Accelerating Roundabout Implementation in the United States – Volume V of VII

Evaluation of Geometric Parameters that Affect Truck Maneuvering and Stability

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

FOREWORD

Since the Federal Highway Administration (FHWA) published the first *Roundabouts Informational Guide* in 2000, the estimated number of roundabouts in the United States has grown from fewer than one hundred to several thousand. Roundabouts remain a high priority for FHWA due to their proven ability to reduce severe crashes by an average of 80 percent. They are featured as one of the Office of Safety *Proven Safety Countermeasures* and were included in the *Every Day Counts 2* campaign for Intersection & Interchange Geometrics.

As roundabouts became more common across a wide range of traffic conditions, specific questions emerged on how to further tailor certain aspects of their design to better meet the needs of a growing number and diversity of stakeholders. The substantial work performed for this project – *Accelerating Roundabout Implementation in the United States* – sought to address several of the most pressing issues of National significance, including enhancing safety, improving operational efficiency, considering environmental effects, accommodating freight movement and providing pedestrian accessibility. This work represents yet another notable step forward in advancing roundabouts in the United States.

The electronic versions of each of the seven report volumes that document this project are available on the Office of Safety website at http://safety.fhwa.dot.gov/.

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16. Abstract

This volume is fifth in a series of seven. The other volumes in the series are: Volume I - Evaluation of Rectangular Rapid-Flashing Beacons (RRFB) at Multilane Roundabouts, Volume II – Assessment of Roundabout Capacity Models for the Highway Capacity Manual, Volume III – Assessment of the Environmental Characteristics of Roundabouts, Volume IV – A Review of Fatal and Severe Injury Crashes at Roundabouts, Volume VI – Investigation of Crosswalk Design and Driver Behaviors, and Volume VII – Human Factor Assessment of Traffic Control Device Effectiveness. These reports document a Federal Highway Administration (FHWA) project to investigate and evaluate several important aspects of roundabout design and operation for the purpose of providing practitioners with better information, leading to more widespread and routine implementation of higher quality roundabouts.

This report presents an evaluation of the combination of horizontal alignment, vertical alignment, cross section, and curb treatments that sometimes leads to truckload instability or rollover within a roundabout. The study includes a literature review, a review of a sample of incidents involving truck overturns at roundabouts, and a modeling simulation using a multibody dynamics simulation model to evaluate the impact of various design and behavior factors that may impact truck stability in single-lane and two-lane roundabouts. The most significant factor found to affect truck stability was truck speed, followed to a lesser degree by the cross-sectional geometry of two-lane circulatory roadways and the use of the truck apron.

17. Key Words
Roundabouts, , trucks, overturn crashes, instability, geometric design, apron, curb, simulation

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CHAPTER 1. INTRODUCTION

The accommodation of large trucks through a modern roundabout has profound influence on many aspects of its design, which in turn affects the overall performance as it concerns all users. As will be noted in the literature review, guidance is available for the accommodation of trucks in the horizontal plane, that is, the swept paths caused by the off-tracking of truck trailers as they pass through a roundabout. However, to date, a key aspect of truck performance has not been studied in depth in the United States: the combination of horizontal alignment, vertical alignment, cross section, and curb treatments that sometimes leads to truckload instability or rollover.

This study attempted to gain insight into the effect that various combinations of these design elements have on truck stability. The study includes a literature review, a review of a sample of incidents involving truck overturns at roundabouts, and a modeling simulation using a multibody dynamics simulation model to evaluate the impact of various design and behavior factors that may impact truck stability in roundabouts. The model was used to perform a study of variation of key input parameters that:

- Included three different truck configurations: a WB-67 semi-truck (a tractor with a 16.2-m (53-ft) box trailer) was the baseline; a single-unit truck (straight truck); and tractor with double 12.2-m (40-ft) trailers (B-train).
- Included three truckload configurations (full, half full, and empty) that were modeled to determine their effect on the trucks' lateral stability.
- Incorporated different speeds at the roundabout's entry, circulatory roadway, and exit. Speeds were varied to evaluate the influence of speed on lateral acceleration.

The roadway features considered for the parametric study included:

- Varying the inscribed circle diameter (ICD).
- Using different circulatory roadway cross-sections. The following scenarios were used: (1, baseline) 2% cross-slope to the outside; (2) 2% cross-slope to the outside and a truck apron; and (3) a crowned circulatory roadway with a truck apron.
- Varying the overall tilt of the roundabout (that is, the grade of the roundabout perpendicular to the approaching direction of the subject vehicle).

This report outlines the study's parameters and methods and the results of modeling using a commercially available truck simulation program.

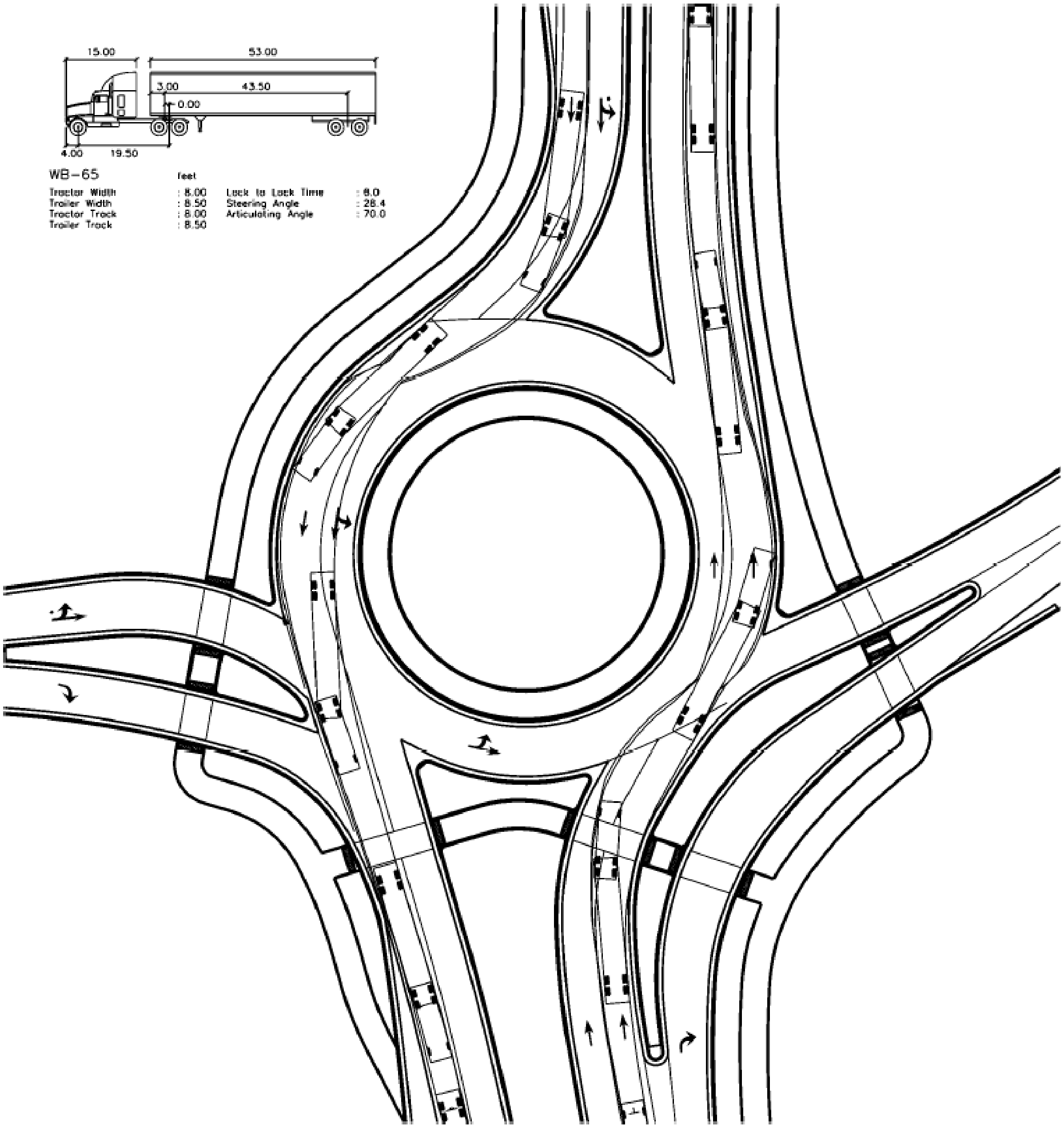
CHAPTER 2. LITERATURE REVIEW

This section summarizes the literature review of existing studies and reports documenting how trucks are affected by the geometric design of roundabouts. The research team reviewed several reports, presentations, and fact sheets to identify guidance for roundabout design to accommodate trucks. The following sections summarize the applicable findings.

ACCOMMODATION OF STANDARD TRUCKS AT MULTILANE ROUNDABOUTS

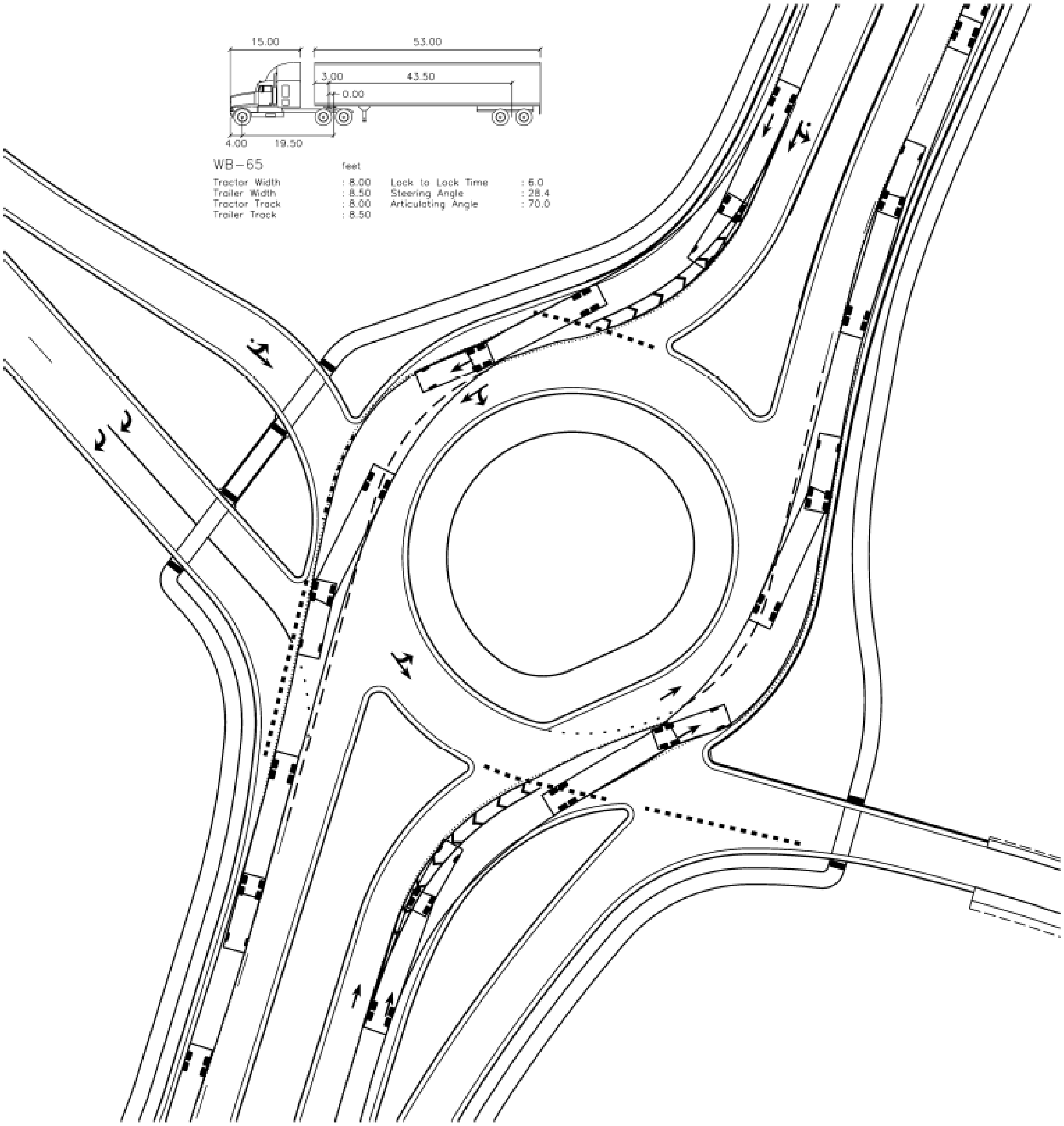
The Minnesota and Wisconsin Departments of Transportation (MnDOT and WisDOT) jointly funded a study to understand how to better accommodate standard trucks at multilane roundabouts (roundabouts with two or more lanes) on state trunk highways by studying current design practices, collecting input from the truck industry, and developing guidelines.[1] Standard trucks, or trucks that are allowed to use the highway system without needing a permit, were defined as a WB-65 in Wisconsin and a WB-62 for Minnesota; oversize/overweight permitted loads were not included in the study. The study was conducted in four phases that included a synthesis of current design practice as summarized into three design cases, video data collection at 18 roundabouts, development of design guidance and recommendations, and a summary of findings and recommendations on how to proceed with implementation. The study included an evaluation of geometry, operations, and crash data.

Phase 1 (review of current design practices) identified three ‘case types’ to describe the movement of trucks through a multilane roundabout. In Case 1, illustrated in figure 1, the roundabout is designed to allow trucks to encroach into adjacent lanes as they approach and traverse the roundabout. In Case 2, illustrated in figure 2, the roundabout is designed to accommodate trucks in their lane as they approach and enter the roundabout, but may require trucks to encroach into adjacent lanes as they circulate and exit the roundabout. In Case 3, illustrated in figure 3, the roundabout is designed to accommodate trucks in one lane as they approach and traverse the entire roundabout.



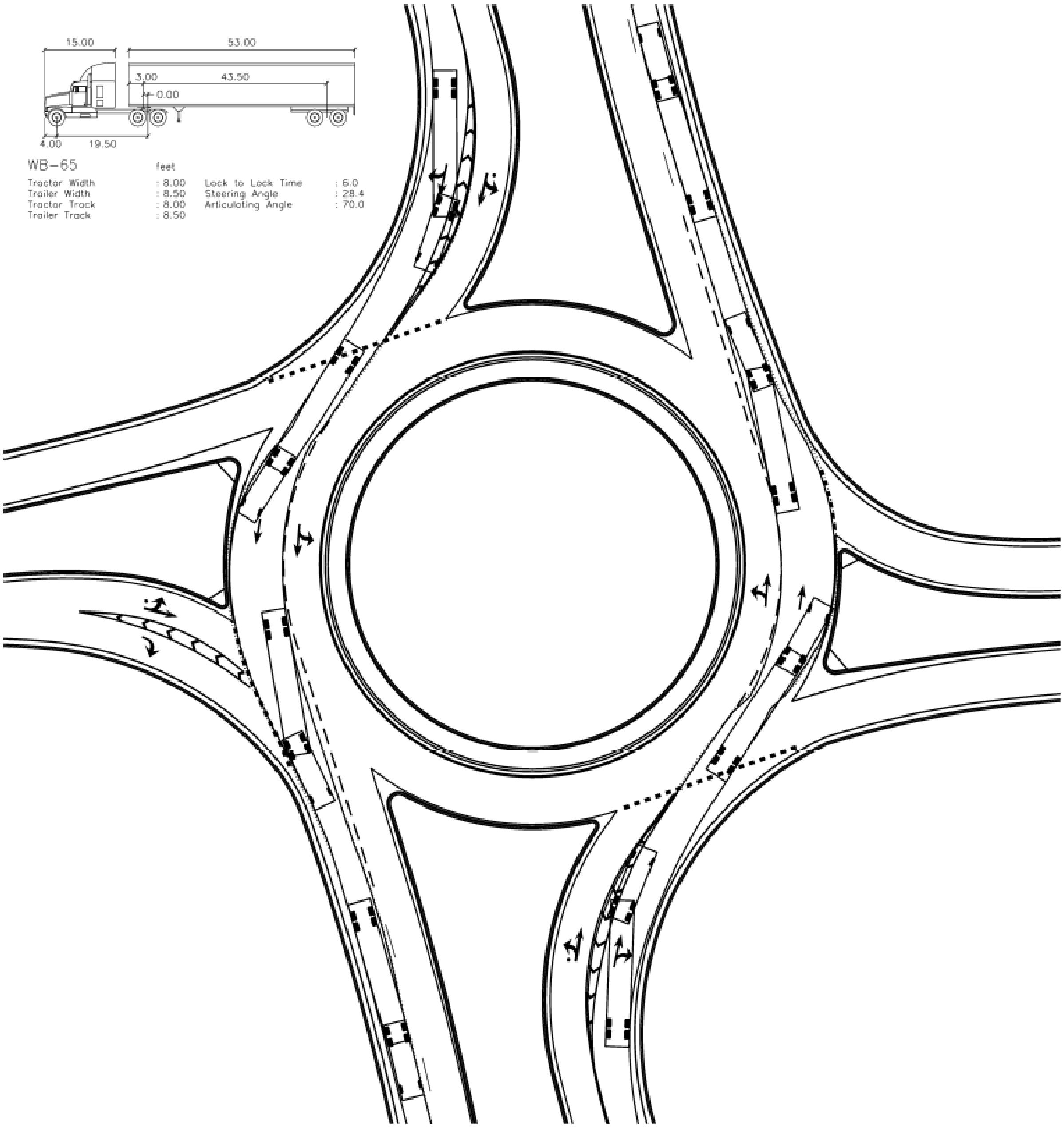
Source: Wisconsin DOT Facilities Development Manual.[5]

Figure 1. Diagram. Accommodation of trucks, case 1: trucks encroach on adjacent approaching and circulating lanes.



Source: Wisconsin DOT Facilities Development Manual.[5]

Figure 2. Diagram. Accommodation of trucks, case 2: trucks encroach only on adjacent circulating lanes.



Source: Wisconsin DOT Facilities Development Manual.[5]

Figure 3. Diagram. Accommodation of trucks, case 3: trucks stay in lane for approach and circulating.

The results showed that Case 2 and 3 roundabouts can be designed such that they are consistent with geometric design principles for roundabouts. Case 1 roundabouts had slightly more truck crashes (sideswipe was the most common) and caused delays at entries due to truck encroachment. Video review showed that trucks at Case 1 roundabouts encroached on adjacent lanes (as expected), and on rare occasions, the trucks drove over outside entry curbs. Trucks at Case 2 and Case 3 roundabouts generally stayed in their lane and used the truck apron when traffic was present in an adjacent lane. When traffic was not present in an adjacent lane, truck drivers typically avoided the use of the truck apron regardless of the design case. One noted limitation of the study is that it did not address increases in other crashes at Case 2 and Case 3 roundabouts due to a larger radius.[3]

Recommended design parameters for each of the cases are summarized in Table 1.[4]

Table 1. Recommended design parameters for Case 1, Case 2 and Case 3 roundabout designs.

Roundabout Design Element	Case 1 Parameter	Case 2 Parameter	Case 3 Parameter
Inscribed circle diameter (ICD)	45.7-57.9 m (150-190 ft)	48.8-64.0 m (160-210 ft)	54.9-67.1 m (180-220 ft)
Inner circulatory lane width	3.4-4.0 m (11-13 ft)	3.4-4.0 m (11-13 ft)	4.0-4.6 m (13-15 ft)
Outer circulatory lane width	4.0-4.6 m (13-15 ft)	4.0-4.6 m (13-15 ft)	4.6-5.5 m (15-18 ft)
Entry width	8.5-9.8 m (28-32 ft)	9.8-10.4 m (32-34 ft)	9.8-10.4 m (32-34 ft)
Entry radius	20+ m (65+ ft)	20+ m (65+ ft)	20+ m (65+ ft)
Exit width	8.5-9.8 m (28-32 ft)	8.5-9.8 m (28-32 ft)	8.5-9.8 (28-32 ft)*

* where larger radius or tangential exit is used

The Wisconsin DOT Facilities Development Manual (FDM) [5] includes guidance for accommodating trucks at roundabouts. The standard design vehicle that WisDOT uses for trucks is a WB-65. The document states that some intersections must also check for accommodation of WB-92, farm combine, and 24.4-m (80-ft) mobile home transport vehicles.

The FDM provides details on a number of geometric elements.[5] Truck aprons should be used, with the truck apron sloped outward at 1%. The minimum truck apron width on both single and multilane roundabouts is 3.6-m (12-ft). Some cases require additional space for off-tracking. Roundabouts generally have a crowned circulatory roadway, 2/3 inward and 1/3 outward. Where off-tracking of trucks may occur, a 100-mm (4-in.) sloped curb and gutter on the outside of the approach may be used; a traversable concrete pad may also be used, provided it does not conflict with the location of pedestrian paths or crossings. The maximum recommended cross-slope in the circulatory roadway is 2%.

The FDM describes the three design cases for accommodating trucks at multilane roundabouts as described in the Joint WisDOT-MnDOT study and states that Case 3 is preferred when feasible and where there are approximately 100 large trucks per day forecasted to use the roundabout. Some of the guidance for Case 2 and Case 3 roundabouts includes the use of wider entries than Case 1 roundabouts; longer curve lengths on the approach geometry; offset-left alignments (left of the center of the roundabout); larger, longer radii with straight tangent sections between curves rather than tight entry radii curves; and width transitions.

ACCOMMODATION OF OVERSIZE/OVERWEIGHT VEHICLES

The WisDOT FDM[5] includes guidance for accommodating oversize/overweight (OSOW) trucks at roundabouts. It is recommended that proposed intersections be designed to accommodate oversize/overweight (OSOW) multiple-trip-permitted vehicles within the curb face, but intersections that did not accommodate these vehicles prior to improvements do not have to accommodate the vehicle after improvements. Intersections on the OSOW Freight Network should be able to accommodate the anticipated OSOW turning movements.

A report led by Kansas State University[2] summarized current practice and research from different states and countries related to the effects that OSOW vehicles have on roundabout location, design, and accommodation to fill in gaps in information about roundabout design and operations for these vehicles.

Based on two surveys of the trucking industry, the report found the following strategies have merit in accommodating OSOWs:[2]

- Provide wide truck aprons of at least 3.6-m (12-ft) with a minimal slope and mountable curb.
- Design center islands to accommodate through and turning movements. This may include making fixed objects in the central island removable or eliminating them altogether.
- Provide paved area behind curb (right side for off tracking).
- Design signs to be removable and use setbacks for permanent fixtures (light poles).
- Allow trucks to cross over the median (stamped, depressed, or corrugated) before entering the roundabout, in a counter flow direction, to make a left turn in the opposing lane and then cross back over after the turn.
- Provide right turn lanes; these are sometimes gated when separated from the roundabout.

The researchers drew a number of general conclusions from the surveys. Vertical clearance in general, and curbs in particular, are an issue for large trucks and OSOWs. The design of these elements should be considered where OSOWs are accommodated. A maximum height of 900-mm (3-in.) should be considered for splitter islands, truck aprons, and curbs. The design of roundabouts, like bridges and many other roadway network components, should consider the needs of OSOW trucks, and the development of statewide freight networks can help ensure that key routes are not overlooked.

EVALUATION OF TRUCK STABILITY

A study of the stability of articulated trucks was conducted in 1978 in the United Kingdom[7] and is cited in literature in the United States.[7] The goal of this study was to determine what vehicle characteristics contributed to trucks rolling over, particularly articulated trucks. The study found that articulated vehicles were twice as likely to roll over as rigid vehicles in all maneuvers leading to injury accidents, and at roundabouts they were four times as likely to roll over.

The research team used three methods to evaluate the roll stability of different trucks. They conducted tilt tests in which they tilted the trucks on a platform until the truck reached a point of balance. They drove some vehicles into rollover conditions to review the stability of different vehicles in these conditions. Finally, they conducted a computer simulation of truck rollovers and compared these to the dynamic tests to determine how well the computer simulation performed relative to the dynamic tests.

The results of this study revealed a number of findings. The tilt method was a good indication of roll stability. The computer simulation needed improvements on its modeling of the impact of springs on stability. Multiple turning maneuvers (an S-curve, or a roundabout) did not appear to increase the risk of a rollover above that of maneuvering through a single curve of the same radius. The lateral acceleration at rollover ranged from 0.2 g to 0.3 g (0.2 to 0.3 times the acceleration of gravity). The articulation angle between the tractor and trailer did not appear to have a significant effect on the roll stability of the vehicles. The trailers rolled more than the tractors and eventually pulled the tractors over.

The authors found that the height of the center of gravity of the vehicle and the load were significant factors in the roll behavior of trucks tested. Loads with high centers of gravity or with centers of gravity further forward than the center of the trailer may experience lower rollover speeds. When the suspension stiffness was higher, the lateral acceleration associated with rollover was higher. Trucks with higher suspension stiffness rolled less relative to the rear axle for a given lateral acceleration. Therefore, the authors concluded that some improvement in roll stability can be obtained by increasing the spring stiffness and using spring bases and overall width and track as wide as permitted. Liquid movement did not appear to have a significant effect on vehicle roll. Power steering did not cause more rollover crashes than manual steering.

The authors offered the opinion that the greatest reduction in rollover crashes may be reached by educating drivers that high speeds and sharp turns are the primary contributing factors to rollovers, and that rollovers can occur even at very low speeds within tight curves.

SUMMARY OF LITERATURE REVIEW

Several common themes from the five studies reviewed were noted and used to develop hypotheses for testing in the simulation modeling phase of the study. The impact of the truck's load and center of gravity is thought to have an impact on truck stability. The speed of the truck in the roundabout is expected to have a significant impact on the truck's likelihood of rollover. The impact of the circulatory roadway cross-section design is expected to impact the truck's stability, although not all of the studies agreed on what impact it would have. Finally, the design and use of the truck apron is expected to impact truck stability in roundabouts.

CHAPTER 3. TRUCK CRASH REVIEW

To help inform the truck stability modeling conducted later in this project, as well as to verify that a better understanding of this issue is needed, the project team conducted a review of truck crashes. A combination of Internet searches, professional contacts, and personal knowledge from project team members, state and local agencies, and FHWA staff helped to identify possible truck crashes at roundabouts in the United States. The project team collected and analyzed crash reports and news stories for 37 crashes.

The crash review produced the following observations. Of the 37 crashes identified, rollover crashes (over 30 crashes) were the most common crash type, followed by trucks getting stuck (3 crashes), fixed-object (1 crash), and sideswipe (1 crash). Speed was identified as a likely factor in five crashes; the presence of a high-speed approach (without confirmation of whether the driver was speeding) was identified in an additional crash. No information on actual travel speed at the time of the crash was available; therefore, this information is based on whether speed was mentioned as a contributing factor. Load shift was identified as a potential contributing factor in six crashes. Several truck types were involved in crashes, with truck-and-trailer combinations the most common. Other truck types included tankers (4 crashes), logging trucks (3 crashes), dump trucks (1 crash), and concrete trucks (1 crash). At least four crashes occurred at roundabouts that were reported to be newly constructed and therefore may have been unfamiliar to drivers. It was unclear what role the roadway cross-section and truck apron played in the majority of the crashes.

Observations from the crash review were consistent with issues identified in prior research. Rollover crashes appear to be a commonly reported type of truck crash at roundabouts, and speed is likely a key contributing factor to rollover crashes.

CHAPTER 4. SIMULATION MODEL DESCRIPTION

TRUCK MODELS

For the simulation modeling portion of this research, trucks were modeled and tested in TruckSim®. TruckSim® is a multibody simulation program that is designed for simulating and analyzing the dynamic behavior of medium to heavy trucks, buses, and articulated vehicles.[8] The mathematical models in TruckSim® are built on decades of research in characterizing vehicles and reproducing their behavior with mathematical models [10], which provides reasonably accurate simulation results. In addition, the road input components in TruckSim® can create complicated road models such as roundabouts.

To create truck models in TruckSim®, users first select a configuration and then define the vehicle parameters. In general, a vehicle consists of several systems, such as tires, suspension system, steering system, powertrain, and so forth. The performance of each of these systems is defined by several key parameters. In TruckSim®, these key parameters and the dimensions and weight properties for the tractor and trailer are used to build a truck model. When the configuration and all the parameters are determined by the user, TruckSim® creates a parametric truck model and uses the parameters in its mathematical models to derive simulation results.

Truck Configurations

Three truck configurations commonly operated on the roads were selected and modeled for this study. The first was a WB-67 interstate semi-trailer, a combination of a (1) three-axle tractor with a 5.69 m (18.7-ft) wheelbase and (2) a two-axle, 16.2 m (53-ft) long box trailer. WB-67 indicates that the combined wheelbase (the distance from tractor's front axle to the center line of trailer's two rear axles) is 20.4-m (67-ft). In addition, the tractor and trailer are hitched by a fifth-wheel coupling, widely used in North America. Hence, in dynamic modeling, the tractor and trailer act as two jointed bodies; i.e., when a semi-truck is moving, its tractor and trailer may have different dynamic responses to road and steering inputs.

The second modeled truck configuration is the SU-30 single-unit truck, a two-axle truck with a cuboid-shaped cargo area. The wheelbase for this single-unit truck model is 6.1-m (20-ft), and the length is 9.1m (30-ft). The single-unit truck's cargo area is fixed to the vehicle body, and it behaves as one body in dynamics, unlike articulated vehicles. According to prior research, the single-unit truck may be more stable when traversing roundabouts.

The last truck configuration is the B-train, a combination of a tractor (identical to that used in the WB-67) with double trailers (each 12.2-m (40-ft) long with a wheelbase of 10.9-m (35.8-ft). The resulting truck configuration is approximately the same length as the WB-92D design vehicle. A fifth-wheel coupling is used between the tractor and the first trailer, and between the first trailer and the second trailer. Thus, this combination performs as three jointed bodies in dynamics. This configuration can be used to determine whether adding length and pivot points decreases truck lateral stability at roundabouts.

Truck Parameters

The parameters for these three truck configurations are listed in table 2 through table 6. The dimensions are those for typical design vehicles from “A Policy on Geometric Design of Highways and Streets (2011),” published by the American Association of State Highway and Transportation Officials.[9] The weight properties of the three truck configurations were determined depending on the truck type. The full weight for the semi-truck was set to meet the maximum gross weight limit without special permit that states enforce on the interstate system, 36,300 kg (80,000 lbs). The gross weight for single-unit trucks was determined based on trucks commonly operated on roadways. For the tractor with double trailers, the general weight limit for all vehicles is 36,300 kg (80,000 lbs); however, overload permits can be issued. This overload gross weight limit varies from state to state, and in some states it is not specified. According to a report,[10] the gross weight for a tractor with double trailers, representing the average overloaded truck weight limits in Minnesota and its neighboring states and provinces, is 63,500 kg (140,000 lbs).

The loads fixed to the trailers were assumed to have a uniform density and rectangular shape. For simulating full-load conditions, the load was assumed to fill the entire trailer. In the half-full cases, the simulated load was assumed to fill the bottom half of the trailer. Shifting loads were not considered here; however, as a major issue in heavy truck steering dynamics, they should be considered in follow-up studies.

Table 2. Dimensions of WB-67 model.

Item	Property	Tractor	Trailer
1	Wheelbase	5.69 m (224.0 in.)	13.26 m (522.0 in.)
2	Bogie Spread	1.28 m (50.4 in.)	1.22 m (48.0 in.)
3	Track Width	1.84 m (72.5 in.)	1.84 m (72.5 in.)
4	Fifth Wheel Height	1.10 m (43.3 in.)	---
5	Length	7.48 m (294.5 in.)	16.15 m (636.0 in.)
6	Width	1.75 m (96.0 in.)	2.59 m (102.0 in.)
7	Height	2.87 m (113.0 in.)	3.83 m (150.4 in.)

Table 3. Weight properties of WB-67 model.

Component(s)	Weight
Tractor	8435 kg (18,600 lbs)
Trailer (Empty)	6531 kg (14,400 lbs)
Tractor + Trailer (Empty)	14966 kg (33,000 lbs)
Tractor + Trailer (Half full)	25624 kg (56,500 lbs)
Tractor + Trailer (Full)	36281 kg (80,000 lbs)

Table 4. Center of gravity estimates of semi-truck (WB-67) model.

Component(s)	x_{CG}	y_{CG}	z_{CG}
Tractor	-2.35 m (-92.5 in.)	0.0 in.	0.96 m (37.8 in.)
Tractor + Trailer (Empty)	-15.86 m (-264.6 in.)	0.0 in.	1.17 m (46.1 in.)
Tractor + Trailer (Half full)	-8.94 m (-352.0 in.)	0.0 in.	1.78 m (70.1 in.)
Tractor + Trailer (Full)	-12.13 m (-477.6 in.)	0.0 in.	2.33 m (91.7 in.)
Note: The *x*-axis runs from the back of the trailer to the front of the cab, with zero at the tractor front-axle center line; the *y*-axis runs along the front axle from the left side of the truck to the right side of the truck, with zero at the middle of the axle; and the *z*-axis runs from the ground to the top of the truck, with zero at the ground.			

Table 5. Dimensions and weight of single-unit truck (SU-30) model.

Item	Property	SU-30
1	Wheelbase	6.10 m (240.0 in.)
2	Length	9.14 m (360.0 in.)
3	Height	3.81 m (150.0 in.)
4	Width	2.44 m (96.0 in.)
5	Gross weight	1270 kg (28,000 lbs)

Table 6. Dimensions and weight of a tractor with double trailers (B-train) model.

Item	Property	Tractor	1st trailer	2nd trailer
1	Wheelbase	5.69 m (224.0 in.)	10.92 m (430.0 in.)	10.92 m (430.0 in.)
2	Length	7.48 m (294.5 in.)	12.19 m (480.0 in.)	12.19 m (480.0 in.)
3	Height	2.87 m (113.0 in.)	3.81 m (150.0 in.)	3.81 m (150.0 in.)
4	Width	2.44 m (96.0 in.)	2.44 m (96.0 in.)	2.44 m (96.0 in.)
5	Gross weight	63500 kg (140,000 lbs) (tractor and trailers)	n/a	n/a

Baseline Truck

In this study, a baseline truck was chosen, and its characteristics were modified to determine the effects of truck characteristics on lateral stability in roundabouts. Of the three commonly operated truck configurations chosen and discussed in prior sections, the WB-67 semi-truck is used more widely than the tractor with double trailers. Although SU-30 trucks are also common, the goal of this study was to evaluate the dynamic behavior of heavy articulated trucks. Therefore, the fully loaded WB-67 semi-truck of GVWT 36,300 kg (80,000 lbs) was selected as the baseline truck model. Its characteristics are described in table 2 through table 4.

ROUNDABOUT MODELS

Modeling Roundabouts

The TruckSim® "Road Segment Builder" and "Road Off-Center Elevation" tools were used in this study to create roundabout models. The horizontal road geometry for a left-turn movement through a roundabout is assembled and simulated using a series of road segments, the first being a straight segment (approaching roadway), followed by a segment curving to the right (entry curve), a segment curving to the left (partial circumference of central island), a segment curving to the right (exit curve), and finally a straight segment (exit roadway). After the horizontal geometry of a road model is determined, the user inputs its vertical geometry using the "Road Off-Center Elevation" tool by specifying the elevation along the road's lateral coordinate.

Roundabout Components

Figure 4 shows a roundabout's basic geometric components and dimensions.

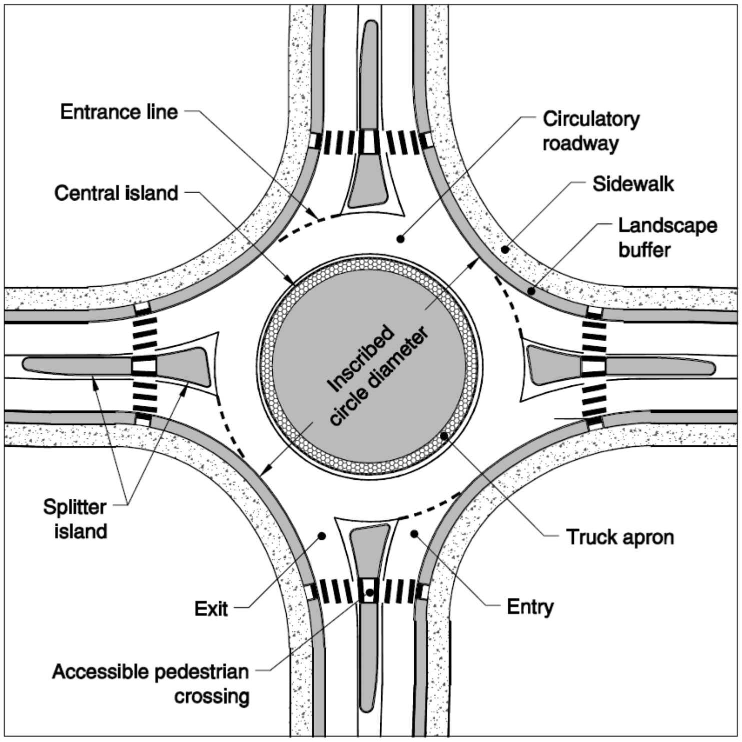


Figure 4. Diagram. Basic geometric elements of a roundabout, adapted from Exhibit 6-2 in NCHRP Report 672.[11]

The roundabout entry plays an important role in roundabout design, for both safety and operation. The entry curve is designed to force the vehicle to slow down before entering the roundabout. The cross-slope of an approaching roadway is usually 2% outward for drainage, meaning the left side of the roadway is higher than the right side. The entry radius is determined by the type of roundabout (single-lane or two-lane) and the roundabout's diameter, among other factors.

The roundabout interior consists of a central island, circulatory roadway, and, for some roundabouts, a truck apron. The central island is a non-traversable elevated area in the center of the roundabout. Vehicles travel around the central island in a counterclockwise direction along the circulatory roadway, which may have one or more lanes. The circulatory roadway's cross-section can have a constant cross-slope or a crown, where the inner section of the circulatory roadway has an inward cross-slope, and the outer section has an outward cross-slope. A truck apron is an additional paved area around the central island allowing large vehicles to over-track without compromising the deflection for smaller vehicles.[11]

The design of a roundabout, like any intersection, requires designers to consider many factors, including operation, safety, and context. This study on truck stability focused on the following key design elements for roundabouts, which were used to create the roundabout models for the simulations:

Number of lanes: Single-lane or two-lane.

Inscribed circle diameter (ICD): This is the distance across the circle from outer edge to outer edge of the circulatory roadway pavement.

Circulatory roadway width: This is the radial distance between the inner edge and the outer edge of the circulatory roadway.

Circulatory roadway cross-slope: The two circulatory roadway slope scenarios considered for this study consisted of (1) a uniform 2% slope away from inner edge to outer edge, and (2) a crowned slope where the inner two thirds of the circulatory roadway sloped to inner edge at 2% and the outer one third sloped to outer edge at 2%.

Truck apron: The truck apron was designed to be 0.0762-m (3-in.) higher than the circulatory roadway, 3.96-m (13-ft) wide, and to have a 2% cross-slope to the outside of the roundabout.

Central island diameter: The central island diameter was calculated as the difference between the roundabout ICD and twice the circulatory roadway width.

Roundabout tilt: Some intersections' topography requires that the roundabout be tilted on a constant plane. For a tilted roundabout, the entire roundabout is tilted at a constant slope. Three basic tilted slopes were considered, as shown in figure 5: no tilt, positive tilt (roundabout is tilted outward), and negative tilt (roundabout is tilted inward). Four tilted slopes were considered in this study: 4 %, 2 %, -4 % and -2 %.

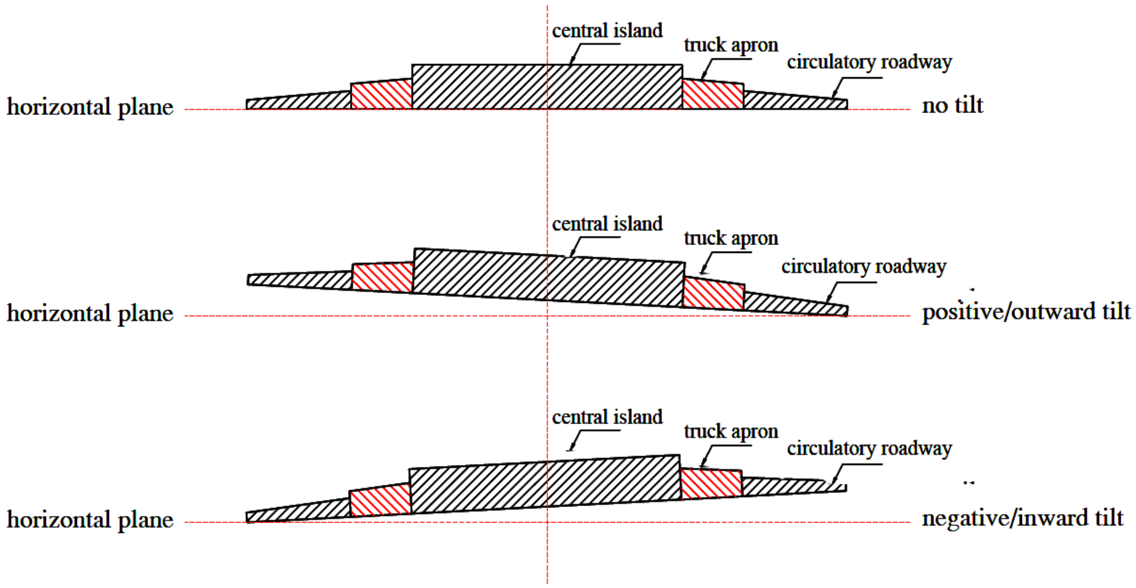


Figure 5. Diagram. Roundabout tilt from the perspective of a driver on the approaching roadway.

Roundabout exit layout is similar to entry layout. The exit curve that connects the circulatory roadway and exit roadway also has a cross-slope of 2% outward. In general, the exit radius is larger than the entry radius. The exit radius is also determined by whether the roundabout is single-lane or two-lane, the roundabout's diameter, and other factors.

Roundabout Parameters

Roundabout design parameters can change from site to site. The roundabout parameters used in this study were determined through consultation with the research team and are intended to be representative of more common design elements.

Single-lane and two-lane roundabout models were created, and their parameters are listed in table 7. Roundabouts with ICDs of 45.7-m (150-ft) and smaller are single-lane, and those with ICDs greater than 45.7-m (150-ft) are two-lane.

Table 7. Roundabout parameters.

Case	ICD [m (ft)]	Type	Entry radii [m (ft)]	Exit radii [m (ft)]	Circulatory Roadway width [m (ft)]	Truck apron	Road crown	Tilt
1	33.5 (110)	Single	22.9 (75)	45.7 (150)	6.1 (20)	Applied	N/A	N/A
2	39.6 (130)	Single	22.9 (75)	45.7 (150)	6.1 (20)	Applied	N/A	N/A
3*	42.7 (140)	Single	22.9 (75)	45.7 (150)	6.1 (20)	Applied	N/A	N/A
4	42.7 (140)	Single	22.9 (75)	45.7 (150)	6.1 (20)	Applied	N/A	Applied
5	45.7 (150)	Single	22.9 (75)	45.7 (150)	6.1 (20)	Applied	N/A	N/A
6	51.8 (170)	Multi	30.5 (100)	122 (400)	9.1 (30)	N/A	N/A	N/A
7**	54.9 (180)	Multi	30.5 (100)	122 (400)	9.1 (30)	N/A	N/A	N/A
8	54.9 (180)	Multi	30.5 (100)	122 (400)	9.1 (30)	Applied	N/A	N/A
9	54.9 (180)	Multi	30.5 (100)	122 (400)	9.1 (30)	Applied	Applied	N/A
10	54.9 (180)	Multi	30.5 (100)	122 (400)	9.1 (30)	N/A	N/A	Applied
11	57.9 (190)	Multi	30.5 (100)	122 (400)	9.1 (30)	N/A	N/A	N/A
12	64.0 (210)	Multi	30.5 (100)	122 (400)	9.1 (30)	N/A	N/A	N/A

*Baseline single-lane roundabout

**Baseline two-lane roundabout

Baseline Roundabouts

Baseline Single-lane Roundabout

The baseline single-lane roundabout has an ICD of 42.7 m (140-ft), a typical ICD for single-lane roundabouts. The rest of the baseline roundabout's parameters are listed in row three of table 7.

The horizontal geometry of the baseline roundabout is shown in figure 6. The hatched area encircling the central island represents the truck apron. Vehicles approach from the left-hand-side to perform the right turn, through-movement, or left turn.

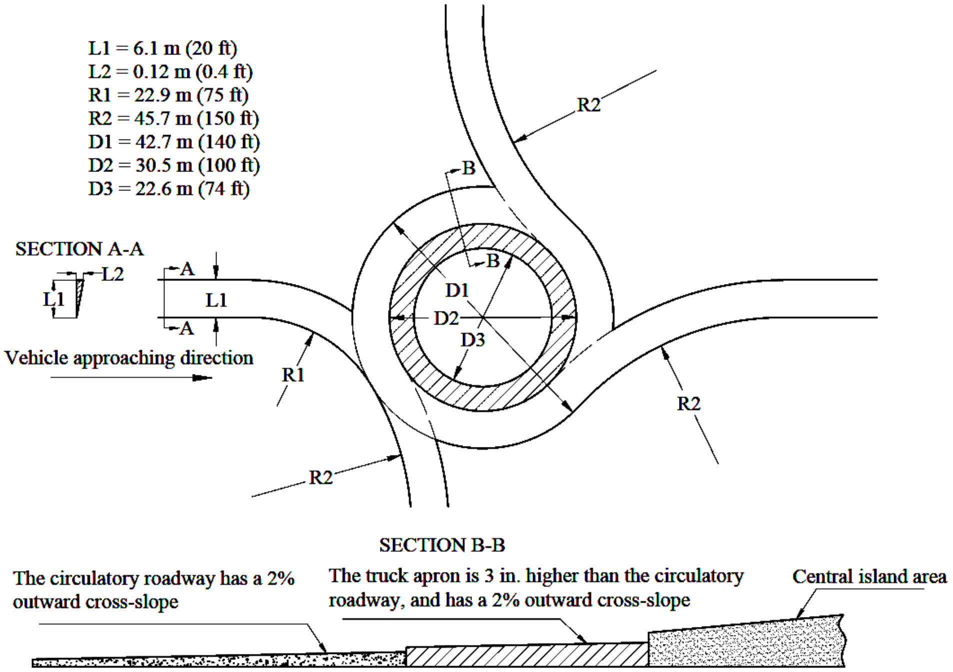


Figure 6. Diagram. Horizontal geometry of 42.7-m (140-ft) baseline single-lane roundabout model.

The cross-sectional geometry of the baseline roundabout is shown in figure 7. The numbers in the rectangles illustrate the vertical height. Detail ① shows the entry geometry, and detail ② shows the exit geometry (the exit geometry is the same for all three movements). The approaching roadway has a 2% outward cross-slope, thus for a 6.1-m (20-ft) roadway, its left edge is 0.12-m (0.4-ft) higher than the right edge. There are two transition areas that transfer the road's vertical geometry from that of the approaching roadway to that of the circulatory roadway. Transition area 1 is where the left edge of the approaching roadway is lowered to match the outer edge of the circulatory roadway, and is 6.1-m (20-ft) long. Transition area 2 is where the lowered left edge of the roadway is raised to meet the circulatory roadway's inner edge, and is 9.6-m (31.5-ft) long. There are also two similar transition areas transferring the vertical roadway geometry from that of the circulatory roadway to that of the exit roadway, as shown in figure 7. In all transition areas, the elevation increases or decreases linearly with respect to the length of the arcs or lines.

Section A-A in figure 6 shows the cross-sectional geometry for the approaching roadway, and Section B-B in figure 7 shows the cross-sectional geometry of the circulatory roadway.

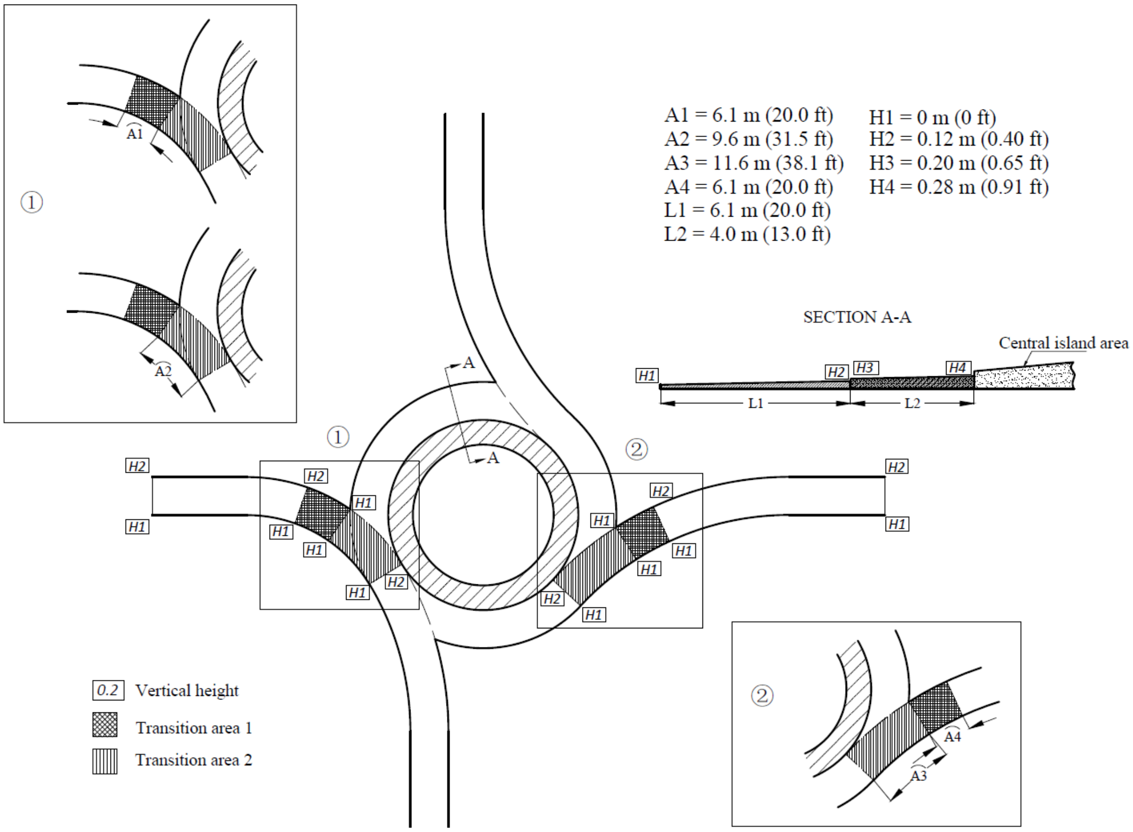


Figure 7. Diagram. Cross-sectional geometry of 42.7-m (140-ft) baseline single-lane roundabout model.

Baseline Two-lane Roundabout

The baseline two-lane roundabout is designed to have two lanes and a 54.9-m (180-ft) ICD. The parameters for the baseline roundabout are listed in row seven of table 7. The model of the two-lane baseline roundabout is similar to that of the single-lane baseline roundabout, except that the geometric parameters, such as entry radii, exit radii, and roadway width, are different.

Figure 8 illustrates the baseline two-lane roundabout's horizontal geometry and the cross-sectional geometry of the entry and circulatory roadways.

Figure 9 illustrates the baseline two-lane roundabout's horizontal geometry, transition areas, and the cross-sectional geometry of the circulatory roadway. In figure 8, detail ① shows the entry geometry, and detail ② shows the exit geometry, and there are two transition areas where the vertical geometries of the approaching and exit roadways are matched to that of the circulatory roadway in the same way as for the single-lane roundabout. For the two-lane roundabout, transition area 1 is 9.1-m (30-ft) long, and transition area 2 is 12.2-m (40-ft) long. Entry transition areas are similar to exit transition areas, and within a transition area the elevation increases or decreases linearly with respect to the length of the arcs or lines.

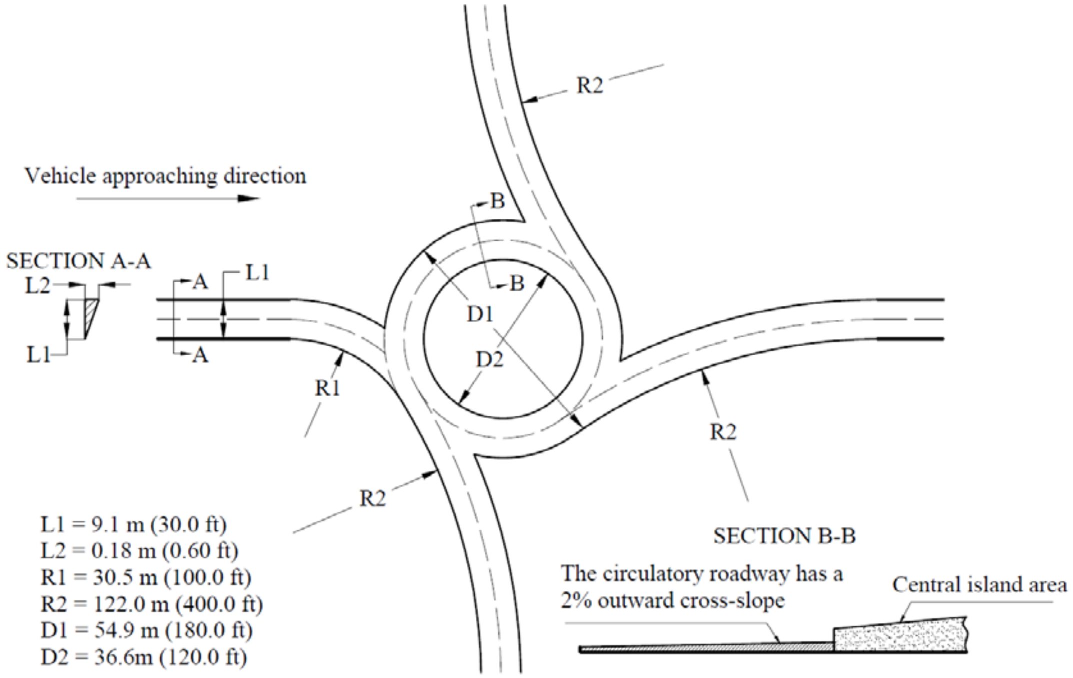


Figure 8. Diagram. Horizontal geometry of 54.9-m (180-ft) baseline two-lane roundabout model.

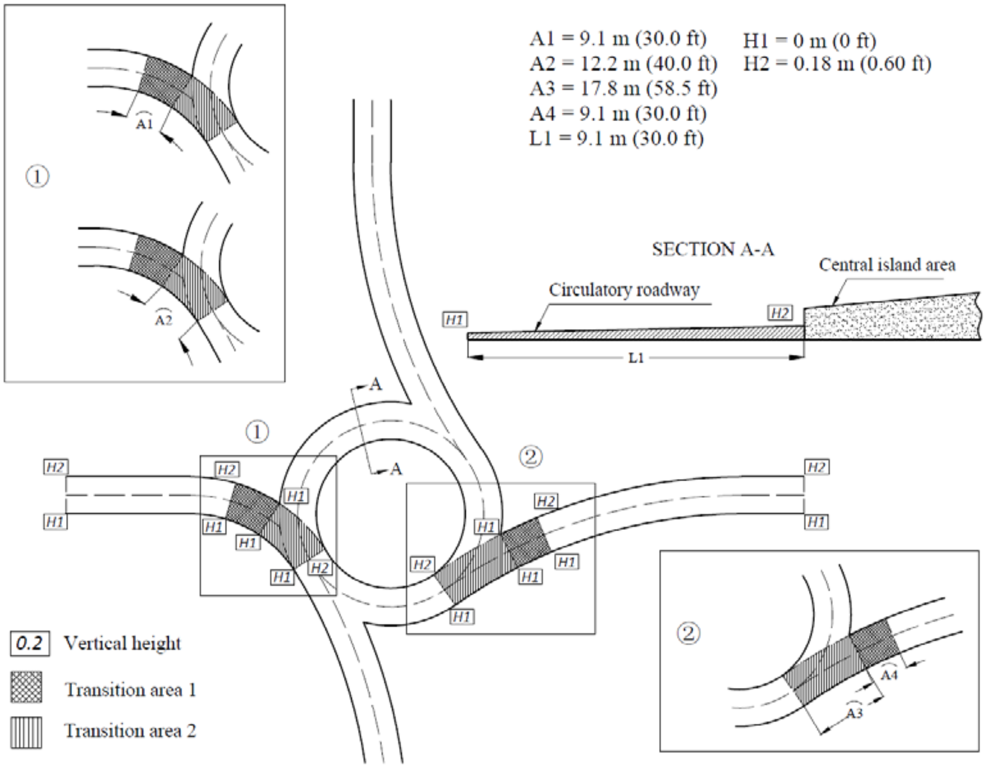


Figure 9. Diagram. Cross-sectional geometry of 54.9-m (180-ft) baseline two-lane roundabout model.

CHAPTER 5. SIMULATION CASE STUDIES

It is suspected that a combination of vehicle characteristics and roadway design elements, along with driver behavior, potentially contribute to the risk of truck overturns at roundabouts. Six features were selected to investigate in this study: truck configuration, load configuration, entry speed, ICD, circulatory roadway cross-section, and roundabout tilt. To perform a parametric study, each case was modeled separately, and only one factor (truck characteristic or roundabout parameter, depending on the case) was modified from the baseline, while the other parameters were kept constant. Then the results for each case were compared with the baseline to determine a parameter's effect on truck lateral stability. For each test, three truck movements through each roundabout were simulated: right turns, through movements, and left turns.

In total, 106 separate cases were created and tested. The details for the cases are summarized in table 8. The terms and abbreviations used in table 8 are:

ICD: Inscribed Circle Diameter.

Lanes: number of lanes (one or two).

Entry/Exit: entry radius and exit radius.

Width: roadway width.

Cross-slope: circulatory roadway cross-slope.

Crown/Apron/Tilt: whether roundabout has road crown, truck apron or tilted slope.

Truck Type: WB-67 semi-truck, SU-30 single-unit truck, or a B-train tractor with double trailers.

Truckload: truckload conditions – empty, half full or full.

Truck Speed: truck travel speed. For example, "32/24/32 (20/15/20)" means that the truck enters at 32 km/h (20 mph), then slows down to 24 km/h (15 mph) to circulate, and accelerates to 32 km/h (20 mph) when exiting the roundabout.

Maneuver: the movements that truck performs to travel through the roundabout. In two-lane cases, 'through (left)' means the truck enters in the left lane and then straddles both lanes to circulate, whereas 'through (right)' means the truck enters in right lane and straddles both lanes to circulate. In addition, 'through (apron)' or 'left (apron)' indicates that the truck enters and keeps the in left lane without straddling to drive through the roundabout, as truck apron is present to accommodate the off-tracking and therefore no straddling is needed.

In table 8 below, the base cases are highlighted in yellow (*), and the modified element in each case is highlighted in gray (†) or green (^).

Table 8. Roundabout dynamic modeling cases.

Case	ICD (m [ft])	Lanes	Entry Curve Radius (m)	Exit Curve Radius (m)	Roadway Width (m)	Cross-slope	Crown	Apron	Tilt	Truck Type	Truck Load	Truck Speed (entry/circle/exit, km/h)	Maneuver
1*	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB-67	Full	32/24/32	Right turn
2*	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB-67	Full	32/24/32	Through
3*	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB-67	Full	32/24/32	Left turn
4	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	B-train^	Full	32/24/32	Right turn
5	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	B-train^	Full	32/24/32	Through
6	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	B-train^	Full	32/24/32	Left turn
7	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	SU-30†	Full	32/24/32	Right turn
8	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	SU-30†	Full	32/24/32	Through
9	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	SU-30†	Full	32/24/32	Left turn
10	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB-67	Empty^	32/24/32	Right turn
11	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB-67	Empty^	32/24/32	Through
12	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB-67	Empty^	32/24/32	Left turn
13	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB-67	Half†	32/24/32	Right turn
14	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB-67	Half†	32/24/32	Through
15	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB-67	Half†	32/24/32	Left turn
16	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	4%^	WB-67	Full	32/24/32	Right turn
17	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	4%^	WB-67	Full	32/24/32	Through
18	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	4%^	WB-67	Full	32/24/32	Left turn
19	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	2%†	WB-67	Full	32/24/32	Right turn
20	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	2%†	WB-67	Full	32/24/32	Through
21	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	2%†	WB-67	Full	32/24/32	Left turn
22	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	-4%^	WB-67	Full	32/24/32	Right turn
23	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	-4%^	WB-67	Full	32/24/32	Through
24	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	-4%^	WB-67	Full	32/24/32	Left turn

* = Base Case; ^ = modified element (gray); † = modified element (green)

Case	ICD (m [ft])	Lanes	Entry Curve Radius (m)	Exit Curve Radius (m)	Roadway Width (m)	Cross - slope	Crown	Apron	Tilt	Truck Type	Truck Load	Truck Speed (entry/circle/ exit, km/h)	Maneuver
25	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	-2%†	WB -67	Full	32/24/32	Right turn
26	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	-2%†	WB -67	Full	32/24/32	Through
27	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	-2%†	WB -67	Full	32/24/32	Left turn
28	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB -67	Full	24/24/24^	Right turn
29	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB -67	Full	24/24/24^	Through
30	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB -67	Full	24/24/24^	Left turn
31	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB -67	Full	40/24/40†	Right turn
32	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB -67	Full	40/24/40†	Through
33	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB -67	Full	40/24/40†	Left turn
34*	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Right turn
35*	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Through (left)
36*	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Through (right)
37*	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Left turn
38	54.9 (180)	2	30.5	122	9.1	2%	N/A	Applied^	N/A	WB -67	Full	32/24/32	Through (apron)
39	54.9 (180)	2	30.5	122	9.1	2%	N/A	Applied^	N/A	WB -67	Full	32/24/32	Left turn
40	54.9 (180)	2	30.5	122	9.1	N/A	Applied†	Applied†	N/A	WB -67	Full	32/24/32	Right turn
41	54.9 (180)	2	30.5	122	9.1	N/A	Applied†	Applied†	N/A	WB -67	Full	32/24/32	Through (left)
42	54.9 (180)	2	30.5	122	9.1	N/A	Applied†	Applied†	N/A	WB -67	Full	32/24/32	Through (right)
43	54.9 (180)	2	30.5	122	9.1	N/A	Applied†	Applied†	N/A	WB -67	Full	32/24/32	Through (apron)
44	54.9 (180)	2	30.5	122	9.1	N/A	Applied†	Applied†	N/A	WB -67	Full	32/24/32	Left turn
45	54.9 (180)	2	30.5	122	9.1	N/A	Applied†	Applied†	N/A	WB -67	Full	32/24/32	Left turn (apron)
46	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	B- train^	Full	32/24/32	Right turn
47	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	B- train^	Full	32/24/32	Through (left)
48	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	B- train^	Full	32/24/32	Through (right)
49	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	B- train^	Full	32/24/32	Left turn

* = Base Case; ^ = modified element (gray); † = modified element (green)

Case	ICD (m [ft])	Lanes	Entry Curve Radius (m)	Exit Curve Radius (m)	Roadway Width (m)	Cross - slope	Crown	Apron	Tilt	Truck Type	Truck Load	Truck Speed (entry/circle/ exit, km/h)	Maneuver
50	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	SU -30†	Full	32/24/32	Right turn
51	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	SU -30†	Full	32/24/32	Through (left)
52	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	SU -30†	Full	32/24/32	Through (right)
53	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	SU -30†	Full	32/24/32	Left turn
54	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Empty^	32/24/32	Right turn
55	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Empty^	32/24/32	Through (left)
56	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Empty^	32/24/32	Through (right)
57	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Empty^	32/24/32	Left turn
58	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Half†	32/24/32	Right turn
59	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Half†	32/24/32	Through (left)
60	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Half†	32/24/32	Through (right)
61	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Half†	32/24/32	Left turn
62	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	4%^	WB -67	Full	32/24/32	Right turn
63	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	4%^	WB -67	Full	32/24/32	Through (left)
64	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	4%^	WB -67	Full	32/24/32	Through (right)
65	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	4%^	WB -67	Full	32/24/32	Left turn
66	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	2%†	WB -67	Full	32/24/32	Right turn
67	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	2%†	WB -67	Full	32/24/32	Through (left)
68	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	2%†	WB -67	Full	32/24/32	Through (right)
69	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	2%†	WB -67	Full	32/24/32	Left turn
70	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	-4%^	WB -67	Full	32/24/32	Right turn
71	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	-4%^	WB -67	Full	32/24/32	Through (left)
72	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	-4%^	WB -67	Full	32/24/32	Through (right)
73	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	-4%^	WB -67	Full	32/24/32	Left turn
74	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	-2%†	WB -67	Full	32/24/32	Right turn
75	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	-2%†	WB -67	Full	32/24/32	Through (left)

* = Base Case; ^ = modified element (gray); † = modified element (green)

Case	ICD (m [ft])	Lanes	Entry Curve Radius (m)	Exit Curve Radius (m)	Roadway Width (m)	Cross - slope	Crown	Apron	Tilt	Truck Type	Truck Load	Truck Speed (entry/circle/ exit, km/h)	Maneuver
76	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	-2%†	WB -67	Full	32/24/32	Through (right)
77	54.9 (180)	2	30.5	122	9.1	N/A	N/A	N/A	-2%†	WB -67	Full	32/24/32	Left turn
78	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	24/24/24^	Right turn
79	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	24/24/24^	Through (left)
80	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	24/24/24^	Through (right)
81	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	24/24/24^	Left turn
82	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	40/24/40†	Right turn
83	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	40/24/40†	Through (left)
84	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	40/24/40†	Through (right)
85	54.9 (180)	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	40/24/40†	Left turn
86^	33.5 (110)^	1	23	150	6.1	2%	N/A	Applied	N/A	WB -67	Full	32/16/32	Right turn
87^	33.5 (110)^	1	23	150	6.1	2%	N/A	Applied	N/A	WB -67	Full	32/16/32	Through
88^	33.5 (110)^	1	23	150	6.1	2%	N/A	Applied	N/A	WB -67	Full	32/16/32	Left turn
89†	39.6 (130)†	1	23	150	6.1	2%	N/A	Applied	N/A	WB -67	Full	32/16/32	Right turn
90†	39.6 (130)†	1	23	150	6.1	2%	N/A	Applied	N/A	WB -67	Full	32/16/32	Through
91†	39.6 (130)†	1	23	150	6.1	2%	N/A	Applied	N/A	WB -67	Full	32/16/32	Left turn
92^	45.7 (150)^	1	23	150	6.1	2%	N/A	Applied	N/A	WB -67	Full	32/24/32	Right turn
93^	45.7 (150)^	1	23	150	6.1	2%	N/A	Applied	N/A	WB -67	Full	32/24/32	Through
94^	45.7 (150)^	1	23	150	6.1	2%	N/A	Applied	N/A	WB -67	Full	32/24/32	Left turn
95†	51.8 (170)†	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Right turn
96†	51.8 (170)†	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Through (left)
97†	51.8 (170)†	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Through (right)
98†	51.8 (170)†	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Left turn
99^	57.9 (190)^	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Right turn
100^	57.9 (190)^	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Through (left)
101^	57.9 (190)^	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Through (right)

* = Base Case; ^ = modified element (gray); † = modified element (green)

Case	ICD (m [ft])	Lanes	Entry Curve Radius (m)	Exit Curve Radius (m)	Roadway Width (m)	Cross - slope	Crown	Apron	Tilt	Truck Type	Truck Load	Truck Speed (entry/circle/ exit, km/h)	Maneuver
102^	57.9 (190)^	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Left turn
103†	64.0 (210)†	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Right turn
104†	64.0 (210)†	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Through (left)
105†	64.0 (210)†	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Through (right)
106†	64.0 (210)†	2	30.5	122	9.1	2%	N/A	N/A	N/A	WB -67	Full	32/24/32	Left turn
107	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB -67	Full	32/16/32†	Left turn
108	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB -67	Empty^	32/16/32^	Left turn
109	42.7 (140)	1	23	45.7	6.1	2%	N/A	Applied	N/A	WB -67	Half†	32/16/32†	Left turn
110	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	4%^	WB -67	Full	32/16/32^	Left turn
111	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	2%†	WB -67	Full	32/16/32†	Left turn
112	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	-4%^	WB -67	Full	32/16/32^	Left turn
113	42.7 (140)	1	23	45.7	6.1	N/A	N/A	Applied	-2%†	WB -67	Full	32/16/32†	Left turn
114	54.9 (180)	2	30.5	122	9.1	2%	N/A	Applied^	N/A	WB -67	Full	32/16/32^	Left turn (apron)
115	54.9 (180)	2	30.5	122	9.1	N/A	Applied†	Applied†	N/A	WB -67	Full	32/16/32†	Left turn (apron)

* = Base Case; ^ = modified element (gray); † = modified element (green)

TRUCK TRAVEL PATH

Three movement scenarios were modeled for single-lane roundabouts. The first was a right turn, where trucks shifted to the left side of the roadway when approaching the roundabout, kept left to accommodate off-tracking, and drove back to the middle of the road to exit the roundabout. Next was a through movement, where trucks first made a slight right turn, then a left turn, and finally a second right turn. For each turn, drivers would keep the vehicle to the outside edge of the lane to accommodate the long wheelbase. Therefore, the vehicle shifted to the left of roadway to make the first right turn, then drove to the right edge when circulating the central island, and finally swung back to the left edge to complete the second right turn. Last was a left-turn movement, where the path was similar to through movements, but the distance traveled in the circulatory roadway was longer.

A greater number of movement scenarios were modeled for two-lane roundabouts. The right-turn movement had vehicles approach from the right lane and then straddle both lanes to complete the turn. For through movements, there were three possible paths: in the first, the truck approached from the middle of the right lane and then straddled both lanes to make the through movement; in the second, the truck entered from the middle of the left lane and then straddled lanes to pass through the roundabout; and in the third, which was commonly performed by trucks in roundabouts with a truck apron, the vehicle kept in the left lane and drove through the roundabout without straddling lanes. The left turn movement depended on whether or not a truck apron was present; if present, the left turn movement had vehicles approach from the middle of the left lane and straddle both circulating lanes when completing the left turn, and when not present, the vehicles would approach from the middle of the left lane and use the left lane and apron without straddling lanes.

TRUCK SPEED

Given their long wheelbase, heavy load, and high center of gravity (CG), articulated-truck drivers usually drive slowly when negotiating roundabouts. This speed may vary from site to site, but is normally 16 km/h (10 mph) for smaller roundabouts and 24 km/h (15 mph) for larger roundabouts.

In practice, semi-truck drivers commonly feel uncomfortable when they experience a lateral acceleration of more than 0.2 g. Therefore, for this study, a lateral acceleration of 0.2 g served as the limit for deciding a proper circulating speed. When curvature is fixed, lateral acceleration is mainly determined by traveling speed, so the proper truck speed in this study was determined based on the roundabout diameters.

In most test cases for this study, the truck entered the roundabout at 32 km/h (20 mph), slowed down to a speed determined by the roundabout diameter, and accelerated back to 32 km/h (20 mph) when exiting the roundabout. Their acceleration time depended on roundabout diameter. For the roundabouts with a 33.5-m (110-ft) ICD and a 39.6-m (130-ft) ICD, the truck slowed down to 16 km/h (10 mph) in the 2.5 s after entering the roundabout. For the roundabouts with an ICD greater than 39.6 m (130-ft), the truck slowed down to 24 km/h (15 mph) within 2 s.

Those speeds were used for most of the test cases, except for the test cases that evaluated speed and whether the trucks could adequately maneuver the roundabout with an entry speed of 24, 32 or 40 km/h (15, 20, or 25 mph).

CHAPTER 6. SIMULATION RESULTS

The roundabout dynamic modeling cases, presented in table 8, consist of 106 separate cases that were tested to obtain the truck lateral dynamics for each scenario. In each case, three parameters were used to evaluate the truck dynamics: roll angle, lateral acceleration, and rollover index. The roll angle and lateral acceleration directly represent the vehicle dynamics; for example, lateral acceleration is strongly influenced by the speed, curvature of the turn, and road vertical geometry. Large lateral acceleration leads to large roll angle, which results in large side-to-side wheel unloading and high possibility of rollover. The dynamic relationship between lateral acceleration, roll angle, and the likelihood of rollover is influenced by both the vehicle and roadway design. If the lateral acceleration and vehicle body roll do not cause significant wheel unloading, then rollover will not occur.

ROLLOVER INDEX

Rollover index indicates the likelihood of rollover, and is calculated using the equation in figure 10:

$$Rollover\ Index = \frac{|F_{z_{left}} - F_{z_{right}}|}{F_{z_{left}} + F_{z_{right}}}$$

Figure 10. Equation. Rollover index.

Where:

F_{z_left} = Left wheel load (rear axles)

F_{z_right} = Right wheel load (rear axles)

For a WB-67 semi-truck, the left and right wheel loads (above) are the sum of the individual wheel loads for the dual wheels on the tandem axles (four on each side) of the tractor and trailer. For example, for the trailer we get the equations in figure 11 and figure 12:

$$F_{z\_left} = F_{z\_4li} + F_{z\_4lo} + F_{z\_5li} + F_{z_{5lo}}$$

Figure 11. Equation. Left wheel load (rear axles).

$$F_{z\_right} = F_{z\_4ri} + F_{z\_4ro} + F_{z\_5ri} + F_{z_{5ro}}$$

Figure 12. Equation. Right wheel load (rear axles).

Where:

F_{z_4li} = Wheel load, left side, inner wheel, trailer axle 1

F_{z_4lo} = Wheel load, left side, outer wheel, trailer axle 1

F_{z_5li} = Wheel load, left side, inner wheel, trailer axle 2

F_{z_5lo} = Wheel load, left side, outer wheel, trailer axle 2

F_{z_4ri} = Wheel load, right side, inner wheel, trailer axle 1

F_{z_4ro} = Wheel load, right side, outer wheel, trailer axle 1

F_{z_5ri} = Wheel load, right side, inner wheel, trailer axle 2

F_{z_5ro} = Wheel load, right side, outer wheel, trailer axle 2

Rollover index varies between zero and one. If there is no load transfer, the vertical loads on both left and right side are equivalent, and rollover index = 0. If all loads are transferred to one side, the terms of the equation in figure 10 become equal, resulting in rollover index = 1. Therefore, a rollover index equal to 0 describes a perfectly weight-balanced vehicle. A vehicle with a rollover index of 0.8 or less is capable of traveling through a roundabout while maintaining stability. Between 0.8 and 0.9 the vehicle becomes unstable, and if peak rollover index exceeds 0.9, the vehicle has a high likelihood of rollover. A peak rollover index equal to 1 describes a vehicle on the threshold of rolling over

EFFECT OF ROUNDABOUT ICD ON TRUCK STABILITY

The purpose of this test was to determine the effect of different ICDs on truck lateral dynamics. The truck model in this test was the baseline full-load semi-truck with an entry speed of 32 km/h (20 mph) for all cases. For roundabouts with a 33.5 m (110-ft) ICD and a 39.6-m (130-ft) ICD, the truck slowed down to 16.1 km/h (10 mph) after entering the roundabout. For the roundabouts with an ICD greater than 39.6 m (130-ft), the truck slowed down to 24 km/h (15 mph). For through movements at the two-lane roundabouts, two paths were followed. For one, the truck approached from the left lane, and then straddled both lanes to pass through the roundabout. For the other, the truck approached from the right lane, and then straddled both lanes to pass through the roundabout. All of the single-lane roundabout models had truck aprons, but the two-lane roundabout models did not.

The 21 cases testing roundabout ICD’s effect on truck stability are summarized in table 9; all dimensions not shown are unchanged within the set of single-lane and two-lane cases (see table 8 for details).

Table 9. Roundabout diameter cases considered for evaluating truck dynamics in roundabouts.

Case No.	Roundabout Diameter - ICD [m (ft)]	Type	Movement	Speed at entry/roundabout/exit [km/h (mph)]
86	33.5 (110)	Single-lane	Right turn	32/16/32 (20/10/20)
87	33.5 (110)	Single-lane	Through	32/16/32 (20/10/20)
88	33.5 (110)	Single-lane	Left turn	32/16/32 (20/10/20)
89	39.6 (130)	Single-lane	Right turn	32/16/32 (20/10/20)
90	39.6 (130)	Single-lane	Through	32/16/32 (20/10/20)
91	39.6 (130)	Single-lane	Left turn	32/16/32 (20/10/20)
92	45.7 (150)	Single-lane	Right turn	32/24/32 (20/15/20)
93	45.7 (150)	Single-lane	Through	32/24/32 (20/15/20)
94	45.7 (150)	Single-lane	Left turn	32/24/32 (20/15/20)
95	51.8 (170)	Two-lane	Right turn	32/24/32 (20/15/20)
96	51.8 (170)	Two-lane	Through (left lane)	32/24/32 (20/15/20)
97	51.8 (170)	Two-lane	Through (right lane)	32/24/32 (20/15/20)
98	51.8 (170)	Two-lane	Left turn	32/24/32 (20/15/20)
99	57.9 (190)	Two-lane	Right turn	32/24/32 (20/15/20)
100	57.9 (190)	Two-lane	Through (left lane)	32/24/32 (20/15/20)
101	57.9 (190)	Two-lane	Through (right lane)	32/24/32 (20/15/20)
102	57.9 (190)	Two-lane	Left turn	32/24/32 (20/15/20)
103	64.0 (210)	Two-lane	Right turn	32/24/32 (20/15/20)
104	64.0 (210)	Two-lane	Through (left lane)	32/24/32 (20/15/20)
105	64.0 (210)	Two-lane	Through (right lane)	32/24/32 (20/15/20)
106	64.0 (210)	Two-lane	Left turn	32/24/32 (20/15/20)

Right Turns

The results for rollover index for trucks performing right turns are shown in figure 13 and figure 14.

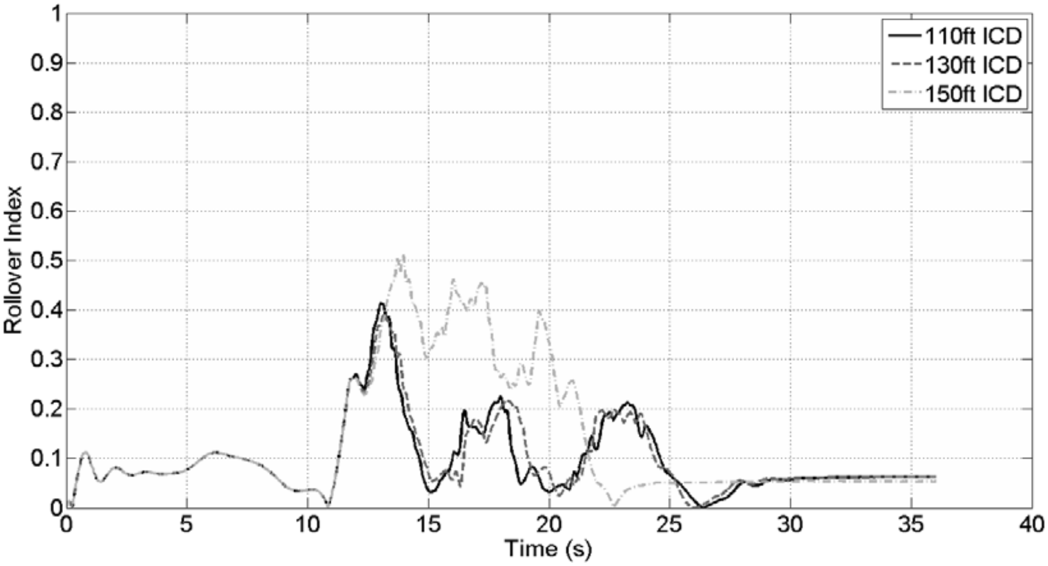


Figure 13. Graph. Effect of roundabout diameter on rollover index (single-lane roundabouts, right turn).

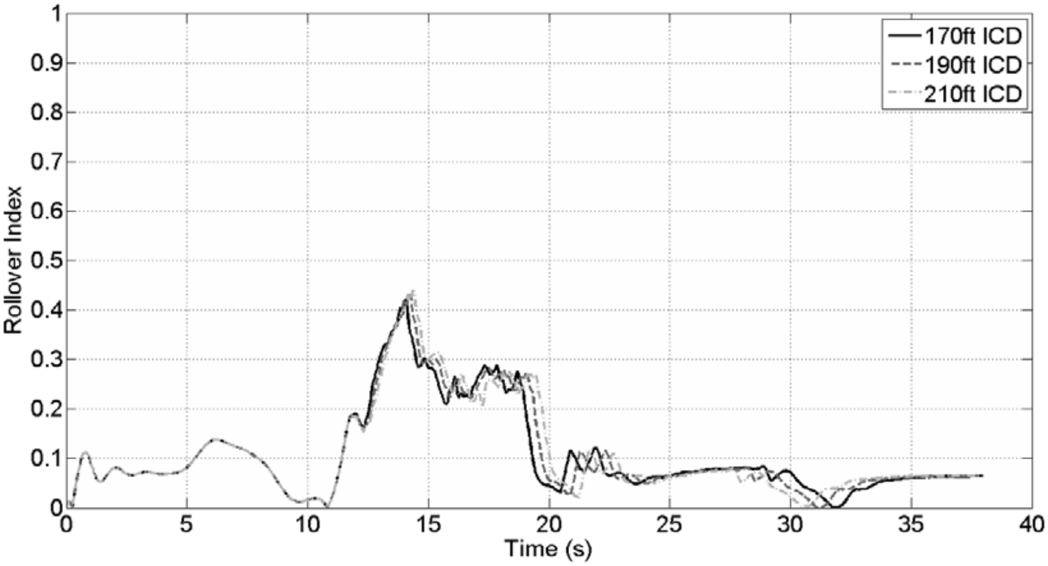


Figure 14. Graph. Effect of roundabout diameter on rollover index (two-lane roundabouts, right turn).

Figure 13 shows that, for single lane roundabouts, the rollover indices for right turns with a 33.5-m (110-ft) ICD and 39.6-m (130-ft) ICD were similar, but those for right turns with a 45.7-m (150-ft) ICD were much larger. This was because trucks negotiated a 45.7-m (150-ft) ICD roundabout at 24 km/h (15 mph), but negotiated the other two roundabouts at a slower 16 km/h (10 mph).

Figure 14 shows that, for two-lane roundabouts, the rollover indices for right turns were nearly identical for the three ICDs.

Through Movements

The results for rollover index for trucks performing through movements are shown in figure 15 and figure 16

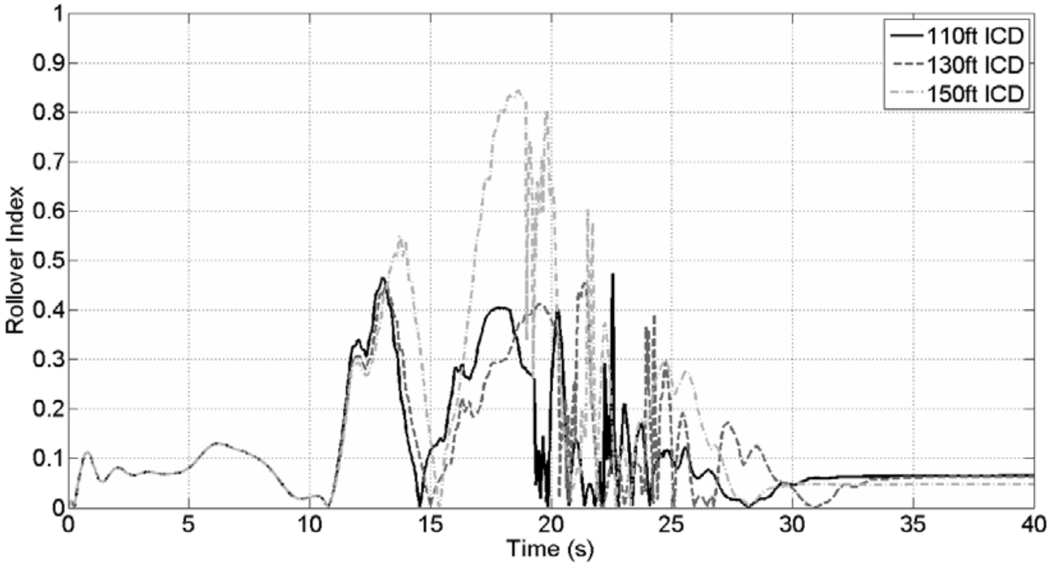


Figure 15. Graph. Effect of roundabout diameter on rollover index (single-lane roundabouts, through movement).

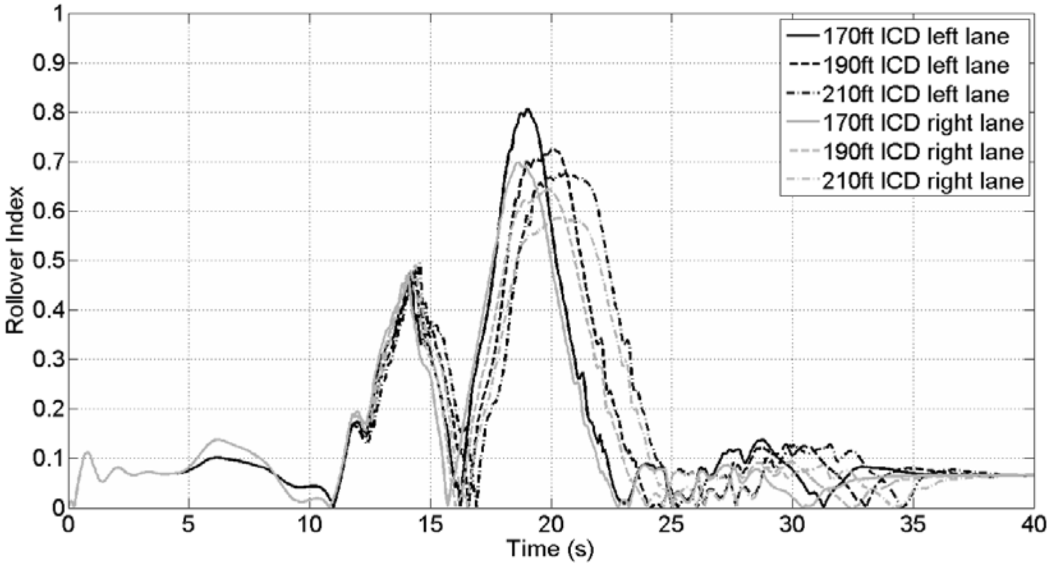


Figure 16. Graph. Effect of roundabout diameter on rollover index (two-lane roundabouts, through movement).

Figure 17 shows the trucks making through movements in single-lane roundabouts. The three ICDs have the same lateral dynamics for the first 13 s. After 13 s, the rollover indices diverge. The 39.6-m (130-ft) ICD again had the lowest rollover index, and the 45.7-m (150-ft) ICD had the largest rollover index, again due to the higher speed. At around 19 s, the trucks moved up onto the truck apron, rapidly changing the vertical load on both sides of the trucks and rocking them side-to-side, as shown by the narrow peaks and troughs between 19 s and 26 s in figure 18.

Figure 18 indicates that roundabouts with larger ICDs had smaller rollover indices and a lower likelihood of rollover. When the truck approached from the right lane and then straddled lanes, the rollover likelihood was smaller than when the truck approached from the left lane.

Left Turns

The results for rollover index for trucks performing left turns are shown in figure 17 and figure 18.

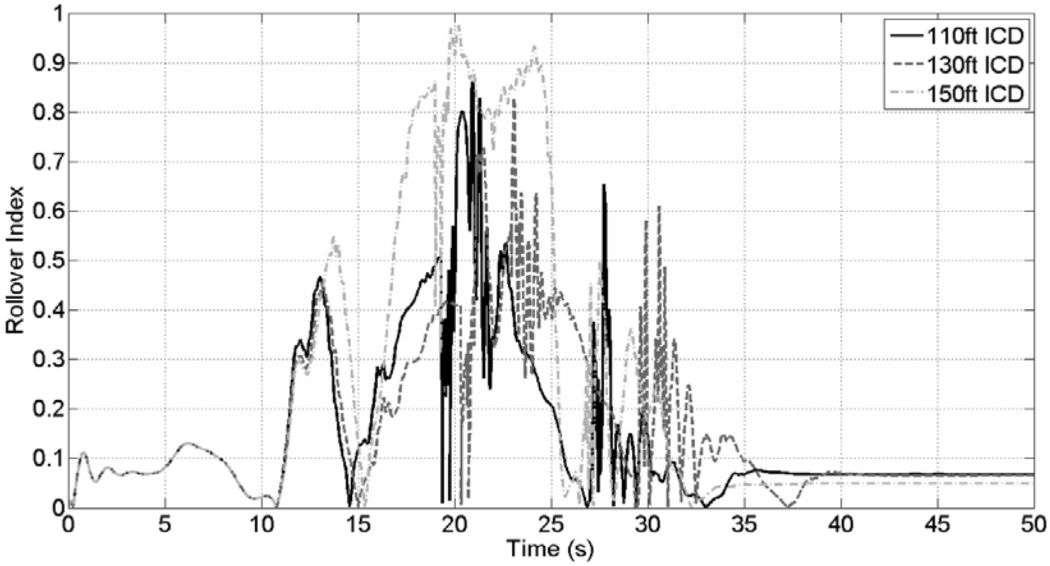


Figure 17. Graph. Effect of roundabout diameter on rollover index (single-lane roundabout, left turn).

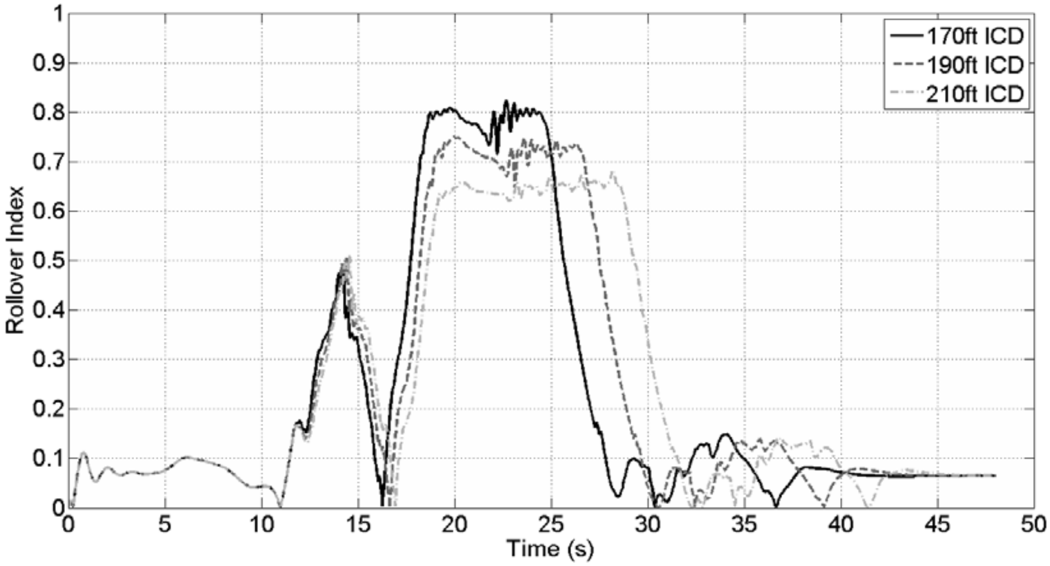


Figure 18. Graph. Effect of roundabout diameter on rollover index (two-lane roundabout, left turn).

Figure 17 and Figure 18 show that the left-turn cases followed the same pattern as the through movement cases: for single-lane roundabouts, the 45.7-m (150-ft) roundabout had the highest rollover index because of the higher circulating speed of 24 km/h (15 mph) rather than 16 km/h (10 mph); and for the two-lane roundabouts, the 64.0-m (210-ft) roundabout had the lowest rollover index because it had the largest ICD.

EFFECT OF CIRCULATORY ROADWAY CROSS-SECTION ON TRUCK STABILITY

The purpose of this test was to determine the effect of roundabout cross-section on truck stability. The truck model for this test was the baseline full-load semi-truck with an entry speed of 32 km/h (20 mph). Twelve cases using two-lane roundabouts were created and tested as summarized in table 10; all dimensions not shown are unchanged (see table 8 for details). For the baseline cross-section, the entire circulatory roadway had a constant 2% cross-slope to the outside of the roundabout. For the crowned cross-section, the inner two-thirds of the circulatory roadway had a 2% inward cross-slope, and the outer third of the circulatory roadway had a 2% outward cross-slope. A truck apron was either present or absent. For the cases with a truck apron, an additional path, called ‘apron,’ was added for through movement. For the apron movement, the vehicle remained in the left lane to ensure it passed over the truck apron.

Table 10. Roadway cross-section cases considered for evaluating truck dynamics in roundabouts.

Case #	Roundabout Diameter - ICD [m (ft)]	Truck Apron	Cross-Section	Movement
34	54.9 (180)	No	Baseline	Right turn
35	54.9 (180)	No	Baseline	Through (left lane)
36	54.9 (180)	No	Baseline	Through (right lane)
37	54.9 (180)	No	Baseline	Left turn
38	54.9 (180)	Yes	Baseline	Through (apron)
39	54.9 (180)	Yes	Baseline	Left turn (apron)
40	54.9 (180)	Yes	Crown	Right turn
41	54.9 (180)	Yes	Crown	Through (left lane)
42	54.9 (180)	Yes	Crown	Through (right lane)
43	54.9 (180)	Yes	Crown	Through (apron)
44	54.9 (180)	Yes	Crown	Left turn
45	54.9 (180)	Yes	Crown	Left turn (apron)

Right Turns

The results of rollover index for right turns are shown in figure 19.

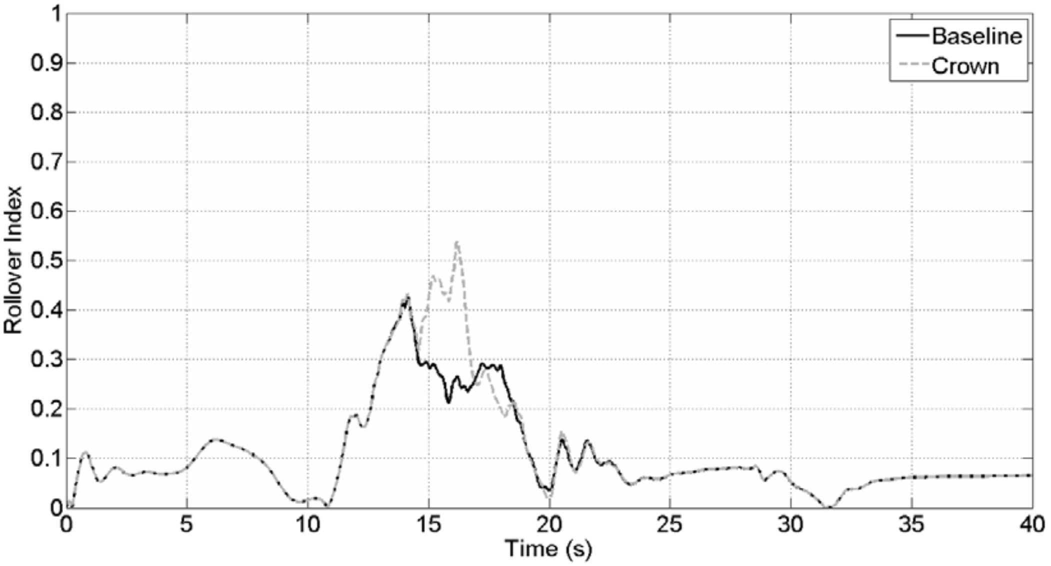


Figure 19. Effect of road crown on rollover index for a 54.9-m (180-ft) roundabout (two-lane, right turn).

As shown in figure 19, the crowned roundabout had a higher peak rollover index and lower truck lateral stability than the baseline roundabout. This was mainly because, for the baseline case, the left side of the roadway was higher than the right side of the roadway. Thus, when the truck made a right turn, the roadway cross-section countered the centrifugal accelerations at the truck's CG, reducing body roll and improving truck stability. For the crowned roundabout, the left edge of the inner two-thirds of the roadway was lower than the right edge. When the truck straddled the lanes to make a right turn, its left wheels ran on the inner, lower part of the roadway, increasing the truck's tendency to lean to the left side and reducing its lateral stability.

Through Movements

The results of rollover index for through movements are shown in figure 20 and figure 21.

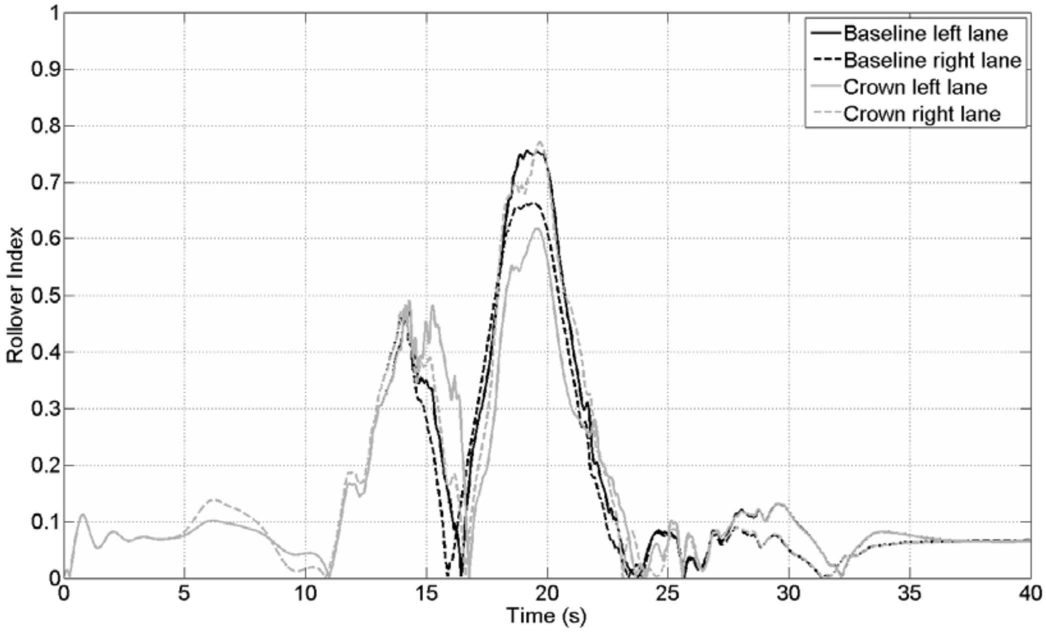


Figure 20. Effect of road crown on rollover index for a 54.9-m (180-ft) roundabout (two-lane, through movement).

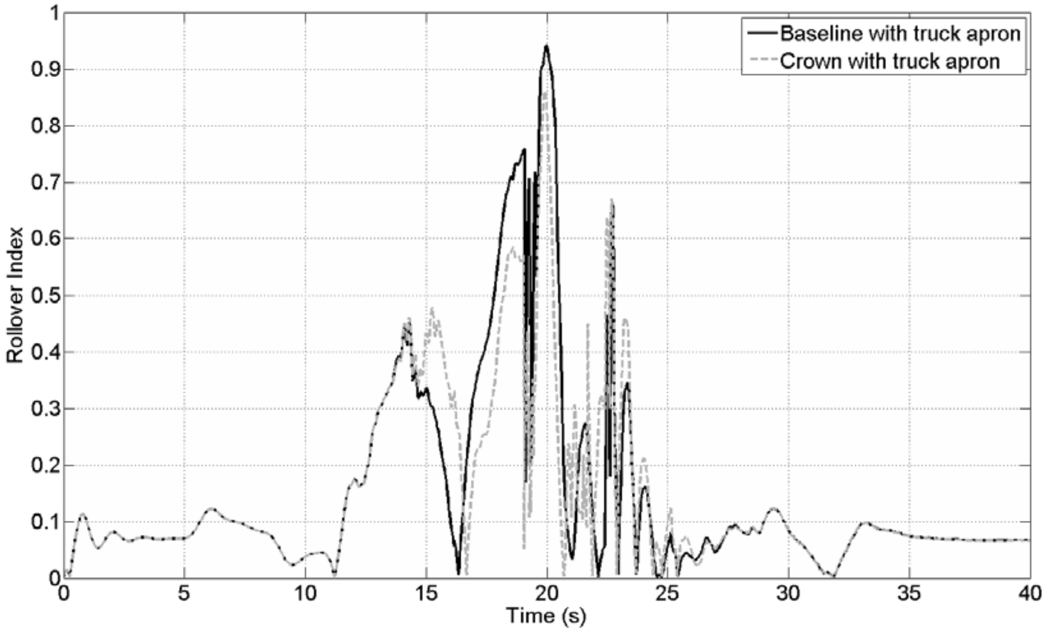


Figure 21. Effect of road crown and truck apron on rollover index for a 54.9-m (180-ft) roundabout (two-lane, through movement).

Figure 20 shows that when the truck passed through the roundabout starting in the left lane, it experienced a higher peak rollover index with the baseline cross-section than with the crowned cross-section (although both are less than 0.8). This is because when the truck was in the left lane on a crowned road, the inward cross-slope on the inner two-thirds of the roadway reduced the truck's lateral acceleration. When the truck started in the right lane, however, the truck experienced a higher rollover index with the crowned cross-section than with the baseline condition (although both are less than 0.8). Figure 21 shows that when the truck passed over the truck apron (light gray traces) to move through the roundabout, it caused rapidly oscillating and high rollover indices, because moving onto the truck apron caused rocking. For the truck apron movement, the baseline cross-section had a higher rollover index than the crowned cross-section, and both were high, above 0.8.

Left Turns

The results of rollover index for left turns are shown in figure 22 and figure 23.

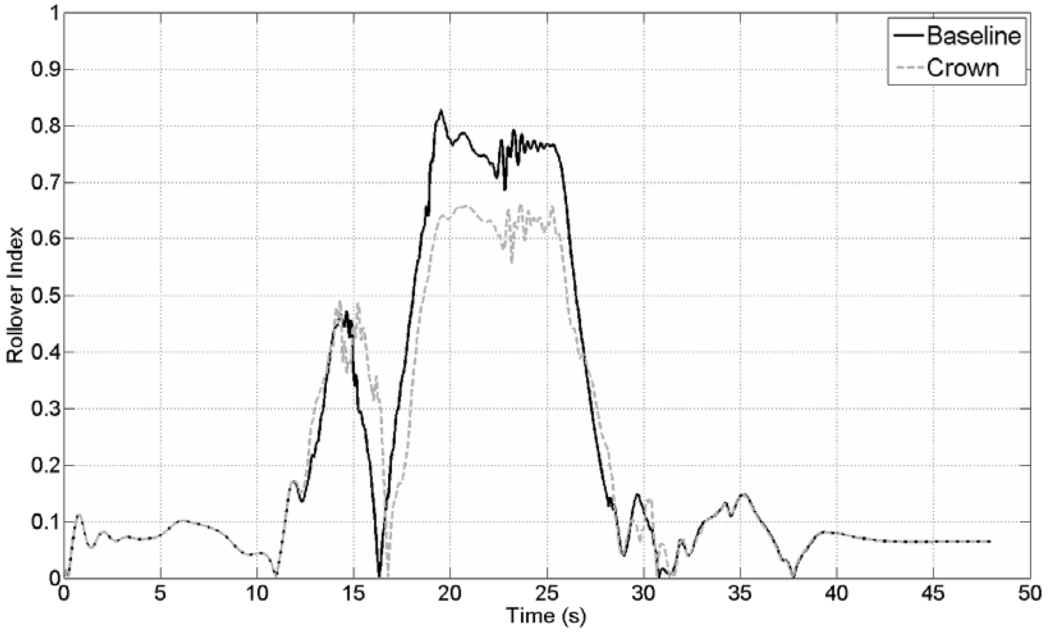


Figure 22. Effect of road crown on rollover index for a 54.9-m (180-ft) roundabout (two-lane, left turn).

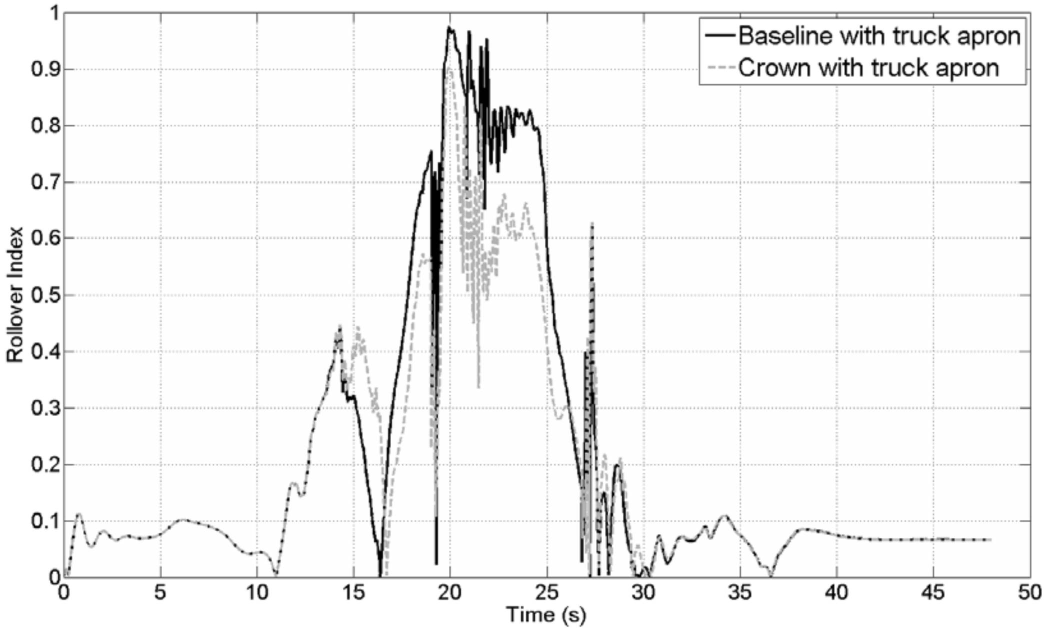


Figure 23. Effect of road crown and truck apron on rollover index for a 54.9-m (180-ft) roundabout (two-lane, left turn).

Figure 22 shows that without a truck apron, a left-turning truck in a 54.9-m (180-ft) two-lane roundabout experienced a lower rollover index under the crowned section than under the baseline section, with the rollover index for the baseline section slightly exceeding 0.8 at 24 km/h (15 mph). Figure 22 shows that the semi-truck experienced a stronger likelihood of rollover when making left turns with a truck apron at 24 km/h (15 mph). Therefore, two additional cases at a lower speed were created and tested, with the other parameters kept constant. For the low-speed cases, the circulating speed was reduced from 24 km/h (15 mph) to 16 km/h (10 mph). The rollover indices are shown in figure 24.

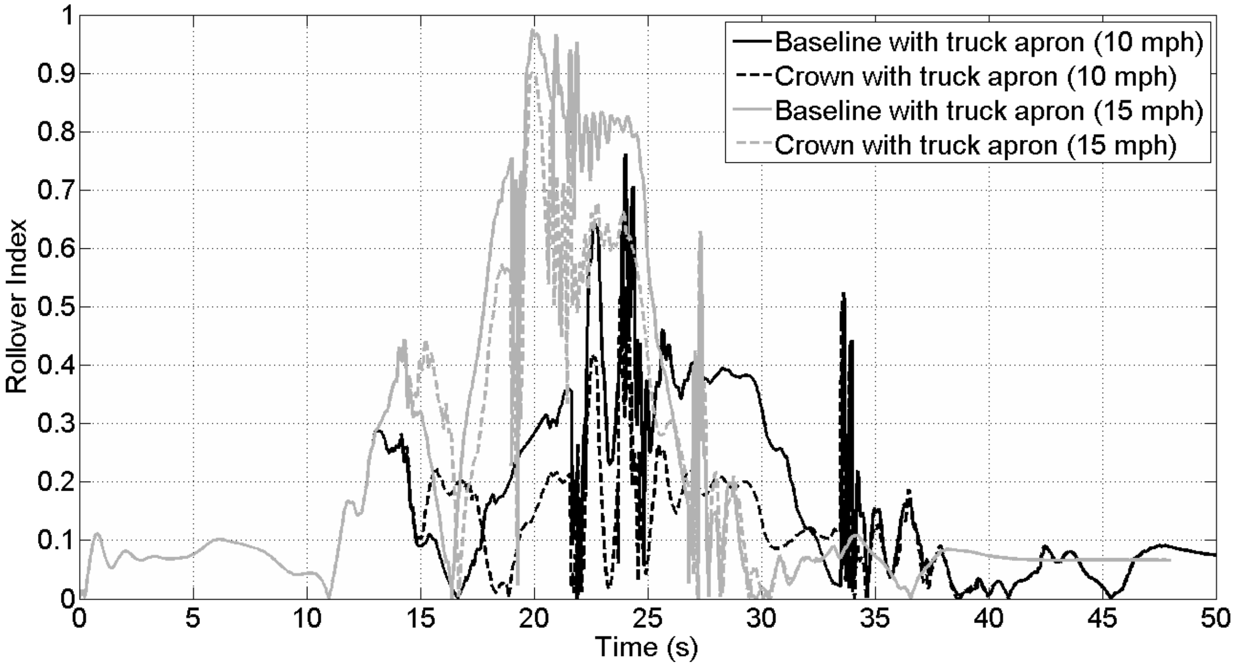


Figure 24. Effect of truck apron and road crown on rollover index at different circulating speeds (16 km/h [10 mph] and 24 km/h [15 mph])(two-lane, left turn).

Figure 24 shows that a fully loaded semi-truck passing over the truck apron to perform a left turn at 24 km/h (15 mph) in the 54.9-m (180-ft) two-lane roundabout resulted in a peak rollover index of almost 1, and a significant risk of rollover. The inward cross slope of the crown reduced the peak rollover index, but it still exceeded 0.9. However, when the circulating speed was lowered to 16.1 km/h (10 mph), the peak rollover indices for the two cross-sections were lower than 0.8, indicating that the semi-truck could safely negotiate the roundabout at the lower speed.

EFFECT OF TRUCK CONFIGURATION ON TRUCK STABILITY

In this test, three different truck configurations, a WB-67 semi-truck, a SU-30 single-unit truck, and a B-train tractor with double trailers, were simulated to determine their lateral dynamics when driving through the baseline single-lane 42.7-m (140-ft) ICD roundabout and the baseline two-lane 54.9-m (180-ft) roundabout. Each truck entered the roundabout at 32 km/h (20 mph), then slowed down to 24 km/h (15 mph) and followed the same path. The cases considered are summarized in table 11; all dimensions not shown are unchanged within the set of single-lane and two-lane cases (see table 8 for details).

Table 11. Truck configuration cases considered for evaluating truck dynamics in roundabouts.

Case #	Roundabout Diameter - ICD [m (ft)]	Movement	Truck configuration
1	42.7 (140)	Right turn	WB-67
2	42.7 (140)	Through	WB-67
3	42.7 (140)	Left turn	WB-67
4	42.7 (140)	Right turn	B-train
5	42.7 (140)	Through	B-train
6	42.7 (140)	Left turn	B-train
7	42.7 (140)	Right turn	SU-30
8	42.7 (140)	Through	SU-30
9	42.7 (140)	Left turn	SU-30
34	54.9 (180)	Right turn	WB-67
35	54.9 (180)	Through (left lane)	WB-67
36	54.9 (180)	Through (right lane)	WB-67
37	54.9 (180)	Left turn	WB-67
46	54.9 (180)	Right turn	B-train
47	54.9 (180)	Through (left lane)	B-train
48	54.9 (180)	Through (right lane)	B-train
49	54.9 (180)	Left turn	B-train
50	54.9 (180)	Right turn	SU-30
51	54.9 (180)	Through (left lane)	SU-30
52	54.9 (180)	Through (right lane)	SU-30
53	54.9 (180)	Left turn	SU-30

Right Turns

The results of the rollover index for right turns in a 42.7-m (140-ft) and a 54.9-m (180-ft) roundabout are shown in Figure 25 and Figure 26, respectively.

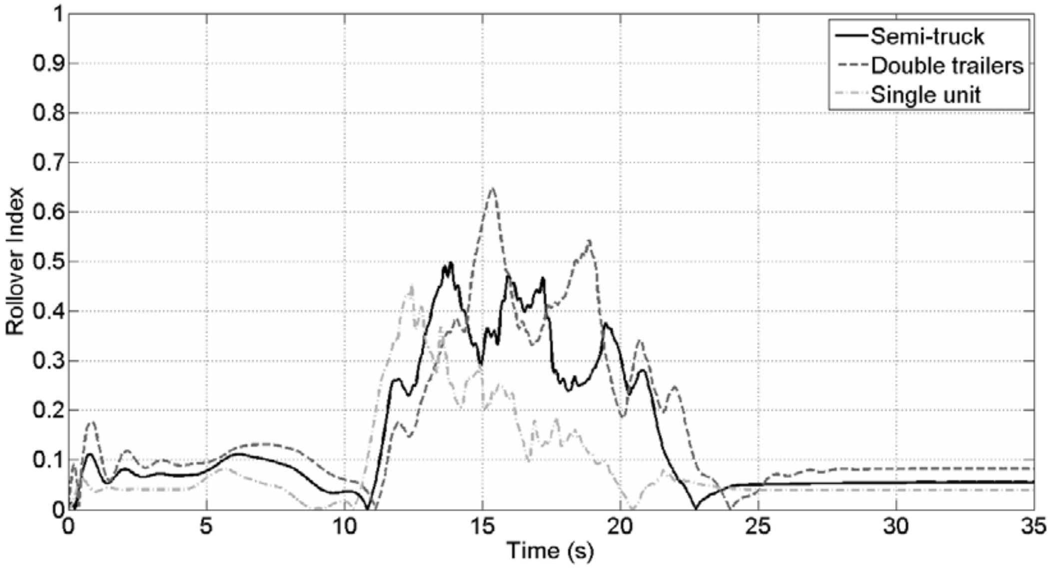


Figure 25. Effect of truck configuration on rollover index for a 42.7-m (140-ft) roundabout (single-lane roundabout, right turn).

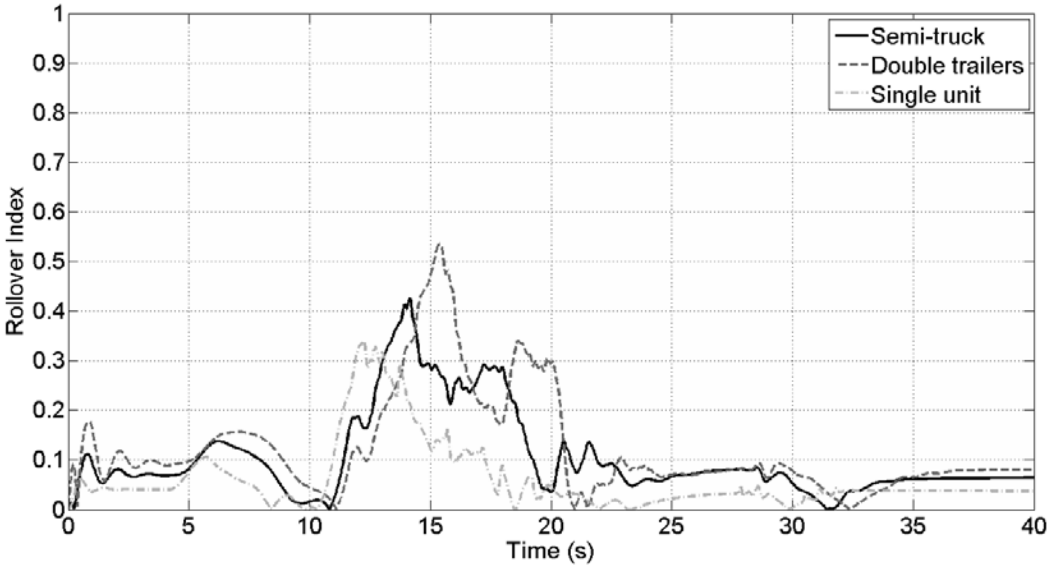


Figure 26. Effect of truck configuration on rollover index for a 54.9-m (180-ft) roundabout (two-lane roundabout, right turn).

As shown in figure 25 and figure 26, the SU-30 single-unit truck had the highest roll stability, followed by the WB-67 semi-truck. The B-train double trailer truck had the lowest roll stability. All three truck configurations, however, could safely make a right turn at a roundabout at the speeds considered here.

Through Movements

The results of the rollover index for through movements in a 42.7-m (140-ft) and a 54.9-m (180-ft) roundabout are shown in Figure 27and Figure 28, respectively.

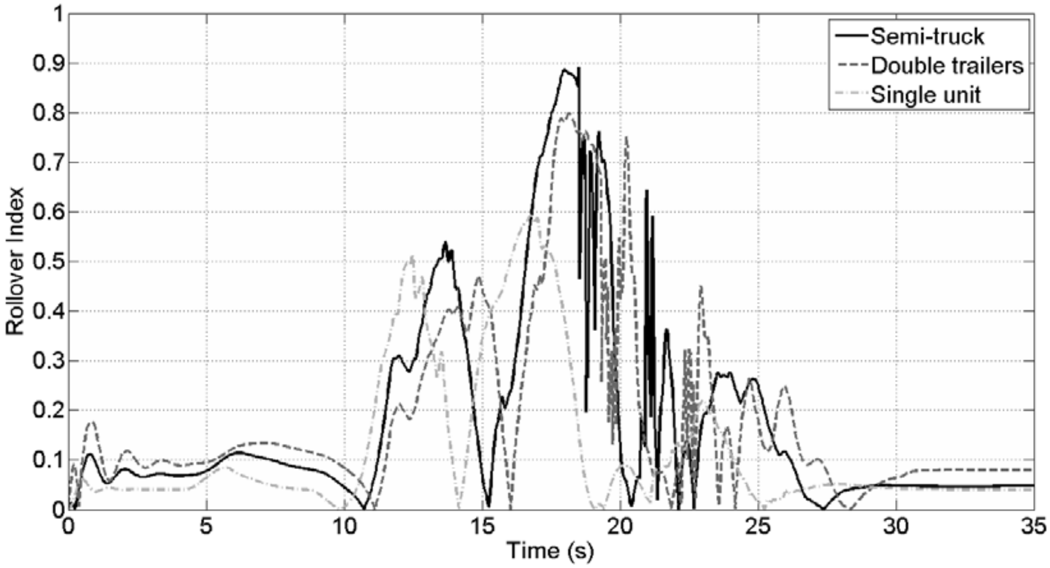


Figure 27. Effect of truck configuration on rollover index for a 42.7-m (140-ft) roundabout (single-lane, through movement).

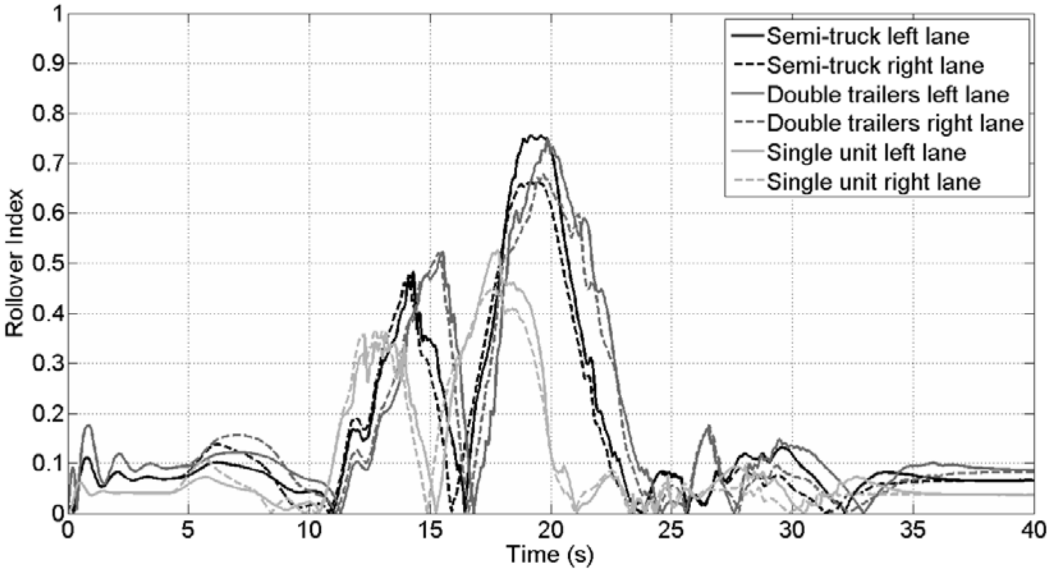


Figure 28. Effect of truck configuration on rollover index for a 54.9-m (180-ft) roundabout (two-lane, through movement).

According to figure 27 and figure 28, the SU-30 single-unit truck had the smallest rollover index, indicating that it was more stable than the other configurations when moving through roundabouts. Even though the B-train tractor with double trailers had a greater overall length than the WB-67 semi-truck, it had a slightly lower rollover index, because the B-train's constituent trailers were both shorter than the WB-67 semi-truck's trailer, allowing it to better conform to the circulatory roadway.

Left Turns

The results of the rollover index for left turns in 42.7-m (140-ft) and 54.9-m (180-ft) roundabouts are shown in figure 29 and figure 30, respectively. Note that a value of 1 or greater indicates a rollover condition, and as a result, the graph and all other similar graphs show a maximum value of 1.

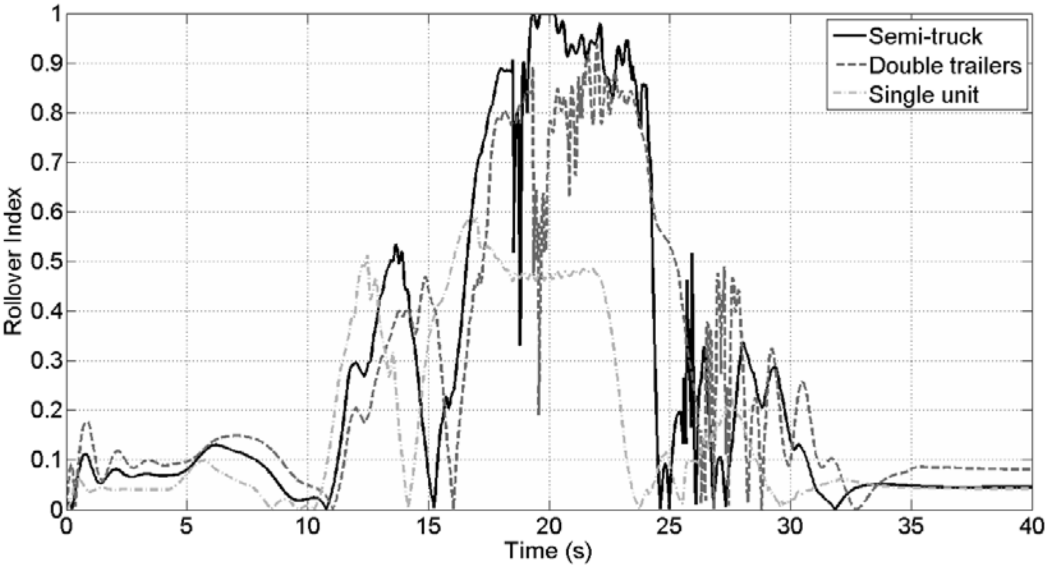


Figure 29. Effect of truck configuration on rollover index for a 42.7-m (140-ft) roundabout (single-lane, left turn).

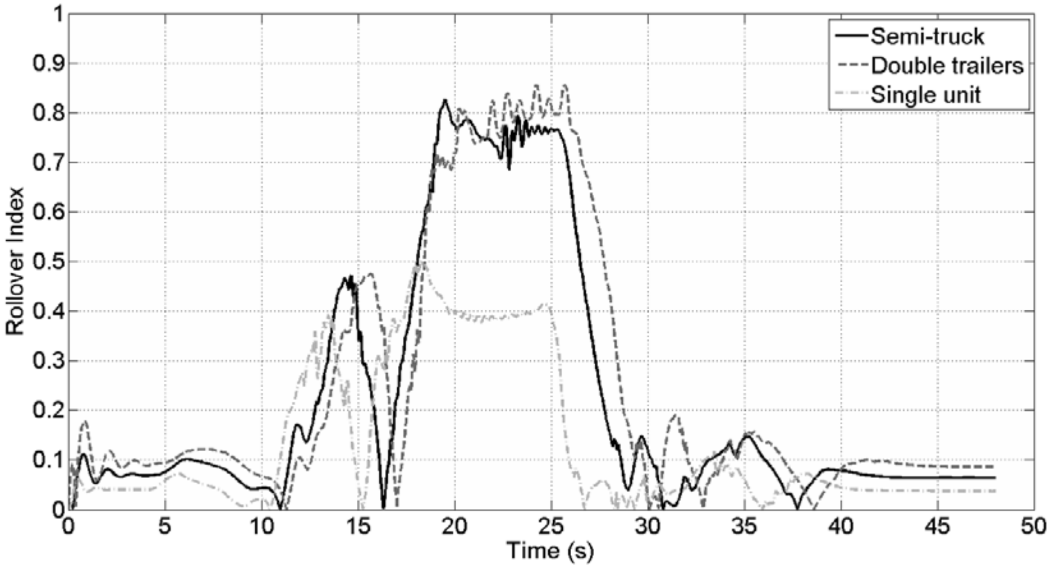


Figure 30. Effect of truck configuration on rollover index for a 54.9-m (180-ft) roundabout (two-lane, left turn).

Figure 29 and figure 30 illustrate that the SU-30 single-unit truck was more stable than the other two configurations.

The WB-67 semi-truck and B-train tractor with double trailers had similar rollover indices in both roundabouts. In the 42.7-m (40-ft) ICD roundabout, the baseline WB-67 semi-truck with a full load (GVWT = 36300 kg [80,000 lbs]), making a left turn and circulating at 24 km/h (15 mph), had a high likelihood of rollover.

EFFECT OF LOAD CONFIGURATION ON TRUCK STABILITY

In this test, three load configurations were studied for the WB-67 semi-truck (the baseline vehicle) to determine whether the load would impact truck stability. The baseline truck was evaluated in empty, half-full, and full load conditions, as summarized in table 12; all dimensions not shown are unchanged within the set of single-lane and two-lane cases (see table 8 for details). The loads were assumed to be fixed, and no shifting loads were considered.

Table 12. Load configuration cases considered for evaluating truck dynamics in roundabouts.

Case #	Roundabout Diameter - ICD [m (ft)]	Movement	Load
1	42.7 (140)	Right turn	Full
2	42.7 (140)	Through	Full
3	42.7 (140)	Left turn	Full
10	42.7 (140)	Right turn	Empty
11	42.7 (140)	Through	Empty
12	42.7 (140)	Left turn	Empty
13	42.7 (140)	Right turn	Half full
14	42.7 (140)	Through	Half full
15	42.7 (140)	Left turn	Half full
34	54.9 (180)	Right turn	Full
35	54.9 (180)	Through (left lane)	Full
36	54.9 (180)	Through (right lane)	Full
37	54.9 (180)	Left turn	Full
54	54.9 (180)	Right turn	Empty
55	54.9 (180)	Through (left lane)	Empty
56	54.9 (180)	Through (right lane)	Empty
57	54.9 (180)	Left turn	Empty
58	54.9 (180)	Right turn	Half full
59	54.9 (180)	Through (left lane)	Half full
60	54.9 (180)	Through (right lane)	Half full
61	54.9 (180)	Left turn	Half full

Right Turns

The results of rollover index for right turns in 42.7-m (140-ft) single-lane roundabout and the 54.9-m (180-ft) two-lane roundabout are shown in figure 31 and figure 32, respectively, for the three load conditions.

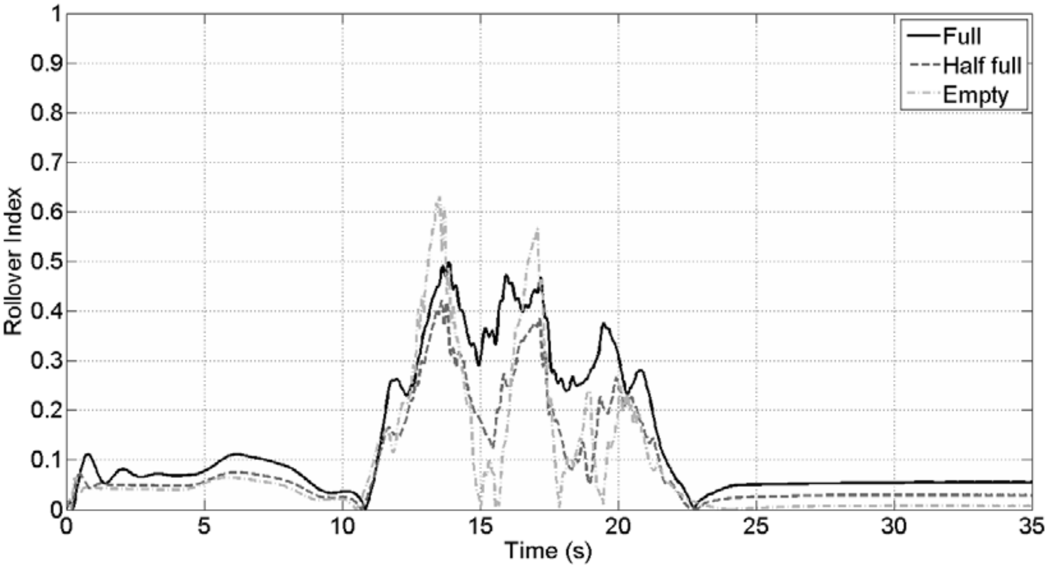


Figure 31. Effect of truck weight on rollover index for a 42.7-m (140-ft) roundabout (single-lane, right turn).

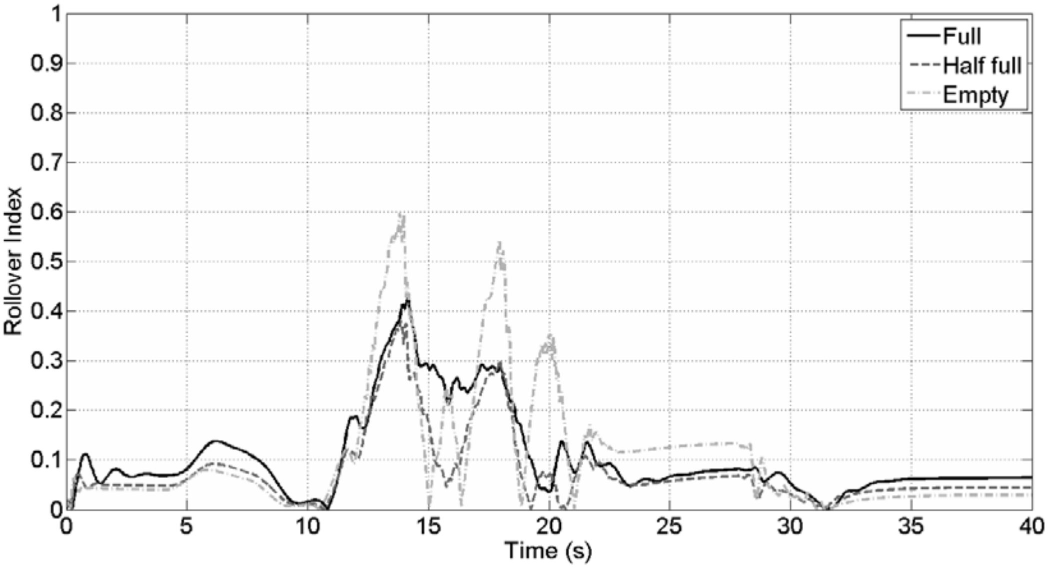


Figure 32. Effect of truck weight on rollover index for a 54.9-m (180-ft) roundabout (two-lane, right turn).

Figure 31 and figure 32 show that the half-full truck had the lowest rollover index for both the single-lane and two-lane roundabouts, and surprisingly, the empty truck had the highest rollover index. The lighter axle load for the empty truck resulted in a smaller denominator in figure 10. Therefore, a larger rollover index occurred for the side-to-side weight transfer that occurred due to lateral accelerations at the truck's CG. Another way to think of this phenomenon is by considering that a lighter axle has less vertical load holding it down against the road, and therefore it could be more easily unloaded. A heavier axle load, such as the fully loaded truck, is more heavily loaded against the road and requires more unloading before it reaches zero wheel loads.

The peaks in figure 31 and figure 32 happened during the transition from one steering configuration (roadway curvature) to another, when the truck changed from turning left to turning right and vice versa. The rapid change in roadway elevation at the left edge of the roadway at curvature transitions contributed significantly to the lateral acceleration and rollover index peaks. For instance, in roundabouts with 54.9-m (180-ft) ICDs, the left edge of the roadway changed from 0 to 0.15-m (6-in.) in elevation within 9.1-m (30-ft) of travel. Such a rapid change in roadway geometry acted like a lateral impulse force, which in turn acted as a large lateral force at the CG, resulting in proportionally large lateral accelerations, wheel unloading, and rollover indices. The higher CG for the fully loaded truck resulted in a somewhat larger rollover index, as compared with the half-full truck.

The half-full truck's configuration optimized the load on the wheelbase and the mass and position of the truck's CG to create a condition with the lowest peak rollover index.

Through Movements

The results of rollover indices for through movements in 42.7-m (140-ft) and 54.9-m (180-ft) roundabouts are shown in figure 33 and figure 34, respectively, for the three load conditions.

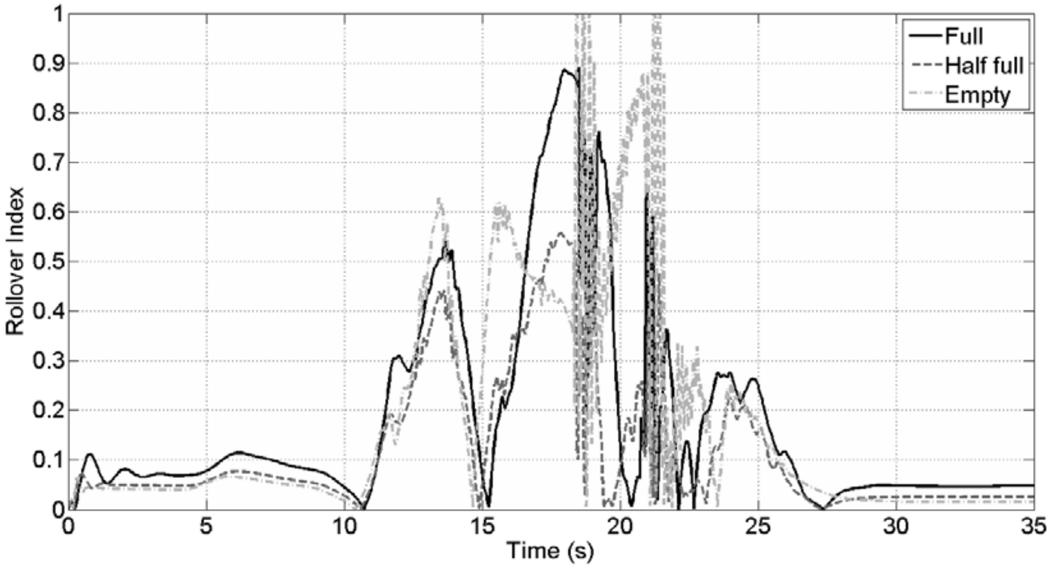


Figure 33. Effect of truck weight on rollover index for a 42.7-m (140-ft) roundabout (single-lane, through movement).

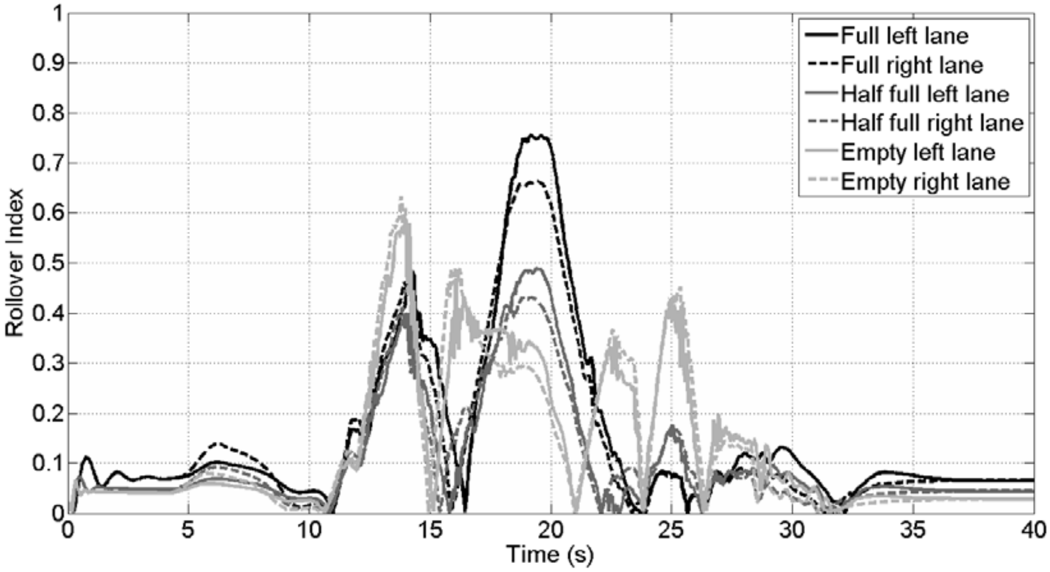


Figure 34. Effect of truck weight on rollover index for a 54.9-m (180-ft) roundabout (two-lane, through movement).

Figure 33 shows that, for through movements in the single-lane roundabout, the empty truck had the highest rollover index similar to the results for right turns. However, for the empty truck, the smaller turning radius of the 42.7-m (140-ft) roundabout and passing over the truck apron resulted in rollover indices exceeding the rollover limit of 1 at the roadway curvature transitions. The peaks in rollover index for the loaded truck reached as high as 0.9. Thus, the empty and full trucks both have a high risk of rollover in this condition. The half-full truck had a peak rollover index of about 0.55, indicating it could safely move through the single-lane roundabout.

For the two-lane roundabout, figure 34 shows that none of the rollover indices exceeded 0.80. The rollover index followed the same trend for trucks starting in the right and left lanes. For full and half-full trucks, those starting in the left lane had higher peak indices than those starting in the right lane due to the tighter curvature of the truck's path and increased lateral acceleration. The half-load truck had the lowest peak rollover index. The empty truck's rollover index exhibited different trends in peaks, and had a peak rollover index between that of the full load and half load trucks.

Left Turns

The results of rollover index for left turns in 42.7-m (140-ft) single-lane and 54.9-m (180-ft) two-lane roundabouts are shown in figure 35 and figure 36, respectively, for the three load conditions.

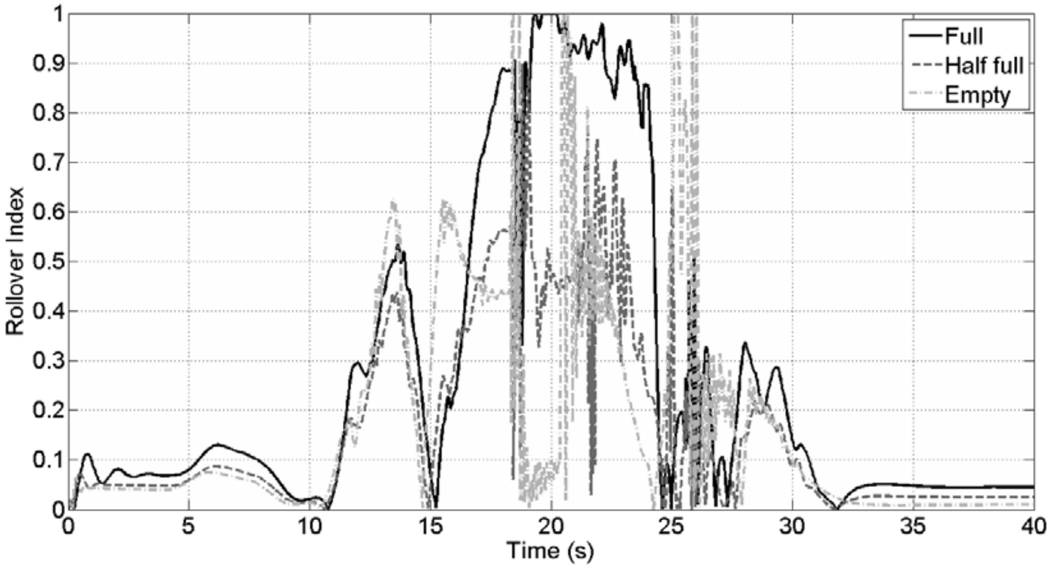


Figure 35. Effect of truck weight on rollover index for a 42.7-m (140-ft) roundabout (single-lane, left turn).

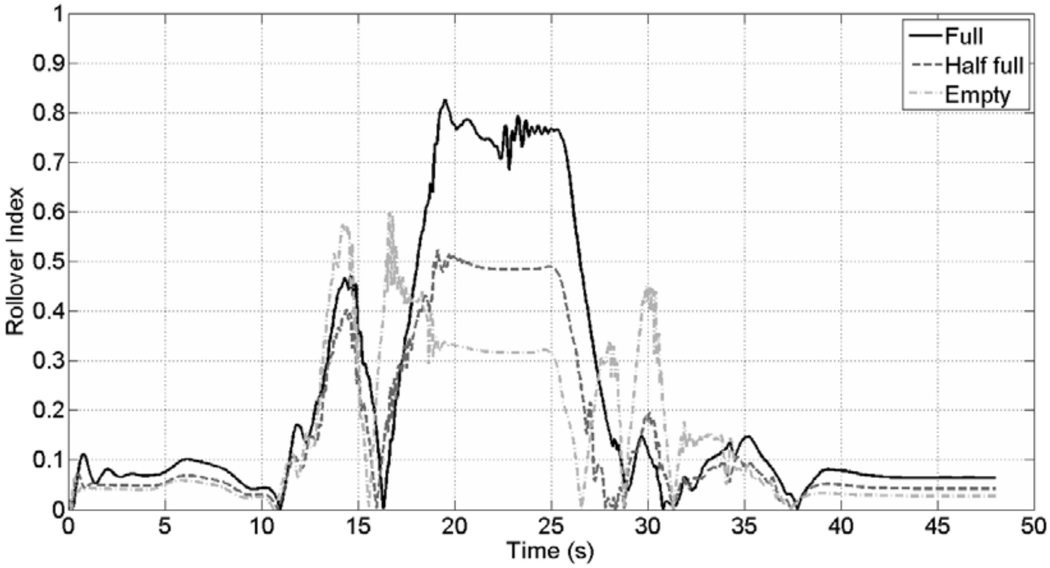


Figure 36. Effect of truck weight on rollover index for a 54.9-m (180-ft) roundabout (two-lane, left turn).

The results in figure 35 and figure 36 are similar in trend to those for through movements. However, for left turns in the single-lane roundabout (figure 35), both full and empty trucks had peak rollover indices of over 1, indicating a high likelihood of rollover, and the half-full truck also exhibited a high peak rollover index of 0.75.

The results in figure 36 show that, for trucks turning left in the two-lane roundabout, all three load conditions resulted in rollover indices that were below 1. Similar to the other turning maneuvers, in the 54.9-m (180-ft) roundabout, the full truck had the highest rollover index, the empty truck had the lowest, and the half-full truck fell in between.

For the single-lane, 42.7-m (140-ft) roundabout, an additional set of cases was tested with the circulating speed reduced to 16 km/h (10 mph) from 24 km/h (15 mph). The rollover indices of the three additional cases are shown in figure 37.

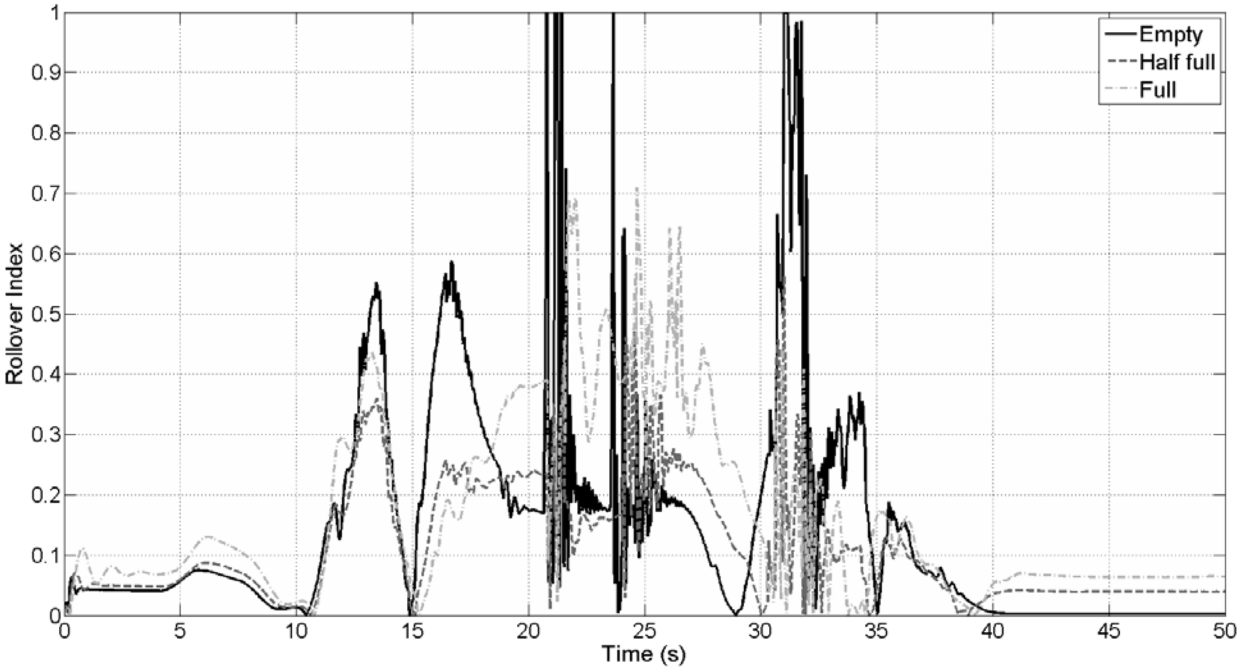


Figure 37. Effect of truck weight on rollover index at different circulating speeds: 16 km/h (10 mph) (left plot) and 24 km/h (15 mph) (right plot); (140-ft single-lane roundabout, left turn).

Figure 37 shows that for both the half-full and full trucks, rollover was significantly less likely when travelling at 16 km/h (10 mph) than at 24 km/h (15 mph), as their peak rollover indices decreased to less than 0.7. As for the empty truck, even though it travelled at a lower speed, its light axle load caused it to have a peak rollover index of 1. The high rollover index is believed to occur when the truck transitions onto the truck apron, which is modeled as a three-inch vertical face. An alternate truck apron design was not modeled in this study.

EFFECT OF ROUNDABOUT TILT ON TRUCK STABILITY

In this test, the entire roundabout was tilted at four constant angles to determine the effect of tilted slope on truck stability. Tilt was with respect to the approaching roadway. Positive tilt indicated that, from the perspective of a driver on the approaching roadway, the entire roundabout was tilted down to the right, i.e., ‘outward’ toward the roadway’s right shoulder. Negative slope indicates that the roadway was tilted, from the perspective of a driver on the approaching roadway, down to the left, i.e., ‘inward’ toward the road’s centerline, as shown in figure 5.

The baseline semi-truck model was used for all of the tilt cases, as summarized in table 13; all dimensions not shown are unchanged within the set of single-lane and two-lane cases (see table 8 for details).

Table 13. Roundabout tilt slope for a 42.7-m (140-ft) and 54.9-m (180-ft) roundabout.

Case #	Roundabout Diameter - ICD [m (ft)]	Movement	Percent Tilt (slope)*
16	42.7 (140)	Right turn	+4
17	42.7 (140)	Through	+4
18	42.7 (140)	Left turn	+4
19	42.7 (140)	Right turn	+2
20	42.7 (140)	Through	+2
21	42.7 (140)	Left turn	+2
22	42.7 (140)	Right turn	-4
23	42.7 (140)	Through	-4
24	42.7 (140)	Left turn	-4
25	42.7 (140)	Right turn	-2
26	42.7 (140)	Through	-2
27	42.7 (140)	Left turn	-2
62	54.9 (180)	Right turn	+4
63	54.9 (180)	Through (left lane)	+4
64	54.9 (180)	Through (right lane)	+4
65	54.9 (180)	Left turn	+4
66	54.9 (180)	Right turn	+2
67	54.9 (180)	Through (left lane)	+2
68	54.9 (180)	Through (right lane)	+2
69	54.9 (180)	Left turn	+2
70	54.9 (180)	Right turn	-4
71	54.9 (180)	Through (left lane)	-4
72	54.9 (180)	Through (right lane)	-4
73	54.9 (180)	Left turn	-4
74	54.9 (180)	Right turn	-2
75	54.9 (180)	Through (left lane)	-2
76	54.9 (180)	Through (right lane)	-2
77	54.9 (180)	Left turn	-2
* "+" indicates outward tilt and "-" indicates inward tilt			

Right Turns

The rollover indices for the baseline truck turning right at roundabouts with the various tilted slopes are shown in figure 38 and figure 39, for a single-lane and a two-lane roundabout, respectively.

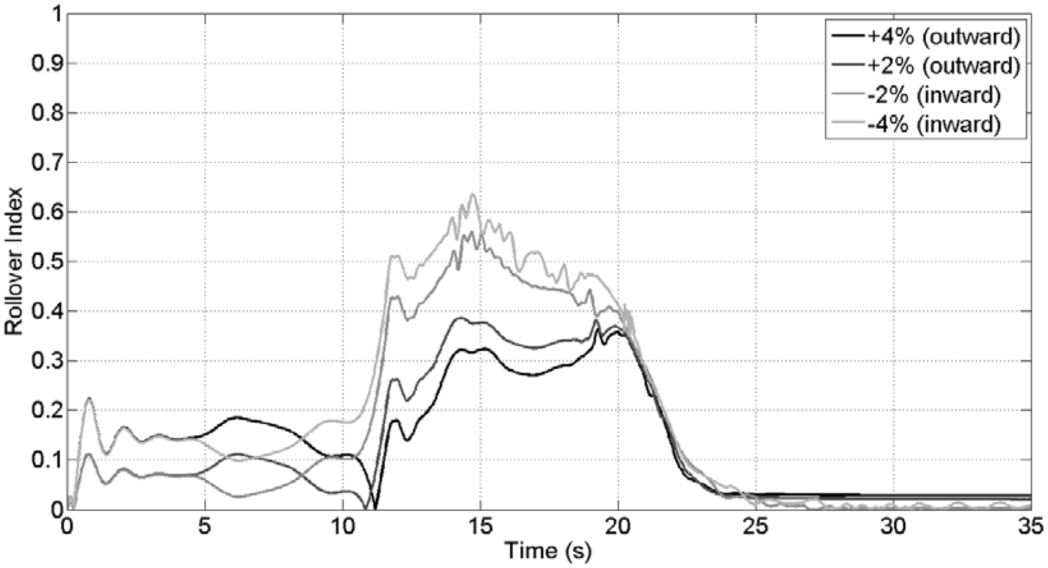


Figure 38. Effect of roundabout tilt on rollover index for a 42.7-m (140-ft) roundabout (single-lane, right turn).

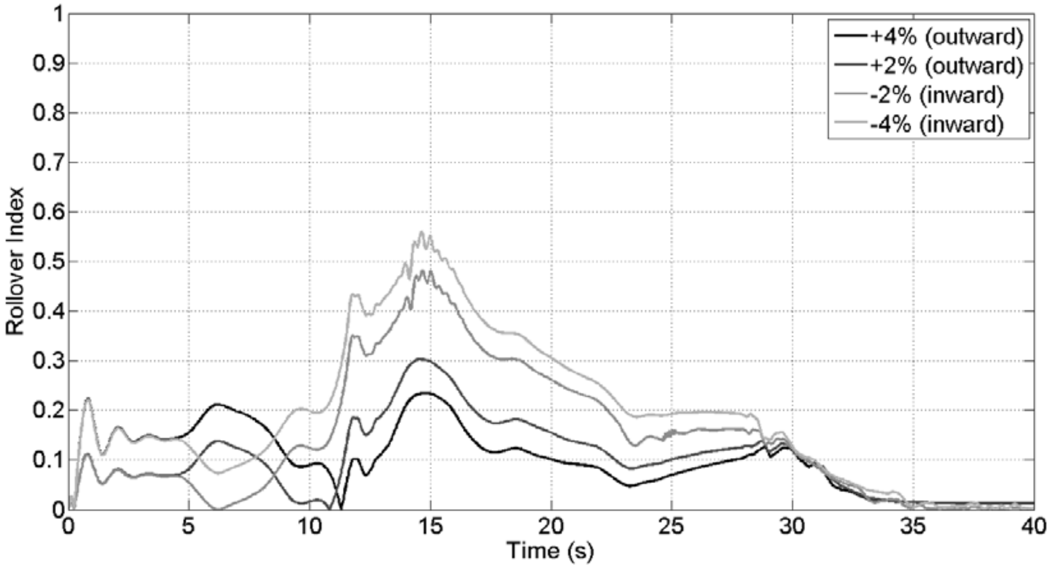


Figure 39. Effect of roundabout tilt on rollover index for a 54.9-m (180-ft) roundabout (two-lane, right turn)

Figure 38 and figure 39 show that the rollover index—and therefore, the likelihood of truck rollover—increased as the roundabout tilt decreased, indicating that tilting the roundabout outward had a stabilizing effect for right-turn movements. The peak rollover index for the semi-truck in the single-lane, 42.7-m (140-ft) roundabout with no tilt (0.50, figure 25), fell between the positive and negative peak rollover indices in figure 38. Similarly, for the semi-truck in the two-lane 42.7-m (140-ft) roundabout with no tilt (0.43, figure 26), the peak rollover index fell between the positive and negative peak rollover indices in figure 39.

Through Movements

The rollover indices for the baseline truck going straight through roundabouts with the various tilted slopes are shown in figure 40 and figure 41, for a single-lane and a two-lane roundabout, respectively.

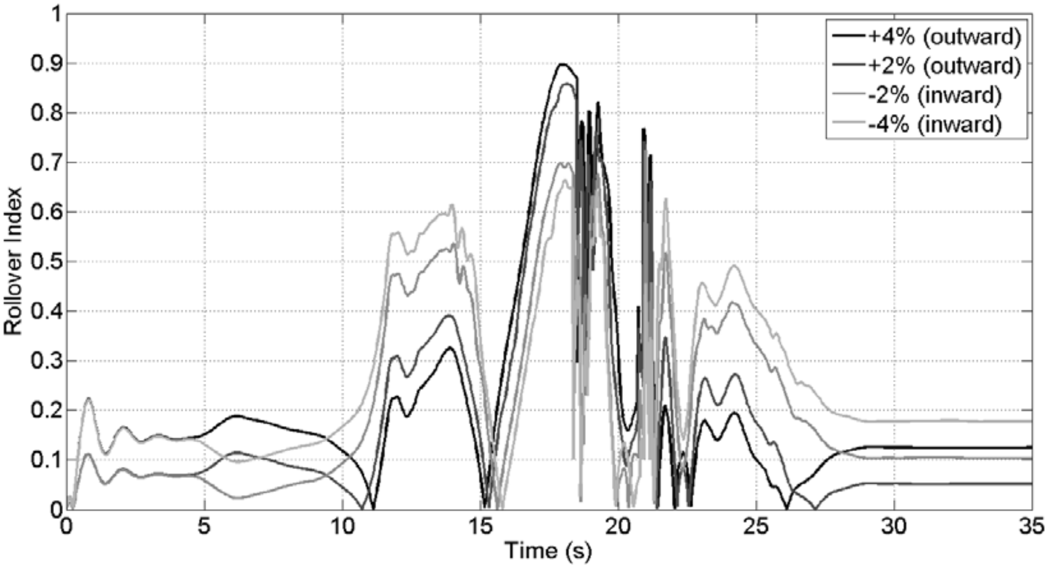


Figure 40. Effect of roundabout tilt on rollover index for a 42.7-m (140-ft) roundabout (single-lane, through movement).

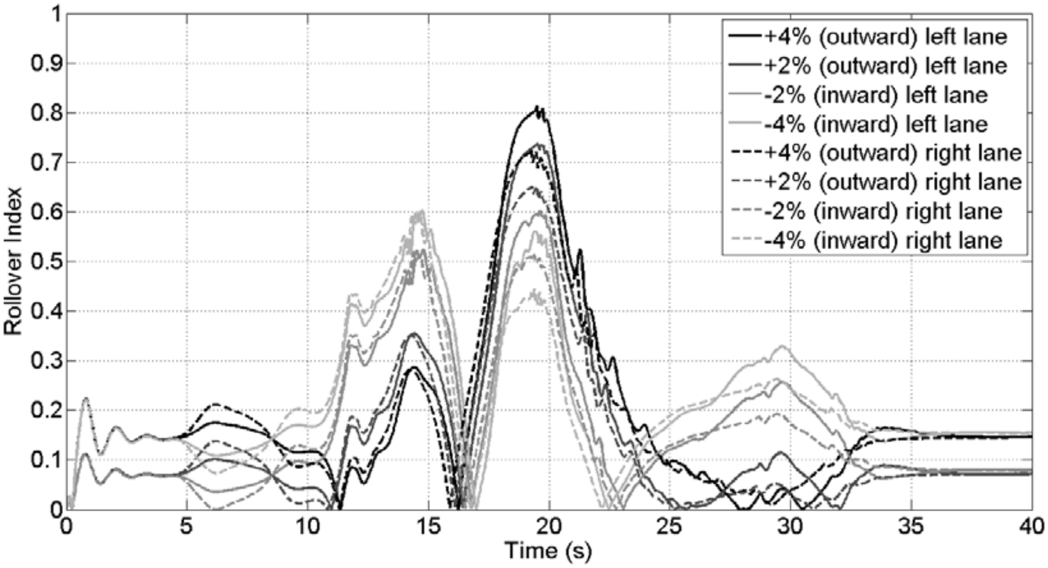


Figure 41. Effect of roundabout tilt on rollover index for a 54.9-m (180-ft) roundabout (two-lane, through movement).

Figure 40 and figure 41 indicate that at the roundabout entry and exit, a more negative/inward tilt increased rollover index. The opposite was true when the truck was in the roundabout, where a more negative/inward tilt decreased rollover index. For the single-lane roundabout (figure 40), all peak rollover indices occurred while the truck was on the circulatory roadway inside the roundabout, and not at the entrance or exit. Thus, for single-lane roundabout, a negative/inward tilt was less likely to cause rollover. For the two-lane roundabout (figure 41), peak rollover indices also occurred while the truck was on the circulatory roadway inside the roundabout, again suggesting that a negative/inward tile is preferable.

Left Turns

The rollover indices for the baseline truck turning left at roundabouts with the various tilted slopes are shown in figure 42 and figure 43, for a single-lane and a two-lane roundabout, respectively.

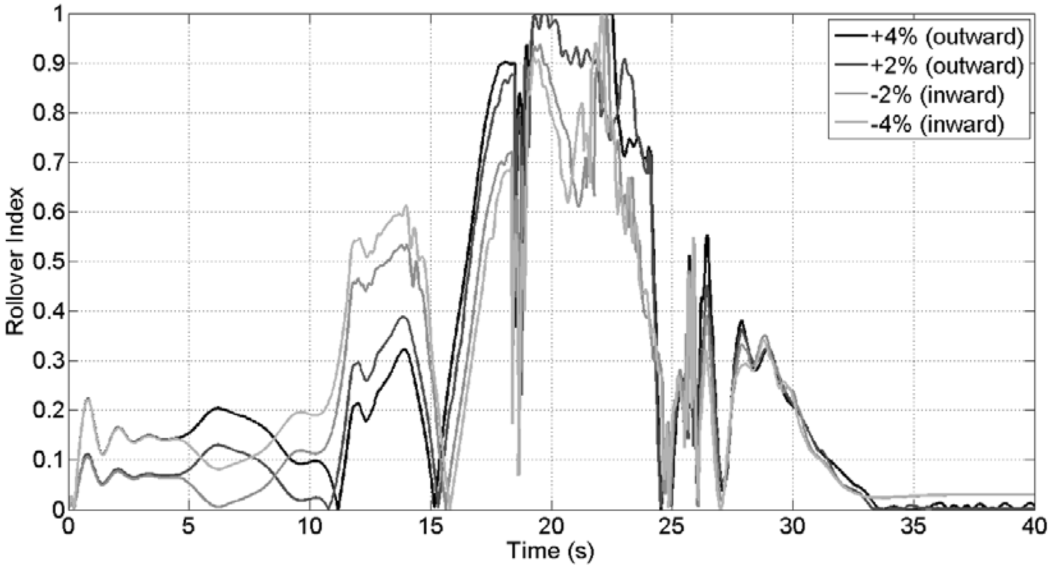


Figure 42. Effect of roundabout tilt on rollover index for a 42.7-m (140-ft) roundabout (single-lane, left turn).

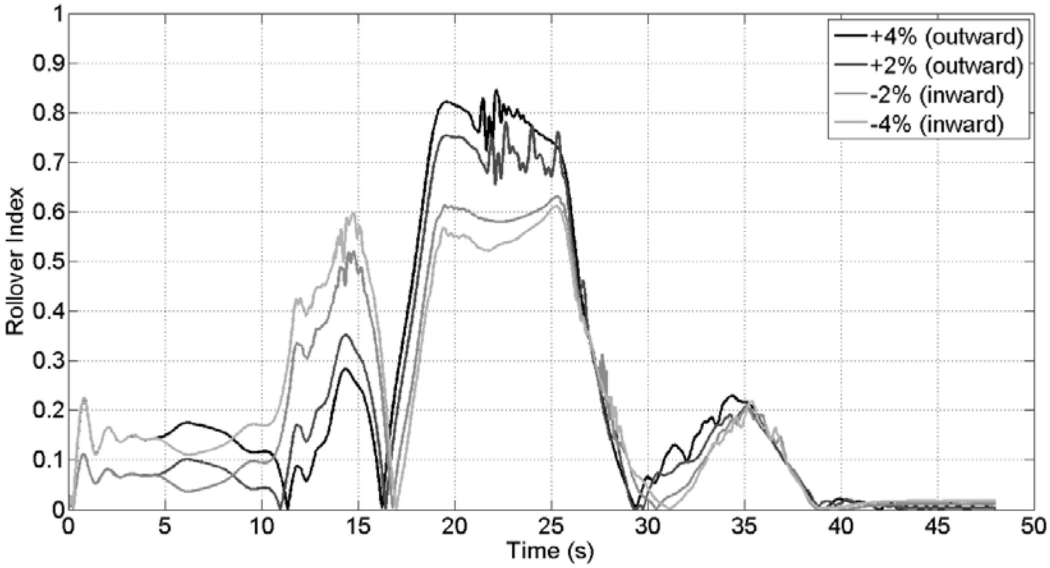


Figure 43. Effect of roundabout tilt on rollover index for a 54.9-m (180-ft) roundabout (single-lane, left turn).

The results for semi-trucks making left turns in the roundabouts, shown in figure 42 and figure 43, followed the same trends as those for trucks moving through the roundabouts, (figure 40 and figure 41). A more positive/outward tilt led to higher rollover indices in the circulatory roadway, but lower rollover indices at the roundabout entrance and exit. For the single-lane roundabout (figure 42), negative/inward tilt resulted in lower peak rollover indices, but for all tilted slopes, the peak rollover index reached 1, indicating a high risk of rollover. For the two-lane roundabout (figure 43), a negative/inward tilt resulted in lower peak rollover indices in the circulatory roadway, but did not raise the peak rollover indices at the entry above those in the circulatory roadway. Thus, for this roundabout, a negative/inward tilt is preferable.

The baseline WB-67 truck had a high risk of rollover when turning left in the 42.7-m (140-ft) single-lane roundabout at 24 km/h (15 mph), where the peak rollover indices for all tilted slopes reached 1 (figure 42). Hence, four additional cases with a lower circulating speed were created and tested. In these cases, the circulating speed was decreased from 24 km/h (15 mph) to 16 km/h (10 mph). The rollover indices for the reduced speed cases are shown in figure 44.

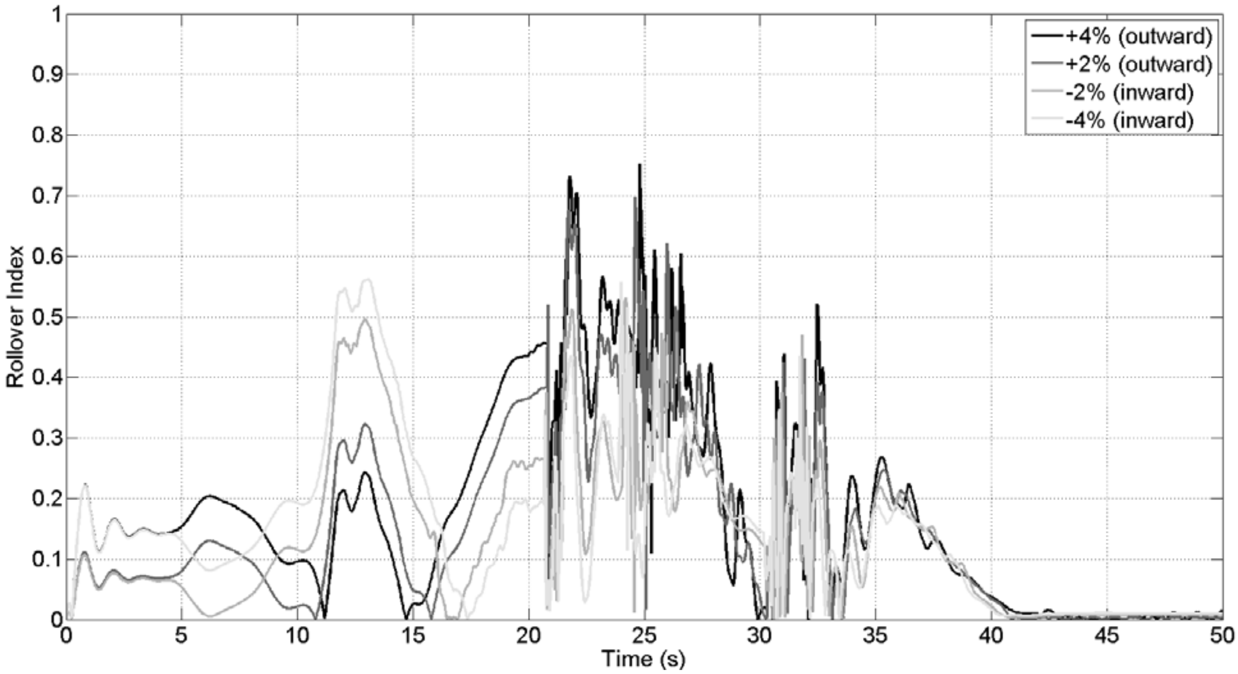


Figure 44. Effect of roundabout tilt on rollover index at different circulating speeds: 16 km/h (10 mph) (left plot) and 24 km/h (15 mph) (right plot); (single-lane roundabout, left turn).

As figure 44 shows, it is evident that the peak rollover indices for all cases with a (16-km/h (10-mph) circulating speed were less than 0.80, indicating that the truck could navigate through the tilted roundabouts at 16 km/h (10 mph). Therefore, a lower circulating speed could result in better truck lateral stability in tilted roundabouts.

EFFECT OF ENTRY SPEED ON TRUCK STABILITY

This test intended to evaluate the effect of entry speeds on truck stability. Three entry speeds were considered for the baseline truck, as summarized in table 14; all dimensions not shown are unchanged within the set of single-lane and two-lane cases (see table 8 for details). For cases with 32 km/h (20-mph) and 40 km/h (25-mph) entry speeds, the truck slowed down to 24 km/h (15 mph) to negotiate the roundabout. For cases with an entry speed of 24 km/h (15 mph), the truck maintained that speed for the entire run.

Table 14. Entry speed cases considered for evaluating truck dynamics.

Case #	Roundabout Diameter - ICD [m (ft)]	Movement	Speed at entry/roundabout/exit [km/h (mph)]
1	42.7 (140)	Right turn	32/24/32 (20/15/20)
2	42.7 (140)	Through	32/24/32 (20/15/20)
3	42.7 (140)	Left turn	32/24/32 (20/15/20)
28	42.7 (140)	Right turn	24/24/24 (15/15/15)
29	42.7 (140)	Through	24/24/24 (15/15/15)
30	42.7 (140)	Left turn	24/24/24 (15/15/15)
31	42.7 (140)	Right turn	40/24/40 (25/15/25)
32	42.7 (140)	Through	40/24/40 (25/15/25)
33	42.7 (140)	Left turn	40/24/40 (25/15/25)
34	54.9 (180)	Right turn	32/24/32 (20/15/20)
35	54.9 (180)	Through (left lane)	32/24/32 (20/15/20)
36	54.9 (180)	Through (right lane)	32/24/32 (20/15/20)
37	54.9 (180)	Left turn	32/24/32 (20/15/20)
78	54.9 (180)	Right turn	24/24/24 (15/15/15)
79	54.9 (180)	Through (left lane)	24/24/24 (15/15/15)
80	54.9 (180)	Through (right lane)	24/24/24 (15/15/15)
81	54.9 (180)	Left turn	24/24/24 (15/15/15)
82	54.9 (180)	Right turn	40/24/40 (25/15/25)
83	54.9 (180)	Through (left lane)	40/24/40 (25/15/25)
84	54.9 (180)	Through (right lane)	40/24/40 (25/15/25)
85	54.9 (180)	Left turn	40/24/40 (25/15/25)

Right Turns

The rollover indices for the right turns and the various entry speeds in the two roundabouts are shown in figure 45 and figure 46.

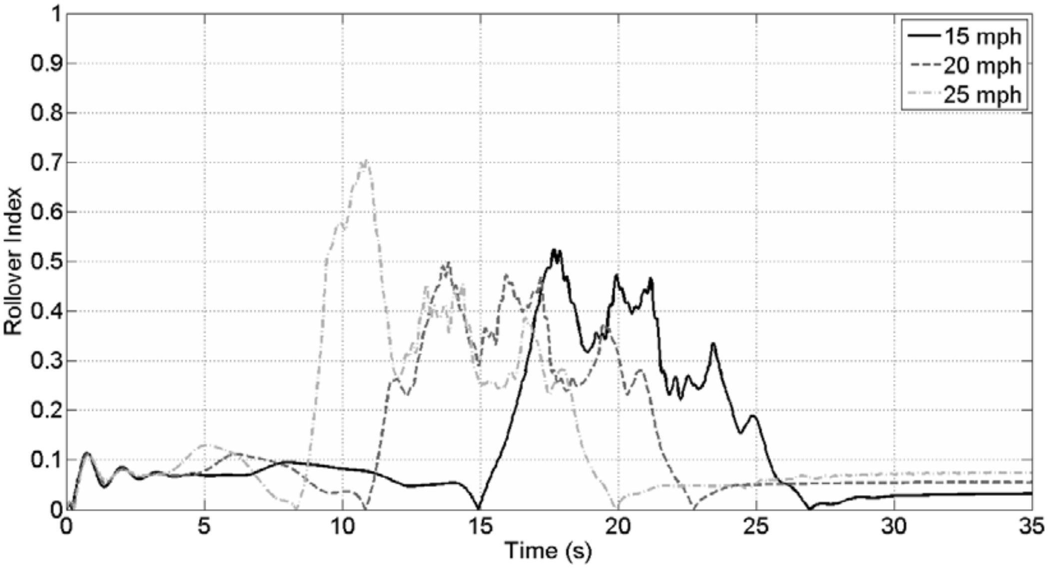


Figure 45. Effect of entry speed on rollover index for a 42.7-m (140-ft) roundabout (single-lane, right turn).

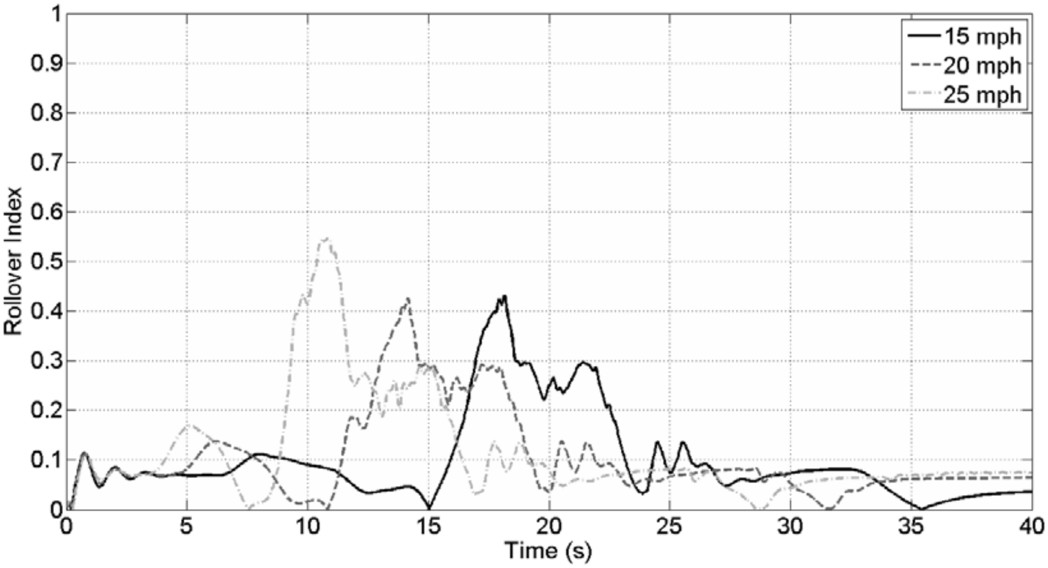


Figure 46. Effect of entry speed on rollover index for a 54.9-m (180-ft) roundabout (two-lane, right turn).

The different speeds of the trucks caused them to encounter roadway features, such as curves and slope, at different times, so the peaks in rollover index corresponding to those roadway features are not aligned in the figures comparing truck speed.

As shown in figure 45 and figure 46, the peak in rollover index when the truck entered the roundabout was higher for the truck traveling at 40 km/h (25-mph) than it was for the other speeds. The peak when the truck exited the roundabout was largely unaffected by truck speed. The reason that trucks traveling at 24 km/h (15 mph) and 32 km/h (20 mph) had generally the same magnitude of peaks in rollover index was because the truck with an entry speed of 32 km/h (20 mph) slowed down to 24 km/h (15 mph) within a very short period of time.

The differences in peaks in rollover index can be explained by the trucks' speeds when they navigated the curvature at the roundabout entry and exit. The trucks traveling at 40 km/h (25 mph) and 32 km/h (20 mph) both slowed to 24 km/h (15 mph), but the truck traveling at 40 km/h (25 mph) took longer to do so, and was thus was traveling faster when it navigated the curvature at the roundabout entry, resulting in a higher rollover index. The truck traveling at 32 km/h (20 mph) was able to slow to 24 km/h (15 mph) by the time it reached the curvature at the roundabout entry, so it exhibited the same rollover-index behavior as the truck traveling at a constant 24 km/h (15 mph). All trucks were traveling at 24 km/h (15 mph) at the roundabout exit, and all had similar peaks in rollover index at that point.

A direct correlation between entry speed and rollover index in at the roundabouts' entry was as expected. For both roundabouts, the rollover index peak remained below the critical limit of 1.0 for the speeds considered in the simulation.

Through Movements

The rollover indices for the through movements and the various entry speeds in the two roundabouts are shown in figure 47 and figure 48.

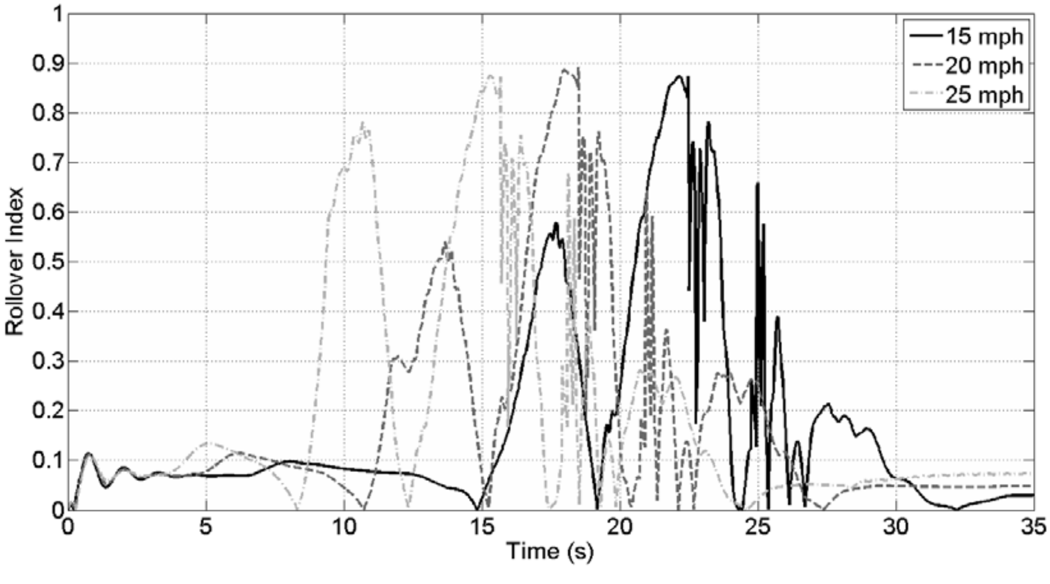


Figure 47. Effect of entry speed on rollover index for a 42.7-m (140-ft) roundabout (single-lane, through movement).

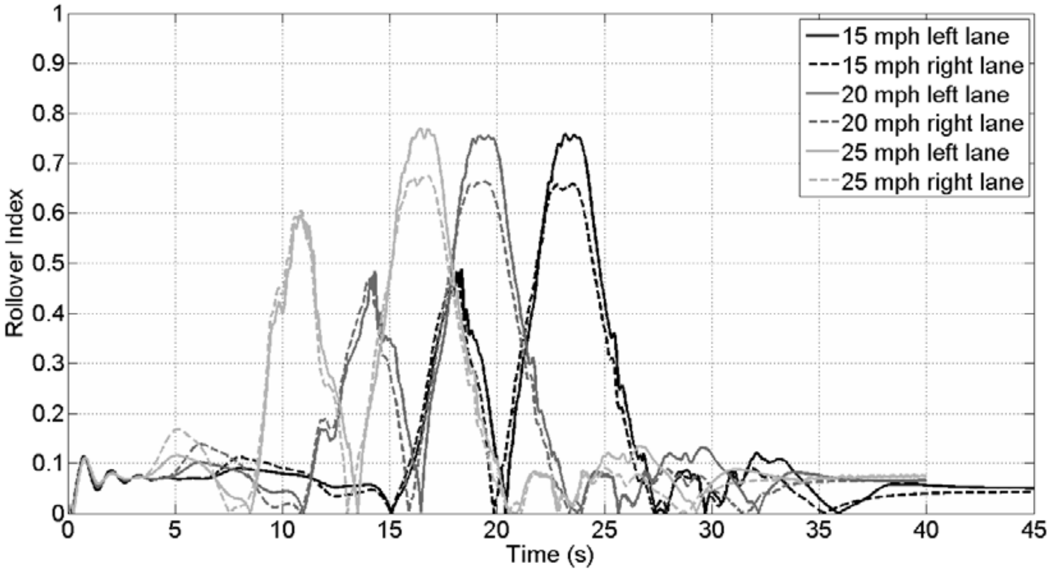


Figure 48. Effect of entry speed on rollover index for a 54.9-m (180-ft) roundabout (two-lane, through movement).

The results shown in figure 47 and figure 48, above, are similar to those for right turns in the previous section. The peak in rollover index was higher for the truck traveling at 40 km/h (25 mph) than for those traveling at the other speeds, because it encountered the curvature at the roundabout's entry while traveling faster. The peak at the roundabout exit was almost the same height for the three speeds, because the three trucks were all traveling 24 km/h (15 mph) before exiting the roundabout.

Left Turns

The rollover indices for the left turns at the various entry speeds in the two roundabouts are shown in figure 49 and figure 50.

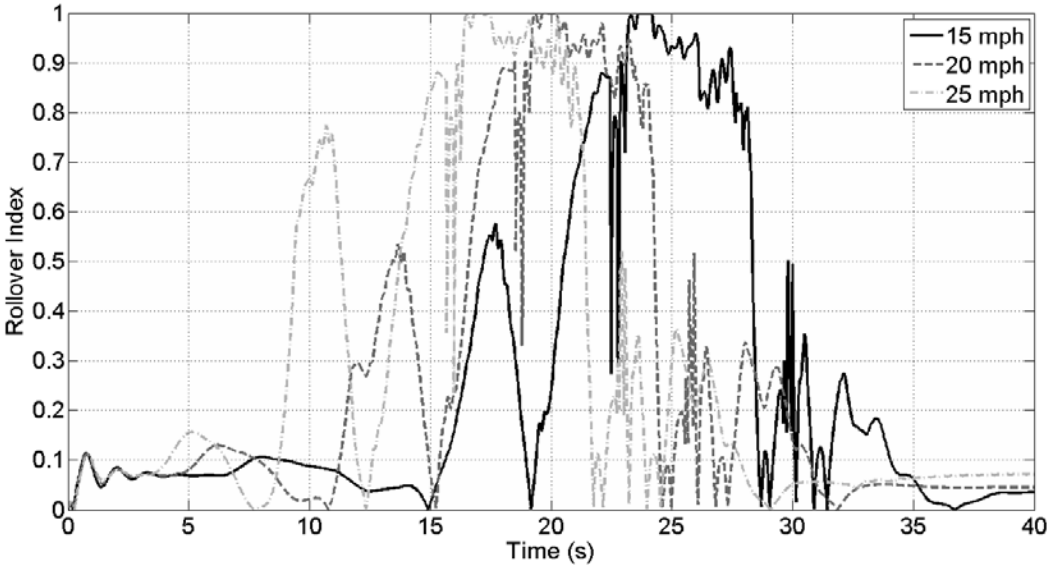


Figure 49. Effect of entry speed on rollover index for a 42.7-m (140-ft) single-lane roundabout (single-lane, left turn).

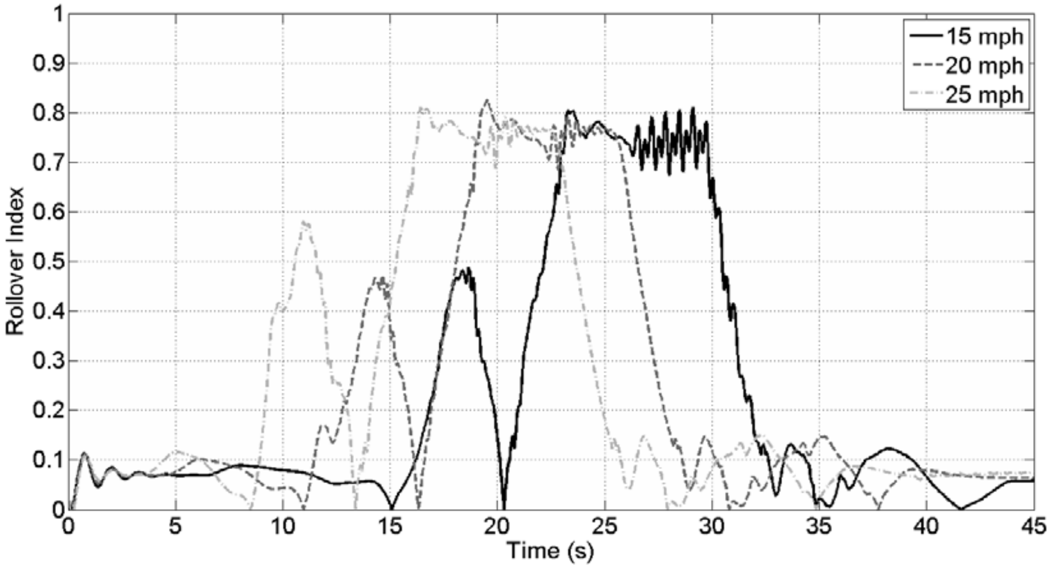


Figure 50. Effect of entry speed on rollover index for a 54.9-m (180-ft) two-lane roundabout (two-lane, left turn).

The results in figure 49 and figure 50 show the same trends as the other movements, but the magnitude of the rollover indices was different. For the single-lane roundabout, trucks traveling at all three speeds experienced rollover indices of 1 at the roundabout exit, indicating a high likelihood of rollover. For the two-lane roundabout, the peak rollover indices at the roundabout exit were 0.80.

SUMMARY OF SIMULATION ANALYSIS

The results of all six tests and some additional cases are summarized in this section. For these analyses, peak rollover index indicates the moment of largest rollover likelihood during the entire movement. A zero rollover index represents a perfectly weight-balanced vehicle. A vehicle with a rollover index lower than 0.8 is capable of traveling through a roundabout and maintaining stability. Between 0.8 and 0.9, the vehicle becomes less stable, and if peak rollover index exceeds 0.9, the vehicle has a high likelihood of rollover.

Effect of Roundabout Inscribed Circle Diameter on Truck Stability

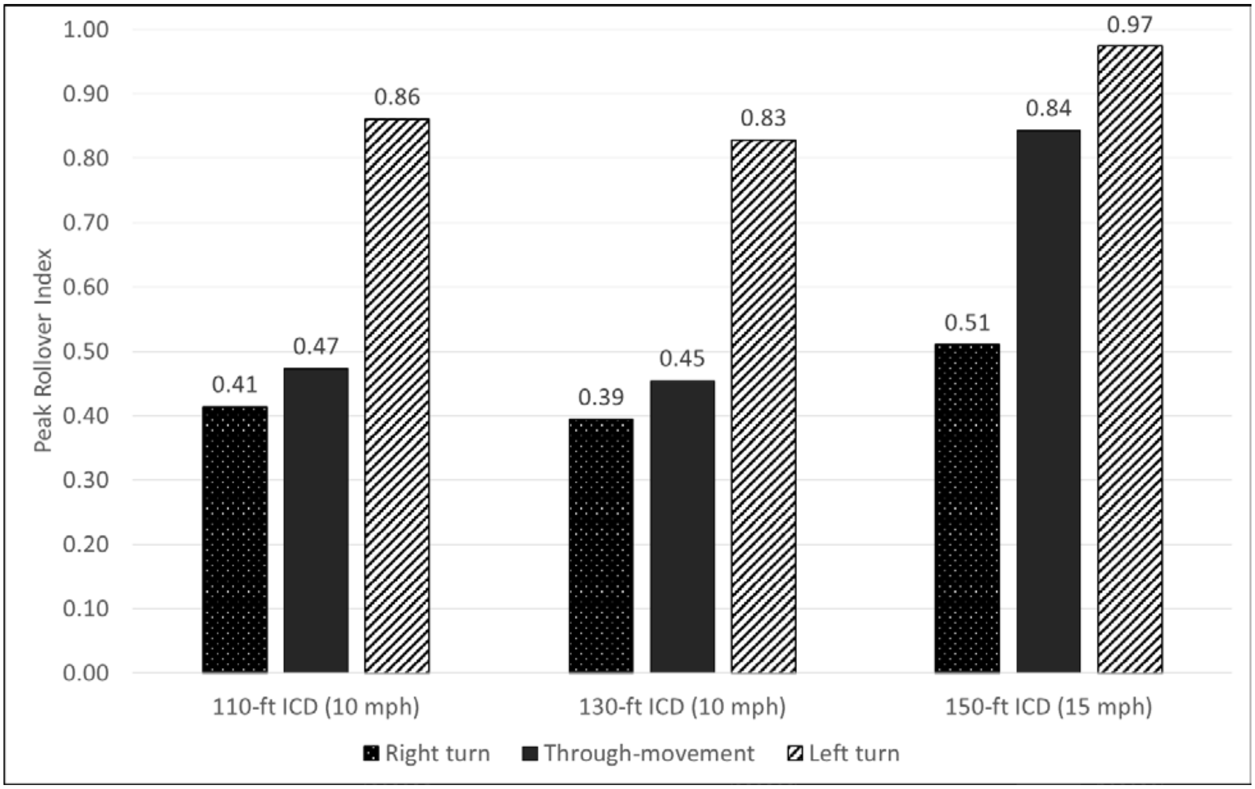


Figure 51. Effect of roundabout diameters on peak rollover index by movement in single-lane roundabouts.

Figure 51 shows that the peak rollover indices were lower for the 39.6-m (130-ft) ICD roundabout than the 33.5-m (110-ft) roundabout. However, the peak rollover indices for the 45.7-m (150-ft) roundabout were much higher than the other ICDs. This was because trucks negotiating the 45.7 (150-ft) roundabout traveled at 24 km/h (15 mph), compared to 16 km/h (10 mph) for the other two roundabout ICDs.

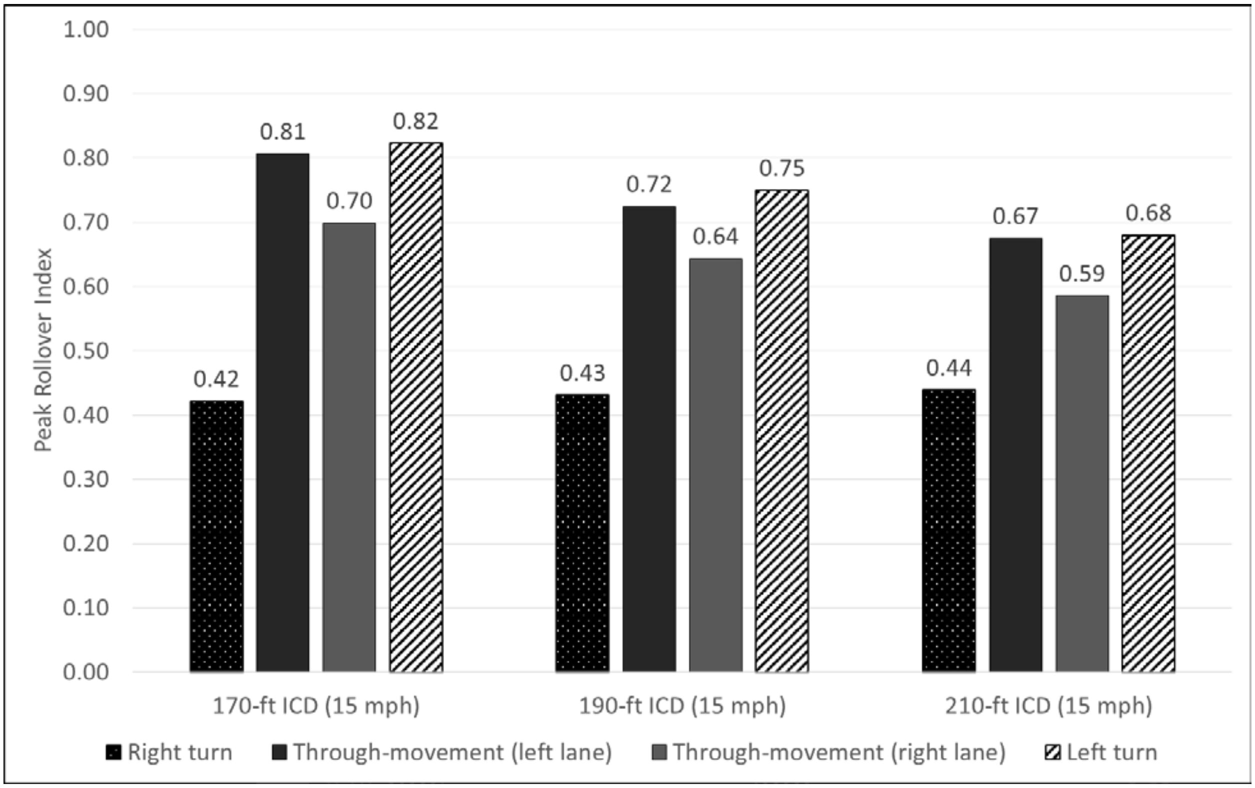


Figure 52. Effect of roundabout diameters on peak rollover index by movement for two-lane roundabouts.

Figure 52 shows that for two-lane roundabouts, all three roundabout ICDs had nearly the same rollover indices for right turns. For through movements and left turns, rollover indices decreased as diameters increased. When the truck performed a through movement from the right lane and straddled lanes, the peak rollover index was lower than when the truck approached from the left lane. Left turns had the highest peak rollover indices of the movements.

In summary, when performing right-turn movements, a roundabout's ICD does not greatly affect the likelihood of rollover, because the vehicle need not negotiate the central island. Therefore, regardless of the cross-sectional design of the roadway, the elements that mainly determine the vehicle lateral dynamics for making right turns are entry radii, exit radii, and especially traveling speed, as indicated in figure 51.

For through movements and left-turn movements, a larger ICD decreased the possibility of vehicle rollover. For the same vehicle speed in the roundabout, lateral accelerations are smaller in a roundabout with a larger diameter. The results of this test show that speed plays a highly significant role in truck lateral dynamics in roundabouts.

Effect of Circulatory Roadway Cross-section on Truck Stability

Three scenarios with different roundabout cross-sections were tested to determine their effect on truck stability. The peak rollover indices of each scenario for a 54.9-m (180-ft) roundabout are shown in figure 53.

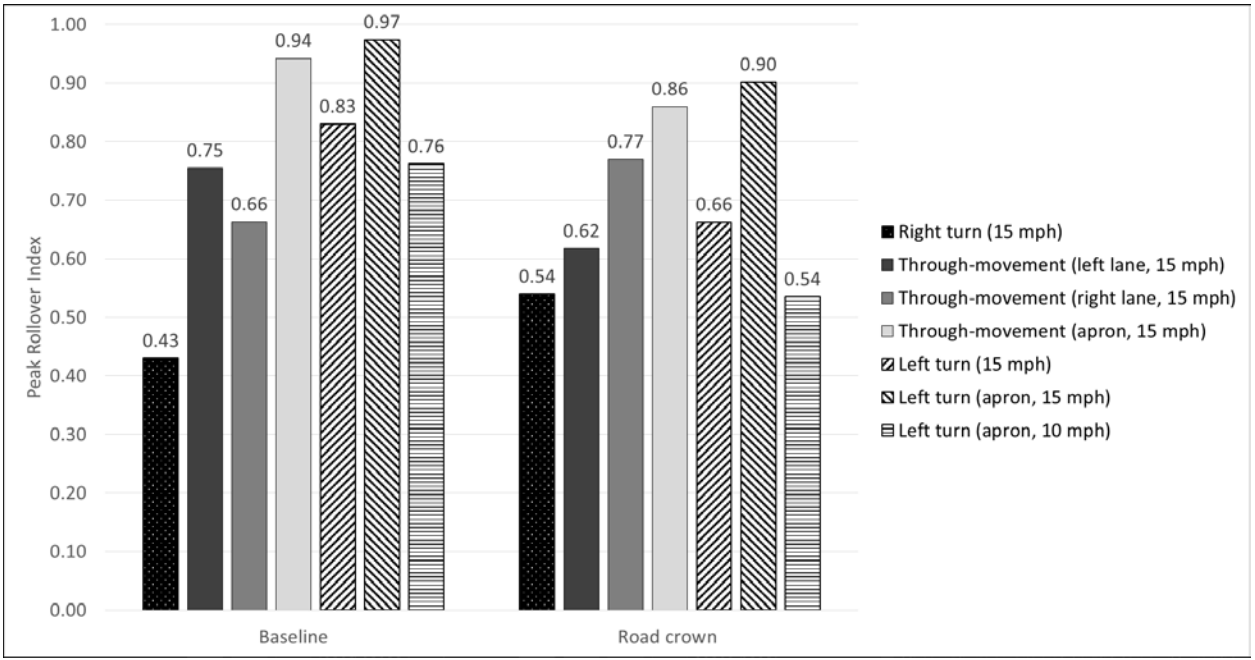


Figure 53. Effect of truck apron and road crown on peak rollover index for a 54.9-m (180-ft) two-lane roundabout by movement.

According to figure 53, for right-turn movements, the crowned cross-section caused the truck to have relatively less lateral stability than the baseline cross-section. This was because for the crowned roundabout, the left edge of the inner two-thirds of the roadway was lower than the right edge. When the truck straddled the lanes to make a right turn, its left wheels ran on the inner, lower part of the roadway, increasing the truck's tendency to lean to the left side and reducing its lateral stability. However, the rollover indices for both the baseline and crowned roundabout were low, indicating a low likelihood of rollover.

For the through movements and left-turn movements, the crowned cross-section had a smaller peak rollover index and lower likelihood of rollover than the baseline cross-section. When the trailer rear tires moved onto the truck apron (denoted by '(apron)' in figure 53's legend), the rollover index was significantly higher than when the truck did not move onto the truck apron. This was mainly because the apron's outward slope caused the truck to lean to the outside in the direction of the centrifugal forces against the trailer, and was also due to transient dynamics caused by the truck moving onto and off of the apron. If the truck did not straddle lanes to make a through movement or left turn, the truck apron and road crown combination resulted in a lower likelihood of rollover than the truck apron and baseline combination.

Because trucks turning left in these test cases had high rollover indices, additional cases at reduced speed were performed to determine whether the extent reduced speed would reduce the rollover indices. When the semi-truck traveled at a slower 16 km/h (10 mph), it had a much lower likelihood of rollover. It should be noted that load configuration, truck suspension properties, and the truck's path all affect the truck's lateral dynamics. For instance, a truck with a shifting load may have less lateral stability than a truck with a fixed load, and more research is needed to cover a larger number of possible cases.

Effect of Truck Configuration on Truck Stability

Three different truck configurations were simulated to determine their lateral dynamics. The peak rollover indices for the truck configurations for a 42.7-m (140-ft) single-lane roundabout and a 54.9-m (180-ft) two-lane roundabout are shown in figure 54 and figure 55, respectively.

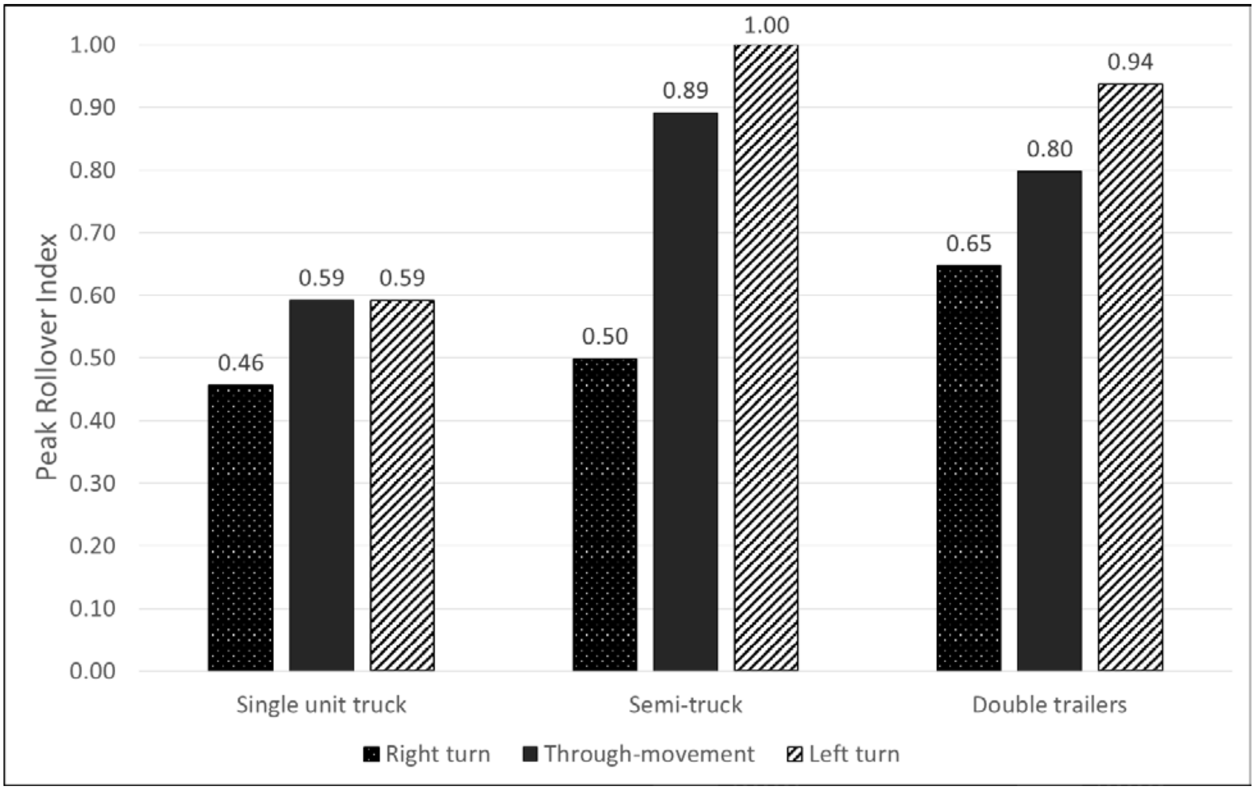


Figure 54. Effect of truck configuration on peak rollover index for a 42.7-m (140-ft) roundabout by movement.

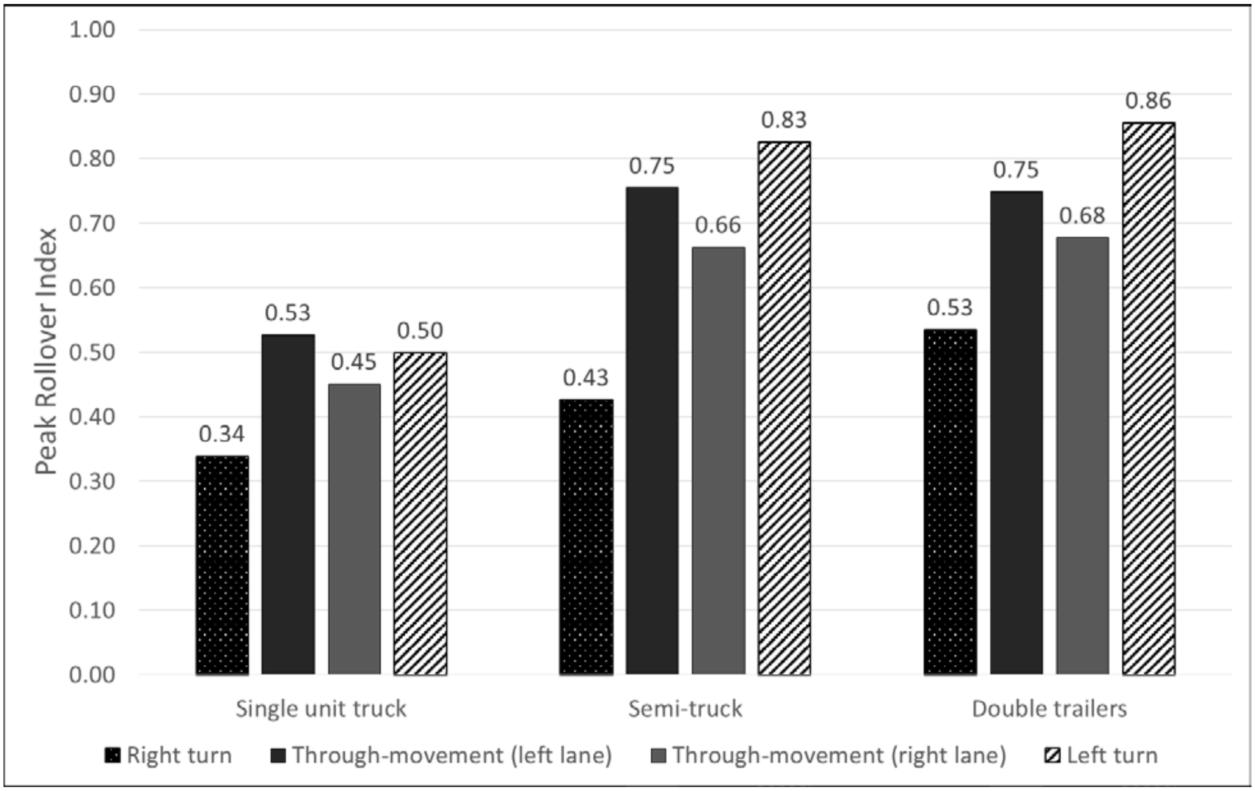


Figure 55. Effect of truck configuration on peak Rollover Index for a 54.9-m (180-ft) roundabout by movement.

Based on figure 54 and figure 55, a SU-30 single-unit truck was more stable than the other two configurations: a WB-67 semi-truck and a B-train tractor with double trailers. Even though a B-train tractor with double trailers was longer than a WB-67 semi-truck, each of the trailers was shorter than the semi-truck's single trailer, and the hitch connection between them allowed the tractor with double trailers to better conform to the roundabout. Additionally, the longer wheelbase meant the tractor with double trailers' second trailer circulated at a lower speed than the semi-truck's trailer, resulting in lower lateral accelerations. Thus, in general, a tractor with double trailers had similar lateral stability to the semi-truck that was modeled.

Effect of Load Configuration on Truck Stability

Three load configurations were studied for the baseline semi-truck to determine whether the load configuration impacted truck lateral stability. The peak rollover indices for each load configuration are shown in figure 56 and figure 57 for the single-lane and two-lane roundabout, respectively.

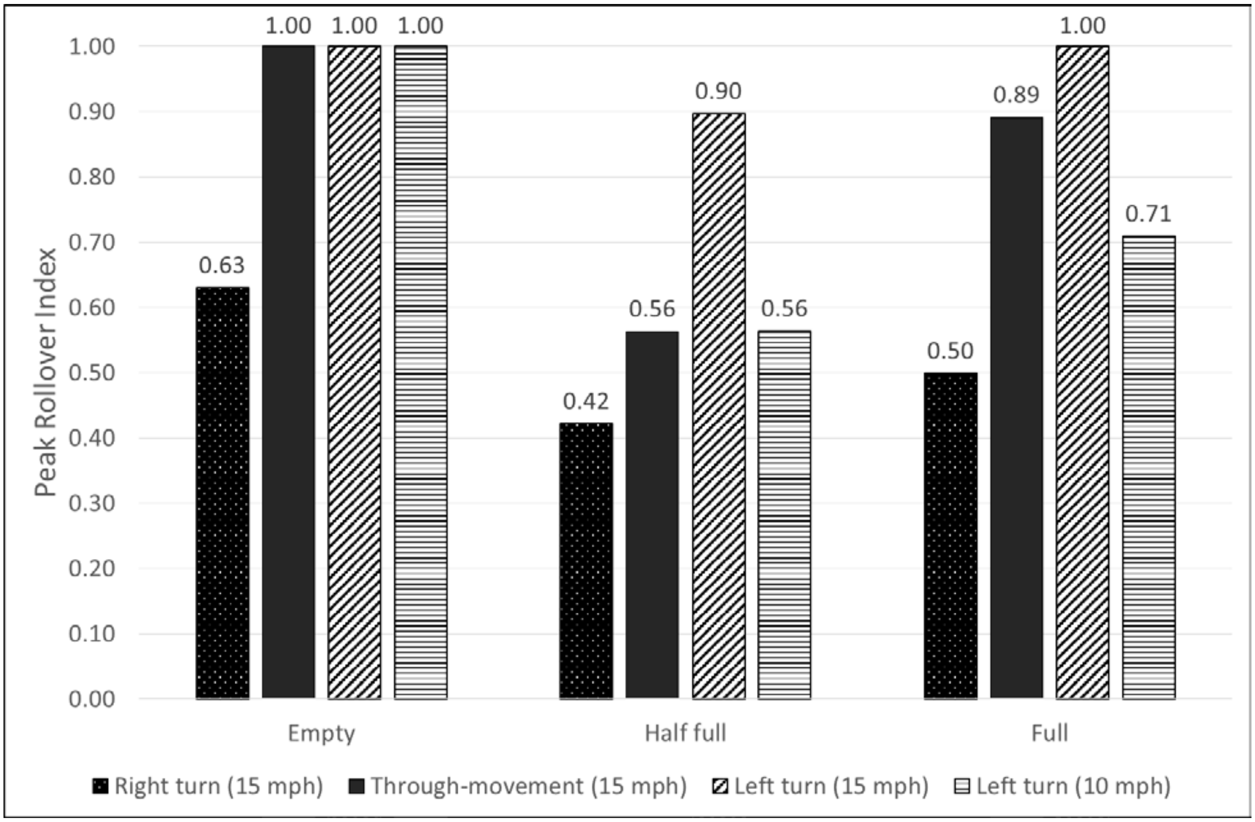


Figure 56. Effect of truck weight on peak Rollover Index for a 42.7-m (140-ft) roundabout by movement.

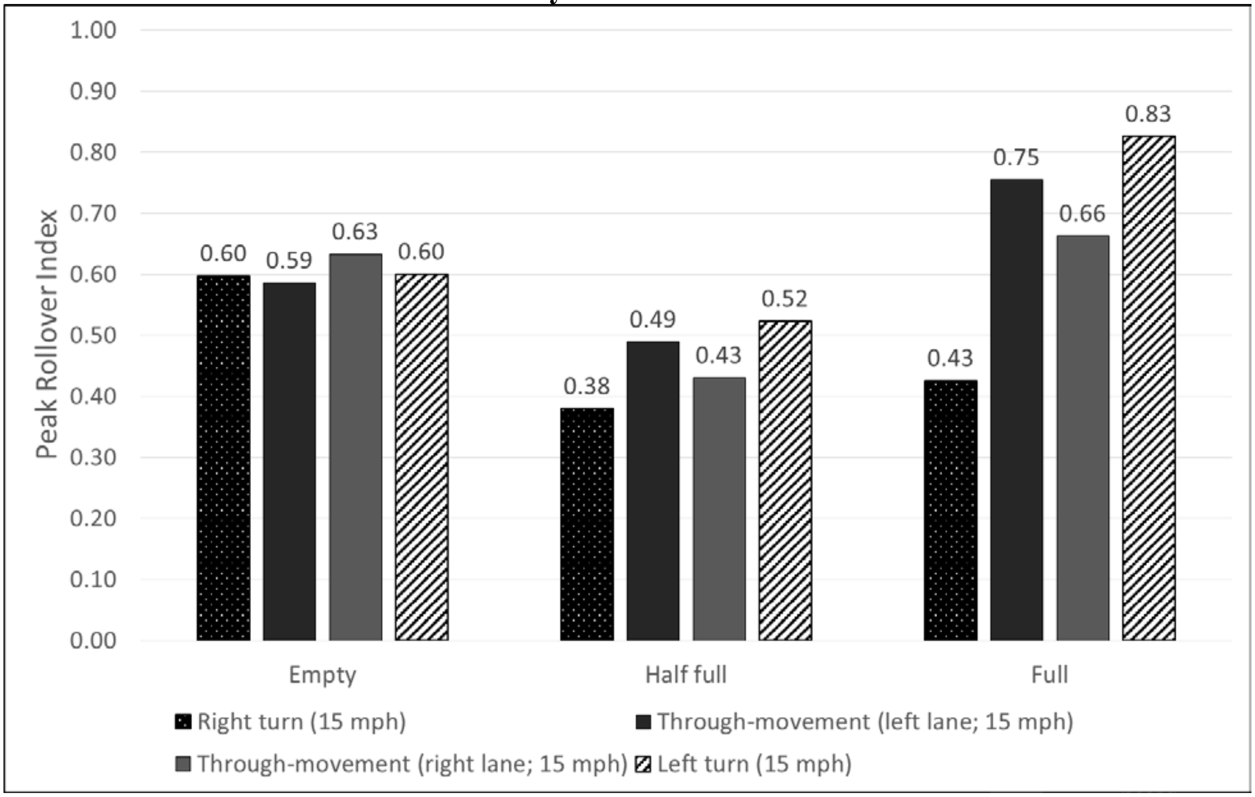


Figure 57. Effect of truck weight on peak Rollover Index for a 54.9-m (180-ft) roundabout by movement.

Figure 56 indicates that in the 42.7-m (140-ft) single-lane roundabout, the half-full truck had the lowest rollover indices and the lowest likelihood of rollover. That is because a lighter axle load has less load weight holding the truck down against the road, and can be more easily unloaded. A heavier axle load, such as in the fully loaded truck, is more heavily loaded against the road and requires more unloading to reach a high likelihood of rollover.

The results in figure 57 show that all of the three load conditions resulted in rollover indices reasonably below 1. For the 54.9-m (180-ft) roundabout, the full truck yielded the largest rollover index, and the half-full truck the smallest.

In summary, trucks with different load configurations had different dynamic responses to the road input, as one might intuit. Somewhat less intuitively, results indicated that an empty truck reached its rollover limit sooner than a loaded or partially loaded truck, particularly in roundabouts with smaller diameters. In practice, maintaining safety would necessitate designing the roadway for the empty truck condition or advising lower speeds.

In addition, changes in roadway curvature and side-to-side elevation resulted in transient lateral dynamics, causing large lateral accelerations, roll angles, and rollover index peaks. This phenomenon was most noticeable when an empty truck moved straight through or turned left at a single-lane roundabout with a truck apron. For larger roundabouts, the balance between the truck's CG height (due to the load condition) and the wheel loads was the primary factor determining rollover index. For the 54.9-m (180-ft) roundabout, the full truck exhibited the largest peaks in rollover index, although the rollover index remained well below the 1 rollover limit. The half-load truck exhibited the lowest rollover index.

Reduced speed cases were added to test truck lateral dynamics with different load configurations at a lower speed. When the circulating speed was decreased to 16 km/h (10 mph), the fully and half loaded truck both exhibited reasonably better lateral stability. However, the lower circulating speed did not greatly reduce the rollover index for the empty truck, due to the lighter load on its axles. Hence full- and half-loaded semi-trucks were more sensitive to the speed and could obtain better stability when traveling at a lower speed. For the empty semi-trucks, a lower speed had relatively little effect on lateral dynamics.

Effect of Roundabout Tilt on Truck Stability

The entire roundabout was tilted at four separate constant slopes to determine the effect of tilted slopes on truck stability. The peak rollover indices for the tilted-slope cases are shown in figure 58 and figure 59 for the single-lane and two-lane roundabouts, respectively.

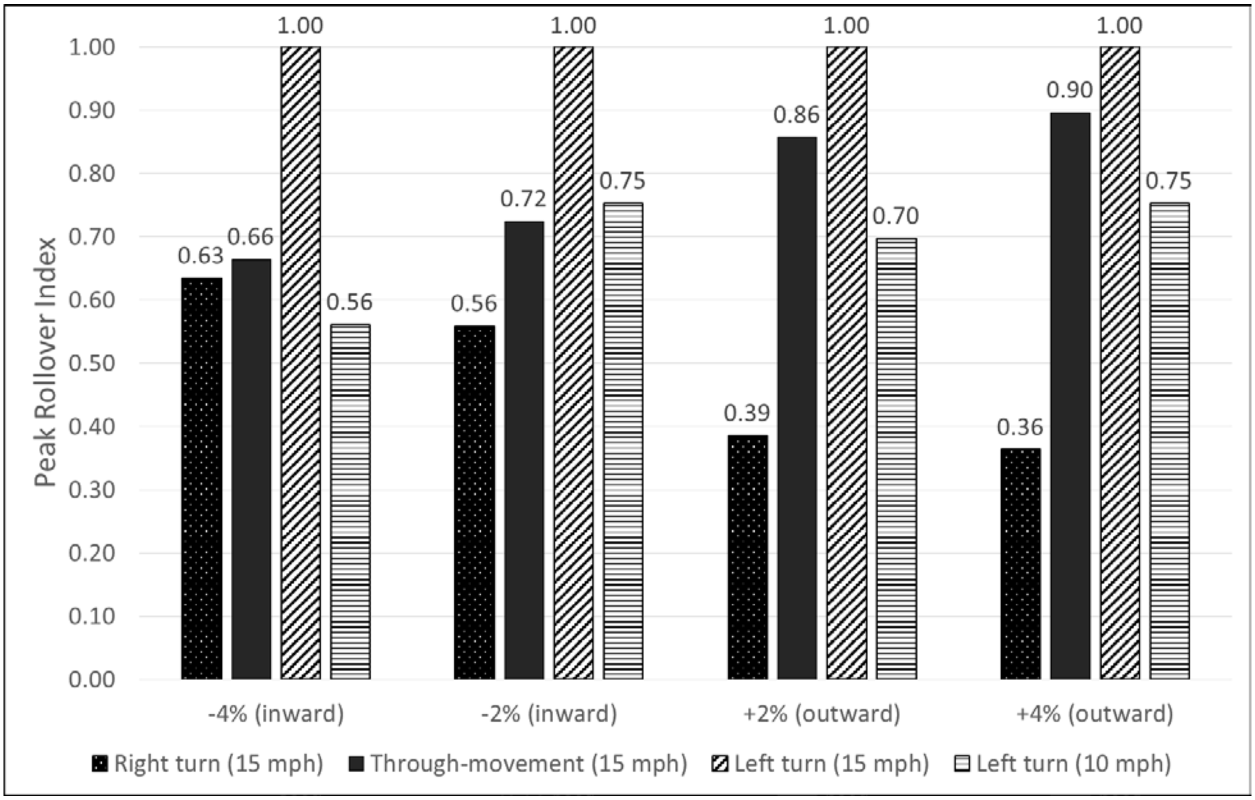


Figure 58. Effect of roundabout tilt on peak rollover index for a 42.7-m (140-ft) roundabout by movement.

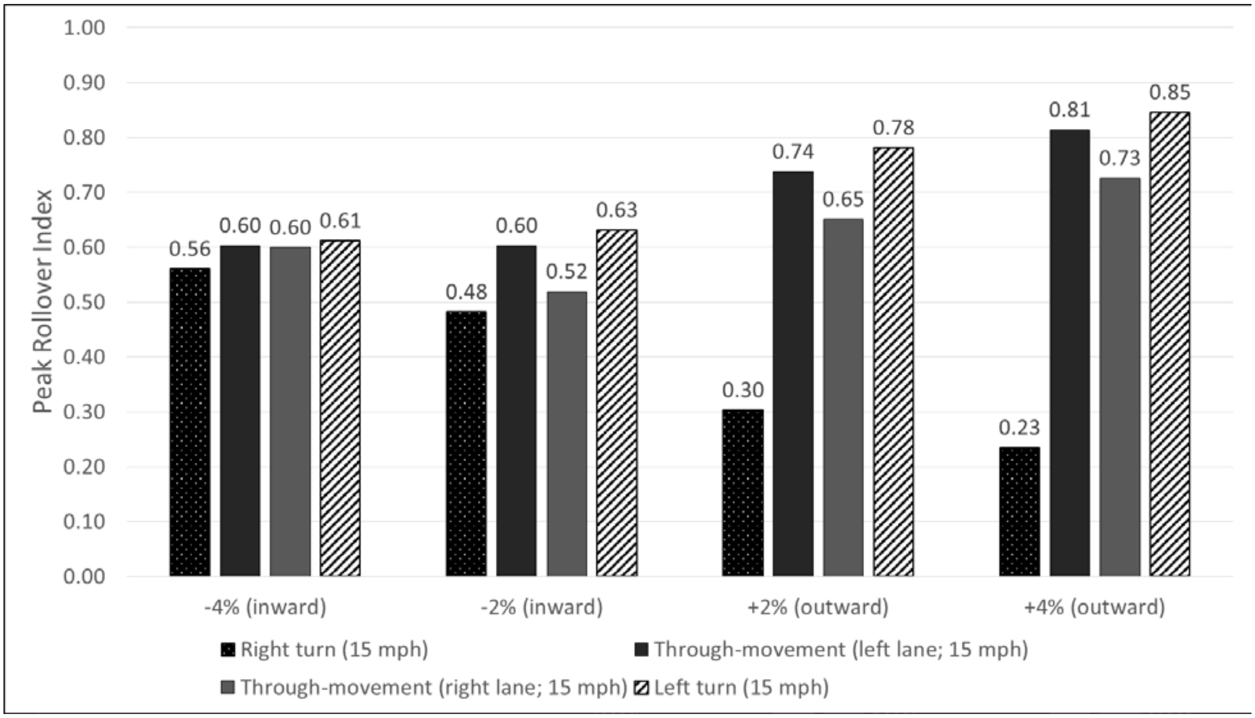


Figure 59. Effect of roundabout tilt on peak Rollover Index for a 54.9-m (180-ft) roundabout by movement.

Figure 58 and figure 59 indicate that for right turns, the positive (outward) tilted slopes resulted in better truck lateral stability than negative (inward) titled slopes. The opposite effect of tilt occurred for through movements and left turns; at the roundabout entry and exit, negative/inward tilt increased rollover index, but in the circulatory roadway, negative (inward) tilt reduced rollover index. This outcome presents a challenge in terms of applying the results. A positive (outward) tilt would reduce rollover index at the entry and exit, but a negative (inward) tilt would reduce rollover index in the circulatory roadway. For through movements and left turns, the rollover index peaks in the circulating roadway were larger than those at the entry and exit, so moderately tilting the roundabout negatively (inward) would increase truck lateral stability in the areas where it experienced the highest rollover index. Several elements interact with roundabout tilt to affect truck lateral dynamics, but, in general, negative (inward) tilting resulted in better truck lateral stability.

Effect of Entry Speed on Truck Stability

The effect of entry speeds on truck stability was evaluated. The peak rollover indices for different entry speeds are shown in figure 60 and figure 61 for the single-lane and two-lane roundabouts, respectively.

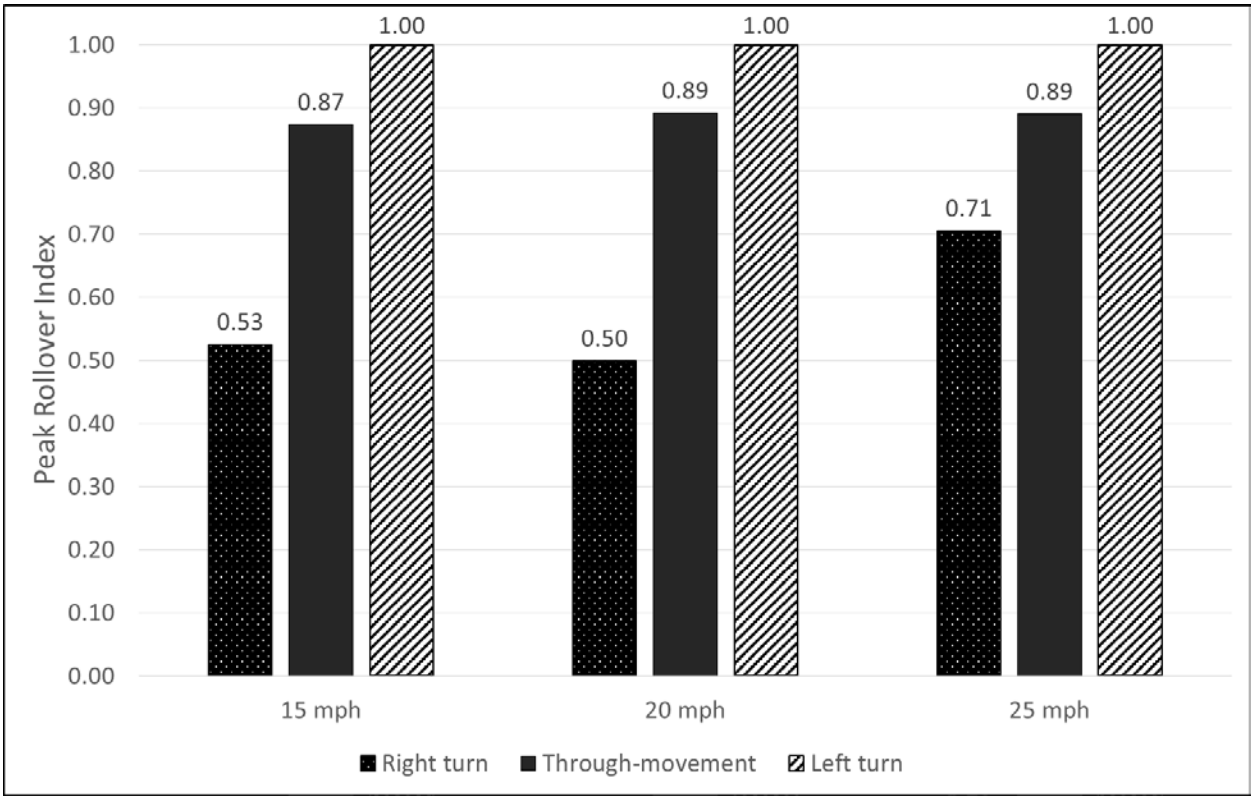


Figure 60. Effect of entry speed on peak rollover index for a 42.7-m (140-ft) roundabout by movement.

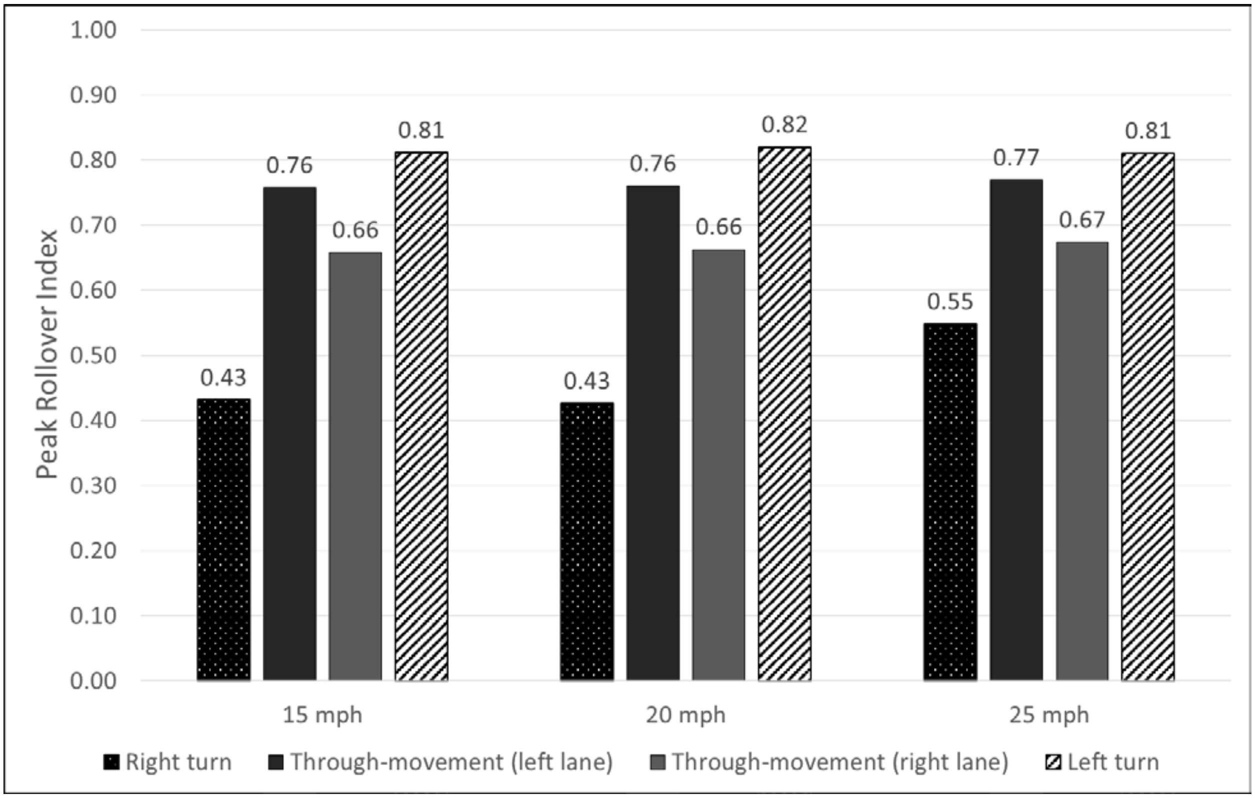


Figure 61. Effect of entry speed on peak rollover index for a 54.9-m (180-ft) roundabout by movement.

For right turning trucks, peak rollover indices occurred at the roundabout entry. According to figure 60 and figure 61, when trucks entered the roundabout at 40 km/h (25 mph) to make a right turn, they experienced much larger rollover indices than at the other two speeds. That was because the truck entering at 32 km/h (20 mph) slowed to 24 km/h (15 mph) within a short time and therefore had behavior at the roundabout entry very similar to that of the truck traveling at a constant 24 km/h (15 mph). However, the truck traveling at 40 km/h (25 mph) did not decelerate to 24 km/h (15 mph) before it reached the roundabout entry, and its peak rollover index at that point was higher because of the higher speed.

The peak rollover indices for through movements and left turns were nearly identical at the three entry speeds. That is because trucks experienced peak rollover index while navigating the central island, and at that point, all trucks had slowed to 24 km/h (15 mph), regardless of entry speed. Therefore, even though the truck entry speed significantly affected the truck's lateral dynamics at the roundabout entry, it did not influence the truck's lateral dynamics while in the circulatory roadway or the roundabout exit.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

Based on the literature review, truck crash review, and simulation results, the following conclusions and recommendations were identified.

DESIGN CONSIDERATIONS

The following sections summarize design features that were identified as having the potential to impact truck stability based on this study. These should be considered in roundabout design, along with other site-specific elements, to determine the most appropriate design for each location.

Circulatory Roadway Cross-Section

Two different circulatory roadway cross-sections were tested during the simulation modeling to determine their effect on truck stability. In two-lane roundabouts, when using both travel lanes to complete through movements or left turns, trucks had better lateral stability with crowned circulatory roadways than they did in roundabouts with a 2% cross slope to the outside. Although the simulation modeling showed that the crowned circulatory roadway increased stability for left turns and through movements at roundabouts, the crowned circulatory roadway resulted in a slightly higher rollover index for trucks making right turns when compared to roundabouts with a 2% cross-slope to the outside. Therefore, it is important to consider truck movements at the roundabout to determine an appropriate design for each site.

Truck Apron

The use of a truck apron is a well-established design practice for accommodating large vehicles at roundabouts, while also providing adequate speed control for passenger cars. During the simulation modeling, trucks performing through or left-turn movements experienced a higher rollover index and rollover risk on the truck trailer at the moment when mounting and dismounting a truck apron modeled with a 3-in. vertical face. The design of the truck apron interface with the circulatory roadway could not be evaluated as part of this study, but the shape of the truck apron curb (e.g., height, slope, etc.) is believed to be a contributing factor.

Speed

The literature review and truck crash review both indicated that speed was a contributing factor in some of the reported truck crashes at roundabouts, with trucks traveling too fast to safely move through the roundabout. Simulation results and the truck crash review indicated that speed within the circulatory roadway was an influential factor in truck stability at roundabouts. The simulation results indicated that speeds of 24 km/h (15 mph) were sufficient to experience a high risk of rollover in some of the single-lane roundabout scenarios tested. In these scenarios, truck stability was improved by reducing the vehicle speed within the circulatory roadway to 16 km/h

(10 mph). The speed within the circulatory roadway was more influential on truck stability than speeds at the entry and exit. Because truck speeds of 24 km/h (15 mph) may be too high for some roundabout configurations, drivers and police officers may not always recognize that speed was a contributing factor in rollover crashes. Education programs for truck drivers to inform them of the effect of truck speed on truck stability would encourage slower truck speeds in roundabouts.

Truck Types and Loads

The literature review indicated that center of gravity and truckload has an impact on truck stability. The crash history review found several crashes that noted load shift as a contributing factor to a rollover incident. The simulation results indicated that truck configurations and load have some influence on truck stability at roundabouts. WB-67 trucks were found to be less stable than SU-30 trucks and B-trains at smaller, single-lane roundabouts, while B-train and WB-67 trucks were found to have similar stability in larger roundabouts. Empty trucks were found to have a higher risk of rollover, particularly for WB-67 and B-train configurations, in single-lane roundabouts, while fully loaded trucks, with higher center of gravity, were found to have the highest rollover indexes in two-lane roundabouts. The balance between the truck's center of gravity height and the wheel loads appeared to be a factor influencing the rollover index for larger two-lane roundabouts. Non-static loads were not tested as part of this effort.

Educating drivers about these influences on stability may impact driver behavior at roundabouts. For instance, the lower stability of empty trucks may be counterintuitive, and better education may inform drivers and impact driver behavior, leading to fewer rollovers.

EDUCATION PROGRAMS AND DRIVER PRACTICE

Several of the conclusions from the simulation testing and information obtained from the crash history review and literature review indicated that factors in truck crashes at roundabouts involved vehicle types, vehicle loads, and driver behavior. Programs focused on educating truck drivers and other vehicle drivers on these findings would help promote appropriate driver behavior related to trucks at roundabouts. These efforts can build upon the collaboration taking place within the trucking industry in a number of states.

RECOMMENDATIONS FOR ADDITIONAL STUDY

This study provided a review of factors associated with truck rollover crashes at roundabouts by reviewing existing literature, by studying crash history involving trucks at roundabouts, and by completing a modeling analysis to evaluate trucks' rollover index under various roadway, vehicle, and driver characteristics. There are several areas of future study that should be considered to continue this work.

An evaluation of the impact of dynamic loads on truck stability was not performed, but would be informative, because unlike in the simulations performed here, loads may shift during travel if not completely secured. Further research should consider the impact of this load shift and different load materials (liquid, solid) on truck stability.

Further work on the effect of the truck apron curb design on stability is recommended. The simulation modeling analysis used for this study could not consider the difference between different curb designs, including more gradually sloped curbs, which may result in a less abrupt point of impact for the truck. Future studies should evaluate the impact of different cross-section slopes and curb heights on lowboys, which may be more likely to get stuck in roundabouts.

Finally, this study could only evaluate one variable at a time, so further studies should consider various combinations of factors studied here, as well as additional factors, to better understand their combined impact on truck stability in roundabouts. These combination studies may be best conducted in collaboration with the trucking industry in lab and/or field settings.

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