn't provide enough time for larger vehicles to enter without impeding traffic

Note: Only minor editing for grammar and spelling was performed for responses for clarification. Any words in brackets [ ] were added by the author.

Table 3.4 Summary of Responses for the Question "If Answer to Q 15 and/or 16 is "yes", what Possible Solutions you think Might Mitigate Problem(s) without Compromising their Safety Benefits to Passenger Vehicles, or Requiring Excessive Right of Way and Cost"

Survey Respondent (OSOW Hauler)	Q17: If the answer to question 15 and/or 16 is "yes";, what possible solutions do you think might mitigate the problem(s) without compromising their safety benefits to passenger vehicles, or requiring excessive right of way and cost?
1	Make them large enough to accommodate all vehicles including stretch trailers as well as over width and keep the entire roundabout at one level; do not raise the center with a curb
2	Do not build them on Interstate or State Highways, or intersections that connect said highways. Do not build a roundabout anywhere before the state, city and county governments have looked at their long term planning for regional projects both public and private. Did not put a cork in the bottle you want to build a ship in!
3	Increase the diameter of the roundabouts. Add directional signs well ahead of the roundabout. Improve public knowledge of the laws pertaining to roundabouts.
4	Roundabouts with rounded raised corners vs square [radii and curbs?] are much better. Roundabouts need to be at least 2 lanes wide. In KS on hwy 420 between Wichita and Joplin is an example of a bad one (square corners, single lane)
5	The concept of the roundabouts is good, however much more room is needed for trucks to safely utilize them.
6	It is nearly impossible to negotiate the roundabout with rocky mountain doubles without bumping the curb with either the outside steer tire or the rearmost inside tire of the rear trailer..... solution? Bigger/wider roundabouts Also, I have noticed that as my trucks SLOWLY navigate the circle, cars are likely to impatiently pull out in front of the trucks...... I have invited the Motor Carriers of Montana (Assn) to come to Billings and video my trucks as they navigate the roundabouts and would be happy to share the results.
7	Use standard [stop] light controlled intersections
8	Making roundabouts double lanes allows room to maneuver. We much prefer a [stop] lighted intersection because it has the room to make a big enough turn to accommodate the extra long or wide loads.
9	Lets have the 'so-called' Highway Engineers that design these roundabouts actually ride along, or better yet attempt to drive a class 8 TT [trailer truck ?] through the road hazards they have designed. They need "Real World Experience". It cant be done sitting in a building.
10	I would like to see the ability to have blockages in the middle that a patrol could remove to travel through them if the radius was 135' or greater. Do not put them on state corridors so we do not limit commerce.
11	Make the lanes wider in the roundabouts.
12	Keep designs free of shrubs, curbs, rocks and signs, and anything that hinders the use of lowboys and other specialized equipment that is currently used to move today's O D [OSOW] cargo.
13	Wider lanes when requiring OSOW loads to follow traffic flow to right.

Note: Only minor editing for grammar and spelling was performed for responses for clarification. Any words in brackets [ ] were added by the author.

3.3.4 Experience with Different Aspects of a Roundabout

Table 3.5 summarizes the respondents' experience with different aspects of a roundabout for different category of haulers. It was observed that the OSOW haulers either had a serious problem or some existing problem which is not so serious at the approach, circulatory roadway, and departure of the roundabout.

3.3.5 Roadway through the Roundabout

Figure 3.3 summarizes the Question 20 responses from OSOW haulers for the question "How beneficial would it be if loads could go straight through a roundabout, if a removable barrier is in place to prevent other vehicles from doing so?". Figure 3.4 summarizes the responses from OSOW haulers for the question "How beneficial would it be if loads could go straight through a roundabout, if the pathway would be offset so the entrance would line up with the left approach (where the driver would have to move to the left lane on the approach)?". It is encouraging to note the majority of OSOW respondents answered that a road through the roundabout would be somewhat or very beneficial. This concept is widely used in Europe and it should be given more consideration in the US. This strategy was designed and it is discussed in Chapter 4.

Table 3.5 Respondents Experience with Different Aspects of a Roundabout

Feature of a Roundabout	Serious Problem Exists			Problem Exists but not so Serious			No Problem		
	All	OSOW	Non OSOW	All	OSOW	Non OSOW	All	OSOW	Non OSOW
The Approach	15	7	7	19	6	11	17	3	14
The Circulatory Roadway	26	12	12	18	4	13	7	0	7
The Departure	15	6	8	27	9	16	9	1	8

Figure 3.3 Summary of OSOW Haulers Responses to the Question "How Beneficial Would it be if Loads Could go Straight Through a Roundabout, if Removable Barrier is in Place to Prevent Other Vehicles from Doing So?"

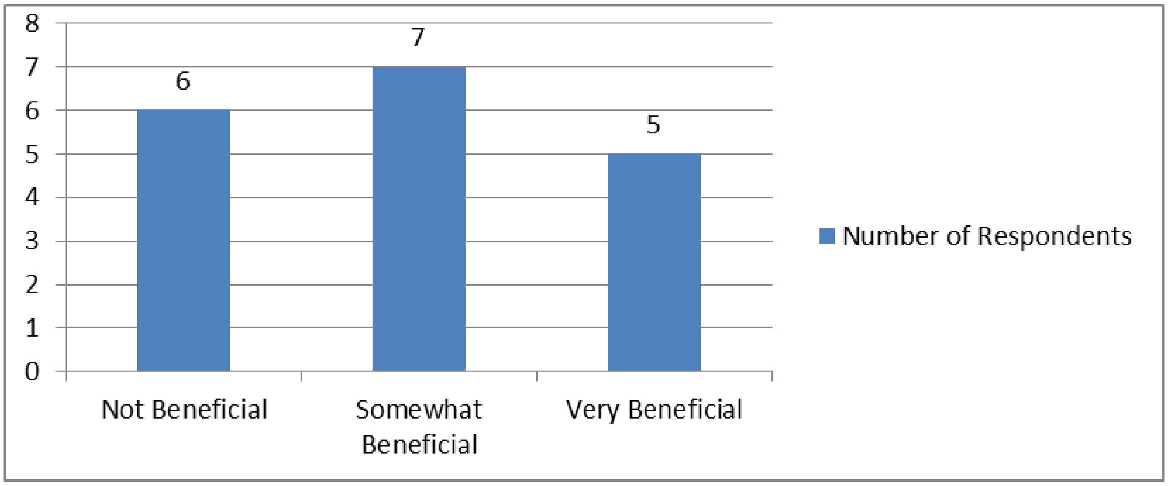
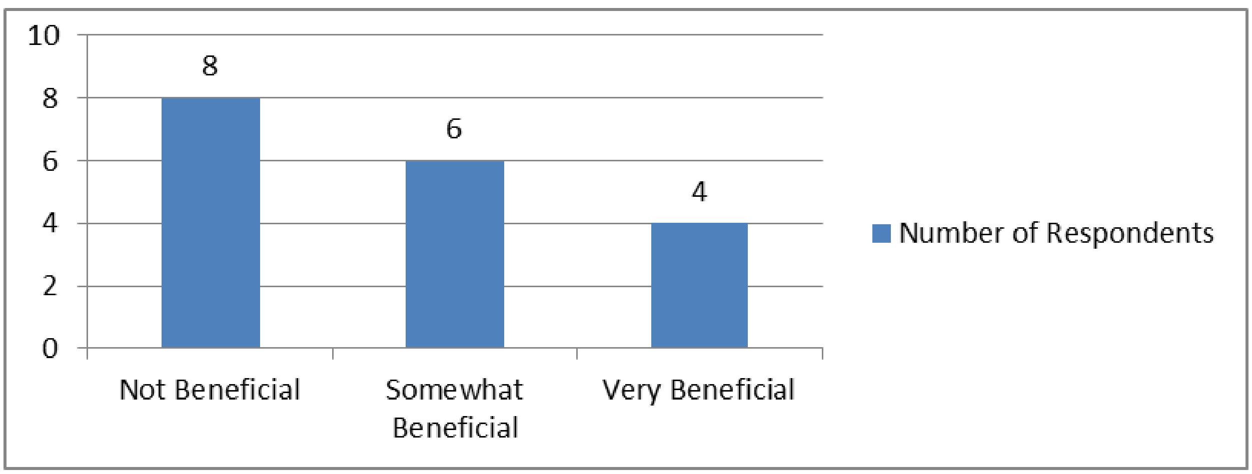


Figure 3.4 Summary of OSOW Haulers Response to the Question "How Beneficial Would it be if Loads Could go Straight Through a Roundabout, if the Pathway Would be Offset so the Entrance Would Line Up With the Left Approach (Where the Driver Would Have to Move to the Left Lane on the Approach)?"



3.3.6 OSOW Loads having Problems Negotiating a Roundabout

Figure 3.5 summarizes the OSOW haulers response to the question: "Do you remove and replace highway signs, or any other highway feature you consider an obstacle, and replace them after passing?". It was observed that 39% of the OSOW haulers responded to the survey remove or replace highway signs, or highway feature to pass through a roundabout. Figure 3.6

summarized the OSOW haulers response to the question "Are there places where you are permitted to hold traffic and travel in the wrong direction to continue toward your destination". It was observed that 33% of the OSOW haulers responded to the survey that they are permitted to hold traffic and travel in the wrong direction to continue toward their destination.

Figure 3.5: Summary of OSOW Haulers Response to the Question, "Do you Remove and Replace Highway Signs, or any other Highway Feature you Consider an Obstacle, and Replace them after Passing?"

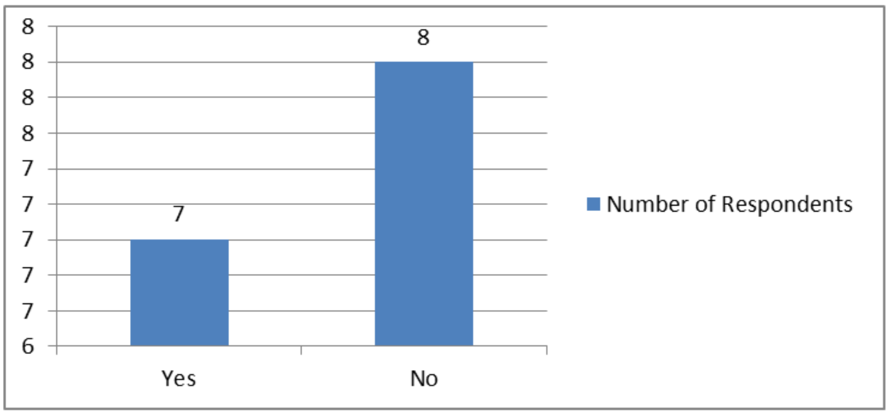
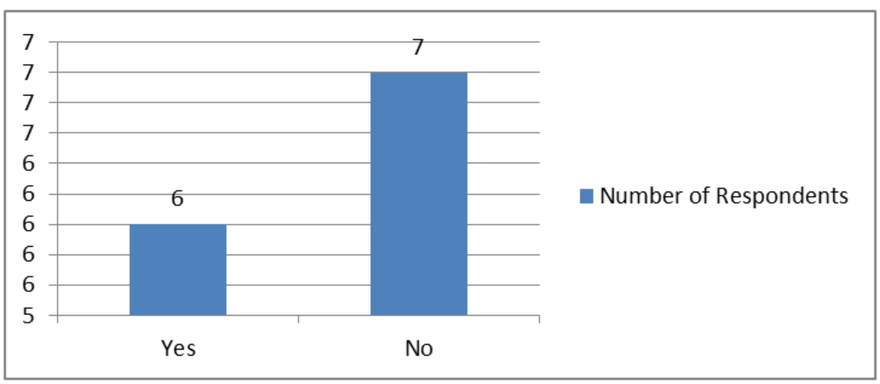


Figure 3.6: Summary of OSOW Haulers Response to the Question, "Are there Places where you are Permitted to Hold Traffic and Travel in the Wrong Direction to Continue toward your Destination?



3.4 Building Statewide Freight Networks

This objective of this task was to investigate strategies, recommendations and guidelines to build statewide freight networks for large truck and necessary OSOW needs, and then recommend state policy.

This objective will be achieved by reviewing documented information on developing freight networks statewide. Based on the literature review, the best recommendations are suggested for building a freight network for effective freight movement and at the same time build corridors that can accommodate OSOW movements.

3.4.1 Statewide Freight Plan Template

Freight transportation issues might be complex as they involve many stakeholders who have different views for understanding and solving the challenges of freight transportation industry (*23*). FHWA has published a "Statewide freight plan template" for assisting state department of transportations (DOTs) for building their freight plan, or incorporating freight elements into their statewide transportation plan (*23*). Various aspects such as safety security, economic development, mobility, and environmental impacts should be addressed by state freight planning template (*23*). Integrating freight in statewide planning process or developing a separate statewide freight plan is importation because:

- "increasing globalization and a corresponding economic (national, state, and local) dependence on expanding supply chains and transportation reliability (water, air, rail, highway, and pipeline),
- recognition by business leaders at all levels that efficient freight transportation is a key factor in economic (national, state, and local) competitiveness and vitality,
- heightened awareness from both private and public sectors that investment from both are needed, if not required, to meet increasing freight transportation demands, and
- increasing demands for transportation among both passenger and freight interests creating stress on the transportation system, resulting in congestion and bottlenecks in key locations detrimental to productivity." (*23*)

The statewide transportation planning process requires the state to develop and use a documented public involvement process which provides the public an opportunity to review and comment on key decision points (*23*). Timely information regarding transportation issues and decision-making processes should be provided to citizens, affected public agencies, representatives of public transportation employees, freight shippers, private providers of transportation, representatives of users of public transportation, representatives of users of pedestrian walkways and bicycle transportation facilities, representatives of the disabled, providers of freight transportation services, and other interested parties (*23*).

Private sector carriers provide almost all the freight service locally, nationally and internationally and therefore private sector stakeholders are considered as a valuable resource to identify regional, statewide, and multijurisdictional challenges and influence transportation programming and investment decisions by local and state decision makers in the overall statewide and metropolitan transportation planning process (*23*).

Various freight stakeholders that need to be engaged from a state or region include:

- shippers,
- carriers,
- terminal operators,
- economic development agencies,
- seaport and airport authorities,
- state and local governments and other public agencies,
- receivers (stores, industry, etc.),
- distribution centers/warehousing representatives, and
- commercial and industrial developers. (*23*)

Engaging private sectors may need activities such as:

- conducting focus groups with private sector stakeholders,
- conducting interviews with private sector stakeholders,
- holding conferences/meetings/workshops with private sector stakeholders,
- implementing a freight advisory council,
- exchanging data, and

- implementing the plan (ask them to help make it a reality). (*23*)

Engaging private sector stakeholders, and a public sector that includes metropolitan planning organizations (MPO's), regional port organizations/authorities, and various municipal, county, state, and federal entities that include enforcement and emergency response, plays a key role in efficient operation of the freight system (*23*).

3.4.2 Western Minnesota Regional Freight Study

This study was conducted to better understand the freight demands on regional transportation infrastructure and provide a framework to address the goals such as (*24*):

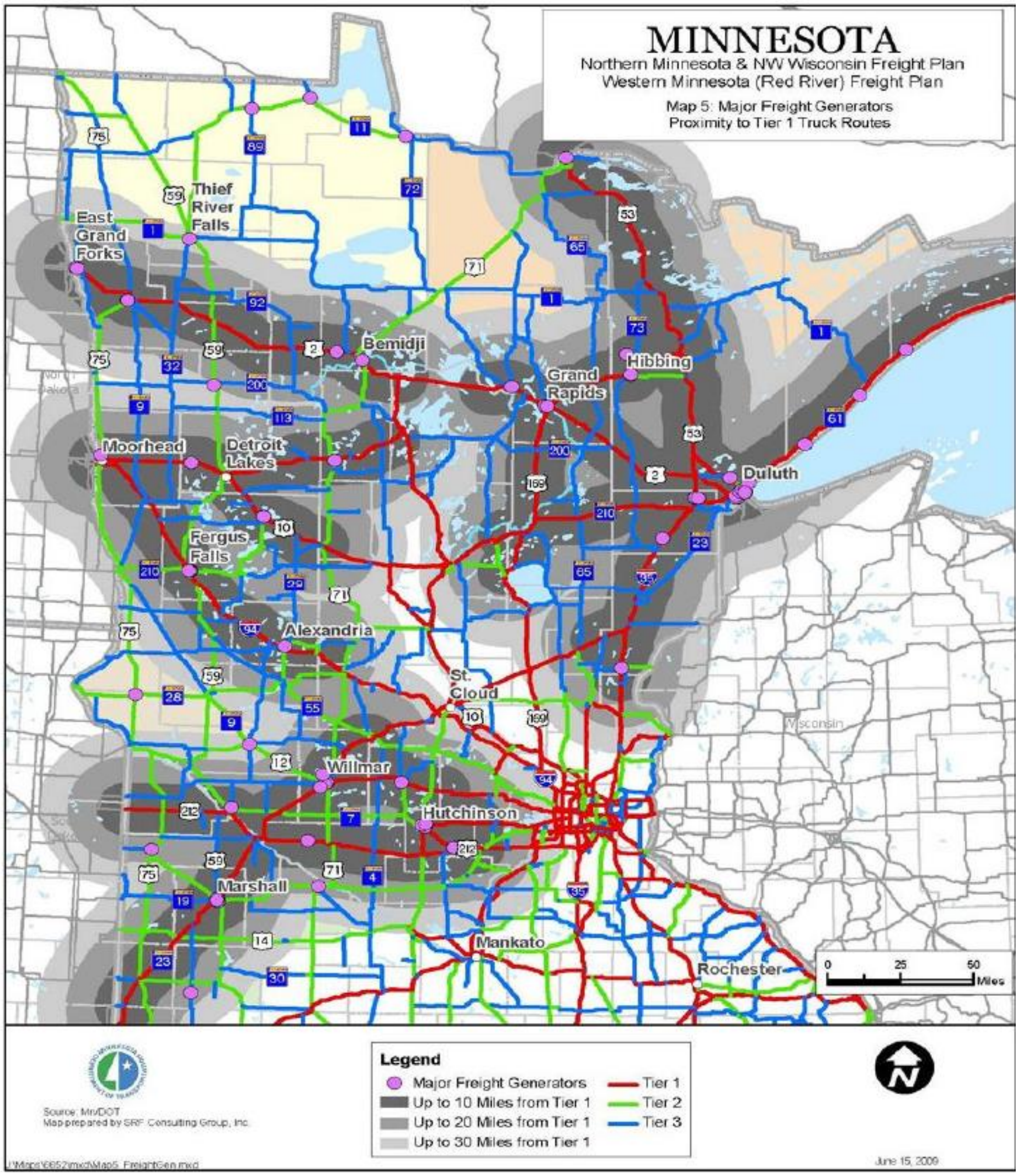
- Study the regional and local issues not captured in previous freight transportation study/planning attempts, including freight issues specific to region.
- Document the existing freight transportation system in Northern Minnesota & Wisconsin, and Western Minnesota and identifying significant existing and projected needs, bottlenecks, infrastructure and regulatory issues, and other constraints in the regions freight transportation and their implications.
- Industry and region-specific issues related to freight transportation and their solutions were identified.
- Planning for improvement of freight region specific movements and strengthen freight considerations in public planning and investment decision-making.

3.4.2.1 Summary of Recommendations Developed for the Western Minnesota Freight Study

Regional Freight Advisory Committee

A Regional Freight Advisory Committee (FAC) was formed with an intention to create a bi-state advisory committee with public representatives from a variety of transportation planning authorities and private sector representatives from a variety of industry and modes work for a common goal of improving regional freight mobility (*24*). The regional FAC would be helpful to facilitate strategic information exchange and coordination among regional business leaders and other diverse freight stakeholders regarding freight needs and potential solutions for building better transportation system (*24*).

Figure 3.7: Tiered truck Roadway Network for Northern Minnesota & Western Wisconsin and Western Minnesota



Source: Western Minnesota Regional Freight Study (*24*)

Designated Tiered Truck Network

The existing designated highway systems, when combined together, resulted in a large system which could not provide any investment guidance. Therefore, a tiered roadway network was developed that highlights the roadways that are most important to truck traffic (*24*). Heavy commercial annual average daily traffic (HCAADT) is an estimate of total number of vehicles on any given day of a year using specific segment of roadway with at least two axles and six tires (*24*). Roads on the highway network with HCAADT greater than 650 were categorized as Tier 1 truck network, HCAADT between 301 and 650 were categorized as Tier 2 truck network, and HCAADT less than 300 are categorized as Tier 3 truck network (*24*). Figure 3.7 shows the Northern Minnesota & Wisconsin freight plan and Western Minnesota freight plan categorized according to the three tiers of truck network. This categorization helps in understanding that the top two tiers having the highest priority for future investment. Therefore heavy vehicle characteristics on each tier were used to identify the design criteria of each tier and understand the network deficiencies.

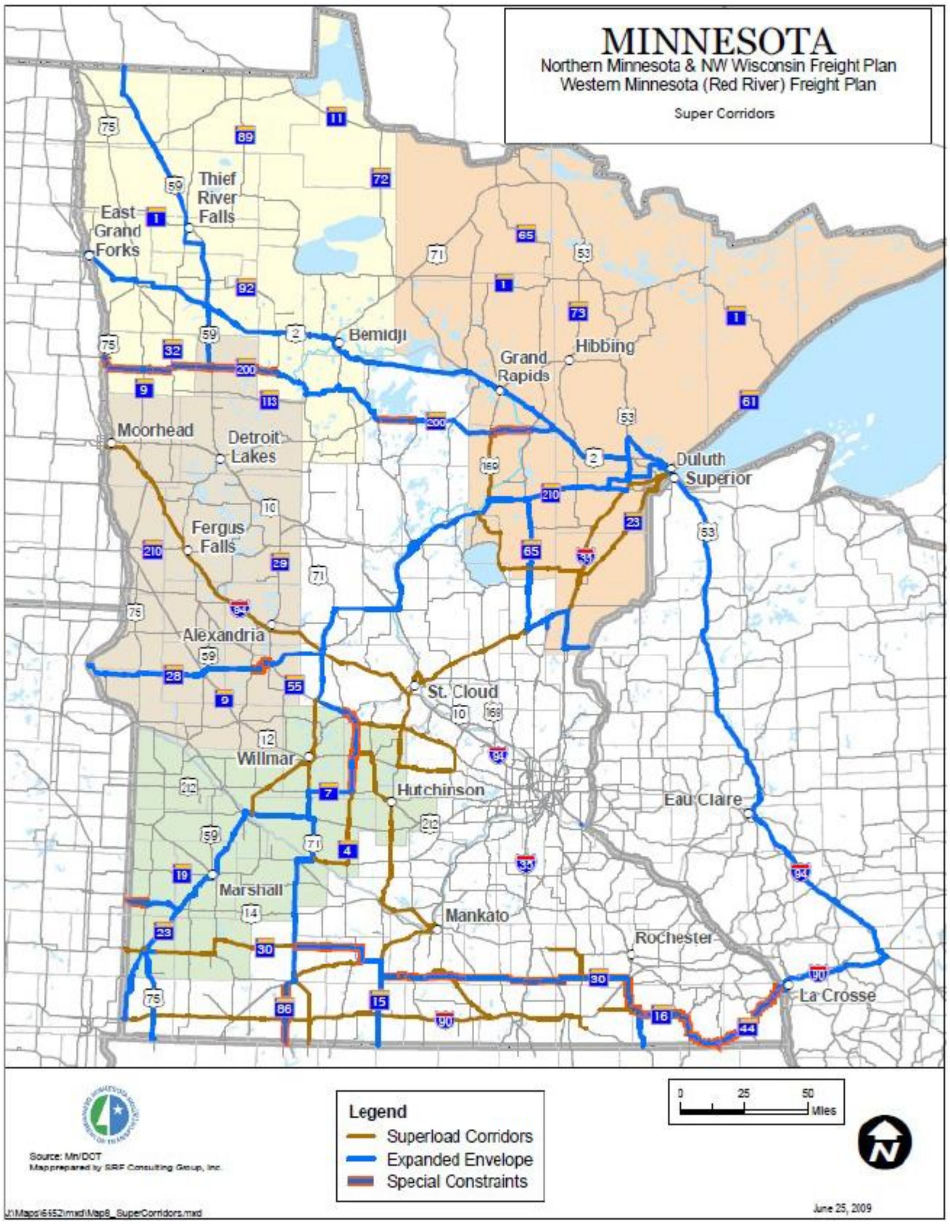
Designated Super-Haul Corridors for Permit Operations

Minnesota DOT provides permitting of oversized overweight loads on trunk roadways throughout the state for manufacturers and/or business within the state which are able to ship large equipment (*24*). "Super corridor routes" are identified as certain routes that are being used by oversized and overweight loads from the Duluth port to other areas of the state, and these routes should be considered for planning improvements. Figure 3.8 shows the super corridor route map that can support a 16'x16'x130' envelope and a weight of 235,000 lbs. Recommendations provided to improve the efficiency along the super corridor routes that provides shipper/trucker a reliable route to use when hauling oversize loads are (24):

- four main parameters such as weight, width, length, and height were addressed when permitting oversized overweight loads
- super-haul corridors were designed in such a way that roadway could accommodate a loaded vehicle with 16-foot height limit, a 16-foot width limit and a 8-foot wide axle, and a 130-foot length limit and a 235,000 lbs weight limit,
- diamond interchanges were preferred on selected routes as they as they allow for easier movements for over-size loads from one roadway to other roadway,

- roundabouts should not be considered on identified super-haul corridors, (note that the author of this dissertation does not agree with this recommendation as it is shown in other places in this dissertation that oversize loads can be accommodated on super corridor routes if they are known), and,
- counties/cities should provide adequate information about the road closures along the route with at least two week notice.

Figure 3.8: Super Haul Corridor in Minnesota

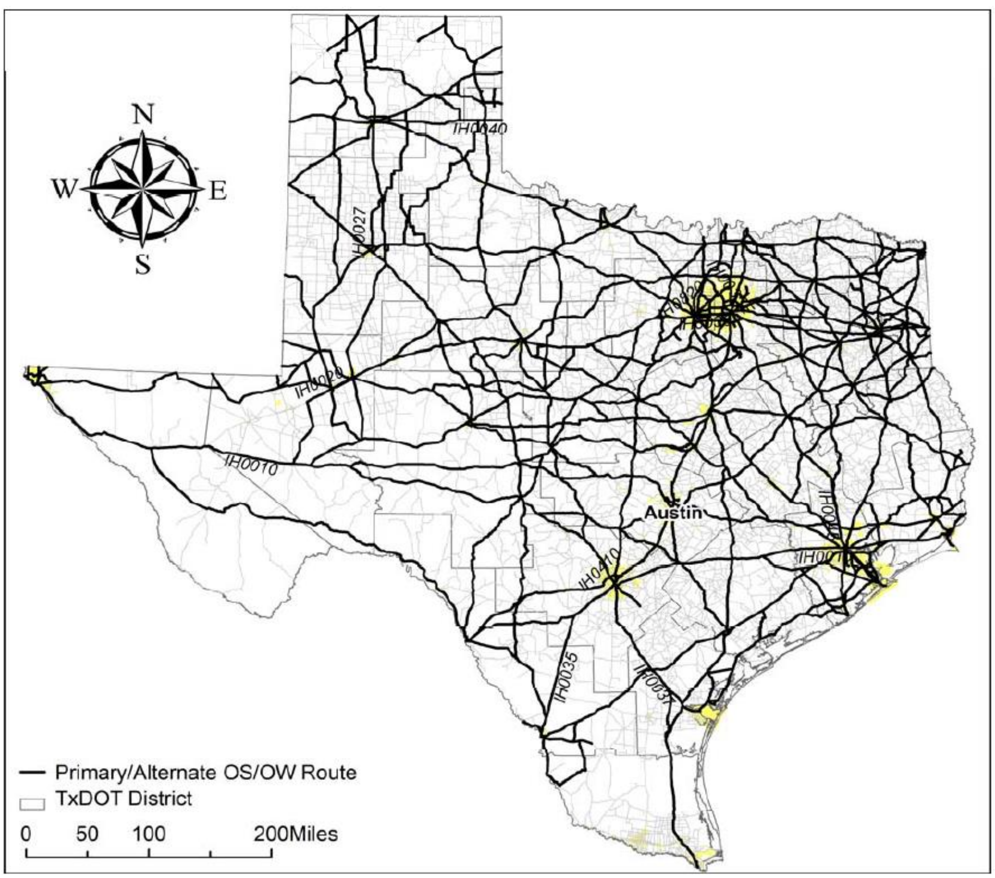


Source: Western Minnesota Regional Freight Study (*24*)

3.4.3 Accommodating Oversize & Overweight Loads

The Texas Transportation Institute (TTI) conducted a study *Accommodation of Oversize & Overweight Loads* to identify the most common OSOW weight groups, criteria for assigning these OS/OW groups to existing road networks, and criteria for assigning current and projected OSOW groups to the future road network (*25*). The research team gathered six-years of historical permit data from FY2004 to FY2009 which included information such as route origins/destinations, load dimensions, weights, axle configuration, and load descriptions (*25*). The research team has mapped the gathered permit routes on their state highway network using aGIS environment so that they can understand how various groups of OSOW loads travelled on their state highway network. GIS-based analysis also helped to understand how permanent restrictions impacted the route choices of OSOW loads (*25*).

Figure 3.9: Primary/Alternative OS/OW Routes in Texas



Source: Accommodating Oversize & Overweight Loads (*25*)

Figure 3.9 shows the Texas statewide map with the primary/alternative OSOW route network for the most common origins and destinations. It was concluded that usage of the non-optimal OSOW routes has resulted in an additional 290 million ton-miles of activity on the state highway network due to primary to physical restrictions and for six year study period the ton-miles totaled more than 1.7 billion (*25*). On annual bases, the additional OSOW ton-miles have resulted in about $42 to $73 million of additional cost for shippers and the public and a total of about $250 to $438 million loss during the study period of six years (*25*).

3.4.4 Conclusions

A good starting point for building and effective state freight network would be following the guidelines mentioned in the *Statewide Freight Plan Template* described in Section 3.4.1 which strongly supports incorporating freight elements in statewide transportation planning process. The *Western Minnesota Regional Freight Study* serves as an excellent reference to build and develop effective freight network by classifying the roadway network into various tiers and effectively plan for future investment at high priority roadways to benefit and develop the freight movement and therefore help for regional economic development.

However, the Western Minnesota Regional Freight Study suggests that roundabouts should not to be used in super haul corridors. This might be their decision due to lack of information on ways to effectively accommodate OSOW loads at roundabouts. This dissertation addresses all the problems OSOW vehicles have at roundabouts, and illustrates designs to accommodate them, and therefore, roundabouts should not be a restriction for OSOW movement. Also, from section 3.1.6 (survey 2 results), it can be understood that 60% (30 states) of the survey 2 responding US States have roundabouts on state or non-state routes on which OSOW vehicles can be routed. Similarly, 48% (24 states) of survey 2 responding states take OSOW routes into consideration when planning or designing a roundabout and 34% (17 states) do not take OSOW routes into consideration when planning or designing a roundabout. It can be noted from survey 4 results that OSOW haulers input for highway design is very valuable for understanding their needs and effectively building freight networks for OSOW movements.

It can also be understood from the TTI study reviewed in section 3.4.3, keeping the strategic routes open for OSOW loads is very important for minimizing the rerouting loads and therefore saving many dollars.

Chapter 4 - Roundabout Designs

This chapter deals with generating roundabout designs that address most of the concerns reported above in chapters 2 and 3, for typical urban and rural roundabout intersections to accommodate all reported types of large trucks and where necessary, OSOW configurations/combinations. The roundabout intersections were generated in two categories, urban roundabouts and rural roundabouts respectively. The objective for the urban roundabout analysis was to modify designs that were designed using a WB-50 design vehicle, as used for most urban roundabouts, to accommodate WB-67s where necessary. The objective for the rural roundabout analysis was to modify designs that were designed using a WB-67 design vehicle (recommended by the author for roundabouts on state highways) to accommodate OSOW vehicles.

Urban roundabouts designs were developed considering WB-50 as the design vehicle, which is the common largest vehicle expected at urban intersections, unless on a known state freight route. These designed urban roundabouts were modified in such a way that they could accommodate trucks larger than WB-50 that occur infrequently.

Rural roundabouts designs were developed considering a WB-67 as the design vehicle, which is a common vehicle expected at rural intersections. These designed rural roundabouts were modified in such a way that they could accommodate oversize/overweight vehicles that occur infrequently.

TORUS software was used to generate roundabout designs based on specific design vehicles in this chapter. Later, trucks larger than the design vehicle that can be expected at the various roundabout configurations were determined and AutoTURN software was used to determine the space requirements based on the vehicle swept path, and then the TORUS roundabout design was modified. AutoTURN is a computer-aided design (CAD) vehicle turn and swept path analysis software used to evaluate standard design or specialized vehicle maneuvers for all types of roadway, highway, and site design projects following the guidelines from AASHTO for turn radii, transition curves, super-elevation, and lateral friction (*26*). TORUS is a CAD-based software for designing modern roundabouts (*27*).

4.1 Urban Roundabouts

This study considered and designed the most common roundabout intersections on urban roads and then modified the roundabout designs for trucks larger than the design vehicle. Roundabout configurations, such as single-lane roundabout and a double-lane roundabout, were considered for this study. For each configuration, roundabout types such as a typical symmetric 3-leg roundabout, a 3-leg roundabout at a T intersection, and a typical 4-leg roundabout were considered. A symmetric 5-leg roundabout was considered for single-lane urban roundabout as the possibility of 5-leg roundabouts is greater in urban areas. A 5-leg roundabout was not considered for a double-lane roundabout as the design might vary according to site specific conditions and vehicle volume and capacity for each leg.

According to NCHRP Report 672, the latest roundabout guide, AASHTO designation WB-50 is considered the most common design vehicle for urban intersections (*1*). Therefore, WB-50 was used as a design vehicle to generate the roundabout design and truck apron design using TORUS software. It was found from the K-State pooled fund study (*2*) that WB-67 was one of the common design vehicles on the state highway system and the most common vehicle for freight transport (*2*). Therefore, it was determined to modify the roundabout designs generated using WB-50 as a design vehicle such that they could accommodate the right turn, through, and left turn movement of WB-67 that can possible occur very infrequently. The roundabout design generated using WB-50 as the design vehicle was then used for conducting swept path analysis (using AutoTURN) of the WB-67 for right turn, through and left turn movements. Based on the simulated tire tracks generated by AutoTURN, for all possible WB-67 movements from all approaches, an outer truck apron, custom center island and custom truck apron were analyzed to develop the design of the roundabout which would accommodate WB-67 movements.

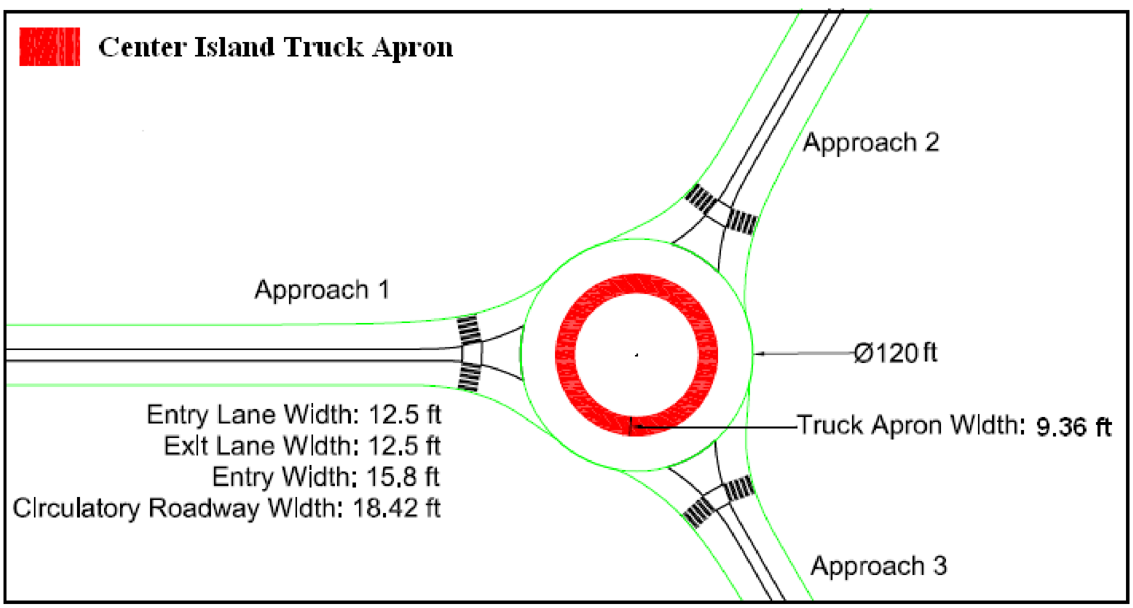
4.1.1 Single-Lane Urban Roundabouts

4.1.1.1 Single-Lane Symmetric 3-Leg Roundabout

According to NCHRP Report 672, the latest FHWA roundabout guide (*1*), WB-50 is commonly the largest vehicle using urban intersections. Therefore WB-50 was considered a design vehicle for building a 3-leg symmetric urban roundabout in this study. This means that the roundabout must accommodate right turn movement, through movement, left turn movement, and U-turn of WB-50 from any approach. According to NCHRP Report 672 (*1*), a single-lane roundabout with WB-50 design vehicle has an inscribed circle diameter (ICD) range of 105 to 150 ft and a ICD of 120 ft was selected randomly for the study. However, it should be noted that a roundabout in an urban setting has more chances that an intersection has insufficient space for construction of a roundabout; therefore, larger diameters might not be a workable option in these cases. Also, as the ICD increases, the vehicles are able to drive through the roundabout at increased speeds, negating some of the safety benefits attributed to low speed. Therefore an ICD of 120 ft was arbitrarily chosen rather than choosing the upper limit ICD of 150 ft.

TORUS software was used to construct a single-lane, 3-leg, symmetric urban roundabout with an ICD of 120 ft, using a WB-50 design vehicle. To accommodate various movements of the WB-50 design vehicle, a 9.36 ft center island truck apron was also designed for the roundabout. Figure 4.1 shows single-lane 3-leg symmetric urban roundabout generated using TORUS software.

Figure 4.1: Single-Lane 3-leg Symmetric Roundabout with 120ft ICD and 9.36ft Center Island Truck Apron



Developing the designs for the roundabouts in this chapter deals with simulating various movements (right, through and left) of either a WB-50 or WB-67 vehicle and modifying the roundabouts design based on vehicle envelopes (sometimes called 'swept path'). Therefore it is important to understand various color lines in an AutoTURN vehicle simulation. Figure 4.2 shows and explains the vehicle simulation in detail with example right turn simulation of WB-50 and WB-67. From Figure 4.2, it has to be understood that the area in between the BLUE color line is the vehicle envelope (swept path) and the PURPLE color line is the path traversed by the vehicle.

Figure 4.2: Understanding a AutoTURN Vehicle Simulation

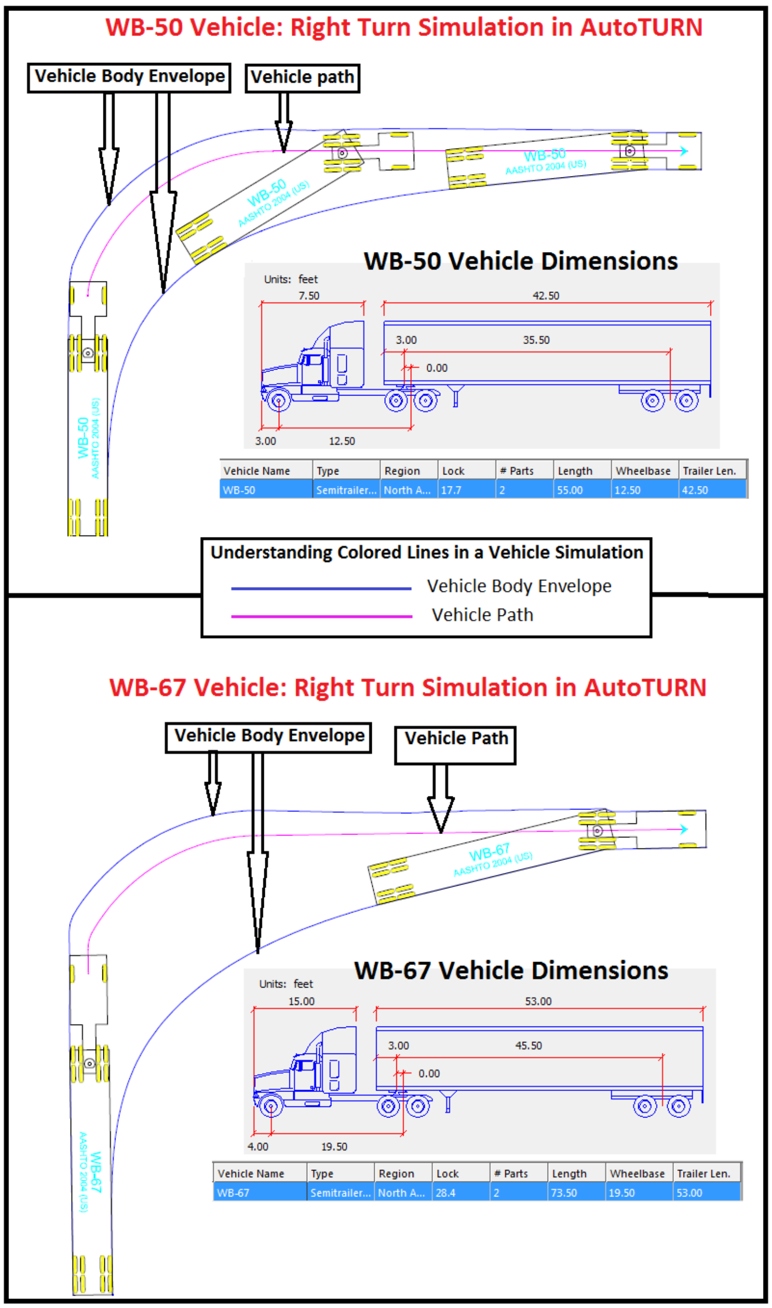
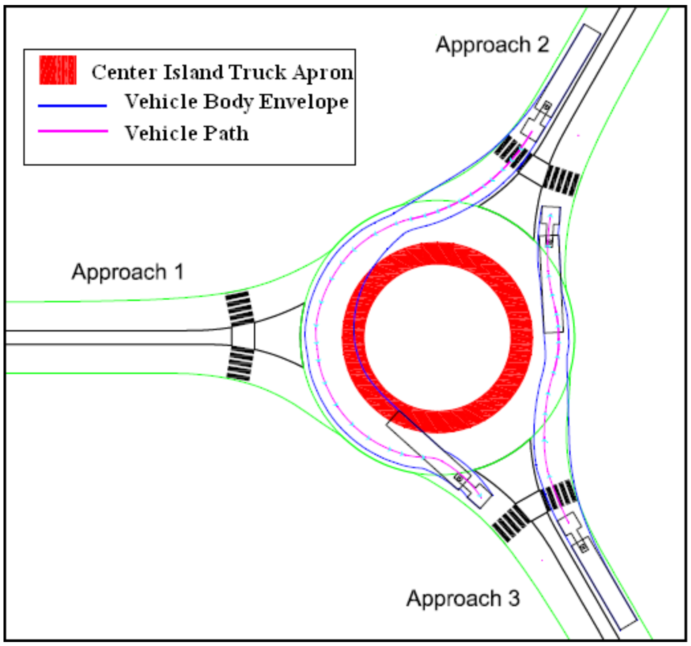


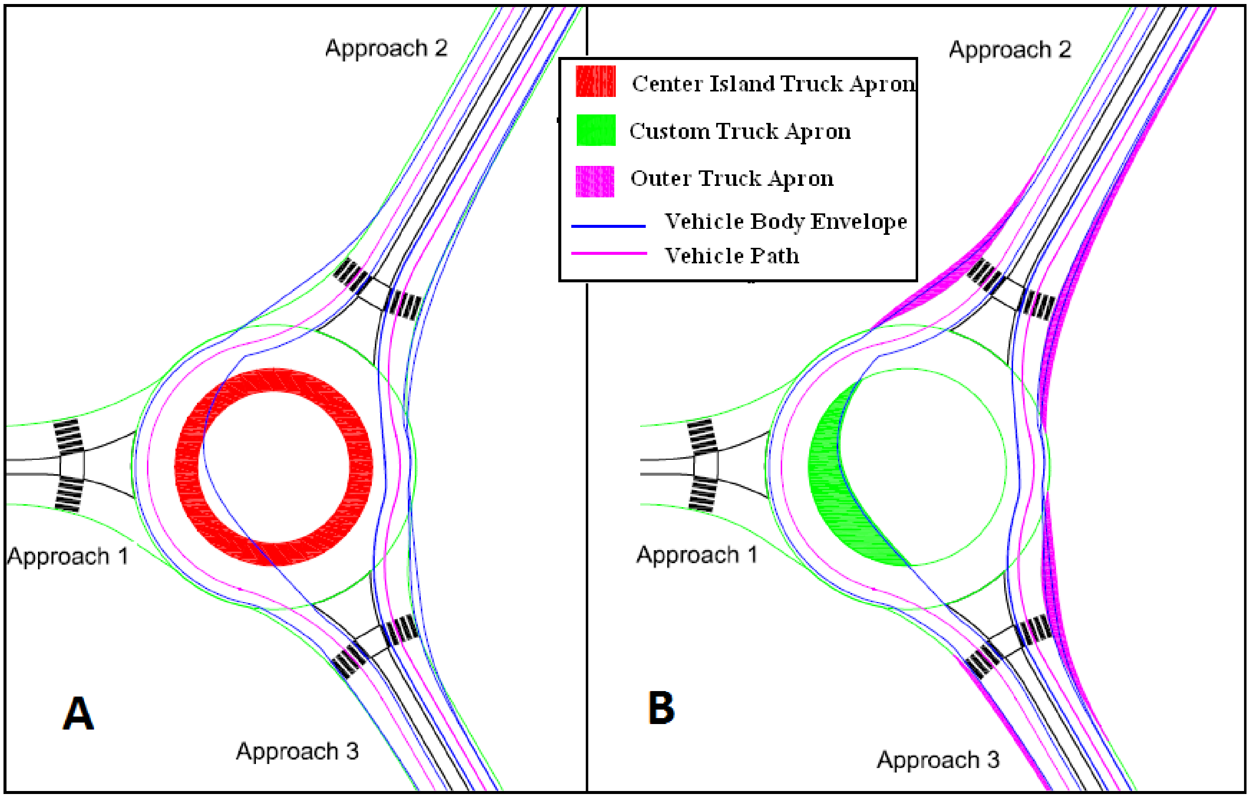
Figure 4.3 shows a sample AutoTURN right turn simulation of a WB-50 from approach 3 to approach 2, and a left turn simulation of a WB-50 from approach 2 to approach 3. As the vehicle used is the design vehicle, it can be observed in Figure 4.3 that these simulations were accommodated inside the designed roundabout and don't need any additional truck apron. However, the current roundabout (shown in Figures 4.1) will be used to be modified for accommodation of a vehicle that is bigger than the WB-50.

Figure 4.3: Example Right Turn and Left Turn Simulations of the Design Vehicle, WB-50



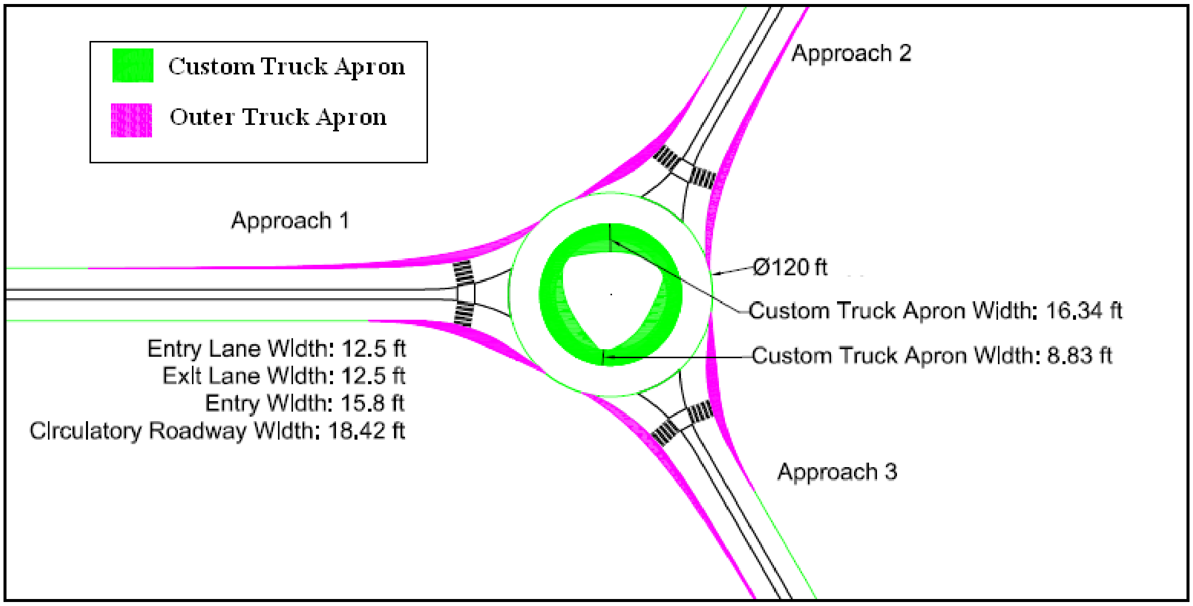
Generally, in urban areas, though most roundabouts are designed for a WB-50, due to possible freight activity, the roundabout might need to accommodate the most common truck WB-67 that may occasionally encounter the roundabout. Therefore a WB-67 is considered as a vehicle (not design vehicle) that may occur infrequently at the roundabout and needs to be accommodated at the roundabout. AutoTURN right turn simulation and left turn simulation of a WB-67 are conducted for each approach of the roundabout to determine the space requirements needed for a WB-67 at the roundabout. Figure 4.4-part A shows an example right turn simulation of a WB-67 from approach 3 to approach 2 and an example left turn simulation of WB-67 from approach 2 to approach 3.

Figure 4.4: Example Right Turn and Left Turn Simulation of WB-67 and Developing External Truck Apron and Custom Center Island Truck Apron



It can be observed from part A of the Figure 4.4 that there is a need for more space to maneuver for the example right turn and left turn simulations of a WB-67. Therefore, the roundabout is modified with outer truck apron (purple) and custom center island (green) to accommodate these movements as shown in part B of Figure 4.4. The outer truck apron and custom truck apron are determined based on the tire tracks of the turning movements of the WB-67 vehicle from all approaches. Based on the right turn and left turn movements of WB-67 from all approaches, a final modified design of the roundabout was generated and shown in Figure 4.5. This final design of a 3-leg symmetric roundabout has a custom central island truck apron with minimum width 8.83 ft and maximum width 16.34 ft and it has outer truck apron with varying widths as shown in Figure 4.5. In this and subsequent examples, it is assumed that to be a practical solution, there is enough space in the intersection to allow for the necessary outer expansion.

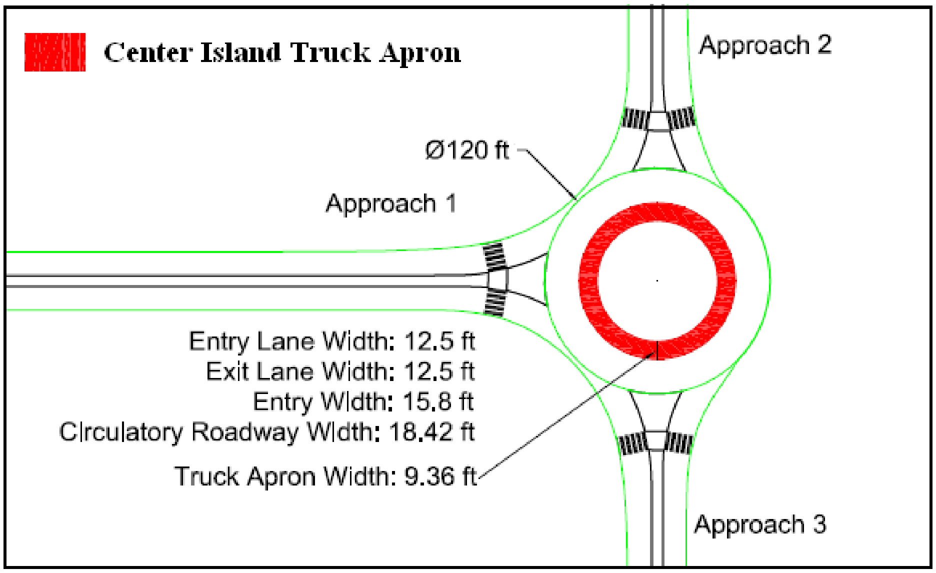
Figure 4.5: Final Modified Design of Single-Lane Symmetric 3-Leg Roundabout



4.1.1.2 Single-Lane 3-Leg Roundabout at T-Intersection

For building a single-lane 3-leg roundabout at an urban T-intersection, an ICD of 120 ft was selected following guidelines in NCHRP Report 672 (*1*) and a WB-50 was used as a design vehicle. TORUS software was used to design the roundabout with specified parameters and is shown in Figure 4.6. To accommodate various movements of the WB-50 design vehicle, a 9.36 ft center island truck apron was designed for the roundabout.

Figure 4.6: Single-Lane 3-leg Roundabout at T-intersection with 120ft ICD and 9.36ft Center Island Truck Apron



The roundabout shown in Figure 4.6 will be used as the basic design to illustrate modification for accommodating the larger WB-67. AutoTURN right turn simulation and left turn simulation of a WB-67 were conducted for each approach of the roundabout to determine the space requirements for the WB-67 at the designed roundabout. Based on the simulated right turn and left turn movements of a WB-67 from all approaches, a final modified design of the roundabout was generated and shown in part A of Figure 4.7. The shape of a custom central island would be irregular and so a suitable, circular central island was chosen as a best fit as shown in part B of Figure 4.7. The final composite design of the single-lane, 3-leg roundabout at the T-intersection is shown in Figure 4.8.

Figure 4.7: Designs Generated to Accommodate WB-67 at Single-Lane 3-leg Roundabout at T-Intersection

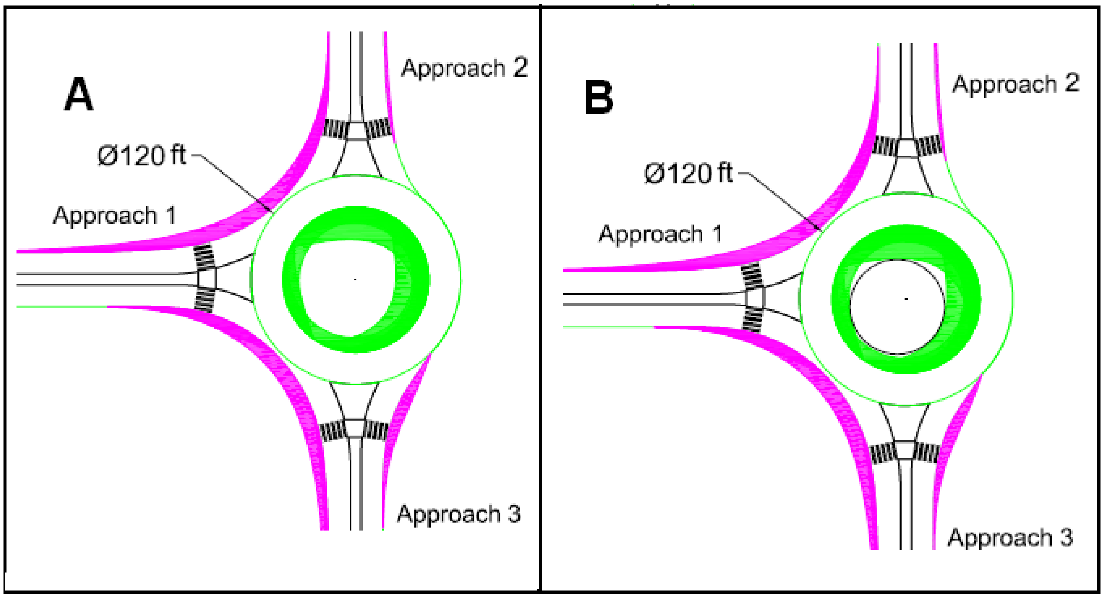
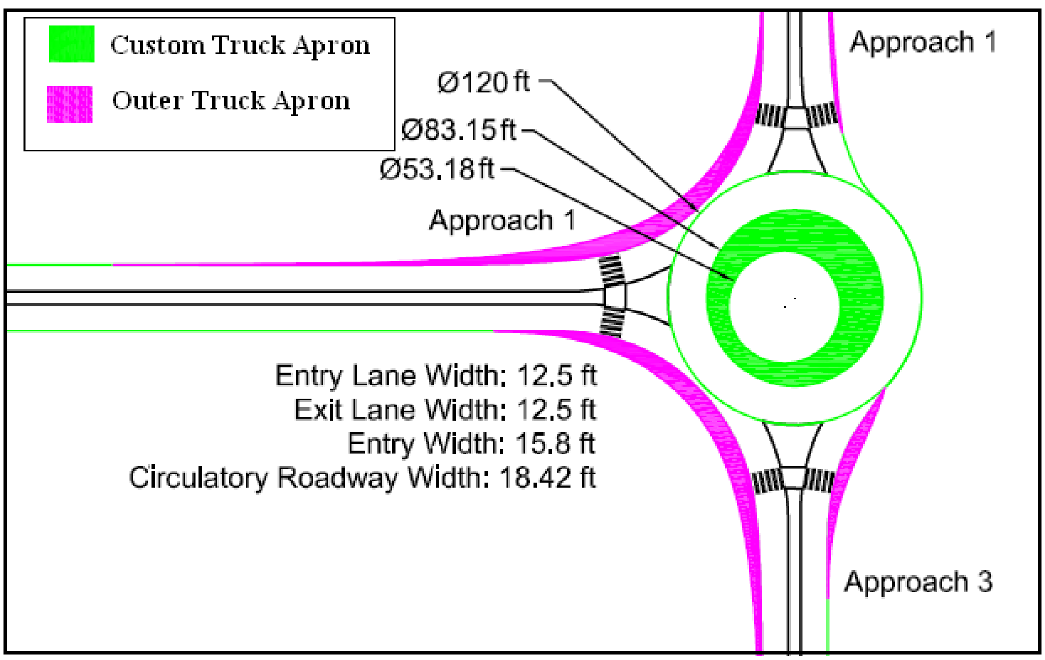


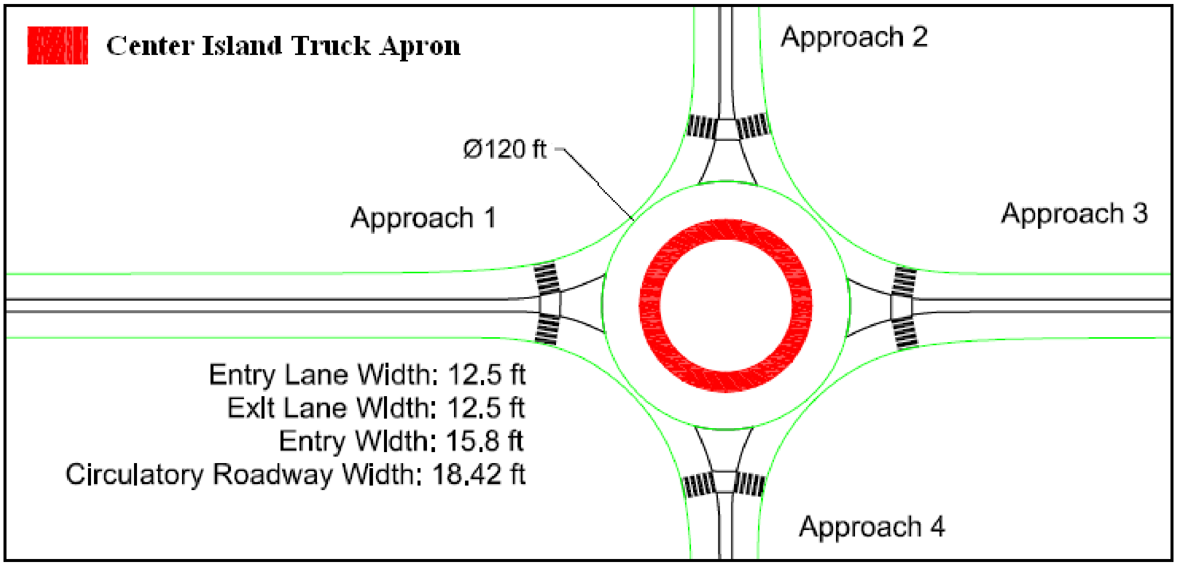
Figure 4.8: Final Modified Design of Single-Lane 3-Leg Roundabout at T-Intersection



4.1.1.3 Single-Lane Typical 4-Leg Roundabout

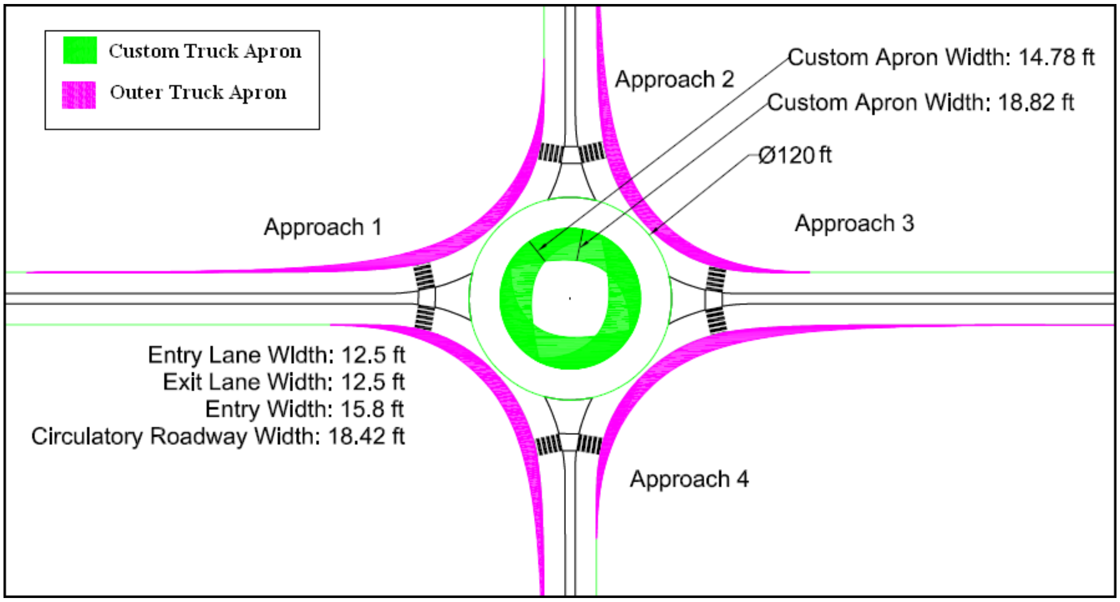
For designing a single-lane, 4-leg symmetric urban roundabout, an ICD of 120 ft and a WB-50 design vehicle was used which in accordance with guidelines in NCHRP Report 672 (*1*). TORUS software was used to design the roundabout with specified features and is shown in Figure 4.9. To accommodate various movements of the WB-50 design vehicle, a 9.36ft center island truck apron was designed for the roundabout. Figure 4.9 shows the single-lane, 4-leg symmetric urban roundabout generated using TORUS software.

Figure 4.9: Single-Lane 4-leg Symmetric Roundabout with 120ft ICD and 9.36ft Center Island Truck Apron



The roundabout shown in Figure 4.9 will be used to illustrate changes for accommodating a larger WB-67. AutoTURN right turn simulations, through movement simulations, and left turn simulations of WB-67 were conducted for each approach of the roundabout to determine the WB-67 space requirements of the roundabout. Figure 4.9 shows an example right turn simulation from approach 1 to approach 4, and left turn simulation from approach 4 to approach 1. Based on the right turn, though, and left turn movements of the WB-67 from all approaches, a final modified, composite design of the roundabout was generated and shown in Figure 4.10.

Figure 4.10: Final Modified Design of Single-Lane 4-Leg Symmetric Roundabout



4.1.1.4 Single-Lane Symmetric 5-Leg Roundabout

For designing a single-lane, 5-leg symmetric urban roundabout, an ICD of 120 ft and a WB-50 design vehicle was used which in accordance with guidelines in NCHRP Report 672 (*1*). TORUS software was used to design the roundabout with specified features and is shown in Figure 4.11.

A right turn simulation, through movement simulation, and two left turn simulations were made at this roundabout using the WB-50 design vehicle. These simulations are shown in Figure 4.12 with right turn simulations from approach 4 to approach 3, through movement simulations from approach 3 to approach 1, left turn simulations from approach 2 to approach 4, and left turn simulations from approach 5 to approach 1. It can be observed that an example right turn simulations shows a need for an outer truck apron, whereas the through movement and two left turn movements were completely accommodated in the basic roundabout design. Therefore an outer truck apron is needed for this roundabout in between every two approaches to accommodate the right turn movement of a design vehicle assuming it may enter from all approaches.

Figure 4.11: Single-Lane 5-leg Symmetric Roundabout with 120ft ICD and 9.36ft Center Island Truck Apron

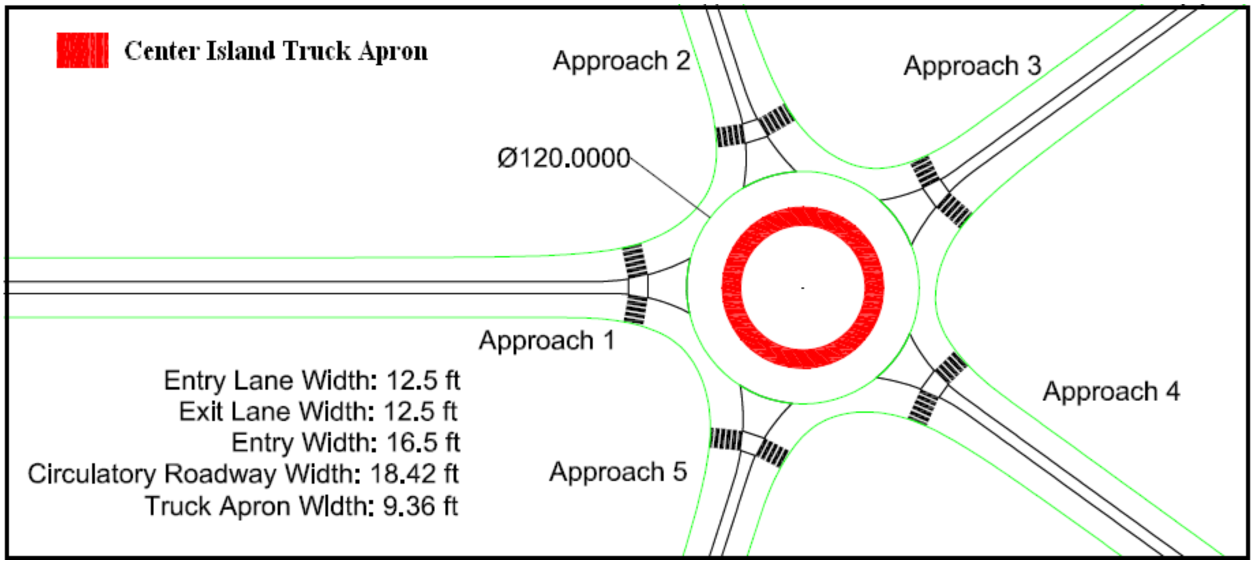
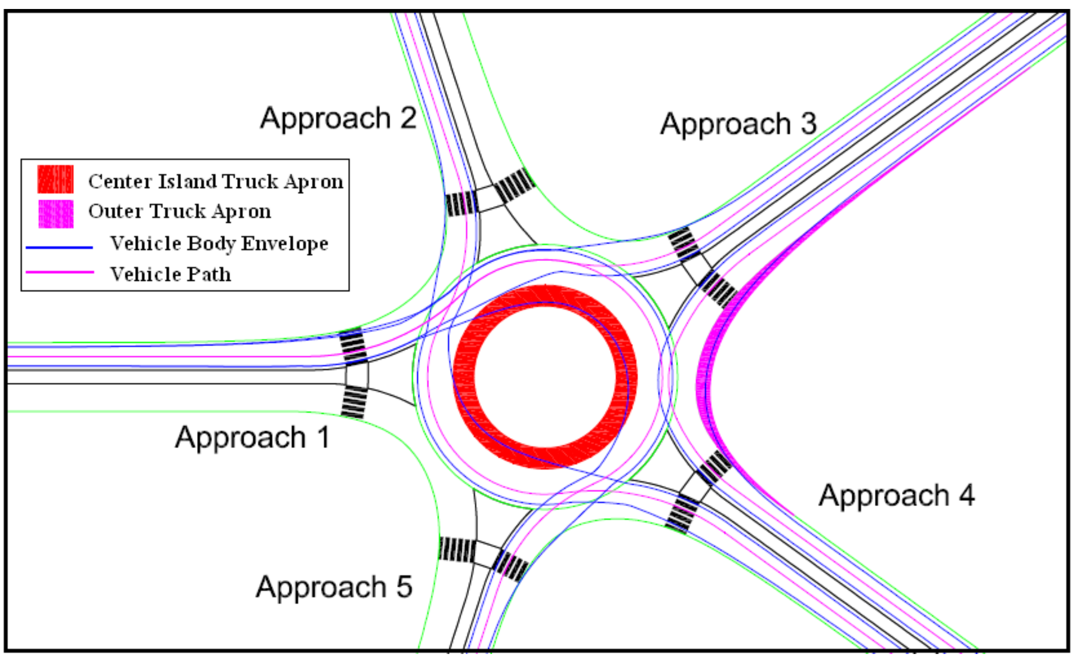


Figure 4.12: Example Right Turn Simulation, Through Simulation, and Left Turn Simulations of WB-50 at the Single-Lane 5-leg Symmetric Roundabout



The roundabout shown in Figure 4.11 will be used to illustrate modifying to accommodate the larger WB-67. AutoTURN right turn simulations, through movement simulations, and left turn simulations of a WB-67 were conducted for each approach of the roundabout to determine the space requirements of the WB-67 t. Figure 4.13 shows a right turn simulation of a WB-67 from approach 4 to approach 3, and a left turn simulation of WB-67 from approach 3 to approach 4. Based on the right turn, though, and left turn movements of a WB-67 from all approaches, a final composite, modified design of the roundabout was generated and shown in Figure 4.14.

Figure 4.13: Example Right Turn and Left Turn Simulation of WB-67 at Single-Lane 5-Leg Symmetric Roundabout

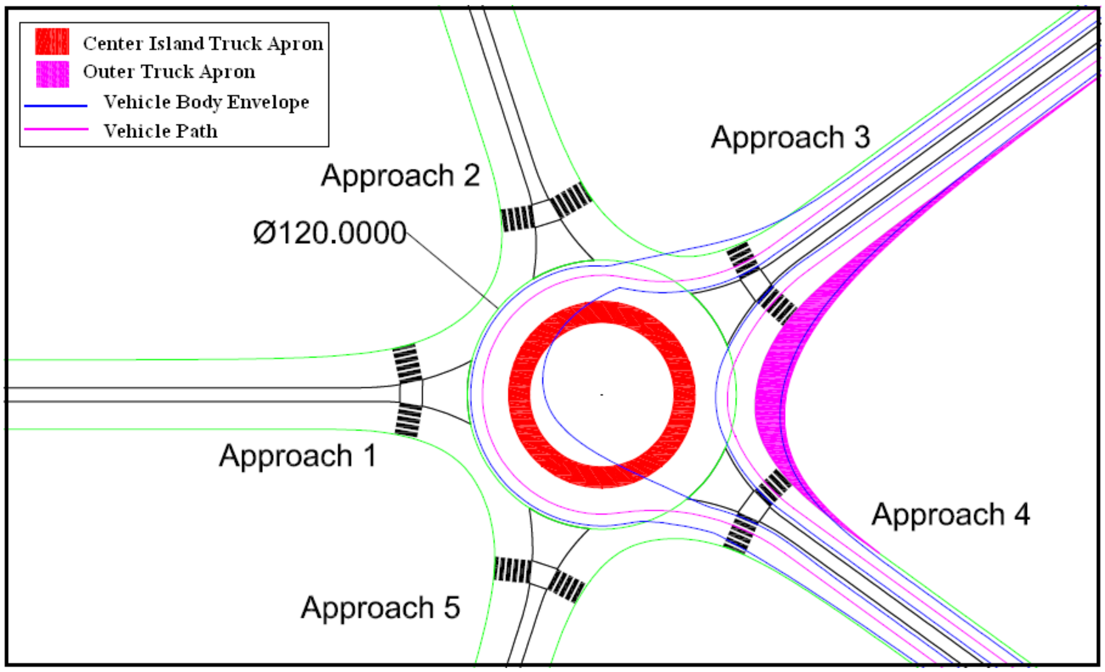
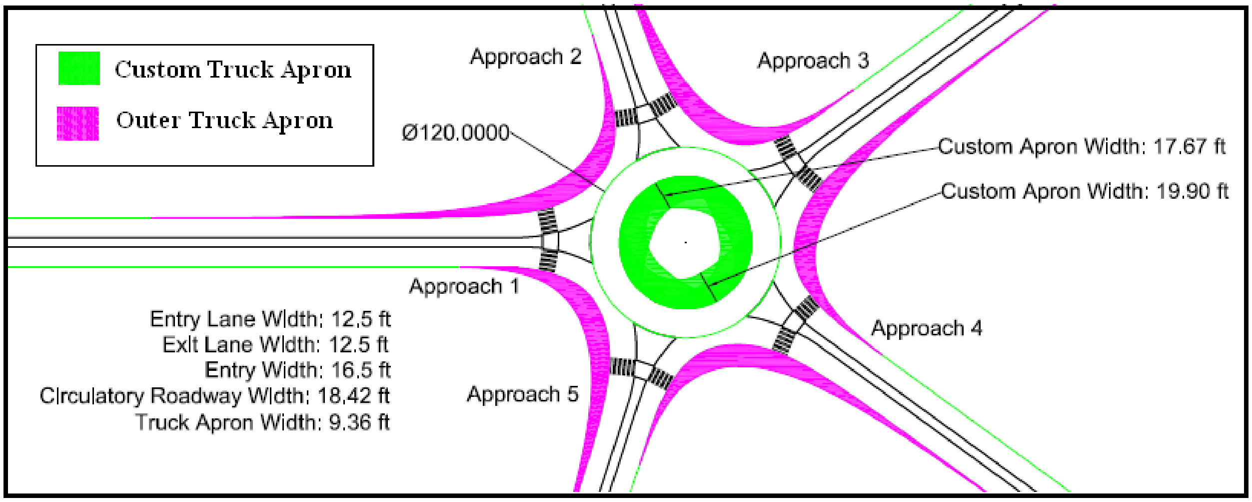


Figure 4.14: Final Modified Design of Single-Lane 5-Leg Symmetric Roundabout



4.1.2 Two-Lane Urban Roundabouts

4.1.2.1 Double-Lane, Symmetric 3-Leg Roundabout

For building a double-lane, 3-leg symmetric urban roundabout, a WB-50 was considered the design vehicle. According to NCHRP Report 672 (*1*), a two-lane, roundabout, using a WB-50 design vehicle, would have an ICD range of 150 to 220 ft, thus an inscribed circle diameter of 200 ft was arbitrarily selected for the study. Again, TORUS software was used to construct a basic, double-lane, 3-leg, symmetric, urban roundabout with an inscribed circle diameter of 200 ft using the WB-50 design vehicle and is shown in Figure 4.15. To accommodate various movements of the WB-50 design vehicle, a 5.27 ft center island truck apron was designed for the roundabout. The roundabout shown in Figure 4.15 will be used to illustrate modifications for accommodating a WB-67.

AutoTURN, right turn simulations and left turn simulations of a WB-67 were conducted for each approach of the roundabout to determine the space requirements of a WB-67 as the WB-67 was considered as a vehicle using the intersection infrequently. It was assumed that the WB-67 vehicle can use all of the two lanes for the roundabout's approach, circulatory roadway, and exit approach, to safely maneuver without a need for extra truck apron. Figure 4.16 shows a right turn simulation of a WB-67 from approach 3 to approach 2, and a left turn simulation of a WB-67 from approach 2 to approach 3. It was observed that the right turn, through and left turn simulations of the WB-67 do not need any external truck apron or additional internal truck apron. Therefore, the final composite modified design of the double-lane, symmetric, 3-leg urban roundabout using a WB-67 design vehicle is the same as the initial roundabout design using a WB-50 design vehicle and is shown Figure 4.17.

Figure 4.15: Double-Lane Symmetric 3-leg Roundabout with 200ft ICD and 5.27 ft Center Island Truck Apron

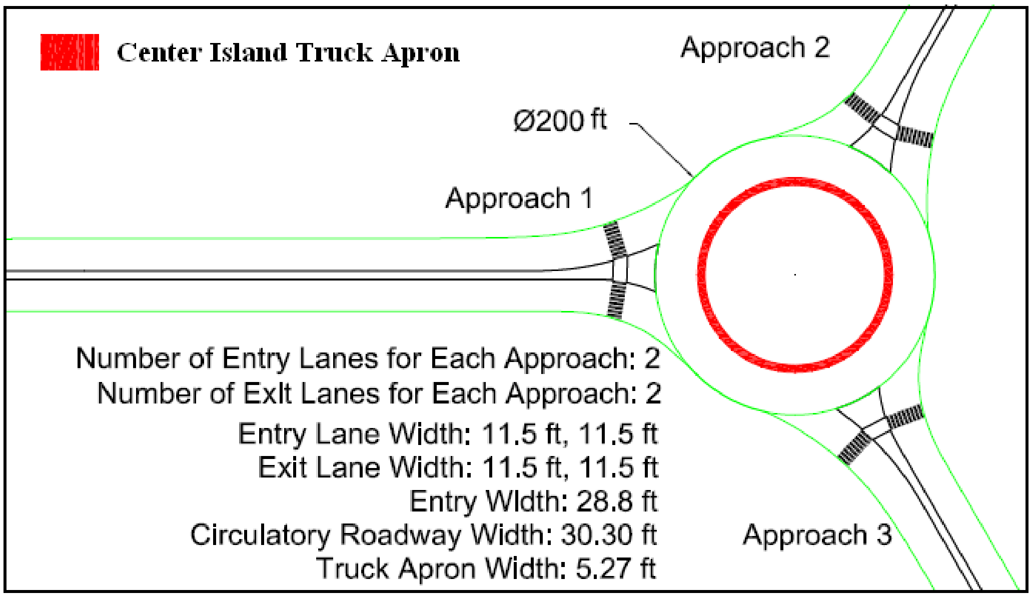


Figure 4.16: Example Right Turn and Left Turn Simulation of WB-67 at Double-Lane Symmetric 3-Leg Roundabout

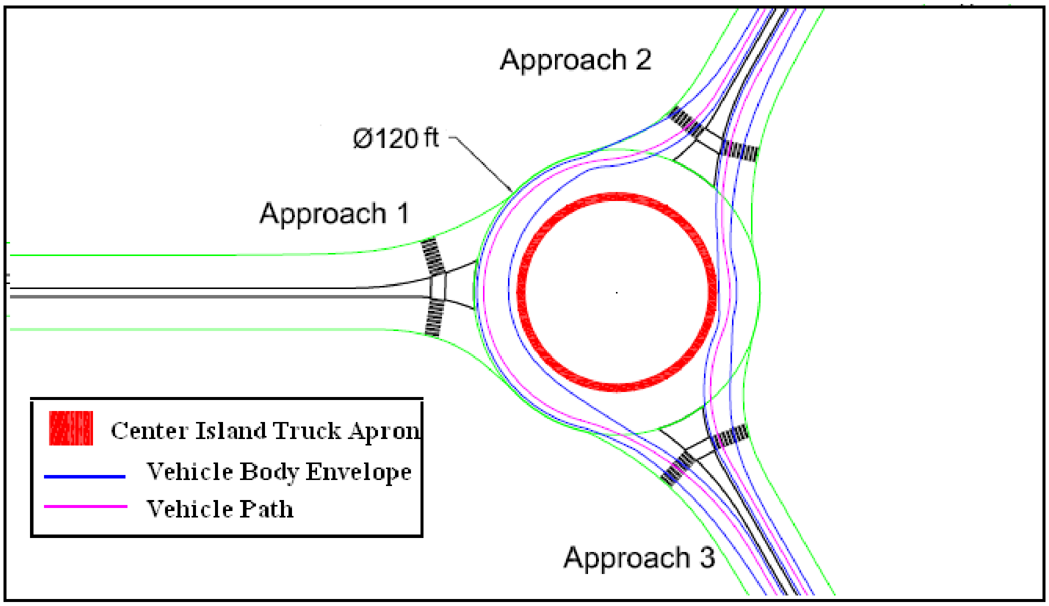
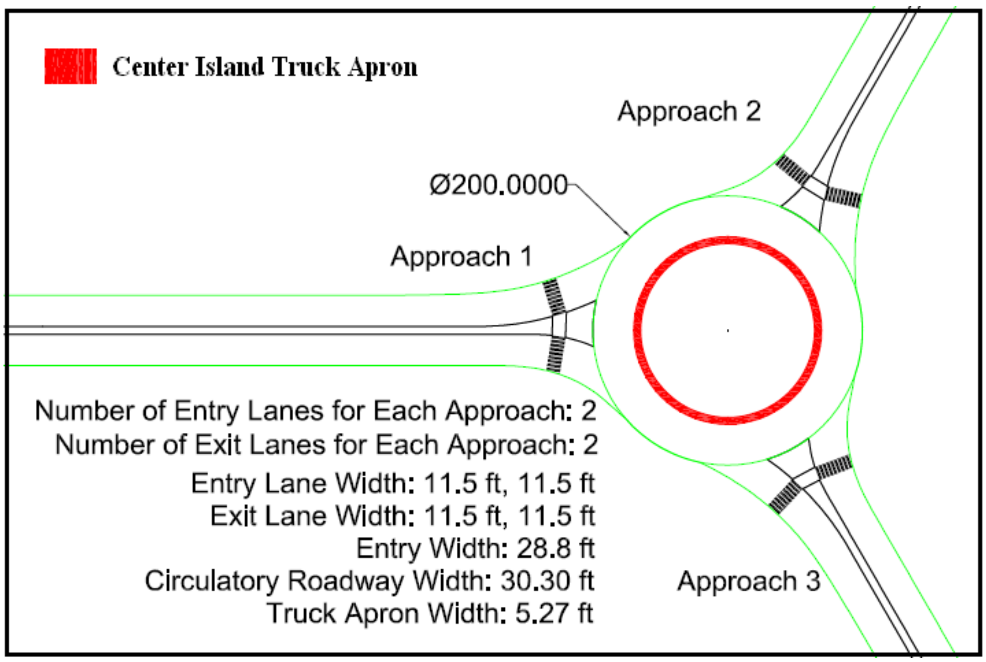


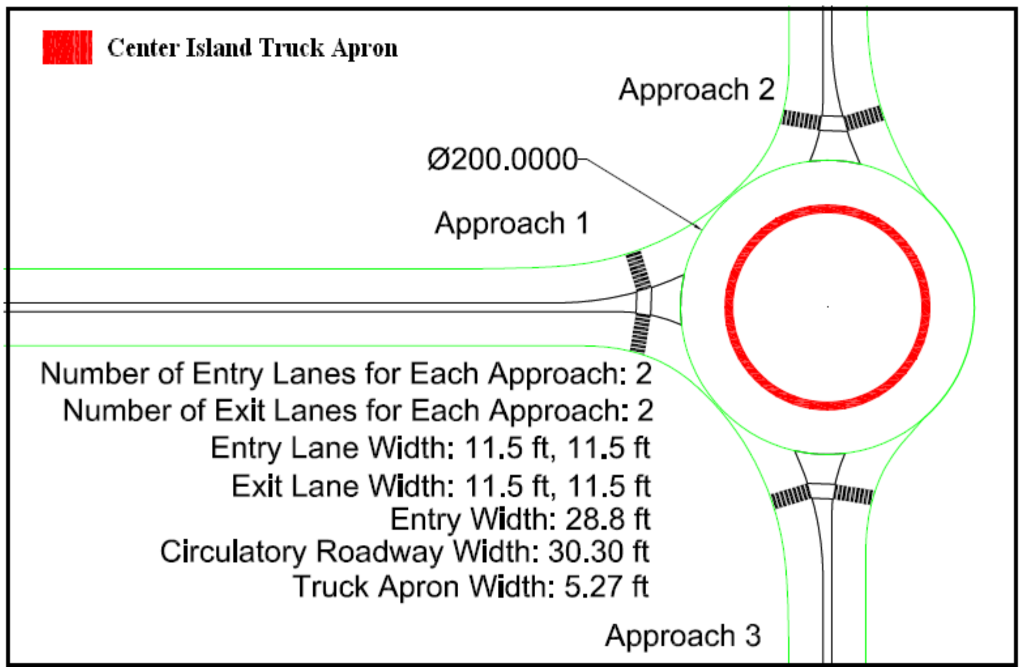
Figure 4.17: Final Design of Double-Lane Symmetric 3-Leg Roundabout



4.1.2.2 Double-Lane 3-Leg Roundabout at T-Intersection

For building a double-lane, 3-leg urban roundabout at a T-intersection, an ICD of 200 ft was selected in accordance with NCHRP report 672 (*1*) and a WB-50 was used as a design vehicle. TORUS software was used to designed the roundabout with specified features and is shown in Figure 4.18. To accommodate various movements for the WB-50 design vehicle, a 5.27 ft center island truck apron was designed for the roundabout. The roundabout shown in Figure 4.18 will be used to demonstrate modifications for accommodating a WB-67. It was observed that the right turn, through and left turn simulations of the WB-67 do not need any external truck apron or additional internal truck apron. Therefore the final, composite, modified design of the double lane 3-leg urban roundabout at T-intersection designed for WB-67 is the same as the initial design and is shown in Figure 4.18.

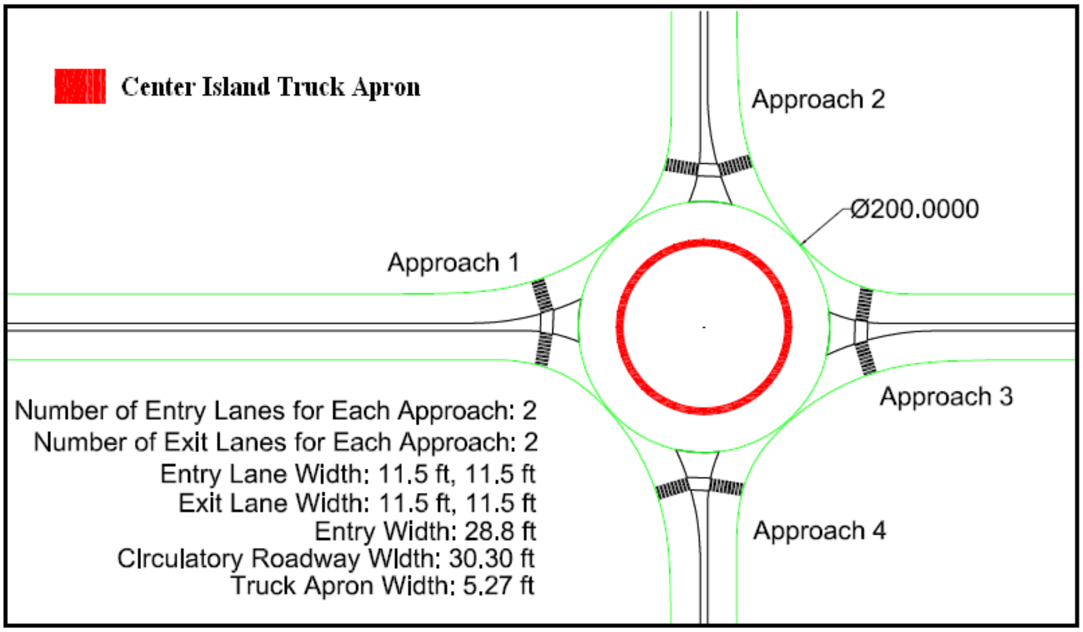
Figure 4.18: Double-Lane 3-Leg Roundabout at T-Intersection with 220 ft ICD and 5.27 ft Truck Apron



4.1.2.3 Double-Lane Typical 4-Leg Roundabout

For building a double-lane, typical 4-leg urban roundabout, an ICD of 200 ft was selected, in accordance with NCHRP report 672 (*1*) and a WB-50 was used as a design vehicle. TORUS software was used to construct the roundabout with specifications and is shown in Figure 4.19. To accommodate various movements of the WB-50 design vehicle, a 5.27 ft center island truck apron was designed for the roundabout. The roundabout shown in Figure 4.19 will be used to demonstrate modifications for accommodating a WB-67. It was observed that the right turn, through, and left turn simulations of the WB-67 do not need any external truck apron or additional internal truck apron. Therefore, the final, composite modified design of the double-lane 4-leg symmetric urban roundabout designed for WB-67 is the same as the initial design and is shown in Figure 4.19.

Figure 4.19: Double-Lane 4-Leg Symmetric Roundabout with 220 ft ICD and 5.27 ft Truck Apron



4.1.3 Summary of Urban Roundabout Designs

Roundabout designs for each configuration (single-lane and double-lane), and for each roundabout type (a typical symmetric 3-leg roundabout, a 3-leg roundabout at a T intersection, and a typical 4-leg roundabout), were considered for this study. It can be observed for all roundabout types with a single-lane roundabout configuration, the roundabout designs generated using design vehicle WB-50 and 120ft ICD have yielded a constant truck apron width (9.36 ft), constant entry lane width (12.5 ft), constant exit lane width (12.5 ft), and constant circulatory roadway width (18.42 ft). However, the entry width for a typical, symmetric 3-leg roundabout, a 3-leg roundabout at a T intersection, and a typical 4-leg roundabout needed to be 15.8 ft, and the entry width for symmetric, 5-Leg roundabout needed to be 16.5 ft. Similarly, it has been observed for all roundabout types in the double-lane roundabout configuration, that the roundabout designs generated using the WB-50 design vehicle and 200ft ICD have resulted in a constant truck apron width (5.27 ft), a constant entry lane width (11.5 ft), a constant exit lane width (11.5 ft), a constant entry width (28.8 ft) and a constant circulatory roadway width (30 ft.).

To safely accommodate a WB-67 vehicle at different types of roundabout in a single-lane roundabout configuration (when initially designed with a WB-50 design vehicle), it can be noted that implementation of external truck aprons, increasing the width of internal truck aprons, and providing custom center islands were helpful. The width of the external truck apron and internal truck apron increases as the ICD selected for the roundabout increases. Also, it has been determined that accommodating a WB-67 vehicle at different types of roundabouts in a double-lane roundabout configuration (when initially designed with a WB-50 design vehicle) do not need any additional space requirements as long as the WB-67 is allowed to use the two lanes on the approach, circulating roadway, and exit of the roundabout. Table 4.1 provides the summary of the designs developed for various roundabout settings in an urban environment.

Table 4.1: Summary of Designs Developed for Urban Roundabout Setting

Roundabout Type	Single-Lane Roundabout (120 ft ICD and Design Vehicle WB-50)		Double-Lane Roundabout (200 ft ICD and Design Vehicle WB-50)	
	WB-50 Accommodation	WB-67 Accommodation	WB-50 Accommodation	WB-67 Accommodation
Symmetric 3-Leg	Figure 4.1	Figure 4.4	Figure 4.15	Figure 4.17
3-Leg at T-Intersection	Figure 4.5	Figure 4.7	Figure 4.18	Figure 4.18
Symmetric 4-Leg	Figure 4.8	Figure 4.10	Figure 4.19	Figure 4.19
Symmetric 5-Leg	Figure 4.11	Figure 4.14	NA	NA

4.2 Rural Roundabouts

This study considered and designed the most common roundabout intersections on rural roads using a basic roundabout design with a WB-67 design vehicle, and then modifying the roundabout designs to better accommodate OSOW movements using various strategies. Roundabout configurations such as a single-lane roundabout and a double-lane roundabout were considered for this study. For each configuration, roundabout types such as a typical, symmetric 3-leg roundabout, a 3-leg roundabout at a T-intersection, and a typical 4-leg roundabout were considered.

According to NCHRP Report 672, the latest roundabout guide, the AASHTO designation WB-67 is considered the most common design vehicle for rural intersections (*1*). Therefore, the WB-67 was used as the design vehicle to generate the basic roundabout design and truck apron design using TORUS software. The design generated was then used for conducting wheel path and swept path analysis with AutoTURN for six OSOW check vehicles (explained below) for right turn, through, and left turn movements. Based on the simulated wheel tracks for all possible OSOW check vehicles (check vehicles are explained below in section 4.2.1) from all approaches, an outer truck apron, custom center island and custom truck apron were analyzed to develop the design of the roundabout which would accommodate the OSOW movement represented by each check vehicle.

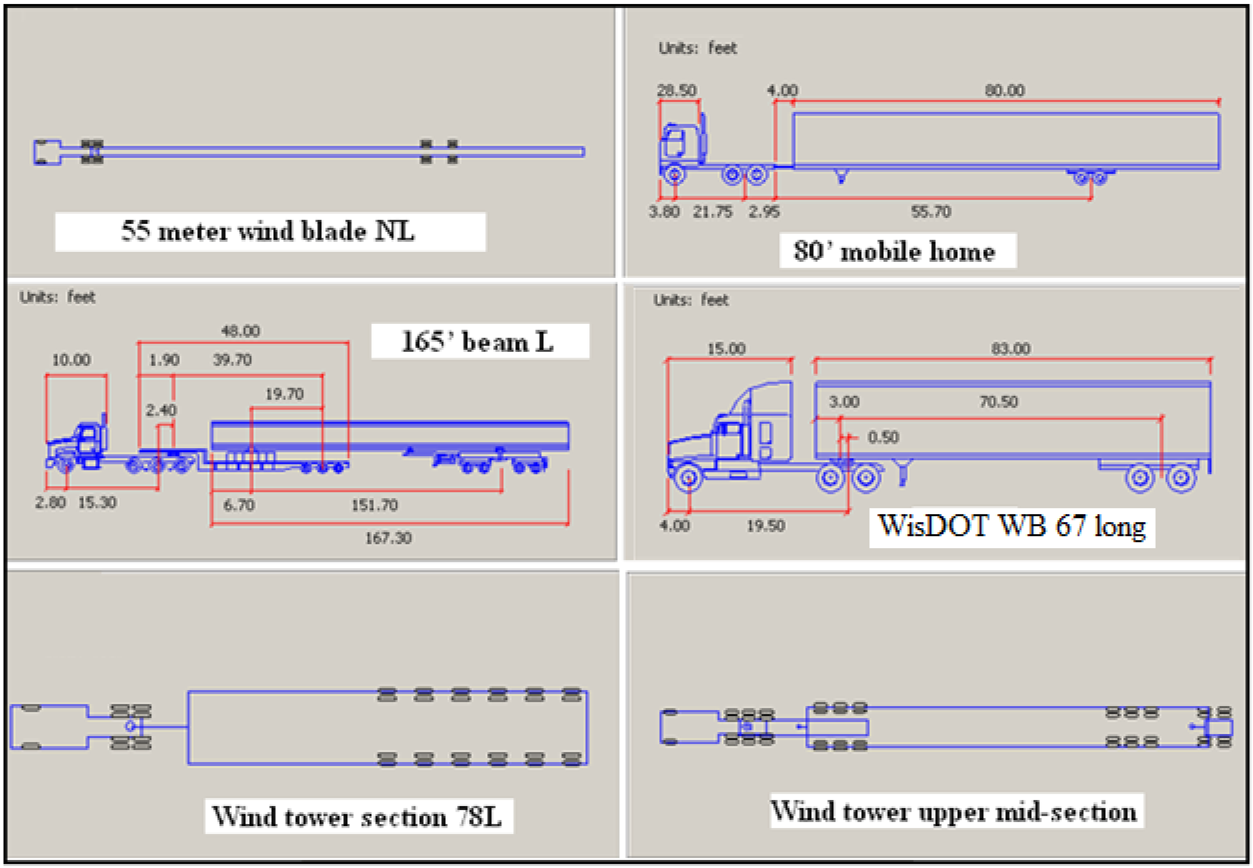
4.2.1 OSOW Vehicles used for the Study

Accommodation of OSOW vehicles at the roundabout was checked by considering wheel path and swept path analysis for a set of six typical OSOW vehicles, called “check vehicles”. The “check vehicles” used were developed for use in Wisconsin for the WisDOT Freight Operations Section which had compiled an inventory file of six OSOW check vehicles that could be used in AutoTURN. These six check vehicles were developed to represent all known configurations of OSOW that could be expected on US highways. Among the six OSOW check vehicles used in this study, the 55 meter wind blade, the wind tower section, and the 165’ beam were vehicles with rear steering capability. It was assumed that if this study can accommodate these six OSOW check vehicles, the same approach can be used to accommodate any OSOW vehicle. The six check vehicles (shown in Figure 4.20) that were obtained from the WisDOT vehicle library are:

1. 55 meter wind blade (Vehicle length=209ft, wheelbase=19.25ft, trailer length=187.5ft),
2. 80’ mobile home (Vehicle length=112.50ft, wheelbase=21.75ft, trailer length=80ft),
3. 165’ beam L (Vehicle length=198.83ft, wheelbase=15.33ft, trailer length=48ft),
4. wind tower section (Vehicle length=112.50ft, wheelbase=19.50ft, trailer length=78ft),

5. wind tower upper mid-section (Vehicle length=148.80ft, wheelbase=20.50ft, trailer length=33.20ft),
6. WisDOT WB-67 long (Vehicle length=103ft, wheelbase=19.50ft, trailer length=83ft).

Figure 4.20: Six OSOW check vehicles from Wisconsin Department of Transportation



Source: WisDOT Vehicle Library (*28*)

4.2.2 Single Lane Rural Roundabouts

For the single-lane roundabout configuration, a typical, symmetric, 3-leg roundabout, a 3-leg roundabout at a T intersection, and a typical 4-leg roundabout were considered. According to NCHRP Report 672 (*1*), the ICD range for single-lane roundabout using a WB-67 design vehicle is 130 to 180 ft. As this study deals with OSOW vehicles which are bigger than WB-67, the upper limit, 180 ft ICD was used for the single-lane roundabouts.

4.2.2.1 Rural Single-Lane, Symmetric 3-Leg Roundabout

Figure 21 shows a sample 90 degree right turn AutoTURN simulation of 'Wind tower section 78L' to understand different lines of the vehicle simulation. A typical, symmetric 3-leg rural roundabout was designed using TORUS software with a 180 ft ICD and WB-67 design vehicle and is shown in Figure 4.22-part A. The roundabout design generated (Figure 4.21-part A) was used to conduct right turn, through and left turn movement simulations of all the six OSOW check vehicles from all three approaches in a normal way. Each simulation was conducted in such a way that the front wheels travel around the roundabout like a normal vehicle and the rear tire impressions were studied if they overrode beyond the roundabout design or onto the center island, beyond the provided truck apron.

If the rear tires of an OSOW check vehicle were found using the space beyond the roundabout design, a truck apron was suggested in such areas. The truck apron can be a center island truck apron or an outer truck apron based on the space requirements. It was found that, except for the left turn movement of the '165' beam', all other OSOW check vehicle simulations were made possible through the roundabout with a 180 ft ICD.

Figure 4.21: Understanding a AutoTURN OSOW Check Vehicle Simulation in this Study

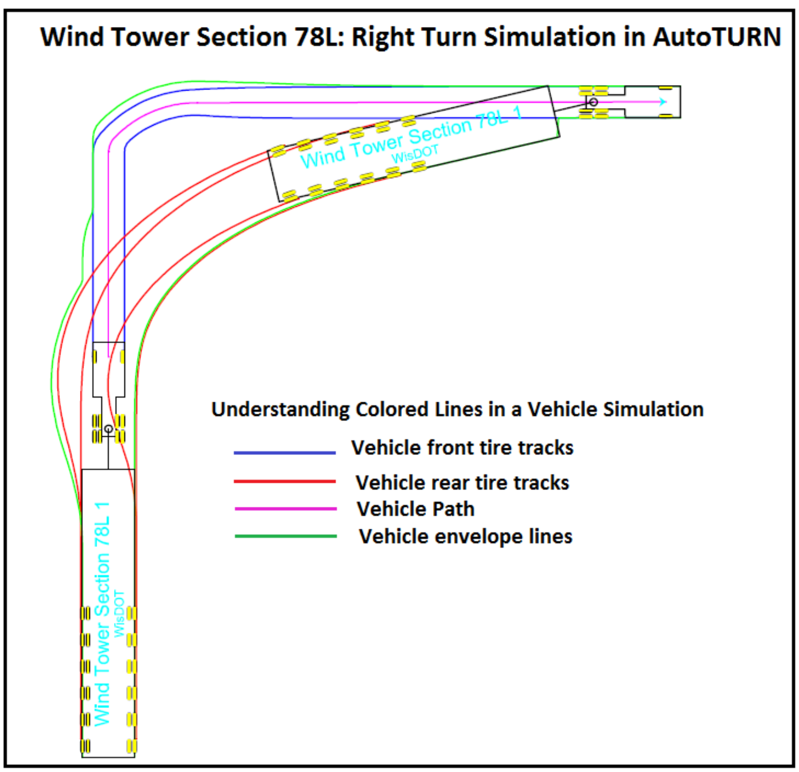


Figure 4.22 part B, shows a “165’ beam” in a possible hang up situation while trying to maneuver a left turn from approach 3 to approach 1. In this figure, it is noted that the magenta line is the path of the vehicle, the blue lines represent the front tire tracks, the red lines represent the rear tire tracks, and the green lines represent the vehicle body clearance. It can also be noted from the simulation in Figure 4.22-part B, that the rear tires travel beyond the design of the roundabout requiring an outer truck apron to accommodate these kinds of movements. Figure 4.22-part C, shows the design generated to accommodate right turn, through and left turn simulations of the 6 OSOW check vehicles from all approaches, except the left turn, of the “165’ beam” from all three approaches.

The center island truck apron area, total outer truck apron area, and the total truck apron area for Figure 4.22-part C, was calculated and presented in Table 4.2. In Figure 4.22-part C, a small no pole/no sign area shaded in orange is the vehicle body clearance area which doesn’t need a traversable truck apron, but should not have any poles or signs that cannot be removed. If a sign was warranted in this area, a removable sign installation should be considered.

It can be observed from Figure 4.22-part C, that there is a need to construct a large area of external truck apron (27,491.46 ft^2), and a fully traversable center island (area = 17,082.68 ft^2). However, the focus of this study is on efficient accommodation of the six OSOW check vehicles by decreasing the need to provide a large area of truck apron and the results are shown in Table 4.2.

Various strategies were studied to design rural roundabouts to better accommodate OSOW movements. These OSOW movements can also be effectively accommodated by certain unique treatments such as: (Note that traffic control would be required for some movements, but OSOW are usually escorted vehicles, so this should be no problem)

1) Making the splitter islands “truck tire friendly” and fully traversable such that the OSOW movements can be made more effective by riding over the splitter island if needed. This means that the traversable splitter islands should not be installed with poles or signs. However, if a sign is warranted, removable signs need to be considered for installation.
2) When needed, use lanes of both directions of traffic and splitter island as approach lane for the OSOW vehicle.

3) Allow the left turn maneuvers of OSOW movements in such a way that the OSOW vehicles enter from the right most lane/side of the approach and travel in the opposite direction of normal traffic flow without circulating the center island (as shown in example in Figure 4.23-part A) such that the need for a large outer truck apron and center island truck apron is decreased.
4) Allowing the right turn maneuvers in such a way that the vehicles enter from the opposite direction of traffic (or left most lane in the approach) at the approach and exit into any lane such that a minimum truck apron is required.

Figure 4.22: Steps Followed for Modifying the Geometry of Single-Lane Typical Symmetric 3-leg Roundabout for OSOW Check Vehicles

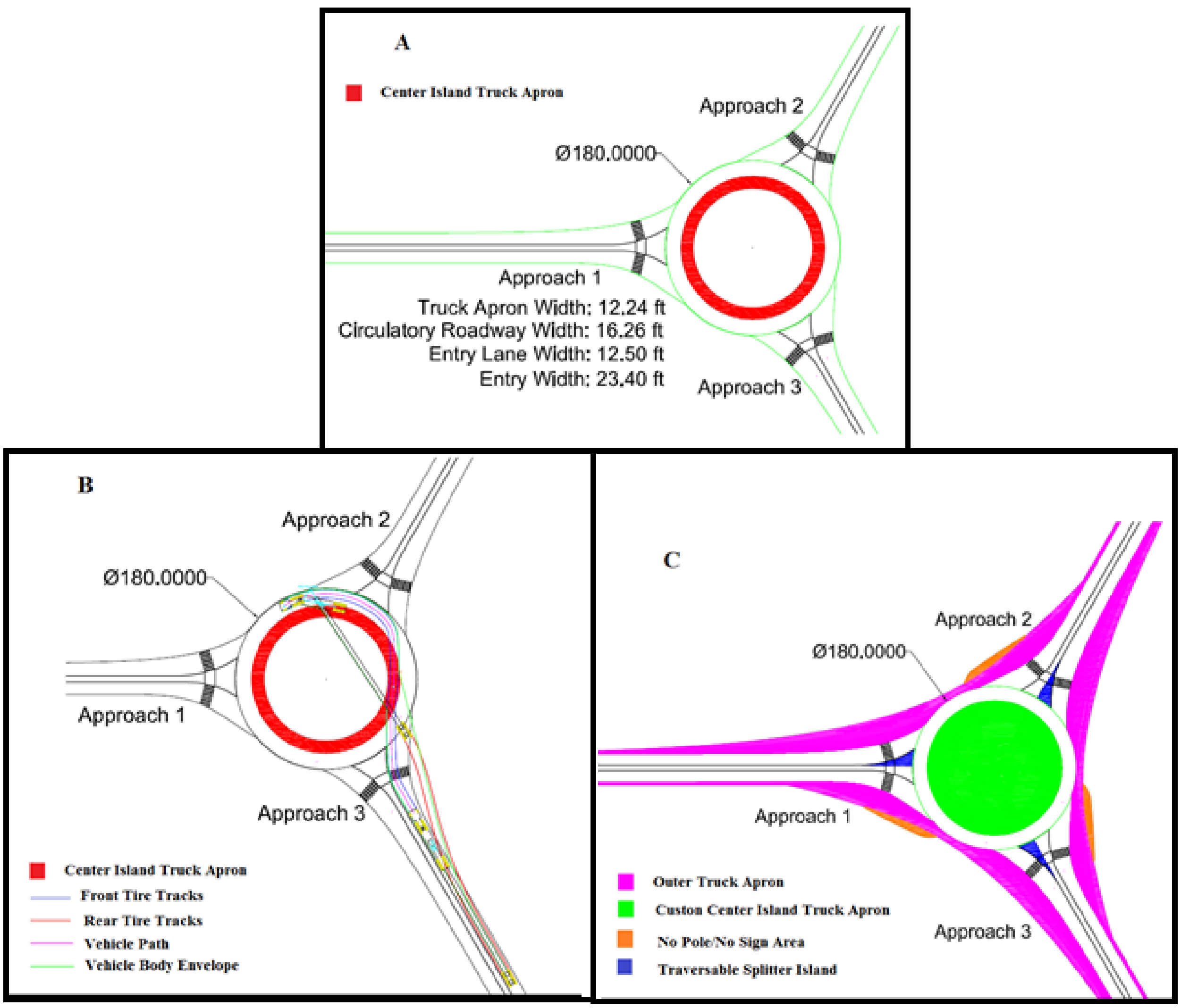


Table 4.2: Center Island Truck Apron Area, Outer Truck Apron Area, and Total Truck Apron area for Roundabouts Designed for Accommodating 6 OSOW Check Vehicles.

Roundabout Type	OSOW Accommodation Method	ICD (ft.)	Center Island Truck Apron Area, (C) (ft^2)	Total Outer Truck Apron Area, (O) (ft^2)	Total Truck Apron, (T = C+O) (ft^2)
Single-Lane Typical Symmetric 3-Leg	Normal	180	17,082.68	27,491.46	44,574.14
	ODT	180	5,200.39	7,657.35	12,857.74
	ODT & FTCI	180	17,082.68	0.00	17,082.68
Single-Lane 3-Leg at T Intersection	Normal	180	17,082.68	32,317.78	49,400.46
	ODT	180	11,210.10	17,872.03	29,082.13
	ODT & FTCI	180	17,082.68	13,434.93	30,517.61
Single-Lane Typical 4-Leg	Normal	180	17,082.68	60,090.27	77,172.95
	ODT	180	9,897.40	37,859.68	47,757.09
	ODT & FTCI	180	17,082.68	26,869.87	43,952.55
Double-Lane Typical Symmetric 3-Leg	Normal	220	16,739.06	11,400.74	28,139.80
	ODT	220	5,220.08	0.00	5,220.08
	ODT & FTCI	220	Not Needed		
Double-Lane 3-Leg at T Intersection	Normal	220	16,191.73	21,437.10	37,628.83
	ODT	220	8,080.41	9,230.76	17,311.17
	ODT & FTCI	220	20,343.13	0.00	20,343.13
Double-Lane Typical 4-Leg	Normal	220	19,382.70	41,847.46	61,230.16
	ODT	220	9,180.60	9,536.14	18,716.74
	ODT & FTCI	220	20,343.13	0.00	20,343.13

ICD: Inscribed Circle Diameter, ODT: Opposite Direction Travel, ODT & FTCI: Opposite Direction Travel and Fully Traversable Central Island

Using the above techniques, the OSOW loads can be accommodated in two ways:

1) Opposite Direction Travel (ODT) (sometimes called “counter flow”): In this technique, the width of the center island truck apron is kept the same as the initial TORUS design to accommodate a WB-67 design vehicle. A right turn for an OSOW vehicle was made in such a way that it may enter from any lane (same direction traffic or opposite direction traffic) of the entering approach and exit into any lane of the exiting approach in such a way that it uses the basic, provided center island truck apron width and a minimum outer truck apron. A through maneuver is simulated in a normal way. However, the front tires

of the vehicle considers the circulatory width as the sum of TORUS designed circulatory width and TORUS designed basic truck apron for a WB-67 such that the need for a large outer truck apron is minimized. The shape and width of the center island truck apron is modified, based on the six OSOW check vehicles through movements. A left turn for an OSOW vehicle was made in such a way that it may enter from any lane (same direction of traffic or opposite direction of traffic) of the entering approach and exit into any lane of the exiting approach in such a way that it uses the basic, provided center island truck apron width, and minimum outer truck apron. Also, it should be noted that the OSOW vehicles make a left turn without traversing the center island as shown in Figure 4.23-part A (left turn maneuver of 165' beam from approach 3 to approach 1). The splitter islands are assumed traversable.

2) ODT and Fully Traversable Center Island (FTCI): In this technique, the center island is made fully traversable and the right turn, through movement, and left turn maneuvers were simulated in such a way that they can completely use the fully traversable center island to minimize the use of an outer truck apron. For this purpose, the OSOW vehicles were also allowed to enter from any lane (same direction traffic or opposite direction traffic) and exit into any lane (same direction traffic or opposite direction traffic) to decrease the use of an outer truck apron area. The splitter islands are assumed traversable.

Figure 4.23-part A, left turn maneuver of the "165' beam" from approach 3 to approach 1, and Figure 4.23-part B, right turn maneuver of the "165' beam" from approach 3 to approach 2 shows an example of using the ODT method of accommodating the OSOW movements. Figure 4.23-part C, shows the first design alternative developed (using ODT) to accommodate all six OSOW check vehicles. Total truck apron area needed is considered a surrogate for roundabout size needed to accommodate the check vehicles for a given strategy. It can be seen from Table 4.2 that the need for a larger center island truck apron and total outer truck apron was decreased by implementing the ODT method for OSOW accommodation. It was also found that the need for a total truck apron area was decreased by 71.15% (Table 4.3) when compared to normal accommodation.

Figure 4.23-part D, left turn maneuver of the "165' beam" from approach 3 to approach 1, and Figure 4.23-part E, right turn maneuver of the "165' beam" from approach 3 to approach 2

shows an example of using the ODT & FTCI method of accommodating the OSOW movements. Figure 4.23-part F, shows the second design alternative developed (using ODT & FTCI method of OSOW accommodation) to accommodate all 6 OSOW check vehicles. It was found that the need for total truck apron area was decreased by 61.67% (Table 4.3) for the second design alternative when compared to normal accommodation.

Figure 4.23: ODT, and ODT & FTCI Method of Accommodating OSOW Movements

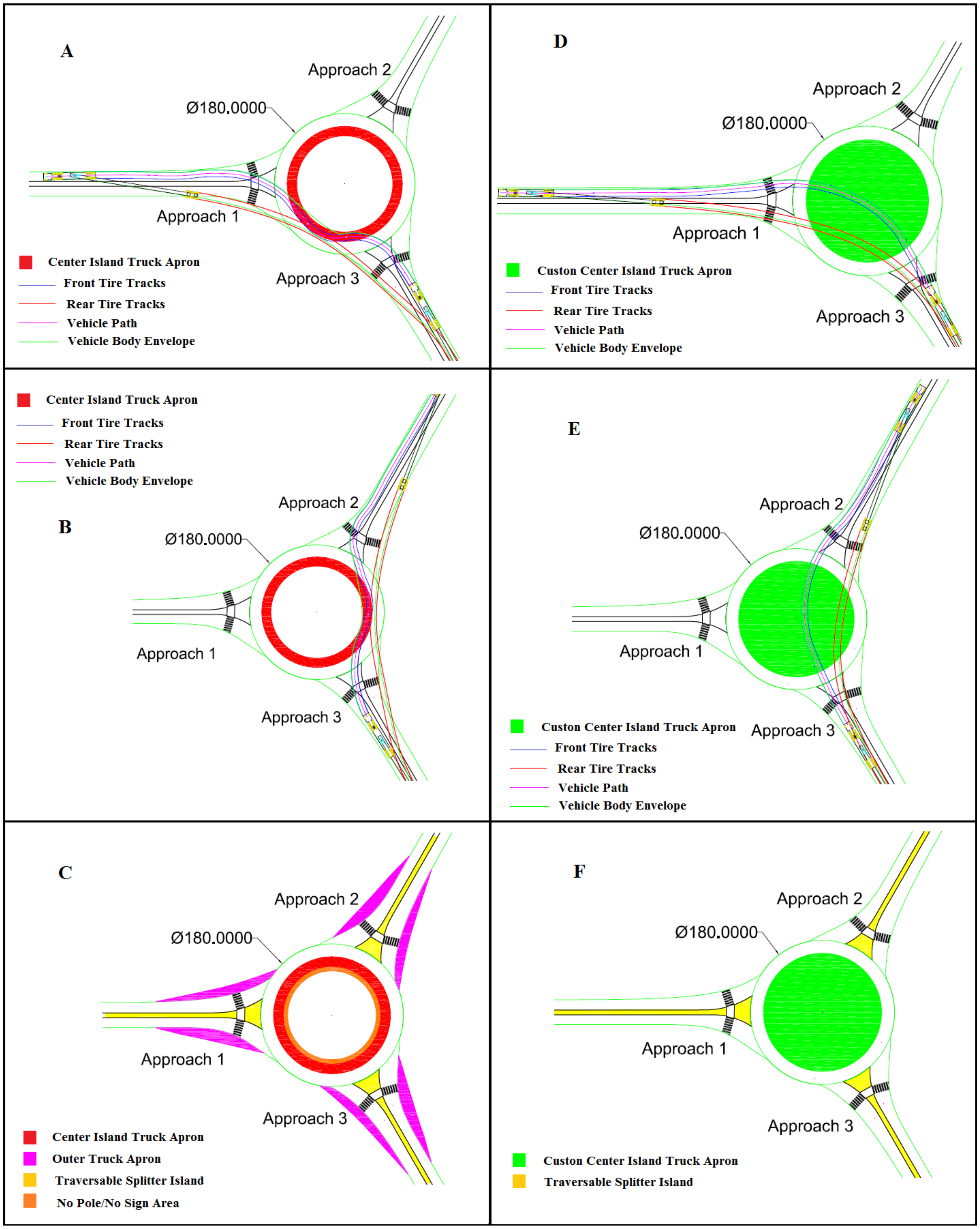


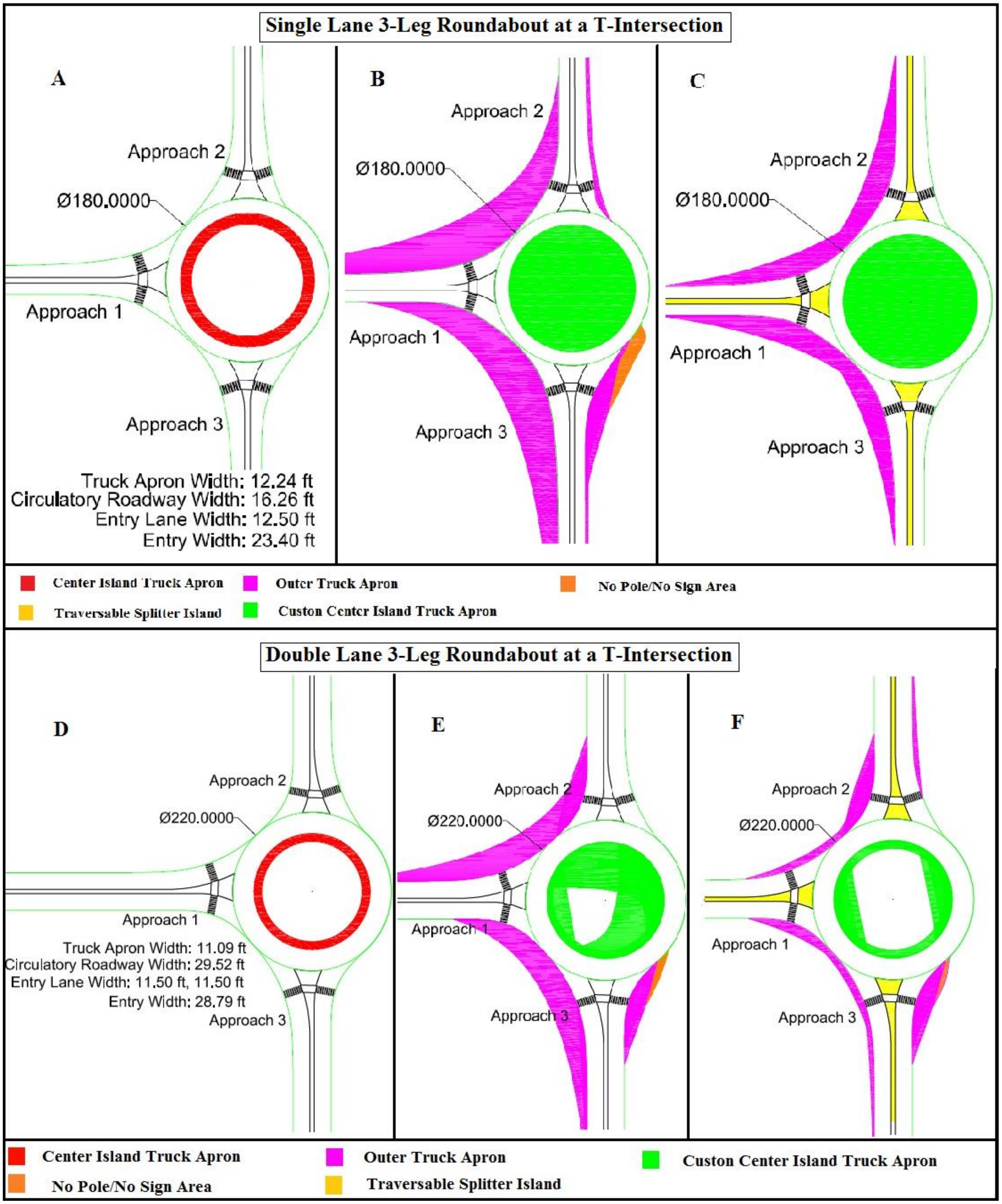
Table 4.3: Total Truck Apron Reduced by ODT, and ODT & FTCI Method

Category of Roundabout	Total Truck Apron Area	
	% of Total Truck Apron Area Decreased by Accommodation of OSOW Vehicles by ODT compared to Normal Accommodation	% of Total Truck Apron Area Decreased by Accommodation of OSOW Vehicles by ODT & FTCI compared to Normal Accommodation
Single-Lane Typical Symmetric 3-Leg	71.15%	61.67%
Single-Lane 3-Leg at T Intersection	41.12%	38.22%
Single-Lane Typical 4-Leg	38.11%	43.04%
Double-Lane Typical Symmetric 3-Leg	81.45%	N/A
Double-Lane 3-Leg at T Intersection	53.99%	45.93%
Double-Lane Typical 4-Leg	69.43%	66.77%

4.2.2.2 Rural Single-Lane, 3-Leg Roundabout at T-Intersection

TORUS software was used to design a 3-leg roundabout at a rural T-intersection with WB-67 as the design vehicle and with a 180 ft ICD (Figure 4.23-part A). Figure 4.24-part B, shows the design generated by simulating the 6 OSOW check vehicles in a normal way. It has to be noted that a normal left turn movement of the “165’ beam” was not possible at this roundabout. Figure 4.24-part C, shows the design alternative developed using the ODT & FTCI method of OSOW accommodation for the 6 OSOW check vehicles. It was found that the need for total truck apron area was decreased by 38.22% (Table 4.3) for this design alternative when compared to normal accommodation. It was also found that the need for a total truck apron area was decreased by 41.12% (Table 4.3) by accommodation of the 6 OSOW check vehicles in ODT method of accommodation when compared to normal flow accommodation.

Figure 4.24: Designs for Single-Lane 3-leg Roundabout at T-Intersection



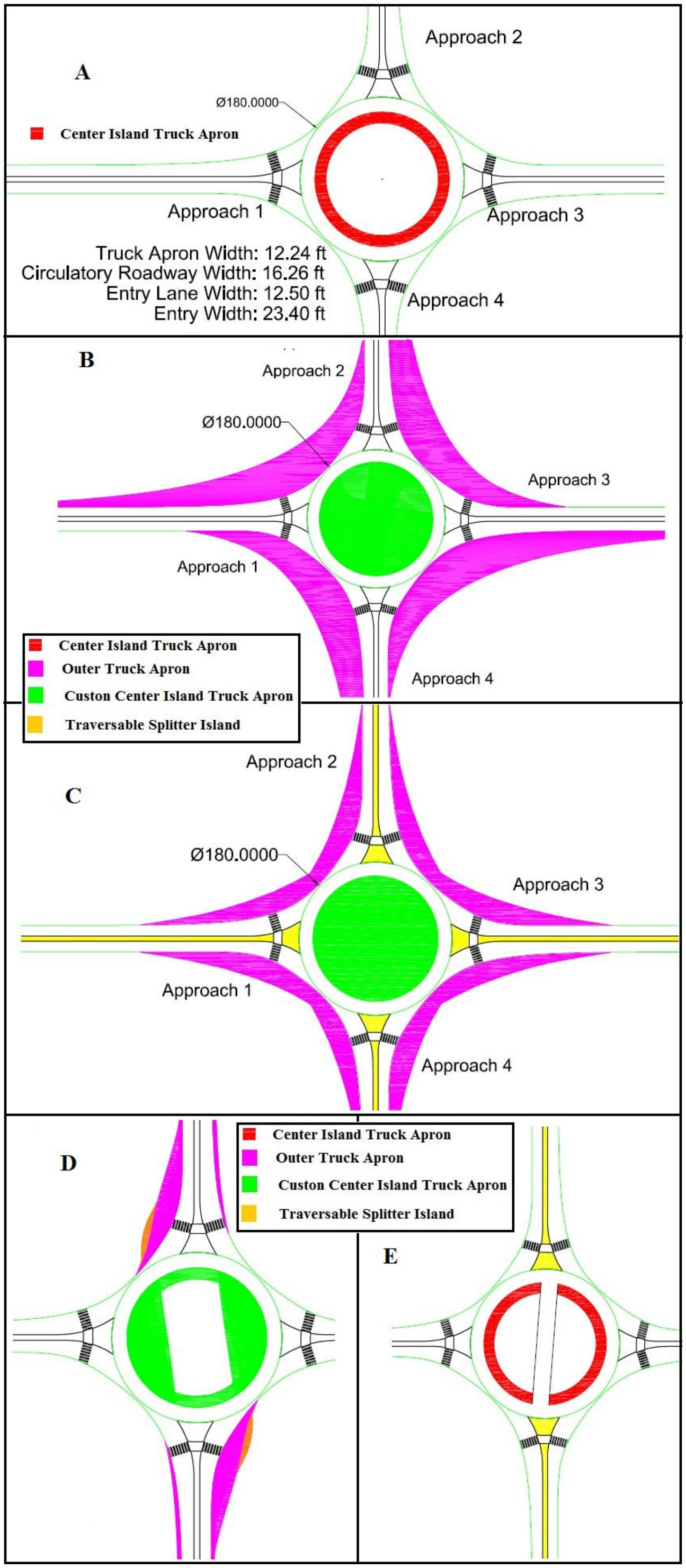
4.2.2.3 Rural Single-Lane Typical 4-Leg Roundabout

TORUS software was used to design a single-lane, typical, 4-leg rural roundabout with WB-67 as the design vehicle, and using a 180 ft ICD (Figure 4.25-part A). Figure 4.25-part B, shows the design generated by simulating the 6 OSOW check vehicles in a normal way. It has to be noted that a normal left turn movement of the “165’ beam” was not possible at this roundabout. Figure 4.25-part C shows the design alternative developed using ODT & FTCI method of OSOW accommodation for the 6 OSOW check vehicles. It was found that the need for total truck apron area was decreased by 43.04% (Table 4.3) for this design alternative when compared to normal accommodation. It was also found that the need for total truck apron area was decreased by 38.11% (Table 4.3) by accommodation 6 OSOW check vehicles in ODT method of accommodation when compared to normal accommodation.

Four-leg roundabouts are very common on rural intersections and most of the time the OSOW loads might enter from only one or two opposite approaches and travel through. For this specific case, providing a straight passage through the center island might be a best option. Therefore, through movements of all 6 OSOW check vehicles were conducted from approach 2 and approach 4 in a normal way and the design was generated as shown in Figure 25-part D. Figure 25-part E shows the alternate design generated by providing a straight through passage through the center island to accommodate the through movements.

It was determined that the total truck apron needed to accommodate six OSOW check vehicle through movements from approach 2 and approach 4 was 14,029.39 ft^2 whereas a straight through passage would just need 4,705.64 ft^2 showing a 66.45% reduction in need total truck apron. However, assuming a 25 ft. roadway/passage through the center island, a 2944.27 ft^2 area of passage should be paved through the center island. It implies that the total paved area (truck apron area and center island passage area) required for center island straight through option is 45.47% less than the total paved area (total truck apron area) required for normal accommodation. If a straight through passage was considered through the center island, gates for the passage need to be installed such that the general road users do not have access to the passage.

Figure 4.25: Designs for Single-Lane Typical 4-Leg Roundabout



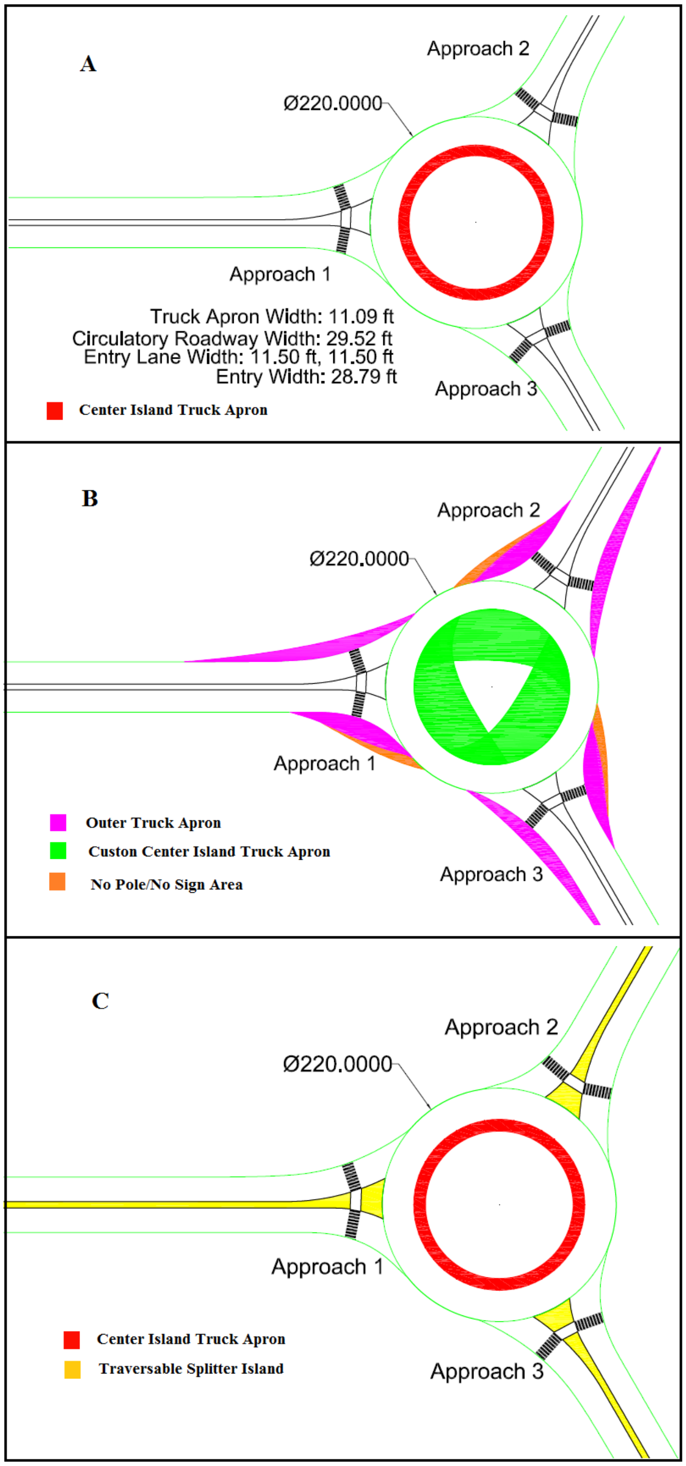
4.2.3 Double-Lane Rural Roundabouts

For the double-lane roundabout configurations, a typical symmetric 3-leg roundabout, a 3-leg roundabout at a T intersection, and a typical 4-leg roundabout were considered. According to NCHRP Report 672 (*1*), the ICD range for double-lane roundabout using WB-67 as the design vehicle is 165 to 220 ft. As this study deals with OSOW vehicles which are bigger than WB-67, the upper limit, 220 ft ICD was considered for double-lane roundabouts.

4.2.3.1 Rural Double-Lane Typical Symmetric 3-Leg Roundabout

TORUS software was used to design a double-lane typical, symmetric, 3-leg rural roundabout using WB-67 as the design vehicle and using a 220 ft ICD (Figure 4.26-part A). For double-lane roundabouts, each OSOW simulation is accommodated in such a way that the vehicle enters from any of the two lanes, circulates in any of the two lanes and exits into any of the two lanes to reduce the need for outer truck apron and/or center island truck apron. Figure 4.26-part B shows the design generated by simulating the 6 OSOW check vehicles in a normal way. It has to be noted that a normal left turn movement of the "165' beam" was not possible at this roundabout. Figure 4.26-part C shows the design alternative developed using the ODT method of OSOW accommodation for 6 OSOW check vehicles. The design proves that there is no need for an external truck apron. It was found that the need for the total truck apron area was decreased by 81.45% (Table 4.3) for this design alternative when compared to normal accommodation. The ODT & FTCI method was not tried as the ODT method has yielded the basic roundabout design without needing extra truck apron to handle all the 6 OSOW check vehicle simulations.

Figure 4.26: Designs for a Double-Lane Typical Symmetric 3-leg Roundabout



4.2.3.2 Rural Double lane 3-Leg Roundabout at T-Intersection

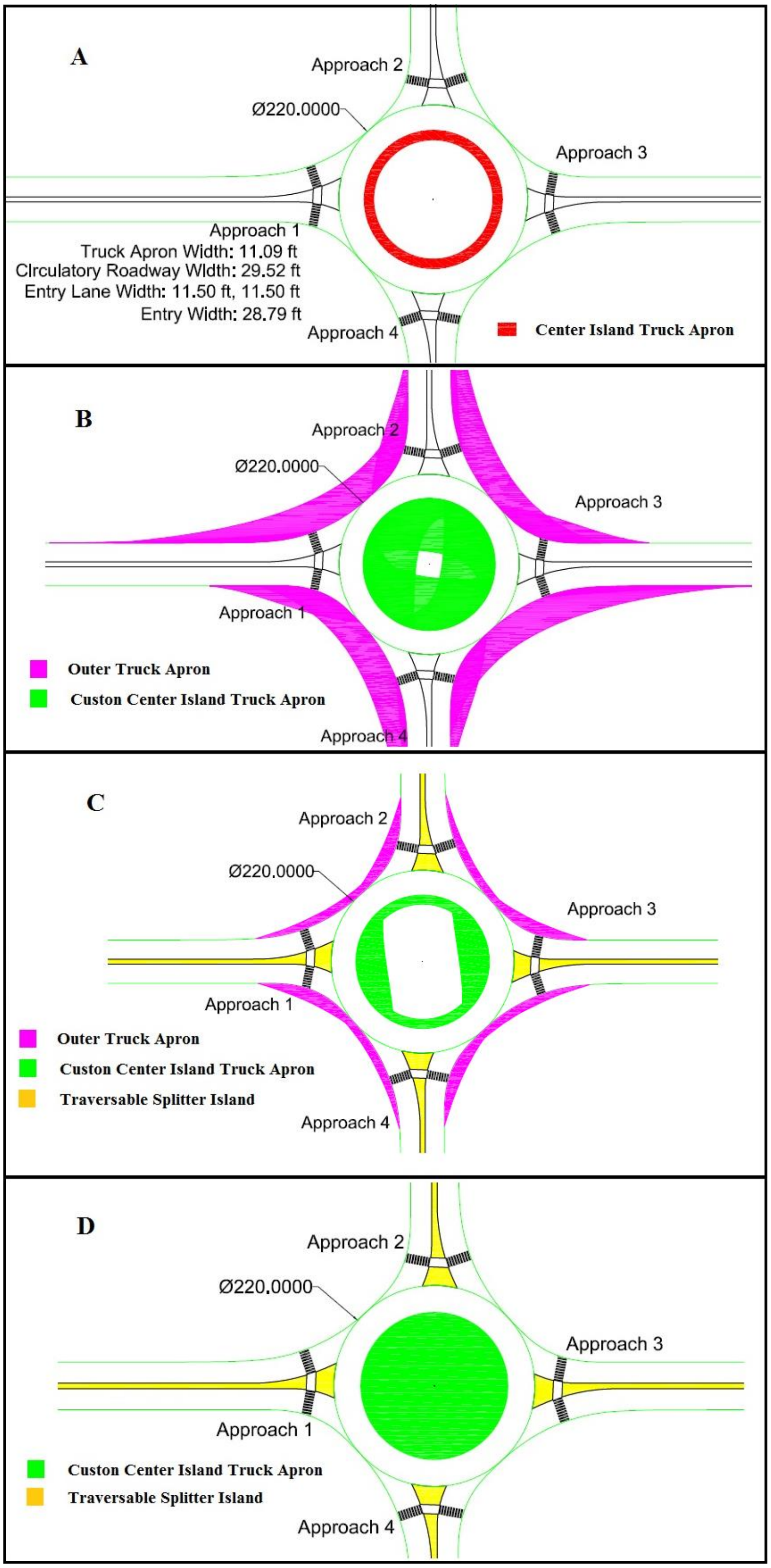
TORUS software was used to design a double-lane, 3-leg rural roundabout at a T-intersection with WB-67 as the design vehicle and using a 220 ft ICD (Figure 4.24-part D).

Figure 4.24-part E shows the design generated by simulating the six OSOW check vehicles in a normal way. The normal left turn movement of the "165' beam" was not possible at this roundabout. Figure 4.24-part F shows the design alternative developed using the ODT method of OSOW accommodation for the six OSOW check vehicles. It was found that the need for total truck apron area is decreased by 53.99% (Table 4.3) for this design alternative when compared to normal accommodation. It was also found that the need for total truck apron area was decreased by 45.93% (Table 4.3) by accommodation six OSOW check vehicles in ODT & FTCI method of accommodation when compared to normal accommodation.

4.2.3.3 Rural Double-Lane, Typical 4-Leg Roundabout

TORUS software was used to design a double-lane, typical 4-leg rural roundabout, with WB-67 as the design vehicle, and a 220 ft ICD (Figure 4.27-part A). Figure 4.27-part B shows the design generated by simulating the 6 OSOW check vehicles in a normal way. The left turn movement of the "165' beam" was not possible at this roundabout. Figure 4.27-part C shows the design alternative developed using the ODT method of OSOW accommodation for the six OSOW check vehicles. It was found that the need for total truck apron area is decreased by 69.43% (Table 4.3) for this design alternative when compared to normal accommodation. Figure 4.27-part D shows the design alternative developed using the ODT & FTCI method of OSOW accommodation for the six OSOW check vehicles. It was found that the need for total truck apron area is decreased by 66.77% (Table 4.3) for this design alternative when compared to normal accommodation. For this roundabout, providing a straight passage through the center island was also investigated while comparing it with normal accommodation when OSOW movements were expected from two apposite approaches. The total truck apron, calculated for accommodating the 6 OSOW check vehicle through movements from approach 2 and approach 4, is 12,314.09 ft^2, whereas a straight through passage would just need 4,665.48 ft^2, a 62.11% reduction in total truck apron area. However, assuming a 25 ft. roadway/passage through the center island, a 3998.65 ft^2 area of passage should be paved through the center island. This implies that the total paved area (truck apron area and center island passage area) required for center island straight through option is 29.64% less than the total paved area (total truck apron area) required for normal accommodation.

Figure 4.27: Designs for Double-Lane Typical 4-leg Roundabout for T-Intersection



4.2.4 Truck Apron Area plots for Single lane and Double – Lane Roundabouts

Figures 4.29 (single lane) and 4.30 (double-lane) show a visual summary of how truck apron area varies for the three types of intersections studied (3-leg symmetrical, 3-leg at T intersection, and 4-leg symmetrical) for normal, ODT and ODT & FTCI, OSOW accommodation strategies. [Note: the plots are not continuous but drawing lines between points makes the differences more visible than points]

Figure 4.28: Truck Apron Area Data Plot for Single-Lane Roundabouts

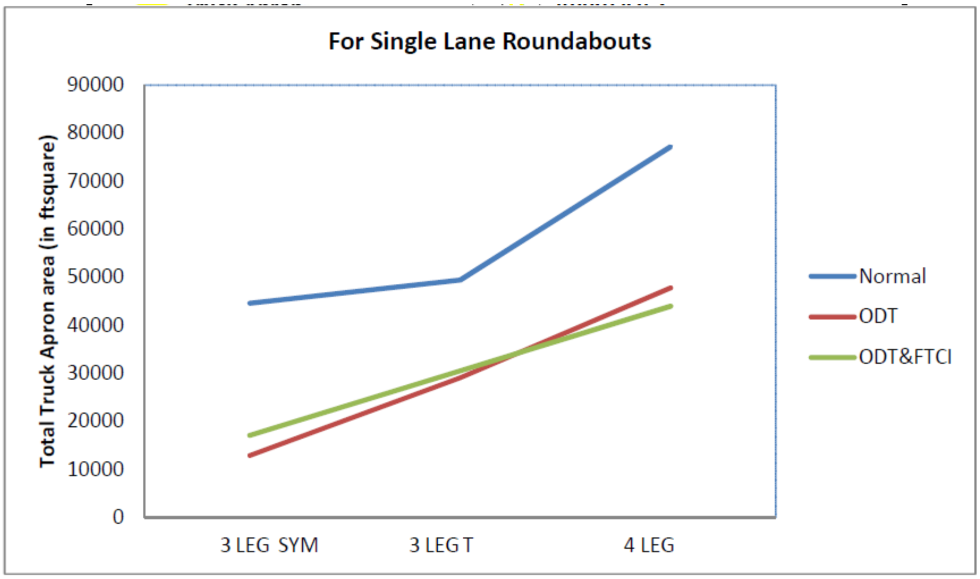
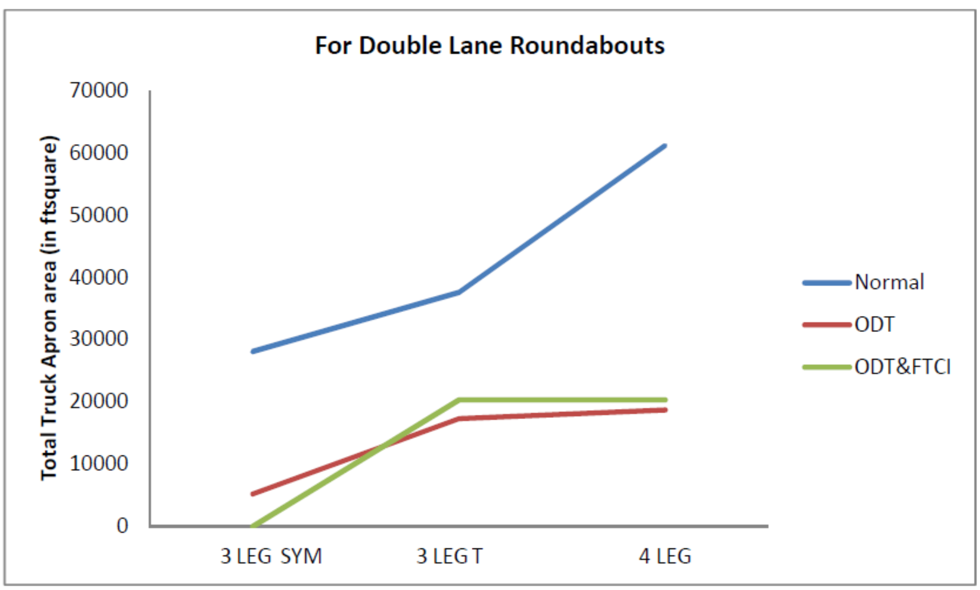


Figure 4.29: Truck Apron Area Data Plot for Double-Lane Roundabouts



4.3 Testing of Check Vehicles on Kansas Roundabout Drawings

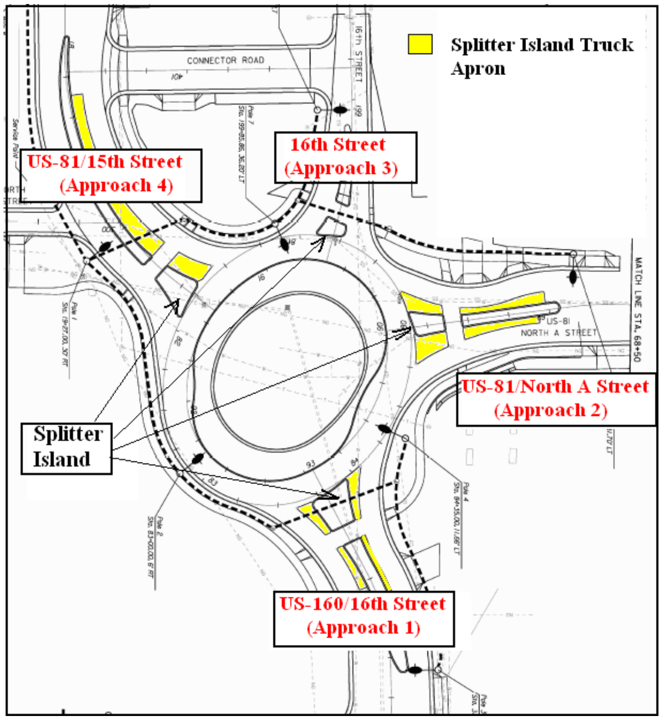
Drawings of roundabouts built in Kansas were considered for this study at the request of Kansas DOT (KDOT), to illustrate different ways or possibly modifying actual roundabout designs could be checked or modified for OSOW load combinations. There was no intent to redesign these roundabouts, but to illustrate a procedure that could be used on analyzing future roundabout designs where OSOW are expected. These roundabouts were assumed to be expecting OSOW loads and they were checked for space requirements using the six OSOW check vehicles using AutoTURN software. Wellington Roundabout, Garnett Roundabout, and Arkansas City Roundabout were the roundabouts considered for the case studies described below.

4.3.1 Wellington Roundabout

The Wellington roundabout was constructed at the intersection of US-81 and US-160 in the city of Wellington, Kansas and will be used initially as an illustration to check the accommodation of the six OSOW check vehicles and find the space requirements of these check vehicles. An alternative way will also be suggested for this roundabout to better accommodate these six check vehicles, which minimizes the need for building an extra truck apron that might be necessary.

The Wellington roundabout has four approaches US-160/16th Street, US-81/North A Street, 16th Street, and US-81/15th Street. These approaches were called approach 1, approach 2, approach 3 and approach 4 simultaneously in the drawings and this writing for easy reference. Figure 4.30 shows the Wellington roundabout with names of the 4 approaches labeled.

Figure 4.30: The Wellington Roundabout with Four Approaches



For each approach, right-turn movements, through movements, and left-turn movements were considered for each of six check vehicles by using AutoTURN. The simulations were made in such a way that the front tires of the vehicle do not ride on the splitter island or roundabout outer curb. However, the rear tires sometimes do because of space constraints of having to ride up onto the outer curbs or splitter islands of the roundabout to maneuver a particular movement. All vehicles enter through their entering lane, and no movement was made in the opposite direction of travel to prevent the vehicle from riding over the curb, splitter island, or center island.

The plan of the Wellington roundabout was received from KDOT personnel as a PDF-formatted, AutoCAD drawing. This PDF drawing of the Wellington roundabout was set up as an image on the AutoCAD screen according to scale and vehicle simulations were run on top of the drawing. It can be observed from the Figure 4.30 that approach 1, approach 2, and approach 4 has a splitter island truck apron installed, which gives the sense they were initially designed to accommodate truck movements. Also, as these three approaches are US highways, these roads might have a lot of truck activity. However, approach 3 has no truck aprons installed, presumably because the designers had information there are no large trucks entering or exiting approach 3. Therefore approaches 1, 2, and 4 will be considered for all six OSOW check vehicles entering (right-turn, through movement, and left turn movement) and exiting. Approach 3 will be only considered for checking the entering and exiting movement of WB-67, which is basically a design vehicle for most state highways in the US.

All possible movements of the six OSOW check vehicles for approaches 1, 2, and 4 and for all possible WB-67 movements for approach 3 were simulated in AutoTURN. Figure 4.31 shows an example right turn simulation of one of OSOW check vehicle (55 meter wind blade) from approach 1. It can be observed from Figure 4.31 that the two red lines represent the front-tire tracks of a vehicle and the center red line indicates the path of the vehicle traversed by the front portion of the vehicle. The green lines represent the rear-tire tracks of the vehicle. The blue lines represent the vehicle body clearance, sometimes referred as a “swept path”.

It can be concluded there is not enough space for six OSOW check vehicles to maneuver through the roundabout paved area and truck apron. In the checked paths it was assumed the front tires were not to mount curbs, splitter islands, and the center island; however, it was found that the maneuver was impossible without the rear tires riding over the curbs, splitter island, and center island. It was also found that the WB-67 design vehicle was not accommodated in the roundabout within its designed, traversable area. It was also determined that the left-turn movement of the 165-ft. beam check vehicle from approaches 1, 2, and 3 was not feasible in a normal way with the available roundabout space.

Figure 4.32 is an integrated illustration showing all possible vehicle simulations with the six OSOW check vehicles for all approaches. This figure can be used to calculate the extra truck apron that might be required to accommodate truck movements that require more space and also the removable sign area. Based on the front-tire impressions and rear-tire impressions from Figure 4.32, the extra paved area required to be constructed at this roundabout to accommodate these movements can be calculated and is shown in Figure 4.33. Based on the vehicle body clearance from Figure 4.32, the removable sign area can be calculated and is shown in Figure 4.34.

It can be concluded from Figures 4.32, 4.33, and 4.34 there would be need of a fully traversable central island, and an external truck apron of variable widths at different locations if it were necessary to maneuver various movements of six OSOW check vehicles through the roundabout as designed.

An alternative was tested where these six OSOW check vehicles were allowed to ride over curbs and splitter islands and assumed to go in the opposite direction of traffic so that they don’t use any extra space other than splitter islands and a fully traversable center island. Figure 4.35 is an integrated picture showing all possible critical vehicle simulations with the six OSOW check vehicles for all approaches. This figure can be used to calculate any extra truck apron that might be required to accommodate truck movements that requires more space and also the removable sign area. It has been found there is no need of any external truck apron for this alternative as this case has fully traversable center island and splitter islands, and the six OSOW check vehicles are allowed to go in the opposite direction of traffic if required to stay in the paved area of the roundabout. Figure 4.36 shows the removable sign area at the roundabout, which is most of the area in the roundabout, hashed in the figure, which is the removable sign area within and beyond the roundabout.

Figure 4.31: Right Turn Simulation of a 55 Meter Wind Blade from Approach 1

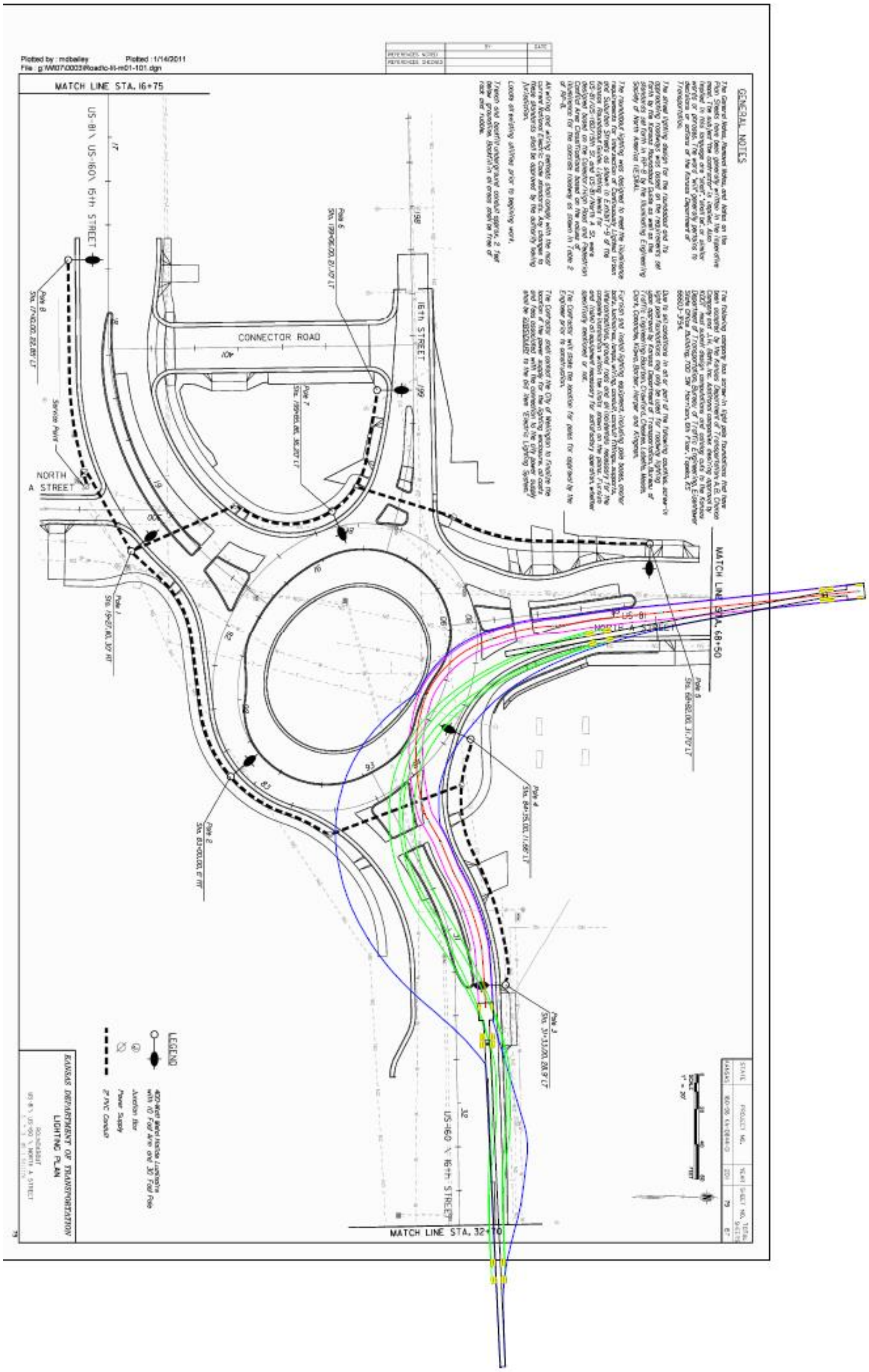


Figure 4.32: Wellington Roundabout Showing all Possible Vehicle Simulations for all Approaches.

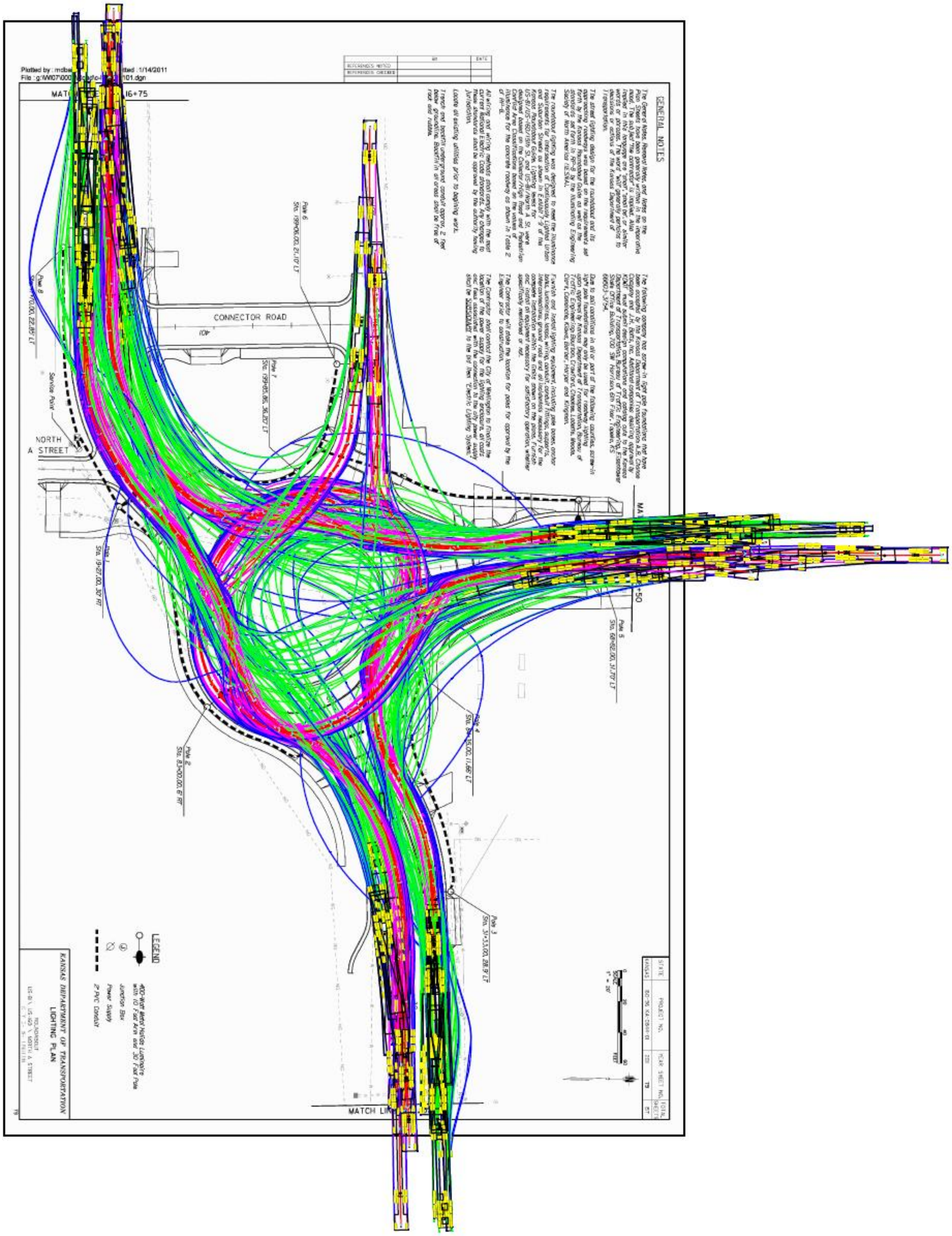


Figure 4.33: Extra Traversable Area/Truck Apron Required for Wellington Roundabout

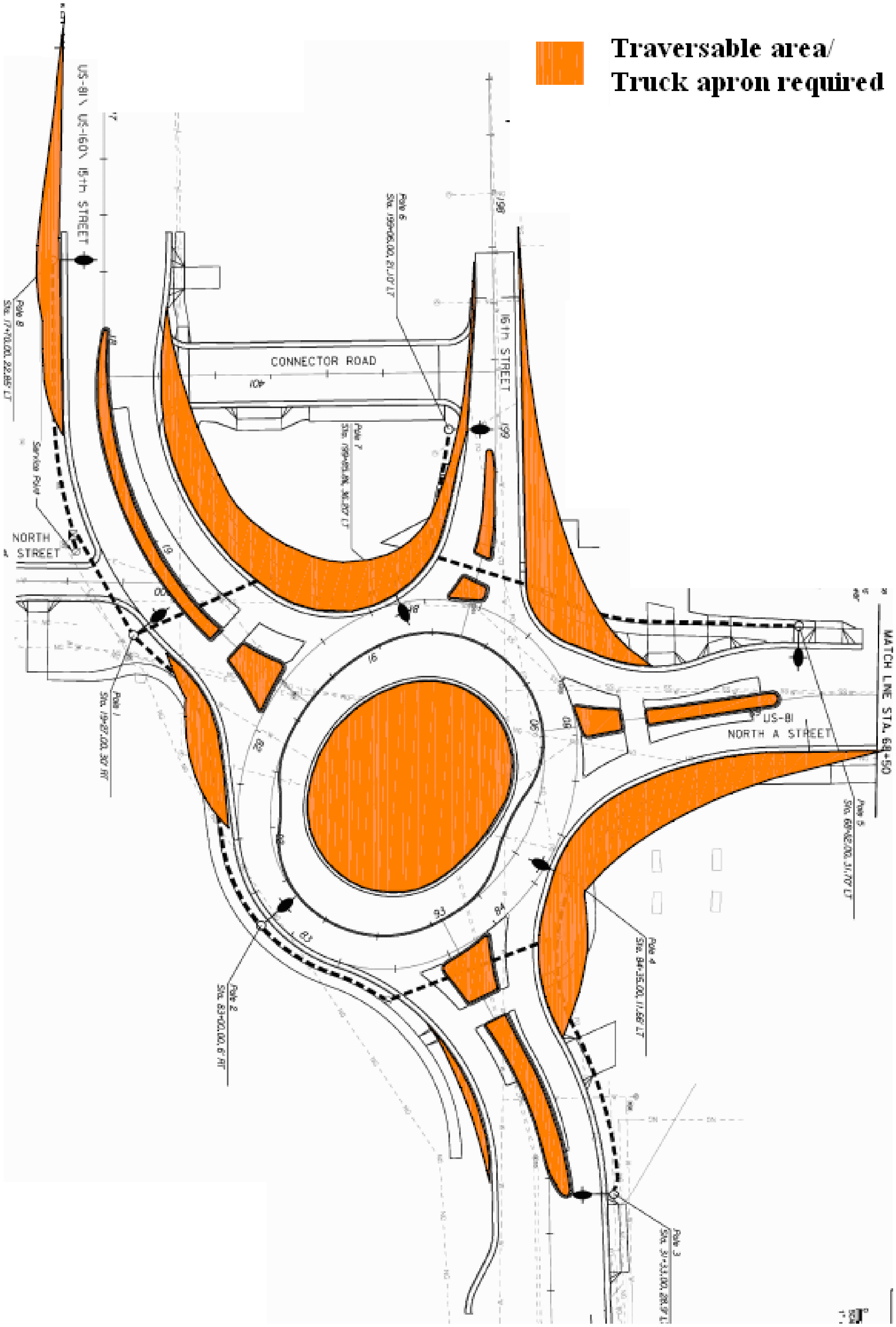


Figure 4.34: Extra Traversable Area Required and Removable Sign Area for Wellington Roundabout

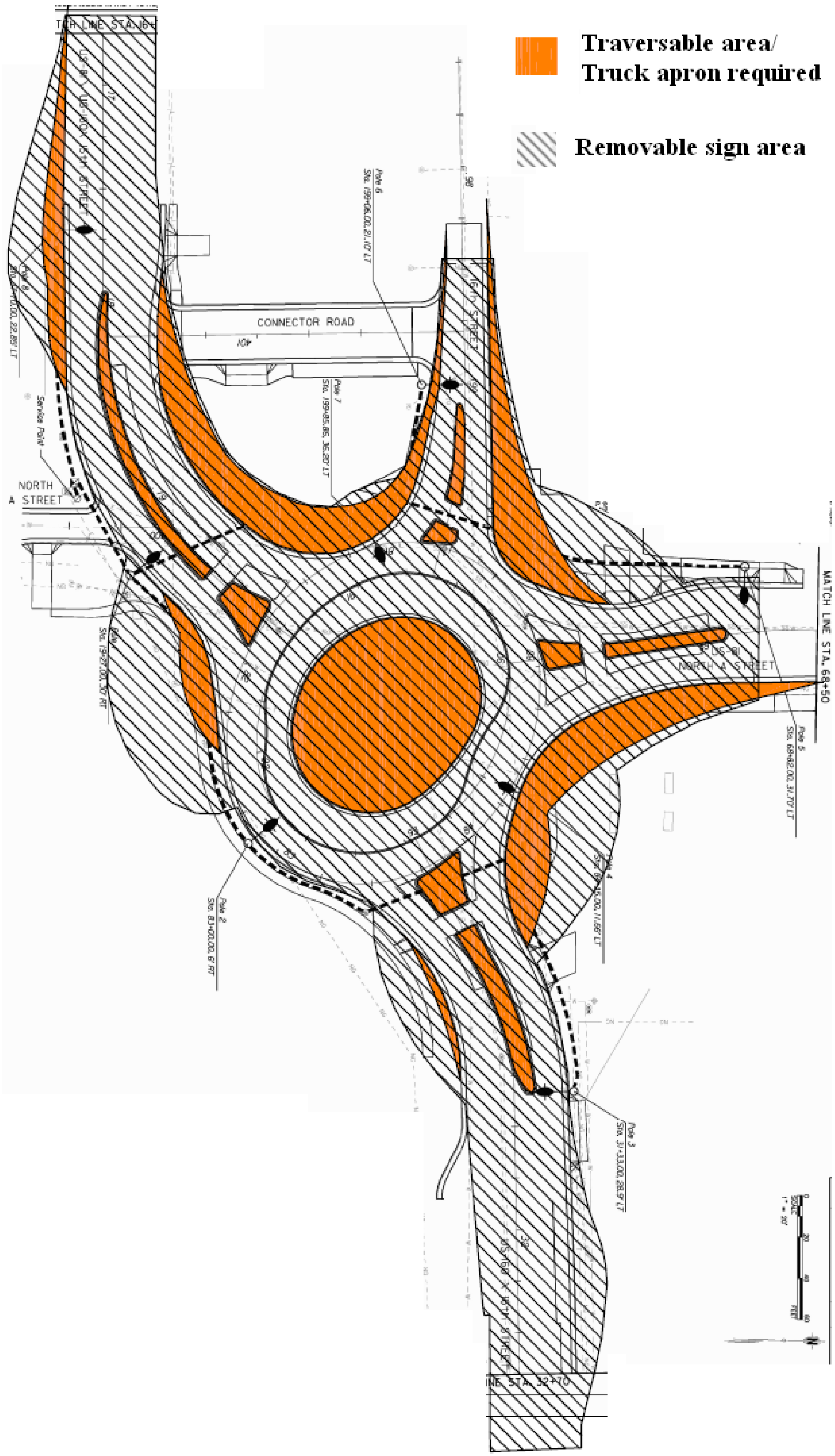


Figure 4.35: All Possible Vehicle Simulations for all the Approaches for Wellington Roundabout

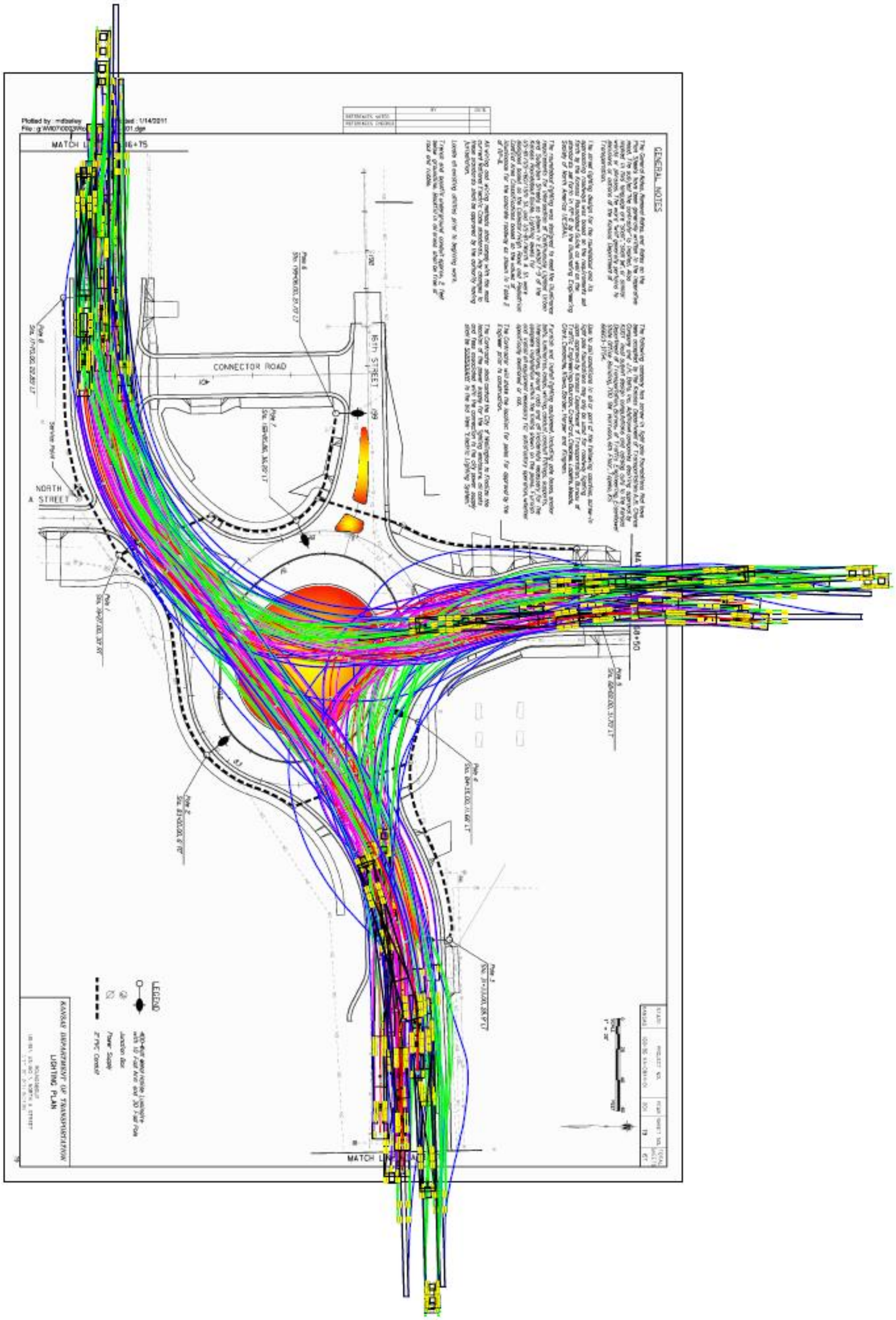
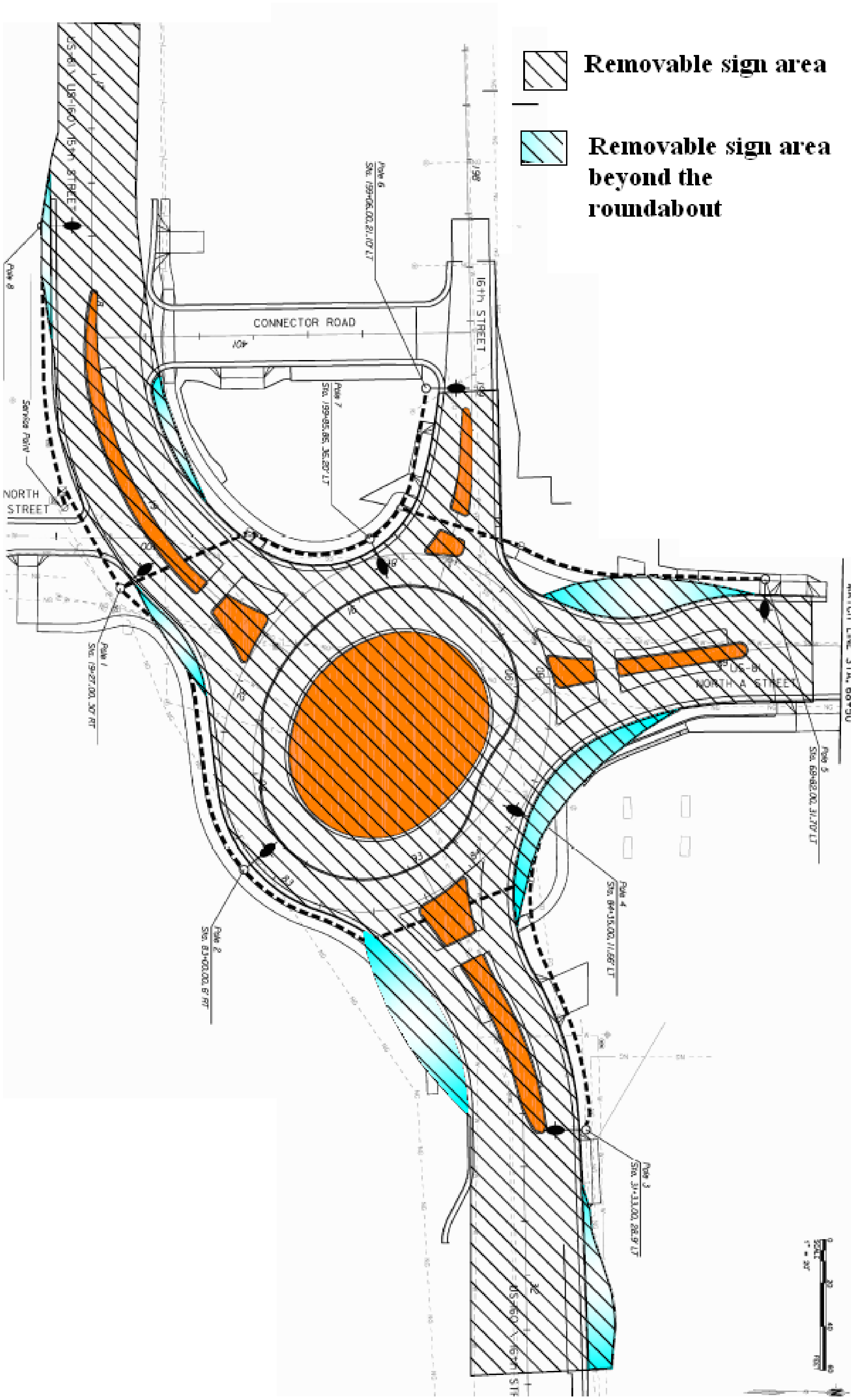


Figure 4.36: Extra Traversable Area and Removable Sign area Required for Wellington Roundabout

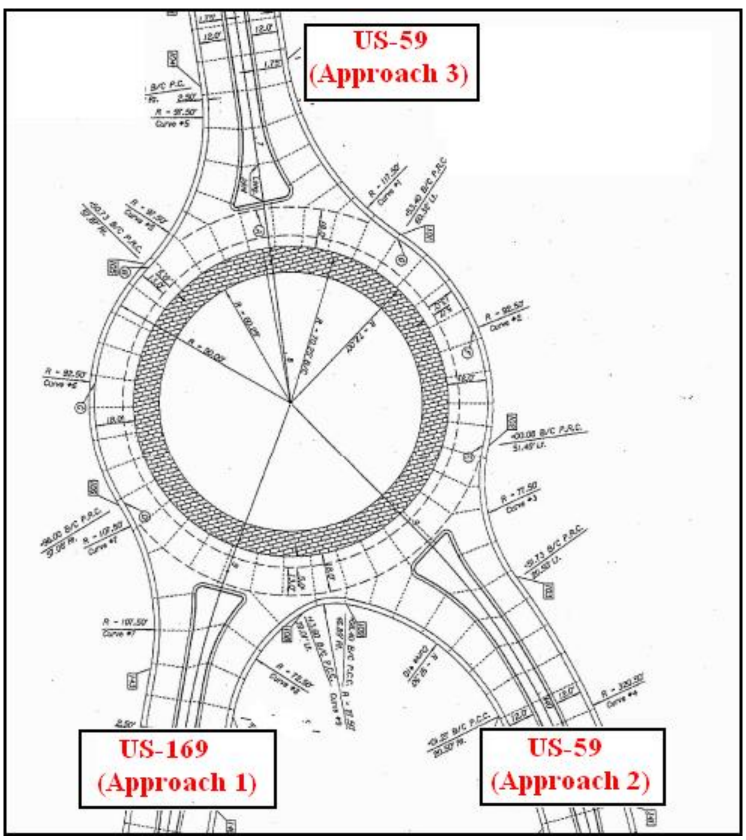


4.3.2 Garnett Roundabout

The Garnett roundabout, constructed at the intersection of US-59 and US-169, was used to check for the accommodation of the six OSOW check vehicles and find the space requirements of these check vehicles. The plan of the Garnett roundabout was received from KDOT personnel as a PDF format AutoCAD drawing. This PDF drawing of the Garnett roundabout was set up as an image on the AutoCAD screen according to the scale, and the vehicle simulations were run on top of the drawing using AutoTURN software.

Figure 4.37 shows the Garnett roundabout with three approaches. Based on the geometry of the roundabout, possible movements of the six check vehicles were assumed as approach 1 to approach 3, approach 2 to approach 3, and approach 3 to approaches 1 and 2. Three different alternatives that could have been used for this roundabout to better accommodate these six check vehicles will be illustrated. They are to be named as Case 1, Case 2, and Case 3.

Figure 4.37: Garnett Roundabout with three Approaches



4.3.2.1 Garnett Case 1

The initial condition considered is for the six check vehicles to traverse the roundabout in the normal way they are supposed to travel, i.e. they are not allowed to enter or maneuver in the opposite direction of normal traffic. The front tires of the truck are assumed to not ride up on splitter islands, curbs, and center islands and use only the space dedicated for trucks to use. However, the path of the rear tires may ride over the curbs, splitter islands, or center islands when there is not enough space.

Vehicle simulations were conducted for all possible movement of the six check vehicles using AutoTURN. Figure 4.38 is an integrated picture showing all critical vehicle simulations for all approaches. This figure can be used to calculate the extra truck apron that might be required to accommodate truck movements that require more space and also the necessary, removable sign area. Based on the front-tire and rear-tire paths from Figure 4.38, the extra paved area that is required to be constructed at this roundabout to accommodate these movements is shown in Figure 4.39. Based on the vehicle body clearance from Figure 4.38, the removable sign area can be determined and is shown in Figure 4.40. This figure also shows an area where standard signage (or any permanent fixture) can be installed in the body of the roundabout, which is hashed in a light yellow color. Figure 4.41 is a combination of Figures 4.39 and 4.40 (showing extra paved area required and removable sign area).

Figure 4.38: Garnett Roundabout Showing all Critical Vehicle Simulations for all Approaches

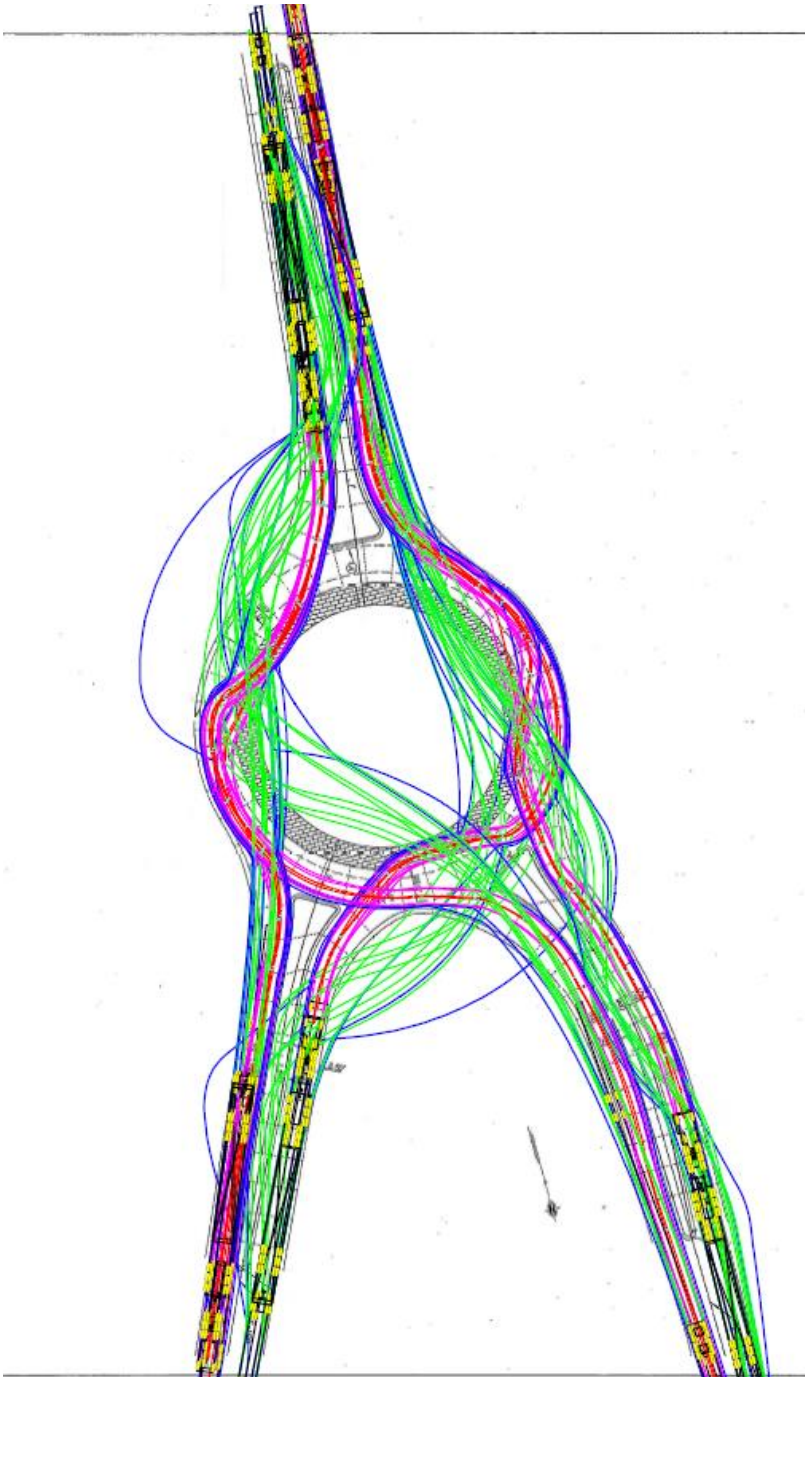


Figure 4.39: Extra Traversable Area/Truck Apron Required for Garnett Roundabout

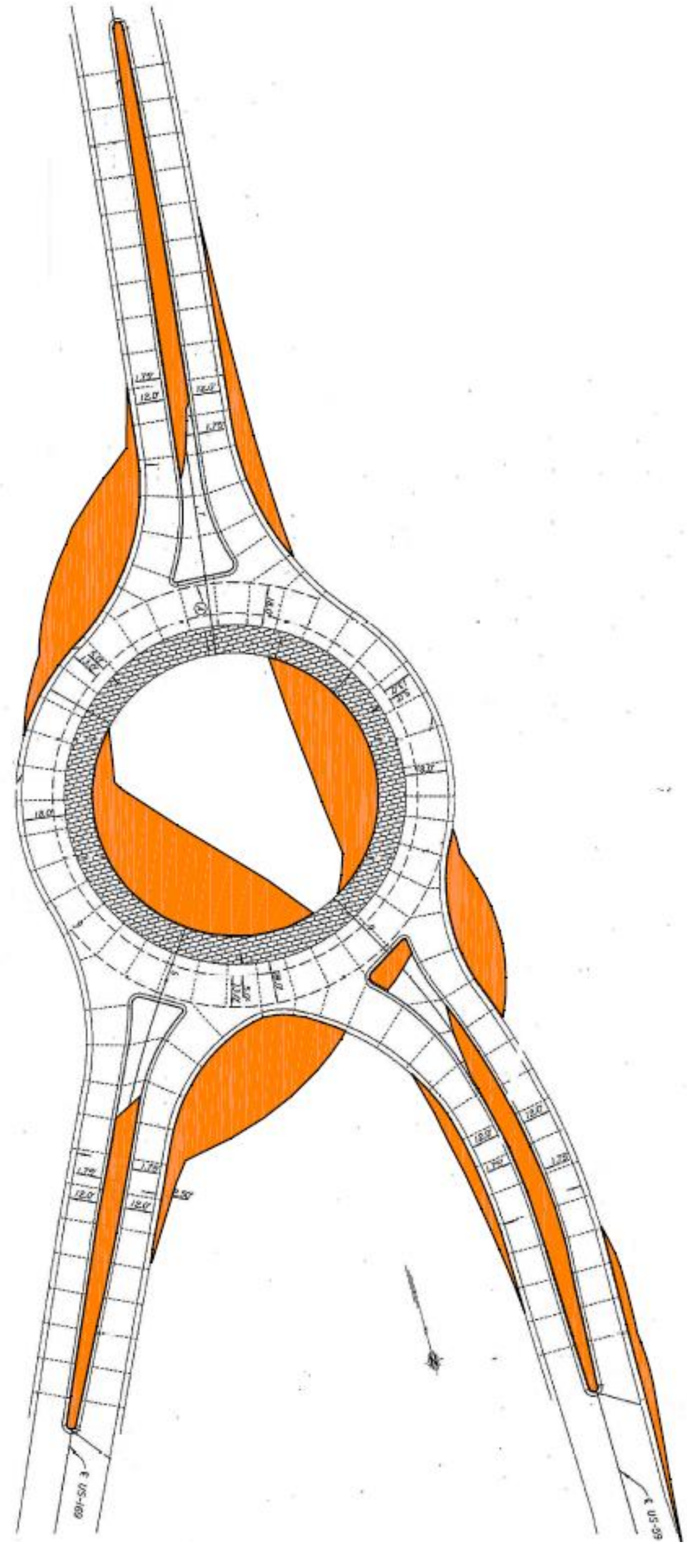


Figure 4.40: Removable Sign Area Required for Garnett Roundabout

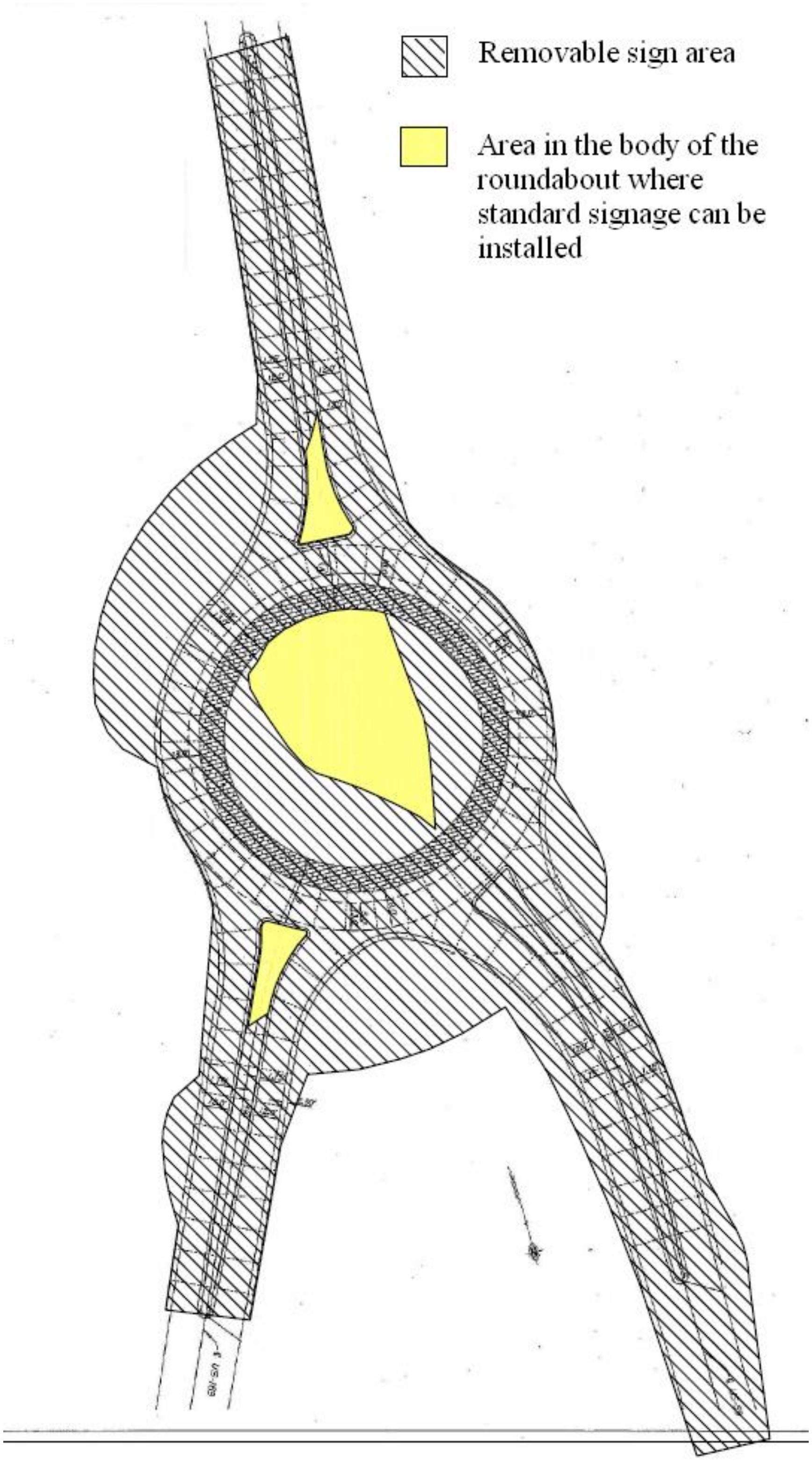
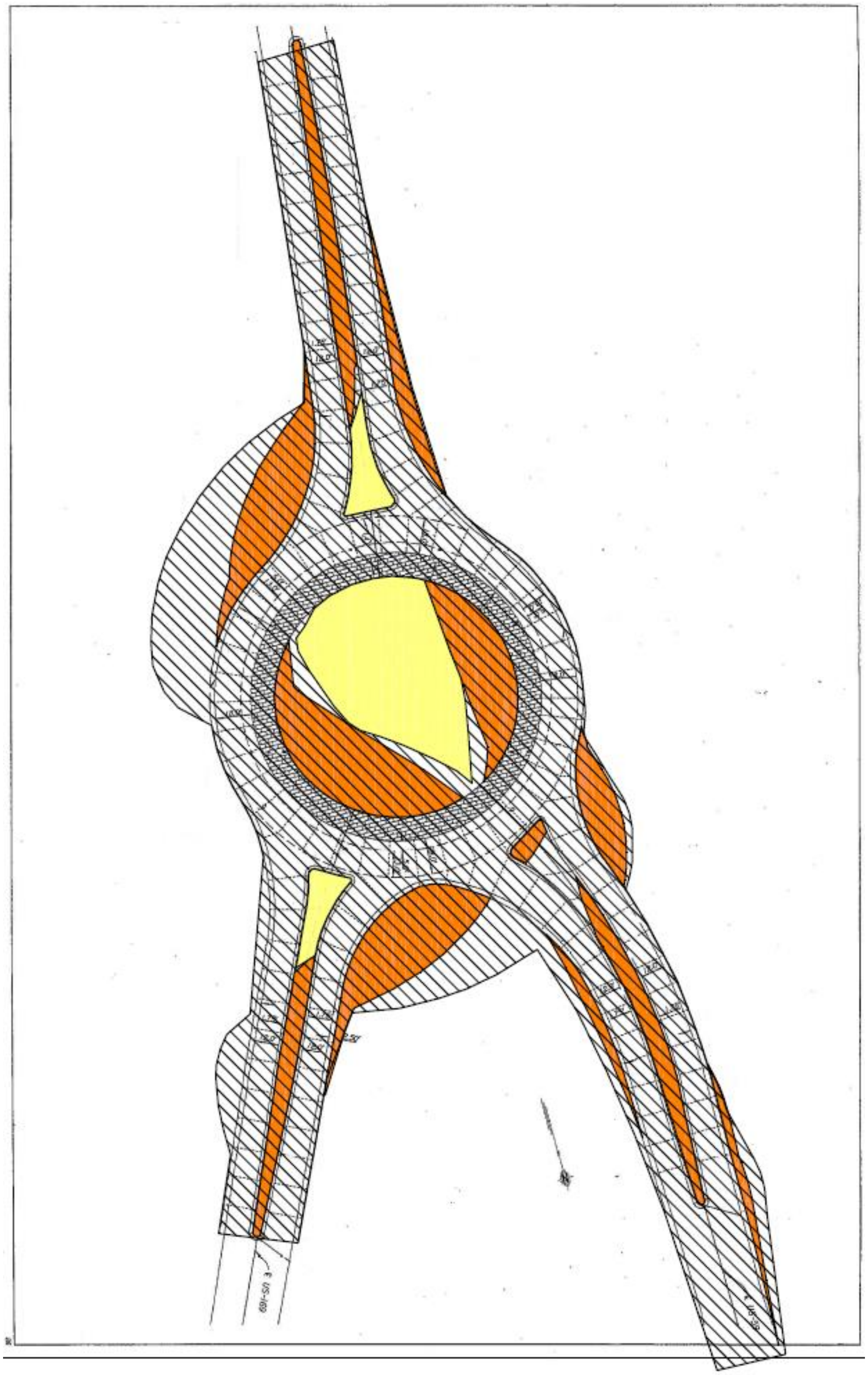


Figure 4.41: Extra Traversable Area and Removable Sign Area Required for Garnett Roundabout



4.3.2.2 Garnett Case 2

The second alternative is considered where the trucks travel in opposite direction of traffic while entering, exiting, and maneuvering through the roundabout (assumed to have necessary and legal traffic control), and they are allowed to ride over the splitter islands while entering and exiting. However, the front tires of the truck are simulated in such a way that the swept path of a vehicle uses minimal center island space.

Vehicle simulations were conducted for all possible movements of the six check vehicles using AutoTURN. Figure 4.42 is an integrated picture showing all critical vehicle simulations for all approaches. This figure can be used to determine the extra truck apron required to accommodate the truck movements which require more space and also the removable sign area. Based on the front-tire and rear-tire tracks from Figure 4.42, the extra paved area required to be constructed at this roundabout to accommodate these movements can be seen in Figure 4.43. It can be observed that all approaches should be fully traversable and therefore, if there is any signage warranted on the approaches, they must be removable signs. Based on the vehicle body clearance from Figure 4.42, the removable sign is shown in Figure 4.44. This figure also shows an area where standard signage can be installed in the body of the roundabout, which is hashed in a light yellow color. It can be observed that Case 2 needs less "extra paved area" and "removable sign area" when compared to Case 1. Figure 4.45 is a combination of Figures 4.43 and 4.44, i.e. extra paved area required and removable sign area.

Figure 4.42: Garnett Roundabout Showing all Critical Vehicle Simulations for all the Approaches

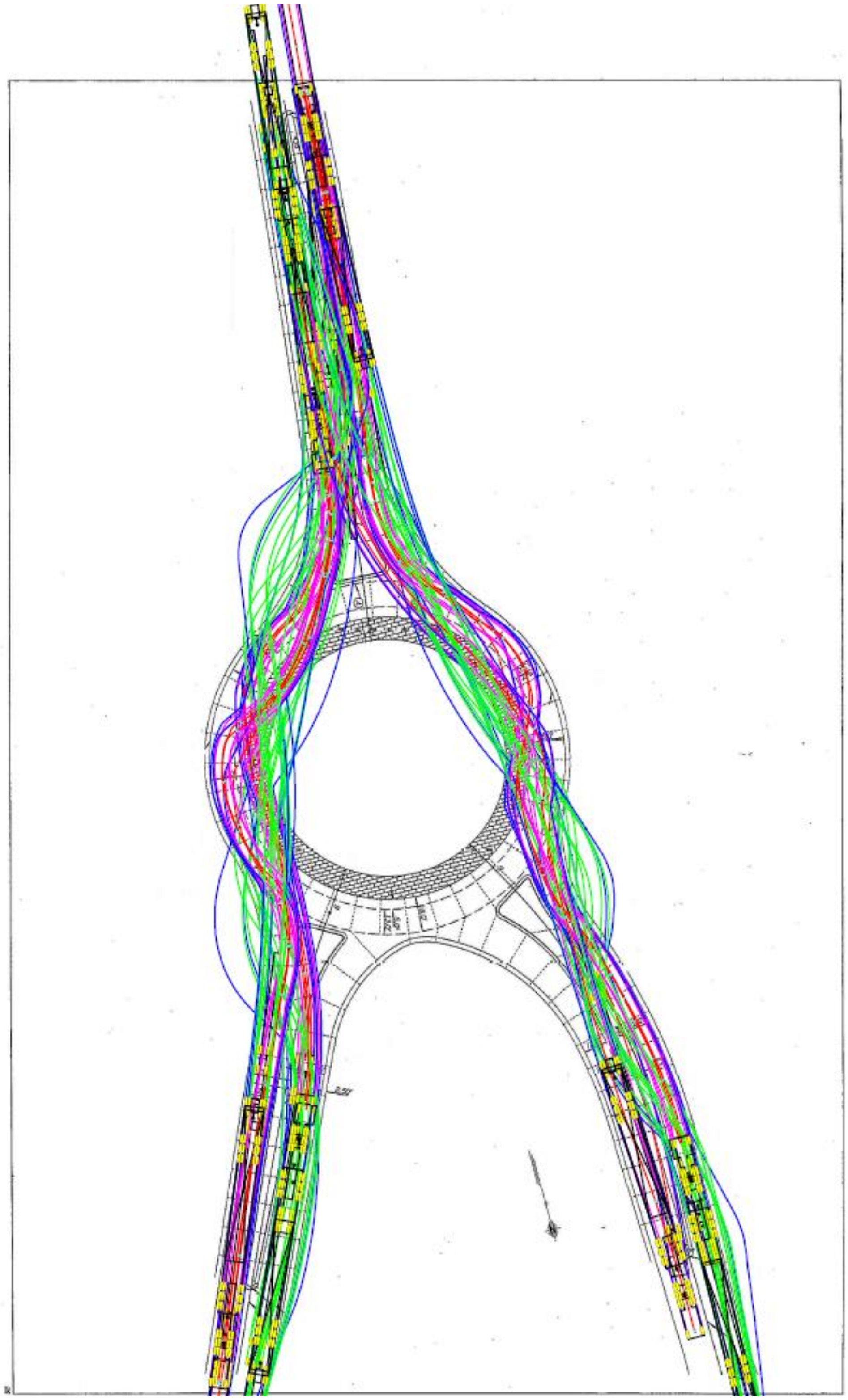


Figure 4.43: Extra Traversable Area/Truck Apron Required for Garnett Roundabout

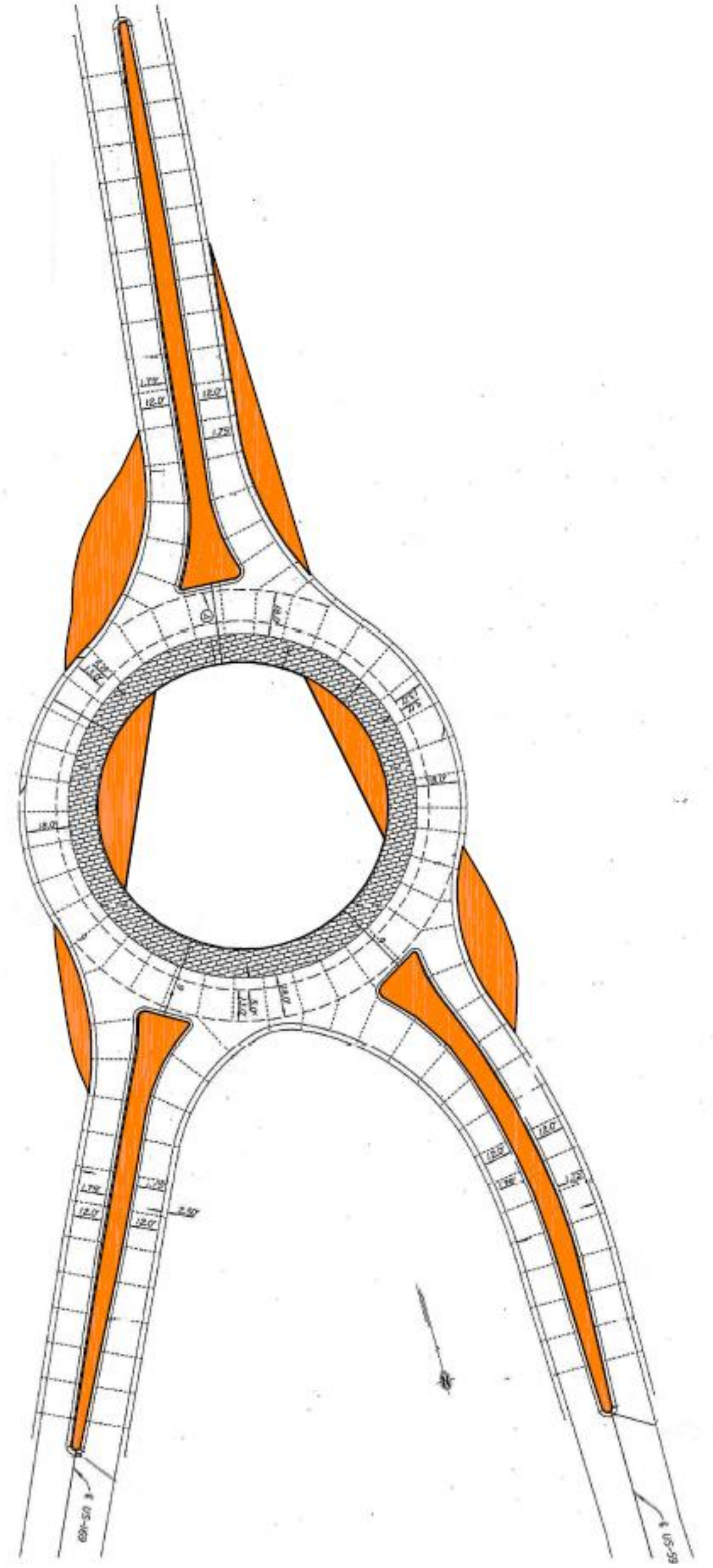


Figure 4.44: Removable Sign Area Required for Garnett Roundabout

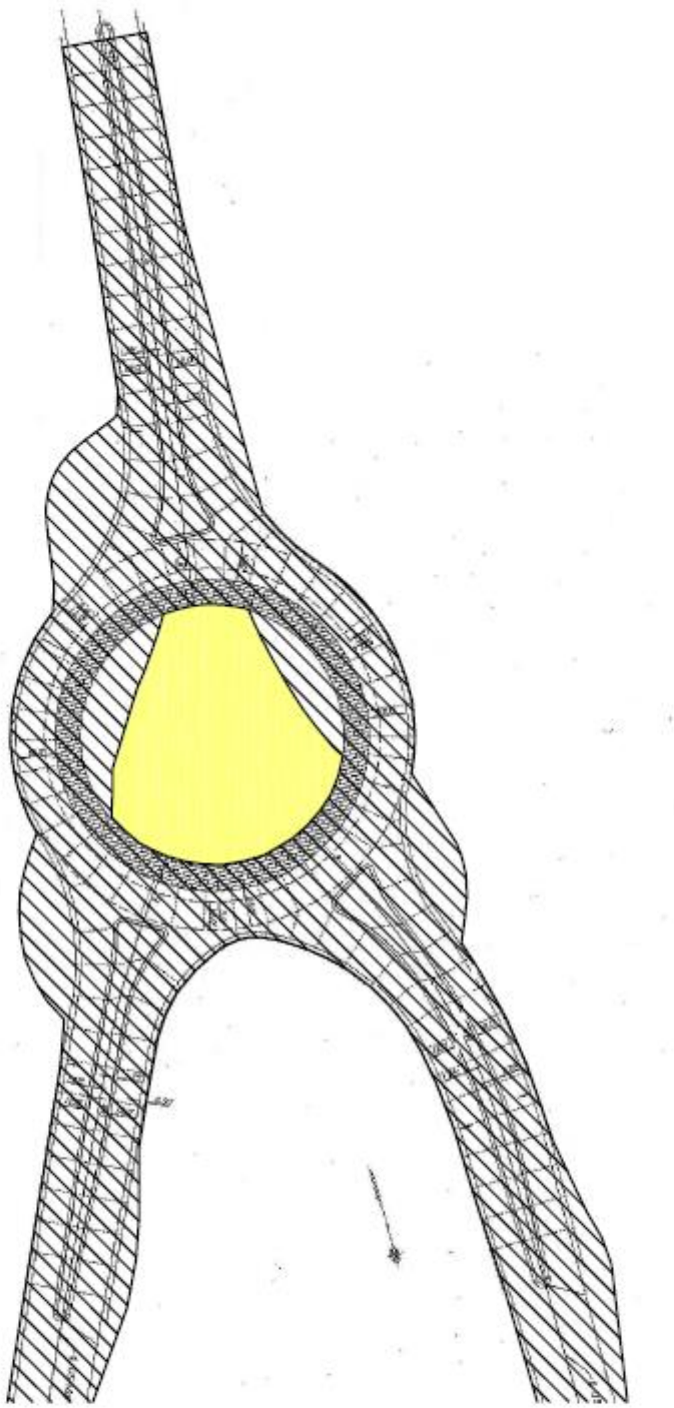
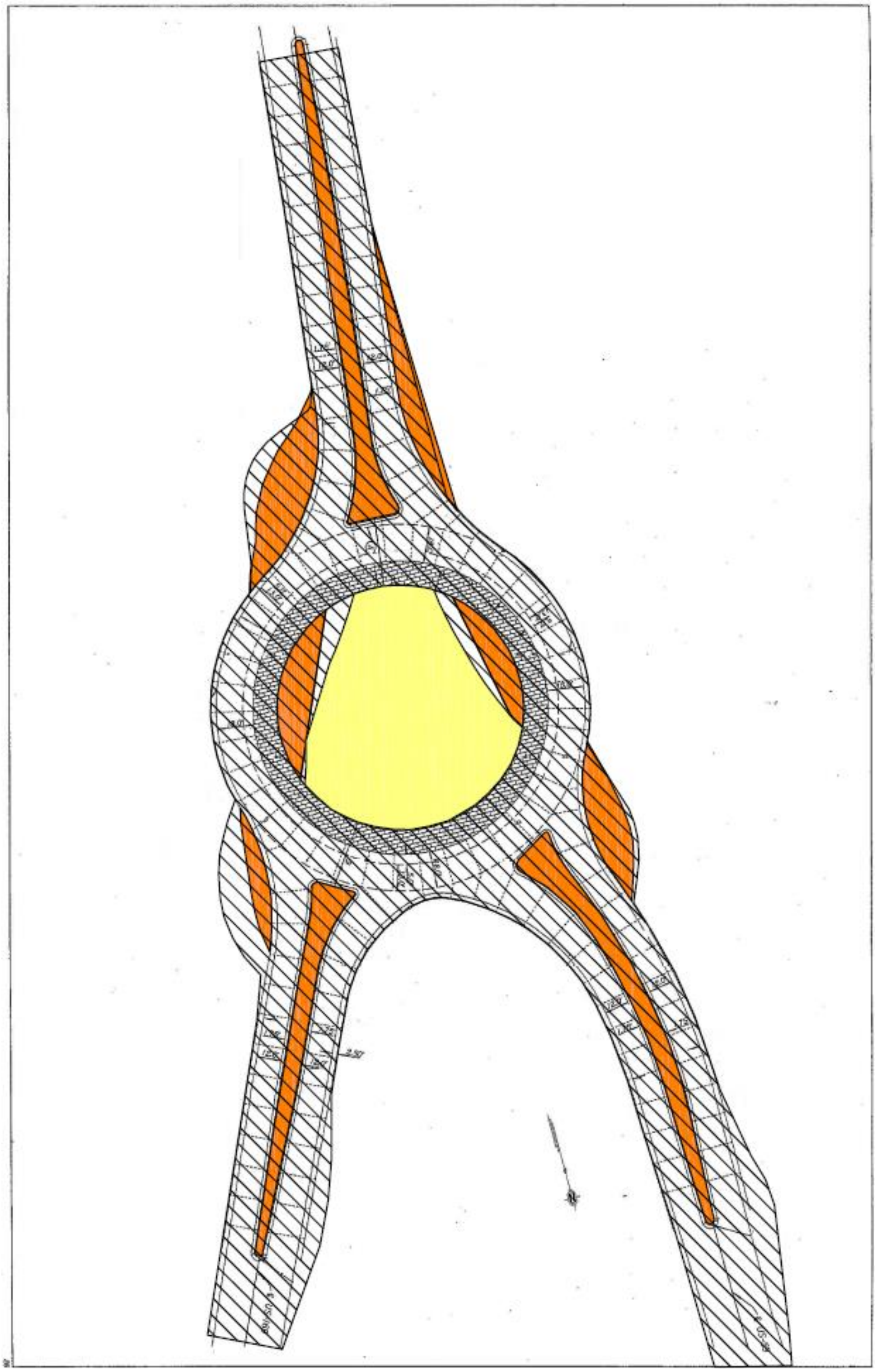


Figure 4.45: Extra Traversable Area and Removable Sign Area Required for Garnett Roundabout



4.3.2.3 Garnett Case 3

The third alternative is considered where the center island is made fully traversable and the six check vehicles were allowed to ride over curbs and splitter islands, and allowed to go in the opposite direction of normal traffic so that they don't use any extra space other than splitter islands and a fully traversable center island.

Vehicle simulations were conducted for all possible movement of the six check vehicles using AutoTURN. Figure 4.46 shows the modified design, which has a fully traversable center island and approach, after considering all critical vehicle simulations. Figure 4.47 shows the roundabout with the modified paved area design and removable sign area. It was found that no extra paved area or removable sign area would be required beyond the body of the roundabout.

Figure 4.46: Extra Traversable Area/Truck Apron Required for Garnett Roundabout

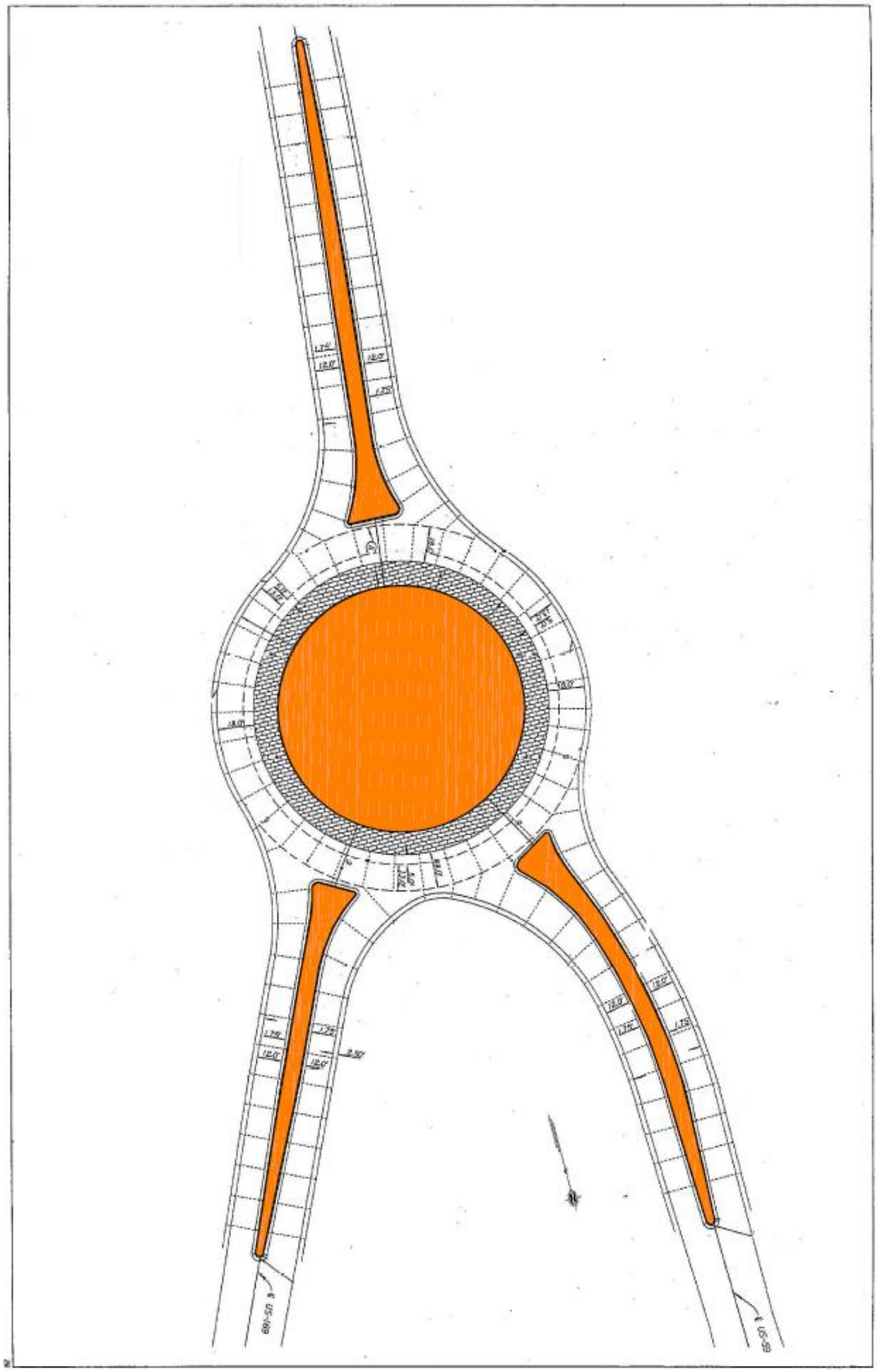
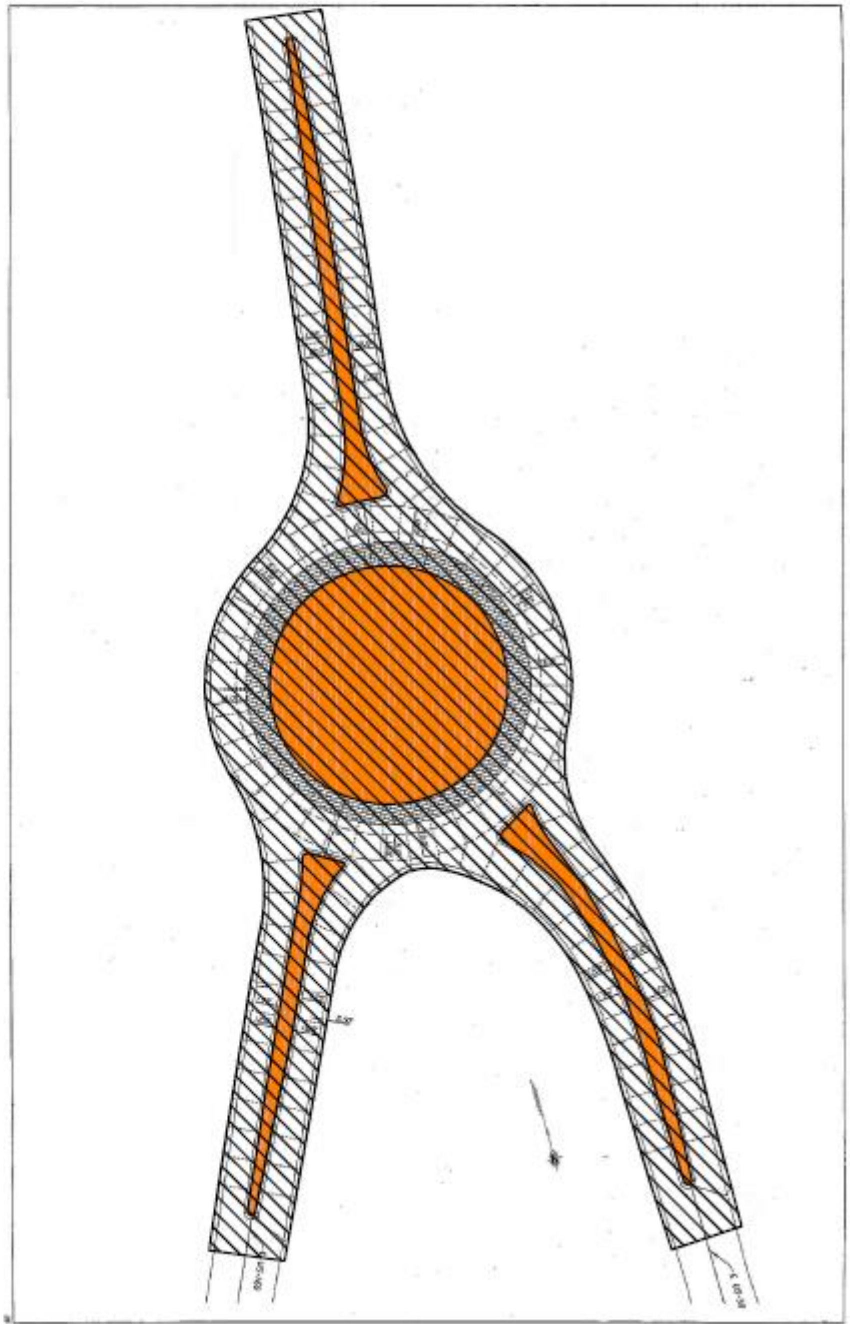


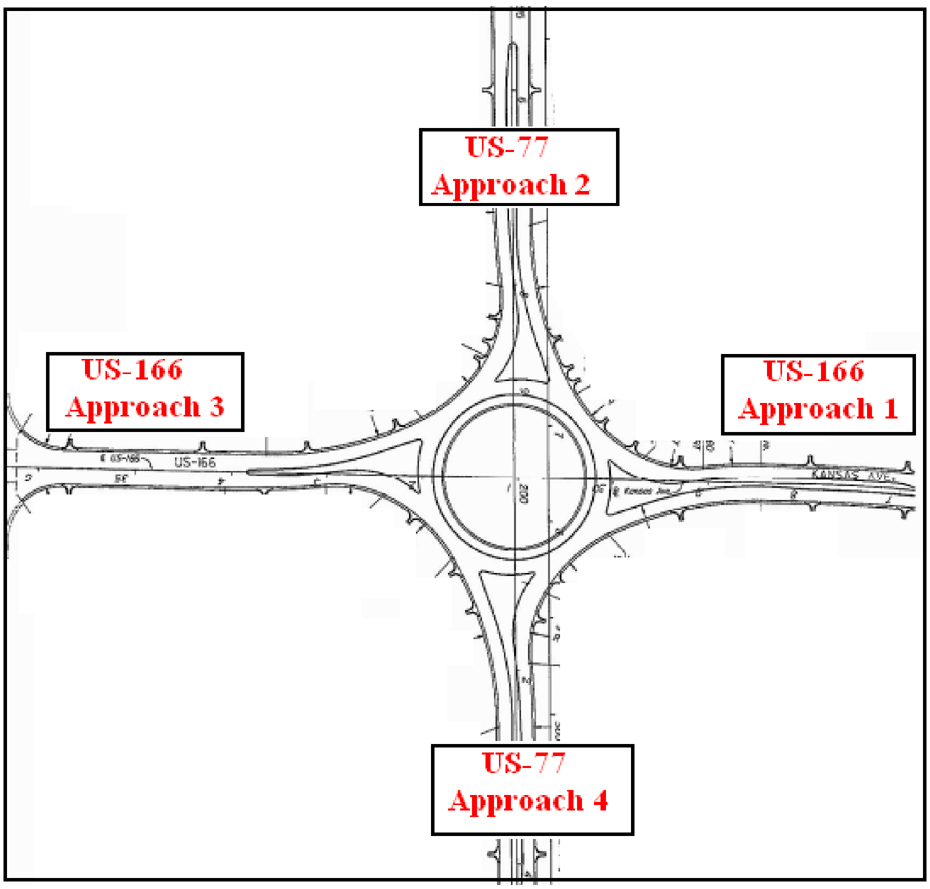
Figure 4.47: Extra Traversable Area and Removable Sign Area Required for Garnett Roundabout



4.3.3 Ark City Roundabout

The Ark City roundabout, constructed at the intersection of US-77 and US-166, was used to check the accommodation of the six check vehicles and find the space requirements of these check vehicles. The plan of the Ark City roundabout was received from KDOT personnel as a PDF format AutoCAD drawing. This PDF drawing of the Ark City roundabout was set up as an image on the AutoCAD screen according to scale, and the vehicle simulations were run on the top of the drawing using AutoTURN software. Figure 4.48 shows a sketch of the Ark City roundabout with four approaches.

Figure 4.48: Ark City Roundabout with four Approaches



As the Ark City roundabout is at the intersection of US-77 and US-166, it was assumed OSOW movements only occur through this roundabout on US-77, and they do not turn at this intersection. Therefore, this roundabout was checked for only through movements of the six check vehicles for Approaches 1 through 4. It was assumed that the six check vehicles traverse the roundabout in the same direction. The front tires of the truck are simulated to not ride up on splitter islands, curbs, and center islands and use only the space that is dedicated for trucks to use. However, the path of the rear tires may ride over the curbs, splitter islands, or center islands when there is not enough space.

Vehicle simulations were conducted for all possible through movements of the six check vehicles using AutoTURN. Figure 4.49 is an integrated picture showing all critical vehicle simulations for all approaches. This figure can be used to calculate the extra truck apron required to accommodate truck movements that require more space and also the removable sign area. Based on the front-tire and rear-tire paths from Figure 4.49, the extra paved area required to be constructed at this roundabout to accommodate these movements can be determined and is shown in Figure 4.50. Based on the vehicle body clearance from Figure 4.49, the removable sign area can be determined and is shown in Figure 4.51. This figure also shows an area where standard signage, or any permanent fixture, could be installed in the body of the roundabout and is shown hashed in light yellow. Figure 4.52 is a combination of Figures 4.50 and 4.51, showing the extra paved area and removable sign area that would be required.

Figure 4.49: Ark City Roundabout showing all Critical Vehicle Simulations for all the Approaches

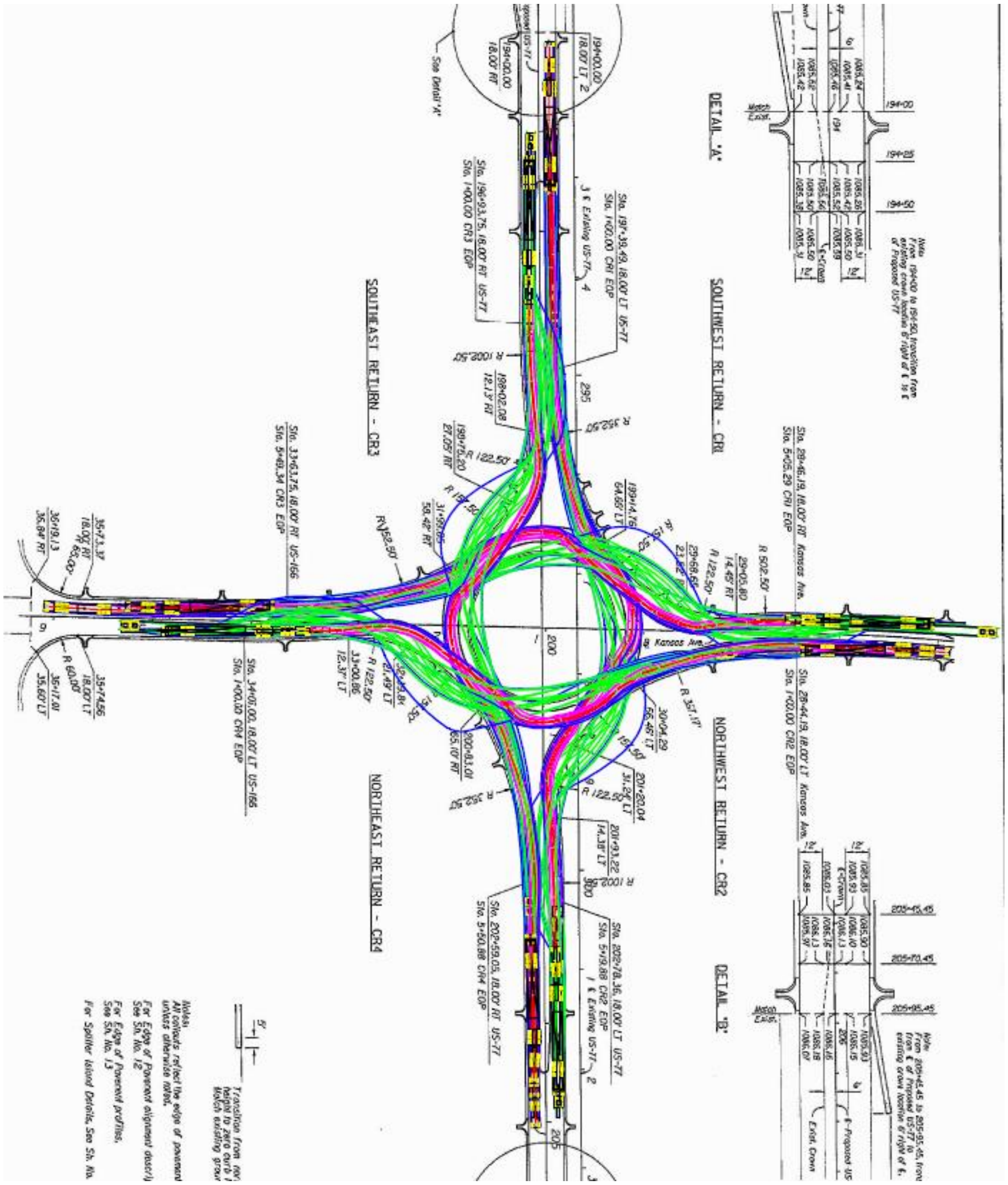


Figure 4.50: Extra Traversable Area/Truck Apron Required for Ark City Roundabout

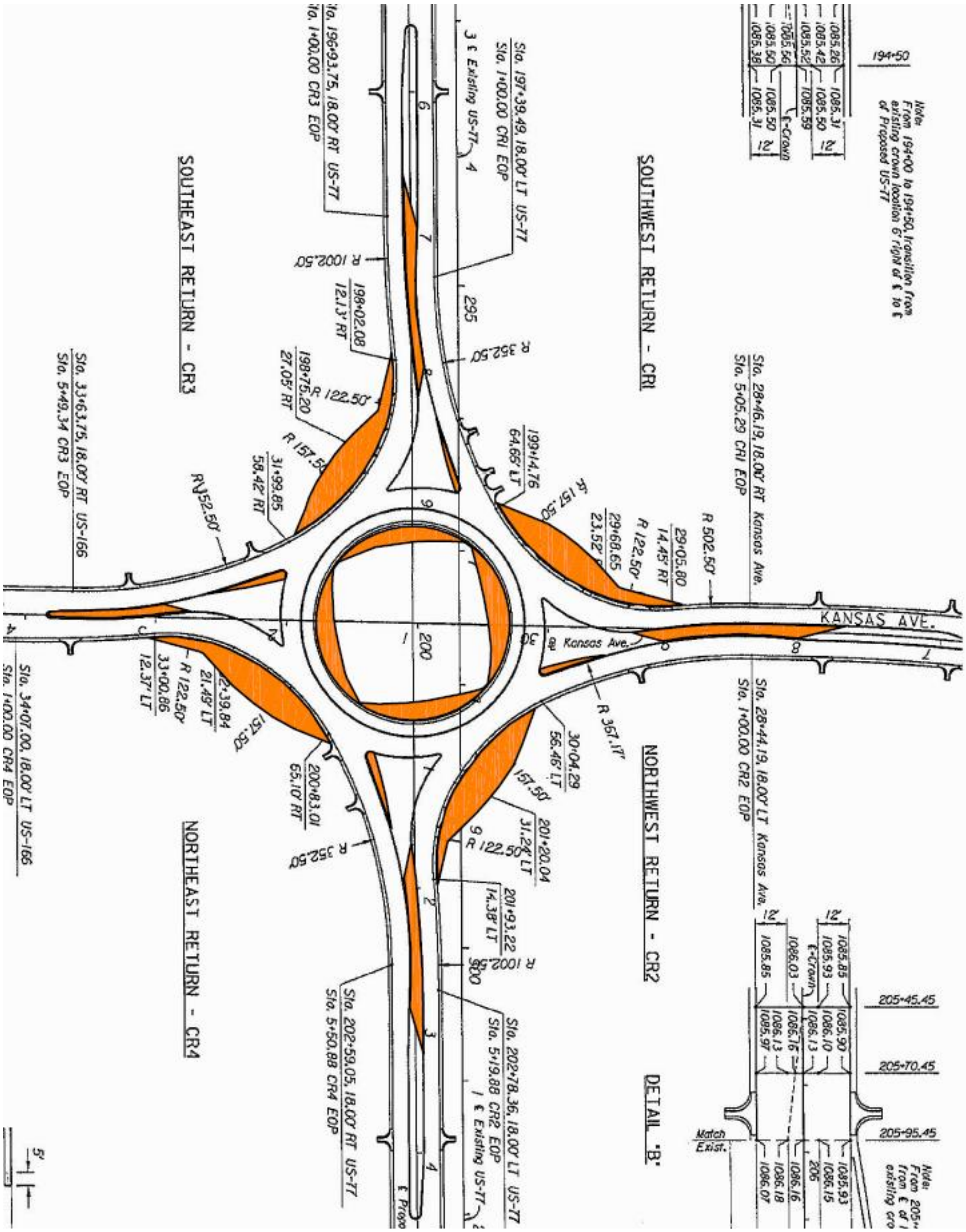


Figure 4.51: Removable Sign Area Required for Ark City Roundabout

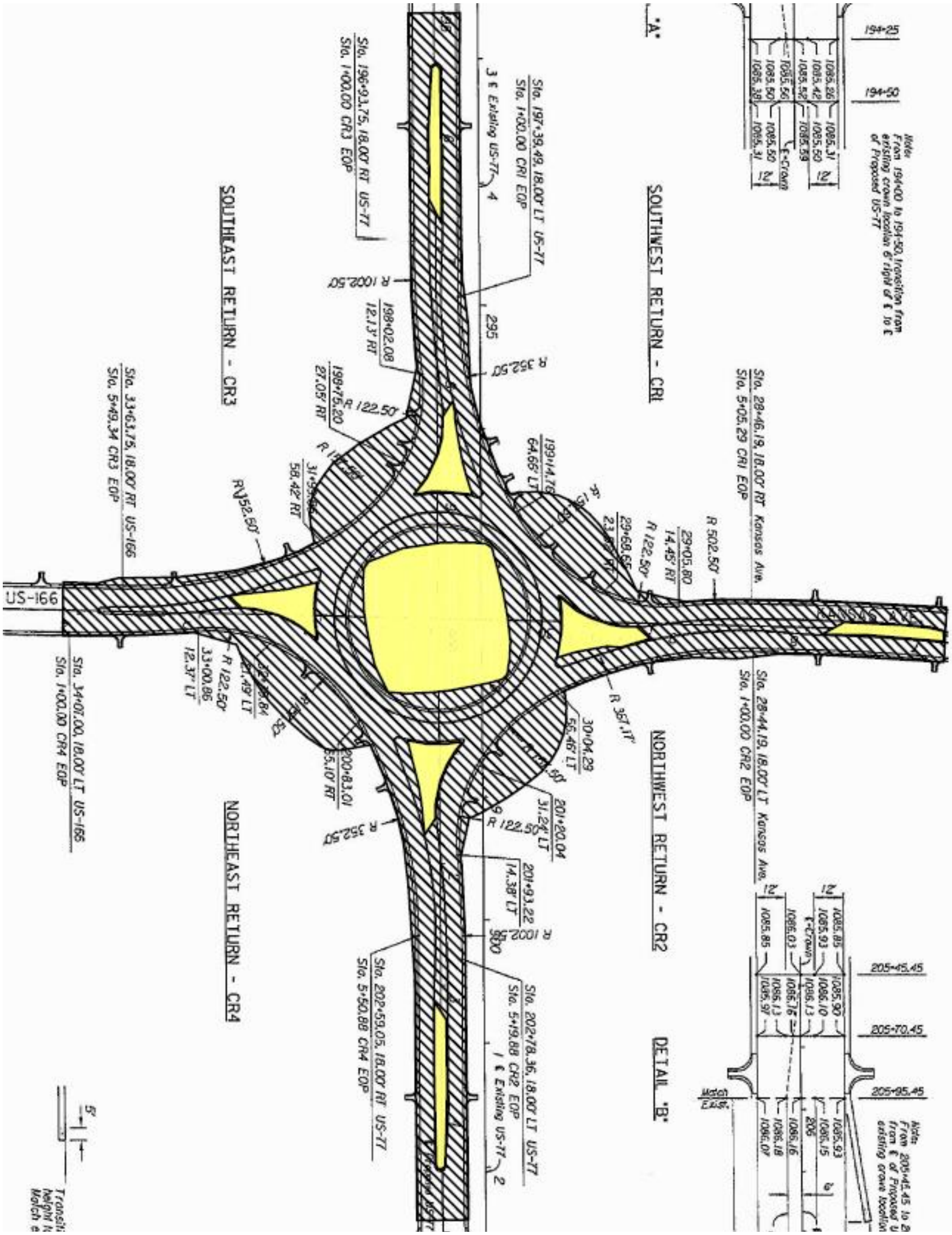
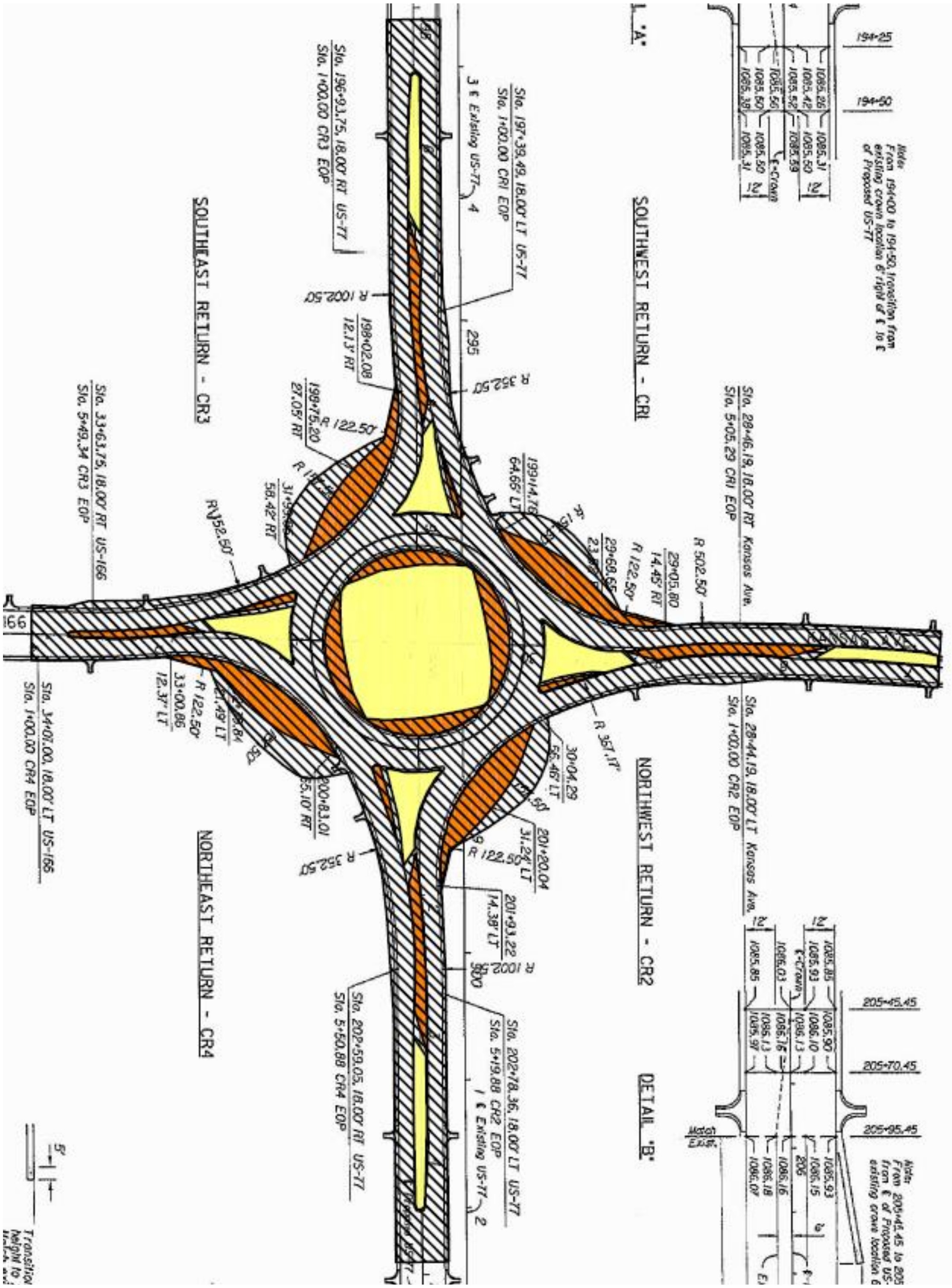


Figure 4.52: Extra Traversable Area and Removable Sign Area required for Garnett Roundabout



Chapter 5 - Vertical Ground Clearance Analysis

5.1 Background and Relevant Literature Review

The vertical ground clearance problem for low, ground clearance (lowboy) vehicles was the number one concern by the trucking industry that was mentioned from survey 3 (section 2.10) and survey 4 (section 3.2) responses. This area has been generally neglected by designers and states except for one recent study by Wisconsin DOT (WisDOT) to check their roundabouts on their designated OSOW routes for any ground clearance problems. After the Wisconsin study (section 2.10.1), this study is conducted as part of this dissertation is only the second know study addressing this important, neglected area (no published literature could be found) and the procedure that is developed in this study is a more general guide for designers and states to address vertical clearance concerns. The WisDOT study does not recommend a truck apron height, approach roadway slopes, or circulatory roadway slopes, for single-lane and double-lane roundabouts which are addressed and recommended in this dissertation.

Various components involved in vertical alignment design of a roundabout include profiles, super elevation, approach grades, and drainage (*1*). Development of approach roadway and center island profiles is the beginning stage for roundabouts vertical design (*1*).

The cross slope chosen for the circulatory roadway for single-lane roundabouts is generally chosen 2% away from the center island for various reasons, such as, better safety by raising the elevation of the center island and improving visibility, promoting lower circulating speeds, minimizing breaks in cross slopes of the entrance and exit lanes, and draining surface water outside of the roundabout (*1*).

Vertical design of the circulatory roadway for multilane roundabouts is mostly done by two methods: outward sloping and crowned circulatory roadways. Outward sloping is the most common method of vertical design for circulatory roadway in US and a grade of 1.5 to 3% with circulatory roadway outward draining is used (*1*). For the crowned circulatory roadway method, the roadway is crowned with approximately two-thirds of the width sloping towards the center island and one-third away from the center island (*1*). A maximum of 2% cross slope for circulatory roadway is considered in this situation (*1*).

If a truck apron is used, the cross slope of the truck apron should generally be no more than 2% towards outside of the roundabout as greater slopes increases the likelihood of loss-of-load incidents (*1*). For installing roundabouts on grades, grades less than 3% are generally considered to not be problematic (*1*).

5.2 Background and Analysis Strategy

Lowboy vehicles generally have low clearance and have problems damaging the curbs and truck apron when there is not sufficient ground clearance. Also, from OSOW survey 2 conducted by KSU (section 3.1 of this dissertation), one of the major concerns at roundabouts from lowboy (low ground clearance) vehicles is that they have problems with curbs and truck aprons which are more than 3 inches. Therefore, the main objective of this portion of the study is to check the ground clearance of lowboy vehicle at a standard (as specified in NCHRP 672) single-lane roundabout and a standard double-lane roundabout and recommend a truck apron width and height that is suitable for a lowboy vehicle using a roundabout.

A standard FHWA single-lane roundabout and double-lane roundabout were designed using TORUS software assuming a design vehicle of WB-67. These roundabout designs were modified with additional truck apron to accommodate a low boy vehicle. Later, roundabouts designed three dimensionally by using various truck apron widths and grading various features of the roundabouts, such as, approach roadway, exit roadway, center island truck apron, and circulatory roadway using TORUS software.

AutoTURN, Pro 3D software has a capability called ‘vehicle clearance analysis’ by which vehicle clearance for any vehicle can be checked when simulated in a 3D environment. Therefore the ‘vehicle clearance analysis’ option in AutoTURN was used to check the ground clearance of a prototype low boy vehicle for a standard roundabout with various truck apron heights and cross slopes designed in a 3D environment.

These roundabouts were analyzed using AutoTURN Pro 3D software by simulating various movements of the prototype lowboy vehicle to check if they have any ground clearance problems while negotiating selected roundabouts.

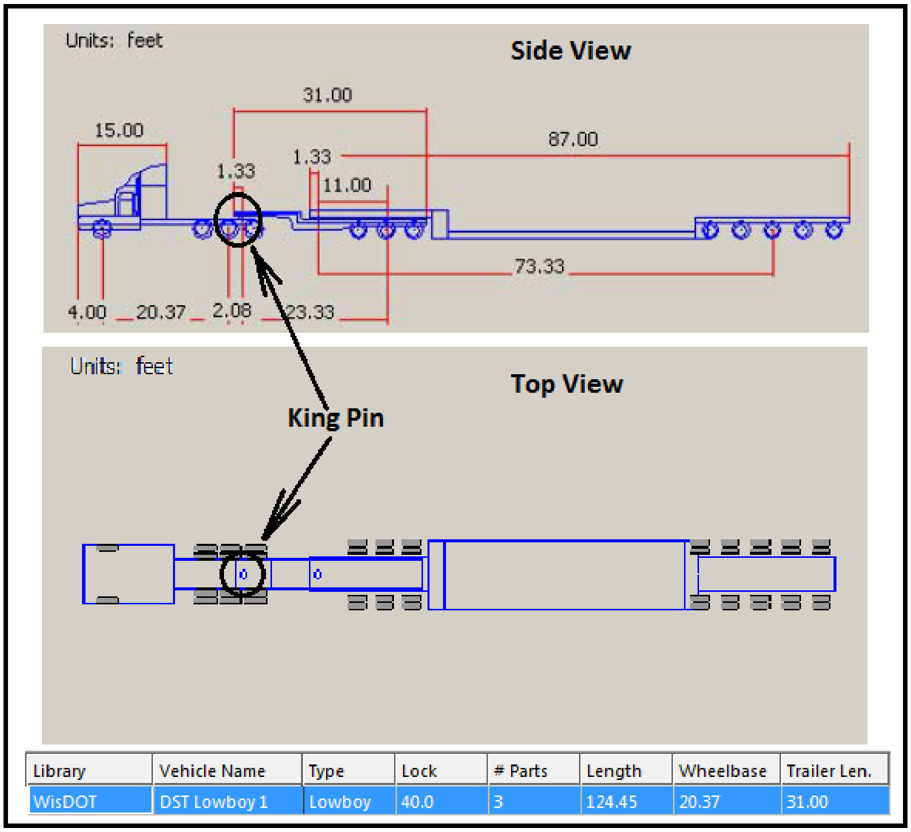
5.3 Wisconsin DOT Lowboy Vehicle

To conduct the 'vehicle clearance analysis' at roundabout to recommend a truck apron width, a lowboy vehicle with height (vertical) details is needed to be used in this study. The vehicle library in the AutoTURN Pro 3D software has standard AASHTO vehicles but does not include any low boy vehicle.

Therefore, a lowboy vehicle from WisDOT library "DST lowboy" was used for this study. This vehicle is a 3-part vehicle with a tractor (front part of the vehicle), jeep (middle part of the vehicle), and the lowboy (rear part of the vehicle) as shown in Figure 5.1 and with total length of 124.45ft. The actual low clearance of the above mentioned lowboy is six inches. However, other aspects such as construction tolerance, variable path chosen by different truck drivers, drainage grate location, airbag pressure to keep the vertical clearance that the deck is supposed to have warrants to having a margin of error, and WisDOT set 1-inch as a margin of error, thus having 5-inch vertical clearance (*29*).

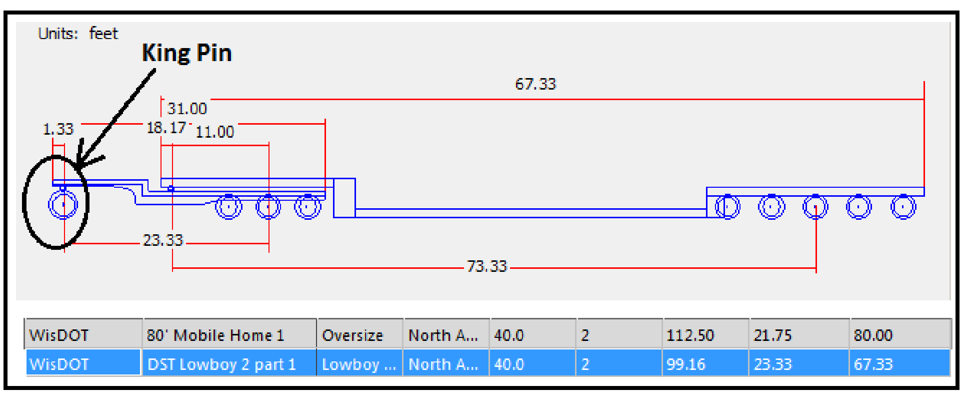
One limitation of AutoTURN Pro 3D software is that, only a two-part or less vehicle can be run in 3D mode for conducting vehicle clearance analysis. Therefore, the "WisDOT, DST lowboy" vehicle was further modified by WisDOT by removing the front tractor to make it a 2 part vehicle such that it can be used for vehicle clearance analysis. This 2-part vehicle is available in WisDOT vehicle library as "DST lowboy 2 part 1" and is shown in Figure 5.2. This vehicle file also has vehicle height (vertical) details apart from length and width of the vehicle.

Figure 5.1: DST Lowboy Vehicle from Wisconsin DOT Library



Source: Wisconsin DOT Vehicle Library (*28*)

Figure 5.2: DST Lowboy 2 Part 1 Vehicle from Wisconsin DOT Library



Source: Wisconsin DOT Vehicle Library (*28*)

5.4 Procedure to Generate a 3D Simulation:

The first step in any states' procedure would be to verify that the WisDOT DST Lowboy is applicable to their state, or, if not, to develop to develop a similar test vehicle that does represent the most critical dimensions of lowboys in their state.

A desired 2D simulation was generated at a roundabout initially with a "DST lowboy" vehicle. While conducting the 2D simulation, properties of simulation were adjusted in such a way that the path of the jeep king pin (shown in Figure 5.1 & Figure 5.2) for the vehicle can be tracked. Later the 2D simulation was removed and the 3D simulation of "DST lowboy 2 part 1" was made to follow the jeep, king pin path that was generated using a previous 2D simulation so that that the 3D simulation of "DST lowboy 2 part 1" is similar to the actual left turn of "DST lowboy".

5.5 Single-Lane Roundabout Ground Clearance Analysis:

Initially a symmetric single-lane roundabout with ICD 180 ft and WB-67 design vehicle was generated using TORUS software shown in Figure 5.3-A.

Figure 5.3: Symmetric Single-Lane Roundabouts Generated by TORUS Software

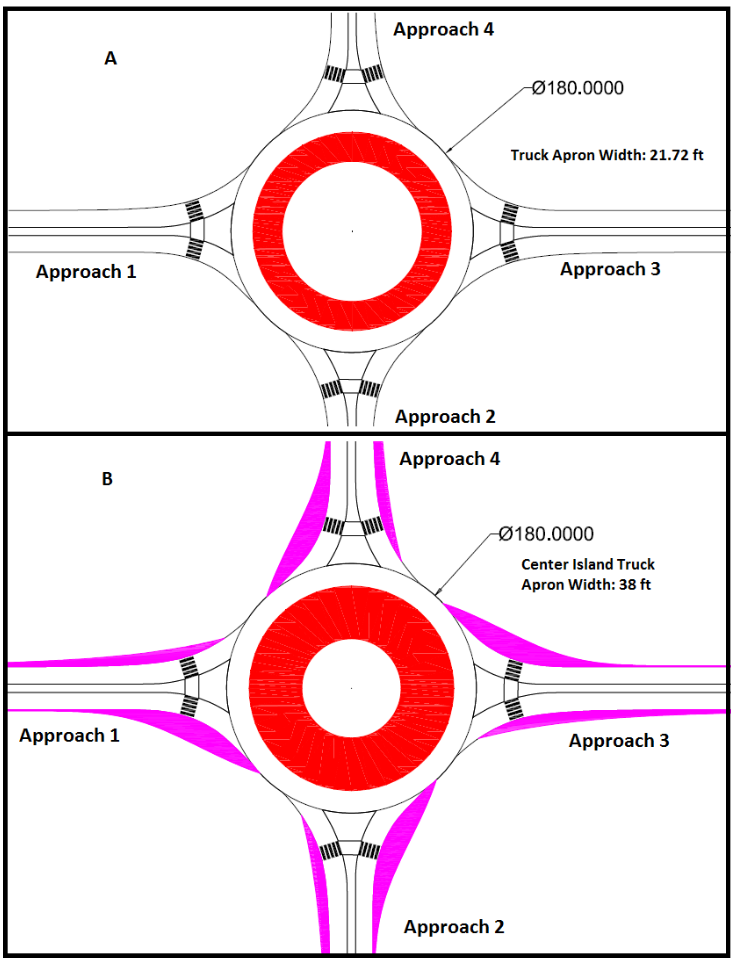


Figure 5.3-A shows the specified single-lane roundabout designed with a 21.72-ft initial truck apron width. This roundabout design was modified to accommodate left turn, through and

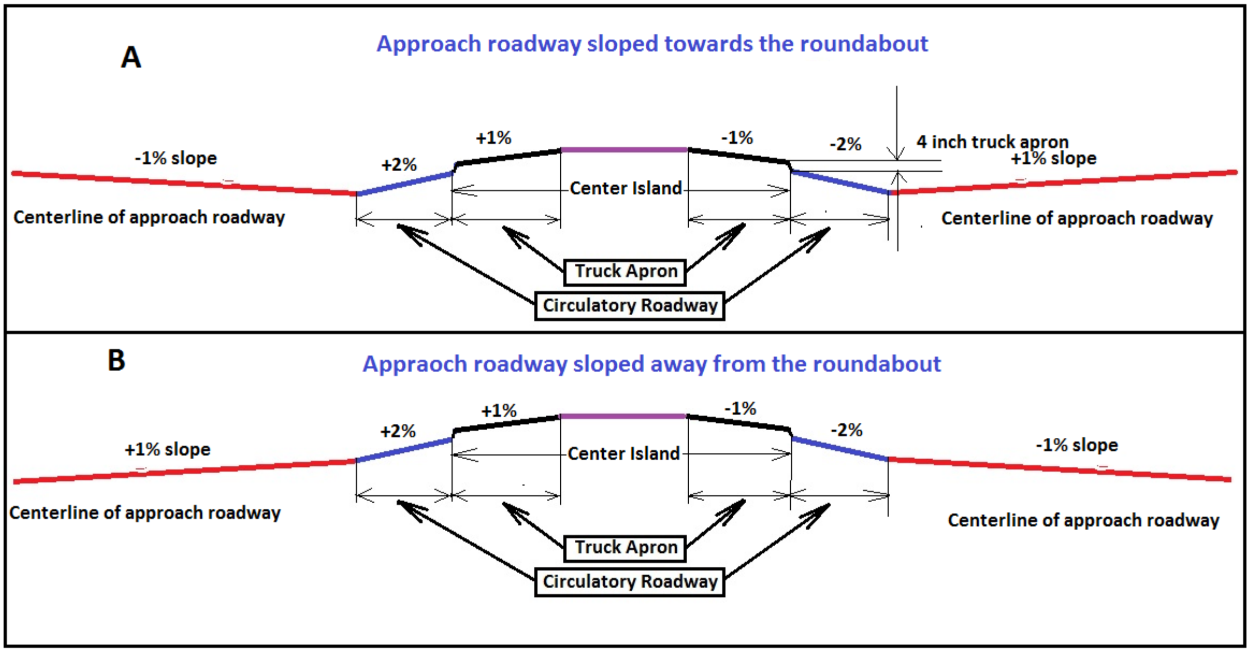
right turn maneuvers of the WisDOT DST lowboy from all approaches as shown in Figure 5.3-B. Figure 5.3-B shows a custom center island truck apron and an external truck apron needed to accommodate DST lowboy.

Grading was designed for this roundabout in TORUS software with various combinations of truck apron width, truck apron cross slope, circulatory roadway cross slope, approach roadway slope (away from the roundabout and towards the roundabout) to check all combinations that work best for the DST lowboy without ground clearance problems. From the survey 2 summary (section 3.1 of this dissertation), it was summarized that a truck apron height of 4 inches had ground clearance problems for lowboys and often a 3 inches truck apron height was used. It was also mentioned, in NCHRP report 672, **that 2 to 3-inch truck apron height must be used to discourage other passengers from using it**. [emphasis added] . However, there is no published information about truck apron heights for lowboy vehicles based on a 3 dimensional analysis. Therefore, truck apron heights of 4 inches, 3 inches, and 2.5 inches were considered to check for any ground clearance problems for DST lowboy vehicles.

As mentioned in section 5.1, a 2% maximum truck apron cross slope designed for water to drain towards the circulatory roadway was used. A 2% maximum circulatory cross slope sloping away from the center island was used. Therefore, truck apron cross slopes of 2%, 1.5%, and 1% sloping towards the circulatory roadway were considered. Circulatory roadway cross slopes of 2%, 1.5%, and 1% sloping away from the center island were considered. Figure 5.4-A and Figure 5.4-B illustrates an example truck apron slope towards the circulatory roadway and an example circulatory roadway slope away from the center island, respectfully.

For designing the approach roadway slope for all the four legs of the roundabout, approach roadway slopes away from the roundabout such as 3%, 2% and 1% and approach roadway slopes towards the roundabout such as 3%, 2%, and 1% were considered. Figure 5.4 shows an example profile showing an approach roadway slope away from the roundabout and towards the roundabout.

Figure 5.4: Example Illustration of Grading for the Symmetric Single-Lane Roundabout

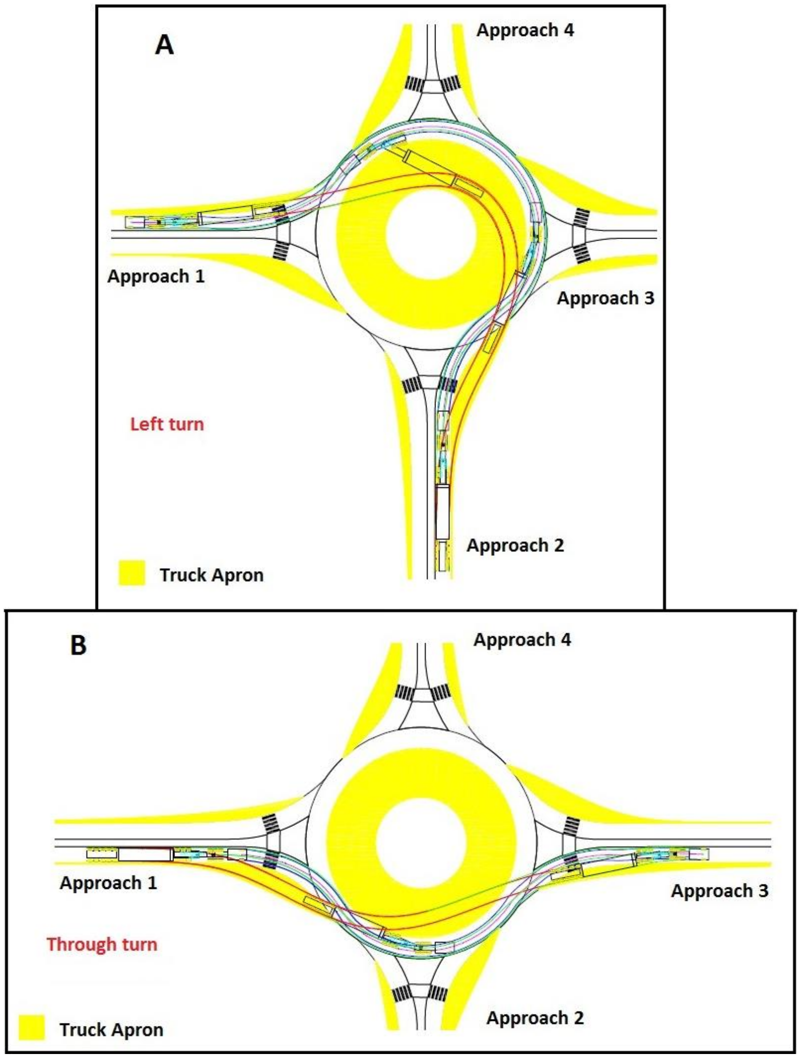


At the modified single-lane roundabout (shown in Figure 5.3-B), for each combination of truck apron height, truck apron slope, circulatory roadway slope, approach roadways slope, a vehicle clearance analysis for left turn movement and through movement of DST lowboy was checked for ground clearance problems.

5.5.1 Illustration of a Vertical Clearance Analysis using an Example:

For this example illustration, the single-lane roundabout in Figure 5.3-B was designed with a 4-inch truck apron height, 1% cross slope for truck apron towards the circulatory roadway, 2% cross slope for the circulatory roadway away from the center island, and 1% slope for approach centerline towards the roundabout for all the 4 approaches. Therefore, the roundabout is graded symmetrically for all the four approaches. For this example, the profile of the roundabout (Figure 5.3-B) cuts across the center line of approach 1 and approach 3 for this example can be illustrated in Figure 5.4-A. This profile is also the same across the center line of approach 2 and approach 4 as the roundabout is a symmetric.

Figure 5.5: Two Dimensional Left and Through Movement Simulation of DST Lowboy at the Single-Lane Roundabout

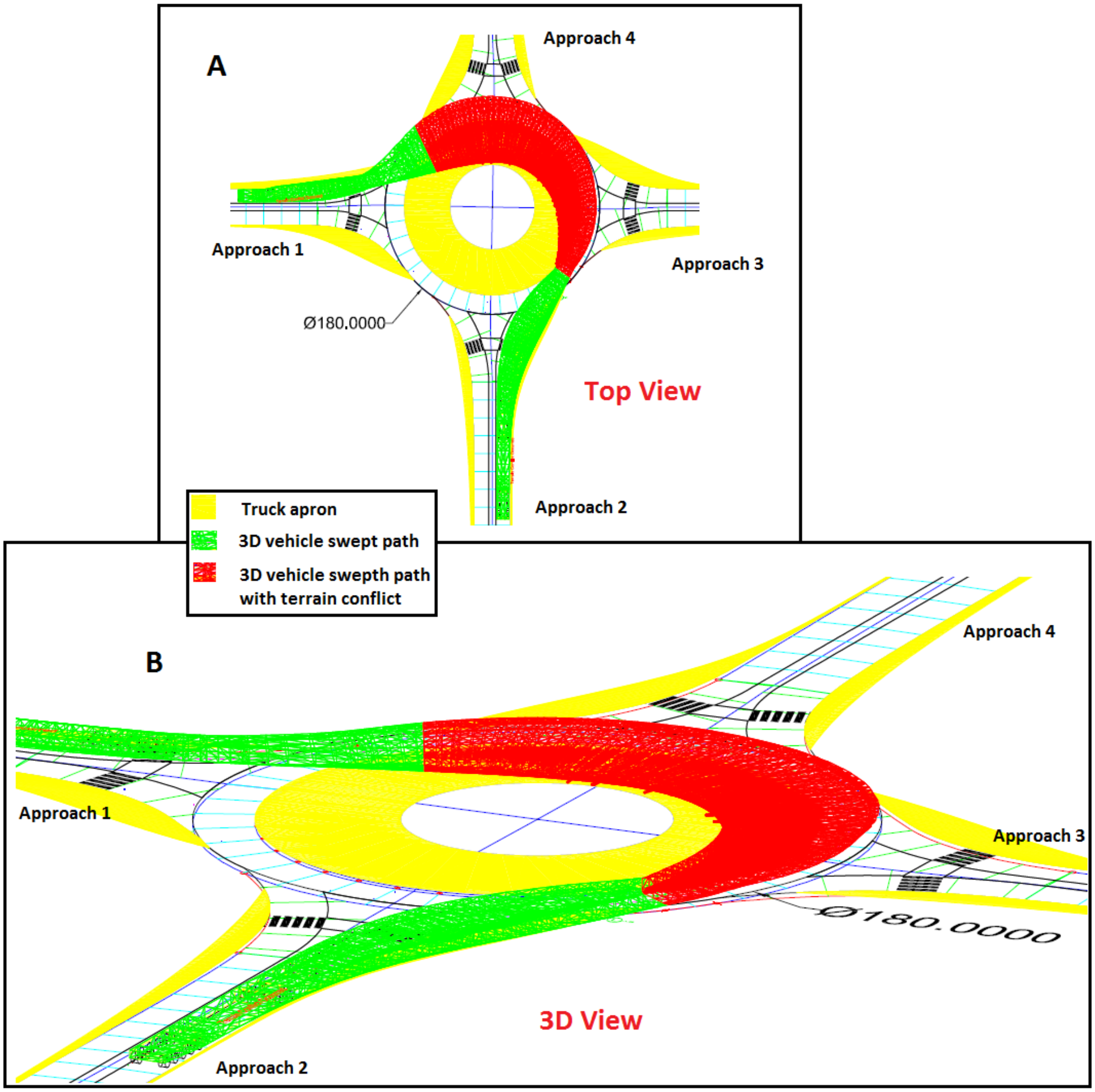


Initially, a two dimensional, left turn simulation, and through simulation, of the 'DST lowboy' vehicle was conducted. A left turn simulation and through simulation of the 'DST Lowboy' vehicle was conducted to check if the designed roundabout can be used for lowboy vehicles without any ground clearance problems. Figure 5.5-A illustrates the left turn simulation of DST lowboy from approach 2 to approach 1 and Figure 5.5-B shows the through movement simulation of DST lowboy from approach 1 to approach 3. The left turn movement and through movement simulations were generated in such a way that the front tractor is assumed to enter the roundabout in its lane and stay in its lane while circulating the roundabout as shown in Figure 5.5-A for a left turn movement and Figure 5.5-B for through movement.

For left and through maneuvers mentioned above, the path of the king pin was traced using AutoTURN software, and a 3D simulation of “DST lowboy 2 part 1” vehicle was placed in the king pin path, to check the ground clearance of the DST lowboy vehicle at this symmetric single-lane roundabout, using the vehicle clearance analysis option in AutoTURN Pro 3D software. Figure 5.6-A shows the 3D simulation of the “DST lowboy 2 part 1” top view. Figure 5.6-B shows the 3D path of the vehicle “DST lowboy 2 part 1” as it maneuvers a left turn from approach 2 to approach 1 of the roundabout. If AutoTURN Pro 3D software detects a conflict for the 3D simulated vehicle, that portion of the 3D simulation is shown in RED color. It can be observed from Figure 5.6-A and Figure 5.6-B that there is a terrain conflict for the left turn of the “DST lowboy 2 part 1” vehicle at the roundabout and this is an area of concern.

The AutoTURN Pro 3D software has the capability to conduct a clearance analysis of the 3D vehicle simulation, where we can check the interaction of vehicle body with the roundabout terrain can be checked. Therefore, AutoTURN Pro 3D software’s ‘vehicle clearance analysis’ option was used to conduct a ground clearance check for the left turn movement of the ‘DST lowboy 2 part 1’ along the ‘vehicle centerline path’ (shown in Figure 5.7), ‘center of rear axle group’ (shown in Figure 5.8), ‘center of the swept path’ (shown in Figure 5.9), the ‘left side of the swept path’ (shown in Figure 5.10), and the ‘right side of the swept path’ (shown in Figure 5.11). For example, from the vehicle clearance analysis report from Figure 5.7, it can be observed that, for the analysis line ‘vehicle centerline path ‘ and at the analysis line length of 139 ft, the lowest ground clearance occurs and the value is +0.26 ft. This means that there is 0.26 ft more clearance analysis available between the vehicle body bottom and roundabout terrain and indicates that there is no terrain conflict along the analysis line ‘vehicle centerline path’.

Figure 5.6: Three Dimensional Simulation of DST Lowboy 2 Part 1 Vehicle at the Single-Lane Roundabout



To conclude, the ground clearance problem for the 3D simulation at the roundabout, the lowest ground clearance occurring along the analysis lines 'vehicle centerline path', 'center of rear axle group', 'center of the swept path', 'left side of the swept path', and 'right side of the swept path', need to be studied and a decision must be made based on the lowest ground clearance occurring among all analysis line lengths. It can be observed (from Figure 5.7 through Figure 5.11) that the lowest ground clearance occurs for the analysis line 'center of swept path' and was observed as -0.23 ft at the analysis line length 161 ft. This means that the vehicle body bottom needs 0.23 ft more clearance indicating a serious terrain conflict. This terrain conflict was further analyzed in the AutoTURN Pro 3D software ‘Punch through’ option and it was found that the conflict occurs as the vehicle body bottom interacts with the truck apron height. Therefore, it can be concluded that the modified, single-lane roundabout shown in Figure 5.3-B designed with 4-ft truck apron, 1% truck apron slope towards the circulatory roadway, 2% circulatory roadway slope away from the center island, and 1% slope of all approaches, toward the roundabout and not adequate for accommodating the DST lowboy used in this example, as a serious terrain conflict can be observed.

The procedure described in the above example vehicle clearance analysis was conducted for all combinations of truck apron heights (4-inch, 3-inch, and 2-inch), truck apron slopes 2%, 1.5%, and 1%), circulatory roadway slopes (2%, 1.5% and 1%), and slopes of approach roadway (3%, 2%, and 1%).

Figure 5.7: Vehicle Clearance Analysis along the Analysis Line 'Vehicle Centerline Path'

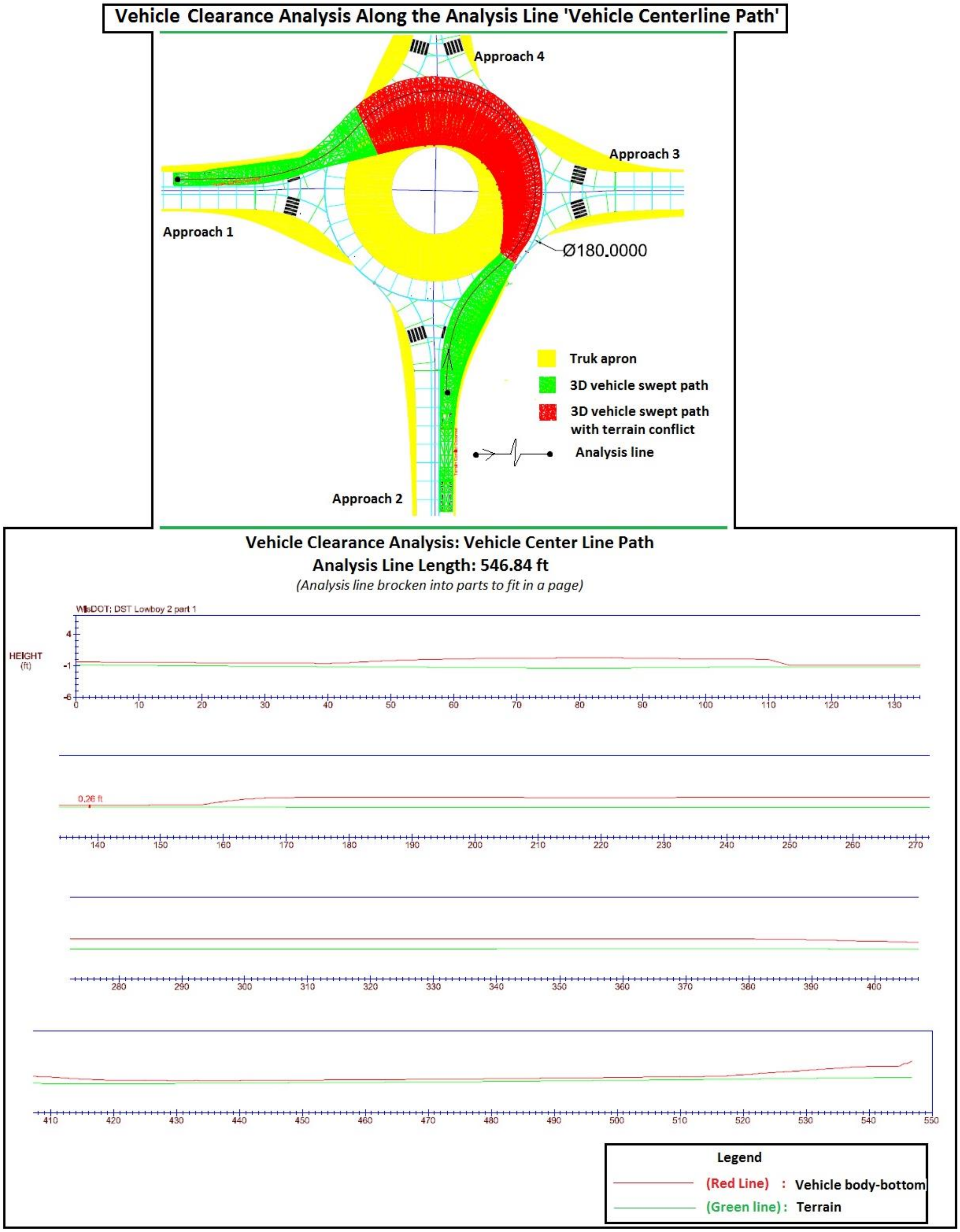


Figure 5.8: Vehicle Clearance Analysis along the Analysis Line 'Center of Rear Axle Group'

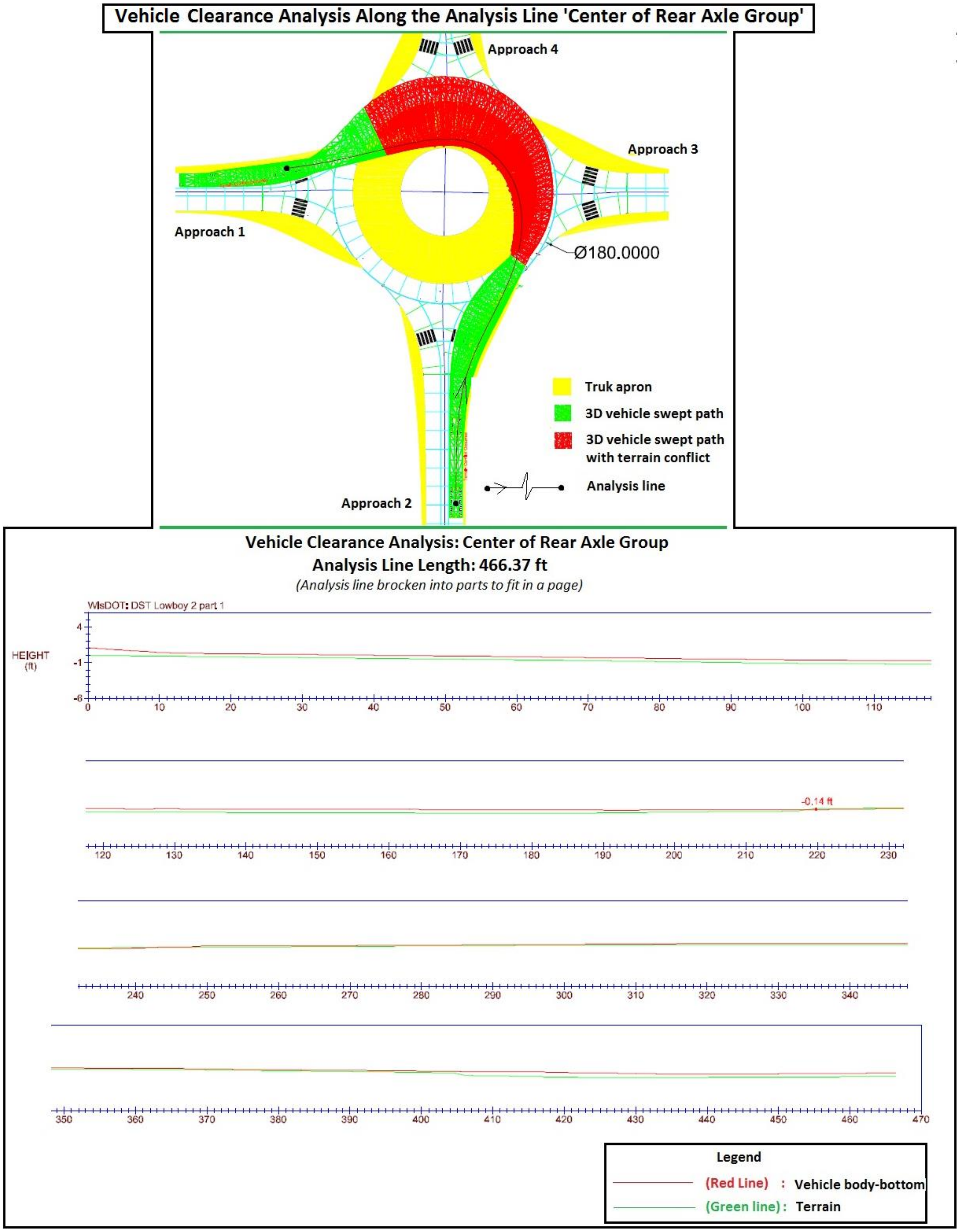


Figure 5.9: Vehicle Clearance Analysis along the Analysis Line 'Center of Swept Path'

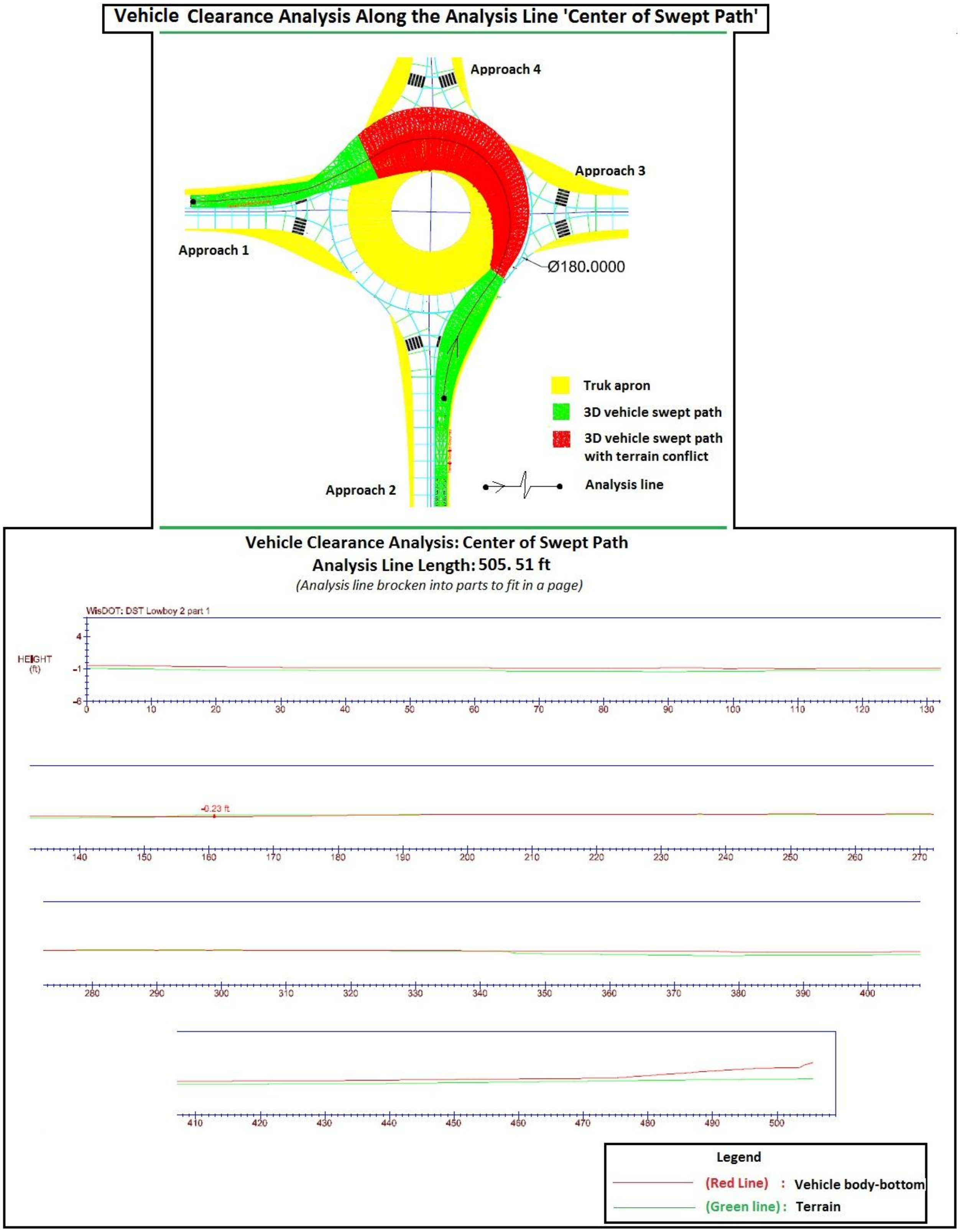


Figure 5.10: Vehicle Clearance Analysis along the Analysis Line 'Left Side of Swept Path'

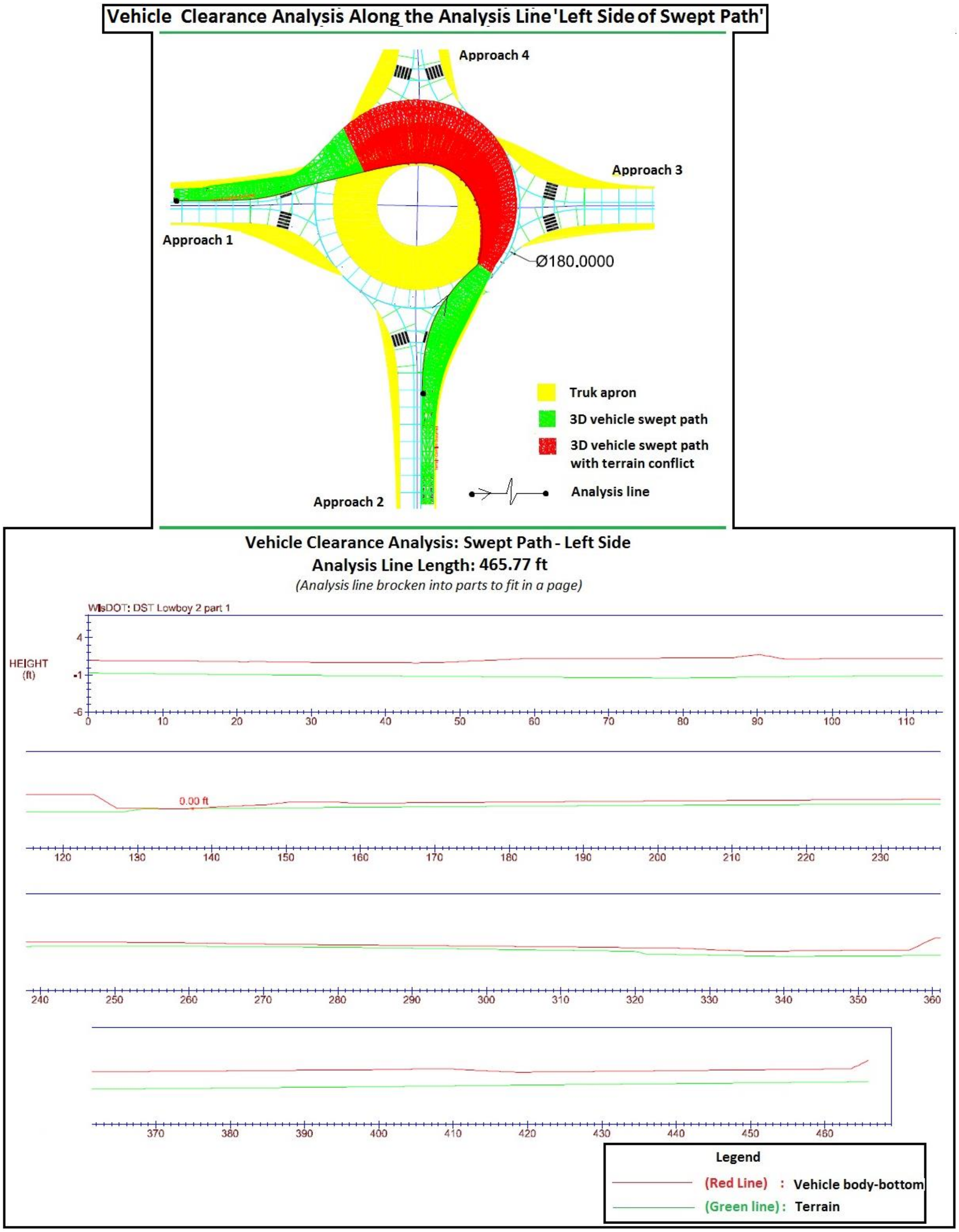
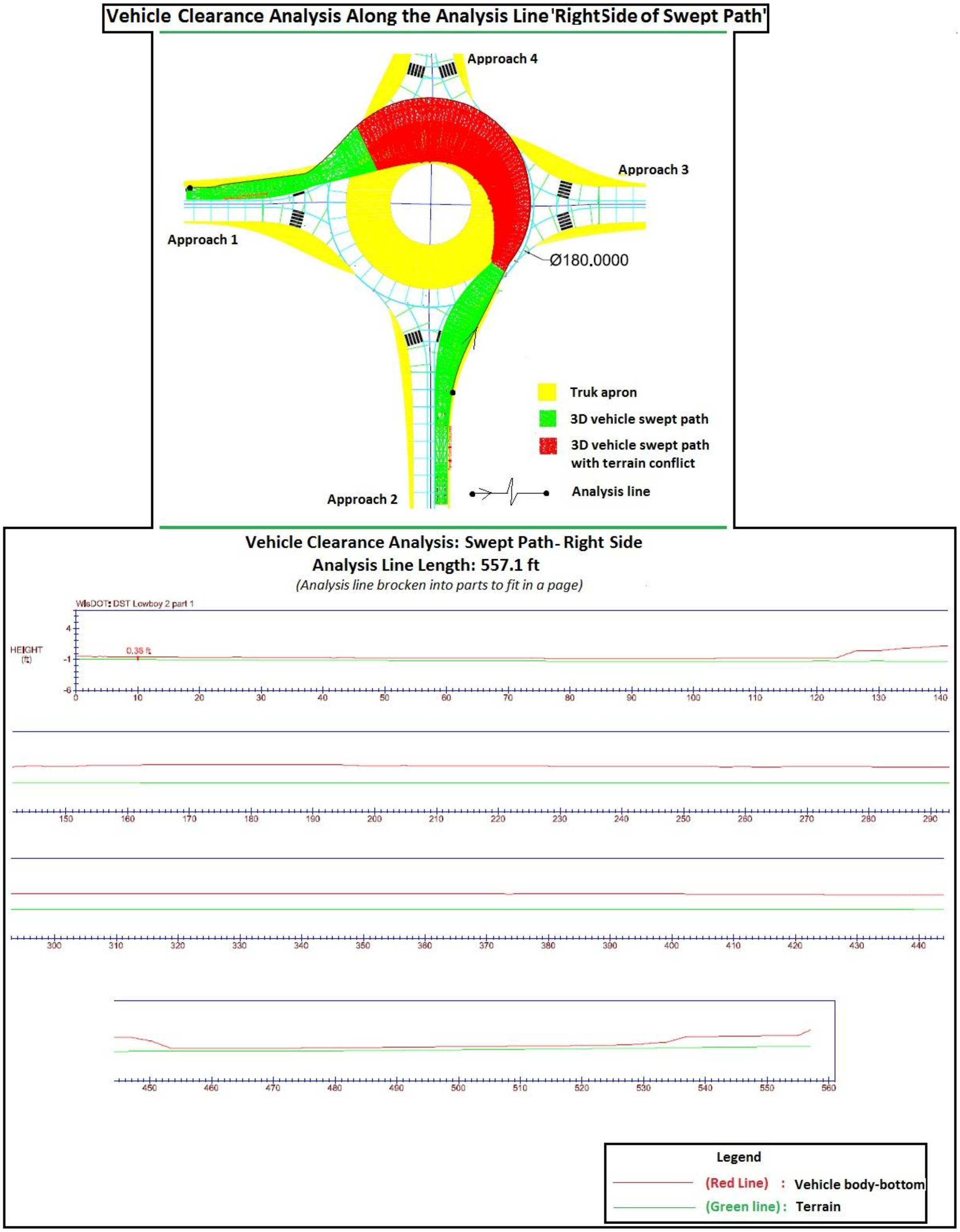


Figure 5.11: Vehicle Clearance Analysis along the Analysis Line ‘Right Side of Swept Path’



5.5.2 Vehicle Clearance Analysis Results of DST Lowboy at Single-Lane Roundabout:

Table 5.1 shows the ground clearance analysis results for the various combinations of 3-inch truck apron height and approaches sloped towards the roundabout, conducted as part of this study. Table 5.2 shows the ground clearance analysis results for various combinations of 3-inch truck apron height and approaches sloped away from the roundabout. Table 5.3 shows the ground clearance analysis results for various combinations of 2-inch truck apron height and approaches sloped towards the roundabout. Table 5.4 shows the ground clearance analysis results for various combinations of 2-inch truck apron height and approaches sloped away from the roundabout. Tables 5.1 through 5.4 were set up in such a way that each combination of truck apron height, truck apron cross slope, circulatory roadway cross slope, and approach roadway slope, were either highlighted in ORANGE color, if there was a ground clearance problem, or highlighted in GREEN color, if there was no ground clearance problem, while a DST lowboy maneuvers left turn or through movements. Therefore it can be summarized from Tables 5.1 to 5.4 that all the combinations highlighted in GREEN color are workable options, for the DST lowboy used, without ground clearance problems.

It is also concluded that a 4-inch truck apron height was not suitable for accommodating the DST lowboy used in this study at single-lane roundabouts for any combinations of the truck apron cross slope, circulatory roadway cross slope, approach roadway slope for two reasons:

1. It can be seen in tables Table 5.1 and 5.2 that a 3-inch truck apron height for all combination of slopes have ground clearance problems, and therefore, a 4-inch truck apron height will make the problem worse.
2. A vertical clearance analysis for 4-inch truck apron height, 1% truck apron cross slope towards the circulatory roadway, 1% circulatory roadway cross slope away from the center island, and 1% slope for all the approach roadways towards the roundabouts have yielded a lowest ground clearance of -0.16, ft, showing a ground clearance problem for these lowest possible slope combinations. Therefore, any other combinations will always have a clearance less than -0.16 ft; and therefore, a 4-inch truck apron height is not a preferred height for accommodating a DST lowboy at the single-lane roundabout. A lower height should be considered.

Table 5.1: Ground Clearance of the DST Lowboy Vehicle at Various Grades of Symmetric Single-Lane Roundabout with 3-inch Truck Apron Height and Approach Roadway Sloping towards the Roundabout

Cross slope of circulatory roadway	Cross slope of truck apron	Slope of approaches for the roundabout	Ground clearance problem exists (Yes/No)		Lowest Ground Clearance (ft)	
			Through turn	Left turn	Through turn	Left turn
2%	2%	3%	yes	yes	-0.11	-0.1
		2%	yes	yes	-0.11	-0.09
		1%	yes	yes	-0.1	-0.09
	1.50%	3%	yes	yes	-0.11	-0.09
		2%	yes	yes	-0.1	-0.08
		1%	yes	yes	-0.1	-0.08
	1%	3%	yes	yes	-0.1	-0.07
		2%	yes	yes	-0.1	-0.07
		1%	yes	yes	-0.09	-0.07
1.50%	2%	3%	yes	yes	-0.08	-0.07
		2%	yes	yes	-0.08	-0.06
		1%	yes	yes	-0.08	-0.06
	1.50%	3%	yes	yes	-0.07	-0.06
		2%	yes	yes	-0.07	-0.05
		1%	yes	yes	-0.07	-0.05
	1%	3%	yes	yes	-0.06	-0.04
		2%	yes	yes	-0.06	-0.04
		1%	yes	yes	-0.06	-0.04
1%	2%	3%	yes	yes	-0.06	-0.04
		2%	yes	yes	-0.06	-0.04
		1%	yes	yes	-0.06	-0.04
	1.50%	3%	yes	yes	-0.04	-0.02
		2%	yes	yes	-0.04	-0.02
		1%	yes	yes	-0.04	-0.03
	1%	3%	Yes	Yes	-0.03	-0.01
		2%	Yes	Yes	-0.03	-0.01
		1%	Yes	Yes	-0.04	-0.01

Table 5.2: Ground Clearance of the DST Lowboy Vehicle at Various Grades of Symmetric Single-Lane Roundabout with 3-inch Truck Apron Height and Approach Roadway Sloping away from the Roundabout

Crossslope of circulatory roadway	Crossslope of truck apron	Slope of approaches for the roundabout	Ground clearance problem exists (Yes/No)		Lowest Ground Ground Clearance (ft)	
			Through turn	Left turn	Through turn	Left turn
2%	2%	3%	yes	yes	-0.13	-0.15
		2%	yes	yes	-0.11	-0.13
		1%	yes	yes	-0.1	-0.09
	1.50%	3%	yes	yes	-0.11	-0.09
		2%	yes	yes	-0.1	-0.08
		1%	yes	yes	-0.1	-0.08
	1%	3%	yes	yes	-0.1	-0.07
		2%	yes	yes	-0.1	-0.07
		1%	yes	yes	-0.09	-0.07
1.50%	2%	3%	yes	yes	-0.08	-0.07
		2%	yes	yes	-0.08	-0.06
		1%	yes	yes	-0.08	-0.06
	1.50%	3%	yes	yes	-0.07	-0.06
		2%	yes	yes	-0.07	-0.05
		1%	yes	yes	-0.07	-0.05
	1%	3%	yes	yes	-0.06	-0.04
		2%	yes	yes	-0.06	-0.04
		1%	yes	yes	-0.06	-0.04
1%	2%	3%	yes	yes	-0.06	-0.04
		2%	yes	yes	-0.06	-0.04
		1%	yes	yes	-0.06	-0.04
	1.50%	3%	yes	yes	-0.04	-0.02
		2%	yes	yes	-0.04	-0.02
		1%	yes	yes	-0.04	-0.03
	1%	3%	Yes	Yes	-0.03	-0.01
		2%	Yes	Yes	-0.03	-0.08
		1%	Yes	Yes	-0.03	-0.05

Table 5.3: Ground Clearance of the DST Lowboy Vehicle at Various Grades of Symmetric Single-Lane Roundabout with 2-inch Truck Apron Height and Approach Roadway Sloping towards the Roundabout

Crossslope of circulatory roadway	Crossslope of truck apron	Slope of approaches for the roundabout	Ground clearance problem exists (Yes/No)		Lowest Ground Ground Clearance (ft)	
			Through turn	Left turn	Through turn	Left turn
2%	2%	3%	yes	yes	-0.03	-0.03
		2%	yes	yes	-0.02	-0.03
		1%	yes	yes	-0.01	-0.02
	1.50%	3%	yes	yes	-0.03	-0.03
		2%	yes	yes	-0.03	-0.02
		1%	yes	yes	-0.01	-0.01
	1%	3%	yes	yes	-0.01	0
		2%	yes	No	0	0.01
		1%	No	No	0.03	0.03
1.50%	2%	3%	No	No	0.03	0.04
		2%	No	No	0.04	0.04
		1%	No	No	0.04	0.05
	1.50%	3%	No	No	0.04	0.04
		2%	No	No	0.04	0.05
		1%	No	No	0.05	0.05
	1%	3%	No	No	0.04	0.05
		2%	No	No	0.05	0.06
		1%	No	No	0.05	0.07
1%	2%	3%	No	No	0.06	0.07
		2%	No	No	0.06	0.06
		1%	No	No	0.07	0.08
	1.50%	3%	No	No	0.07	0.08
		2%	No	No	0.07	0.08
		1%	No	No	0.07	0.09
	1%	3%	No	No	0.07	0.08
		2%	No	No	0.09	0.07
		1%	No	No	0.1	0.07

Table 5.4: Ground Clearance of the DST Lowboy Vehicle at Various Grades of Symmetric Single-Lane Roundabout with 2-inch Truck Apron Height and Approach Roadway Sloping away from the Roundabout

Crossslope of circulatory roadway	Crossslope of truck apron	Slope of approaches for the roundabout	Ground clearance problem exists (Yes/No)		Lowest Ground Ground Clearance (ft)	
			Through turn	Left turn	Through turn	Left turn
2%	2%	3%	yes	yes	-0.03	-0.03
		2%	yes	yes	-0.02	-0.03
		1%	yes	yes	-0.01	-0.02
	1.50%	3%	yes	yes	-0.03	-0.03
		2%	yes	yes	-0.03	-0.02
		1%	yes	yes	-0.01	-0.01
	1%	3%	yes	yes	-0.01	0
		2%	yes	yes	-0.01	0
		1%	Yes	No	0	-0.01
1.50%	2%	3%	No	No	0.03	0.03
		2%	No	No	0.04	0.04
		1%	No	No	0.04	0.05
	1.50%	3%	No	No	0.04	0.04
		2%	No	No	0.04	0.05
		1%	No	No	0.05	0.05
	1%	3%	No	No	0.04	0.05
		2%	No	No	0.06	0.06
		1%	No	No	0.05	0.07
1%	2%	3%	No	No	0.07	0.07
		2%	No	No	0.06	0.06
		1%	No	No	0.07	0.08
	1.50%	3%	No	No	0.07	0.08
		2%	No	No	0.07	0.08
		1%	No	No	0.07	0.09
	1%	3%	No	No	0.07	0.08
		2%	No	No	0.09	0.08
		1%	No	No	0.09	0.08

Based on the vehicle clearance analysis, it can be concluded that, neither a 4-inch truck apron height nor a 3-inch truck apron height is suitable for accommodating the DST lowboy vehicle used in this study at a symmetric single-lane roundabout, graded according to NCHRP report 672 (*1*), as ground clearance problems were observed. A 2-inch truck apron height can be used for the single-lane roundabout considered for accommodating a DST lowboy vehicle, without ground clearance problems, when the cross slope of the circulatory roadway is not more than 1.5% away from the center island, and when the cross slope of the truck apron is not more than 2% towards the circulatory roadway.

The recommendations above are applicable for the symmetric, single-lane roundabout with an ICD 180 ft, designed with a WB-67 design vehicle, and graded according to guidelines provided in NCHRP report 672 (*1*). These recommendations may or may not be applied for other single-lane roundabouts with varying ICD and design vehicles, but others should be checked in AutoTURN Pro 3D (or similar) software for their ground clearance for validating other designs . The procedures used in this study serve as guidelines that can be followed to conduct ground clearance analysis to determine truck apron height at any single-lane roundabout needed to accommodate a lowboy vehicle.

5.5.2.1 Reliability of Recommendations Provided for Symmetric Single-Lane Roundabouts:

One limitation of the TORUS software is that, it can design grading needed for various features of the roundabout but not for an external truck apron. Therefore, TORUS assumes the external truck apron to be flat starting from the place the grading was terminated. This means that TORUS assumes that the external truck apron is not raised in height above the roadway and has 0% cross slope. It can be observed from Figure 5.5-A and Figure 5.5-B that the rear tires of the DST lowboy use the external truck apron while entering and exiting the roundabout and therefore grading of the external truck apron is also required for precise vehicle clearance analysis results, and for making reliable recommendations. However, the truck apron height and grading recommendations for symmetric double-lane roundabouts described below in section 5.6 are reliable, as the double-lane roundabout doesn't need an external truck apron to accommodate DST lowboy in this study. The next version of TORUS software which is scheduled to be released in 2013 is expected to have the capability of designing grading for an external truck apron. Therefore, this study also serves as a procedure that needs to be followed for better validating the results for a single-lane roundabout when the later versions of TORUS software are available.

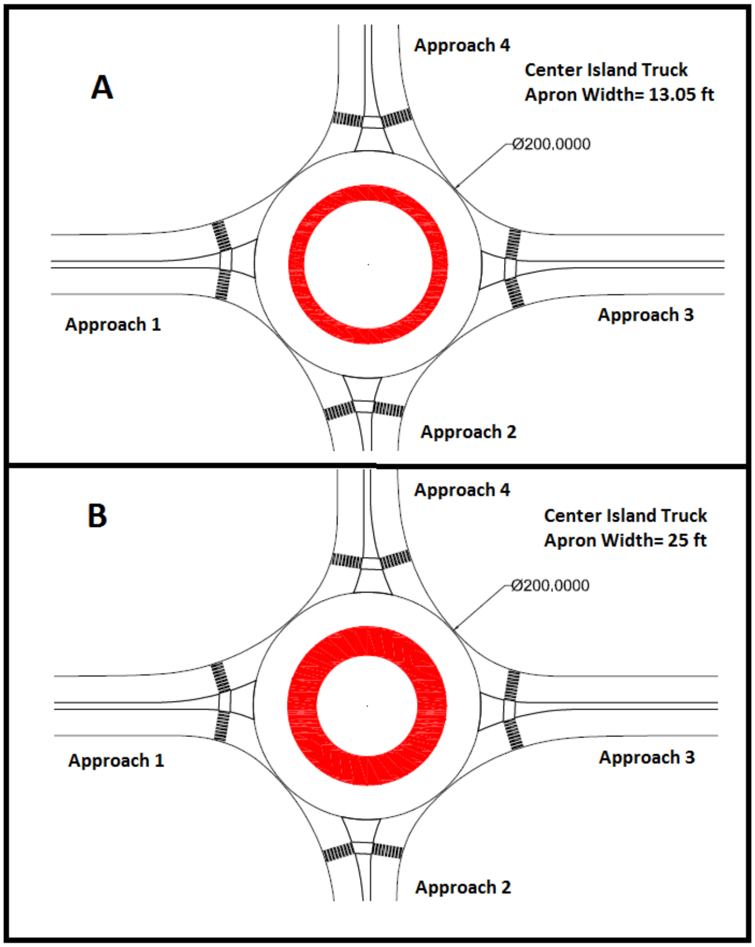
5.6 Double-Lane Roundabout Ground Clearance Analysis:

A symmetric, double-lane roundabout with ICD 200 ft and WB-67 design vehicle was generated with TORUS software and is shown in Figure 5.12-A. It has a 13.05-ft center island truck apron width. It should be noted that TORUS software does not have the capability of constructing lane markings for this roundabout to make it look more like a two-lane roundabout. However, this roundabout has two entering lanes and two exit lanes for all the approaches, and two circulating lanes.

This roundabout design was modified to accommodate left turn, through and right turn maneuvers of the WisDOT, DST lowboy from all approaches as shown in Figure 5.12-B. While modifying the double-lane roundabout in Figure 5.12-A, to accommodate various movements of DST lowboy, each simulation of the DST lowboy was developed in such a way that the vehicle enters from any of the two lanes, circulates in any of the two lanes and exits into any of the two lanes to reduce the need for and a center island truck apron and an outer truck apron. Figure 5.13 illustrates a two dimensional left and through movement simulations of the DST lowboy vehicle. Figure 5.12-B shows a custom center island truck apron width of 25 ft and it was also observed that there was no need for an external truck apron to accommodate the various movements of DST lowboy.

Grading was designed for this roundabout in TORUS software with various combinations of truck apron width, truck apron cross slope, circulatory roadway cross slope, and approach roadway slope (away from the roundabout and towards the roundabout) to check all combinations that work best for DST lowboy without having ground clearance problems. It was mentioned in NCHRP report 672 (*1*) that a 2-inch to 3-inch truck apron height must be used to discourage other passengers from using it. Therefore, truck apron heights of 3 inches and 4 inches were considered in this study to check for any ground clearance problems for the DST lowboy vehicle used in this study. As mentioned in section 5.1, a 2% maximum cross slope of the truck apron sloping towards the circulatory roadway was used. The outward method of sloping the circulatory roadways was selected for this study and a slope of 1.5% to 3% away from the center island was used. Therefore, truck apron cross slopes of 2%, and 1%, sloping towards the circulatory roadway, were used. Circulatory roadway cross slope of 3%, 2.5%, 2%, 1.5%, and 1% sloping away from the center island were considered. For designing the approach roadway slope for all the four legs of the roundabout, approach roadway slopes away from the roundabout such as 3%, 2% and 1% and approach roadway slopes towards the roundabout, such as 3%, 2%, and 1% were considered.

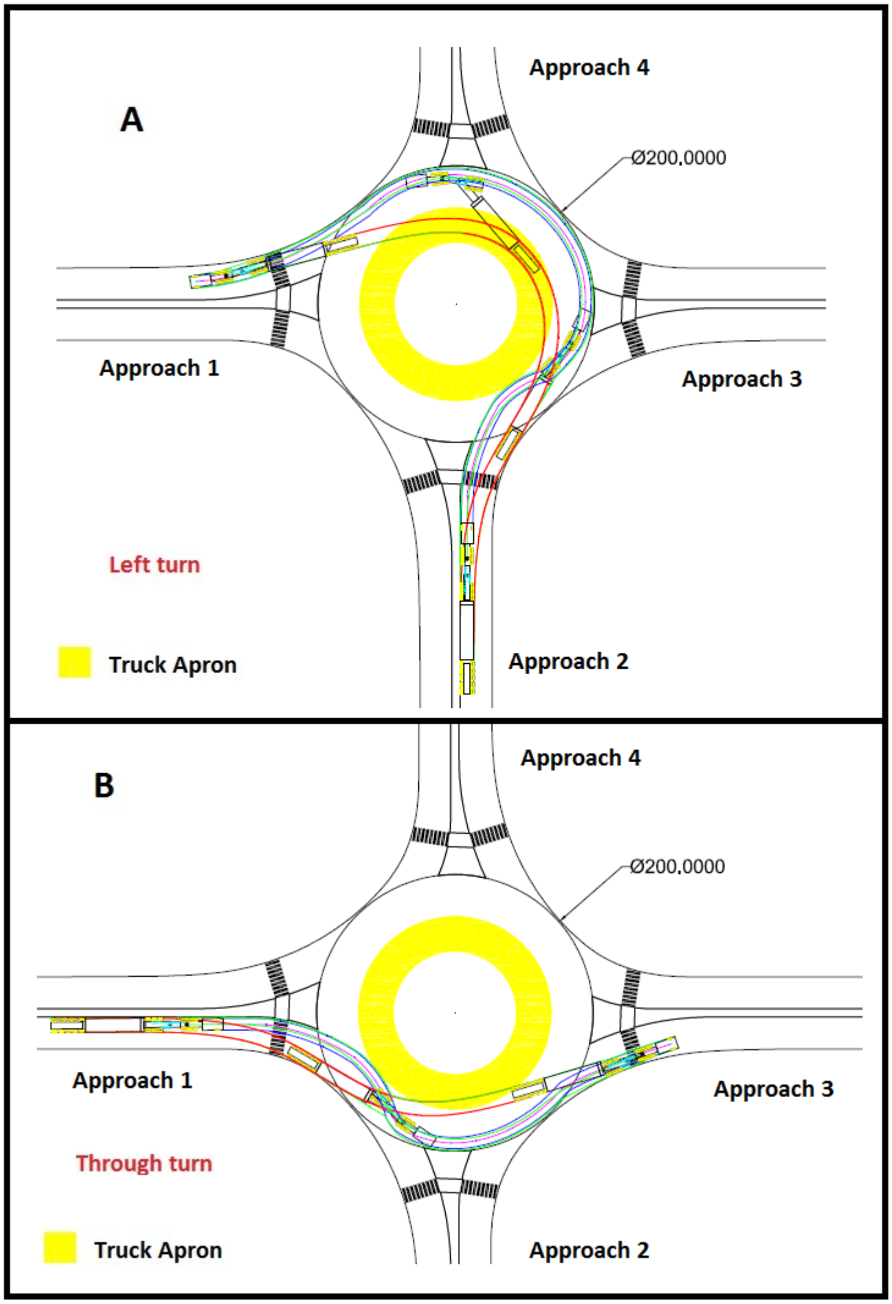
Figure 5.12: Symmetric Double-Lane Roundabouts Generated by TORUS Software



At the modified double-lane roundabout (shown in Figure 5.12-B), for each combination of truck apron height, truck apron slope, circulatory roadway slope, approach roadways slope, a vehicle clearance analysis for a left turn movement and a through movement of the DST lowboy was checked for any ground clearance problems. The vehicle clearance analysis procedure described in section 5.5.1 was conducted for all combinations of truck apron heights (4-inch and

3-inch), truck apron slopes (2%, and 1%), circulatory roadway slopes (3%, 2.5%, 2%, and 1.5%) and approach roadway slopes (3%, 2%, and 1%).

Figure 5.13: Two Dimensional Left and Through Movement Simulation of DST Lowboy at the Double-Lane Roundabout



5.6.1 Vehicle Clearance Analysis Results of DST Lowboy at Double-Lane Roundabout:

Table 5.5 shows the ground clearance analysis results for various combinations of a 4-inch truck apron height and approaches sloped towards roundabout as indicated in the previous section. Table 5.6 shows the ground clearance analysis results for various combinations of 4-inch truck apron height and approaches sloped away from the roundabout. Table 5.7 shows the ground clearance analysis results for various combinations of a 3-inch truck apron height and approaches sloped towards the roundabout. Table 5.8 shows the ground clearance analysis results for various combinations of 3-inch truck apron height and approaches sloped away from the roundabout. Tables 5.5 through 5.8 were set up in such a way that each combination of truck apron height, truck apron cross slope, circulatory roadway cross slope, and approach roadway slope were highlighted in ORANGE color if there was a ground clearance problem, and in GREEN color if there was no ground clearance problem for DST lowboy left turn and through movements. Therefore it can be summarized from Tables 5.5 to 5.8 that all the combinations highlighted in GREEN color are workable options for the DST lowboy with no ground clearance problems.

Based on the vehicle clearance analysis at the symmetric double-lane roundabout, it can be concluded that a 4-inch truck apron height was not suitable for accommodating a DST lowboy vehicle at a symmetric double-lane roundabout graded according to guidelines provided in NCHRP report 672 as serious ground clearance problems were observed. A 3-inch truck apron height can be used for the considered double-lane roundabout for accommodating a DST lowboy vehicle used with no ground clearance problems when the cross slope of the circulatory roadway is not more than 2% away from the center island, and when the cross slope of the truck apron is not more than 2% towards the circulatory roadway. For these recommendations, approach roadway slopes of 1%, 2%, or 3%, towards the roundabout or away from the roundabout can be used. These recommendations are only applicable for the symmetric, double-lane roundabouts with ICD 200-ft designed with a WB-67 design vehicle and graded according to guidelines provided in NCHRP report 672, which were used in this study. These recommendations may or may not be apply to other double-lane roundabouts with varying ICD and other design vehicle, but they should be checked in AutoTURN Pro 3D (or similar) software for ground clearance analysis for validating the results. This study also serves as a procedure that should be followed to conduct a ground clearance analysis to determine maximum truck apron height to accommodate a lowboy vehicle at any double-lane roundabout.

Table 5.5: Ground Clearance of the DST Lowboy Vehicle at Various Grades of Symmetric Double-Lane Roundabout with 4-inch Truck Apron Height and Approach Roadway Sloping towards the Roundabout

Crossslope of circulatory roadway	Crossslope of truck apron	Slope of approaches for the roundabout	Ground clearance problem exists (Yes/No)		Lowest Ground Ground Clearance (ft)	
			Through turn	Left turn	Through turn	Left turn
3.00%	2%	3%	Yes	Yes	-0.14	-0.13
		2%	Yes	Yes	-0.14	-0.13
		1%	Yes	Yes	-0.14	-0.13
	1%	3%	Yes	Yes	-0.14	-0.12
		2%	Yes	Yes	-0.13	-0.12
		1%	Yes	Yes	-0.13	-0.12
2.50%	2%	3%	Yes	Yes	-0.13	-0.12
		2%	Yes	Yes	-0.13	-0.12
		1%	Yes	Yes	-0.12	-0.11
	1%	3%	Yes	Yes	-0.12	-0.11
		2%	Yes	Yes	-0.11	-0.11
		1%	Yes	Yes	-0.11	-0.1
2.00%	2%	3%	Yes	Yes	-0.1	-0.1
		2%	Yes	Yes	-0.1	-0.1
		1%	Yes	Yes	-0.09	-0.09
	1%	3%	Yes	Yes	-0.09	-0.09
		2%	Yes	Yes	-0.08	-0.08
		1%	Yes	Yes	-0.08	-0.07
1.50%	2%	3%	Yes	Yes	-0.07	-0.06
		2%	Yes	Yes	-0.06	-0.05
		1%	Yes	Yes	-0.05	-0.05
	1%	3%	Yes	Yes	-0.03	-0.03
		2%	Yes	Yes	-0.02	-0.02
		1%	Yes	Yes	-0.02	-0.01

Table 5.6: Ground Clearance of the DST Lowboy Vehicle at Various Grades of Symmetric Double-Lane Roundabout with 4-inch Truck Apron Height and Approach Roadway Sloping away from the Roundabout

Crossslope of circulatory roadway	Crossslope of truck apron	Slope of approaches for the roundabout	Ground clearance problem exists (Yes/No)		Lowest Ground Ground Clearance (ft)	
			Through turn	Left turn	Through turn	Left turn
3.00%	2%	3%	Yes	Yes	-0.14	-0.13
		2%	Yes	Yes	-0.14	-0.13
		1%	Yes	Yes	-0.14	-0.13
	1%	3%	Yes	Yes	-0.14	-0.12
		2%	Yes	Yes	-0.13	-0.12
		1%	Yes	Yes	-0.13	-0.12
2.50%	2%	3%	Yes	Yes	-0.13	-0.12
		2%	Yes	Yes	-0.13	-0.12
		1%	Yes	Yes	-0.12	-0.11
	1%	3%	Yes	Yes	-0.12	-0.11
		2%	Yes	Yes	-0.11	-0.11
		1%	Yes	Yes	-0.11	-0.1
2.00%	2%	3%	Yes	Yes	-0.1	-0.1
		2%	Yes	Yes	-0.1	-0.1
		1%	Yes	Yes	-0.1	-0.09
	1%	3%	Yes	Yes	-0.09	-0.09
		2%	Yes	Yes	-0.08	-0.08
		1%	Yes	Yes	-0.07	-0.07
1.50%	2%	3%	Yes	Yes	-0.07	-0.06
		2%	Yes	Yes	-0.05	-0.04
		1%	Yes	Yes	-0.03	-0.03
	1%	3%	Yes	Yes	-0.02	-0.02
		2%	Yes	Yes	-0.02	-0.01
		1%	Yes	Yes	-0.01	-0.01

Table 5.7: Ground Clearance of the DST Lowboy Vehicle at Various Grades of Symmetric Double-Lane Roundabout with 3-inch Truck Apron Height and Approach Roadway Sloping towards the Roundabout

Crossslope of circulatory roadway	Crossslope of truck apron	Slope of approaches for the roundabout	Ground clearance problem exists (Yes/No)		Lowest Ground Ground Clearance (ft)	
			Through turn	Left turn	Through turn	Left turn
3.00%	2%	3%	Yes	Yes	-0.13	-0.13
		2%	Yes	Yes	-0.1	-0.11
		1%	Yes	Yes	-0.08	-0.08
	1%	3%	Yes	Yes	-0.07	-0.07
		2%	Yes	Yes	-0.06	-0.07
		1%	Yes	Yes	-0.05	-0.06
2.50%	2%	3%	Yes	Yes	-0.05	-0.05
		2%	Yes	Yes	-0.04	-0.04
		1%	Yes	Yes	-0.03	-0.03
	1%	3%	Yes	Yes	-0.03	-0.03
		2%	Yes	Yes	-0.02	-0.02
		1%	Yes	Yes	-0.01	-0.01
2.00%	2%	3%	No	No	0.01	0.02
		2%	No	No	0.01	0.02
		1%	No	No	0.02	0.02
	1%	3%	No	No	0.02	0.02
		2%	No	No	0.03	0.02
		1%	No	No	0.03	0.02
1.50%	2%	3%	No	No	0.05	0.04
		2%	No	No	0.04	0.04
		1%	No	No	0.04	0.04
	1%	3%	No	No	0.06	0.06
		2%	No	No	0.07	0.08
		1%	No	No	0.07	0.08

Table 5.8: Ground Clearance of the DST Lowboy Vehicle at Various Grades of Symmetric Double-Lane Roundabout with 3-inch Truck Apron Height and Approach Roadway Sloping away from the Roundabout

Crossslope of circulatory roadway	Crossslope of truck apron	Slope of approaches for the roundabout	Ground clearance problem exists (Yes/No)		Lowest Ground Ground Clearance (ft)	
			Through turn	Left turn	Through turn	Left turn
3.00%	2%	3%	Yes	Yes	-0.12	-0.13
		2%	Yes	Yes	-0.11	-0.12
		1%	Yes	Yes	-0.08	-0.08
	1%	3%	Yes	Yes	-0.07	-0.07
		2%	Yes	Yes	-0.06	-0.07
		1%	Yes	Yes	-0.05	-0.06
2.50%	2%	3%	Yes	Yes	-0.05	-0.05
		2%	Yes	Yes	-0.04	-0.04
		1%	Yes	Yes	-0.03	-0.03
	1%	3%	Yes	Yes	-0.03	-0.03
		2%	Yes	Yes	-0.02	-0.02
		1%	Yes	Yes	-0.01	-0.01
2.00%	2%	3%	No	No	0.02	0.03
		2%	No	No	0.01	0.02
		1%	No	No	0.02	0.02
	1%	3%	No	No	0.03	0.01
		2%	No	No	0.03	0.02
		1%	No	No	0.03	0.02
1.50%	2%	3%	No	No	0.05	0.04
		2%	No	No	0.04	0.04
		1%	No	No	0.04	0.04
	1%	3%	No	No	0.06	0.06
		2%	No	No	0.07	0.08
		1%	No	No	0.08	0.09

Chapter 6 - Integrating Roundabouts in Freight Networks

A 2004 FHWA report estimated that about 40 percent of traffic congestion in general, as opposed to freight congestion specifically, is caused by bottlenecks, resulting in stop-and-go traffic flow and long backups (*7*). A recent study conducted by FHWA has shown that freight bottlenecks cause upwards of 243 million truck hours of delay and the direct user cost per this delay is about $7.8 billion per year (*7*). Signalized, arterial intersections account for a total of 18 percent of the delay - about 43 million hours of delay - for different freight routes comprised of urban freight corridors, intercity freight corridors, truck access routes and intermodal connectors (*7*).

There are also air pollution concerns from heavy congestion in urban areas. According to the *Freight Fact and Figures 2009 - Office of Freight Management and Operations Report* - diesel-fueled heavy trucks emit small amounts of carbon monoxide (CO) but large amounts of nitrogen oxides (NO_x) when compared to gasoline-fueled cars affecting the air quality (*8*). Freight transportation contributes to 27 percent of the total NO_x emissions and one-third of emissions of particulate matter 10 microns in diameter (PM-10) from mobile sources in US. Trucks take a two-thirds share of the NO_x emissions from the freight sector. Apart from the above emissions, the transportation sector releases large quantities of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane, nitrous oxide, and hydro fluorocarbons and these gases trap heat in the atmosphere which affects the earth's temperature. Therefore, the increase in the congestion of the trucks at urban intersections can affect the quality of air by the emissions which can be mitigated by better traffic flow techniques such as less delay at urban intersections (*8*).

The above challenges clearly show that there is a need for improving traffic flow at interchanges, intersections and other transportation facilities to better accommodate vehicles and trucks with less congestion and delay time thereby saving many dollars and improving the environment.

Therefore, the objective of this part of the dissertation study is to investigate hypothetically (since no before/after comparisons are possible), with available software , integrating the greater use of roundabouts in freight networks in and around urban areas to optimize goods movement while enhancing air quality by decreasing air pollution due to trucks using t intersections in and around communities. In this study, this objective was addressed by selecting cities of different sizes (big city, medium city, and small city) in Kansas. Selected intersections in urban freight networks with expected high truck volumes in each city were analyzed. The different sizes of cities considered were Overland Park as a big city, Topeka as a medium sized city, and Manhattan as a small sized city. Most of the intersections in the urban freight networks were signalized intersections. Therefore, the delay and emissions of vehicles at signalized intersections that were analyzed and theoretically compared to the intersections (should roundabouts replace the existing traffic control) with roundabouts using available software capable of making comparisons of roundabouts and other types of intersection traffic control, to determine if roundabouts can improve delay and emissions at these intersections. This approach was considered valid in previous roundabout studies conducted at Kansas State University. (*11, 30*)

6.1 Objective of the Study and Work Procedure

The objective of this part of the dissertation study is to investigate integrating the greater use of roundabouts in freight road networks in and around urban areas to optimize goods movements, and decrease delay, congestion, and emissions, thus enhancing air quality in and around the communities. Most of the intersections in urban freight networks were signalized intersections and therefore the delay and emissions of vehicles at signalized intersections were analyzed and theoretically compared to a roundabout, should roundabouts be designed and built at these intersections for improving the delay and emissions.

This comparative analysis was achieved by analyzing selected intersections (signalized) in urban freight networks for intersection level of service, effective intersection capacity, control delay (average, worst lane, and worst movement), emissions (Carbon dioxide (CO2), hydrocarbons (HC), carbon monoxide (CO), and NOx), and intersection annual performance (delay and cost) and comparing them by adapting a roundabout treatment theoretically using SIDRA INTERSECTION software. SIDRA INTERSECTION is an advanced micro-analytical traffic evaluation tool used worldwide for intersection capacity, level of service, and performance analysis, and is the only software known to the author capable of making these comparisons of traditional intersection control vs. roundabouts (*31*). SIDRA INTERSECTION 5.1 version was used in this study for the performance analysis. SIDRA INTERSECTION 5.1 generates various performance measures for an intersection being analyzed and among them intersection level of service, effective intersection capacity, control delay (average, worst lane, and worst movement), emissions (Carbon dioxide (CO2), hydrocarbons (HC), carbon monoxide (CO), and NOx), and intersection annual performance (delay and cost) were considered to be compared between signalized treatment that was present with the roundabout treatment theoretically using INTERSECTION software. However, control delay, vehicular emissions, such as carbon monoxide (CO), hydro carbons (HC), carbon dioxide (CO2), and NOx, were used as performance measures to make conclusions about the most effective intersection treatment.

6.1.1 Limitations of the Study

One caveat regarding this study is that due to the limited scope of available cities and freight data, and in one case, specific traffic count data, the conclusions should not be considered universal; however, the procedure could be used anywhere and therefor, the procedure can be considered universal and, in that respect, is of greater importance. Using these procedures for analyzing the air quality impact of roundabouts and/or roundabout corridors on freight movements has never been done but should be an important tool in the future.

6.1.2 Performance Measures

Various performance measures that were generated and considered in this study are described below in detail:

6.1.2.1 Intersection Control Delay

The delay to a vehicle which decelerates from the approach cruise speed to a full stop (due to a reason such as a red signal, a queue ahead, or lack of an acceptable gap), waits and then accelerates to the exit cruise speed, is considered to include the delay due to a deceleration from the approach cruise speed down to an approach negotiation speed and then to zero speed, idling time, acceleration to an exit negotiation speed along the negotiation distance, travelling the rest of the negotiation distance (if any) at the constant exit negotiation speed, and then acceleration to the exit cruise speed (*31*). This is the sum of stop-line and geometric delays, thus it includes all deceleration and acceleration delays experienced in negotiating the intersection (*31*).

6.1.2.2 Level of Service (LOS)

SIDRA INTERSECTION output includes Level of Service (LOS) results based on the basic concept described in the US Highway Capacity Manual (HCM) (*31*). As specified by the HCM, SIDRA INTERSECTION uses the *average control delay* as the LOS measure for vehicles at signalised and un-signalised intersections (*31*).

Figure 6.1: HCM Method of Level of Service Based on Vehicle Delay

Level of Service	Control delay per vehicle in seconds (d)		
	Signals (*SIDRA standard default for roundabouts*)	"SIDRA Roundabout LOS" option	Sign Control
A	d ≤ 10	d ≤ 10	d ≤ 10
B	10 < d ≤ 20	10 < d ≤ 20	10 < d ≤ 15
C	20 < d ≤ 35	20 < d ≤ 35	15 < d ≤ 25
D	35 < d ≤ 55	35 < d ≤ 50	25 < d ≤ 35
E	55 < d ≤ 80	50 < d ≤ 70	35 < d ≤ 50
F	80 < d	70 < d	50 < d

Source: SIDRA INTERSECTION User Guide (*31*)

6.1.2.3 Effective Intersection Capacity

An aggregate measure of intersection capacity is determined as the ratio of total intersection demand flow to the intersection degree of saturation, where the intersection degree of saturation is the largest lane degree of saturation considering all lanes of the intersection (*31*).

6.1.2.4 Cost

The operating cost estimates include (*31*):

(i) the direct vehicle operating cost (the resource cost of fuel and additional running costs including tyre, oil, repair and maintenance as a factor of the cost of fuel), and (ii) the time cost to driver and passengers.

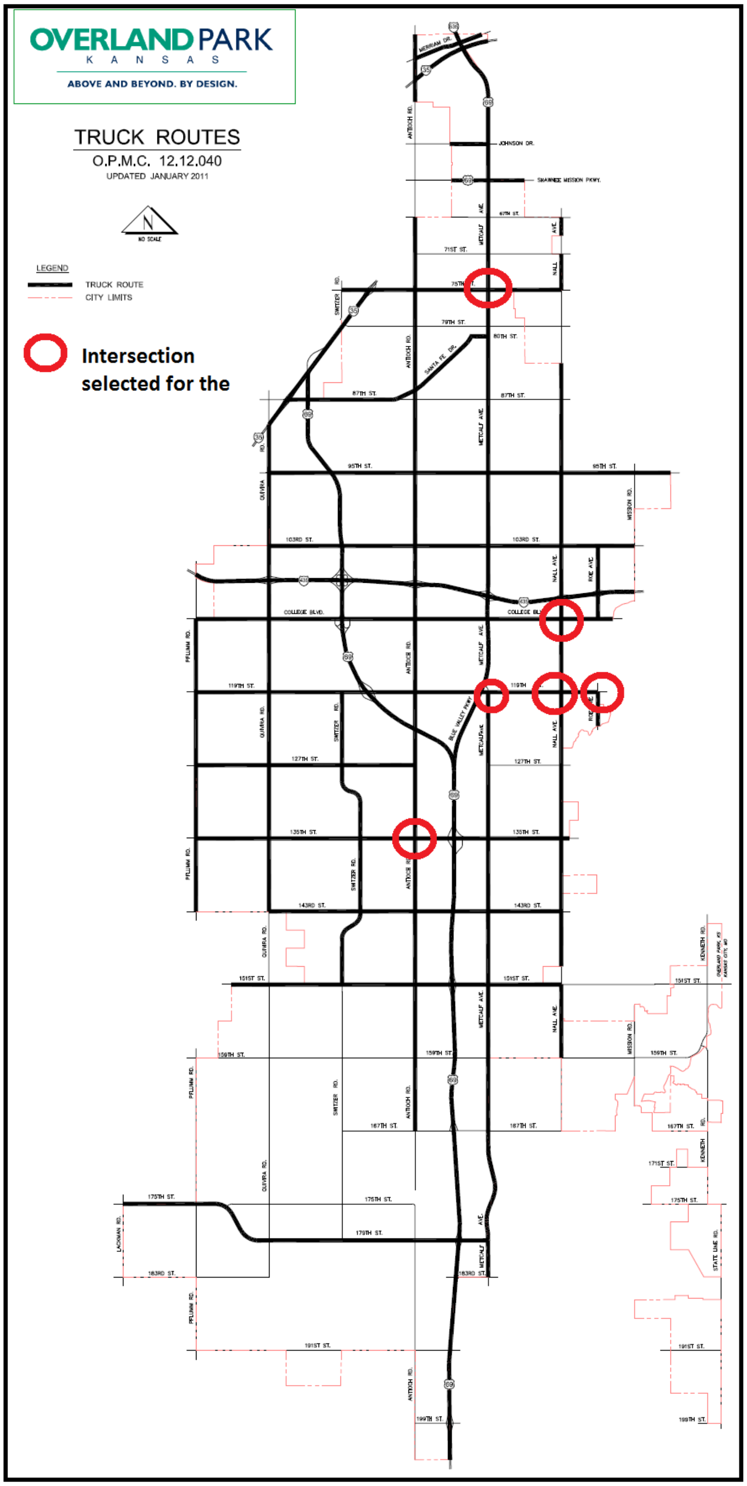
To analyze the performance of an intersection using SIDRA INTERSECTION software, data such as traffic turning counts for each leg of an intersection for 1 hour, peak hour factor, percentage of trucks using the intersection, lane geometry of the intersection, and signal phasing and phase times of the intersection was required.

This study was conducted by selecting cities of different sizes such as big city, medium city, and small city in Kansas. The different sizes of cities considered were: Overland Park as a big city, Topeka as a medium city, and Manhattan as a small sized city. City officials in each city were contacted to obtain the freight roadway networks (if available) or routes that have a lot of trucking activity. Based on the routes obtained that had a lot of trucking activity, and data on trucks usage, intersections were selected that have higher truck usage, and also, have reliable data for conducting performance analysis in SIDRA INTERSECTION software.

City of Overland Park has a freight network developed and is shown in Figure 6.2. Based on the discussions with the city traffic engineer for Overland Park, Mr. Brian Shields, and based on the traffic data availability from the city for this study, six intersections (shown in Figure 6.2) were decided to be studied for performance comparison between the signalized intersection that was present and roundabout treatment theoretically using SIDRA INTERSECTION software.

City of Manhattan and City of Topeka do not have a developed freight roadway network to identify the roads that were used by trucks. However, the staff of the City of Manhattan traffic engineering office were helpful in selecting intersections with high truck traffic and providing peak hour traffic data for six intersections that were selected to be studied. There was no input from City of Topeka regarding selecting the intersections with high truck traffic. However, traffic counts for five major intersections in Topeka were obtained from Mr. Dean Landman and Dr. Eugene Russell from their recent previous studies to be used in this study (*32*).
The intersection analysis for selected intersections in each city will be described in next sections in detail.

Figure 6.2: Map showing Overland Park Truck Routes and Intersections Selected for the Study



Source: City of Overland Park website (*33*)

6.1.3 Manhattan (Small City)

City of Manhattan was selected as a small city category of this study in Kansas. Traffic engineers from City of Manhattan office were contacted to get the list of intersections which expect a lot of truck traffic and at the same time have intersection count data available with percentage of trucks using the intersection. Their staff was helpful to shortlist six intersections which expect a lot of truck traffic and have the intersection traffic counts available. However, the intersection traffic counts were obtained as total number of vehicles entering the intersection for every 15 minutes and the percentage of trucks using the intersection was unknown. The obtained traffic data set was found to not be useful for conducting an analysis in SIDRA INTERSECTION software, as it needs directional traffic counts (number of left turn vehicles, through movement vehicles, and left turning vehicles) for each leg for 1 hour, peak hour factor, signal phasing and timing, and percentage of trucks using the intersection. However, the obtained traffic counts were used to identify the peak hour volume and therefore able to calculate the peak hour factor. In addition, manual traffic data counts were made on site at all the selected six intersections to get the directional traffic counts for all the legs, percentage of trucks using the intersections, and signal phasing and timing. The lane geometry of the intersection was precisely measured from Google maps. The 6 intersection selected for this study in Manhattan are:

1) Fort Riley Blvd & Richards Rd
2) McCall Rd & Hays Dr
3) McCall Rd & Carlson Rd
4) Seth Childs Rd & Southwind
5) Tutle Creek Blvd & Kimball
6) Tutle Creek Blvd & McCall Rd

The intersection treatment at all the six intersections was “signalized treatment”. Using the available data, SIDRA INTERSECTION software was used to perform an intersection analysis for the signalized treatment vs the proposed roundabout treatments.

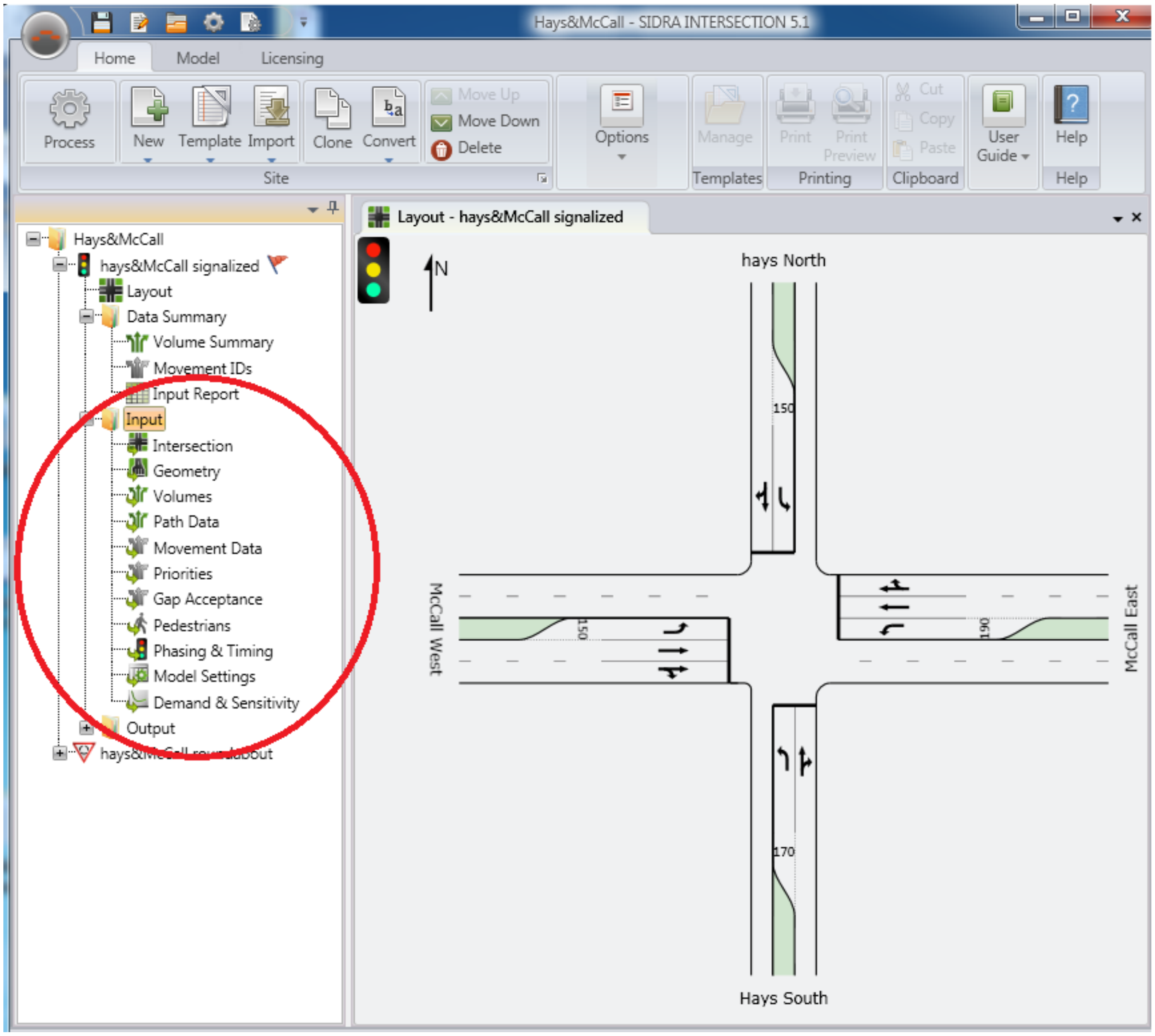
6.1.3.1 SIDRA INTERSECTION Analysis

The intersection analysis procedure will be described using an example analysis for the intersection “McCall Road & Hays Drive”.

6.1.3.2 Example Intersection Analysis

The directional traffic counts and truck counts for the intersection McCall Road & Hays Drive were counted manually on site and used an input in the SIDRA INTERSECTION software.

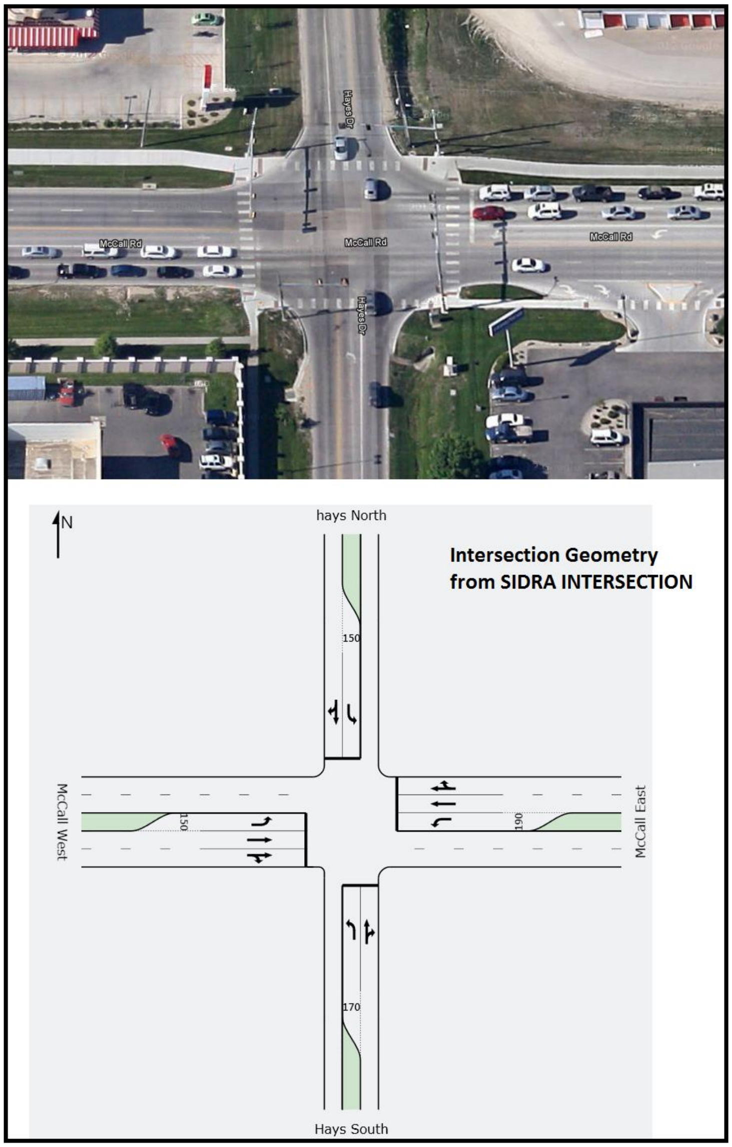
Figure 6.3: SIDRA INTERSECTIONS Working Interface



The input panel in the SIDRA INTERSECTION software has various input options as shown in Figure 6.3. The 'Intersection' tab in the input panel was used to enter the intersection name and signal analysis method (actuated or fixed/pre-timed). The 'Geometry' tab was used to construct the geometry of the intersection by specifying the number of lanes, their lane length, and lane configuration for each leg of the roundabout. Figure 6.4 shows the Google map of the

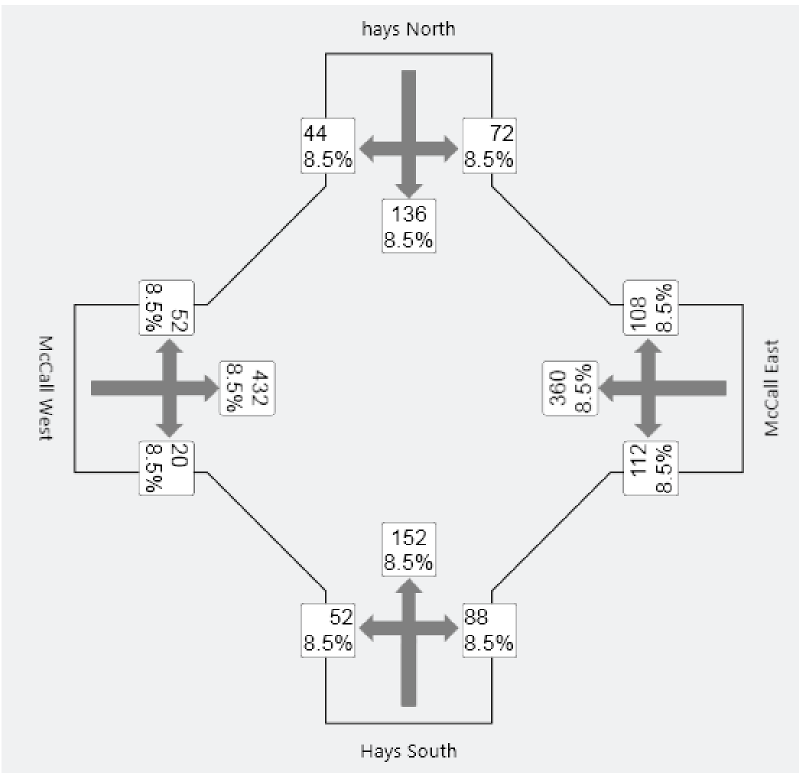
McCall Road & Hays Drive intersection and intersection geometry developed in SIDRA INTERSECTION software.

Figure 6.4: McCall Road & Hays Drive Intersection from Google Maps and Geometry Generated from SIDRA INTERSECTIONS



The ‘Volume’ tab was used to enter the left turn, through and right turn movement vehicle volumes for each leg for 1 hour, peak hour factor, and percentage of trucks using the intersection. Figure 6.5 shows the intersection vehicle volume summary and truck percentages for 1 hour that were the manual traffic counts conducted from the site. The ‘Path Data’ tab was used to enter the approach cruise speed and exit cruise speed observed from the site. ‘Movement Data’ tab was used to enter the queue space for normal vehicle (a standard of 25 ft was assumed this study in), queue space for heavy vehicle (truck) (a standard of 73 ft was assumed in this study), vehicle length of normal vehicle (a standard of 17 ft was assumed in this study), and vehicle length of heavy vehicle (a standard of 73 ft was assumed in this study). SIDRA INTERSECTION default values were assumed for the remaining other minor parameters. Signal phasing and timing was again designed in the software similar to the phasing and timing on site. The output for signalized intersection performance was generated and is presented in Table 6.1.

Figure 6.5: Intersection Traffic Counts and Truck Percentages for McCall Road & Hays Drive

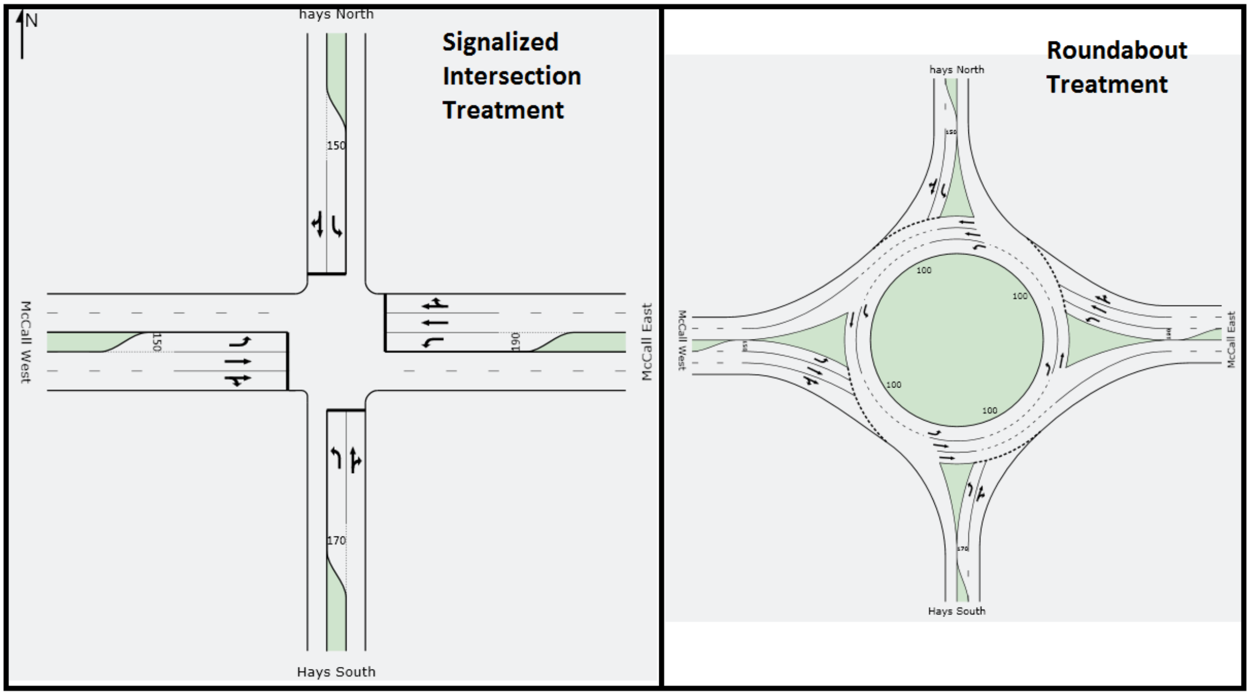


Similar intersection traffic counts, percentage of trucks, and all other parameters (except the signal phasing and timing) mentioned above were used to construct a roundabout at the intersection using SIDRA INTERSECTION software. A center island diameter of 100 ft, entry radius of 100 ft, and entry angle of 30 degrees, was used to construct the roundabout. The number of circulating lanes was determined based on the number of left turn and through turn lanes for each approach. Also, roundabouts with more than three circulating lanes were not considered in this study. The roundabout generated at the McCall Road & Hays Drive intersection was analyzed using SIDRA INTERSECTION software for the performance measures discussed above and were presented in Table 6.1. Figure 6.6 shows the signalized intersection geometry and roundabout geometry at the intersection McCall Road & Hays Drive generated using the software.

6.1.3.2.1 Example Intersection (McCall Road & Hays Drive) SIDRA INTERSECTION analysis results

It can be observed from Table 6.1 that the LOS of the intersection was improved by adapting a roundabout treatment (LOS A) when compared to signalized intersection (LOS C) that was already present. The average control delay was decreased by 71.2% ((25.7-7.4)/25.7), worst lane control delay was decreased by 79.2%, and worst movement control delay was decreased by 78.6% with a roundabout treatment compared to signalized treatment. Table 6.1 also proves that the CO_2, HC, CO, and NO_x emissions were also decreased by adapting a roundabout treatment. It was also observed from SIDRA results that the intersection annual delay was decreased by 6,443 veh-h/y (9,040-2597) and annual intersection cost (vehicle operating cost and time cost to drivers and passengers) was decreased by $94,078 by using a roundabout treatment instead of a signalized treatment at the McCall Road & Hays Drive intersection.

Figure 6.6: Signalized Intersection Geometry and Roundabout Geometry at the Intersection McCall Road & Hays Drive Generated using SIDRA INTERSECTION



A similar intersection analysis was performed for all the remaining five intersections by testing the effectiveness of "signalized treatment" and "roundabout treatment" and the results were presented in Table 6.1. It can be observed from Table 6.1 that, for all the six intersections that were studied in Manhattan, the roundabout treatment proved to be having better LOS, less control delay, less emissions, and better annual performance when compared to the signalized treatment.

Table 6.1: Performance Measures of Selected Intersections in Manhattan for Signalized and Roundabout Treatment Generated using SIDRA INTERSECTIONS

Intersection, Truck %	Intersection Treatment	Apprach No. of Lanes Decreased for Roundabout	Intersection LOS	Effective Intersection Capacity (veh/hr)	Control Delay (seconds/vehicle)			Emissions (kg/h)				Intersection Annual Performance	
					Average	Worst Lane	Worst Movement	CO2	Hydro carbons	CO	NOx	Delay (veh-h/y)	Cost ($/y)
Fort Riley Blvd & Richards Rd, 5.7%	Signalized		C	2916	25.7	70.6	70.6	577.7	0.933	43.15	1.355	9,040	432,088
	Roundabout	Yes	A	5727	7.4	14.7	15.1	509.8	0.783	39.39	1.253	2,597	338,010
McCall Rd & Hays Dr, 8.5%	Signalized		C	1711	32	86.7	86.7	408	0.651	29.19	0.911	7,548	319,484
	Roundabout	No	A	4895	7.6	16.3	16.3	351.1	0.523	26.46	0.836	1,802	234,757
McCall Rd & Carlson Rd, 4.6%	Signalized		B	3229	13.7	25.3	25.3	191.5	0.305	14.56	0.46	1,741	134,433
	Roundabout	No	A	6531	6.5	13.3	13.3	176.3	0.271	13.28	0.428	829	117,662
Seth Childs Rd & Southwind, 4.3%	Signalized		D	3948	40.2	64	64	862.1	1.478	64.52	1.948	19,891	713,632
	Roundabout	Yes	A	6347	9.4	17.1	17.1	704.6	1.12	55.76	1.727	4,662	482,394
Tutle Creek Blvd & Kimball, 6.6%	Signalized		B	3062	17.2	37.4	37.4	479.6	0.777	38.73	1.182	4,858	333,376
	Roundabout	Yes	B	2919	10.8	17.5	17.5	456	0.713	37.84	1.166	3,061	292,332
Tutle Creek Blvd & McCall Rd, 8.7%	Signalized		B	3088	15.8	28.6	28.6	404.1	0.63	27.58	0.827	4,563	327,388
	Roundabout	Yes	A	5487	6.3	10.7	10.7	367.3	0.54	24.22	0.749	1,807	279,811

Table 6.2: Performance Measures of Selected Intersections in Topeka for Signalized and Roundabout Treatment Generated using SIDRA INTERSECTIONS

Intersection, Truck %	Intersection Treatment	Apprach No. of Lanes Decreased for Roundabout	Intersection LOS	Effective Intersection Capacity (veh/hr)	Control Delay (seconds/vehicle)			Emissions (kg/h)				Intersection Annual Performance	
					Average	Worst Lane	Worst Movement	CO2	Hydro carbons	CO	NOx	Delay (veh-h/y)	Cost ($/y)
SW Wanamaker & Huntoon, 5%	Signalized		C	4084	29.2	68.6	54.8	953.5	1.601	75.67	2.294	15,919	716,747
	Roundabout	No	B	5120	11.8	19	19	847.3	1.348	69.39	2.143	6,420	560,171
SW Wanamaker & SW Winding, 5%	Signalized		C	3443	33.7	78.2	78.2	786.6	1.378	61.54	1.844	15,830	630,998
	Roundabout	No	B	4659	13	20.9	20.9	682.7	1.134	55.67	1.703	6,122	474,474
SW Wanamaker & Westridge Mall, 5%	Signalized		B	3918	11.3	21.2	21.2	518.6	0.82	40.62	1.283	3,853	349,141
	Roundabout	No	A	6084	7.4	15.4	16.6	492.3	0.762	38.38	1.226	2,515	322,484
Wanamaker & 17th St, 5%	Signalized		C	3966	29.8	49.2	49.2	745.2	1.246	58.95	1.794	12,654	560,257
	Roundabout	Yes	B	4713	11.6	17.9	21	662.1	1.055	54.66	1.684	4,926	435,638
Wanamaker & 19th St, 5%	Signalized		C	2671	30.3	114.1	114.1	657.2	1.099	52.44	1.59	11,234	492,154
	Roundabout	No	A	6119	8.8	20.1	20.1	556.5	0.873	44.65	1.401	3,265	364,537

Table 6.3: Performance Measures of Selected Intersections in Overland Park for Signalized and Roundabout Treatment Generated using SIDRA INTERSECTIONS

Intersection, Truck %	Intersection Treatment	Apprach No. of Lanes Decreased for Roundabout	Intersection LOS	Effective Intersection Capacity (veh/hr)	Control Delay (seconds/vehicle)			Emissions (kg/h)				Intersection Annual Performance	
					Average	Worst Lane	Worst Movement	CO2	Hydro carbons	CO	NOx	Delay (veh-h/y)	Cost ($/y)
Antioch & 135, 2%	Signalized		E	4814	66.4	156.5	156.5	1518.5	2.777	111.44	3.3	51,766	1,391,678
	4 Lane Roundabout	Yes	B	6782	16.1	34.9	34.9	1165.3	1.951	95.93	2.913	12,528	818,506
	3 Lane Roundabout	Yes	D	4767	53.4	134.6	135.1	1440.4	2.584	111.82	3.285	41,629	123,731
Metcalf & 75, 2%	Signalized		F	5040	158.5	213.9	213.8	2398.3	4.708	150.61	4.379	140,362	2,732,601
	Roundabout	No	F	4272	130.8	271.8	270.5	2222.5	4.289	152.64	4.376	115,808	2,361,954
Nall & 119, 2%	Signalized		F	4256	136.9	314.2	314.2	2296	4.462	150.74	4.378	123,712	2,500,024
	Roundabout	Yes	F	4546	114.7	244.1	242.8	2149.1	4.102	151.47	4.439	103,624	2,209,390
Nall & College Blvd, 2%	Signalized		E	6308	73.2	121.4	121.4	2003.9	3.702	150.72	4.379	71,590	1,846,954
	4 Lane Roundabout	Yes	E	5136	77.4	207.7	207.1	2009.7	3.701	148.42	4.337	75,615	1,882,241
	3 Lane Roundabout	Yes	F	3634	202.4	470.3	469.6	3053.8	6.122	195.26	5.492	197,777	3,586,945
Roe & 119, 2%	Signalized		E	4046	74.7	123.2	123.2	1209.5	2.225	85.55	2.559	45,299	1,146,175
	3 lane Roundabout	Yes	B	4745	16.2	32.3	30.3	907.7	1.519	74.45	2.261	9,795	639,893
Metcalf & 119, 2%	Signalized		E	4976	60.7	192.8	163.2	1459	2.623	101.32	3.118	48,330	1,338,656
	3 lane Roundabout	Yes	D	5348	38.8	109.8	109.1	1370.6	2.406	109.33	3.237	30,898	1,100,765

6.1.4 Topeka (Medium City)

City of Topeka was selected as a medium city category of this study in Kansas. Traffic engineers from City of Topeka office were contacted to get the list of intersections which expect a lot of truck traffic and at the same time have intersection count data available with percentage of trucks using the intersection. There was no input from the officials regarding selecting sites, traffic counts, and percentage of trucks. However, traffic counts for five major intersections in Topeka were obtained from Mr. Dean Landman and Dr. Eugene Russell from their previous studies (*32*). These 5 intersections with their traffic counts were used for this study assuming five percent of total traffic are trucks. The five intersection selected for this study in Topeka are:

1) SW Wanamaker & Huntoon
2) SW Wanamaker & SW Winding
3) SW Wanamaker & Westridge Mall
4) Wanamaker & 17^{th} St
5) Wanamaker & 19^{th} St

The intersection treatment existing at all the five intersections was “signalized treatment”. Using the available data, SIDRA INTERSECTION software was used to perform intersection analysis (as shown in section 6.1.3.2) for the signalized treatment and proposed “roundabout treatment”.

6.1.4.1 Intersection Analysis Results

Intersection analysis was performed for all the five selected intersections by testing the effectiveness of signalized treatment vs roundabout treatment and the results were presented in Table 6.2. It can be observed from Table 6.2 that, for all the five intersections that were studied in Topeka, roundabout treatment proved to have a better LOS, less control delay, less emissions, and better annual performance when compared to the signalized treatment.

6.1.5 Overland Park (Big City)

City of Overland Park was selected as the big city category of this study in Kansas. Traffic engineers from City of Topeka office were contacted to get the list of intersections which expect a lot of truck traffic and at the same time have intersection count data available with percentage of trucks using the intersection. Mr. Brian Shields, traffic engineer for the city of

Overland Park was helpful in selecting six intersections for the study and provided traffic counts required for the study. A truck percentage of two percent trucks was also suggested for the selected intersections. The six intersections selected for this study in Overland Park were:

:

1) Antioch & 135th
2) Metcalf & 75th
3) Nall & 119th
4) Nall & College Blvd
5) Roe & 119
6) Metcalf & 119

The existing intersection treatment at all the six intersections was signalized treatment. Using the available data, SIDRA INTERSECTION software was used to perform intersection analysis (as shown in section 6.1.3.1) for the signalized treatment vs proposed roundabout treatment.

6.1.5.1 Intersection Analysis Results

Intersection analysis was performed for all the six selected intersections by testing the effectiveness of signalized treatment and roundabout treatment and the results were presented in Table 6.3. It was observed from six selected intersections in Overland Park that the intersection geometry that was present would require of designing four-lane or five-lane roundabouts which the author considered to be not practical at this point in time in the US. Therefore, in such situations, four- lane roundabouts, albeit of questionable practicality and unknown validity of the software models) and three- lane roundabouts were constructed and their performance was measured and compared with signalized intersections. It can be observed from Table 6.3 that, for all the six intersections that were studied in Overland Park, roundabout treatment was overall seemed to have similar performance measures like the signalized treatment. Also, there is no evidence of more than three- lane roundabouts that were constructed in the US at this point in time, and therefore, the huge roundabout designs generated at an Overland Park intersection may not be feasible,. and the results may be questionable and may not apply where more than a three- lane roundabout is theoretically needed.

6.2 Statistical Analysis for Testing Various Performance Measures for Signalized and Roundabout Intersection Treatment in Urban Freight Networks: Randomized Complete Block Design

Blocking is a technique to have precise comparison among treatments and it is a way to reduce and control experimental error and variance (*34*). The simplest of a blocking design is a randomized complete block design experiment (*34*). The experimental units are stratified into blocks of homogeneous units. Each treatment is randomly assigned to an equal number of experimental units in each block such that precise comparison among the treatments can be made within the experimental units (*34*).

The objective of this analysis was to analyze the performance of signalized and roundabout intersection treatments in various sized cities and suggest the best treatment to be used on urban freight networks. This objective was achieved by testing performance measures such as average control delay, and vehicular emissions such as CO, HC, CO2, and NOx for signalized and roundabout treatments for all the selected cities.

The randomized complete block design was conducted for selected the intersections that were described above, in city of Manhattan, city of Topeka, and City of Overland Park. Figure 6.7, Figure 6.8, and Figure 6.9 shows the randomized complete block design layout for these selected intersections in Manhattan, Topeka, and Overland Park. The selected intersections in each city were used as blocks, such that any difference in the responses (control delay or emissions) caused by specific intersection treatment can be associated with the blocks. For example, from Figure 6.7 it can be understood that we have a randomized complete block design with six random blocks (intersections) of two treatments each. SIDRA INTERSECTION software was used to calculate the response variables based on characteristics of each selected intersection for this design layout. The design layout in Figure 6.7, Figure 6.8, and Figure 6.9 were used multiple times to conduct statistical analysis with various response variables such as control deal, CO emissions, HC emissions, CO2 emissions, and NOx emissions.

Figure 6.7: Randomized Complete Block Design Layout for Manhattan Intersections

- **For Manhattan**

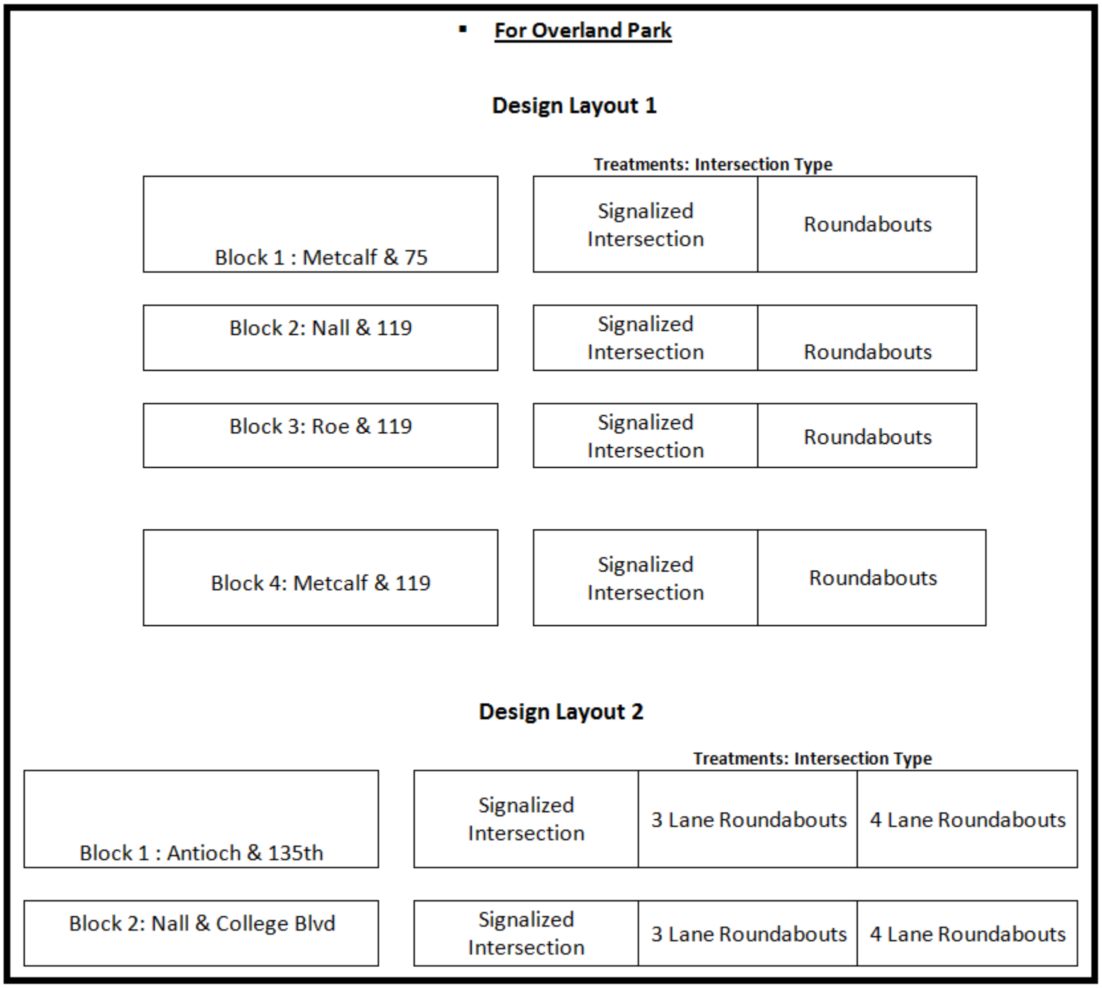
	Treatments: Intersection Type	
Block 1 : Fort Riley Blvd & Richards Rd	Signalized Intersection	Roundabouts
Block 2: McCall Rd & Hays Dr	Signalized Intersection	Roundabouts
Block 3: McCall Rd & Carlson Rd	Signalized Intersection	Roundabouts
Block 4: Seth Childs Rd & Southwind	Signalized Intersection	Roundabouts
Block 5: Tuttle Creek Blvd & Kimball	Signalized Intersection	Roundabouts
Block 6: Tuttle Creek Blvd & McCall Rd	Signalized Intersection	Roundabouts

Figure 6.8: Randomized Complete Block Design Layout for Topeka Intersections

- **For Topeka**

	Treatments: Intersection Type	
Block 1 : SW Wanamaker & Huntoon	Signalized Intersection	Roundabouts
Block 2: SW Wanamaker & SW Winding	Signalized Intersection	Roundabouts
Block 3: SW Wanamaker & Westridge Mall	Signalized Intersection	Roundabouts
Block 4: Wanamaker & 17th St	Signalized Intersection	Roundabouts
Block 5: Wanamaker & 19th St	Signalized Intersection	Roundabouts

Figure 6.9: Randomized Complete Block Design Layout for Overland Park Intersections



Statistical Model for the Randomized Complete Blocks (*34*):

The linear model for this study can be written as

$$Y_{ij}=\mu+\tau_i+b_j+e_{ij} \quad \text{where } i=1.,.,t \text{ and } j=1,2\ldots..b$$

- Y_{ij} is the observed response (for example: observed control delay (in seconds/vehicle)), for the i^{th} intersection type with respect to the j^{th} intersection.
- μ is the overall mean response (For example: Overall mean control delay measured in seconds/vehicle).
- τ_i is the fixed effect of i^{th} intersection type on the response

- The random block effect b_j represents the effect of intersection j on the response, with mean 0 and variance $\sigma^2_{b.}$
- e_{ij} is the experimental error which are independently and identically distributed(IID) as a Normal distribution with mean 0 and variance σ^2.

Assumptions:

- The treatment type effects (signalized and roundabout) and random block effects (intersection effects) are assumed to be additive i.e. It is assumed there is no interaction between the intersection treatment types and Intersections.

6.3 Results

The results from the hypothesis testing is summarized in Table 6.4 to 6.6. By examining Table's 6.1- 6.6, it can be concluded that the roundabout treatment performed better for decreasing the delay and improving the air quality when compared to the signalized treatment in small cities and medium cities, although results were inconclusive in the large city intersections, as discussed in section 6.1.5.1 Also statistical significant results were observed for decreased delay, and decreased emissions (CO, HC, CO2, and NOx) when theoretically implementing a roundabout treatment in freight networks of small and medium cities. Therefore, it can be concluded that the process developed and used in this chapter should be an important tool to plan and develop freight networks that minimize the effects of congestion and air pollution. Also, although of limited universal application, using a series of roundabouts on freight routes, or routes with a large number of trucks, is something the author believes has never been studied and/or published, the local results show that the roundabouts in small and medium cities freight networks in Kansas can reduce delay to the drivers, thereby decreasing congestion and improve the flow of traffic. It can also be concluded that the emissions were also decreased by implementing a roundabout treatment in small and medium cities', urban, freight intersections, leading towards a better environment. In big city urban freight networks, roundabout treatment did not yield a statistically significant results to prove that they decrease emissions when compared to signalized treatments; however, these results were based on a small study with limited data and should not be considered to be transferable to general applications. The author believes the procedure developed is an important tool available for studies with larger scope and more extensive and reliable data and/or improved computer models. Considering the limitations, the following results are presented.

Table 6.4: Randomized Complete Block Design Results for Manhattan Intersections

Manhattan Intersections: Statistical Significance of Various Performance Measures by Adapting a Roundabout Treatment	
Performance Measure	**Randomized Complete Block Design results**
Average Control Delay	Statistical significant reduction of average control delay was observed with a roundabout treatment
CO2 Emissions	Statistical significant reduction of CO2 emissions were observed
HC Emissions	Statistical significant reduction of HC emissions were observed
CO Emissions	Statistical significant reduction of CO emissions were observed
NOx	Statistical significant reduction of NOx emissions were observed

Table 6.5: Randomized Complete Block Design Results for Topeka Intersections

Topeka Intersections: Statistical Significance of Various Performance Measures by Adapting a Roundabout Treatment	
Performance Measure	**Randomized Complete Block Design results**
Average Control Delay	Statistical significant reduction of average control delay was observed with a roundabout treatment
CO2 Emissions	Statistical significant reduction of CO2 emissions were observed
HC Emissions	Statistical significant reduction of HC emissions were observed
CO Emissions	Statistical significant reduction of CO emissions were observed
NOx	Statistical significant reduction of NOx emissions were observed

Table 6.6: Randomized Complete Block Design Results for Overland Park Intersections

Overland Park Intersections: Statistical Significance of Various Performance Measures by Adapting a Roundabout Treatment	
Performance Measure	**Randomized Complete Block Design results**
Average Control Delay	Statistical significant reduction of average control delay was observed with a roundabout treatment
CO2 Emissions	Statistical significant reduction of CO2 emissions were **not** observed
HC Emissions	Statistical significant reduction of HC emissions were **not** observed
CO Emissions	Statistical significant reduction of CO emissions were **not** observed
NOx	Statistical significant reduction of NOx emissions were **not** observed

This study was to illustrate a procedure to check if the roundabouts will operate better on urban freight networks to improve flow and decrease emissions. Although the results obtained from this study might not be applicable for other state freight networks, a more extensive study could be performed to better understand the benefits of integrating the roundabouts in urban freight networks.

One limitation of the software used in this study is that the emissions from trucks could not be analyzed separately to precisely check the truck emissions at signalized intersections and intersection with a roundabout treatment. However, the next version of SIDRA INTERSECTION software will analyze emissions separately for normal vehicles and trucks (*35*). The procedure mentioned in this study might be adapted with the next version of SIDRA INTERSECTION software to get better results to check the truck emissions for various intersection treatments

Chapter 7 - Summary and Conclusions

There is no knowledge if roundabouts can be accommodated at rural intersections which expect oversize overweight (OSOW) vehicles infrequently and, if expected, there are no guidelines available to design the geometry and vertical profile of the roundabout to safely and effectively accommodate OSOW movements, and at the same time prove to be safer for the remaining road users. This study has addressed all known issues that bigger trucks and OSOW vehicles face at roundabouts, as determined by the literature search and personal contacts with designers and four surveys conducted as part of this study.

From the literature review of accommodating trucks at roundabouts, it was found by using available, accepted software, that larger trucks can be accommodated at roundabouts by providing a fully traversable center island, widened entry and exit lanes, providing wider truck aprons, gated through lanes, lane striping and other procedures.

There are many studies that concluded that roundabouts are advantageous over signalized and stop controlled intersection treatments, providing better overall safety performance, reduced intersection injury crashes and fatalities, lower delays, shorter queues, and providing better management of speed and opportunities for community enhancement. However, there are very few studies that have addressed designing roundabouts for truck traffic and no published studies were found addressing accommodation of OSOW at roundabouts. Also, no published study could be found that addressed the integration of roundabouts in states' urban freight networks to reduce delay and congestion and improve air quality by reducing emissions.

7.1 Survey Results with US State Officials

Four surveys were conducted to obtain valuable information regarding accommodating OSOW vehicles at roundabouts (*1*). Survey 1 was conducted with 50 US States and among the 37 responding states, it was concluded that among various physical obstructions for OSOW loads on their roads, the order for seriousness of the obstructions are bridges, overhead structures, signs and signals, intersections, interchanges, rail-highway grade crossings, utilities, overhead wires, roundabouts, curbs, and raised channelization. It has been observed that roundabouts were the 9th most reported restriction for OSOW loads among the 11 possible obstructions listed above, concluding that they are not the most serious problem for OSOW loads, as many perceive.

From survey 2 responses, the most mentioned concerns for permit loads at roundabouts that create major disruption of traffic flow and create a problem are lowboy vehicles having ground clearance problems with curbs more than three inches in height, OSOW vehicles riding up on the curb on the exterior of the roundabout, trucks requiring to stay in lanes in the approaches and/or in the roundabout, fixed object within the center island of the roundabout creating problems, roundabouts with tight radii, long loads, and trucks not using truck aprons. The mitigation strategies that were suggested by the survey 2 respondents to overcome these above concerns are installing wide truck aprons with minimum slope and mountable curbing, custom center island shape to accommodate any specific (through or left turn movements) OSOW movements, provide paved area behind curb (external truck apron), install removable signage to get rid of permanent fixtures, build truck tire friendly medians such that trucks can cross over the median, and build larger roundabouts to accommodate larger vehicles. All the accommodating strategies that were suggested were considered in this study when appropriate for designing roundabouts for larger trucks at urban intersections and for OSOW vehicles at rural intersections.

7.2 Survey Results with OSOW Haulers

Most (88.9%) of the OSOW haulers responded to surveys 3 and 4 felt that roundabouts are more of a problem compared with other intersections. Similarly, most (83.3%) of the OSOW haulers responded that roundabouts are more of a problem that other highway features, which may be a concern to oversize/overweight loads; such as, narrow bridges, wires, curbs, ramps, and so forth. These results does not match with the results from the survey of US state officials who mentioned roundabouts that roundabouts were the 9th most reported restriction for OSOW loads among 11 possible restrictions. It can be concluded that there is less coordination between the US state officials and OSOW haulers regarding understanding of the roundabout concerns for loads requiring a permit, which warrants better coordination between the public and private sector for better understanding the problems.

Most OSOW haulers reported either a serious problem, or problem which is less serious, at various aspects of the roundabouts such as the approach, the circulatory roadway, and the departure. The majority (66.7%) of the OSOW hauler respondents felt that it would be somewhat or very beneficial if OSOW loads could go straight through a roundabout, if a removable barrier is in place to prevent other vehicles from doing so. Similarly, a majority, (55.6%) of the OSOW hauler respondents, felt that it would be somewhat or very beneficial if OSOW loads could go straight through a roundabout, if the pathway would be offset so the entrance would line up with the left approach (where the driver would have to move to the left lane on the approach). It was observed that 39% of the OSOW haulers responding to the survey favored removing, then replacing, highway signs, and eliminating fixed highway features, such as light poles, to help passage through a roundabout.

7.3 Guidelines to Build Statewide Freight Networks

A few relevant reports such as *Statewide Freight Plan Template*, *Western Minnesota Regional Freight Study,* and *Accommodation Oversize & Overweight Loads* were reviewed to investigate strategies, recommendations, and guidelines to build statewide freight networks for large trucks and necessary OSOW needs, and then recommend a state policy.

It was concluded from these studies that following the guidelines mentioned in the *Statewide Freight Plan Template* which strongly supports incorporating freight elements in statewide transportation planning process is a good way to start building effective state freight networks. Also, as mentioned in *Western Minnesota Regional Freight Study*, classifying the roadway network into various tiers and effectively planning for future investment at high priority roadways would be beneficial to develop freight movement and facilities where needed.

7.4 Roundabout Designs

7.4.1 Urban Roundabouts

Urban roundabout designs for each configuration (single-lane and double-lane), and for each of four roundabout types (a typical symmetric, a 3-leg roundabout, a 3-leg roundabout at a T intersection, and a typical 4-leg roundabout), were designed in this study using an American Association of State Highway and Transportation Officials (AASHTO) designation, WB-50 design vehicle and 120 ft Inscribed Circle Diameter (ICD) for a single-lane roundabout and 200 ICD for double-lane roundabout as recommended by the FHWA roundabout guide. These roundabouts were considered for design modifications where smaller design vehicles were used to design urban roundabouts but then a need for a larger WB-67 (usually used or recommended as a design vehicle on state highways) to accommodate a larger WB-67 vehicle, common when needed in urban areas. The designs were modified in such a way that when required by a WB-67 vehicle, either the internal truck apron width is, or an external truck apron is added, to provide off-tracking of the rear wheels beyond the roundabout.

Table 7.1: Summary of Designs Developed for Urban Roundabout Setting

Roundabout Type	Single-Lane Roundabout (120 ft ICD and Design Vehicle WB-50)		Double-Lane Roundabout (200 ft ICD and Design Vehicle WB-50)	
	WB-50 Accommodation	WB-67 Accommodation	WB-50 Accommodation	WB-67 Accommodation
Symmetric 3-Leg	Figure 4.1	Figure 4.4	Figure 4.15	Figure 4.17
3-Leg at T-Intersection	Figure 4.5	Figure 4.7	Figure 4.18	Figure 4.18
Symmetric 4-Leg	Figure 4.8	Figure 4.10	Figure 4.19	Figure 4.19
Symmetric 5-Leg	Figure 4.11	Figure 4.14	NA	NA

To safely accommodate a WB-67 vehicle when necessary at different types of smaller roundabouts in a single-lane roundabout configuration (when initially designed with a WB-50 design vehicle, commonly used in urban roundabout designs), it can be noted that implementation of external truck aprons, increasing the width of internal truck aprons, and providing custom center islands, were all helpful. Table 7.1 provides the summary of the designs developed for various roundabout settings in an urban environment. The width of the external truck apron and internal truck apron increases as the ICD selected for the roundabout increases. Also, it has been determined that accommodating a WB-67 vehicle at different types of roundabouts in a double-lane, roundabout configuration (when initially designed for a WB-50 design vehicle) do not need any additional space requirements as long as the WB-67 is allowed to use the two lanes on the approach, circulating roadway, and exit of the roundabout.

7.4.2 Rural Roundabouts

Rural roundabout designs for two roundabout lane configurations (single-lane and double-lane), and for each roundabout type considered (a typical symmetric 3-leg roundabout, a 3-leg roundabout at a T intersection, and a typical 4-leg roundabout), were first designed in this study using a WB-67 design vehicle and 180 ft ICD for single-lane roundabout and 220 ICD for double-lane roundabout, as recommended by the FHWA roundabout guide, then modified for a set of OSOW vehicles.

These roundabouts were considered for design modifications to accommodate the six Wisconsin DOT (WisDOT) OSOW check vehicles, developed to represent all known OSOW configurations on US highways, as shown in section 4.2.1. The original designs were modified in such a way that, when required by the six check vehicles, either the internal truck apron width is increased or an external truck apron is added to provide off tracking beyond the roundabout, or unconventional flow patterns were investigated. These six check vehicles were accommodated at the rural roundabouts in three different accommodation strategies such as normal accommodation, an opposite direction travel (ODT) accommodation strategy, and an opposite direction of travel and fully traversable center island (ODT & FTCI) and the effectiveness of each strategy was evaluated based on the truck apron area used as a surrogate for design "efficiency", i.e., accommodating OSOW while keeping the roundabout as small to maintain safety for all users, which should also generally keep costs down.

It was concluded from the study that when compared to normal accommodation of the six OSOW check vehicles, the ODT accommodation strategy reduces the need for a truck apron by 71.15% for a single-lane (refer Table 7.2), symmetric 3-leg roundabout, 41.12% for single-lane, 3-leg roundabout at a T-intersection, 38.11% at single-lane, symmetric 4-leg roundabout, 81.45% at a double-lane, symmetric 3-leg roundabout, 53.99 % for a double-lane, 3-leg roundabout at a T-intersection, 69.43% at a double-lane, symmetric 4 leg roundabout. Similarly, when compared to normal accommodation of the six OSOW check vehicles, ODT & FTCI accommodation strategies reduce the need for truck aprons by 61.67% for a single-lane, symmetric 3-leg roundabout, 38.22% for a single-lane, 3-leg roundabout at a T-intersection, 43.04% at a single-lane, symmetric 4-leg roundabout, 45.93 % for a double-lane, 3-leg roundabout at a T-intersection, 66.77% at a double-lane, symmetric 4-leg roundabout.

Table 7.2: Total Truck Apron Reduced by ODT, and ODT & FTCI Method

Category of Roundabout	Total Truck Apron Area	
	% of Total Truck Apron Area Decreased by Accommodation of OSOW Vehicles by ODT compared to Normal Accommodation	% of Total Truck Apron Area Decreased by Accommodation of OSOW Vehicles by ODT & FTCI compared to Normal Accommodation
Single-Lane Typical Symmetric 3-Leg	71.15%	61.67%
Single-Lane 3-Leg at T Intersection	41.12%	38.22%
Single-Lane Typical 4-Leg	38.11%	43.04%
Double-Lane Typical Symmetric 3-Leg	81.45%	N/A
Double-Lane 3-Leg at T Intersection	53.99%	45.93%
Double-Lane Typical 4-Leg	69.43%	66.77%

7.4.3 Straight Passage through the Roundabouts

When OSOW loads enter from only one or two opposite approaches and travel through, a straight through passage, it was found advantageous in reducing the need for truck apron area and paved area when compared to normal accommodations. It was also observed from survey 3 and survey 4 results that providing a straight passage through the roundabout was accepted to be either somewhat or very advantageous by majority of the OSOW haulers who responded to the survey. It was determined that accommodating the six OSOW check vehicles by providing a straight through passage at single-lane roundabout reduces the truck apron area by 66.45% and paved area by 45.47% when compared to a normal accommodation strategy. Similarly, accommodating the six OSOW check vehicles by providing a straight through passage at double-lane roundabouts reduces the truck apron area by 62.11% and the paved area by 29.64% when compared to normal accommodation strategy. Therefore, it is concluded that providing a straight through passage through the center island is advantageous when OSOW loads enter from only one or two opposite approaches and travel through. However, gates should be provided for this passage to avoid other road users from using the straight passage.

7.4 Ground Clearance Analysis

The current version of AutoTURN Pro software with 3D capability was used for this part of the study. A WisDOT developed 'DST Lowboy', specified to represent the typical low ground clearance vehicle (often referred to as "low boys") that often "hang up" on roundabouts, was used in this study to analyze various truck apron and curb heights at single-lane and double-lane roundabouts to check the ground clearance of the DST lowboy at roundabouts designed and graded by following the guidelines in the FHWA roundabout guide (NCHRP Report 672). The design consists of a cross slope of the circulatory roadway of not more than 1.5%, away from the center island, and a cross slope of the truck apron not more than 2% towards the circulatory roadway

Based on the vehicle clearance analysis, it was concluded that, a 4-inch truck apron height and a 3-inch truck apron height were not suitable for accommodating the DST lowboy vehicle at the symmetric single-lane roundabout tested. A 2-inch truck apron height was recommended for consideration at single-lane roundabouts for accommodating the DST lowboy vehicle without ground clearance problems with the given cross slopes given above. For these recommendations, approach roadway slopes of 1%, 2%, or 3%, towards the roundabout or away from the roundabout can be used. However, these values should be recalculated by following a similar procedure with then next version of TORUS is released, as the version used in this study does not have capability to design the external truck apron width or grade, which could change some results. Also, other states should verify the (WisDOT) DST lowboy is the typical low ground clearance in their state.

Based on the vehicle clearance analysis, it was concluded that a 4-inch truck apron height was not suitable for accommodating a DST lowboy vehicle at the symmetric double-lane roundabout used in this study. A 3-inch truck apron height was recommended for consideration at double-lane roundabouts for accommodating the DST lowboy vehicle without ground clearance problems when the cross slope of the circulatory roadway is not more than 2% away from the center island, and when the cross slope of the truck apron is not more than 2% towards the circulatory roadway. For these recommendations, approach roadway slopes of 1%, 2%, or

3%, towards the roundabout or away from the roundabout were used. These values should be validated by following a similar procedure with then next version of TORUS as the version used in this study does not have capability to design the external truck apron width or grade. Also, other states should verify the WisDOT DST lowboy is the typical low ground clearance in their state.

7.5 Integrating Roundabouts in Urban Freight Networks

It was concluded from this study that roundabout treatments at intersections performed better when compared to the signalized treatment for urban freight networks in small cities and medium cities. Statistical significant results were observed towards decreased delay, and decreased emissions (CO, HC, CO2, and NOx) by implementing roundabout treatments in freight networks of small and medium cities. Therefore, it was concluded that the roundabouts in small and medium cities freight networks in Kansas can reduce delay to the drivers, decrease congestion and contribute to improved traffic flow. It can also be concluded that emissions were also decreased, decreasing air pollution, by implementing a roundabout treatment in small and medium cities urban freight route intersections. For selected intersections in Overland Park, the roundabout treatment did not yield statistically significant results to conclude that they decrease the emissions when compared to signalized treatments. As discussed in the body of this dissertation, this could be due to a small sample, limitations in numbers of lanes that are practical at this time in the US and limitations of the current version of the software used. Therefore, it is recommended that further studies be performed.

This study was conducted to illustrate a procedure to check if the roundabouts will operate better on urban freight networks to improve flow and decrease emissions. Although the results obtained from this study might not be applicable for other state freight networks, a more extensive study should be performed to better understand the benefits of integrating the roundabouts in urban freight networks. Also, as the current version of SIDRA INTERSECTION software could not analyze emissions from trucks separately, the procedure mentioned in this dissertation can be adapted with the next version of SIDRA INTERSECTION software to get better results to check the truck emissions for various intersection treatments.

7.6 Conclusions

The following are specific, key conclusions of this study:

- From the literature review it is concluded that following the guidelines mentioned in the *Statewide Freight Plan Template,* which strongly supports that incorporating freight elements in the statewide transportation planning process is a good way to start building effective state freight networks with segments where known OSOW vehicles could be accommodated.
- From the literature review it is concluded that all states would benefit from designing appropriate roundabouts, as well as addressing all OSOW obstructions, by developing a set of check vehicles specifically for their state and designated OSOW routes on which these OSOW check vehicles are expected.
- It was observed from survey 1 results that roundabouts were the 9th most reported restrictions by states for Oversize/Overweight (OSOW) vehicles among the 11 possible obstructions listed above, thus it is concluded that they are not the most serious problem for OSOW loads, as many perceive; however, most of the OSOW haulers who responded to surveys 3 and 4 felt that roundabouts are more of a problem compared with other intersections.
- To safely accommodate a WB-67 vehicle when necessary at different types of smaller roundabouts in a single-lane roundabout configuration (when initially designed with a WB-50 design vehicle), it is concluded that implementation of external truck aprons, increasing the width of internal truck aprons, and providing custom center islands, will be sufficient in most cases.
- To safely accommodate a WB-67 vehicle when necessary at different types of smaller roundabouts in a double-lane roundabout configuration (when initially designed for a WB-50 design vehicle) it is concluded that they do not need any additional space requirements as long as the WB-67 is allowed to use the two lanes on the approach, circulating roadway, and exit of the roundabout.
- It was found that accommodating the six OSOW check vehicles, at roundabouts designed with WB-67 design vehicles, resulted in a need for constructing internal and external truck apron areas; however, it is concluded that the Opposite Direction of Travel (ODT),

and combined ODT & Fully Traversable Center Island (FTCI) accommodation strategies are effective in decreasing truck apron areas when compared to normal direction of flow accommodation strategies.

- It is concluded that when compared to normal direction of flow accommodation strategies for the six OSOW check vehicles, the ODT accommodation strategy reduces the need for a truck apron by 71.15% for a single-lane, symmetric 3-leg roundabout, 41.12% for single-lane, 3-leg roundabout at a T-intersection, 38.11% at single-lane, symmetric 4-leg roundabout, 81.45% at a double-lane, symmetric 3-leg roundabout, 53.99 % for a double-lane, 3-leg roundabout at a T-intersection, 69.43% at a double-lane, symmetric 4 leg roundabout. Similarly, when compared to normal direction of flow accommodation strategies for the six OSOW check vehicles, combined ODT & FTCI accommodation strategies reduce the need for truck aprons by 61.67% for a single-lane, symmetric 3-leg roundabout, 38.22% for a single-lane, 3-leg roundabout at a T-intersection, 43.04% at a single-lane, symmetric 4-leg roundabout, 45.93 % for a double-lane, 3-leg roundabout at a T-intersection, 66.77% at a double-lane, symmetric 4-leg roundabout.
- It is concluded that accommodating the six OSOW check vehicles by providing a straight through passage at single-lane roundabout reduced the truck apron area by 66.45% and paved area by 45.47% when compared to other accommodation strategies. Similarly, it is concluded that accommodating the six OSOW check vehicles by providing a straight through passage at double-lane roundabouts, reduced the truck apron area by 62.11% and the paved area by 29.64% when compared to other accommodation strategies.
- It is concluded that a 2-inch truck apron height should be considered at single-lane roundabouts for accommodating the DST lowboy vehicle used in this study, without ground clearance problems, when the cross slope of the circulatory roadway is not more than 1.5%, sloped away from the center island, and when the cross slope of the truck apron is not more than 2%, sloped towards the center island.
- It is concluded that a 3-inch truck apron height should be considered at double-lane roundabouts for accommodating the DST lowboy vehicle used in this study, without ground clearance problems, when the cross slope of the circulatory roadway is not more than 2%, away from the center island, and when the cross slope of the truck apron is not more than 2% toward the center island.

- It is concluded that implementing roundabout treatments in freight networks of small and medium city intersections, and resulted in decreased delay, and decreased emissions of CO, HC, CO2, and NOx.
- It is concluded that the accommodation techniques and strategies developed can be used on actual states' designs to check if known or expected OSOW can be accommodated.

7.7 Recommendations

This study has designed various standard rural roundabouts using a WB-67 design vehicle and modified them for accommodating six custom OSOW check vehicles that were generated by the Wisconsin DOT. However, the actual vehicle turning characteristics of the six OSOW check vehicles in the field should be checked with the turning characteristics that were defined in AutoTURN software to validate the designs that were generated..

All the rural roundabouts designed in chapter 4 of this study were designed according to the latest roundabout guide (*1*), and therefore, it can be assumed that the roundabout should be safe and function well. However, the operational performance and safety performance of the rural roundabouts designed in this study should be field tested as they involve one or more unique features such as: custom center island truck apron, external truck apron, removable signage, counter flow of traffic for OSOW check vehicles, and straight passage through the roundabout.

The results from the vehicle clearance analysis of the Wisconsin DOT, DST lowboy vehicle, used in this study at a single lane roundabout could be questioned because the version of TORUS software used in this study does not have a capability of completely designing the grading of a roundabout (grading of external truck apron was not possible). Therefore, the vehicle clearance analysis of a DST lowboy vehicle at a single lane roundabout should be conducted again with the upcoming, updated version of TORUS software, or other, more comprehensive, r terrain grading computer software.

At the time of this study, the author was restricted to using only one lowboy vehicle (the WisDOT DST lowboy) in the AutoTURN, Pro software available for conducting the ground clearance analysis; however, the vertical dimensions suggested in this study might vary with other configurations of lowboy vehicles. Therefore, other possible lowboy vehicles travelling on

US roads should be analyzed with AutoTURN, or other swept path analysis software, such that, vertical design features can be analyzed for other specific lowboy vehicles that can be expected at a specific location.

This study demonstrated a procedure to check the advantages of integrating roundabouts into urban freight network for improving the traffic flow, reducing delay, and improving air quality. A limitation was that the SIDRA INTERSECTION, 5.1 software, used in this study was not capable of separately calculating the emissions caused by the trucks and normal vehicles to better analyze the reduction of truck emissions by using a roundabout treatment. Therefore, it is recommended that emissions at roundabouts and signalized intersections by trucks should be studied separately, using either upcoming version of SIDRA INTERSECTION software, or any other capable software, to better analyze the truck emissions by implementing a roundabout treatment.

It is also recommended that the emissions results obtained from the SIDRA INTERSECTION software output should be checked with a U S field study for validating the results.

Due to data limitations in the large city example used in this study, results of the benefits of integrating roundabouts into freight networks in large cities were inconclusive. It is recommended that additional, more comprehensive studies be conducted to verify potential benefits.

Since some professionals are concerned that truck apron heights of 2 or 3 inches, recommended in this study, may be not safe by not keeping some small vehicle drivers from cutting across them, it is recommended that research be conducted to study if 2-inch and 3-inch heights are sufficient to deter small vehicle drivers from driving on them.

Curb height was also mentioned as a problem by the survey respondents of OSOW vehicles, and it is recommended that curb design and curb height also be studied to better accommodate OSOW vehicles and insure designs minimize load shifting and that do not damage OSOW tires.

References

1. Rodegerdts, L., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson, M. Moule, B. Persaud, C. Lyon, S. Hallmark, H. Isebrands, R. B. Crown, B. Guichet, A. O'Brien. *Roundabouts: An Informational Guide, Second Edition,* NCHRP Report 672, Transportation Research Board of the National Academics, Washington, D.C., 2010.
2. Russell, Eugene R, E. Dean Landman and Ranjit Godavarthy, *Accommodating Oversize/Overweight Vehicles at Roundabouts, Pooled Fund Program*, Project TPF-5(2200), July 2012.
3. *A Policy on Geometric Design of Highways and Streets,* American Association of State Highway and Transportation Officials, Washington, D.C., 2004.
4. Dr. Eugene R. Russell Photo Collection
5. White, K., and L. R. Grenzeback, *Public Roads: Understanding Freight Bottlenecks,* Publication Number FHWA-HRT-07-003. FHWA, U.S. Department of Transportation, 2007.
   http://www.fhwa.dot.gov/publications/publicroads/07mar/05.cfm, accessed 02/18/12.
6. *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation,* Cambridge Systematics and Texas Transportation Institute, September 2005.
7. *An Initial Assessment of Freight Bottlenecks on Highways,* Cambridge Systematics and Battelle Memorial Institute, FHWA, October 2005.
8. *Freight Facts and Figures*, Office of Freight Management and Operations, FHWA 2009.
9. *Integrating Freight Facilities and Operations with Community Goals*, NCHRP Synthesis 320, Transportation Research Board of the National Academics, Washington, D.C. 2003.
10. Rodegerdts, L., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. Troutbeck, W. Brilon, N. Wu, B. Persaud, C. Lyon, D. Harkey, and D. Carter. *Roundabouts in the United States*, NCHRP Report 572, Transportation Research Board of the National Academics, Washington, D.C., 2007.
11. Russell, Eugene R, Srinivas Mandavilli, Margaret Rys. *Operational Performance of Kansas Roundabouts: Phase II*. Report No. K-TRAN: KSU-02-1, May 2005.
12. Mandavilli, Srinivas, Eugene R. Russell, Margaret Rys. *Environmental Impact of Kansas Roundabouts*. Paper prepared for the presentation at the Emerging Technologies in

Traffic Operations Session of the 2003 Annual Conference of the Transportation Association of Canada, September 2003. http://www.tac-atc.ca/english/resourcecentre/readingroom/conference/conf2003/pdfs/russell.pdf accessed 09/15/2012

13. Wikipedia search – Swept Path, http://en.wikipedia.org/wiki/Swept_path_analysis accessed 10/01/2012.
14. Burks, S.V., M. Belzer, Q. Kwan, S. Pratt, S. Shackelford. *Trucking 101: An Industry Primer*, Transportation Research Circular, No. E-C146, Transportation Research Board of the National Academics, December 2010.
15. *American Trucking Trends 2011*, American Trucking Associations, Virginia, 2011.
16. Sprung M. J. *Increased trade spurs growth in North American Freight transportation.* BTS Special Report, U.S. Department of Transportation. May 2007. http://www.bts.gov/publications/special_reports_and_issue_briefs/special_report/2007_05/html/entire.html, accessed 02/18/12.
17. *Comprehensive Truck Size and Weight Study, Volume 1: Summary Report.* Federal Highway Administration, U.S. Department of Transportation, FHWA. Washington, DC 2000.
18. *A Synthesis of Safety Implications of Oversize/Overweight Commercial Vehicles,* American Association of State Highway and Transportation Officials, December 2009.
19. Preserving and Protecting Freight Infrastructure and Routes. NCFRP Report 16. 2012.
20. *Guidebook for Understanding Urban Goods Movement.* NCFRP Report 14. 2012.
21. *Accommodating Trucks in Single and Multilane Roundabouts,* Ourston Roundabout Engineering, National Roundabout Conference, Transportation Research Board, Missouri, May 2008.
22. *Joint Roundabout Truck Study: Draft Report for phase 1; Synthesis of Current Design Practice,* Short Elliott Hendrickson Incorporated, DLZ National, and Roundabouts and Traffic Engineering, Draft report prepared for Wisconsin and Minnesota DOT.
23. *Statewide Freight Plan Template*, FHWA Report. http://www.trb.org/Main/Blurbs/165843.aspx accessed 08/09/2012.

24. Smith, Wilbur , and Associates Roess, Robert and Jose, Ulerio), in partnership with SRF Consulting Group, Inc., C.J. Peterson, and Associates, and the University of Toledo, Western Minnesota Regional Freight Study, Final Report, September, 2009.
25. Middleton, Dan., Yingfend Li, Jerry Le, and Nick Koncz, *Accommodating Oversize & Overweight Loads* Texas Transportation Institute, Report Number FHWA/TX-12/0-6404-1, July 2012.
26. AutoTURN Product Brochure, Advance Vehicle Simulations, http://c464509.r9.cf2.rackcdn.com/autoturn.pdf accessed 02/29/2012.
27. TORUS Product Brochure, Every Generation Needs a Design Revolution, http://c464509.r9.cf2.rackcdn.com/torus.pdf accessed 02/29/2012.
28. Wisconsin DOT Vehicle Library, Received from Patrick Fleming, 2011.
29. Private e-mail conversation with Patrick Fleming, Septmber 27, 2012.
30. Sudhakar Sathyanarayanan, Eugene R. Russell, Margaret J. Rys. *Further Studies of Roundabouts: Hutchinson, Kansas Study* Mack-Blackwell Mational Rurual Transportation Study Center. 2004.
31. SIDRA INTERSECTION User Guide, SIDRA INTERSECTION 5.1 Version Software.
32. Russell, Eugene R, E. Dean Landman and Ranjit Godavarthy, A Study of Roundabouts on Traffic Flows and Business, K-Tran Final Report Under Review, Kansas DOT, December 2011.
33. City of Overland Park Website http://www.opkansas.org/wp-content/uploads/downloads/city-truck-route-map.pdf accessed 01/08/2012.
34. Robert O. Kuehl, Statistical Principles of Research Design and Analysis
35. Private e-mail from Rahmi Akcelik, October 8, 2012.
36. Review of Truck Characteristics as factors in Roadway Design, NCHRP Report 505, Transportation Research Board of the National Academics, Washington, D.C., 2003.

Appendix A - Dimensions and Turning Path Requirements of Design Vehicles

Figure A.1: Design Vehicle Dimensions from the 2001 Green Book

US Customary

		Dimensions (ft)											
		Overall			Overhang								
Design Vehicle Type	Symbol	Height	Width	Length	Front	Rear	WB_1	WB_2	S	T	WB_3	WB_4	Typical Kingpin to Center of Rear Axle
Passenger Car	P	4.25	7	19	3	5	11	–	–	–	–	–	–
Single Unit Truck	SU	11-13.5	8.0	30	4	6	20	–	–	–	–	–	–
Buses													
Inter-city Bus (Motor Coaches)	BUS-40	12.0	8.5	40	6	6.3[a]	24	3.7	–	–	–	–	–
	BUS-45	12.0	8.5	45	6	8.5[a]	26.5	4.0	–	–	–	–	–
City Transit Bus	CITY-BUS	10.5	8.5	40	7	8	25	–	–	–	–	–	–
Conventional School Bus (65 pass.)	S-BUS 36	10.5	8.0	35.8	2.5	12	21.3	–	–	–	–	–	–
Large School Bus (84 pass.)	S-BUS 40	10.5	8.0	40	7	13	20	–	–	–	–	–	–
Articulated Bus	A-BUS	11.0	8.5	60	8.6	10	22.0	19.4	6.2[a]	13.2[a]	–	–	–
Trucks													
Intermediate Semitrailer	WB-40	13.5	8.0	45.5	3	2.5[d]	12.5	27.5	–	–	–	–	27.5
Intermediate Semitrailer	WB-50	13.5	8.5	55	3	2[d]	14.6	35.4	–	–	–	–	37.5
Interstate Semitrailer	WB-62*	13.5	8.5	68.5	4	2.5[d]	21.6	40.4	–	–	–	–	42.5
Interstate Semitrailer	WB-65** or WB-67	13.5	8.5	73.5	4	4.5-2.5[e]	21.6	43.4-45.4	–	–	–	–	45.5-47.5
"Double-Bottom"-Semitrailer/Trailer	WB-67D	13.5	8.5	73.3	2.33	3	11.0	23.0	3.0[b]	7.0[b]	23.0	–	23.0
Triple-Semitrailer/ Trailers	WB-100T	13.5	8.5	104.8	2.33	3	11.0	22.5	3.0[c]	7.0[c]	23.0	23.0	23.0
Turnpike Double-Semitrailer/Trailer	WB-109D*	13.5	8.5	114	2.33	2.5[d]	14.3	39.9	2.5[d]	10.0[d]	44.5	–	42.5
Recreational Vehicles													
Motor Home	MH	12	8	30	4	6	20	–	–	–	–	–	–
Car and Camper Trailer	P/T	10	8	48.7	3	10	11	–	5	19	–	–	–
Car and Boat Trailer	P/B	–	8	42	3	8	11	–	5	15	–	–	–
Motor Home and Boat Trailer	MH/B	12	8	53	4	8	20	–	6	15	–	–	–
Farm Tractor[f]	TR	10	8-10	16[g]	–	–	10	9	3	6.5	–	–	–

* = Design vehicle with 48 ft trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).
** = Design vehicle with 53 ft trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).
a = Combined dimension is 19.4 ft and articulating section is 4 ft wide.
b = Combined dimension is typically 10.0 ft.
c = Combined dimension is typically 10.0 ft.
d = Combined dimension is typically 12.5 ft.
e = This is overhang from the back axle of the tandem axle assembly.
f = Dimensions are for a 150-200 hp tractor excluding any wagon length.
g = To obtain the total length of tractor and one wagon, add 18.5 ft to tractor length. Wagon length is measured from front of drawbar to rear of wagon, and drawbar is 6.5 ft long.

- WB1, WB2, and WB4 are the effective vehicle wheelbases, or distances between axle groups, starting at the front and working towards the back of each unit.
- S is the distance from the rear effective axle to the hitch point or point of articulation.
- T is the distance from the hitch point or point of articulation measured back to the center of the next axle or center of tandem axle assembly.

Source: Review of Truck Characteristics as Factors in Roadway Design (36)

Figure A.2: Minimum Turning Radii of Design Vehicles from the 2001 Green Book

US Customary

Design Vehicle Type	Passenger Car	Single Unit Truck	Inter-city Bus (Motor Coach)		City Transit Bus	Conventional School Bus (65 pass.)	Large[2] School Bus (84 pass.)	Articulated Bus	Intermediate Semi-trailer	Intermediate Semi-trailer
Symbol	P	SU	BUS-40	BUS-45	CITY-BUS	S-BUS36	S-BUS40	A-BUS	WB-40	WB-50
Minimum Design Turning Radius (ft)	24	42	45	45	42.0	38.9	39.4	39.8	40	45
Centerline[1] Turning Radius (CTR)	21	38	40.8	40.8	37.8	34.9	35.4	35.5	36	41
Minimum Inside Radius (ft)	14.4	28.3	27.6	25.5	24.5	23.8	25.4	21.3	19.3	17.0

Design Vehicle Type	Interstate Semi-trailer		"Double Bottom" Combination	Triple Semi-trailer/ trailers	Turnpike Double Semi-trailer/ trailer	Motor Home	Car and Camper Trailer	Car and Boat Trailer	Motor Home and Boat Trailer	Farm[3] Tractor w/One Wagon
Symbol	WB-62*	WB-65** or WB-67	WB-67D	WB-100T	WB-109D*	MH	P/T	P/B	MH/B	TR/W
Minimum Design Turning Radius (m)	45	45	45	45	60	40	33	24	50	18
Centerline[1] Turning Radius (CTR)	41	41	41	41	56	36	30	21	46	14
Minimum Inside Radius (m)	7.9	4.4	19.3	9.9	14.9	25.9	17.4	8.0	35.1	10.5

* = Design vehicle with 48 ft trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

** = Design vehicle with 53 ft trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

[1] = The turning radius assumed by a designer when investigating possible turning paths and is set at the centerline of the front axle of a vehicle. If the minimum turning path is assumed, the CTR approximately equals the minimum design turning radius minus one-half the front width of the vehicle.

[2] = School buses are manufactured from 42 passenger to 84 passenger sizes. This corresponds to wheelbase lengths of 132 in to 237 in, respectively. For these different sizes, the minimum design turning radii vary from 28.8 ft to 39.4 ft and the minimum inside radii vary from 14.0 ft to 25.4 ft.

[3] = Turning radius is for 150-200 hp tractor with one 18.5 ft long wagon attached to hitch point. Front wheel drive is disengaged and without brakes being applied.

Source: Review of Truck Characteristics as Factors in Roadway Design (36)

Appendix B - Survey 2 and Survey 4 Questions Used for the Study

OSOW Survey 2 with US State Agencies

Note: The numbering of survey questions shown below is the actual survey question numbers used in the actual survey.

Q8: Have you heard any concerns about your roundabouts from companies that deal with a vehicle requiring a permit, i.e Oversize/Overweight (OSOW) vehicles?

Q11: If 'yes' to question 8, do the OSOW companies/organizations that deal with OSOW vehicles have any input into your highway design, particularly roundabout design? If 'yes', please explain:

Q12: Do you know of any studies in your state or have any information or insight into how OSOW vehicles or trucking associations accept roundabouts in your state ?

Q13: Do you ever interact with OSOW vehicle or trucking associations on designs such as roundabouts?

Q16: Do you have roundabouts on state or non-state routes on which OSOW vehicles might be routed ?

Q17: If 'yes' to question 15, have you heard of any problems with OSOW vehicles navigating roundabouts?

Q20: When planning or designing roundabouts, are OSOW routes taken into consideration ? Please explain:

Q20: Do you have roundabouts in agriculture areas where large farm equipment, operating under its own power on state highways, or where vehicle hauling agricultural or animal trailers might be an issue? If 'yes' please explain:

Q29: Has there ever been a roundabout design in your state to address any concerns with OSOW or agricultural equipment or animal trailers operating on their own power on state highways?

OSOW Survey 4 with OSOW Haulers

Q14: Are roundabouts any more of a problem compared with other intersections?

Q15: Are roundabouts any more of a problem than other Highway features which may be a concern to oversize overweight loads such as narrow bridges, wires, curbs, ramps, and so forth?

Q16: Do you have any unique problems with roundabouts, and if so, please explain?

Q18: If the answer to question 15 and/or 16 is "yes";, what possible solutions do you think might mitigate the problem(s) without compromising their safety benefits to passenger vehicles, or requiring excessive right of way and cost?

Q18. What is your fleet's experience with these particular aspects of a roundabout: 1: The approach
Q18.What is your fleet's experience with these particular aspects of a roundabout: 2: The circulatory roadway
Q18.What is your fleet's experience with these particular aspects of a roundabout: 3: The departure

Q20: How beneficial would it be if loads could go straight through a roundabout, if a removable barrier is in place to prevent other vehicles from doing so?

Q21: How beneficial would it be if loads could go straight through a roundabout, if the pathway would be offset so the entrance would line up with the left approach (where the driver would have to move to the left lane on the approach)?

Q22: Do you feel there is a need for you to provide more input to roundabout designers, and if so, about what topics?

Q23: What are your views on the roundabout concern 'Low boy(low clearance) vehicles have problems with curbs over 4 inches in height'

Q24: What are your views on the roundabout concern 'There are issues with OSOW riding up on the curb on the exterior of the roundabout'

Q25: What are your views on the roundabout concern 'OSOW vehicles don't like hauling their long loads through roundabouts with tight radii'

Q26: What are your views on the roundabout concern 'Fixed objects within the center of the roundabout cause problems'

Q27: What are your views on the roundabout concern 'Slopes of circular roadway and/truck apron cause fear of overturning'

Q28: What are your views on the roundabout concern 'Drivers do not understand what the truck apron is for and need education'

Q29: Please add any additional concerns you have about roundabouts that were not mentioned in Questions 23 to 28:

Q30: Do you use OSOW permits?

Q40: Do you use your own escort or do you use a certified escort service?

Q41: If you use a certified escort service, does your escort service provide traffic control when traffic is interrupted or are police required?

Q43: Do you remove and replace highway signs, or any other highway feature you consider an obstacle and replace them after passing?

Q44: Do you pay the government agency to replace signs or repair damaged fixtures?

Q45: Are there places where you are permitted to hold traffic and travel in the wrong direction to continue toward your destination?

Q46: Do you report problems negotiating a given route to the permitting agency?

Appendix C - Concerns about Roundabouts from Companies that deal with a Vehicle Requiring a Permit, i.e Oversize/Overweight (OSOW) Vehicles

US State	Have you heard any concerns about your roundabouts from companies that deal with a vehicle requiring a permit, i.e. Oversize/Overweight (OSOW) vehicles?	
	(Yes/No)	Comments from the responder:
Alaska	yes	Concerns about long trailers (53' plus) and long doubles > 120' total
Arizona	yes	None that I am aware of, but our roundabout specialist always requests OSOW / permit vehicle info during design phase to accommodate OSOW vehicles. We now require trucks to stay in lane in the approaches wherever possible.
Connecticut	yes	Low-Boy vehicles were a major consideration at one of the roundabouts that has now been built due to limited vertical clearance (approx. 3') and raised truck apron.
Georgia	yes	Concern is we dont identify a roadway network based on geometric design limitations.
Iowa	yes	They don't like hauling their long loads through the roundabouts with tight radii. They also have clearance issues.
Kansas	yes	Trying to get bridge beams to a KDOT project.
Maine	yes	We have had issues with low clearance vehicles bottoming out on truck aprons and we have had issues with oversize loads riding up on curb on the exterior of the roundabout.
Massachusetts	yes	
Michigan	yes	'Low-boy' trailer issue at Mattawan roundabout. High profile curb was installed on the edge of the truck apron instead of low profile mountable.
Minnesota	yes	We have heard concerns from construction haulers with 10-12 axle vehicles. We also had a hauler with a windmill blade try to get through a roundabout. This truck caused damage to the landscaping and curb of the roundabout. Our permits staff was unaware of the roundabout on that route. We are developing methods to assist permits staff to be aware of roundabout locations.
Mississippi	yes	I have heard that some OS loads are routed to by-pass our roundabout on MS 475 at Airport Road.
Nebraska	yes	Mostly wind generation companies that indicate that they struggle getting the long and heavy low loads through these intersections.
New Hampshire	yes	Concern for getting trucks through the roundabout. Concern was mostly that they are too narrow.

US State	Have you heard any concerns about your roundabouts from companies that deal with a vehicle requiring a permit, i.e. Oversize/Overweight (OSOW) vehicles?	
	(Yes/No)	**Comments from the responder:**
New York	yes	The Department's Central Permits Bureau [CPB] has noted that they have been informed by carriers using particular longer vehicles such as manufactured homes, wind tower components, or multi-axle superload trailers. The CPB was informed that one roundabout was located in a manner to reduce truck traffic and essentially eliminated a key OS/OW route resulting in significantly longer routing. In conversations with carriers, the CPB has found that while a roundabout has been designed with mountable curbs, it is not intuitive to truck or automobile drivers that they were put there to be mounted by tractor/trailer combination vehicles as they use the roundabout. Some carriers have identified placement of signs and landscaping as creating a problem in using the roundabout as originally designed.
Oregon	yes	There has been much concern in Oregon from several road user groups as well as the trucking industry as a whole and not just OSOW haulers. There has been an attempt to craft an Oregon Revised Statute to drastically reduce or eliminate roundabouts on state highways. Oregon DOT was able to halt the proposed legislation by implementing a temporary halt to roundabout design/construction until discussion, education and collaboration can take place to allay the concerns from the trucking industry. We are currently making inroads on that.
South Carolina	yes	Private industry has expressed concerns about objects being placed within the center island.
Vermont	yes	VT Truck and Bus Association
Washington	yes	WSDOT hosted a 'Truck Listening Session' and also met with 'Heavy haulers' on two occasions who specifically handle OSOW. At the time of this writing, OSOW companies stated that they have all sorts of problems with standard intersections however have not had any issues with roundabouts but recommended the following for roundabouts specifically: 1. Mountable curbing 2. Removable signage 3. Addressing stationary landscape features 4. Larger radius design to accommodate longer vehicles

US State	Have you heard any concerns about your roundabouts from companies that deal with a vehicle requiring a permit, i.e. Oversize/Overweight (OSOW) vehicles?	
	(Yes/No)	**Comments from the responder:**
Wisconsin	yes	Primary concern is ability to enter and get through without load shift/turn over (especially Left turn) we have incorporated many modifications to accommodate these loads plus a dedicated network so designers know where and when enhancements are needed. Law enforcement is also involved in concerns related to roundabouts, such as sign removals and additional number of authorized vehicles to direct/maintain traffic operations. If roundabouts are built close together (say 300? or so) this traffic control problem is heightened.
Arkansas	no	
California	no	Resolved during design development
Colorado	no	
Delaware	no	Only concerns we have had are with the farming and emergency response communities.
Florida	no	
Illinois	no	
Indiana	no	Field observations have shown that where a car and a truck enter a roundabout side-by-side, the smaller vehicle tends to avoid driving beside the larger vehicle.
Kentucky	no	
Louisiana	no	
Maryland	no	
Montana	no	
New Jersey	no	
New Mexico	no	
North Carolina	no	
Ohio	no	
Pennsylvania	no	
Rhode Island	no	We are not aware of such concerns.
South Dakota	no	
Tennessee	no	
Virginia	no	
Wyoming	no	
Missouri	No reply	Contact our Motor Carriers Division @ 573-751-7410

Appendix D - Input of OSOW Companies into Roundabout Design

US State	Do the OSOW companies/organizations that deal with OSOW vehicles have any input into your highway design, particularly roundabout design? If 'yes', please explain:
Alaska	Direct communications as needed. Special Design meetings when requested. Plan Review by OSOW permitting staff.
California	During public hearings (part of environmental process) their concerns are recorded and addressed
Iowa	We've asked them about curb heights and shapes of curbs.
Kansas	They only have input if we ask.
Minnesota	Limited involvement - through project meetings.
Washington	Rolled curbs and understanding OSOW routes has assisted us in having the right conversations on projects including central island landscaping

Appendix E - When planning or designing roundabouts, are OSOW routes taken into consideration?

US State	When planning or designing roundabouts, are OSOW routes taken into consideration? Please explain:	Comments
Alaska	yes	Route maps are published by the permitting division. When in a constrained area, routes are discussed with the Alaska Trucking Association. We can always improve on communication, but it is occurring.
Arizona	yes	When known.
California	yes	Roundabouts are designed to accommodate OSOW trucks
Connecticut	yes	If OSOW vehicles are expected to use the roundabout, we will design the roundabout to accommodate these vehicles, or if this is not possible, would ask the permit section to route any OSOW vehicles to avoid the roundabout, if possible.
Georgia	yes	Our planning and concept development process identifies OSOW industry in the vicinity of planned roundabouts.
Illinois	yes	Probably not. Unless there is an apparent need or demand to accommodate OSOW vehicles, IDOT uses WB-65 as the largest design vehicle.
Indiana	yes	Where truck volume is high, warning signs are posted in advance so that no other vehicles should drive next to or pass a truck in a roundabout, unless the roundabout has been designed to specifically allow for trucks to travel side-by-side with another vehicle.
Kansas	yes	We need to determine what design vehicle to use in the design.
Louisiana	yes	When the designer knows that the route will be utilized for oversize loads.
Maine	yes	We don't have a good way of checking OSOW turning templates, but we try to make sure we are conservative with WB-67 templates. We also pay close attention to truck apron and central landscaped island treatment and types of curb used.
Massachusetts	yes	

US State	When planning or designing roundabouts, are OSOW routes taken into consideration? Please explain:	Comments
Michigan	yes	Truck aprons are provided on all state trunkline roundabouts. Larger vehicle turning pathways have been evaluated on proposed roundabouts using modeling software.
Minnesota	yes	For house moving routes, we do consider impacts. Mn/DOT is looking into creating superload corridors similar to what WisDOT has done.
Montana	yes	We would consider design changes if alerted to the potential for OSOW routing through project corridors.
Nebraska	yes	
Nevada	yes	
New Hampshire	yes	
New York	yes	
Oregon	yes	As designers, we check with the Motor Carrier permit section to find out what OSOW loads are using the highway section. Then we design using our standard WB-67 vehicle, but make accommodations for the larger vehicles using the highway by permit. We make custom AutoTurn templates if necessary to model the OSOW vehicles for accommodation. Design means the vehicle can move through the highway section in a normal manner. Accommodate means a vehicle can negotiate the highway section, but may need to use specific methods.
Rhode Island	yes	We design for the biggest vehicle expected to use the roundabout.
Tennessee	yes	

US State	When planning or designing roundabouts, are OSOW routes taken into consideration? Please explain:	Comments
Washington	yes	WSDOT Truck Permitting managers are routinely in discussions with Design/Traffic Offices as new roundabouts are proposed and design team is educated on needs of OSOW. Standard curb details, removable signs are becoming standard practice because of this input. The roundabout's superior safety and operational considerations make it necessary to work diligently to save roundabout option.
Wisconsin	yes	On OSOW FN there is a 7 vehicle inventory that is used to represent a broader set of vehicles to evaluate intersections on the OSOW FN or at intersection were we know in advance OSOW will access the OSOW FN from the local system. One of the 7 vehicles represents a multi-trip permit type vehicle or annual permit (103.5 feet overall length and 70 feet for king pin to center of rear duals) to evaluate designs on the long truck route (broader than OSOW FN but not entire State Network) since these loads are not route specific and use the broader long truck routes in the state.
Wyoming	yes	We have reviewed the geometrics to see if they could accommodate common oversize loads, such as trucks hauling wind turbine blades. We also discuss nearby alternate routes for oversize loads which may not be able to navigate around the roundabouts.

US State	When planning or designing roundabouts, are OSOW routes taken into consideration? Please explain:	Comments
Arkansas	no	
Delaware	no	
Florida	no	We design to the WB62-FL vehicle which is a modified WB62.
Iowa	no	No - But we are trying to develop of a process.
Kentucky	no	
Maryland	no	
Mississippi	no	
Missouri	no	We are looking into making that a requirement when considering a potential roundabout location.
New Jersey	no	
New Mexico	no	
North Carolina	no	We know of one project in Division 9 where roundabouts were specifically not permitted at a re-designed interchange because of objections from truckers.
Ohio	no	
Pennsylvania	no	
South Carolina	no	OSOW routes are not specifically identified on a statewide basis.
South Dakota	no	There are not any roundabouts on state highways therefore SDDOT staff have not designed a roundabout.
Vermont	no	
Virginia	no	
Colorado	NR	

Appendix F - Roundabouts in Agricultural Areas

US State	Do you have roundabouts in agriculture areas where large farm equipment, operating under its own power on state highways, or where vehicle hauling agricultural or animal trailers might be an issue? If 'yes' please explain:	Comments
Arizona	yes	Not aware of any problems
Colorado	yes	
Delaware	yes	We had an issue with a roundabout built on a roadway that had large farm equipment traffic.
Georgia	yes	
Illinois	yes	Much of Illinois is rural. It is likely agricultural equipment will travel through rural communities where roundabouts are present, which at this time is along one state route. As stated above, there may be more roundabouts unaccounted for in other rural communities.
Iowa	yes	Iowa is an agricultural state and we have roundabouts on our non-state routes, as well as state routes.
Kentucky	yes	
Louisiana	yes	
Maryland	yes	We have roundabouts in agriculture areas of the state but there isn't an issue with them.
Massachusetts	yes	Near a farm stand in Amherst MA
Michigan	yes	M-46 at M-37 is located near farmland and apple orchards. Other rural roundabouts have been accessed by larger farm equipment. No documented issues thus far.
Minnesota	yes	We design our rural roundabouts with entry widths of 20 foot curb-to-curb to accommodate implements of husbandry.
Montana	yes	Billings, Montana has a major N-S urban highway that was just reconstructed to include 2-lane roundabouts at 8 intersections.
Nebraska	yes	
Nevada	Yes	
New Mexico	yes	
New York	yes	No problems that we're aware of.

North Carolina	yes	

US State	Do you have roundabouts in agriculture areas where large farm equipment, operating under its own power on state highways, or where vehicle hauling agricultural or animal trailers might be an issue? If 'yes' please explain:	Comments
Ohio	yes	Some roundabouts are near the edge of developed areas where farming is still active.
Oregon	yes	There are a few on city/county roads where farm equipment may need to travel at times.
South Carolina	yes	SC is a very rural state which a thriving agricultural industry.
Washington	yes	Two roundabouts to our knowledge used a combine harvester and a potato picker as their 'default design vehicles in addition to the WB-67 or WB - 50
Wisconsin	yes	Rural portions of the state.
Alaska	no	
Arkansas	no	
California	no	Most are not along ag routes for veh of husbandry
Indiana	no	None.
Kansas	no	
Maine	no	
Mississippi	no	
Missouri	no	
Pennsylvania	no	
Rhode Island	no	
South Dakota	no	
Tennessee	no	
Wyoming	no	
Connecticut	NR	
Florida	NR	
New Hampshire	NR	
New Jersey	NR	
Vermont	NR	
Virginia	NR	