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Heavy Vehicle Rollover Propensity At Roundabouts On Highspeed Roads

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HEAVY VEHICLE ROLLOVER PROPENSITY AT ROUNDABOUTS ON HIGH-SPEED ROADS

A Thesis

Submitted to the Faculty

of

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by

Thomas M. Hall

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of

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ABSTRACT

Hall, Thomas M. M.S.C.E., Purdue University, December 2014. Heavy Vehicle Rollover Propensity at Roundabouts on High-speed Roads. Major Professor: Andrew Tarko.

There is a recent trend of building roundabouts on high-speed roads, often with significant heavy vehicle traffic. With the increased presence of trucks on roundabouts, the issue of rollover has become a concern. Geometric features that allow excessive speed on the approach and entry have been connected to rollover, as well as sudden changes in crossfall and radius. However, the effect on the rollover threshold of changing the roundabout's circulatory superelevation is not fully understood. The impact of aggressive driving behaviors, as displayed by high driver speed far from the roundabout, as well as errors that are manifested by the driver maintaining excessive speed in close proximity to the roundabout, should also be further examined and quantified.

This thesis describes a rollover model more generalized than those previously used for design considerations. It accounts for the intricacies of semi-trailers and other heavy vehicles by incorporating both complex trailer paths that do not conform to the road alignment and the resulting vehicle tilt. The proposed model is applied in the aforementioned scenarios after introducing Δv - the difference between the critical rollover speed determined from the model and the actual speed.

In the comparison of inward vs. outward circulatory superelevation, the study revealed that the 2% inward scenario produces a 1.5-1.9 mile per hour higher (depending on the assumed trailer loading) Δv than 2% outward. As expected, the difference becomes greater (1.8-2.4 mph) when the inward superelevation is increased to 3%. However, these differences are too weak to recommend the inward design given its other shortcomings. The study also showed that aggressive driver behavior, as exemplified by speed far from the roundabout, does not have a significant effect on the critical rollover threshold at the roundabout circulation. However, drivers who maintain high speeds in close proximity to the roundabout do show a greater tendency to encroach on the critical rollover speed at the roundabout circulation. Properly placed measures such as Variable Message Signs (VMS) can be utilized to help slow these drivers down. Better driver training is also recommended. A final accommodation measure, based on a review of literature and crash reports, involves improvement of the truck apron design so they are easily traversable and more conspicuous.

CHAPTER 1. INTRODUCTION

1.1 Background

Alternative intersections and interchanges are becoming more prevalent across the United States for the replacement of traditional intersection designs. A number of types have emerged, including single point and diverging diamond interchanges, median u-turn, continuous flow, and roundabouts. Roundabouts are predominantly used due to their safety and capacity benefits. Around 3200 now exist throughout the United States, with the largest concentrations in Washington, Wisconsin, and Florida (Rodegerdts, 2014).

According to National Cooperative Highway Research Program (NCHRP) report 672, a 76% reduction in injury crashes and a 35% drop in total crashes was observed in a nationwide roundabout study (Rodegerdts et al., 2010). The converted intersections had previously been controlled as two way stops, all way stops, or signalized. Similar crash reductions have been seen in European countries (Jensen, 2013). Benefits of installing roundabouts can be attributed to a variety of factors, including fewer and less severe conflict points, lower speeds, and enhanced pedestrian safety (Rodegerdts et al., 2010). They are also known to reduce queuing and the delays faced by drivers, thus allowing better traffic progression than conventional intersections.

The Indiana Department of Transportation (INDOT) installed its first roundabout in 2008 in Valparaiso, with nearly 30 additional roundabouts planned on state roads by 2017.

A question that needs to be better answered before roundabouts can be confidently built is how they will perform on high-speed roadways. 45 mph is the commonly used distinction between low and high-speed roadways. These conditions exist on the edges of towns and cities where there is a need to transition from a high-speed rural environment to lower speed urban roads (Torbic et al., 2012). Roundabout safety examinations on these types of roads have been rather brief, but show consistency with results from lower speed roads in reducing accidents, particularly those that are most severe (Bill, Qin, Chitturi, & Noyce, 2011) & (Isebrands, 2011). Figure 1-1 shows such a roundabout in Kansas, where posted speeds on the approaches can be as high as 65 mph.

Figure 1.1 US-400 and K-47 Roundabout near Fredonia, KS (Google Earth)

As more and more roundabouts are built on high-speed roadways, there is a key safety concern for larger vehicles despite the fact that they can reduce overall crashes. This is the issue of truck rollover. Kansas has considerable experience. Since 2000, half of the heavy vehicle crashes at roundabouts on high-speed roads have been rollovers. The common theme among these accidents was excessive speed given the environmental conditions. Despite restrictions on heavy vehicles for many local roundabouts, the United Kingdom observes 50-60 injury rollovers per year on roundabouts (Highways Agency, 2007). An examination of 100 urban and rural roundabouts in Queensland, Australia found articulated vehicles "overrepresented in the single-vehicle accident data" due to their tendency to roll (Arndt & Troutbeck, 1998). Truck rollover at roundabouts is an issue many agencies seek to better understand and address.

Geometric features that allow excessive speed on the approach and entry have been connected to rollover, as well as sudden changes in cross fall and radius (Highways Agency, 2007). However, research has not quantified the proximity to rollover for heavy vehicles and how factors such as high-speed approaches affect this threshold. What is needed is an improved model that describes rollover propensity at roundabouts.

1.2 Objectives

The scope of work in this thesis includes a literature review and examination of previous studies, including crash reports. A more generalized model than those currently used for analysis at roundabouts will be derived and applied to study common design considerations, particularly for roundabouts on high-speed roads. This includes the following:

(1) Examine whether inward circulatory superelevation affords considerable safety advantages over the commonly used outward design

(2) Determine whether aggressive driver behavior, as displayed by high speeds far from the roundabout, suggest drivers are more likely to encroach on critical rollover conditions at the roundabout

(3) Determine whether drivers who maintain high speeds (that is, have errant speed selection) on the roundabout approach come significantly closer to critical rollover conditions at the roundabout

1.3 Thesis Organization

This remainder of this thesis is organized into the following chapters:

- Chapter 2 Literature Review
- Chapter 3 Derivation of Heavy Vehicle Rollover Model
- Chapter 4 Data
- Chapter 5 Effect of Circulatory Superelevation on Rollover Propensity
- Chapter 6 Effect of Aggressive Driver Behavior on Rollover Propensity
- Chapter 7 Effect of Errant Approach Speed Selection on Rollover Propensity
- Chapter 8 Conclusions
- Appendix

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This chapter reviews roundabout safety and factors affecting this safety, first generally for roundabouts and then with a focus on those installed on high-speed roads. Heavy vehicle rollover is discussed, particularly in the context of roundabouts. Gaps in knowledge are identified and provide the framework for the rest of the thesis.

2.2 Background

2.2.1 Crash statistics

Roundabouts have a good record of decreasing the number of severe crashes. Persaud et al. observed improvements in injury (80%) and total crashes (40%) for US roundabouts (2001). Fatal and incapacitating injury crashes were nearly eliminated, a trend echoed in Wisconsin (Bill, Qin, Chitturi, & Noyce, 2011) and Maryland (Rice & Niederhauser, 2010).

Internationally, Europe has the most roundabouts by a wide margin. An analysis at 332 Danish intersections converted to roundabouts revealed decreases in injury (47%) and PDO crashes (16%) (Jensen, 2013). More significant safety improvements were observed for roundabouts located on high-speed roads. The United Kingdom and France have the most roundabouts: 25,000 and 32,000, respectively (Baranowski, 2014).

A summary of the observed crash reductions in these countries and others after building a roundabout are presented in Table 2.1.

Table 2.1 International Mean Crash Reductions at Roundabouts

Country	**Reduction**	
	All crashes (%)	Injury crashes (%)
Australia	41-61	45-87
France	-	57-78
Germany	36	-
Netherlands	47	-
United Kingdom	-	25-39

Source: Robinson et al., 2000

2.2.2 Roundabout geometric factors affecting crash rates

The effect of certain roundabout geometric factors on accident rates has been examined. One of the first studies from the United Kingdom found that the entry width and entry path curvature are significant (Maycock & Hall, 1984). Research was later extended to 100 urban and rural roundabouts in Queensland, Australia (Arndt & Troutbeck, 1998). Factors affecting both single and multiple-vehicle accident rates were studied. About 18% of accidents involved a single-vehicle. Lengthy curves with heavily-used side friction, high absolute speed on elements, and significant speed reductions between elements increased the crash rate. The majority of accidents occurred in the circulation. Articulated vehicles were overly represented due to their rollover propensity. The remaining 82% of crashes involved multiple vehicles. Poor visibility and speed difference between motorists increased the rate. Geometric features known to affect crash rates are shown in Table 2.2.

Table 2.2 Geometric Factors Affecting Crash Rates

Geometric Factor	**Effect on:**	
	Entering/circulating crashes	Exiting/circulating crashes
Increased entry width	Increase	-
Increased central island diameter	Decrease	Increase
Increased angle between legs	Decrease	-
Increased inscribed circle diameter	-	Increase
Increased circulating width	-	Increase
Increased lane width	Increased approach crashes	

Source: Based on Rodegerdts et al., 2010

Single and multilane roundabouts are common in the United States. The most common crash type among single lane roundabouts are entering-circulating accidents, due to an inability of entering drivers to predict the behavior of circulating drivers (Zheng, Qin, Tillman, & Noyce, 2013). Multilane roundabouts introduce other conflict types, including turns from improper lanes and lane changing within the roundabout (Hourdos & Richfield, 2014). Although every accident pattern tends to increase at multilane roundabouts, the increase is largest for sideswipe accidents (Zheng, Qin, Tillman, & Noyce, 2013).

2.3 High-speed Conditions

2.3.1 Crash statistics

Roundabouts have traditionally been built on low-speed roads, but they are becoming more prevalent on high-speed roads. Safety examinations have been rather cursory at these roundabouts. A five-state study of rural roundabouts found 88% and 63% reductions in injury and total accidents, respectively (Isebrands, 2011). Research from high-speed intersections converted to roundabouts in Wisconsin showed a 30% drop in total accidents and elimination of fatal accidents (Bill, Qin, Chitturi, & Noyce, 2011). Table 2.3 summarizes the results and highlights the trend of larger improvements for the more severe crash types.

Table 2.3 Crash Reductions at Roundabouts on High-speed Roads in Wisconsin

Crash Type	**% Decrease**
Fatal	100%
Incapacitating injury	75%
Non-incapacitating injury	60%
Possible injury	67%
Property damage only	9%
Overall (121 crashes before, 85 crashes after)	30%

Source: Bill, Qin, Chitturi, & Noyce, 2011

2.3.2 Roundabout design on high-speed roads

From the roundabout design perspective, drivers must be adequately warned so they may reduce their speeds. In this regard, studies have compared roundabouts with more traditional intersection controls, such as stop signs. Isebrands et al. studied roundabouts and two-way stop-controlled intersections in Iowa, Kansas, and Minnesota (2014). Table 2.4 provides a speed comparison at different distances from the yield line/stop bar.

Table 2.4 Mean Speed Comparison of Roundabout and Stop-controlled Approaches

Distance from Yield Line/Stop Bar (ft)	Roundabout (mph)	Stop-controlled (mph)	Difference (mph)
100	26.4	28.9	2.5
250	35.5	34.8	-0.7
500	45.3	45.0	-0.3
1500	53.9	52.6	-1.3

Source: Isebrands et al., 2014

Roundabouts, at least those without approach rumble strips, showed greater approach speeds compared to stop-controlled intersections at far distances, but lower speeds in close proximity (100 ft). This suggests that roundabouts are more effective at slowing drivers down near an intersection.

The roundabout geometry, particularly the splitter and central islands, is critical in limiting speed. Both islands must be designed to be conspicuous while preventing excessive sight distance, which encourages high speed (Ritchie & Lenters, 2005). Whereas roundabouts on low speed roads may have significant entry deflection, this design can result in crashes on the approach curve when applied on high-speed roads. Insufficient entry deflection encourages high entry speed and can shift accidents from the approach curve to the circulation. Hence, the splitter island entry deflection must be properly balanced, serving as a compromise between these two scenarios.

2.4 Heavy Vehicle Rollover

When cornering a tight curve such as that of a roundabout, small vehicles such as passenger cars tend to skid instead of roll (Harwood, Torbic, Richard, Glauz, &

Elefteriadou, 2003). However, a rollover risk is introduced for long, heavy vehicles such as semi-trailers. Roundabout geometric features that are associated with an increased risk of rollover include: approaches with high speeds, small entry deflection, low-circulating traffic volume, excessive visibility, a significant decrease in radius within the roundabout, and sudden crossfall changes (Highways Agency, 2007). The first four factors are related to excessive speed on the approach and entry, while the latter two are associated with the road geometry.

Although the influence of the roundabout layout on overturning has been well studied, the effect of the circulating roadway superelevation is not well understood and has been suggested for further research (Gingrich & Waddell, 2008). Circulating speeds are known to be similar for inward vs. outward slopes (Gingrich & Waddell, 2008). This is important as it suggests that drivers do not discern these differences in superelvation. Differences do arise in the lateral force component experienced by a vehicle in these situations.

Vehicle factors relevant in truck overturning include speed, track width, center-of-gravity height, suspension, and tires (New Zealand Transport Agency, 2008). Furthermore, load factors such as overall weight and longitudinal and lateral weight distribution contribute to the rollover propensity (Harwood, Torbic, Richard, Glauz, & Elefteriadou, 2003). Fully loaded semi-trailers tend to have a higher center of gravity height compared to those that are empty. A one-inch increase in the center of gravity height reduces the threshold necessary for initiating rollover by 0.005 G (Harwood, Torbic, Richard, Glauz, & Elefteriadou, 2003).

Basic quasi-static models have been developed to describe the rollover situation. In their simplest form, the relation can be reduced to the Static Stability Factor (SSF), alternatively known as the Static Rollover Threshold (SRT). This quantity relates the lateral, tipping acceleration to the height of the vehicle's center of gravity and its width and is quantified in G's (Milliken & de Pont, 2005). The situation becomes more complex when considering the geometrical features of the roadway. The following equation takes into account the roadway cross slope in determining the critical lateral acceleration needed for rollover (Milliken & de Pont, 2005) & (Gillespie, 1992):

$$a_r = SRT_{ef} g \tag{2.1}$$

Where: a_r = critical lateral rollover acceleration

g = acceleration due to gravity

$SRT_{ef} = \sigma - \theta$ = effective Static Rollover Threshold (SRT)

σ = Static Rollover Threshold (SRT)

θ = Cross slope of the roadway

2.5 Limitations of Past Research

Roundabouts on high-speed roads are emerging across the United States. The initial studies that have been conducted show crash reductions over traditional intersections, but the issue of heavy vehicle rollover has emerged as a safety concern for agencies such as state DOTs.

The effective static SRT shown in Equation 2.1 takes into account the roadway cross slope. However, the SRT fails to account for variations in the cross slope.

Furthermore, heavy vehicles such as semi-trailers follow complex paths that are different from the circulatory road alignment, and tractors and trailers rarely stay parallel to the roadway edge. The lateral tilt of the vehicle body in such cases can be quite different from the superelevation and is strongly influenced by the actual vehicle position. These issues need to be properly addressed by developing a rollover model more general than in Equation (2.1) that better reflects the complexity of the motion of long vehicles in a roundabout.

Furthermore, a key roundabout design parameter is the circulatory superelevation of the roadway. Outward superelevation is commonly used in the United States. Despite this, inward superelevation suggests a reduced rollover propensity (Gingrich & Waddell, 2008); however, the effect has not been quantified. An analysis is needed to determine whether the potential benefits afforded by inward superelevation design outweigh its shortcomings.

A subset of drivers are prone to aggressive behavior, which includes driving at excessive speeds. It is not known whether aggressiveness correlates with a higher rollover propensity at the roundabout. In the literature, this issue was recommended for further study to discern whether these drivers need special accommodation in the design process.

Finally, a related factor that may affect rollover propensity relates to high speed at the approaches near the roundabout. Drivers unfamiliar about how to properly traverse a roundabout can approach too fast; as a result, their margin to rollover may be smaller than those who approach more moderately. This warrants further analysis to determine if countermeasures are needed to offset this behavior.

CHAPTER 3. DERIVATION OF HEAVY VEHICLE ROLLOVER MODEL

3.1 Introduction

The rollover scenario is generated by inertial forces acting around a vehicle's rolling axis. These forces produce torques about the axis; the rollover tendency comes primarily from the torque generated by centrifugal force, which passes through the vehicle center of gravity. Its magnitude is determined by the longitudinal speed and instantaneous curvature of the vehicle's center of gravity path.

When the moment arm between the rolling axis and a force increases, the force can generate a larger torque. Thus, heavy vehicles with high centers of gravity tend to have a greater rollover propensity. When the vehicle is cornering, it will reach a speed at which rollover becomes imminent. This condition is called the critical speed and can be assessed by Δv, or the difference between the critical rollover speed and the actual vehicle speed at that moment. The quantity changes along the vehicle path and typically becomes smallest in the sharpest portion of the curve.

3.2 General Equation for Heavy Vehicle Rollover

In a simplified, two-dimensional model representing "quasi-static" rollover, the rolling axis can be considered as passing through the center of the footprint of the outside front and rear tires.

Overturning occurs when the torque generated by the centrifugal force about the rolling axis is greater than that produced by the vehicle weight. This model assumes constant superelevation and can be derived from a free-body diagram (Figure 3.1). The normal force on the inside tires reaches zero just as the truck begins to tip.

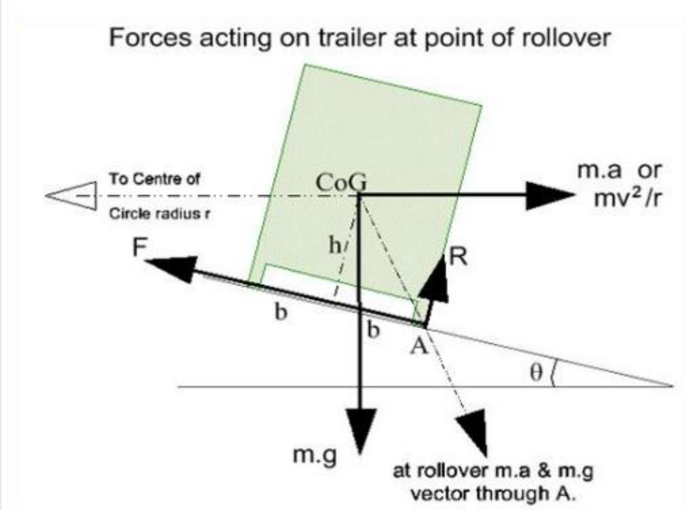


Figure 3.1 Components of the Quasi-static Rollover Condition (Sawers, 2011)

Taking moments about point "A" (counterclockwise positive), the following expression is obtained:

$$-\frac{hmv^2}{r}cos\theta-\frac{bmv^2}{r}sin\theta-hmgsin\theta+bmgcos\theta=0 \qquad (3.1)$$

Where: v = speed of vehicle,

m = mass of vehicle,

r = radius of center of gravity path,

b = half the width between tires,

h = center of gravity height,

g = acceleration due to gravity,

θ = superelevation of roadway.

Rearranging, Equation 3.1 becomes:

$$v_{crit} = \sqrt{\frac{rg(bcos\theta - hsin\theta)}{bsin\theta + hcos\theta}} \tag{3.2}$$

In this equation v_{crit} represents the critical speed at which rollover is initiated, the model does not account for changes in the cross slope. Heavy vehicles, such as semi-trailers, are often similar in size to the roundabout dimensions; hence, the path and corresponding elevation of points on the vehicle may be very different from one another. A more generalized model that accounts for the complexities of the actual vehicle position is needed.

A great diversity of models are used to assess the situation. Not only can vehicle factors be accounted for, but also pavement conditions and dynamic components such as suspension and tires. A considerable number of vehicles are analyzed in this analysis; hence, a three-dimensional static analysis provides a suitable approximation. The derivation of such a model is discussed for semi-trailers, the heavy vehicle type that is most prone to rollover.

3.3 Derivation of Rollover Model

The original derivation of the rollover model is from an unpublished research note (Tarko, Hall, & Lizarazo, 2014). The derivations below further refine these ideas and posit a new method for determining the critical rollover threshold. A diagram is drawn, from which two critical points, the center of trailer mass and the center of the tractor/trailer connection point (fifth wheel) can be determined:

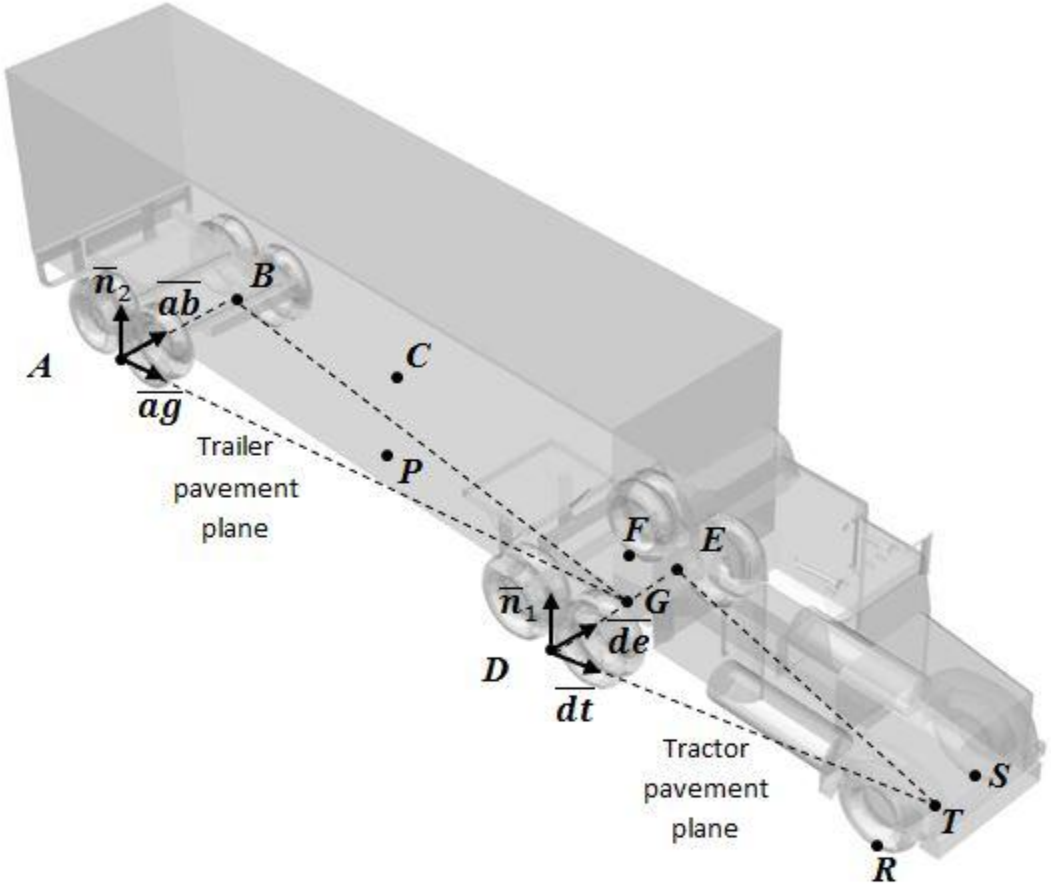


Figure 3.2 Diagram for Finding Center of Mass and Fifth Wheel Coordinates

The following points are used in the derivation of the rollover condition:

A and ***B*** = centers of the right and left rear trailer tires' footprints, respectively,

C = center of trailer mass,

P = perpendicular projection of point ***C*** on the trailer pavement (ground) plane,

D and ***E*** = centers of the right and left rear tractor tires' footprints, respectively,

F = center of the tractor/trailer connection point (fifth wheel),

G = perpendicular projection of point ***F*** on the tractor pavement (ground) plane,

R and ***S*** = centers of the right and left front tractor tires' footprints, respectively,

T = midpoint between points ***R*** and ***S***.

Note: The position of $\boldsymbol{P}$ is determined based on the dimensions of a standard-sized trailer and the typical distribution of the trailer weight and load. This distribution varies depending on whether the trailer is loaded or not loaded. Chapter 4 explains in detail the assumptions made.

The following notation is introduced and utilized throughout the remaining derivations:

$\boldsymbol{A} = (x_A, y_A, z_A)$ = point in the Cartesian coordinate system,

$\overline{\boldsymbol{AB}} = (x_{AB}, y_{AB}, z_{AB}) = (x_B - x_A, y_B - y_A, z_B - z_A)$ = vector between points $\boldsymbol{A}$ and $\boldsymbol{B}$,

$||\overline{\boldsymbol{AB}}|| = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2}$ = length of vector $\overline{\boldsymbol{AB}}$,

$\overline{\boldsymbol{ab}} = (x_{ab}, y_{ab}, z_{ab}) = \frac{\overline{\boldsymbol{AB}}}{||\overline{\boldsymbol{AB}}||}$ = unit vector corresponding to vector $\overline{\boldsymbol{AB}}$,

The above notation applies to any pair of points.

Points $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{P}$, $\boldsymbol{D}$, $\boldsymbol{E}$, $\boldsymbol{R}$, and $\boldsymbol{S}$ are known. Points $\boldsymbol{G}$ and $\boldsymbol{T}$ are determined as follows:

$$\boldsymbol{G} = \frac{\boldsymbol{D}+\boldsymbol{E}}{2} \qquad \boldsymbol{T} = \frac{\boldsymbol{R}+\boldsymbol{S}}{2} \tag{3.3), (3.4}$$

The points $\boldsymbol{D}$, $\boldsymbol{E}$, and $\boldsymbol{T}$ define the pavement plane of the tractor. Two vectors along this plane are $\overline{\boldsymbol{DT}}$ and $\overline{\boldsymbol{DE}}$. The cross product between the two vectors gives the normal vector to the pavement plane of the tractor, denoted as $\overline{\boldsymbol{N}}_1$:

$$\overline{\boldsymbol{N}}_1 = \overline{\boldsymbol{DT}} \times \overline{\boldsymbol{DE}} \tag{3.5}$$

From this vector, the unit normal $\overline{\boldsymbol{n}}_1$ can be found. Given the height from the ground of the tractor-trailer connection point (h_F), the coordinates of the connection point $\boldsymbol{F}$ can be found:

$$\boldsymbol{F} = \boldsymbol{G} + h_F\overline{\boldsymbol{n}}_1 \tag{3.6}$$

Similarly, the points $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{G}$ describe the pavement plane of the trailer. Two vectors along this plane are $\overline{\boldsymbol{AG}}$ and $\overline{\boldsymbol{AB}}$. The vectors give the normal vector $\overline{\boldsymbol{N}}_2$ to the trailer's pavement plane:

$$\overline{\boldsymbol{N}}_2 = \overline{\boldsymbol{AG}} \times \overline{\boldsymbol{AB}} \tag{3.7}$$

From this vector, the unit normal $\overline{\boldsymbol{n}}_2$ can be found. The height from the ground of the trailer center of mass (h_C) allows the coordinates of the trailer center of mass $\boldsymbol{C}$ to be determined:

$$\boldsymbol{C} = \boldsymbol{P} + h_C\overline{\boldsymbol{n}}_2 \tag{3.8}$$

After points $\boldsymbol{F}$ and $\boldsymbol{C}$ have been found, they are used in determining the rollover plane:

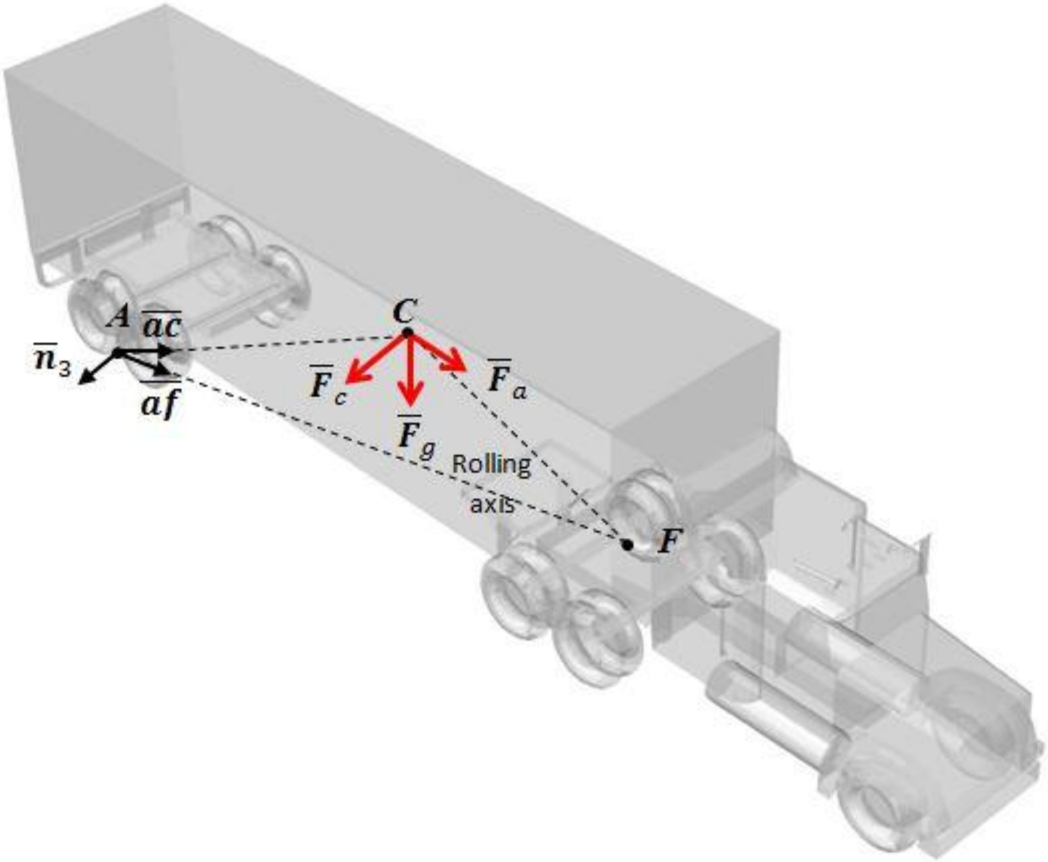


Figure 3.3 Semi-trailer Diagram of Rollover Plane

The following scalars describe the forces acting during a rollover:

m = trailer mass,

a = longitudinal acceleration,

c = centrifugal acceleration,

g = gravity acceleration,

$F_a = ma$ = longitudinal force,

$F_c = mc$ = centrifugal force,

$F_g = mg$ = gravity force.

During a rollover, the trailer rotates around the $\boldsymbol{AF}$ line if the tractor is turning left. At the moment of turnover, the inside-curve tires lose contact with the ground and the only forces acting at the trailer are: $\overline{\boldsymbol{F}}_a, \overline{\boldsymbol{F}}_c, \overline{\boldsymbol{F}}_g$. It occurs when the component normal to plane $\boldsymbol{ACF}$ of the combined forces points outside of the curve. The coordinates of both the tractor/trailer connection point $\boldsymbol{F}$ and the center of trailer mass $\boldsymbol{C}$ are used to define two vectors originating at point $\boldsymbol{A}$: $\overline{\boldsymbol{AF}}$ and $\overline{\boldsymbol{AC}}$, respectively. The cross product between the vectors $\overline{\boldsymbol{AF}}$ and $\overline{\boldsymbol{AC}}$ define a third normal vector, $\overline{\boldsymbol{N}}_3$:

$$\overline{\boldsymbol{N}}_3 = \overline{\boldsymbol{AF}} \times \overline{\boldsymbol{AC}} \tag{3.9}$$

From this vector, the unit normal $\overline{\boldsymbol{n}}_3$ can be found. This vector will be further utilized in the calculations to follow. First, a digression is necessary regarding changes in the center of mass location with time.

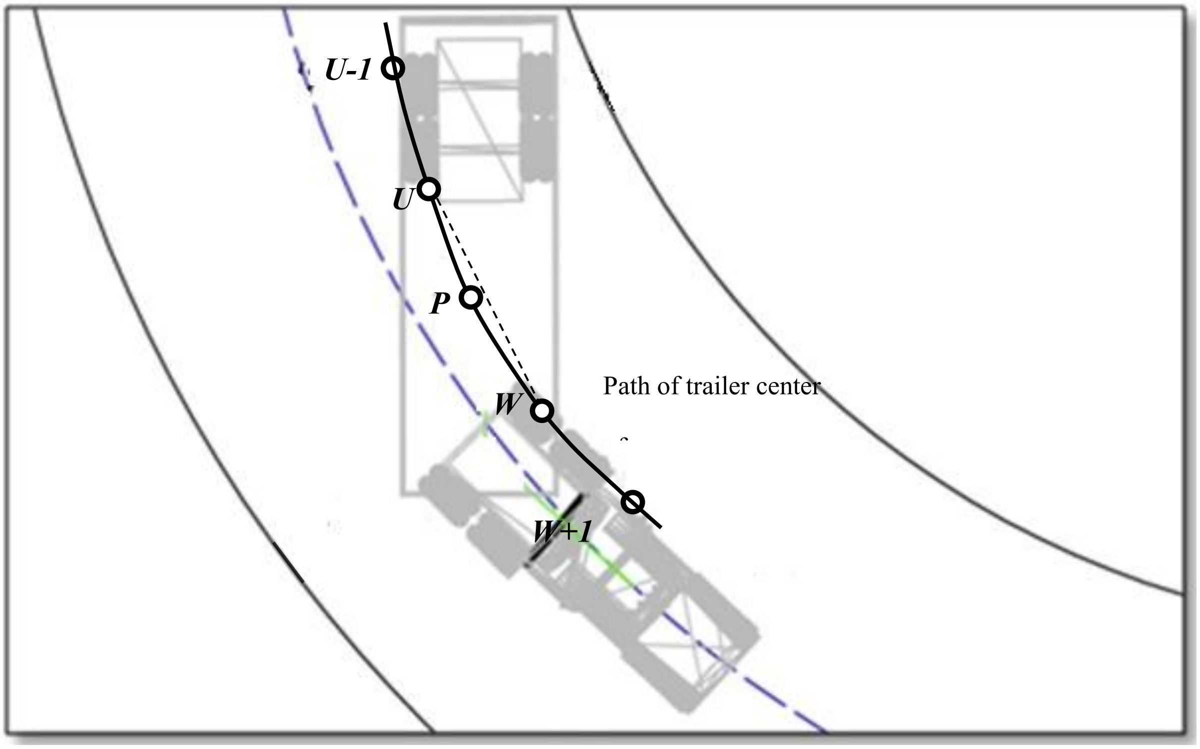


Figure 3.4 Location of Trailer Center of Mass

The following points describe the perpendicular projection of point ***C*** on the trailer pavement (ground) plane with respect to time:

U-1 = location of ***P*** two time intervals before its current location,

U = location of ***P*** one time interval before its current location,

P = perpendicular projection of point ***C*** on the trailer pavement (ground) plane,

W = location of ***P*** one time interval after its current location,

W+1 = location of ***P*** two time intervals after its current location.

The $\overline{\boldsymbol{F}}_a$ force tangent to the trailer's path at point ***P*** is non-zero if the trailer changes speed at this point. The path is assumed flat, an acceptable assumption for most roundabouts. Vector $\overline{\boldsymbol{UW}}$ is a good approximation of the direction of $\overline{\boldsymbol{F}}_a$. Its corresponding unit vector $\overline{\boldsymbol{uw}}$ is also the unit vector $\overline{\boldsymbol{u}}_a$ of the $\overline{\boldsymbol{F}}_a$ force:

$$\overline{\boldsymbol{u}}_a = (x_{uw}, y_{uw}, 0) \tag{3.10}$$

The $\overline{\boldsymbol{F}}_c$ force is the centrifugal force normal to the path and at point ***P***. Its unit force $\overline{\boldsymbol{u}}_c$ is perpendicular to $\overline{\boldsymbol{u}}_a$:

$$\overline{\boldsymbol{u}}_{\boldsymbol{c}} = (-y_{uw}, x_{uw}, 0) \tag{3.11}$$

The unit vector $\overline{\boldsymbol{u}}_g$ of the gravity force $\overline{\boldsymbol{F}}_g$ is:

$$\overline{\boldsymbol{u}}_g = (0, 0, -1) \tag{3.12}$$

Finally, the three forces can be presented as properly scaled unit vectors:

$\overline{\boldsymbol{F}}_{\boldsymbol{a}} = ma\,\overline{\boldsymbol{u}}_a,\ \overline{\boldsymbol{F}}_c = mc\,\overline{\boldsymbol{u}}_c,\ \overline{\boldsymbol{F}}_g = mg\,\overline{\boldsymbol{u}}_g.$

The rollover condition is given as the following:

$$(\overline{\boldsymbol{n}}_3) \cdot (\overline{\boldsymbol{F}}_a + \overline{\boldsymbol{F}}_c + \overline{\boldsymbol{F}}_g) > 0 \tag{3.13}$$

Thus, the following condition applies when the vehicle reaches the critical rollover condition:

$$(\overline{\boldsymbol{n}}_3) \cdot (\overline{\boldsymbol{F}}_a + \overline{\boldsymbol{F}}_c + \overline{\boldsymbol{F}}_g) = 0 \tag{3.14}$$

Note: The above derivation applies to a left-turning curve. Point ***A*** belongs to the line of trailer's rotation. In the case of a right-turning curve, point ***B*** should be used instead of point ***A***. The rest of the derivation remains unchanged.

Substituting in the above equation, the following expression is obtained:

$$(\overline{\boldsymbol{n}}_3) \cdot (ma\,\overline{\boldsymbol{u}}_a + mc\,\overline{\boldsymbol{u}}_c + mg\,\overline{\boldsymbol{u}}_g) = 0 \tag{3.15}$$

The longitudinal acceleration a is first determined. To find it at point $\boldsymbol{P}$, the vectors $\overline{\boldsymbol{U-1\,U}}$, $\overline{\boldsymbol{UP}}$, $\overline{\boldsymbol{PW}}$, and $\overline{\boldsymbol{W\,W+1}}$, which represent the vehicle's motion, are used along with the time interval Δt to approximate the longitudinal speed v and its change rate a:

$$v_u = \frac{\|\overline{\boldsymbol{U-1\,U}}\| + \|\overline{\boldsymbol{UP}}\|}{2\cdot\Delta t} \tag{3.16}$$

$$v_p = \frac{\|\overline{\boldsymbol{UP}}\| + \|\overline{\boldsymbol{PW}}\|}{2\cdot\Delta t} \tag{3.17}$$

$$v_w = \frac{\|\overline{\boldsymbol{PW}}\| + \|\overline{\boldsymbol{W\,W+1}}\|}{2\cdot\Delta t} \tag{3.18}$$

$$a_p = \frac{v_w - v_u}{2\cdot\Delta t} \tag{3.19}$$

The centrifugal acceleration c is calculated as:

$$c = v^2 \cdot \rho \tag{3.20}$$

where v is the longitudinal speed of the vehicle at point P and ρ is the curvature of the vehicle's path at point P.

In addition, the vectors $\|\overline{\boldsymbol{P\,W+1}}\|$ and $\|\overline{\boldsymbol{U-1\,P}}\|$ form angles with their x and y components. These angles, denoted as θ_W and θ_U, are visualized below:

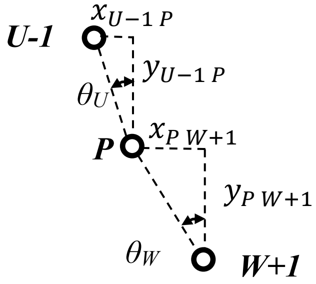


Figure 3.5 Geometric Relation of Trailer Center of Mass Location over Time

From the diagram, the following relations can be derived using coordinate geometry:

$$\theta_W = \cos^{-1}\left(\frac{y_{P\,W+1}}{\left\|\overline{\boldsymbol{P\,W+1}}\right\|}\right) \tag{3.21}$$

$$\theta_U = \cos^{-1}\left(\frac{|y_{U-1\,P}|}{\left\|\overline{\boldsymbol{U-1\,P}}\right\|}\right) \tag{3.22}$$

The angles θ_W and θ_U must be expressed in radians. The curvature ρ is expressed as:

$$\rho = \frac{\theta_W - \theta_U}{\left\|\overline{\boldsymbol{UP}}\right\| + \left\|\overline{\boldsymbol{PW}}\right\|} \tag{3.23}$$

The critical longitudinal speed v_{cr} in rollover conditions has a finite value of the curvature ρ that is non-zero:

$$v_{cr} = \sqrt{\frac{(\overline{\boldsymbol{n}}_3)\cdot(-g\,\overline{\boldsymbol{u}}_g - a\,\overline{\boldsymbol{u}}_a)}{(\overline{\boldsymbol{n}}_3)\cdot(\rho\,\overline{\boldsymbol{u}}_c)}} \tag{3.24}$$

The difference between the critical rollover and the actual speed is:

$$\Delta v = v_{cr} - v_p \tag{3.25}$$

CHAPTER 4. DATA

4.1 Data Collection

Roundabouts have been built on Indiana's state highway system since 2008. Given their location on state roads, a number of these roundabouts have approaches that are high speed (45 mph or greater).

It was desired to select nearby roundabouts: one on a high-speed road and the other on a low-speed road to discern the differences between these conditions while maintaining similar driver characteristics. Roundabouts were chosen in two areas: Lafayette and Noblesville. Table 4.1 provides a description of the selected roundabouts.

Table 4.1 Description of Study Roundabouts

Roundabout	Number of Approaches	Highest Approach Speed	Number of lanes and width	Super-elevation	Year Built
SR 25	3	55 mph	2 x 16 ft	-2% to 2%	2012
Concord Rd/Maple Point Dr	3	30 mph	1 x 16 ft	2%	2012
SR 32-38/Promise Rd	4	30 to 55 mph	2 x 16 ft	2% (varies)	2011
SR 32-38/Union Chapel Rd	3	30 to 55 mph	2 x 16 ft	2% (varies)	2011

The State Road (SR) 25 and Concord Road/Maple Point Drive roundabouts are located in Lafayette. The latter is the only single lane roundabout studied and is not built on the state highway system. It was selected due to it being the only such low-speed roundabout with significant heavy vehicle traffic in the Lafayette area.

The SR 32-38 roundabouts at Promise Road and Union Chapel Road are located on the edge of Noblesville on this main thoroughfare to nearby Anderson. Two of the approaches to the roundabouts are high-speed. The short connecting road in between provides two low-speed approaches for comparison.

Figure 4.1 SR 32-38 Roundabouts in Noblesville (Google Maps)

Data was collected from March to May 2014 during morning and afternoon hours in good weather conditions. Data collection was facilitated by the Purdue Mobile Traffic Lab (MTL), a van featuring two high-resolution dome cameras mounted atop a 42-foot extendable mast. The data could be reviewed on the monitors in the back of the van and 4 terabytes of capacity were available for video storage. The van location allowed for simultaneous viewing of the approach and circulation of the same vehicle. The van setup is illustrated in Figure 4.2.

Figure 4.2 Purdue Mobile Traffic Lab (MTL) Setup

Over one-hundred hours of video data were collected from the roundabouts. Data extraction was performed utilizing a special video tracking software developed in the Purdue Center for Road Safety. A summary of the heavy vehicles extracted is included in Table 4.2.

Table 4.2 Heavy Vehicle Types at Each Study Roundabout and Approach

Roundabout	**Semi-trailers**	**Single-unit trucks**
SR 25 high speed (55 mph) approach	57	27
Concord Rd./Maple Point Dr. low speed (30 mph) approach	59	40
SR 32-38/Promise Rd. high speed (55 mph) approach	3	18
SR 32-38/Promise Rd. low speed (30 mph) approach	13	20
SR 32-38/Union Chapel Rd. high speed (55 mph) approach	19	53
SR 32-38/Union Chapel Rd. low speed (30 mph) approach	12	45
Total	163	203

4.2 Data Collection at State Road 25 Roundabout

The State Road 25 roundabout was selected for further study due to its close proximity to Purdue and particularly high concentration of heavy vehicles. A new construction project resulted in a four-lane section of the road opening in October 2012. At the western terminus of the highway is a multilane roundabout that transitions from a 55 mph rural zone to an urban arterial into Lafayette. Table 4.3 summarizes the key geometrical features of the roundabout:

Table 4.3 Description of State Road 25 Study Roundabout

Roundabout characteristics	**Value**
Number of approaches	3
Highest approach speed	55 mph
Inner radius	56 ft
Truck apron width	10 ft
Truck apron slope	2%
Number of lanes and width	2 x 16 ft
Approach curve radius	121 ft
Super-elevation	-2% to 2%

A total of 57 semi-trailers entering the study roundabout from the SR 25 approach were randomly selected for analysis. Semi-trailers used in the analysis were unaffected by external influences such as other vehicles and free to move along their own path. For the selected semi-trailers, the same points were marked near the bottom of the tractor and trailer tires in successive frames. A calibration mode allowed the user to mark additional points useful in determining the vehicle's dimensions and center-of-gravity location.

After extraction, a stabilization process in the software corrected for any small mast movements during data collection. Finally, geometrical smoothing of the trajectory resulted in x, y, and z coordinates for the trailer and its center-of-gravity. Since the weight distribution was unknown, two distinct cases were considered: unloaded and loaded. For the unloaded case, a standard-sized trailer weighing approximately 12,640 lb was considered. Loaded semi-trailers were assumed to be at the federal maximum gross vehicle weight, 80,000 lb in the United States (Federal Highway Administration, 2003), with the load evenly distributed and filling the box to half of its capacity. While the actual vehicle weight is expected to be somewhere in between, the unloaded and loaded cases provide upper and lower bounds of the rollover threshold Δv.

The obtained coordinates were entered into an Excel spreadsheet to determine the curvature, trajectories, actual speed, and critical rollover speed (based on the equations previously derived). The software and spreadsheet are seen below.

To quantify how close the semi-trailers came to rollover, the difference between the critical rollover and actual speed Δv was computed every 0.1 s during the entire vehicle approach and circulation time.

Time marked 0.00

Interval 0.2

Select time 9000

Position 9268.

Current point 0

Current video 1

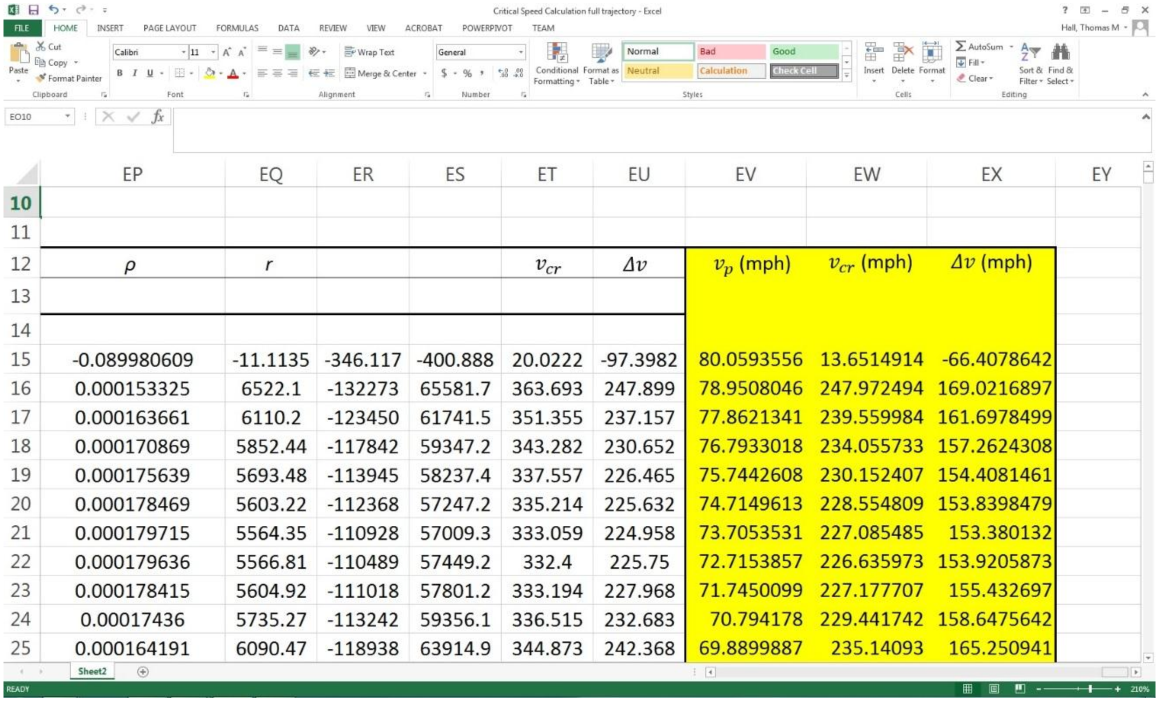
Current Vehicle 0

	Time	X0	Y0	Video0
▶	9268.43	307.4	259.6	2.08
	9268.63	310.2	258.9	2
*				

	Data
▶ Lane position	1
*	

Points marked on ground at semi-trailer tires to determine path

Figure 4.3 Interface Snapshot of Video Tracking Software



EO10

	EP	EQ	ER	ES	ET	EU	EV	EW	EX	EY
10										
11										
12	ρ	r			v_{cr}	Δv	v_p (mph)	v_{cr} (mph)	Δv (mph)	
13										
14										
15	-0.089980609	-11.1135	-346.117	-400.888	20.0222	-97.3982	80.0593556	13.6514914	-66.4078642	
16	0.000153325	6522.1	-132273	65581.7	363.693	247.899	78.9508046	247.972494	169.0216897	
17	0.000163661	6110.2	-123450	61741.5	351.355	237.157	77.8621341	239.559984	161.6978499	
18	0.000170869	5852.44	-117842	59347.2	343.282	230.652	76.7933018	234.055733	157.2624308	
19	0.000175639	5693.48	-113945	58237.4	337.557	226.465	75.7442608	230.152407	154.4081461	
20	0.000178469	5603.22	-112368	57247.2	335.214	225.632	74.7149613	228.554809	153.8398479	
21	0.000179715	5564.35	-110928	57009.3	333.059	224.958	73.7053531	227.085485	153.380132	
22	0.000179636	5566.81	-110489	57449.2	332.4	225.75	72.7153857	226.635973	153.9205873	
23	0.000178415	5604.92	-111018	57801.2	333.194	227.968	71.7450099	227.177707	155.432697	
24	0.00017436	5735.27	-113242	59356.1	336.515	232.683	70.794178	229.441742	158.6475642	
25	0.000164191	6090.47	-118938	63914.9	344.873	242.368	69.8899887	235.14093	165.250941	

Figure 4.4 Spreadsheet used to Compute Critical Rollover Speed

CHAPTER 5. EFFECT OF CIRCULATORY SUPERELEVATION ON ROLLOVER PROPENSITY

As drivers pass through a roundabout, certain locations stand out where rollover is of particular concern. These tend to occur where the horizontal radius of the roadway is small (less than 150 ft in most cases): the approach curve and circulatory roadway. It is necessary to discern which of the two locations is critical to adequately focus the investigation. This was accomplished by finding the lowest Δv on the approach curve and on the circulatory roadway for every studied vehicle and for two assumptions about the load. As explained earlier, the actual load could not be observed. Thus, we conducted our analysis for two alternative assumptions: all the trucks were unloaded and all the trucks were fully loaded. The majority of trucks have loading somewhere in between, so the correct result falls between the two obtained results. Since there are expected to be relatively few trucks that are overweight, they are not explicitly considered. However, the conclusion of this thesis describes how the developed rollover model performs for these trucks.

Figures 5.1 and 5.2 present the cumulative distributions of the minimum Δv values on both the approach curve and circulation for the sample vehicles. From this, it is clear that the analysis may focus on the circulatory roadway. Hence, the vehicle trajectories along this portion were selected for further analysis.

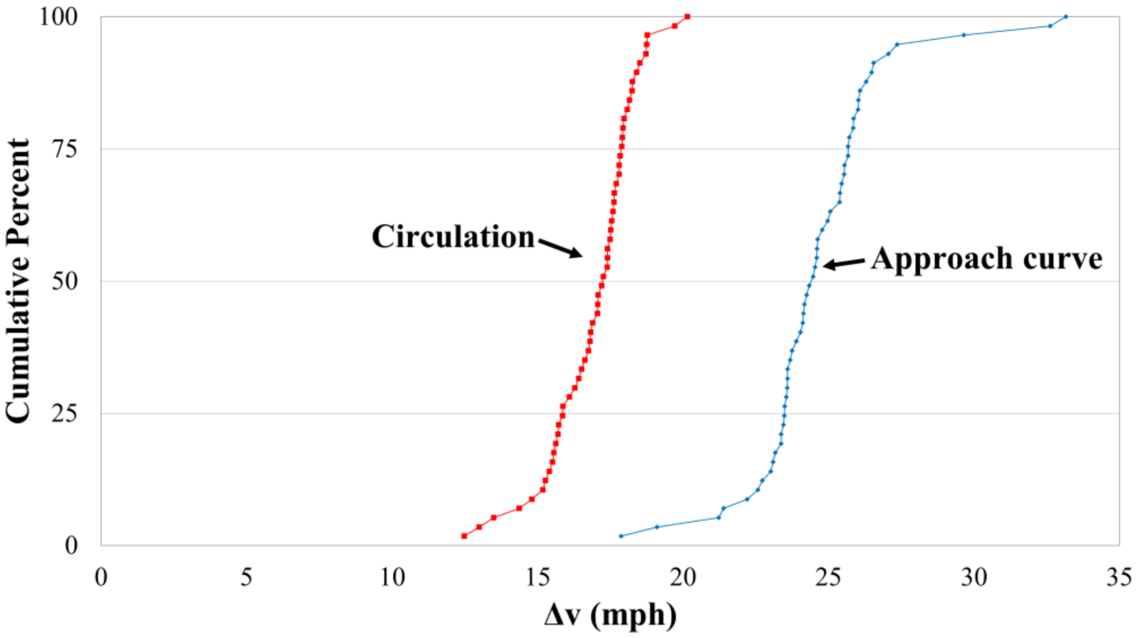


Figure 5.1 CDFs of Minimum *Δv* for Approach and Circulation Curves (all trailers assumed unloaded)

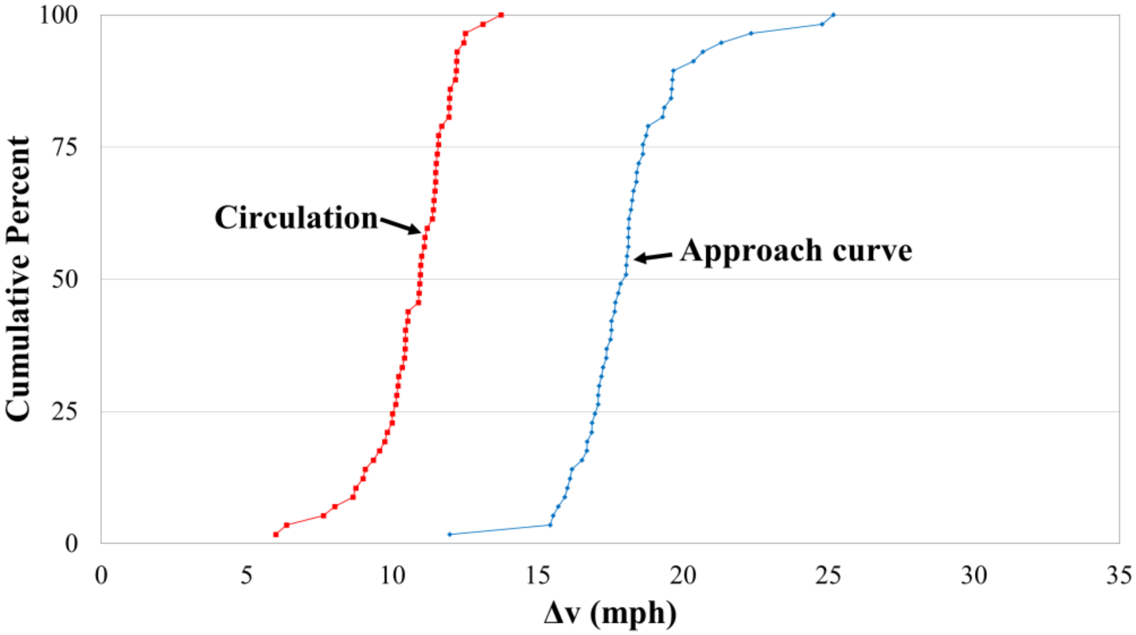


Figure 5.2 CDF of Minimum *Δv* for Approach and Circulation Curves (all trailers assumed fully loaded)

The current design practices in the United States favor using an outward superelevation (Gingrich & Waddell, 2008), often at a 2% slope. Given the benefits of inward sloping roadways in reducing the rollover risk, the commonly used 2% outward slope and alternative of 2% inward slope were assumed for the studied roundabout to quantify the proximity to rollover between these two alternatives. An assumption was made that limited changes in the pavement elevation are not noticeable by truck drivers, or do not affect truck driver behavior as would be evidenced in their selection of path and speed (Gingrich & Waddell, 2008). This assumption allowed estimating the threshold speeds and corresponding Δv values for the two pavement elevation scenarios using the observed trajectories. Figures 5.3 and 5.4 display graphically the distribution of minimum Δv values during circulation for the two studied scenarios and for the third scenario with 3% inward slope.

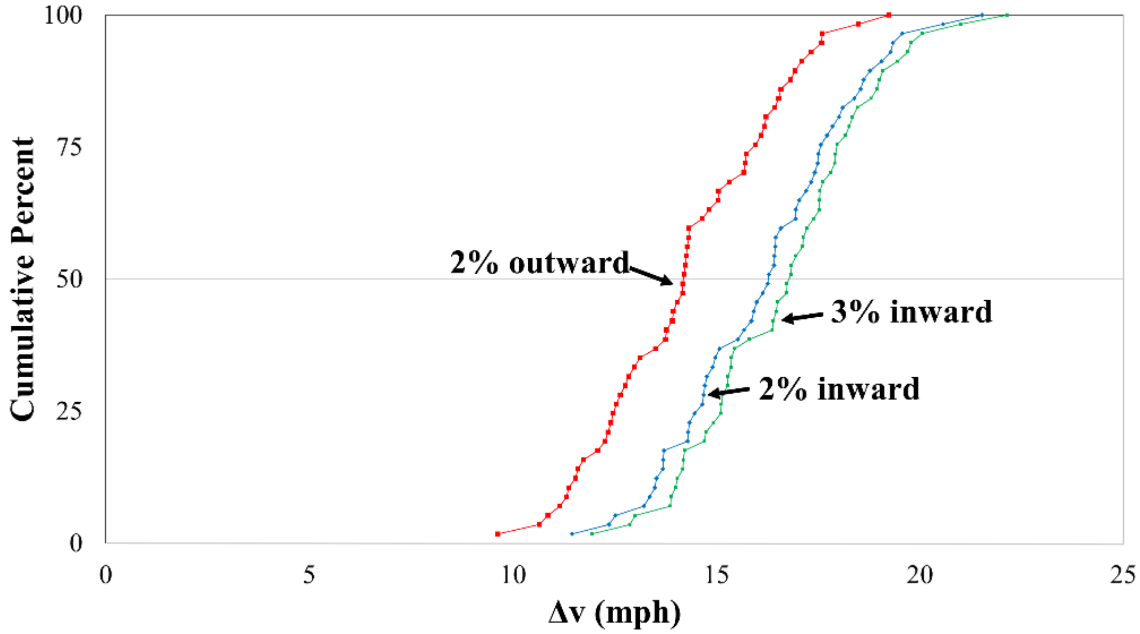


Figure 5.3 CDF of Minimum Δv for Superelevation Scenarios (all trailers assumed unloaded)

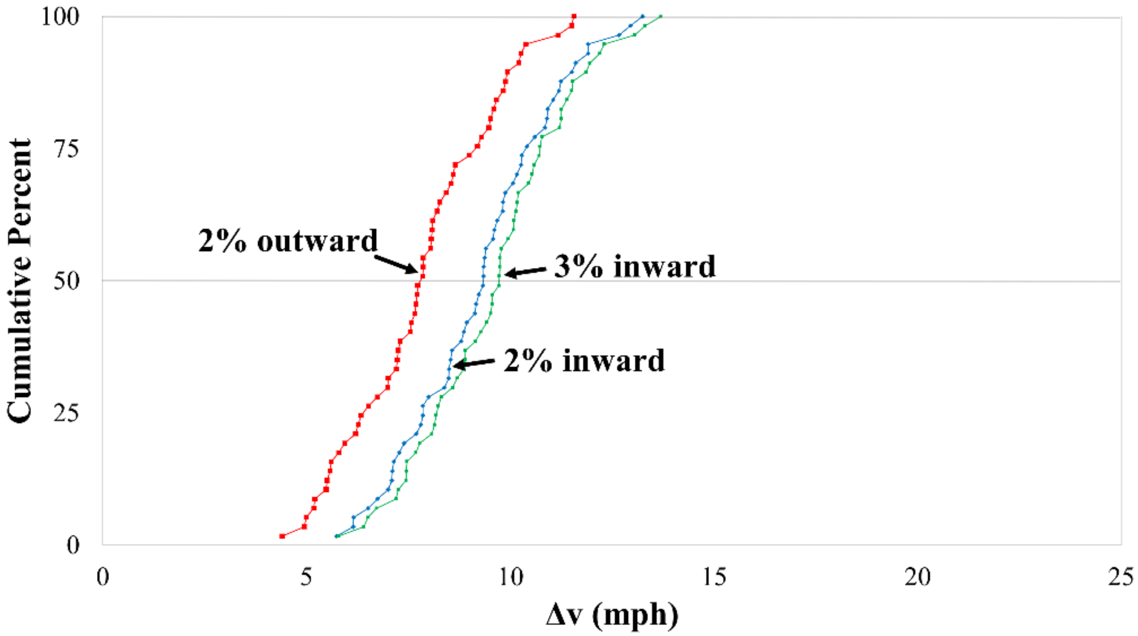


Figure 5.4 CDF of Minimum *Δv* for Superelevation Scenarios (all trailers assumed fully loaded)

As the inward superelevation increases, the tendency for a cornering vehicle to rollover is expected to decrease. It has been confirmed by analyzing the case with 3% inward superelevation (Figures 5.3 and 5.4). Table 5.1 provides a summary of the results.

Table 5.1 Comparison of Mean Minimum *Δv* (mph) for Superelevation Scenarios

	Superelevation			**Difference**	
	3% inward	**2% inward**	**2% outward**	**2% inward vs.**	**3% inward vs.**
		Mean Minimum *Δv*		**2% outward**	**2% outward**
Unloaded	16.67	16.19	14.25	1.94	2.42
Loaded	9.63	9.28	7.84	1.45	1.79

For both the unloaded and loaded trailer cases, the difference between the minimum *Δv* values for outward and inward superelevations was tested with the *t* statistic applied to paired observations (two pavement elevation scenarios for each vehicle). All the comparisons produced highly significant *t* statistics. The comparison of the 2% inward and 2% outward superelevation scenarios produced the *t* value of 47.20 for the unloaded case and 48.23 for the loaded case. The comparison of the 3% inward and 2% outward scenarios yielded values of 47.09 and 47.06. One noteworthy aspect is the magnitude of the differences. Despite having a higher rollover margin, the unloaded case had a larger difference between the superelevation scenarios than loaded. It is likely that the actual trailer weight falls in between; hence the differences in the rollover threshold between superelevation scenarios will fall in between and are bounded by those of the unloaded and loaded cases.

The results suggest that inward circulatory superelevation indeed decreases rollover propensity. However, the actual difference is small. Inward sloping superelevation also presents other challenges. Relatively abrupt changes in cross fall between the approach curve and circulation, in addition to drainage issues, are challenges of the design. The former has been confirmed by previous studies as increasing rollover propensity (Highways Agency, 2007). The latter results from the added costs of draining water from the roundabout's center. Coupled with indications of higher crash rates resulting from an inward slope (Jacquemart, 1998), we can conclude that there is no strong basis to discontinue the common practice of using outward circulatory superelevation. Further studies should be conducted to confirm this result, as well as determine the ideal outward slope to reduce rollover propensity while avoiding the pitfalls of the inward design.

CHAPTER 6. EFFECT OF AGGRESSIVE DRIVER BEHAVIOR ON ROLLOVER PROPENSITY

Certain drivers are prone to aggressive behavior, such as driving at excessive speeds. To determine if this behavior correlates with a decreased rollover margin at the roundabout, drivers should be classified according to their actual speed far from the roundabout's influence. As such, a distance of 800 ft from the roundabout yield line was selected for determination of actual vehicle speed. This represents the farthest distance at which speed can be reasonably estimated based on the conditions of this study. The 57 studied vehicles were separated based on the percentile of their actual speed at 800 ft from the yield line. Two comparisons were made: upper 50th-percentile vs. lower 50th-percentile, as well as upper 75th-percentile vs. lower 25th-percentile to further discern the differences between driver behavior. As the circulation has previously been confirmed as the most critical location for rollover, Δv was computed here for each of the studied vehicles. Figure 6.1 shows the comparison between minimum Δv at the circulation based on the upper 50th-percentile and lower 50th-percentile of speeds at a distance of 800 ft from the yield line. Both unloaded and loaded trailers are assumed separately for the studied vehicles. The actual minimum Δv is expected to be bounded by these cases. Figure 6.2 compares the minimum Δv for the upper 75th-percentile and lower 25th-percentile of speeds for the same distance and assumed loading scenarios.

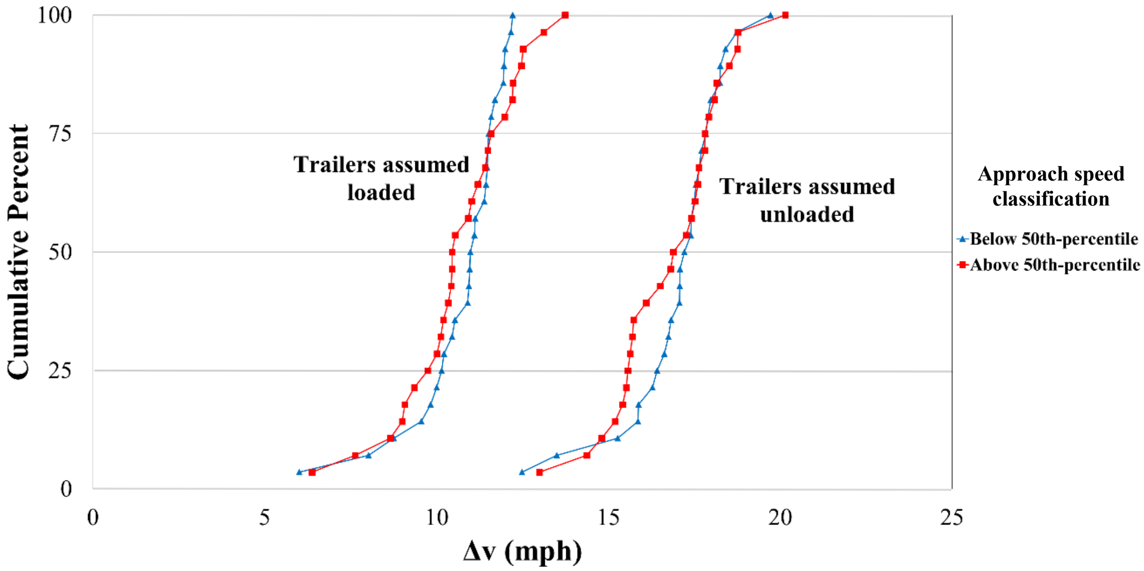


Figure 6.1 Minimum *Δv* at Roundabout Circulation for Drivers with Upper 50th and Lower 50th-percentile Speeds at 800 ft

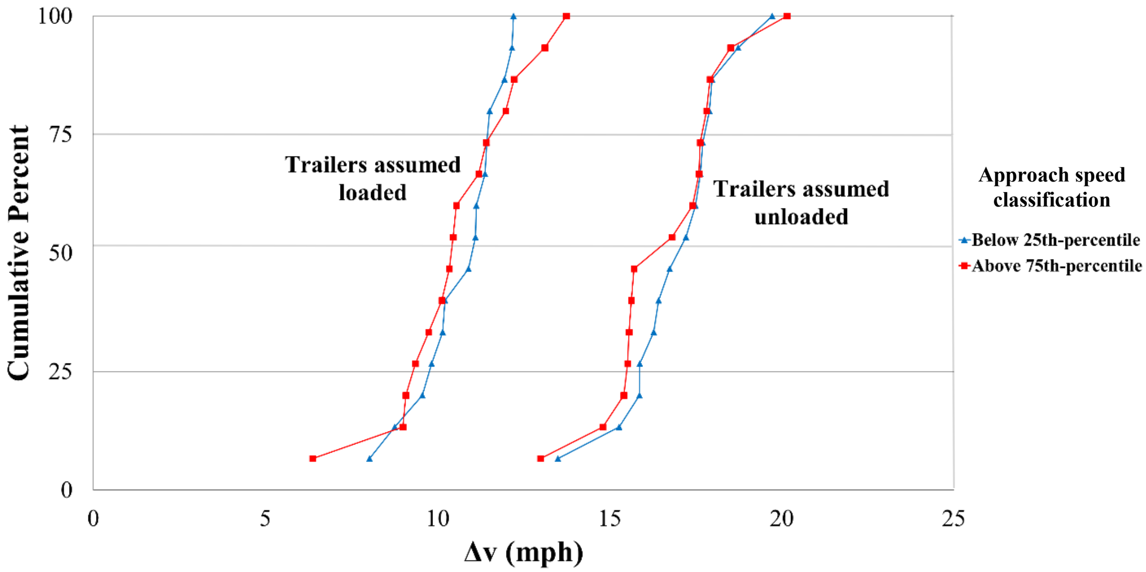


Figure 6.2 Minimum *Δv* at Roundabout Circulation for Drivers with Upper 75th and Lower 25th-percentile Speeds at 800 ft

A *t* test is performed to determine the statistical significance of the difference between mean minimum Δv for the scenarios. The results are displayed in Tables 6.1 and 6.2.

Table 6.1 Mean Minimum Δv (mph) at Roundabout Circulation for Drivers with Upper 50th and Lower 50th-percentile Speeds at 800 ft from the Yield Line

Approach speed classification	Unloaded	Loaded
Below 50th-percentile	17.02	10.73
Above 50th-percentile	16.81	10.65
t-statistic	**-0.52**	**-0.19**

Table 6.2 Mean Minimum Δv (mph) at Roundabout Circulation for Drivers with Upper 75th and Lower 25th-percentile Speeds at 800 ft from the Yield Line

Approach speed classification	Unloaded	Loaded
Below 25th-percentile	16.95	10.69
Above 75th-percentile	16.63	10.58
t-statistic	**-0.54**	**-0.19**

The cumulative frequency diagrams and the results of the *t* tests indicate drivers displaying more aggressive behavior, based on speed, come marginally closer to the critical rollover threshold at the roundabout circulation. However, the *t* statistics do not indicate significance at typical confidence levels. Based on the conditions of this study, there is no convincing connection between aggressive driver behavior and a tendency for encroaching on the rollover threshold at the roundabout. Future studies should examine roundabouts with low-speed approaches and varying driver and environmental conditions.

CHAPTER 7. EFFECT OF ERRANT APPROACH SPEED SELECTION ON ROLLOVER PROPENSITY

At distances far from the roundabout, excessive speeding may be interpreted as aggressive driver behavior. In close proximity, fast driving may be an indication of a driver's misperception about how to safely traverse the roundabout. The effect of errant speed selection on the rollover propensity is examined in this chapter.

Distances of 250 ft and 100 ft from the roundabout's yield line are selected for measuring the actual speed of the studied vehicles, consistent with those used in previous studies (Isebrands, Hallmark, & Hawkins, 2014). Drivers were separated based on the percentile of their actual speed at the 250 ft and 100 ft distances. Upper 50th-percentile vs. lower 50th-percentile, as well as upper 75th-percentile vs. lower 25th-percentile were the examined scenarios. As the roundabout circulation was previously determined as the most critical location for rollover, Δv was computed here for all 57 studied vehicles. Figures 7.1 and 7.2 show the comparison between the minimum Δv at the circulation based on the upper 50th-percentile and lower 50th-percentile actual speeds at distances of 250 ft and 100 ft from the yield line. Figures 7.3 and 7.4 compare the minimum Δv for the upper 75th-percentile and lower 25th-percentile actual speeds for the aforementioned distances. In addition to being the most critical case (smallest Δv), the majority of carriers maintain full or nearly full trailers to reduce shipping costs; thus, the loaded trailer case is assumed in this analysis.

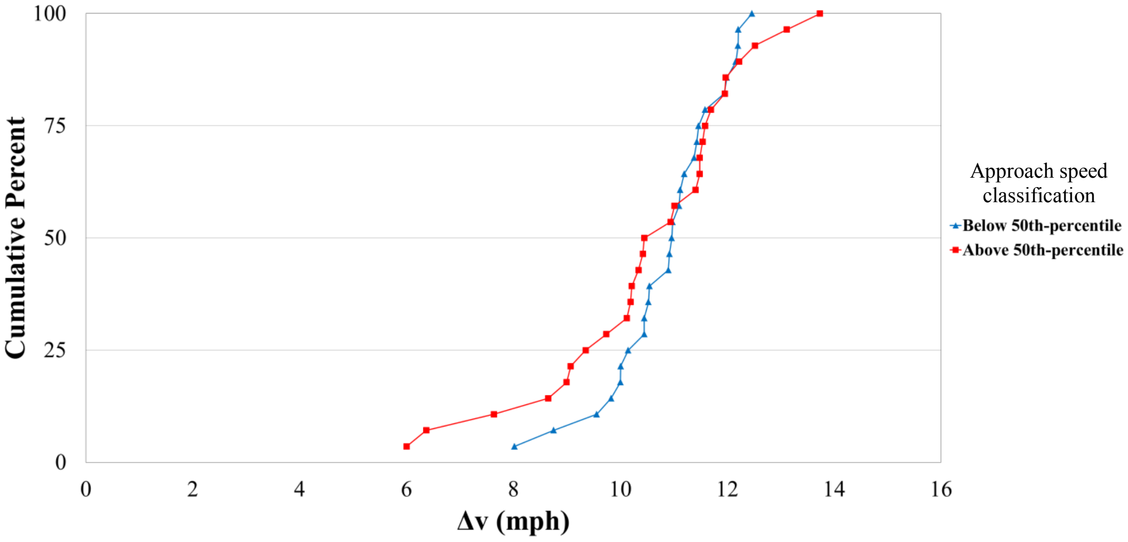


Figure 7.1 Minimum *Δv* at Roundabout Circulation for Drivers with Upper 50th and Lower 50th-percentile Speeds at 250 ft

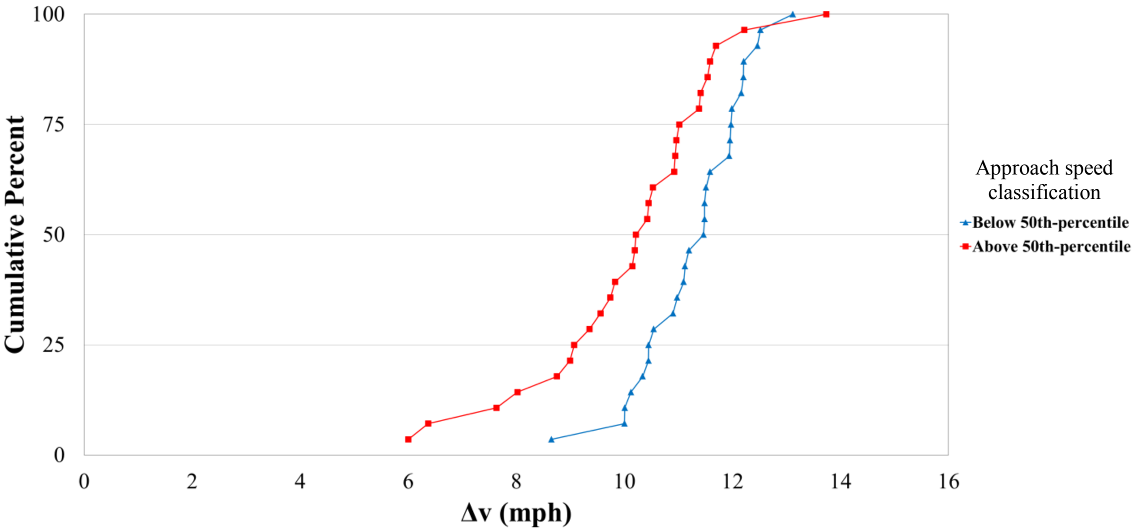


Figure 7.2 Minimum *Δv* at Roundabout Circulation for Drivers with Upper 50th and Lower 50th-percentile Speeds at 100 ft

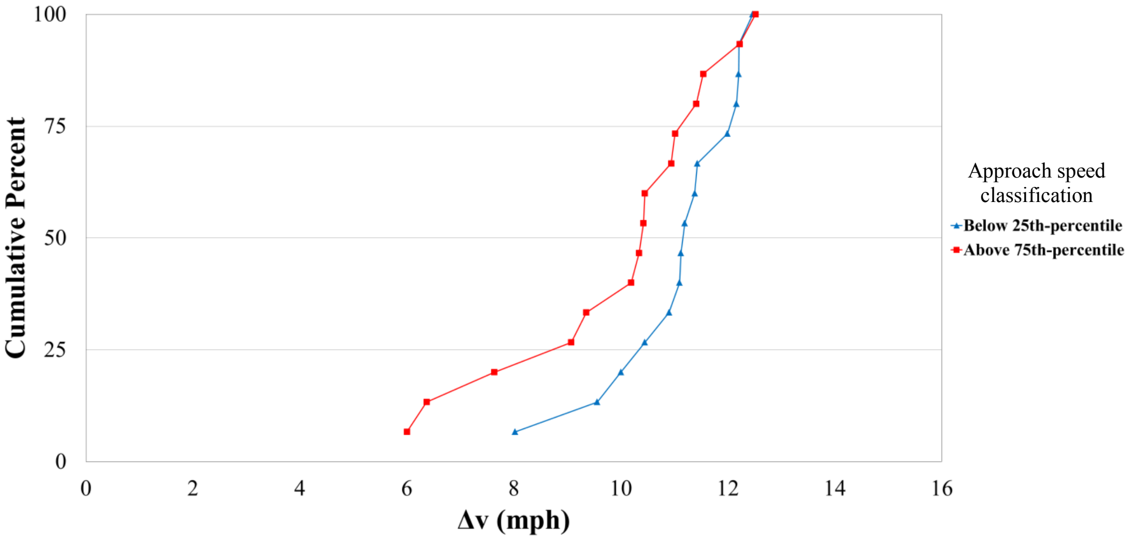


Figure 7.3 Minimum *Δv* at Roundabout Circulation for Drivers with Upper 75th and Lower 25th-percentile Speeds at 250 ft

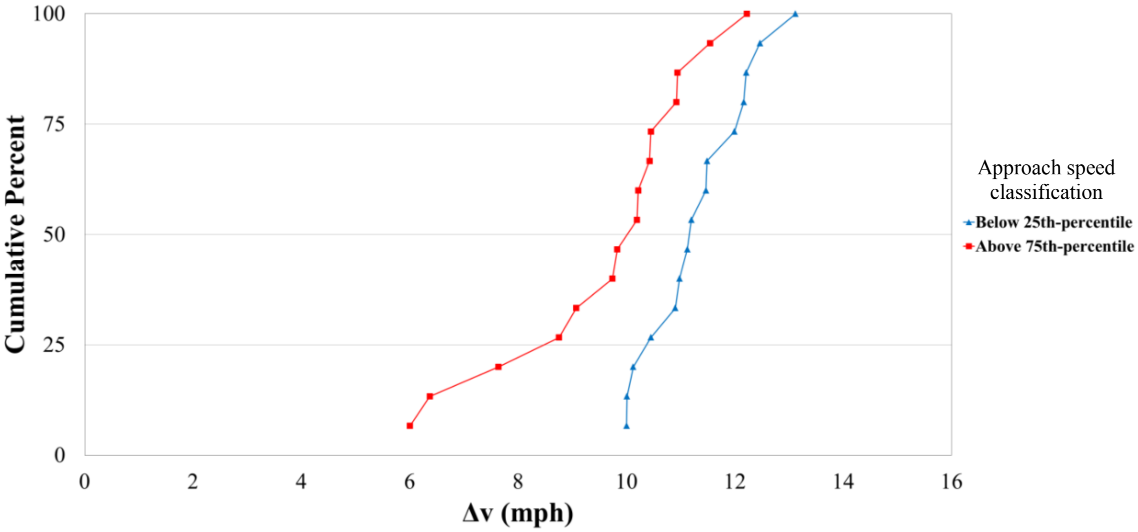


Figure 7.4 Minimum *Δv* at Roundabout Circulation for Drivers with Upper 75th and Lower 25th-percentile Speeds at 100 ft

A *t* test is performed to determine the statistical significance of the difference between mean minimum Δv for the scenarios. The results are displayed in Tables 7.1 and 7.2.

Table 7.1 Mean Minimum Δv (mph) at Roundabout Circulation for Drivers with Upper 50th and Lower 50th-percentile Speeds

Approach speed classification	**Distance from yield line**	
	250 feet	**100 feet**
Below 50th-percentile	10.87	11.28
Above 50th-percentile	10.51	10.10
t-statistic	**-0.90**	**-3.21**

Table 7.2 Mean Minimum Δv (mph) at Roundabout Circulation for Drivers with Upper 75th and Lower 25th-percentile Speeds

Approach speed classification	**Distance from yield line**	
	250 feet	**100 feet**
Below 25th-percentile	11.08	11.31
Above 75th-percentile	9.97	9.62
t-statistic	**-1.88**	**-3.24**

The difference in mean minimum Δv does not show statistical significance based on the upper and lower 50th-percentile approach speeds at 250 ft. When drivers are further categorized into upper 75th and lower 25th-percentile speeds, the differences become more pronounced. As distance is decreased to 100 ft from the yield line, differences for mean minimum Δv between the upper and lower 50th-percentile and upper 75th and lower 25th-percentile become significant. In each case, drivers classified as having greater actual speed at 100 ft from the yield line have a lower mean minimum *Δv* at the roundabout circulation.

In addition to the *t* test performed, the percentage of drivers under a certain critical threshold of minimum *Δv* was computed for the observed approach speeds at 250 ft and 100 ft from the roundabout yield line. Previous studies utilized this approach to detect safety-critical cases in order to evaluate safety and to detect safety changes (Wang, Wang, Tremont, & Tarko, 2014). The *Δv* value of 10 mph was selected in this study, which is close to the 15th-percentile speed. The results are displayed in Tables 7.3 and 7.4.

Table 7.3 Cases with Minimum *Δv* below Critical Threshold (10 mph) based on Approach Speed at 250 ft

Speed at 250 ft	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**
Number of Cases	0	1	2	2	4	4	6	7	8	9	10	11	11	12
% Total	0	10	17	13	15	13	16	16	16	17	18	20	20	21

Table 7.4 Cases with Minimum *Δv* below Critical Threshold (10 mph) based on Approach Speed at 100 ft

Speed at 100 ft	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Number of Cases	0	1	1	3	5	8	10	11	12
% Total	0	5	4	9	12	16	19	20	21

Based on the analysis, we can conclude that drivers who have errant speed selection on the approach come closer to the critical rollover threshold at the roundabout, particularly those at 100 ft from the yield line. Hence, measures are needed to slow down drivers who commit errors so that they are able to reduce their speed to an adequate level.

A potential solution are Variable Message Signs (VMS) that display a message instructing fast moving truck drivers to slow down. Exceeding the critical high speed by a truck driver approaching the roundabout triggers the warning message intended to slow down the driver. The distance where the speeds are measured should be as close as possible to the spot with the lowest Δv but sufficiently far to allow drivers to correct their speeds. The results of this study may help determine the best location of the speed trap and the VMS sign. Another possible measure is better training of truck drivers to improve their traversing roundabouts.

CHAPTER 8. CONCLUSIONS

Due to their safety and capacity benefits demonstrated in past research, roundabouts are likely to continue their emergence as a choice alternative intersection. With regards to safety, the literature suggests that roundabouts are highly effective in reducing severe and fatal accidents. Roundabout construction on high-speed roads has recently commenced. Although crash statistics show consistency with those on low-speed roads in reducing the most severe accidents, these roundabouts bring new challenges on how to safely accommodate the considerable heavy vehicle traffic. Experience from the United States and other countries show that the rollover risk of heavy vehicles should be considered in roundabout design. Roundabout geometric features linked with rollover have been identified, but there are questions that need to be answered before efficient safety countermeasures can be determined. One such unknown is the effect roundabout circulatory superelevation has on the vehicle tendencies for rollover. It is also useful to know if aggressive driving or excessive approach speed affects the rollover propensity.

This study provides primary contributions and a foundation for future research. It presents a generalized model for heavy vehicle rollover that accounts for complex paths and tilt experienced by semi-trailers and other long, heavy vehicles in roundabouts. As the traditional model used by road designers, the model presented here is quasi-static and considers neither the effect of the vehicle mass distribution nor the suspension system.

Due to the comparative nature of the analysis performed, the limitations of the model are expected to be small and negligible. Future research should further examine this component.

The presented study applied the advanced rollover propensity model to data collected in the field. The established methodology can be readily utilized for investigating other types of road solutions if sufficient geometric and motion data are available.

The obtained research results have practical implications. It was confirmed that inward superelevation gives a statistically significant, higher Δv than the typically used outward design. However, the safety effect is too small to provide support for the inward design given its other shortcomings, such as a sudden change in cross slope between the roundabout approach curve and circulation and difficulties in inward drainage. These results may point toward continuing the design practice of outward circulatory superelevation.

The thesis indicates that aggressive driving manifested through high speed far from the roundabout does not imply a larger risk of rollover in the roundabout.

Drivers who made errors by maintaining excessive speed close to the roundabout (this applies to both aggressive and non-aggressive driving) are associated with a greater rollover propensity. The suitable accommodation measures involve Variable Message Signs (VMS), which can be programmed to display messages informing the driver to slow down.

The literature review and the inspection of crash statistics gave additional insight into the rollover issue leading to proposing additional design improvements for consideration. To prevent rollover after a truck goes over the apron, the apron should be designed as easily mountable, or better, flashed and marked with the texture and color different from the pavement in the circulatory roadway. Drivers of heavy vehicles need to be better informed and trained to maneuver a roundabout without increasing the risk of rollover.

Finally, although not explicitly considered in the analysis due to their relative scarcity, trucks that are overweight (in excess of 80,000 lb gross vehicle weight) are expected to have a smaller margin to rollover Δv than those not overweight. This is partially due to the increased load weight, but more attributable to the increased center of mass height. With the appropriate truck loading information, the developed rollover model is applicable for studying overweight vehicles.

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APPENDIX

US-400 and K-47 near Fredonia

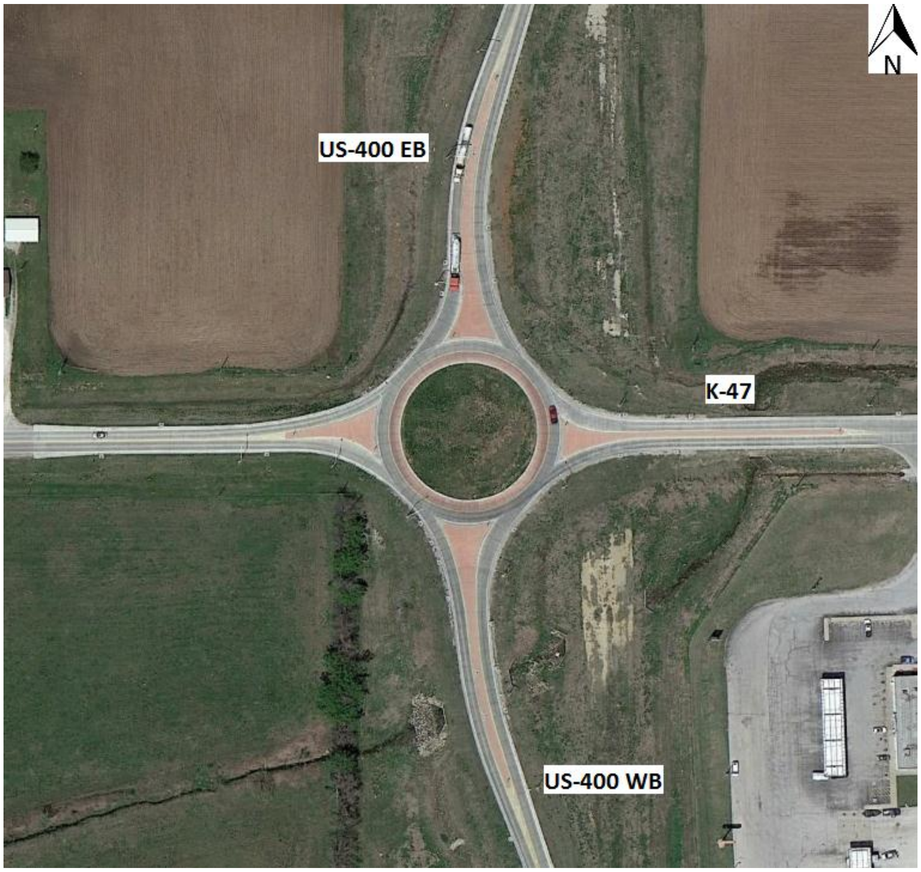

Figure A.1 US-400 and K-47 Roundabout near Fredonia, KS (Google Earth)

Date: 12/29/2010 **Light:** Daylight **Weather:** Fog

Narrative: "Vehicle was eastbound on U400 approaching the roundabout at the K47 junction. Vehicle's speed was too fast approaching the roundabout and overturned while negotiating the curves prior to it."

Date: 1/10/2011 **Light:** Dark, with street lights on **Weather:** Snow

Narrative: “D1 was traveling east on U-400. D1 was traveling too fast for the road conditions. D1 lost control of V1 as he entered curve prior to round-about. V1 slid sideways until it struck curb and rolled over onto its driverside and spun around facing north or west U-400.”

Date: 3/5/2012 **Light:** Daylight **Weather:** No adverse weather

Narrative: “Vehicle was west bound on U400 approaching the round about at K47. Vehicle entered the round about with too much speed to safely negotiate the round about and rolled onto it’s left side.

Date: 06/16/2013 **Light:** Daylight **Weather:** No adverse weather

Narrative: “Vehicle 1 was traveling east on U400. Vehicle 1 came into roundabout to fast and overturned on it’s passenger side.”

US-50 and I-35 Access Road at Emporia

Figure A.2 US-50 and I-35 Access Road Roundabout at Emporia, KS (Bing Maps)

Date: 07/23/2011 **Light:** Dark, with street lights on **Weather:** No adverse weather

Narrative: "V1 was going east on US Hwy 50. V2 was going east on US Hwy 50 ahead of V1. V2 entered the roundabout. V1 attempted to turn intro the roundabout, turned over on it's side, and slid across the roadway hitting V2."

US-50, US-77, and 8th Street near Florence

Figure A.3 US-50, US-77, and 8th Street Roundabout near Florence, KS (Google Earth)

Date: 1/2/2007 **Light:** Daylight **Weather:** No adverse weather

Narrative: “V1 approached the roundabout on US 50 Highway East. V1 failed to slow down. V1 traveled through the roundabout. DV1 over corrected V1, units three and four over turned. Damaging Units 2-4 and two State traffic signs.”

Date: 5/4/2013 **Light:** Dark, with street lights on **Weather:** Rain

Narrative: “Unit 1 raveling entered roundabout speed to great hit center of intersection veered right crossed lane hit other curb overturned landing in north ditch.”

US-59 and US-169 near Garnett

Figure A.4 US-59 and US-169 Roundabout near Garnett, KS (Google Earth)

Date: 8/29/2011 **Light:** Daylight **Weather:** No adverse weather

Narrative: “V1 was S/B on U-169. V1 entered the roundabout and turned over as traveling through the roundabout.”

56th Avenue and Plum Street near Hutchinson

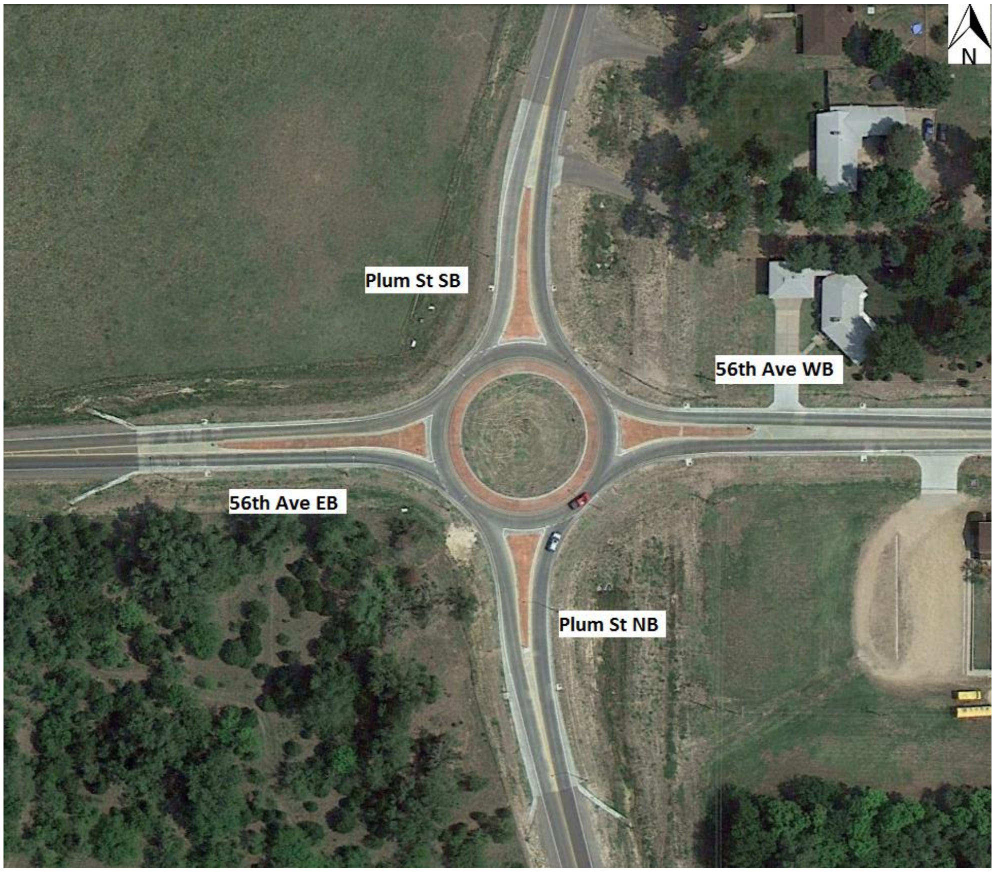

Figure A.5 US-59 and US-169 Roundabout near Garnett, KS (Google Earth)

Date: 7/15/2010 **Light:** Daylight **Weather:** No adverse weather

Narrative: “U1 was traveling through the roundabout at 56th/Plum. The trailer wheels went up onto the brick curb of the roundabout and caused the cargo in the trailer to shift and the tractor trailer overturned onto its right side.