MOUNTAIN-PLAINS CONSORTIUM

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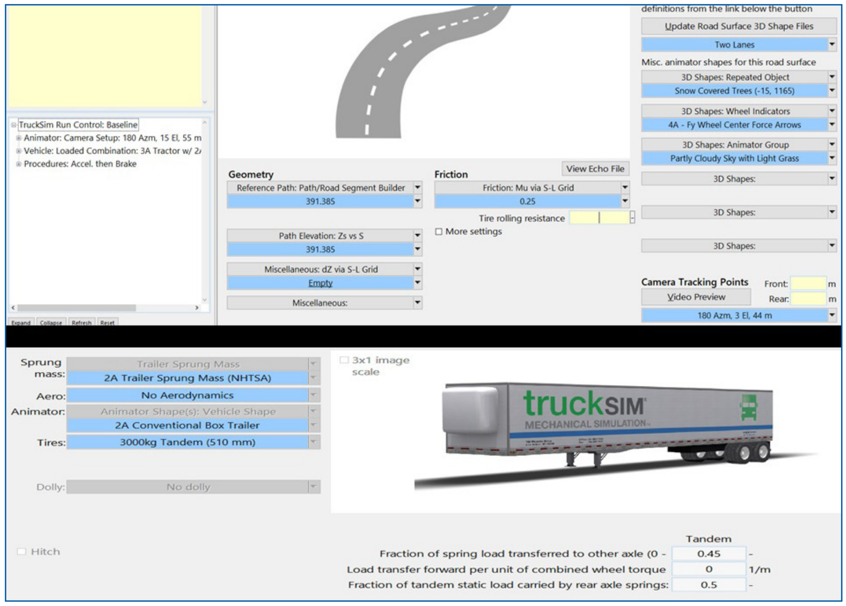
PROPOSING NEW ADVISORY SPEEDS IN MOUNTAINOUS AREAS CONSIDERING THE EFFECT OF LONGITUDINAL GRADES, VEHICLE CHARACTERISTICS, AND THE WEATHER CONDITION



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MOUNTAIN-PLAINS CONSORTIUM REGION 8

Proposing New Advisory Speeds in Mountainous Areas Considering the Effect of Longitudinal Grades, Vehicle Characteristics, and the Weather Condition

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ABSTRACT

Speed limits play a pivotal role in traffic safety on mountainous roadways. Due to Wyoming's unique conditions, designing mountainous roadways with appropriate design speeds is challenging. These roadways are characterized by adverse weather conditions and tight horizontal curves with steep downgrades or vertical curves (combined horizontal and vertical curves). Skidding and rollover toward the outer direction of the curve are the main threats on these curves. The current speed limit design policy in the Green Book (AASHTO 2011) obtained from the design of the horizontal curve does not account for these challenges and has shortcomings. This research aims at evaluating the appropriateness of the posted speed limits and vehicle stability on Wyoming's hazardous curves. This research also intends to propose a new design framework to set speed limits on combined curves with respect to vehicle stability. Therefore, a high-fidelity dynamic simulation modeling approach was used to assess lateral and roll stability of different vehicle types on various road surface conditions. The results showed that the current speed limits are unsafe and should be modified under some circumstances. Vehicle stability significantly changes based upon the vehicle type and configuration coupled with weather conditions, and therefore appropriate speed limits vary accordingly. The developed models of SMs and RMs quantify accurately the impact of the geometric and environmental characteristics on the vehicle performance when cornering. The proposed framework and assessment will assist Wyoming's roadway authorities in imposing more appropriate speed limits for vehicles on hazardous sections based on the weather conditions and vehicle configurations. Furthermore, the results would be beneficial for companies developing automated trucks.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS/ABBREVIATIONS

CG	Center of Gravity
CIREN	Crash Injury Research and Engineering Network
CR	Critical Rate
EPDO	Equivalent Property Damage Only
HSM	Highway Safety Manual
IEM	Iowa Environmental Masonite
LTR	Load Transfer Ratio
MSC	Mechanical Simulation Corporation
MVMT	Million Vehicles Miles Traveled
MT	Mountainous Terrain
MPC	Mountain-Plains Consortium
NHTSA	National Highway Traffic Safety Administration
NOAA	National Oceanic and Atmospheric Administration
NM	Non-Mountainous Terrain
PC	Passenger Car
RM	Rollover Margin
SL	Speed Limit
SUV	Sports Utility Vehicle
AASHTO	The American Association of State Highways and Transportation Officials
VDM	Vehicle Dynamic Models
WYDOT	Wyoming Department of Transportation
WHP	Wyoming Highway Patrol
WRDP	Wyoming Roadway Data Portal
ZINB	Zero Inflated Negative Binomial

1. INTRODUCTION

1.1 Background

Design speed is a factor in horizontal curve design process based on the AASHTO (American Association of State Highway and Transportation Officials, 2011). The posted speed limits on these curves are assigned depending on the advisory speed obtained from the designs set as per the Green Book. Assigning an appropriate speed limit is a vital task regarding traffic safety due to the high crash rates on these curves. Crashes are 1.5 to four times higher on horizontal curves compared with straight segments (Aram, 2010). In the presence of steep vertical profiles, the risk is greater. The combination of tight horizontal curves and steep vertical alignments (combined curve) are common on mountainous terrain. These challenges substantially affect the dynamic and kinetic characteristics of vehicle trajectories. The current policy adopted by AASHTO (Green Book) to design speed limits as a factor of the radius equation on these horizontal curves has significant shortcomings. It adopts a simplified approach (point-mass model) where the vehicle is represented as a point-mass with unsprung (rigid) characteristics in a manner that this approach is independent of vehicle dimensions and features such as a suspension system. The vehicle is also assumed to be on a planar surface instead of a three-dimensional surface. This design criterion does not consider the impact of multiple factors such as grades, vehicles' dynamic characteristics, and adverse weather conditions (wet, snowy road surfaces and severe crosswinds). The distribution of weight on tires and axles changes when negotiating combined curves. An increase in the side friction demand and a decrease in available side friction occurs due to steep downgrades. This fact is more prominent for heavy vehicles (i.e., semi-trucks) due to their complex dynamic features.

To show a clear vision of this issue, Figure 1.1 illustrates how the center of gravity (CG) continuously shifts for a different component of a truck when traversing a horizontal curve combined with a downgrade. This phenomenon drastically impacts vehicle stability. Generally, skidding and rollover events are the main hazards on these curves regarding stability. These risks vary according to the prevailing weather conditions and roadway geometric features. In states such as Wyoming, it was reported that the weather conditions are the most effective parameters influencing vehicle stability and mountainous roads' safety due to the harsh winters. These critical circumstances require comprehensive studies and advanced methods to capture the significant precursors of skidding and rollover events. Therefore, several researchers (Psarianos et al., 1998; Kontaratos et al., 1994; Bonneson, 1999) pointed out that more sophisticated models are needed to simulate accurate vehicle performances and evaluate its safety on curves.

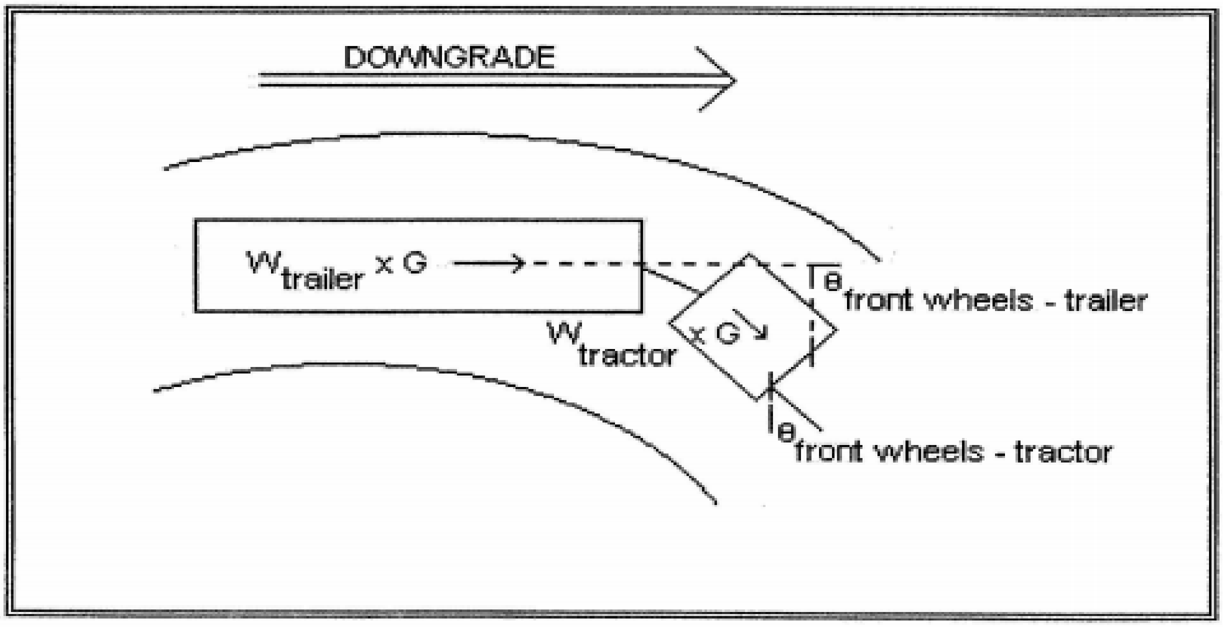


Figure 1.1 The condition of the center of gravity in tractor and trailer of an articulated vehicle on combined horizontal curves with vertical alignments (Eck and French 2003)

1.2 Research Objectives

The purpose of this research is to assess the current speed limits and vehicle stability on combined curves and then propose a new holistic framework to design speed limits on such challenging segments. This will be achieved in accordance with various conditions by using a more advanced approach than currently used methods and policies. Particularly, the following are the objectives of the research:

- Evaluate vehicle performance on the mountainous interstate and two-lane curves under various road surface conditions in terms of rollover and skidding events via simulation modeling software.
- Assess the posted speed limits on selected combined curves.
- Investigate the combined effect of truck gross weight and payload CG height on truck roll stability.
- Investigate the effect of severe crosswind conditions on truck stability while cornering.

1.3 Expected Outcomes

This research will provide a holistic framework to design appropriate speed limits on combined curves on the basis of two criteria: skidding and rollover events using dynamic simulation modeling. This framework will assess the current speed limits of curves coupled with a distribution of operating speeds to identify a safe speed according to prevailing conditions and overcome the limitations of the current design policies. The results can be used by policymakers such as WYDOT to assign appropriate speed limits corresponding to the vehicle types and configurations on various weather conditions. Moreover, it would assist in proposing appropriate safety countermeasures that mitigate the occurrences of stability-related crashes.

1.4 Report Organization

This report is organized into seven chapters and two appendixes. Appendix A and B illustrate the output of the simulation modeling for passenger cars and trucks, respectively. The organization of this research is summarized below:

- Chapter 1 introduces the research context, introduction, background, research objectives and the expected outcomes of this research.
- Chapter 2 shows the methodologies including the simulation process, considered key inputs, and the statistical approaches in the research.
- Chapter 3 aims to assess dynamically the performance of different vehicle types against skidding and rollover events on interstate combined curves. Instead of utilizing observational methods that inhibit the control of key variables, vehicle dynamics simulation modeling is employed considering varying geometric features and environmental characteristics.
- Chapter 4 fills the gaps in the impact of truckload variations on truck roll stability. The vehicle dynamics simulation modeling is employed to investigate the impact of truck weights and CG payload height of trucks on roll stability.
- Chapter 5 reveals the impact of crosswind parameters (speed and direction) on truck roll stability on curves.
- Chapter 6 aims to propose a holistic framework to design appropriate speed limits on combined two-lane rural curves on the basis of two criteria: skidding and rollover events using dynamic simulation modeling.
- Chapter 7 summarizes the research, demonstrates the conclusion of the results, and recommends future work.

2. METHODOLOGY

2.1 Simulation Model Process

To overcome the shortcomings in the point-mass model adopted to design horizontal curves and their speed limits, high-fidelity vehicle dynamic simulation modeling was used. It captures accurately the dynamic behavior of vehicles. This multi-body approach represents the response of the vehicle to the load, speed, weather, and geometric conditions. The dynamic vehicle simulation estimates vehicle performance and analyzes the dynamic behavior of vehicles, such as the loads on each tire and lateral friction demand that results while cornering. The commercial vehicle simulation package, CarSim, and the similar truck-oriented software package, TruckSim, are well-known multibody simulation packages developed by Mechanical Simulation Corporation (MSC) software. These software packages have the ability to account for the weight transfer of vehicles and suspension dynamics when cornering. These packages are selected because they are the most widely utilized in the industry. Regarding validation of the simulation outputs, the software package has been validated for many years by several studies that compared the experimental output related to vehicle stability with the simulation outcomes and found they were consistent. One of the recent research projects showing this was the NCHRP 774 study (Torbic et al., 2014). They conducted various field tests to examine different operating speeds and conditions. The results were in line with the TruckSim implications.

The goal of this process is to evaluate speed limits and the operating speeds of vehicles in terms of lateral and roll stability. This is conducted by defining the skidding margins (SMs) and rollover margins (RMs) whether vehicles could maintain their desired trajectory through different geometric situations. The simulation outcomes are used to develop new empirical models to estimate the distributions of these margins. Regarding SMs, when the demand friction exceeds the supply tire-pavement friction, the impending skidding point occurs. This depends mainly on the road surface conditions. The centrifugal forces acting on the vehicle tires create the demand side friction. The SM is the excessive amount of the supply friction excluding the developed demand side friction. Equation 1 illustrates this definition as follows:

$$f_{margin} = f_{y\,supply} - f_{y\,demand} \qquad (2\text{-}1)$$

Where f_{margin} is the safety SM, $f_{y\,supply}$ is the supply friction between tire and pavement, and $f_{y\,demand}$ is the demand friction (side friction factor). Instead of the deterministic approach used in the current design guides, considering this method would offer a probabilistic approach to determine the margin of the impending skidding cases and not only one specific value.

The demand friction $f_{y\,demand}$ in each of the simulation tests is equal to the lateral force acting on the tire over the vertical load. Maximum demand friction values are considered in the model for each run, which represents the worst case. Regarding the supply friction, three road surfaces were considered: dry, wet, and snowy. The friction values were obtained from field studies conducted in previous studies using the dynamic friction tester research (Fambro et al., 2000; Himes, 2013) (Torbic et al., 2014). The mean of the normal distribution of the supply friction for dry conditions is 0.818 with a 0.095 standard deviation (SD). For wet conditions, the mean is 0.653 with a 0.055 SD. For snowy friction that represents the lowest supply friction; the Ghandour study (Ghandour et al., 2010) reported that its mean supply value is 0.25 with a 0.074 SD.

To estimate the RMs along with corners, the load transfer ratio (LTR) is used. It is a metric commonly used to predict wheel lifting. This dynamic approach outperforms the regular statistic rollover margin that is defined only by the available lateral acceleration when exceeding the fixed value of the rollover threshold.

For each axle, the metric is defined as (R. Ervin, 1983):

$$LTR = \frac{N_i - N_O}{N_i + N_O} \qquad (2\text{-}2)$$

The terms N_i and N_o are the normal (vertical) loads on the axle's inside and outside tires while cornering, respectively. This metric varies from -1 to 1. This metric can be considered as the portion of the total axle load supported by the outside tire. Therefore, the dynamic rollover margin, RM_{LTR}, defined by the probability of the *LTR* reaching the critical value which would lead to wheel lifting is expressed as:

$$RM_{LRT} = 1 - \frac{N_i - N_O}{N_i + N_O} \qquad (2\text{-}3)$$

This margin varies between 0 and 1, where 0 represents a rollover incident and 1 denotes the absence of the probability of overturning. Among the axles of the truck, the lowest rollover margin was considered in the analysis as the worst-case scenario. The primary focus of this study was to determine the circumstances under which the truck rollover margin would decrease and become susceptible to overturning ($RM = 0$)

2.1.1 Site Selection

Three main components are assigned in the software: driver control mode, the vehicle model, and the three-dimensional road-building model. It is critical to select the most hazardous curves on Wyoming's roadways. Identifying locations that are characterized by high skidding and rollover incidents will possibly result in proposing safety improvements. The critical rate (CR) safety evaluation method, equivalent property-damage-only (EPDO) method, and other methods were utilized. The first two quantitative approaches are specified in the Highway Safety Manual (HSM) provided by AASHTO (*Highway Safety Manual*, 2010). The CR method has been widely used by traffic safety practitioners. In this method, the crash rate at a curve is compared to a critical crash rate unique to each curve considering traffic volumes. A curve is identified as a hazardous curve when its crash rate exceeds the critical rate. The critical crash rate method is more robust than other approaches in which the average crash frequency, or the crash rate, is used as assessment criteria. This is because it provides a comparison between the crash rate at a site and that of a reference site group (Dhillon, 2004). Also, it considers the exposure of the traffic as the AADT is a variable in the critical rate equation. The first approach takes the traffic exposure into account, while the second approach considers the crash severity of the locations (the EPDO method) by obtaining the EPDO score for each site. Each crash severity was assigned a score according to the crash severity in a manner that serious injuries and fatalities receive higher scores than other crashes and lower scores are assigned to lower crash severities. Property-damage-only crashes receive the lowest score. Accounting for both approaches of traffic exposure and crash severity would provide robust outcomes regarding the most hazardous sites. Only downgrade alignments were considered in the study since the change in weight distribution and transfer between tires is more significant compared with upgrades, according to Kordani et al. (Kordani and Molan, 2014). As a result, the dynamic operational performance would be altered on downgrades by the developed forces and accelerations while cornering (Kordani and Molan, 2015).

Twelve interstate curves were selected for the study. All curves have a speed limit of 75 mph. Table 2.1 presents these curves with their geometric features. Curve data, such as grade, superelevation, curve runoff, and tangent runout, were obtained from several sources. Considering a wide range of curve features would provide a better understanding of the impact of these features on vehicle stability in order to obtain the critical limits beyond which hazardous situations would arise. Road inventory files from the WYDOT Roadway Data Portal (RDP) and Pathway video logs were consulted to export the geometric features data of the selected curves. The geometric characteristics comprised a wide range of curves. The degree of curvature of the selected curves varied between 1.5 and 5.9. Similarly, downgrades and superelevations ranged from -2.1% to -5.5% and from 2.22% to 6.55%, respectively. The grade represents the maximum grade either approaching the curve or in the curve. The superelevation value is the average superelevation on the curve. As noticed from previous field studies, considering the adjacent segments before and after the curve is critical (Chen et al., 2018a). This is because these segments influence vehicle stability when cornering. It was reported that the impact area consists of 150 to 300 feet (Wang et al., 2019). before and after the curve. Therefore, in addition to the curve's features, the simulation accommodated the geometric features for the 300 feet before and after the curve. The simulation runs reflect realistically human-vehicle behavior when negotiating curves (Wang et al., 2019). All geometric inputs were inserted in the software to establish the test sites that precisely reflect the real-world sites.

Table 2.1 Geometric features of the selected curves

Interstate Curve	**Deflection Angle (°)**	**Radius (ft)**	**Degree of Curvature (units)**	**Maximum Grade (%)**	**Superelevation on Average (%)**
1	58.00	3,820	1.5	-2.1	2.22
2	52.36	3,012	1.9	-4.9	2.27
3	37.45	3,015	1.9	-5.4	3.26
4	50.19	3,000	1.9	-3.8	5.86
5	36.11	4,587	1.2	-3.3	3.61
6	36.8	2,214	2.6	-4.6	6.13
7	36.81	3,121	1.8	-3.7	3.32
8	42.09	1,562	3.7	-2.5	6.08
9	59.08	1,128	5.1	-5.5	6.55
10	45.49	976	5.9	-5.4	5.39
11	54.29	1,467	3.9	-2.2	6.17
12	66.53	1,775	3.2	-3.2	6.22

2.1.2 Operating Speeds

In the presence of combined alignments, the vehicle operation needs to be consistent by offering driving performance that meets the driver's expectations. The driver's operating speed choice then would be proper and consistent throughout challenging road segments. The concept of design speed assumes that all vehicles will transport at or below the design speed. This assumption is invalid for all roadways and in different weather conditions (Krammes et al., 1995) since road users are sometimes incautious in challenging driving conditions. Therefore, the vehicle performance is assessed for different conditions of road geometry at various operating speeds to investigate the impact of the vehicle speeds on lateral and roll stability. This would calculate the skidding and rollover safety margins on the hazardous curves. Five speed categories are considered: the speed limit that is associated with the design speed (SL), SL+5 mph, SL+10 mph, SL-5 mph, and SL-10 mph. This would evaluate the impact of vehicle speeds exceeding the speed limits, since this is the case in numerous crashes in Wyoming, and assess the speed limits in Wyoming's rural highways. This would provide insights regarding appropriate and safe operating speeds and if there is any need to adjust to the posted speed limit in order to prevent hazardous situations

2.1.3 Define Vehicle Types

The dynamic parameters vary by vehicle type. Therefore, it is significant to include the most popular vehicle types to measure the safety margins. The three types of vehicles considered were the passenger car (sedan), the sport utility vehicle (SUV), and the semi-trailer truck. The semi-trailer truck was selected among many truck types because, as reported in a previous field study, it had the highest risk of skidding on roadways with challenging geometry (Torbic et al., 2014). It is also the most common type in the freight shipping industry.

2.1.4 Brake Application

Since drivers tend to avoid the possibility of running off the curve by decelerating (Yu et al., 2012), it is critical to investigate the impact of the brakes on stability while cornering. The friction values are represented by a friction ellipse that comprises the maximum friction in the longitudinal (braking) direction and the lateral (side) direction. The operating point that represents the demand friction should remain within the friction ellipse to negotiate a curve without deviation. The force available in the lateral direction is decreased when braking and therefore reduces the vehicle's ability to maintain the trajectory. The variation in decelerations was measured by Bonneson (2000) using an instrumented vehicle. He suggested that the usual deceleration upon the curve's entry be 3 ft/s^2 since the maximum lateral friction is developed at the curve's entry point, The brakes are applied at this location of the curve (Alrejjal and Ksaibati, 2021a). Hence, the simulation achieves a deceleration state that mimics a human driver applying and releasing the brakes intermittently.

2.2 Multiple Regression Model

To analyze the simulation tests and quantify the impact of the considered factors on the skidding and rollover margins (SM and RM), a multiple regression model was applied. This would interpret the results of the simulation and unveil the tendency of each factor on the safety margins This approach is suitable to fit the test data since the response variable (SM and RM) is a continuous variable between zero and one. Thus, a function determining SM and RM is defined as (Bhat, 2001; Greene, 2003; Train, 1997):

$$S_{in} = \boldsymbol{\beta_{in}} \boldsymbol{X_{in}} + \varepsilon_{in} \tag{2-4}$$

Where, $\boldsymbol{\beta_{in}}$ is a vector of parameters estimated for rollover margin i, which are allowed to vary across observations, $\boldsymbol{X_{in}}$ is a vector of explanatory variables determining rollover margin, and ε_{in} is a stochastic error term.

2.3 Elasticity Analysis

An elasticity analysis was conducted to explore the insights into the implications of the estimation results. Therefore, the marginal effects of the variables are determined by the predicted RMS. The elasticity of the estimated skidding and RMs to the variables as proposed by Shankar et al. (1995) in general is:

$$E(y)=\frac{\partial\lambda}{\partial x}\frac{x}{\lambda} \tag{2-5}$$

Where x is the explanatory variable and λ is the mean of the RMs.

3. IMPACT OF COMBINED ALIGNMENTS ON VEHICLE SKIDDING AND ROLLOVER

3.1 Skidding Margin

The developed methodology for the simulation modeling included combinations of key geometric elements and other elements. These factors were simulated in CarSim and TruckSim software to assess their impact on vehicle stability and therefore the skidding (side friction) safety margins when navigating a curve. Figure 3.1 demonstrates the general simulation process.

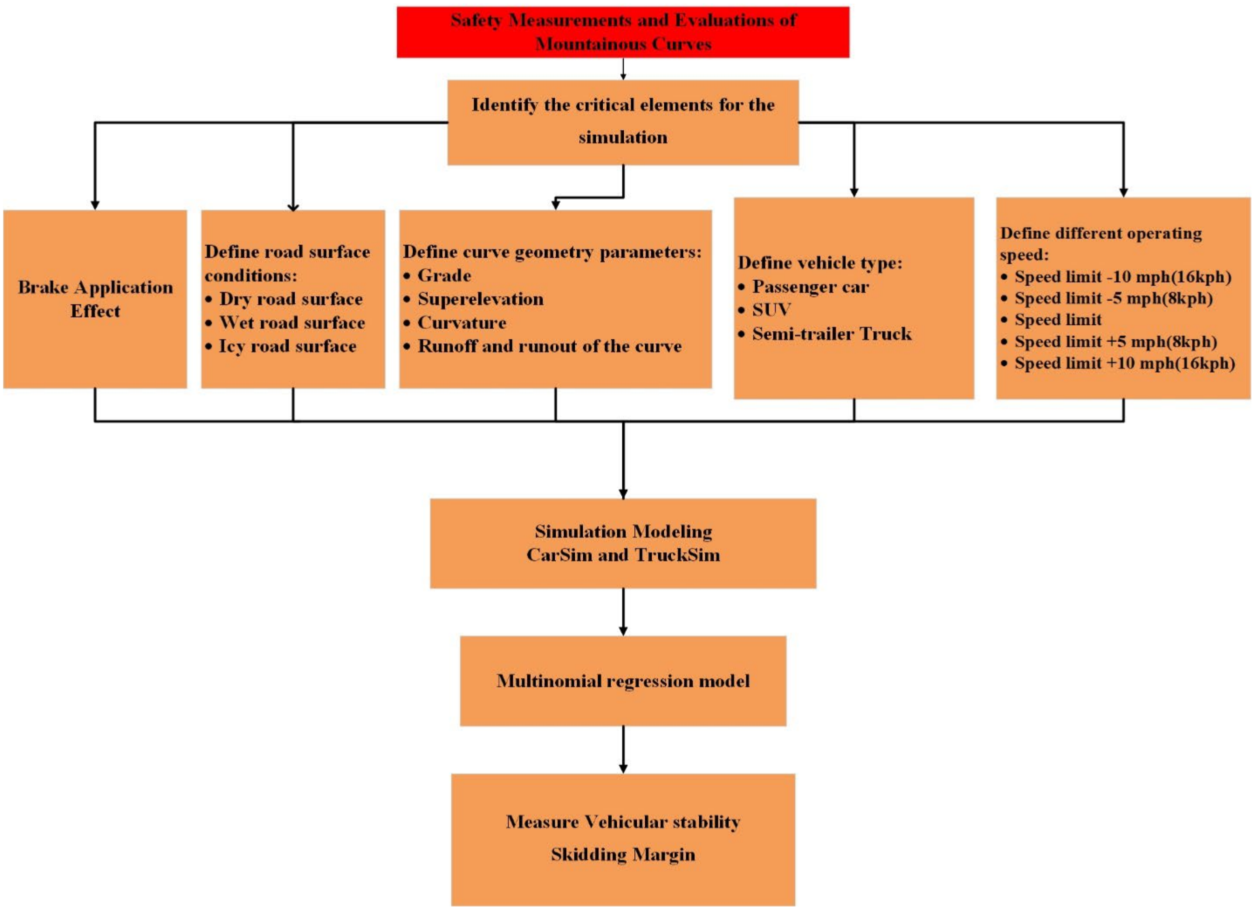


Figure 3.1 Study methodology

By including the considered factors, combinations of simulation tests are conducted. A total of 1,080 simulation scenarios were tested. Table 3.1 articulates combinations of the simulation scenarios based on the different parameters shown in the figure above. For each simulation, the side friction margins were assessed. This process would provide an understanding of the risky curves and the scenarios in which a vehicle was more likely to deviate from the desired trajectory.

Table 3.1 The combinations of the running simulations based on the considered parameters shown in Figure 3.1

Number of considered curves	Road surface conditions	Vehicle types	Operating speeds	Brake application	Total combinations
12 curves	3 road conditions	3 vehicle types	5 different speeds	2 states (applied, not applied)	12*3*3*5*2 =1080 scenarios

3.1.1 Effect of Road Geometry

The superelevation is responsible to counterbalance the centrifugal forces developed when cornering. However, the simulation outcomes show that the superelevation impact is insignificant compared to grade and curvature degree. This indication is in line with previous studies (Torbic et al., 2014). The real values of superelevation obtained from the curve sites indicate there is an inconsistent relationship between these values and curve sharpness levels. Generally, sharper curves require greater superelevation values, and this might be attributed to construction deficiencies when establishing the curves. Therefore, it is crucial to adjust superelevation values according to the curve sharpness.

Table 3.2 displays a sample of (SMs) obtained from the simulation tests for passenger cars traveling at 75 mph on combined curves. The safety margins as noticed decrease in all tests for sharper curves and steeper downgrades. Yet, all margins are still positive because the supply friction on dry road surfaces is high, and this means that the vehicle is in the desired trajectory. Furthermore, both downgrade values and degree of curvature significantly influenced the SMs.

Table 3.2 Sample side friction margins of passenger cars traveling at 75 mph (121 km/h) on a dry road surface for different curves

Interstate Curve	Downgrade Values in percentage %	Degree of Curvature in degrees	$f_{y\ margin}$
1	-2.3	1.5	0.71
2	-4.9	1.9	0.59
3	-5.4	1.9	0.59
4	-3.8	1.9	0.68
5	-3.3	1.2	0.72
6	-4.6	2.6	0.65
7	-3.7	1.8	0.65
8	-2.5	3.7	0.50
9	-5.6	5.1	0.47
10	-5.4	5.9	0.22
11	-2.2	3.9	0.58
12	-3.2	3.2	0.60

3.1.2 Side Friction Margin for Different Operating Speeds and Vehicle Types

The results show that higher operating speeds increased the demand friction when negotiating curves, and thus the SMs dropped. Greater vehicle speeds are expected in the simulation scenarios as combined curves include downgrades since the downgrade was usually associated with higher speeds (Montella et al., 2014). The results were confirmed with multiple crash studies, as they exhibited that greater speed significantly increased the skidding probability (Chen et al., 2018; XU et al., 2013). Also, when the available friction (supply) decreases according to the road surface conditions, the speed impact is more prominent. Figure 3.2 illustrates the negative influence of the operating speed of passenger cars on different surface road conditions when negotiating a moderately sharp curve. As noticed, in the case of snowy road conditions, the SMs converged to almost zero. Therefore, adjusting the operating speeds is critical in this case to maintain the vehicle in the desired trajectory. This phenomenon is more stressed in the case of sharper curves on steeper downgrades.

With regard to vehicle type, results show that the SMs are impacted differently according to the type of vehicle. The influence of vehicle type on the probability of skidding when cornering was noticeable with different sizes and dynamic characteristics. Passenger cars had the highest side friction demand for all tests compared with other considered vehicle types. Thus, the potential for skidding events was higher for passenger cars. This was mainly attributed to the fact of passenger cars' low center of gravity. Similarly, the act of steering produced a small amount of slippage in the outside tires. This rendered passenger cars to skid prior to rolling over. On the other hand, in the case of SUVs and trucks, the higher center of gravity would increase the rollover event more so than skidding. The heavy gross weights of these vehicles produce higher vertical loads, and therefore greater vertical forces were acted on the tires compared with passenger cars. This will reduce the demand friction as it is equal to the lateral forces over the vertical forces. Semi-trailers had a high center of gravity and amplified weight transfer effects, and this reduced the lateral friction margins. Figure 3.3 shows the impact of different vehicle types on the side friction margins.

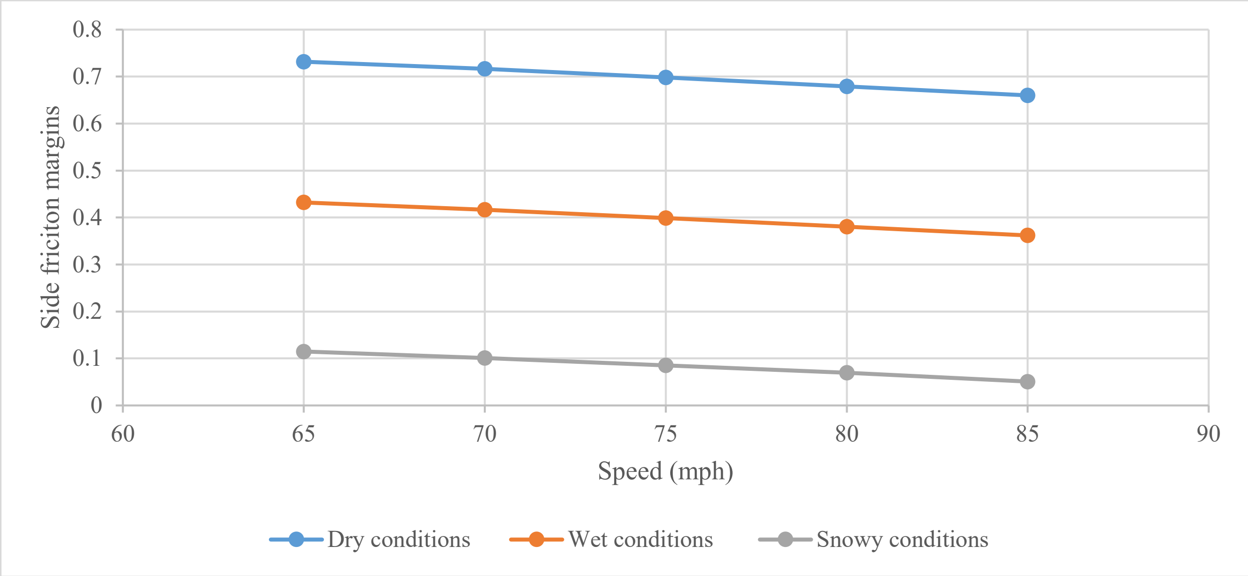


Figure 3.2 The impact of passenger car's speed on the side friction margin for different road surface conditions (moderately sharp curve)

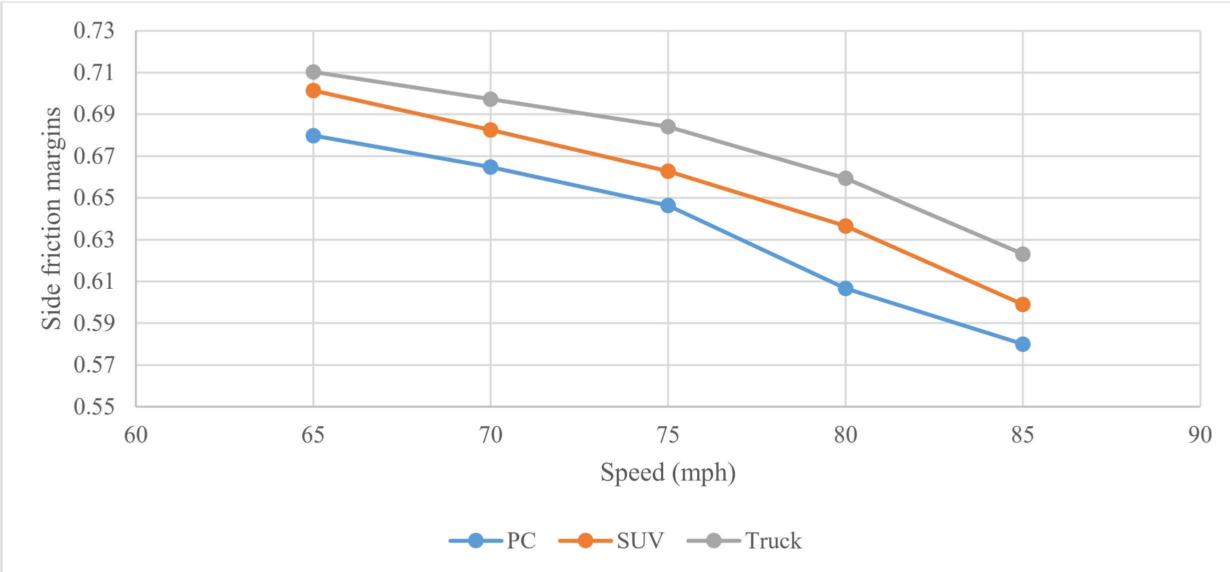
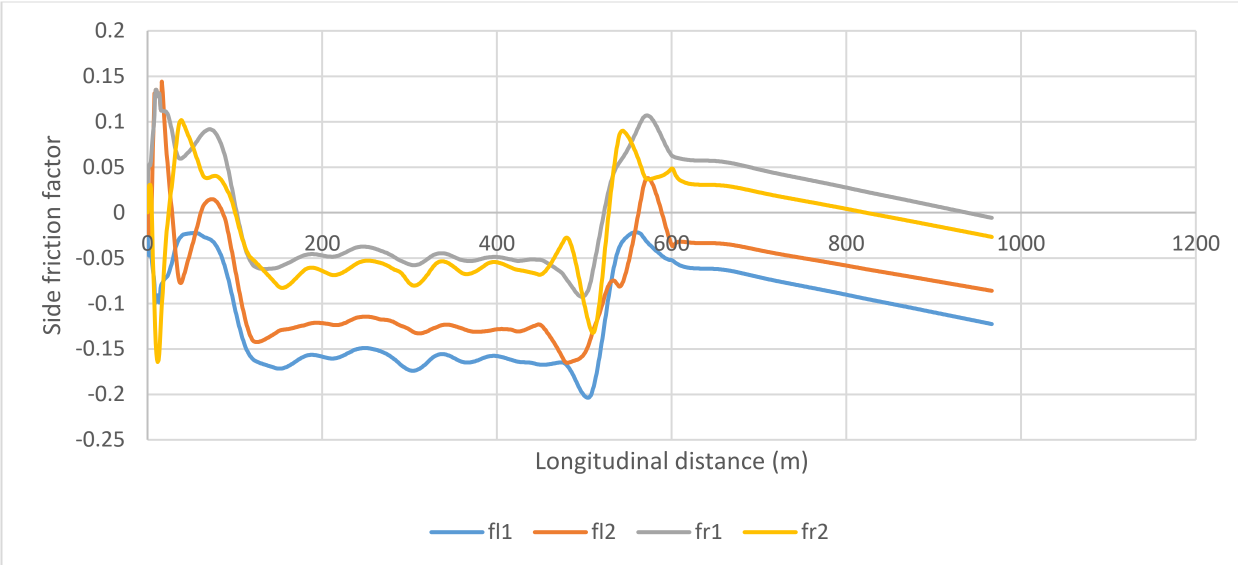


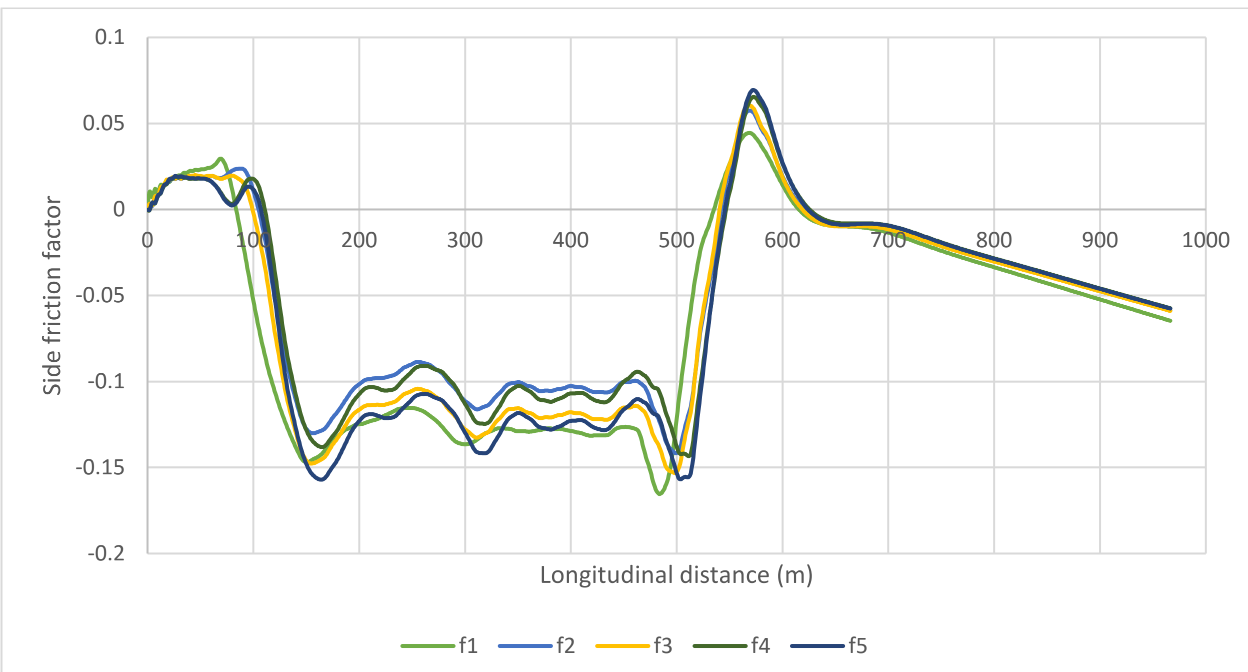
Figure 3.3 The impact of different types of vehicles on the side friction margin

3.1.3 The Effect of Vehicle Tires and Axles on the Skidding Margins

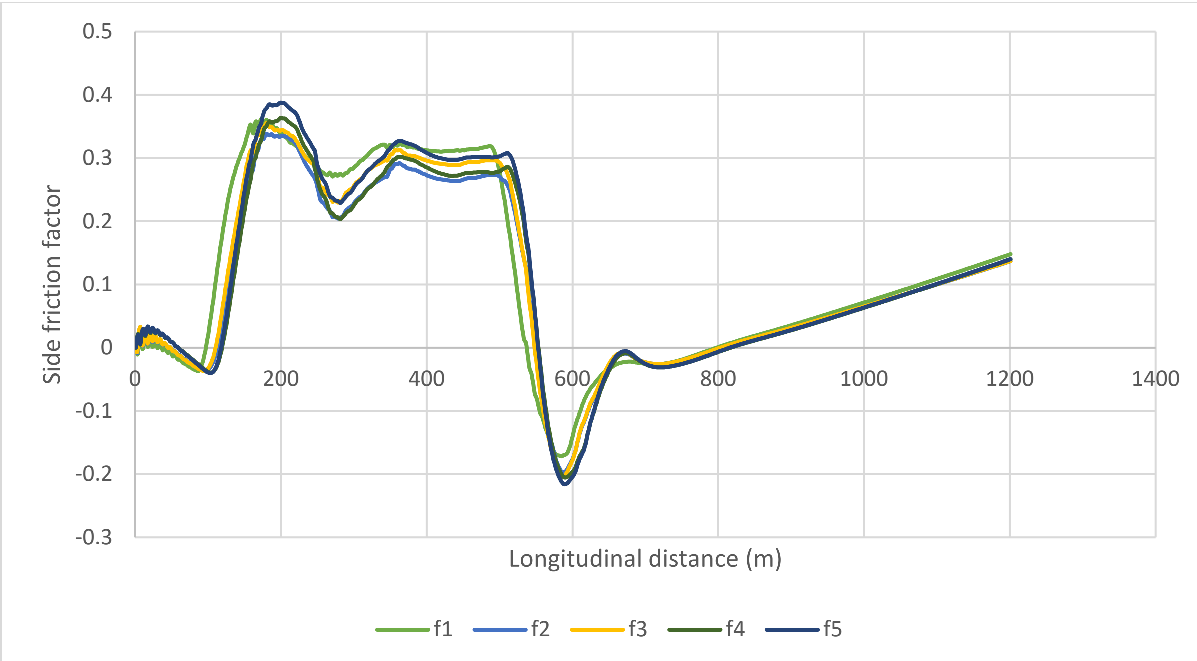
The results of the multibody model provided the acting forces on each tire. This provides more accurate outcomes related to vehicle stability compared with the point-mass model adopted by AASHTO because it considers the variation of the weight distribution on each vehicle tire when cornering. Figure 3.4 (a) shows the side friction factor (demand friction) for each passenger car tire on dry conditions (fl1: left tire in the front axle, fl2: left tire in the rear axle, fr1: right tire in the front axle, fr2: right tire in the rear axle) along the curved roadway while cornering. The highest side friction factors occurred at the beginning of the curve, which was the most crash-prone location of the combined vertical and horizontal curve. This was due to the continuous changes in the angle of the vehicle steering when cornering (A Mehrara Molan and Kordani, 2014). The left tire on the front axle had the greatest demand friction and it was more prominent for the passenger car due to the higher side friction factors developed when cornering compared to the SUV. Typically, 55% to 60% of the vehicle's gravity loads act on the front axle and 40% to 45% act on the rear axle (Kordani and Molan, 2015). Also, because of the steering geometry issues, the front tires experienced more disparity than the rear tires (Torbic et al., 2014). As a result of the shifting in the mass center toward the outer part of the curve, more than 55% of the lateral and vertical forces acted on the left tire (Kordani, 2015). This fact was omitted in the simplified vehicle models such as the point-mass model. Similar implications were drawn from the SUV simulation results. Regarding semi-trailer trucks, the weight transfer played a pivotal role in defining the axle with the highest lateral demand friction because of the downgrade alignment. Figure 3.4 (b) displays that the load transfer is insignificant on a moderate sharpness curve, and therefore the front axle experienced the highest side friction factor for the same reason as the passenger cars. In the case of a sharp curve combined with steep downgrade shown in Figure 3.4 (c), a contradictory tendency was observed when traversing on a left curve. Considerable loads were transferred from the rear axle to the front axle; consequently, the vertical forces at the rear axles were reduced (f1: front axle, f2: second axle, f3: third axle, f4: fourth axle, and f5: rear axle). This increased the side friction factor on that axle. As noticed, the impact of downgrades on weight transfer between axles was stronger in the trucks compared with other vehicle types because of the heavier gross weight of the truck. The impact of combined alignment significantly affected the lateral stability of vehicles; therefore, the safety margins of these curves are different than the single curves while cornering.



a) Side friction factor for each passenger car tire on a right-turn curve (moderate downgrade)



b) Side friction factor for each truck axle on a right-turn curve (moderate downgrade)

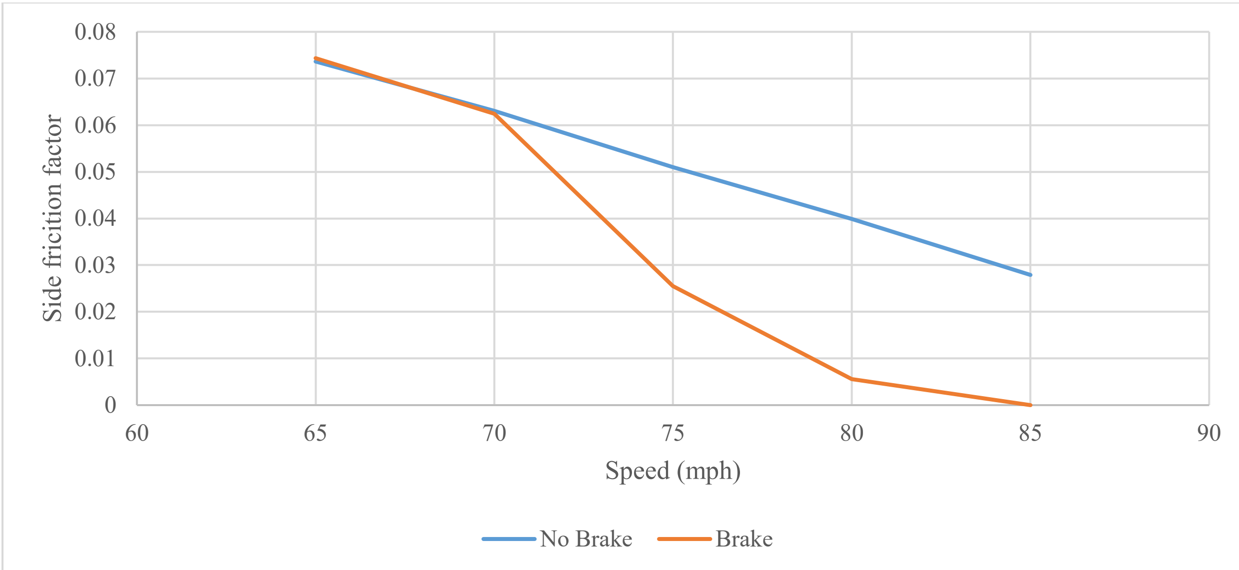


c) Side friction factor for each truck axle on a left-turn curve (steep downgrade)

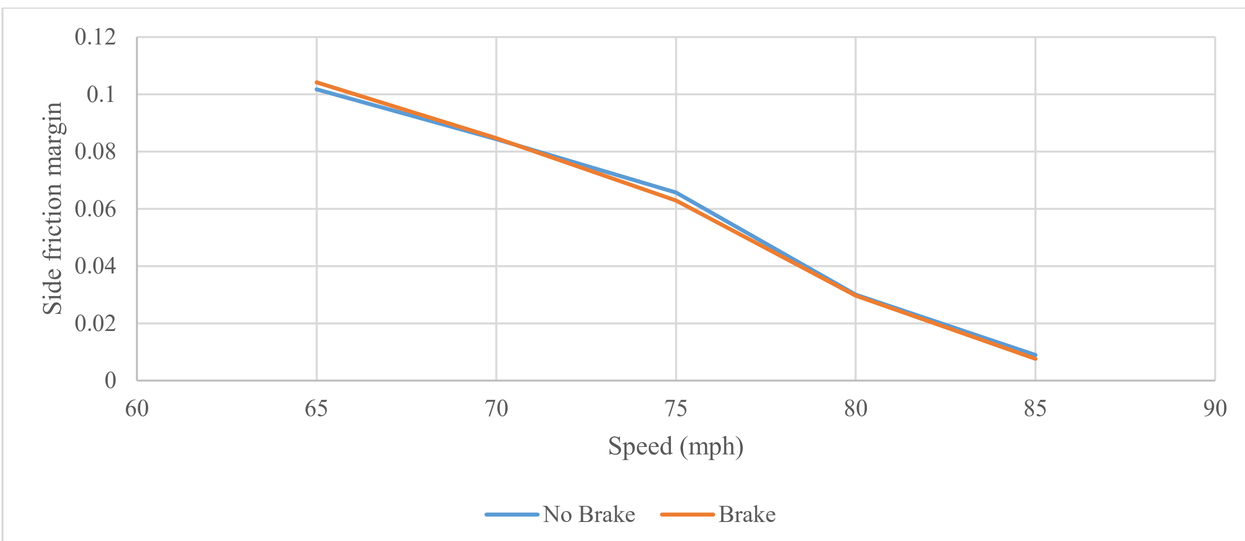
Figure 3.4 Side friction factor for each passenger car tire and truck axle for different downgrades

3.1.4 The Effect of Brake Application

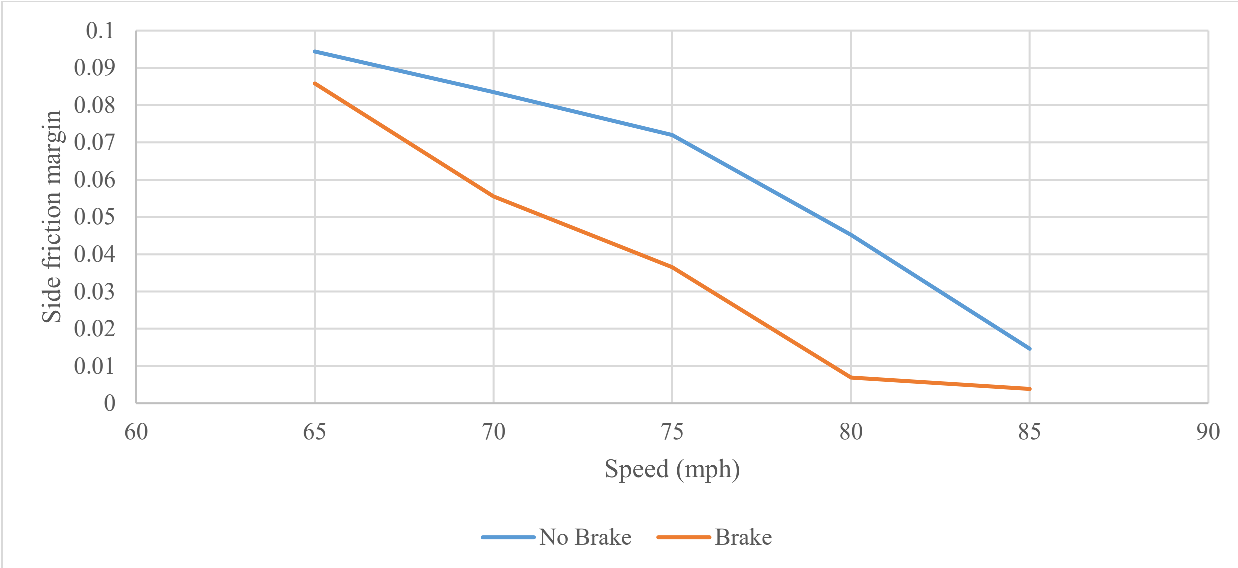
The simulations have shown profound implications based on the road surface when applying the brakes at the curve entry point, the most critical location, and mimicking human behavior. Generally, applying brakes would decrease the operating speed and therefore increase the side friction margin preventing skidding. This was the case in dry surface conditions since the brakes acted on the tires more efficiently as the friction between the tire and the pavement was high. The influence would be stronger when the deceleration is greater than 3 ft/s^2 in instances such as those involving emergency brake situations. Furthermore, the brake effect was found to be insignificant for wet road surface conditions. This is because the friction supply was moderate between the friction supply of dry and snowy road conditions. For the lowest supply friction value (snowy surfaces), the impact was contradictory compared with dry road surface conditions. The available force in the lateral direction would be reduced when increasing the brake force. This rendered the vehicle more vulnerable to skid when braking. Figure 3.5 illustrates the effect of brake application for different vehicle types on snowy road conditions. The impact of brakes on reducing the available friction is stronger in trucks than in passenger cars due to the effect of load distribution and transfer when cornering. The demand side friction was the highest in the passenger car [Figure 3.5 (a)] and therefore the SM is affected to the greatest extent compared to SUVs. Again, truck stability was more affected by brakes on snowy roadways; therefore, truck drivers ought to be aware of how to apply brakes in adverse weather conditions. Wyoming highway patrols reported that drivers are more likely to get into “too fast for the condition” traffic violations that lead to severe crashes (Buddemeyer and Young, 2010). This is because drivers think they are familiar with the roadways even with adverse weather conditions. Also, they did not take into consideration the impact of combined curves on their vehicles and how the loads on tires transfer when applying brakes.



a) The impact of brake application on snowy road surfaces for the passenger car



b) The impact of brake application on snowy road surfaces for the SUV



c) The impact of brake application on snowy road surfaces for the semi-trailer truck

Figure 3.5 The impact of brake application on snowy road surfaces for different vehicle types

3.1.5 Multiple Regression Model

A multiple regression model was developed to describe the relationship between SMs and several key factors and on ascertaining the results from the simulation tests. The factors included vehicle type, roadway geometric design, and environmental conditions. All simulation tests were considered in the model where the SM was the outcome, and the simulation parameters are the predictors that were described in the methodology section. The predictors were speed, grade, degree of curvature, vehicle type (passenger car was the reference), road surface condition (dry road surface condition was the reference), and brake application (yes or no). Since the response variable is normally distributed and is not over-dispersed, linear regression would be the appropriate approach. Table 3.3 shows the results of the regression model. The regression analyses yielded mixed results. Six variables were found to be statistically significant at the 95th percentile confidence level. Compared with passenger cars, SUVs and trucks increased the SMs. The results are consistent with Figure 3.5 since the estimated coefficient of the vehicle types show how the regression line is shifted upward or downward based on the type of vehicles. Wet and snowy road surfaces, as expected, decreased the side friction margin compared with dry road surfaces. The available lateral friction (supply) on these road surfaces was less than that on dry surfaces. Regarding curve characteristics, the degree of curvature was found to contribute to a reduction in the SM, whereas, grade was an insignificant variable. Equation 3-1 represents the regression model with significant variables. There was no correlation between the superelevation and the SM, and thus superelevation was excluded from the model. Table 3.4 presents the elasticity values of the continuous variables to examine the relative effects of the variables considered in the model that infer the average change in SM due to a change in an explanatory variable.

Table 3.3 Skidding margin multiple regression model results

Variable	Estimate	T-Statistic	Standard Error	P-value	95% Confidence interval limits	
					2.5%	97.5%
Constant	1.203	32.540	0.036	<0.001	1.13	1.27
SUV*	0.018	2.210	0.008	0.0274	0.002	0.034
Truck*	0.043	5.300	0.008	<0.001	0.027	0.059
Wet**	-0.281	-34.470	0.008	<0.001	-0.297	-0.265
Snowy**	-0.519	-63.560	0.008	<0.001	-0.535	-0.503
Speed	-0.005	-12.240	0.001	<0.001	-0.006	-0.004
Degree of Curvature	-0.071	-30.760	0.002	<0.001	-0.070	-0.060
Model Fit Statistics						
Adjusted R-squared		**0.920**				
F-statistic		**862.3**				
RMSE		**0.069**				
P-value		**< 0.001**				
AIC		**-1097.27**				

*The passenger car is the reference **Dry road surface condition is the reference

Equation 3-1

$$f_{y\ \text{margin}} = 1.23 + 0.018(SUV) + 0.043(Truck) - 0.281(Wet) + 0.519(Icy) - 0.005(Speed) - 0.07(Curvature) \quad (3\text{-}1)$$

Where ‘SUV’ is the SUV presence while cornering (Yes=1, no=0), ‘Truck’ is the truck presence variable (Yes=1, no=0), ‘Wet’ is if the road surface conditions are wet road (Yes=1, no=0), and ‘Snowy’ is if the road surface conditions are snowy road (Yes=1, no=0). For the continuous variables, ‘Speed’ is the operating speed for vehicles in mph and ‘Curvature’ is the degree of curvature of the curved roadways.

Table 3.4 Variable elasticity effects

Variable	Elasticity Effect
Operating Speed (*Mph*)	-1.515
Degree of curvature	-0.832

The elasticity effects illustrate that the operating speed and degree of curvature both have an impact in decreasing the SM. When increasing the vehicle speed on the curve by 10%, the SM dropped by 15%. Similarly, this margin drops by 8% when the degree of curvature rises by 10%. These implications show how important it is to assign safe and appropriate speed limits since the skidding likelihood is significantly sensitive to vehicle speeds.

3.2 Rollover Margin

To investigate the roll stability of vehicles while cornering, the same factors considered in the previous section were included. Three vehicle types were considered similar to the SM section. “Fully loaded truck” was the weight condition of the semi-trailer trucks. A total of 1,080 simulation scenarios were tested, including the same critical variables used in the SM tests. This process would provide insight into the risky curves and the risky conditions that lead to rollovers

3.2.1 The Effect of Roadway Geometry

A sample of rollover margins (RMs) for trucks traversing different curves at a speed of 75 mph for dry surface road is shown in Table 3.5. Degrees of curvature and rollover margin are unitless.

Table 3.5 Sample of rollover margins of a heavy truck traveling 75 mph on a dry road surface for each curve

Interstate curve	Downgrade values %	Degree of curvature	Rollover Margin
1	-2.3	1.5	0.77
2	-4.9	1.9	0.65
3	-5.4	1.9	0.62
4	-3.8	1.9	0.75
5	-3.3	1.2	0.79
6	-4.6	2.6	0.52
7	-3.7	1.8	0.67
8	-2.5	3.7	0.32
9	-5.6	5.1	0
10	-5.4	5.9	0
11	-2.2	3.9	0
12	-3.2	3.2	0.31

The RMs, as expected, decreased in all tests for sharper curves and steeper downgrades and particularly for heavy trucks. Three curves experienced a rollover event as the margin reached zero when the degree of curvature is 3.9 or more; however, the operating speed was the speed limit. Hence, complying with the current speed limits is not enough to avoid a rollover event under some circumstances. Regarding the geometric features, both the degree of curvature and the downgrade values significantly influenced the RMs.

3.2.2 The Effect of Different Road Surfaces and Vehicle Types

With higher operating speeds, the results show that the rollover margin decreased when cornering. On downgrade profiles, it is expected that vehicles have greater speeds. However, the impact of operating speeds varies based upon the road surface. Figure 3.6 shows the RMs of a semi-trailer truck on different road surface conditions. Trucks on dry road surfaces experienced the lowest rollover margin; therefore, they are more vulnerable to rollover on high supply friction compared with the other road surfaces. Also, since the friction supply for the snowy road condition was low, the lateral acceleration would be higher, and the vehicle would be susceptible to skidding before rolling over.

The simulation outcomes show that vehicle types affect roll stability differently, as shown in Figure 3.7. The highest lateral acceleration was produced in the case of trucks; therefore, they have more potential to roll over in comparison with the other considered vehicle types. This is mainly because trucks have a higher center of gravity, which renders them prone to deviate from their desired path and tip over. The semi-trailer truck's imposing mass contributed to large vertical forces on the tires. On the other hand, with a low center of gravity for passenger cars, they are less prone to rollovers and have more tendency to skid. For SUVs, due to their raised center of gravity, the produced lateral acceleration was greater than that of passenger cars. Therefore, SUVs were more likely to roll over than passenger cars. This inference confirmed rollover crash statistics that SUVs were almost twice as likely to be involved in rollover crashes as passenger cars (USDOT, 2012). However, most of the previous research concluded that there is no significant difference between SUVs and passenger cars in terms of rollover likelihood (Abdi et al., 2019; Amirarsalan Mehrara Molan, and Kordani, 2014).

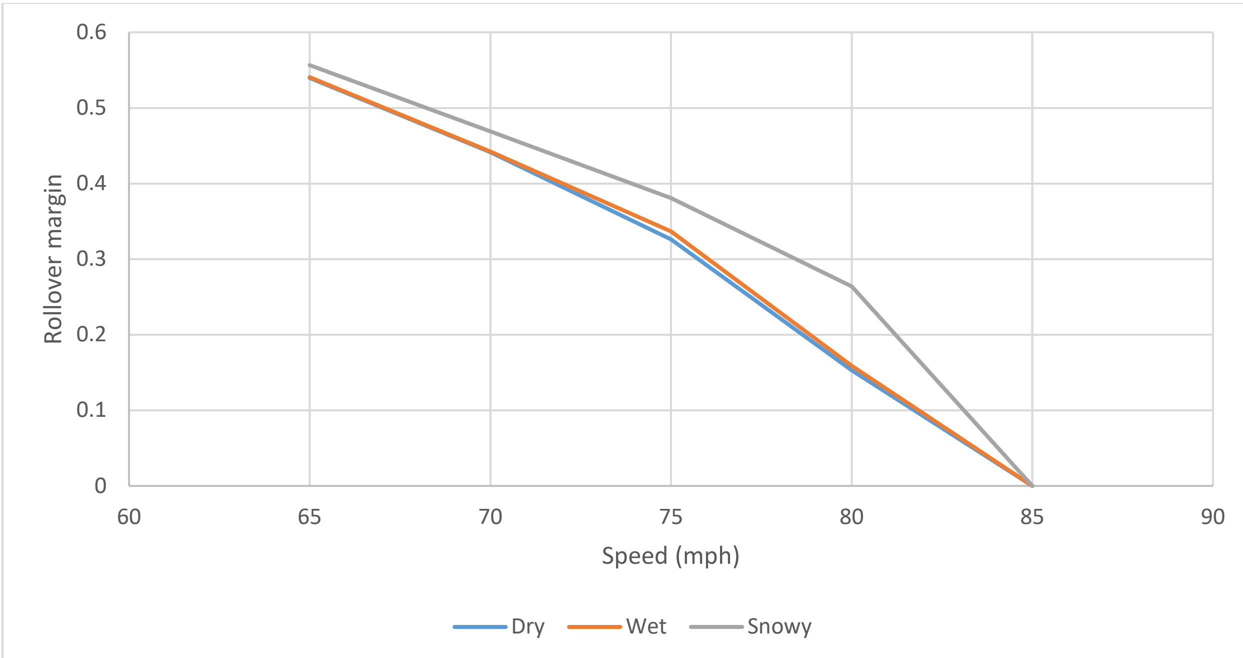


Figure 3.6 Impact of semi-trailer truck speeds on rollover margins by road surface condition

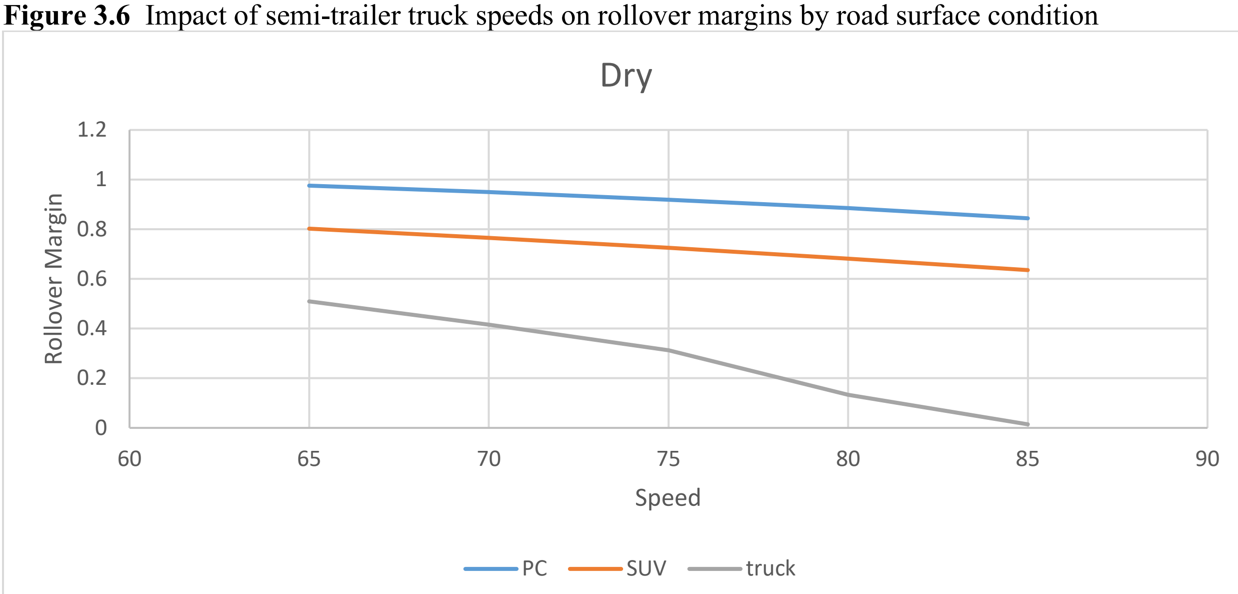
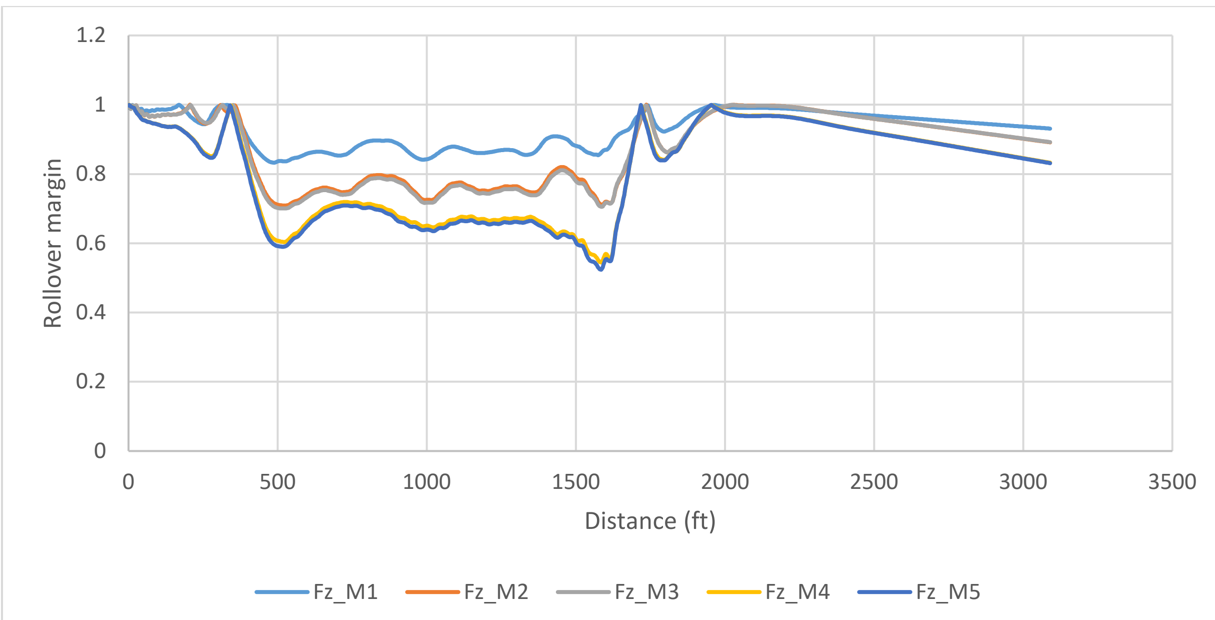


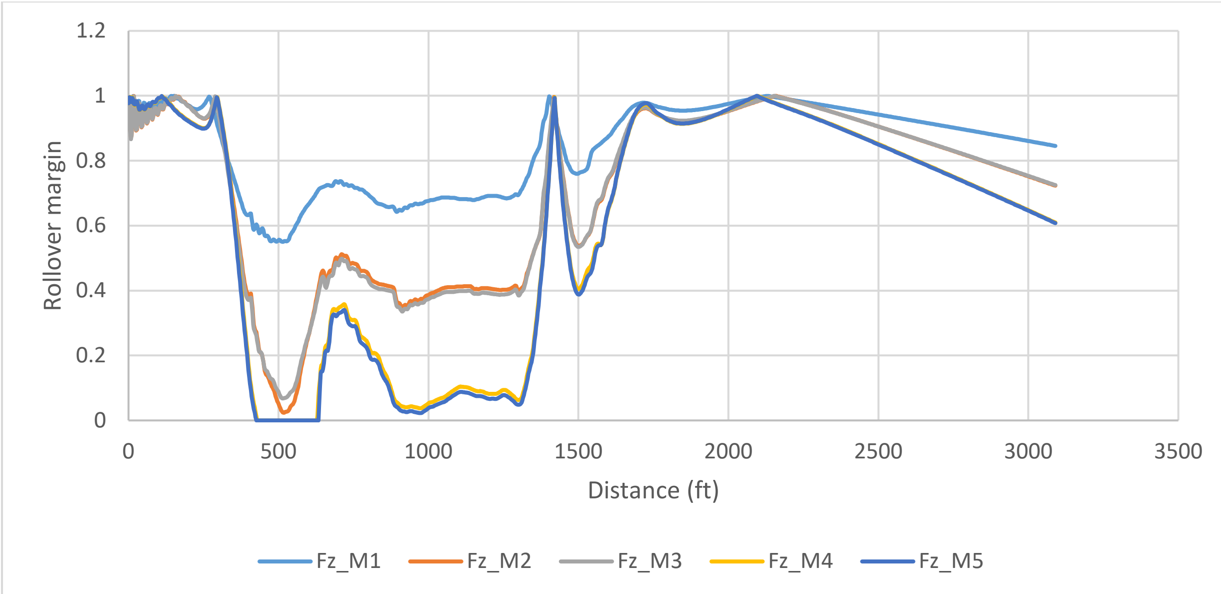
Figure 3.7 Impact of vehicle type on rollover margins

3.2.3 The Effect of the Vehicle Tires and Axles on Rollover Margins

Since the dynamic multibody model accounted for the variation of weight distribution and load transfer on each vehicle tire when cornering, it outperformed the other models, namely the point-mass model used by AASHTO. Similar to the SM section, the results show that the highest lateral acceleration occurred at the beginning of the curve as the most crash-prone part of the curve. More importantly, the results demonstrated that the rear axle experienced the highest lateral acceleration for all considered vehicle types. For trucks, the fifth axle experienced the lowest rollover margin due to the weight transfer between axles when traveling on combined curves. Also, the shifting in the mass center outside the curve gave rise to wheel lifting in the outside tires and caused vehicles to roll over in the outside direction of the curve (Alrejjal et al. 2021a). Figure 3.8 illustrates the RMs for trucks navigating moderate and sharp combined curves. As noticed, the rear two axles exceeded the rollover threshold, and wheel lifting occurred when negotiating the tight combined curve. The vertical loads were significantly transferred from the rear axle to the front axle and, consequently, the vertical forces acting on the rear axles were reduced, which led to a surge in the lateral acceleration on that axle. The weight transfer is greater in sharper curves and, therefore, drivers should be more cautious on these challenging alignments.



a) Rollover margin for each truck axle on a right-direction moderate curve



b) Rollover margin for each truck axle on a left-direction tight curve

Figure 3.8 Side friction factor for each truck axle with different curves (Fz_M1: front axle, Fz_M5: rear axle)

3.2.4 Multiple Regression Model

To further interpret the results from the simulation tests, a multiple regression model was developed to explore the relationship between RMs and several key factors. These factors were the vehicle and geometric design characteristics. All simulation tests were considered in the model where the rollover margin was the outcome. The predictors were the degree of curvature, grade (%), operating speeds (mph), Truck (yes=1, no=0) and SUV (yes=1, no=0), road surface condition (dry road surface condition was the reference), and brake application (yes=1, no=0). Table 3.6 illustrates the results of the model. Mixed results were obtained from the regression analyses. Six variables were found to be statistically significant at the 95th percentile confidence level. The regression analyses produced significant interactions between the variables, which are important to consider in the model. In terms of road surface conditions, the wet and icy road surfaces were not significant compared with the dry surface on roll stability. This is expected since dry roads required much more acting forces on tires than wet or icy road surface conditions. Also, superelevations were not significant. Several studies made the same inference—that the impact of superelevation has a minimum effect on roll stability on vehicles (Torbic et al., 2014; Varunjikar, 2011). This indication is important because superelevation is a critical factor responsible to counterbalance the centrifugal forces produced when cornering and thus preventing rollovers. This might be attributed to the problem in constructing these slopes and need to be modified. Trucks have the highest negative impact on the rollover margin among other considered vehicle types. Regarding brake application, the general tendency is positive on rollover margin because of the speed reduction resulting from brakes.

To calculate the marginal effect of the continuous factors, elasticity analysis was developed as shown in Table 3.7. The analysis indicates the average change in rollover margin due to a change in an explanatory variable. The binary variables were not considered in the elasticity analysis since this approach is only applied to continuous variables. The operating speed variable has the highest impact on the rollover margin and therefore assigning safe speed limits is essential in terms of vehicle stability. Furthermore, the rollover margin decreased by 4.6% when increasing the curvature degree by 10%. The results show that the impact of curvature degree is higher than grade values.

Table 3.6 Rollover margin multiple regression model results

Variable	Estimate	T Statistic	P-value
Constant	2.128	24.156	< 0.001
Degree of Curvature	-0.143	-15.890	< 0.001
Grade (%)	0.035	-4.098	< 0.001
Truck	-0.158	-4.070	< 0.001
SUV	-0.144	-6.170	0.001
Brake applications	0.064	-4.610	< 0.001
Operating Speed (*Mph*)	-0.011	-11.314	< 0.001
Truck*Curvature	-0.114	-10.109	0.002
SUV*Brake	-0.126	-4.223	< 0.001
Brake* Curvature	-0.022	-2.198	0.028
Model Fit Statistics			
Adjusted R-squared	**0.852**		
AIC	**-435.1**		
F-statistic	**207.9**		
P-value	**< 0.001**		

Table 3.7 Variable elasticity effects

Variable	Elasticity Effect
Degree of curvature	-0.457
Grade (%)	0.079
Operating Speed (*Mph*)	-1.310

Interesting inferences were drawn from the interaction effect between variables as they seem meaningful in this case. This leads to a better understanding of real-world rollover events. The interactions in the model were plotted by a special package in Rstudio software (Allaire, 2012). As shown in Figure 3.9, the interaction between SUVs and brake applications is significant. Though the model shows how significant it is to apply brakes while cornering, SUVs were more prone to rollover when applying brakes compared with other considered vehicles. This is because SUVs are characterized by a combination of a higher center of gravity compared with passenger cars and a lighter gross weight compared with large trucks. These two major features render SUVs to be more vulnerable to rollovers when braking. Also, the impact of brakes, as shown in Figure 3.10, is more critical when negotiating sharper curves. The available force in the lateral direction would be reduced when increasing the brake force, and the vertical loads would be greater and lead to wheel lifting. Therefore, it is recommended to install warning signs to advise using brakes carefully on sharp curves. The last interaction from the model in Figure 3.11 shows that when the degree of curvature increases, trucks, compared with other vehicles, are more susceptible to sharper curves. This is due to the increased developed lateral acceleration, which results when cornering, that decreases the rollover margin. The above implications show how the influences of the contributing factors vary according to various conditions. This fact was omitted in the literature, and this study filled this gap thoroughly. Previous research (McKnight and Bahouth, 2009) examined only the impact of different key factors contributing to rollovers in one direction and for specific situations, and then generalized these outcomes to all situations.

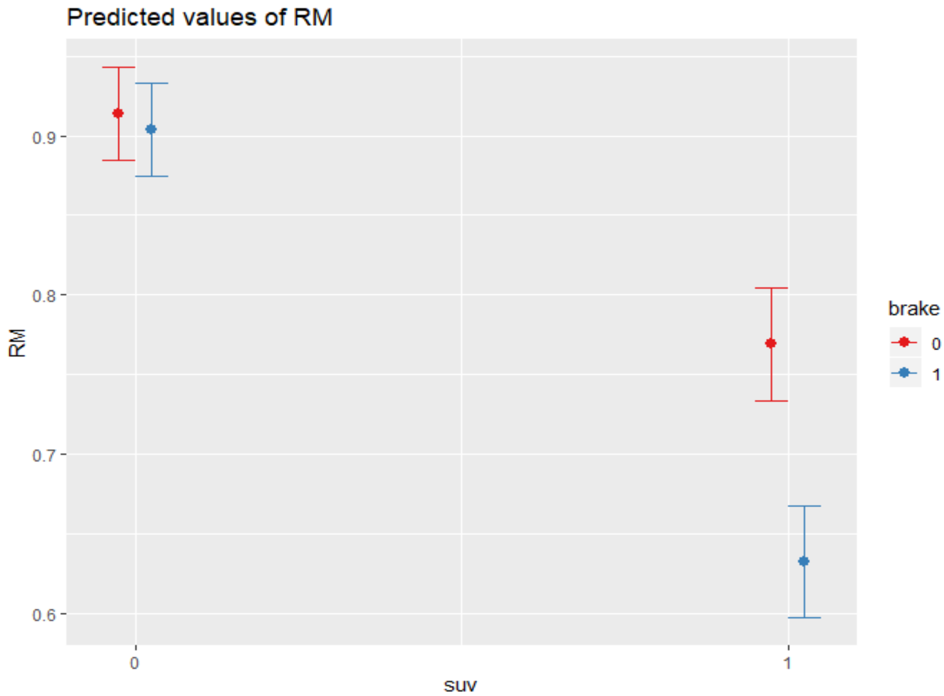


Figure 3.9 The interaction impact between SUV vehicle and brake application on rollover margin (RM: rollover margin)

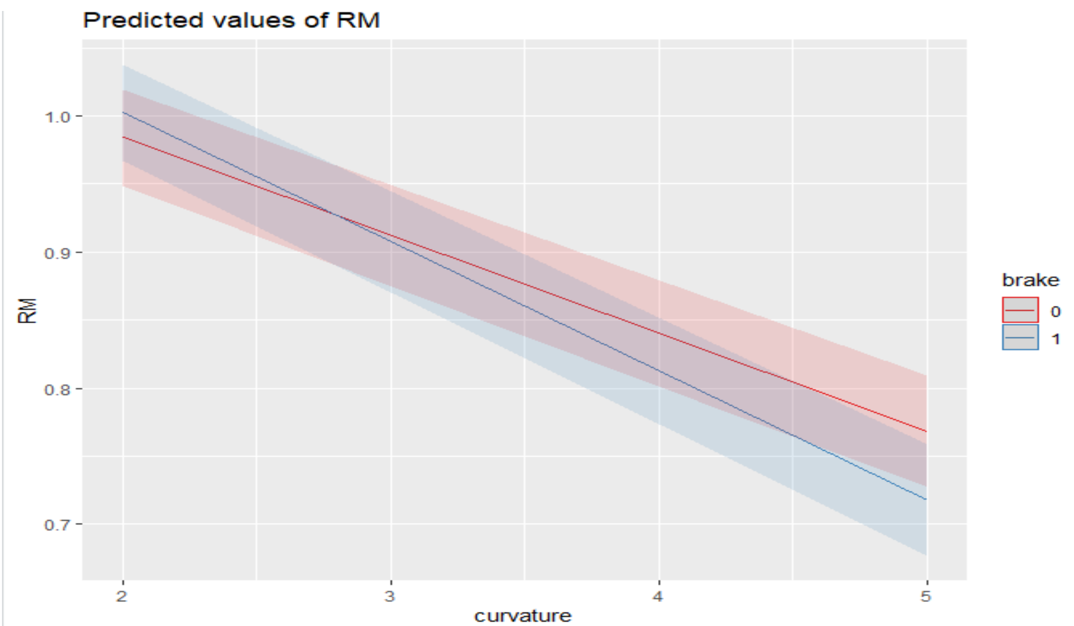


Figure 3.10 The impact of brake application on rollover margin for different degrees of curvature for SUV (RM: rollover margin)

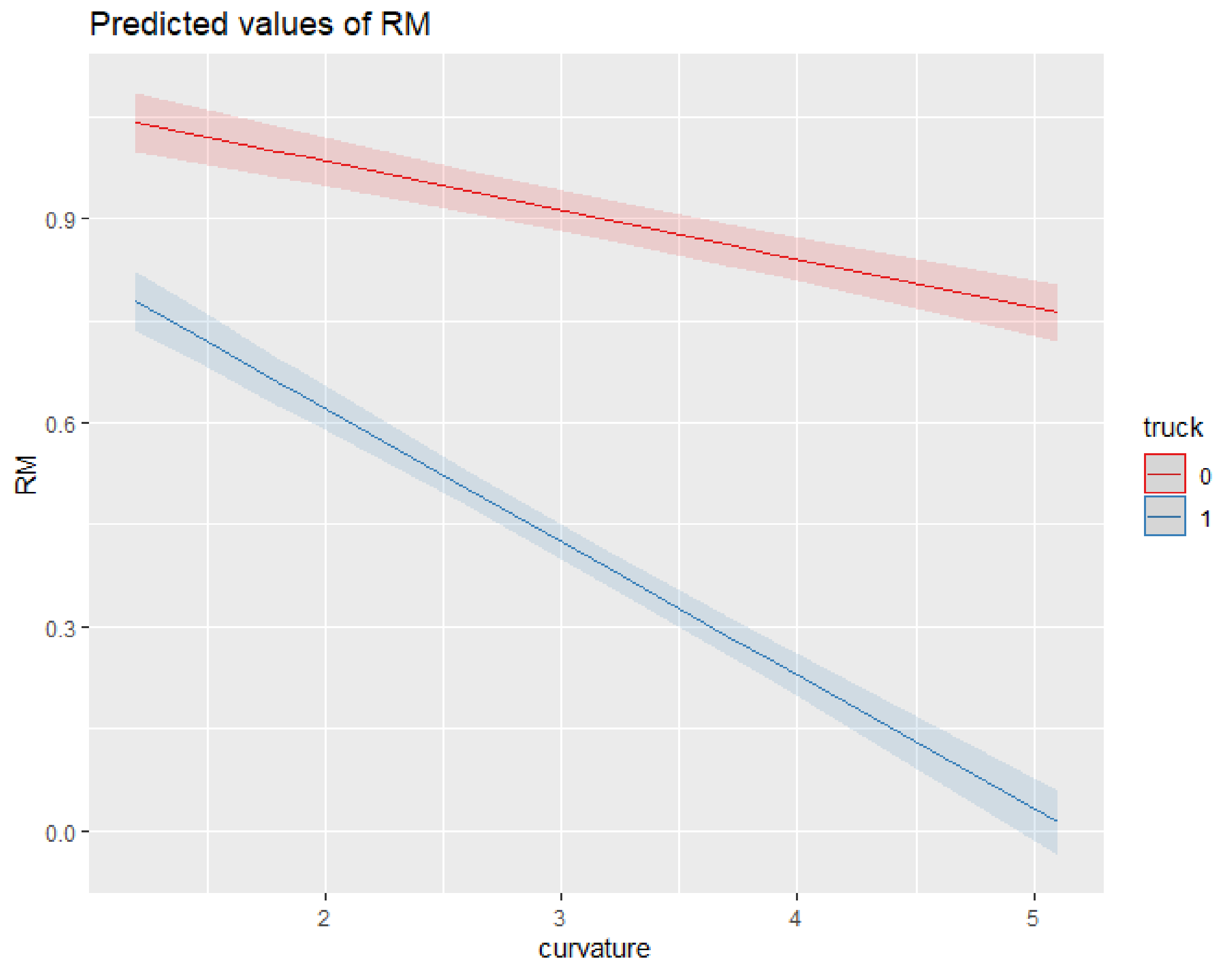


Figure 3.11 The interaction impact between the truck vehicle and different curvature degrees on rollover margin (RM: rollover margin)

3.2.5 Safety Assessment for Curve Speed Limits

A wide range of operating speeds associated with the speed limit were evaluated in terms of the RMs for three curve levels (least sharp, moderate sharpness, and sharp curves). The speed limit of these curves, labeled in red, is 75 mph. The rollover risk status is categorized by the literature into four categories: safe state when RM >= 0.4, warning state when RM is between 0.4 and 0.2, risky state when RM is between 0.2 and 0, and rollover state when RM=0 (Qu et al., 2018). The considered speeds are two higher operating speeds and two lower speeds (85 mph, 80 mph, 70 mph, and 65 mph). This would offer the appropriate speed limit of the curves. Table 3.8 displays the assessment results with the rollover risk status. The results show that in some cases the speed limit is not safe in terms of roll stability for trucks on sharp curves. More attention from transportation authorities is needed for these conditions by adjusting the speed limits according to the curve features and vehicle type.

Table 3.8 Speed limit assessment for three curves with 75-mph speed limit

Vehicle type	Curve type	Degree of curvature	Downgrade (units)	Speed, mph	Rollover safety margin	Rollover risk
Passenger car	Least sharp curve	1.5	-2.3	65	0.959	Safe
				70	0.95	Safe
				75	0.942	Safe
				80	0.924	Safe
				85	0.905	Safe
	Moderate sharpness curve	2.6	-4.6	65	0.937	Safe
				70	0.922	Safe
				75	0.902	Safe
				80	0.88	Safe
				85	0.849	Safe
	Sharp curve	5.9	-5.4	65	0.798	Safe
				70	0.759	Safe
				75	0.72	Safe
				80	0.679	Safe
				85	0.637	Safe
SUV	least sharpness curve	1.5	-2.3	65	0.937	Safe
				70	0.924	Safe
				75	0.909	Safe
				80	0.822	Safe
				85	0.711	Safe
	Moderate sharpness curve	2.6	-4.6	65	0.859	Safe
				70	0.846	Safe
				75	0.82	Safe
				80	0.782	Safe
				85	0.743	Safe
	Sharp curve	5.9	-5.4	65	0.691	Safe
				70	0.638	Safe
				75	0.582	Safe
				80	0.523	Safe
				85	0.457	Safe
Truck	least sharpness curve	1.5	-2.3	65	0.875	Safe
				70	0.843	Safe
				75	0.814	Safe
				80	0.757	Safe
				85	0.698	Safe
	Moderate sharpness curve	2.6	-4.6	65	0.771	Safe
				70	0.69	Safe
				75	0.592	Safe
				80	0.483	Safe
				85	0.369	Warning
	Sharp curve	5.9	-5.4	65	0.093	Risky
				70	0	Rollover
				75	0	Rollover
				80	0	Rollover
				85	0	Rollover

4. IMPACT OF TRUCK CONFIGURATION ON ROLLOVER PROPENSITY

Trucks are complex vehicles that consist of several correlated parameters and have an interactive impact on truck stability when cornering. Namely, payload weight and height of the truckload change the weight distribution and lateral acceleration acting on tires. Omitting one of these significant factors when investigating truck roll stability may not capture the hazardous situations on truck safety. Due to issues associated with data availability, examining the impact of these parameters accurately is challenging. Particularly, variables related to different payload weights and CG payload heights are not stated in the rollover crash report, and it is costly to investigate their impact via field tests. Most of the previous literature could not investigate the impact of these parameters on the roll stability of trucks when cornering. Instead, the high-fidelity vehicle dynamic simulation modeling approach that represents the truck response to the payload weight and height, speed, and geometric conditions would be more appropriate. In this section, the speed limits of the curved roadways are evaluated with respect to the truck roll stability, including critical combined curves and truck characteristics and configurations. Thus, this would release the point mass model restrictions.

The same curves were considered in the simulation tests. Regarding the gross weight of the truck and the height of the center of gravity (CG) of truckloads, various values were included based on the previous test field. The baseline condition for the CG height of the payload is 83.5 inches and then the next height, which is the mid-height, is 95 inches. The upper limit of the CG payload height is 105 inches from the ground, which represents the full-cube loading condition. These heights were the critical limits from R. Ervin (1983), who conducted multiple field studies on truck stability. For each CG height, a variation of load weight was considered (five categories) starting with an empty payload state (almost 27,000-lb. gross weight) until reaching the maximum allowable gross weight in Wyoming (80,000 lbs.). The TruckSim package has the ability to redistribute the load for the load-bed (trailer box) based on the variation in the payload weight and size. The methodology chart shows all considered gross weights.

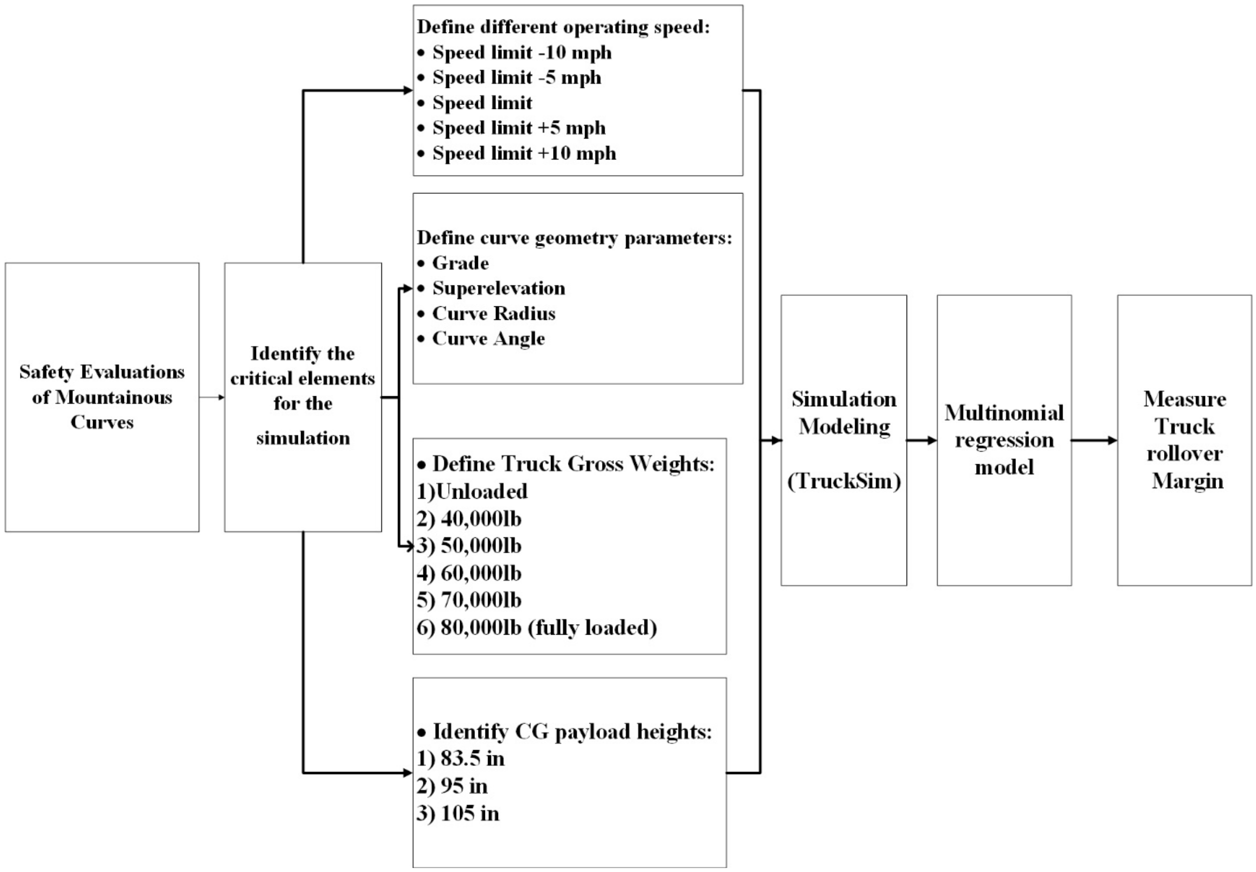


Figure 4.1 Study methodology

With 12 curves, 6 gross weights, 3 CG payload heights and 5 different operating speeds, a total of (12*6*3*5) = 1,080 scenarios were conducted in this section.

4.1 The Impact of Different Operating Speeds, Gross Weight, and Curve Characteristics on Rollover Margins

The results from TruckSim software show a variation in the rollover margins (RMs) for different truck gross weights at various operating speeds. Figures 4.2 and 4.3 illustrate this impact for moderate and sharp curves, respectively. Many conclusions can be drawn from the plots. Increasing the operating speed significantly reduces the rollover margin, and this impact is amplified with higher truck weights. Speedy drivers with high-weight trucks would be riskier since the weight transfer when cornering is greater and affects the roll stability of trucks. Therefore, safe speed limits should be assigned according to the truck configurations. For sharper curves and steeper downgrades, it was found that the higher operating speeds coupled with heavier trucks would be more dangerous. As noticed from the plots, trucks reached zero rollover margin, although the operating speed is at the current speed limit in the case of high-loaded trucks. Usually, trucks need a longer time to reduce their speeds on sharper curves with steeper downgrades (Tarko et al., 2016). Therefore, the truck driver does not have enough time to accommodate the truck speed under the prevailing conditions and consequently would lose control of the truck and roll over.

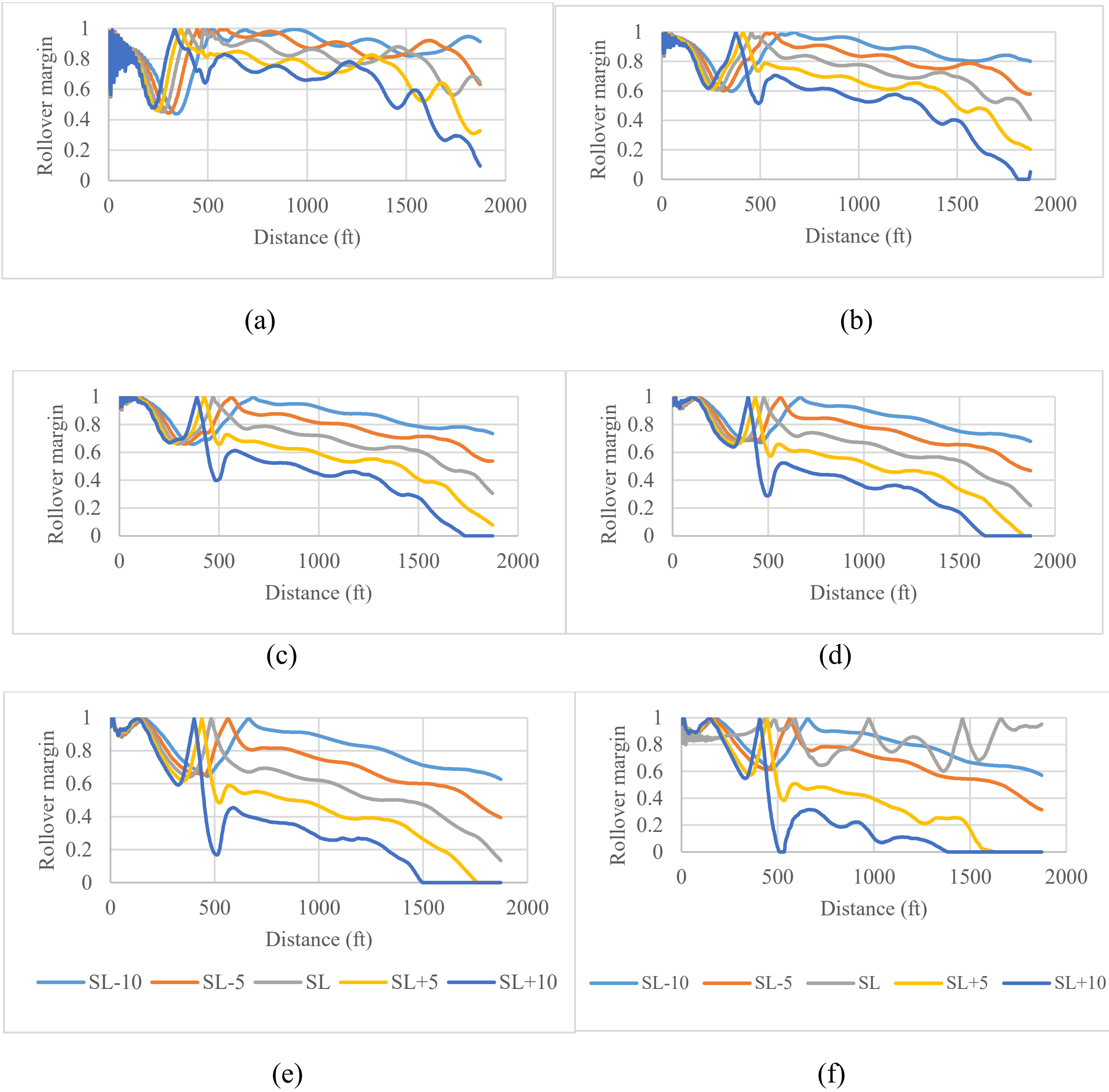


Figure 4.2 Rollover margins for different operating speeds (SL=speed limit) and different truck gross weights on a moderate curve (a–unloaded weight, b–40,000 lb, c–50,000 lb, d–60,000 lb, e–70,000 lb,f–80,000 lb)

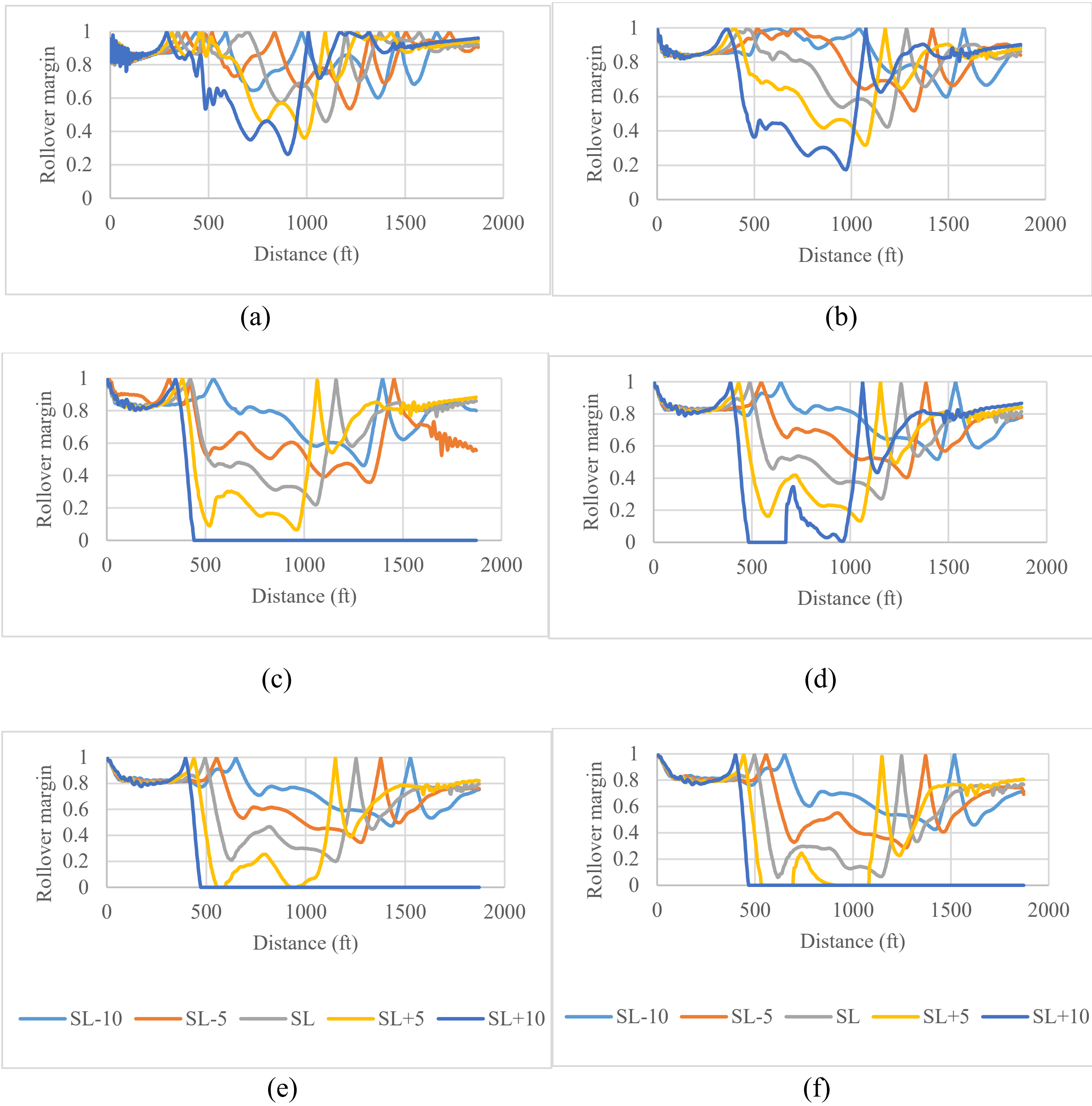


Figure 4.3 Rollover margins for different operating speeds (SL=speed limit) and different truck gross weights on a sharp curve (a–unloaded weight, b–40,000 lb, c–50,000 lb, d–60,000 lb, e–70,000 lb, f–80,000 lb)

4.2 The Impact of CG Height Payload for Different Grade Categories

The simulation outcomes in Figure 4.4 illustrate that the CG height of the truck payload significantly affects the rollover margin. Trucks with higher CG payload height are more likely to roll over since the rollover threshold is lower for higher CG payload (You et al., 2012). Considering different levels of downgrades provided critical insights into how the effect of CG height changes according to the degree of downgrade of the curve. It was indicated that steeper downgrades amplify the impact of the CG height of the truckloads. This is due to the accuracy of the simulation package to capture the weight transfer from the rear axle to the front one when having steeper profiles as shown in Figure 4.5. Simple models, such as the mass-point model adopted by AASHTO (The American Association of State Highways and Transportation Officials (AASHTO) (2011b) to assign speed limits based on the curve radius formula, cannot address this complicated behavior of trucks that are concurrently affected by a combination of several significant factors.

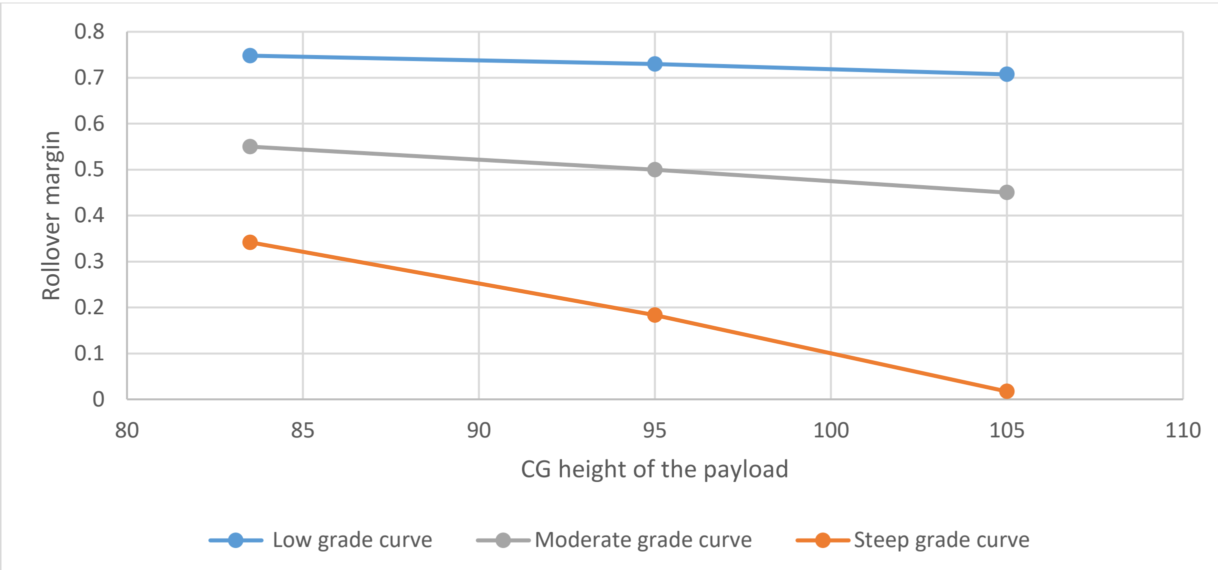


Figure 4.4 Rollover margin for different downgrades along with CG height values of payload

4.3 Multiple Regression Model Results

A multiple regression model was developed to quantify the impact of all considered factors on rollover margin and capture any potential interactions between them. Since the response variable (rollover margin) is a continuous variable between zero and one, this approach is suitable to fit the test data. The predictors were the speed, payload weight, payload CG height, grade, curve radius, superelevation, and curve angle. Table 4.1 illustrates the results of the model. The regression analysis yielded significant interactions between the variables, which are important to consider in the model to better understand the realistic truck performance when cornering. The parameters were interpreted from the models assuming all else was controlled. Table 4.2 presents the elasticity values of the parameters to examine the relative effects of the variables considered in the model. All considered variables were found to be statistically significant at the 95^{th} percentile confidence level except superelevation. Similar to the previous sections, superelevation was statistically insignificant on the rollover margin model. Grade and degree of curvature were found to contribute to the rollover margin. Generally speaking, positive grade values infer upgrades and negative values indicate downgrades. The positive sign of the grade parameter in the model indicates that steeper downgrades (smaller grade values due to the negative sign of downgrade) would decrease the rollover safety margin. The truck rollover safety margins would decrease for sharper curves and steeper downgrades. A decrease of 7.6% in the safety margin of rollover occurs when the grade profile reduces (the downgrade is getting steeper) by 10%. Similarly, the elasticity effects illustrate that the rollover margin increases by almost 5% when increasing the radius of the curve by 10%. The slightly higher impact of the grade might be attributed to the fact that downgrade alignment is usually associated with shifting in the CG position and with higher speeds (Montella et al., 2014). The curve angle is negatively associated with the rollover risk margin. This is because of the inverse relationship between curve radius and angle through the curve design process (Fildes and Triggs, 1985). Decreased curve angles come with flattening curves and therefore are safer curves against truck rollover events.

Among all considered variables, the elasticity analysis showed that the rollover margin is the most vulnerable to the operating speed variable and CG height. An increase of 1% in the operating speed and CG height decreases the rollover risk margin by 2.03% and 2.72%, respectively. Regarding the impact of truck gross weight, the truck rollover risk margin would decrease by 4.9% when increasing the truck weight by 10%. Generally, these results confirm previous studies (R. D. Ervin, 1983; Lemp et al., 2011; You et al., 2012). However, these studies could not provide the quantitative impact of these parameters on truck stability. Furthermore, they ignored the interactive effect of these factors, and this study showed the importance of including all factors and their interactions.

Table 4.1 Rollover margins' multiple regression model results

Variable	**Estimate**	**T Statistic**	**P-value**
Constant	2.049	21.442	< 0.001
Curve Angle (Degree)	-0.0049	-16.256	< 0.001
Grade (%)	0.050	3.789	< 0.001
Curve Radius (ft)	$1.258*10^{-4}$	-2.618	0.009
Truck gross weight (lb)	$-2.401*10^{-6}$	-3.223	0.001
Center of gravity CG height (inch)	-0.0086	-11.096	< 0.001
Operating Speed (*Mph*)	-0.0117	-31.545	< 0.001
Grade*Radius	$3.943*10^{-6}$	6.169	< 0.001
Grade*Weight	$5.004*10^{-7}$	3.272	0.001
CG *Radius	$1.417*10^{-6}$	2.945	0.003
Model Fit Statistics			
Adjusted R-squared	**0.894**		
AIC	**-806.122**		
P-value	**< 0.001**		

Table 4.2 Variable elasticity effects

Variable	**Elasticity Effect**
Curve Angle (Degree)	-1.035
Grade (%)	0.766
Curve Radius (ft)	0.497
Truck gross weight (lb)	-0.426
Center of gravity CG height (ft)	-2.718
Operating Speed (*Mph*)	-2.030

4.3.1 Interaction Effects in the Model

The interactions in the model were plotted by a special package in the Rstudio software. There is a significant interaction between curve radius and CG payload height as shown in Figure 4.6. The impact of CG height variations is more significant for sharper curves (radius less than 2,000 ft.), and the combination of high CGs with lower curve radius would be more hazardous in regard to roll stability. The interaction between the curve radius and the gross weight of trucks displayed the same tendency as shown in Figure 4.7. Furthermore, the interaction between downgrades and the gross weights is significant. As shown in Figure 4.8, the probability of rollover occurrence increases on steeper downgrades for heavier trucks. This is attributed to the higher weight transfer between the rear axles and the front ones that surges the lateral acceleration and therefore decreases the rollover margin.

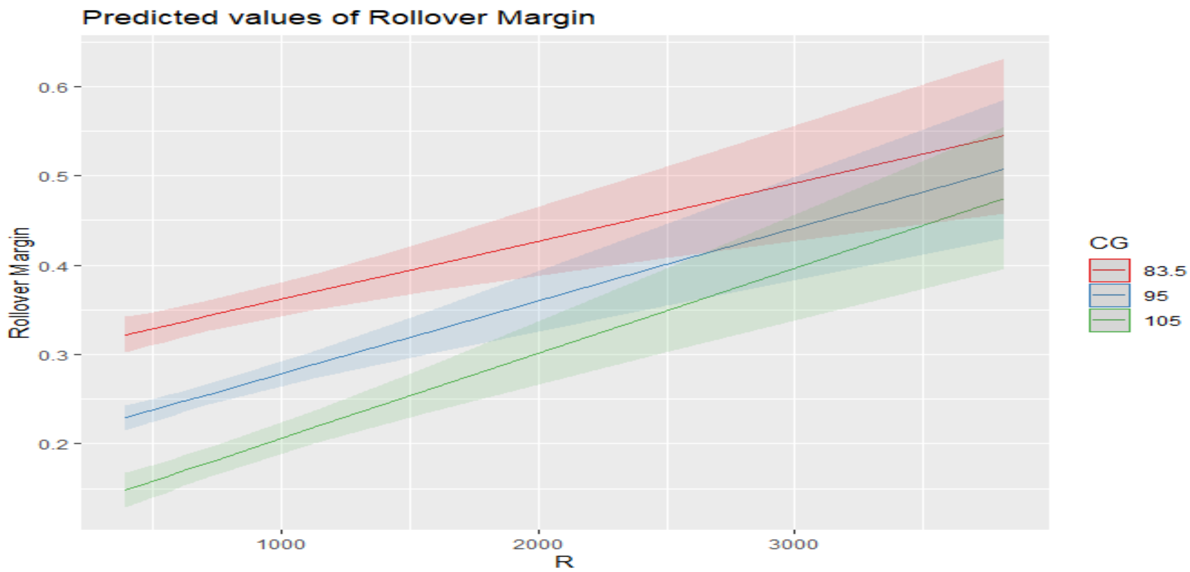


Figure 4.5 Rollover margin for different CG heights of payload with curve radius values

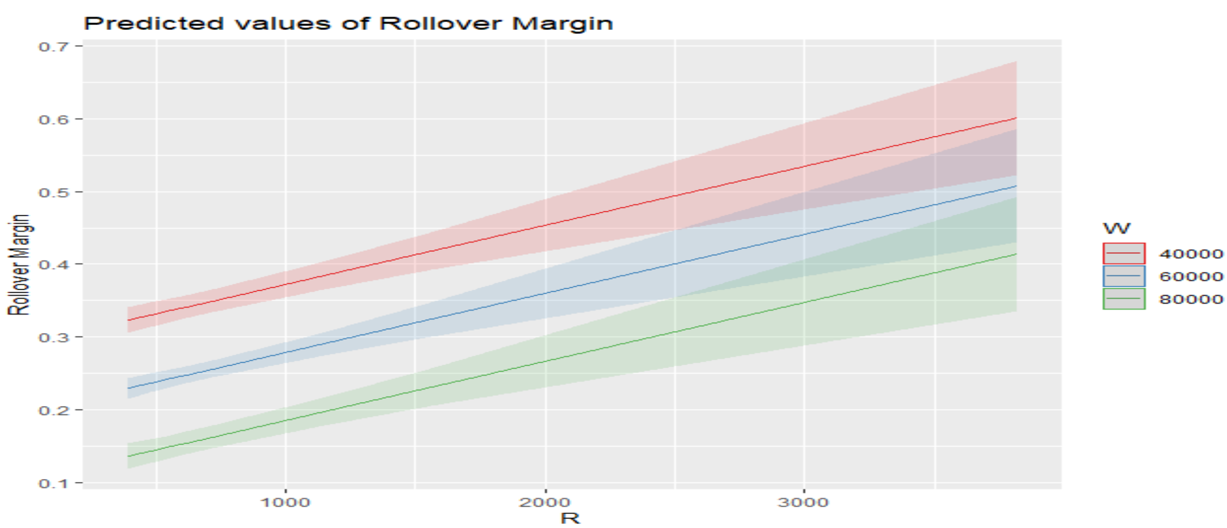


Figure 4.6 Rollover margin for different truck gross weights along with curve radius values

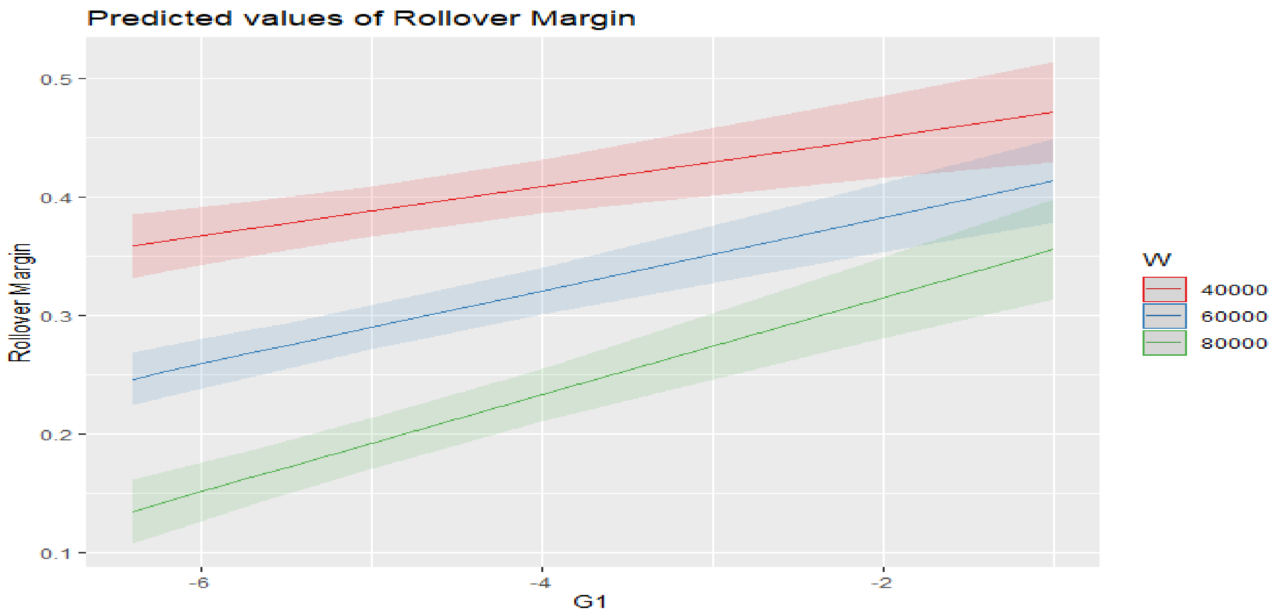


Figure 4.7 Rollover margin for different truck gross weights along with grade values

4.4 Truck Operating Safety Assessment

A truck roll stability assessment was conducted for moderate and sharp curves with a 75-mph speed limit. Two operating speeds (70 mph and 65 mph), in addition to the speed limits, were considered to evaluate the appropriateness of the assigned speed limits of the curves. The assessment covered all considered truck gross weights and CG heights. Table 4.3 shows the operating safety assessment for trucks. The results show that, in some cases, complying with the speed limit is not enough to avoid roll stability problems; therefore, these current speed limits should be modified accordingly.

Table 4.3 The rollover margin for two of the selected curves (moderate and sharp curves) with a 75-mph speed limit

Curve type	Radius (ft)	Angle (degree)	Grade (%)	CG (in)	Weight (klb)	Speed (mph)	Rollover Margin	Rollover risk
Moderate curve	3820	58	-2.1	83.5	40000	65	0.782	Safe
				83.5	40000	70	0.707	Safe
				83.5	40000	75	0.633	Moderate
				83.5	60000	65	0.821	Safe
				83.5	60000	70	0.748	Safe
				83.5	60000	75	0.672	Moderate
				83.5	80000	65	0.832	Safe
				83.5	80000	70	0.763	Safe
				83.5	80000	75	0.694	Moderate
				95	40000	65	0.771	Safe
				95	40000	70	0.687	Moderate
				95	40000	75	0.605	Moderate
				95	60000	65	0.808	Safe
				95	60000	70	0.730	Safe
				95	60000	75	0.648	Moderate
				95	80000	65	0.807	Safe
				95	80000	70	0.724	Safe
				95	80000	75	0.645	Moderate

Curve type	**Radius (ft)**	**Angle (degree)**	**Grade (%)**	**CG (in)**	**Weight (klb)**	**Speed (mph)**	**Rollover Margin**	**Rollover risk**
				105	40000	65	0.765	Safe
				105	40000	70	0.676	Moderate
				105	40000	75	0.585	Moderate
				105	60000	65	0.792	Safe
				105	60000	70	0.707	Safe
				105	60000	75	0.618	Moderate
				105	80000	65	0.785	Safe
				105	80000	70	0.691	Moderate
				105	80000	75	0.597	Moderate
Sharp Curve	1128	59.08	-5.5	83.5	40000	65	0.408	risky
				83.5	40000	70	0.311	risky
				83.5	40000	75	0.232	risky
				83.5	60000	65	0.302	risky
				83.5	60000	70	0.172	risky
				83.5	60000	75	0.083	Very risky
				83.5	80000	65	0.186	Very risky
				83.5	80000	70	0.019	Very risky
				83.5	80000	75	0.000	Rollover
				95	40000	65	0.369	risky
				95	40000	70	0.267	risky
				95	40000	75	0.189	Very risky
				95	60000	65	0.205	risky
				95	60000	70	0.088	Very risky
				95	60000	75	0.000	Rollover
				95	80000	65	0.000	Rollover
				95	80000	70	0.000	Rollover
				95	80000	75	0.000	Rollover
				105	40000	65	0.338	risky
				105	40000	70	0.233	risky
				105	40000	75	0.157	Very risky
				105	60000	65	0.135	Very risky
				105	60000	70	0.017	Very risky
				105	60000	75	0.000	Rollover
				105	80000	65	0.000	Rollover
				105	80000	70	0.000	Rollover
				105	80000	75	0.000	Rollover

5. IMPACT OF CROSSWINDS ON ROLLOVER PROPENSITY

5.1 Simulation Process

In addition to the challenging mountainous terrain, severe crosswinds are common on Wyoming's roadways. This increases the risk while driving on these roadways. The roll stability of freight trucks in these challenging conditions (geometric and environmental conditions) is of great concern for transportation officials and safety researchers due to the increased risks of rollover crashes. The crosswind effect acts as an additional force with the centrifugal forces on the truck roll stability if the wind is blowing toward the outer direction of the combined curve. Designing such alignment with the appropriate design speed is challenging due to many complex components that ought to be considered, such as challenging terrain and adverse weather conditions. Therefore, there is a critical need for an advanced approach to assigning safe speed limits to account for the combined impact on the roll stability of trucks when cornering. Moreover, there is a dearth of research to investigate the crosswind impact accurately to reflect the real-world scenarios and draw comprehensive conclusions related to truck roll stability.

Table 5.1 Geometric features of the selected interstate curves

Interstate Curve	Deflection Angle (°)	Radius (ft)	Degree of Curvature	Maximum Grade (%)	Superelevation on Average (%)
1	58.00	3,820	1.5	-2.3	2.22
2	36.11	4,587	1.2	-3.3	3.61
3	36.8	2,214	2.6	-4.6	6.13
4	42.09	1,562	3.7	-2.5	6.08
5	59.08	1,128	5.1	-5.6	6.55
6	45.49	976	5.9	-5.4	5.39

In this study, high-fidelity vehicle dynamic simulation modeling was used to investigate vehicle maneuvering through several combined curves in Wyoming interstates under various crosswind conditions. Six curves on Interstate 80 were selected among the most hazardous curves that were previously selected. Table 5.1 shows the selected curves with their geometric features. All of them are located on I-80 at the same roadway direction. The wind parameters (speed, direction) are relatively well known on this interstate. It is critical to select wind parameters (speed and direction) in the simulation tests that reflect real-world scenarios. The wind parameter values (speed and direction) in this study were considered according to the available wind data for the last three years from the Meteorological Assimilation Data Ingest System (MADIS). MADIS is a meteorological observational database and data delivery system that provides weather observations. The data are available through Iowa Environmental Masonite (IEM) website via the link: https://mesonet.agron.iastate.edu/request/rwis/fe.phtml. It shows the observing stations located along major roads in Wyoming. It can be noticed that due to the higher number of stations along I-80, the wind data would be accurate and their values reflect the wind conditions on the selected curves. Based on the dominant speed and directions for the last five years on I-80, the values of the wind parameters were included. The wind data show that during the winter season the dominant wind speeds vary from 10 to 30 mph as shown in Figure 5.1. However, it was observed that 10 mph has a minimal impact on truck roll stability in the simulation tests and therefore it was excluded. Further, a previous field study stated that the wind speeds reach 30 to 40 mph in Wyoming for frequent periods (Young et al., 2010), and to account for the worst cases of the wind impact of 40 mph is included in the simulation tests. In total, three wind speeds were included: 20, 30, and 40 mph.

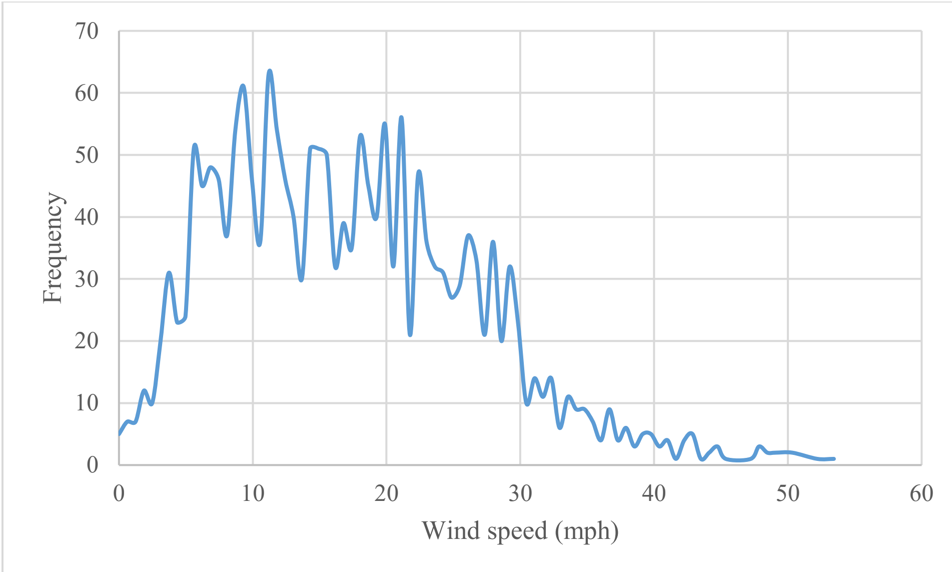


Figure 5.1 Frequency periods of the wind speeds on I-80 for the last three years in the winter season

For the dominant directions of the wind, the wind data show the most frequent wind directions on I-80 for the last three years vary between 240^0 (-60^0) and $300^0(-120^0)$. Figure 5.2 presents these directions with their corresponding frequencies. These inferences are supported by a previous study conducted in Wyoming by using historical data in Wyoming for 34 years (Ohara et. al, 2017). Considering all wind directions is critical for the roll stability evaluation since it was reported that the most vulnerable wind direction is not always 90 degrees. This is because the truck is also subject to its speed, and effective wind direction defers when there is a curve. The headwind directions were excluded since the driving speed decreases in this situation; thus, the probability of rollover is reduced when the wind is blowing toward the front of the vehicle (Young et al., 2005).

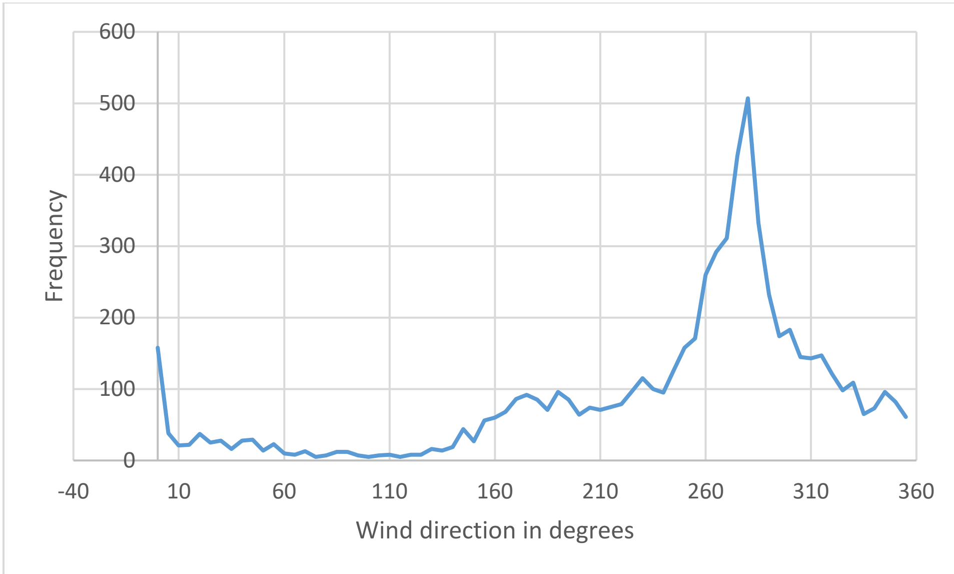
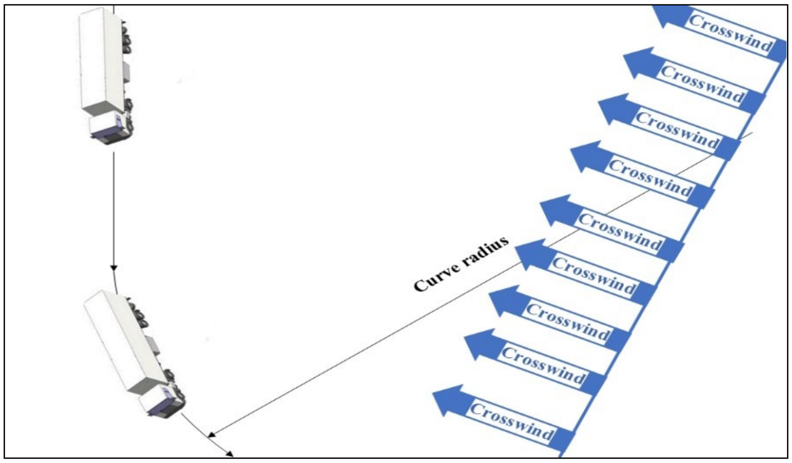
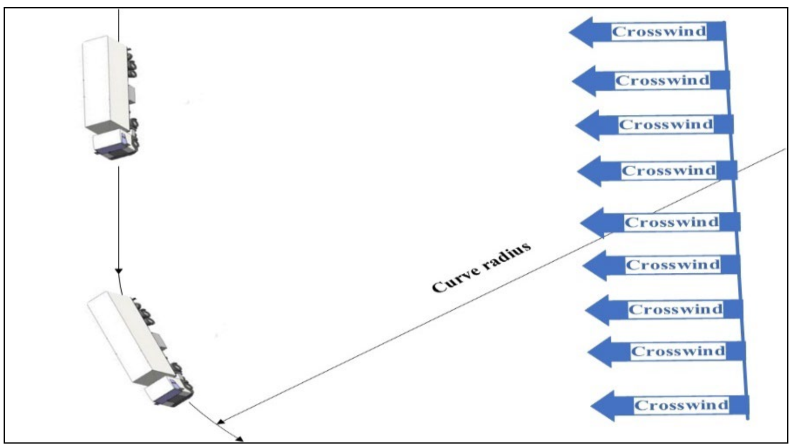


Figure 5.2 Frequency periods of the wind directions on I-80 for the last three years in the winter season

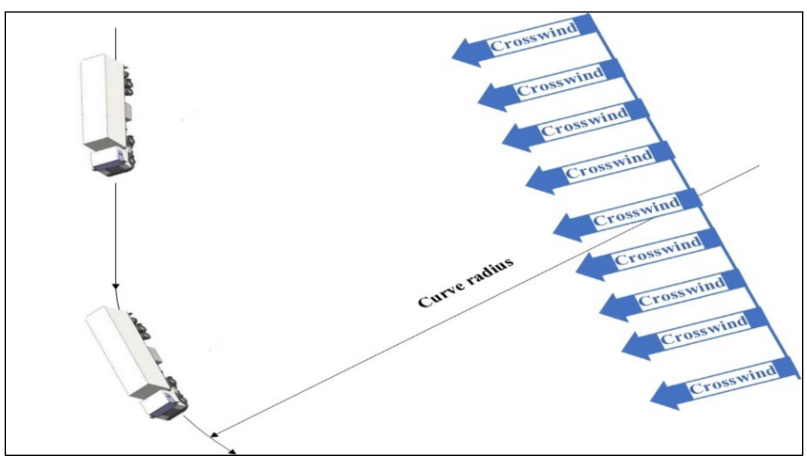
Furthermore, these curves are located in a position that has the blowing directions coming from the inside of the curve to the outer direction of the curve. This may provide an additional force with the centrifugal force that increases the rollover forces. This case represents a worst-case scenario compared with having winds blowing in the opposite direction that help keep the truck from overturning (Balsom et al., 2006). Figure 5.3 shows the considered wind directions when a truck is traveling on a curve. It is clear that the effective angle between roadway and truck changes continuously when traversing from the straight alignment to the curved section.



(a)



(b)



(c)

Figure 5.3 The considered crosswind directions in the study on the truck while cornering for the three directions; (a) 60^0crosswind, (b) 90^0crosswind, (c) 120^0crosswind

In addition to the wind parameters, the same truck configurations and operating speeds used in the previous section were included in the simulation tests. In total, the study comprised a matrix of 1,296 simulation tests to include all considered factors in the study. The combinations consist of (6 curves)*(6 gross weights)*(3 wind speeds)*(3 wind directions)*(4 different operating speeds)=6*6*3*3*4=1,296 scenarios. Figure 5.4 demonstrates the general simulation process.

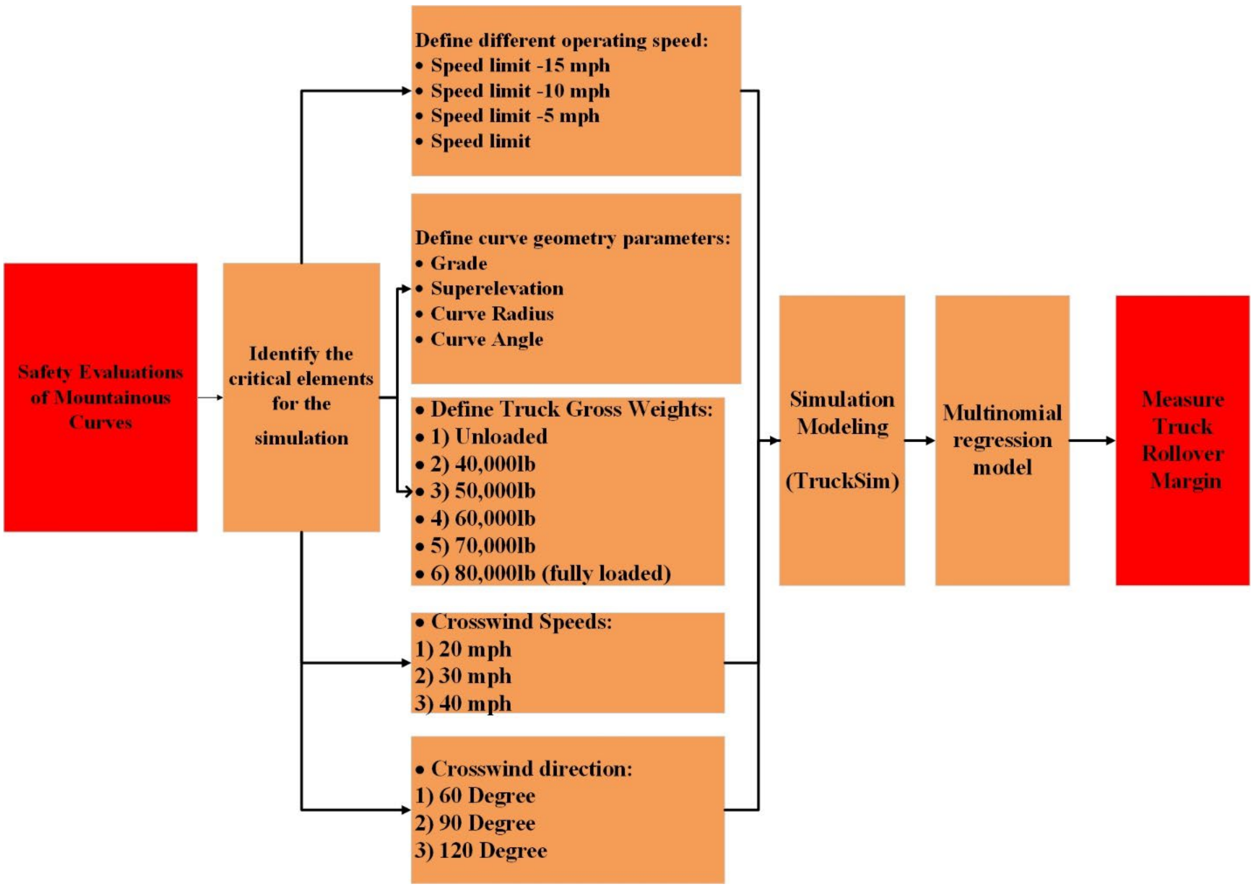


Figure 5.4 Study methodology

5.2 Analysis, Results, and Discussion

5.2.1 Wind Speed Effect

Rollover margins (RMs) were calculated for all tests including all inputs. Regarding wind speed impact, Figure 5.5 shows that the wind speed indicator is correlated to rollover margin, and when the wind speed rises and reaches 40 mph, the RMs drastically plummet. Regarding the truckload effect, the simulation outcomes reported that roll stability is affected by the truck weights. Generally, lighter trucks are more vulnerable to rollover than heavy trucks. When the wind speed is 20 mph, the rollover margin for an empty truck was almost 0.5 and dropped to 0.12 for a 40-mph wind speed. In this case, the probability of having a rollover increased by 76%. This is attributed to the fact that aerodynamic forces give a rollover moment greater than the restoring moment provided from the weight (gravity forces) (Young et al., 2010). Therefore, the higher influence of the aerodynamic loads is against trucks when the vertical loads on the tires resulting from the truck weight are minimal (Batista and Perkovič, 2014).

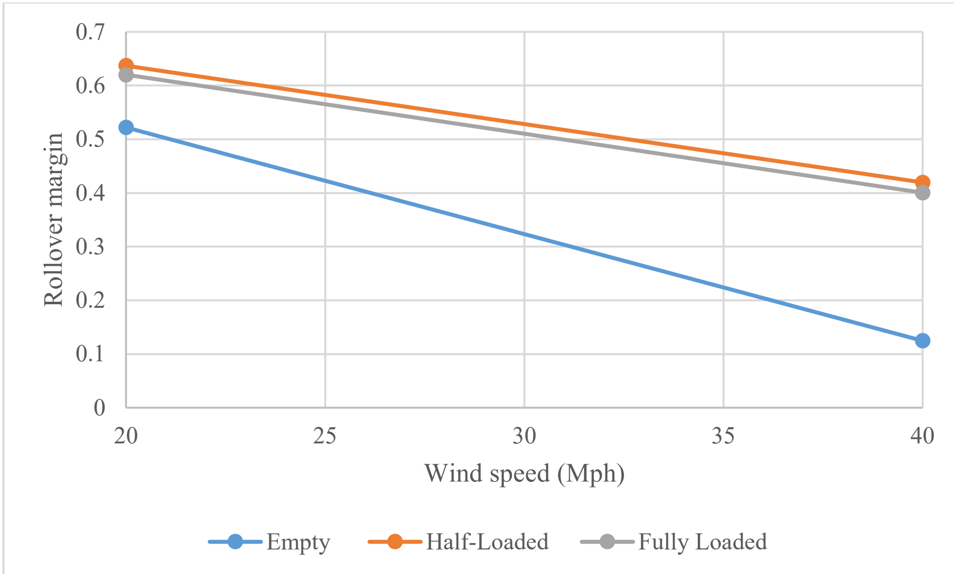
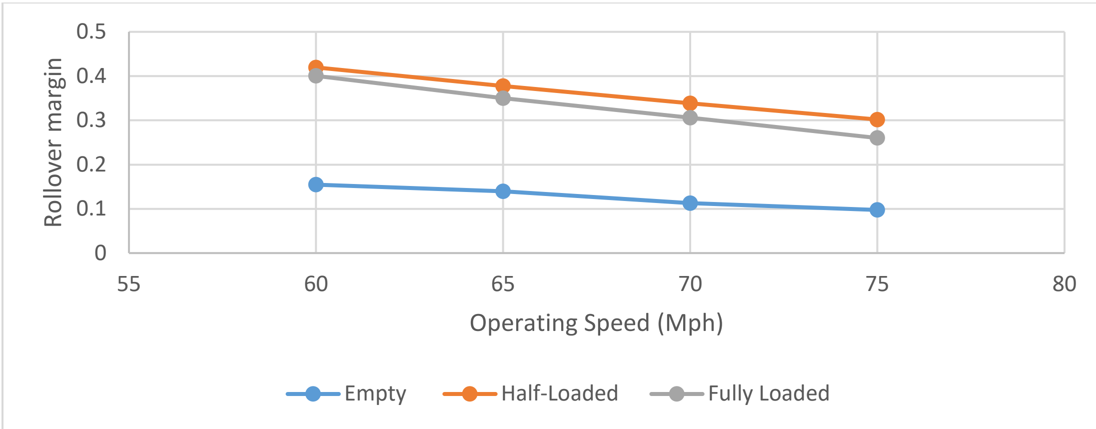


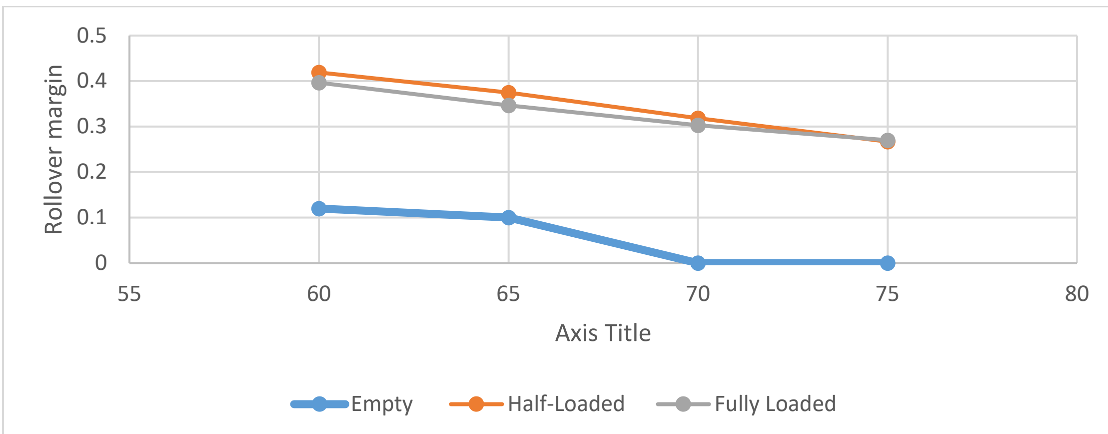
Figure 5.5 Rollover margins for different truckload conditions under various wind speeds

5.2.2 The Impact of Truck Gross Weights Along with Different Curve Features

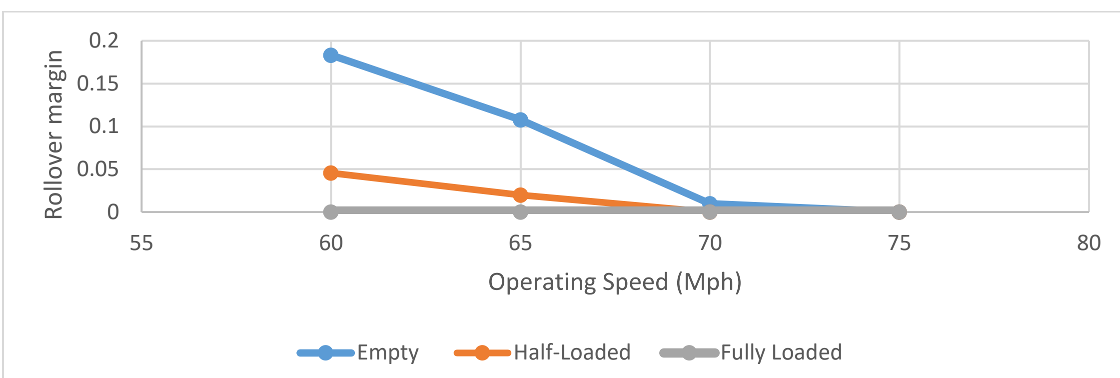
Prominent indications were obtained from the interactive effect between truckloads and the effect of curve geometry when a crosswind is blowing. As the curve radius is high, the weight transfer between axles was minimal and thus the dominant force on roll stability is the wind load. In this case, the empty truck condition is more vulnerable to the wind effect shown in Figure 5.6 (a). This inference confirmed with most of the literature that examined only one state of truckloads when blowing crosswinds. For the moderately sharp curve, the same tendency was obtained; however, the RMs are much lower as shown in Figure 5.6 (b). It was noticed that decreasing the empty truck speed by 5 mph with regards to the speed limit of the curve is still unsafe to avoid rollover events. A previous study reported that overturning crashes are most likely to happen when the wind speed is over 45 mph (Young et al., 2010). This study demonstrated that trucks may roll over for wind speeds less than 40 mph. A contradictory trend was observed in the case of a sharp combined curve. Figure 5.6 (c) shows that the fully-loaded truck in this case is more vulnerable compared with other truckload states to roll over when severe winds are blowing while traversing sharp curves. This is because the impact of the weight transfer resulting from these curves is greater than the restoring weight forces and the truckload impact. Young et al. (2005) reported that the critical wind speed in Wyoming is 40 mph for empty trucks and 60 mph for all other truckload states. This trend is not always correct for Wyoming's roadways as shown in the simulation outcomes. Further, this impact is more noticeable with higher truck speeds. The high truck weights accompanied by speedy behaviors would be riskier for truck drivers while cornering under crosswind conditions. Assigning safe speed limits should be applied based on these variations of the impact of each of these factors.



(a) Least sharp and steep curve



(b) Moderate sharpness and steepness curve case

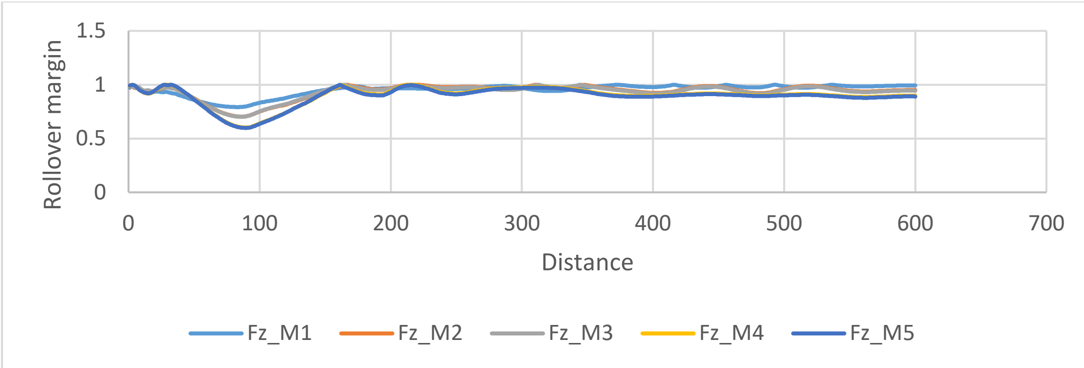


(c) Sharp and steep curve case

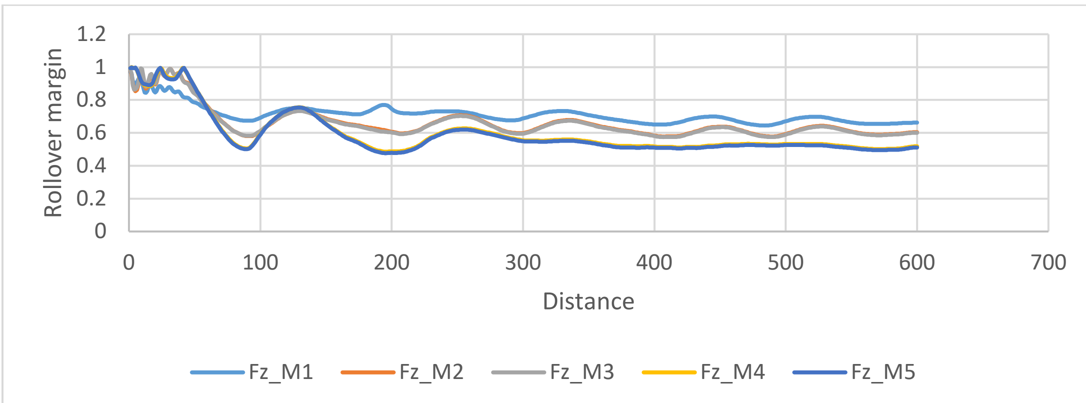
Figure 5.6 Rollover margin for different truckload conditions under different combined curve levels when the wind speed is 40 mph

5.2.3 Wind Direction Effect

Considering three different crosswind directions (60, 90, and 120 degrees), the results illustrated the crosswind in 120° direction is the most hazardous direction on the vulnerability of truck roll stability compared with the other directions as shown in Figure 5.7. An approximate reduction of 60% in the rollover margin occurred when the wind directions changed from 60° to 120°. This substantial variation demonstrated the significant impact of crosswind directions exerted on the roll stability of trucks. This is because the crosswind directions are influenced by the driving speed (Young et al., 2010) and the curvature degree that changes the positions of the truck instantaneously on the curved road and leads to a change in the angle between the wind and the truck (Hou et al., 2019). This impact is more significant with higher operating speeds as shown in Figure 5.8. With higher truck speeds, larger wind forces are produced against the truck and contribute to higher rollover vulnerability (Hou et al., 2019). Additionally, there is a positive correlation between wind direction and wind speed. The most significant drop in the rollover margin, as seen in Figure 5.9, occurs when the wind speed increases from 20 to 40 mph with 120° crosswind direction. On the other hand, Kim et al. (2016) reported that the critical wind speed and direction are 30 mph and 60°, respectively, ignoring any positive correlation between the wind parameters. These confounding results might be due to the constant truck speed (31 mph) considered in their study.



(a)



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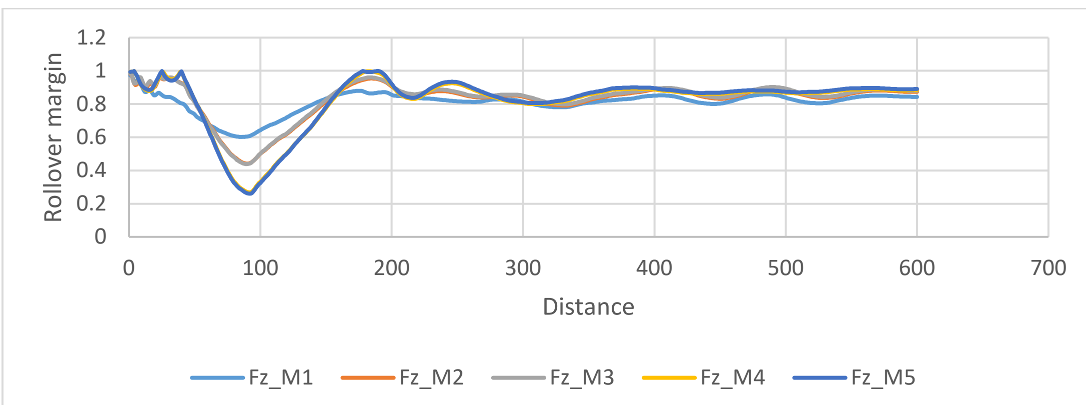


(c)

Figure 5.7 Rollover margins for a truck under 3 crosswind directions controlling for all other factors; (a) 60°, (b) 90°, and (c) 120° (Truck axles: M1, M2, M3, M4, M5)

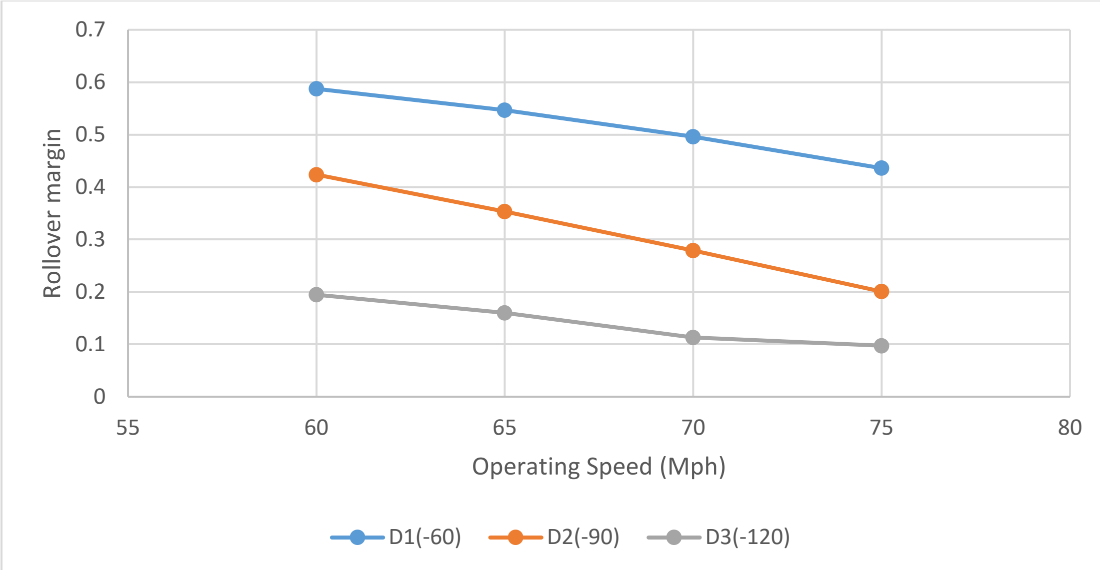


Figure 5.8 Rollover margins for different crosswind directions

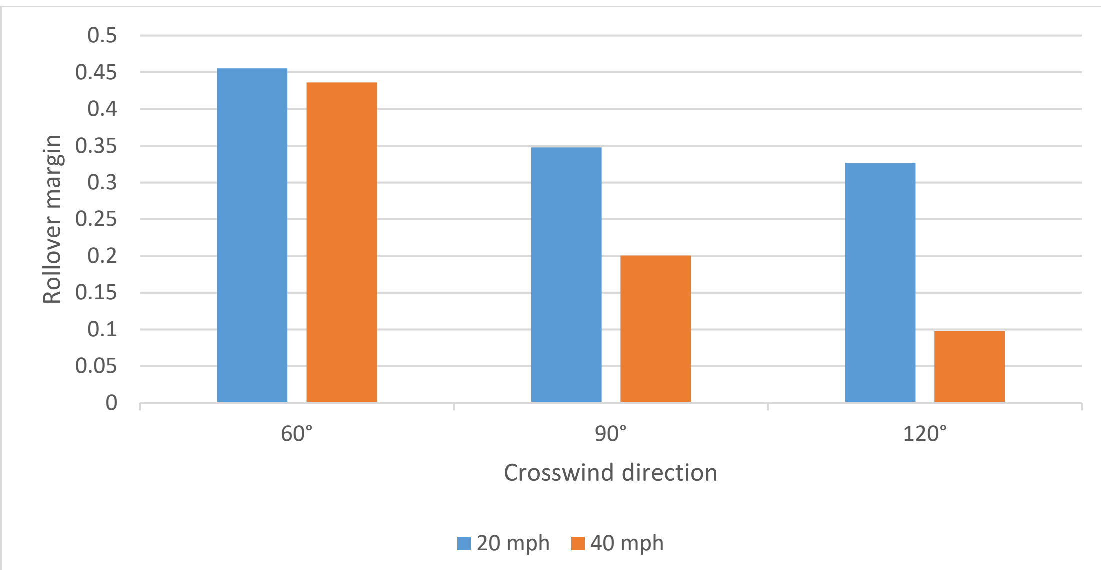


Figure 5.9 The relationship between the wind speed and direction with respect to the rollover margin

5.2.4 Multiple Regression Model Results

Similar to the previous sections, a multiple regression model was developed to quantify the exact impact of the considered factors on truck RMs resulting from the 2,296 simulation tests. Table 5.2 illustrates the results of the model. The regression analysis yielded significant interactions between the variables, which are important to consider in the model to better understand the realistic truck performance when cornering as referred to previously. The parameters were interpreted from the models assuming all else was controlled. All considered variables in the table were found to be statistically significant at the 95th percentile confidence level except superelevations. Table 5.3 presents the elasticity values of the parameters to examine the relative effects of the variables considered in the model that infer the average change in rollover margin due to a change in an explanatory variable.

Table 5.2 Rollover margins' multiple regression model results

Variable	Estimate	T Statistic	P-value
Constant	0.9011	8.339	< 0.001
Curve Radius (ft)	$6.565*10^{-5}$	3.638	< 0.001
Grade (%)	0.043	3.937	< 0.001
Truck gross weight (lb)	$-2.576*10^{-6}$	-3.074	0.002
Operating Speed (*Mph*)	-0.0095	-7.008	< 0.001
Wind Speed (*Mph*)	$-4.175*10^{-3}$	-4.458	< 0.001
Wind Direction (-90)	-0.0073	-3.926	<0.001
Wind Direction (-120)	-0.0108	-5.757	<0.001
Radius*gross weight	$1.952*10^{-9}$	6.129	<0.001
Model Fit Statistics			
Adjusted R-squared	**0.707**		
AIC	**-806.122**		
F-statistic	**109.4**		
P-value	**< 0.001**		

Table 5.3 Variable elasticity effects

Variable	Elasticity Effect
Curve Radius (ft)	0.469
Grade (%)	0.167
Truck gross weight (lb)	-0.403
Operating Speed (*Mph*)	-1.935
Wind Speed (*Mph*)	-0.375

The multiple regression model fits the data very well since the impact tendency of the key factors in the statistical model confirms the results from the simulation outcomes. The RM is the most vulnerable to the operating speed variable among all considered variables. When negotiating curves with higher operating speeds, the RMs would plummet. An increase of 10% in the operating speed decreases the rollover risk margin by 19.3%. Therefore, adjusting the operating speed would be crucial to maintain the truck in the desired trajectory. Regarding curve characteristics, both curve radius and downgrade values (negative grade values) significantly influence the RMs. For sharper curves and steeper downgrades, the truck RMs would decrease. The curve radius has a higher impact on the roll stability of trucks (0.469) compared with the grade profile of the curve (0.167) as shown in the elasticity effects. The wind parameters, speed and direction, decrease the RMs. The RM decreases by 3.75% with a 10% increase in the wind speed. Also, the impact of the 120° direction contributes to a higher reduction in the RM than the crosswind in the 90° direction. Furthermore, the interaction term ascertained statistically the interactive effect of the truckloads and different curve features mentioned previously. With crosswinds blowing against the high-profile vehicles (trucks), light trucks are more vulnerable to rollover events than heavy trucks when traversing fewer sharp curves. Heavy trucks, when cornering on tight curves, are more exposed to tip over due to the higher weight transfer when moving on these curves. Figure 5.10 illustrates this phenomenon.

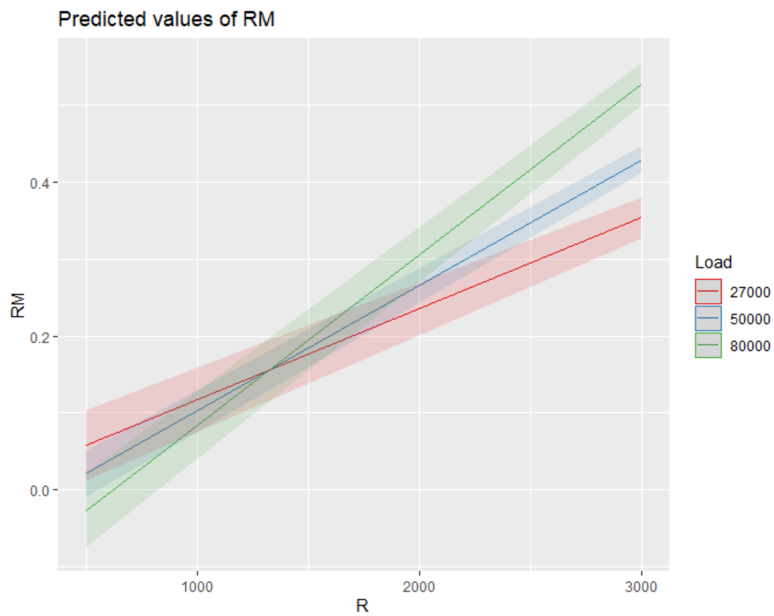


Figure 5.10 The interaction impact of the curve radius and truck gross weight on the rollover margin

6. VEHICLE-STABILITY-BASED DESIGN OF SPEED LIMITS FOR TRUCKS ON TWO-LANE RURAL HIGHWAYS

6.1 Introduction

Two-lane rural highways are characterized by sharper curves than interstate highways with a wider range of speed limits. Since the trucks as complicated vehicles are more vulnerable on these challenging alignments, it is critical to investigate their stability with low, medium, and high speed-limit curves. Furthermore, establishing a robust design framework for a wide range of speed limits is needed since the existing roadway design policies have significant shortcomings as discussed previously. This section aims at proposing a holistic framework to design appropriate speed limits on combined two-lane rural curves on the basis of two criteria: skidding and rollover events using dynamic simulation modeling. Multiple regression models are developed, including truck configuration, weather condition, and geometric features. The truck was examined at impending skid and rollover by defining the breakpoint where skidding and rollover safety violations occur during truck cornering. This framework would assess the current speed limits of curves coupled with a distribution of operating speeds to identify the safe speed according to the prevailing conditions.

Following the same selection procedure of the interstate curves, 10 two-lane rural curves were selected in the study. Table 6.1 illustrates these curves with the geometric characteristics accompanied by speed limits. From the selected curves, it is clear that due to the combination of the horizontal and vertical characteristics there is variability in the combinations of curve sharpness and steepness. The grade values vary between -3.8% and 7%, and superelevation values range from 1% to 8.8%. This is important for the proposed framework to cover many possible cases and achieve holistic outcomes.

Table 6.1 Geometric features of the selected curves

Curve	Radius (R) (ft)	Angle (Degree)	Super Elevation (SE)	Grade (G) %	Current Speed Limit (Mph)
Curve 1	80.97	123.12	7.7	-6	40
Curve 2	483	100.78	8.8	-5.7	50
Curve 3	620	57.8	8.8	-6.4	45
Curve 4	393	71.12	8.3	-5	45
Curve 5	2499	11.3	4.5	-4	50
Curve 6	719	106.9	4.5	-6.2	45
Curve 7	557	72	3.6	-5	55
Curve 8	654	70	10	-6.6	50
Curve 9	950	58.6	8	-7	50
Curve 10	2800	45.47	1	-3.8	70

Including combinations of key geometric elements and trucks, gross weights on different weather conditions determine the effect of these factors on a truck's ability to recover from veering off or rolling over on a curved roadway. The same gross weight categories used in the previous chapter are considered for this simulation tests. The skidding and rollover safety margins are identified for each test when navigating a curve; therefore, an assessment of the truck speed can be conducted accordingly. Figure 6.1 demonstrates the general simulation process.

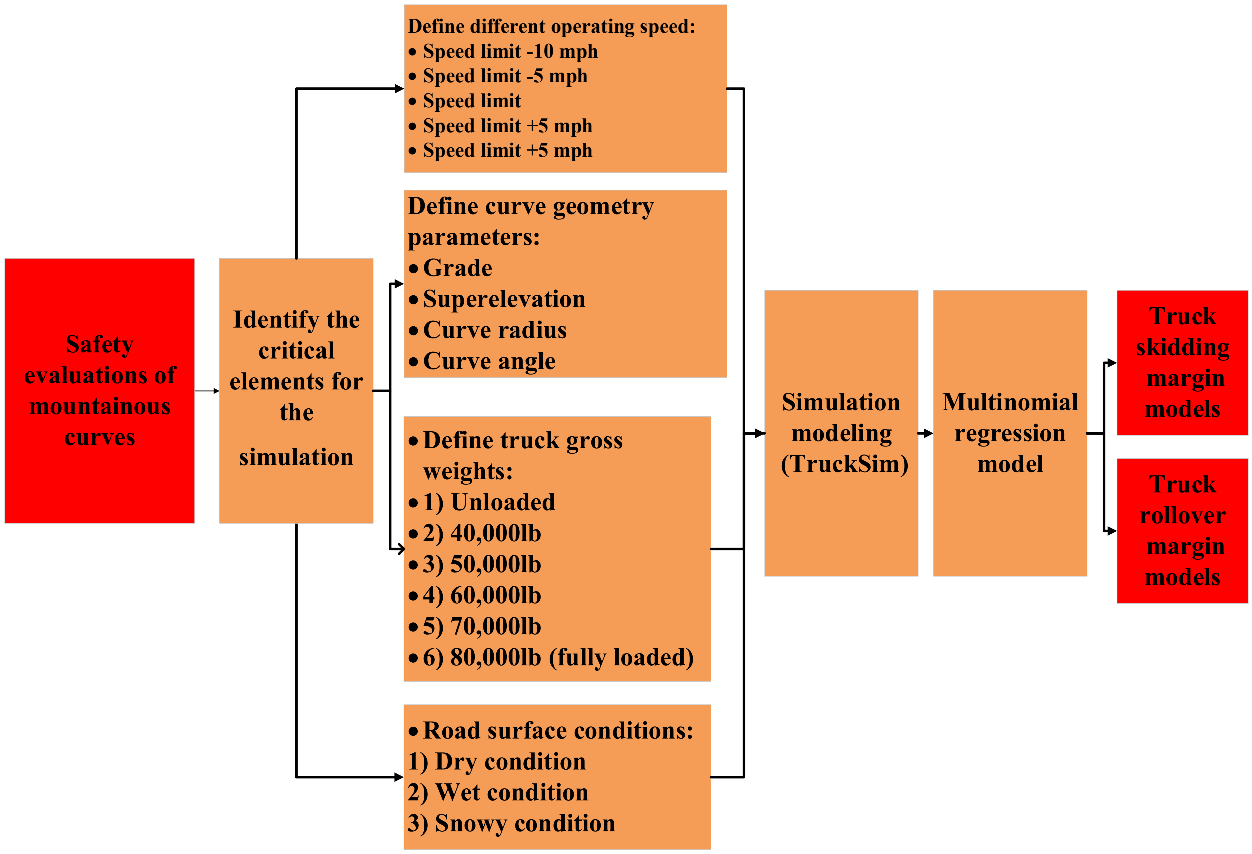


Figure 6.1 Study methodology

6.2 Simulation Results

A matrix of 900 tests that represents all possible combinations between the inputs are conducted, including all key factors. Table 6.2 presents the combinations of the included factors in the study.

Table 6.2 The combinations of the simulation runs based on the parameters shown in Figure 6.1

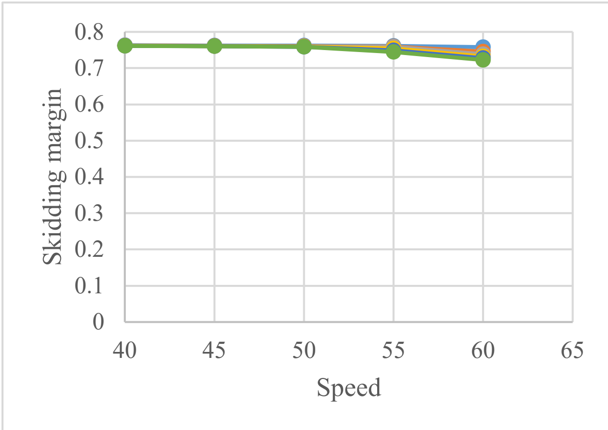
Number of considered curves	Truck gross weights	Road surface conditions	Crosswind directions	Operating speeds	Total combinations
10 curves	6 gross weights	3 road conditions	3 directions	5 different speeds	10*6*3*5 =900 scenarios

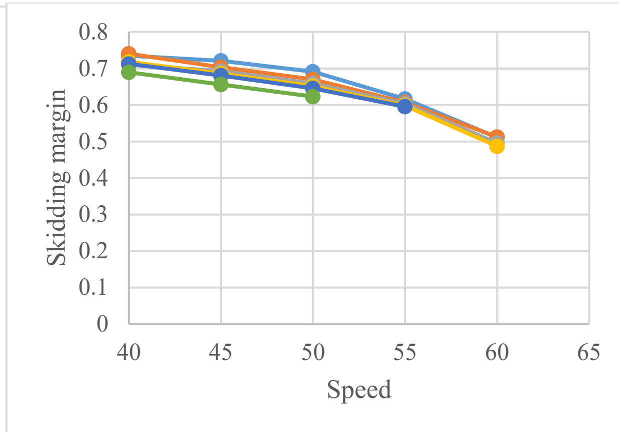
At various operating speeds, the influence of truck weights on lateral and roll stability was investigated. This influence was explored on different curve features with the considered road surfaces to better understand the truck performance on a variety of conditions. As shown in Figures 6.2 and 6.3, many conclusions can be drawn from simulation results. A comparison was conducted between moderate sharpness and sharp curves for dry (a and b charts), wet (c and d charts), and snowy road surfaces (e and f charts) for SMs and RMs. When negotiating curves with higher operating speeds, the demand friction and lateral acceleration increased. Consequently, the SMs and RMs would drop in this case. The impact of truck weights was minimal in terms of SMs, particularly on dry road surfaces. Yet, the impact was significant on snowy sharp curves due to the low supply friction between tires and pavement. On sharp curves and snowy conditions, the truck with the near-full and fully loaded truck conditions (70,000 and

80,000 gross weights) started deviating off the road at 50 mph, which is the posted speed limit of the curve as shown in Figure 6.2 (f). Speedy behavior coupled with high gross weights would be more hazardous for truck drivers as the impact of decreasing the truck speed would be more significant. This indicates that under some situations, the current speed limits are unsafe to avoid skidding events.

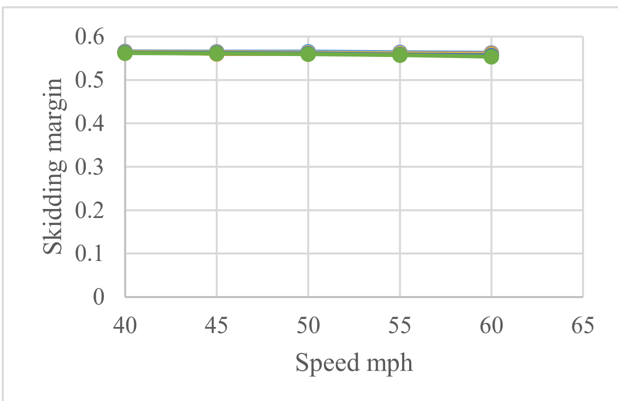
Regarding truck roll stability, the weight impact was significantly high on dry road surface curves. When the truckload increases, RMs change with different truck weights since the truck is more vulnerable to rollover. This effect is more obvious on sharper curves and steeper downgrades due to the significant weight transfer while cornering. Truck rollover probability increases considerably on high-supply friction road conditions before skidding. Likewise, the posted speed limits are also inappropriate and hazardous for truck drivers in terms of roll stability even in favorable weather conditions. This finding is opposite of the trend observed in previous studies (Tavassoli Kallebasti et al., 2020; Torbic et al., 2014), in which the rollover risk was examined only on the minimum curve radius and the corresponding design speed limits. The problem with this approach is that when investigating the impact of curve sharpness on trucks and start increasing the minimum radius, the design curve speed increases due to the positive relationship in the minimum radius equation in the Green Book. Therefore, this approach leads to incorrect implications and cannot observe the actual radius-speed interaction impact on truck rollover stability.

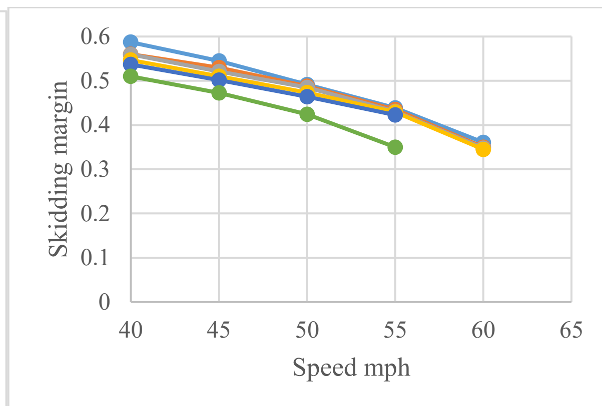
The results exhibited how important it is to examine SMs and RMs concurrently. This is because the rollover event occurs before skidding in dry conditions, and in the snowy condition the opposite is more likely to occur. Figure 6.2 (b) shows this phenomenon clearly for the fully loaded case where the green line disappeared suddenly in the skidding investigation due to the occurrence of rollover. Alike, the green line in Figure 6.3 (f) disappeared because the SM reached zero before the RM. The RMs are not significantly affected by adverse weather conditions. Therefore, investigating each event of skidding and rollover without considering the other would not capture the holistic impact of the significant factors related to these events. Previous studies inferred these implications regarding the impact of higher traveling speeds, heavier truck weights, and curve features on SMs and RMs (Bauer and Harwood, 2013; Shin and Lee, 2015; You et al., 2012). However, these studies investigated each event (truck skidding or rollover) separately. The speed limit design cannot be generalized to all trucks with various loads and on different road surface conditions since the results depend on road conditions combined with curve features. Therefore, it is important to develop a design framework considering both safety margins to assign safe speed limits on challenging curves. A multiple regression model was applied considering all simulation tests to achieve this purpose.



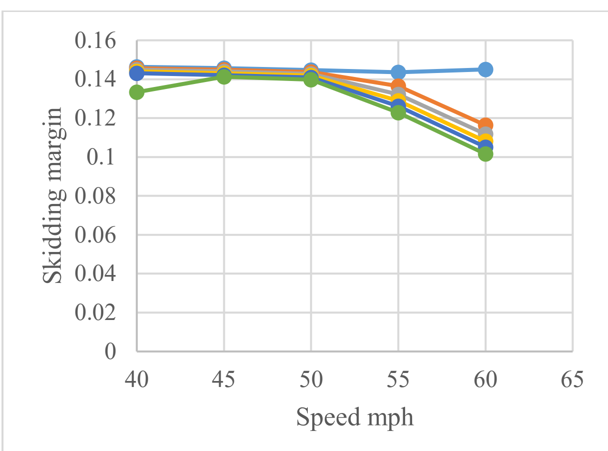


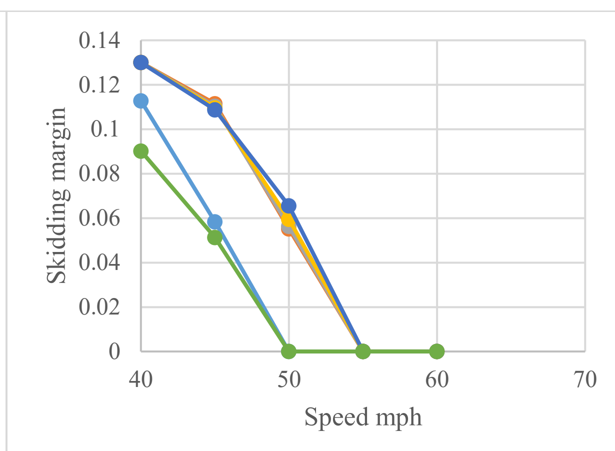
(a) (b)





(c) (d)





(e) (f)

Figure 6.2 The impact of truck speeds with different gross weights on skidding safety margins for moderate-sharpness and sharp curves on dry (a, b), wet (c, d), and snowy roads (e, f)

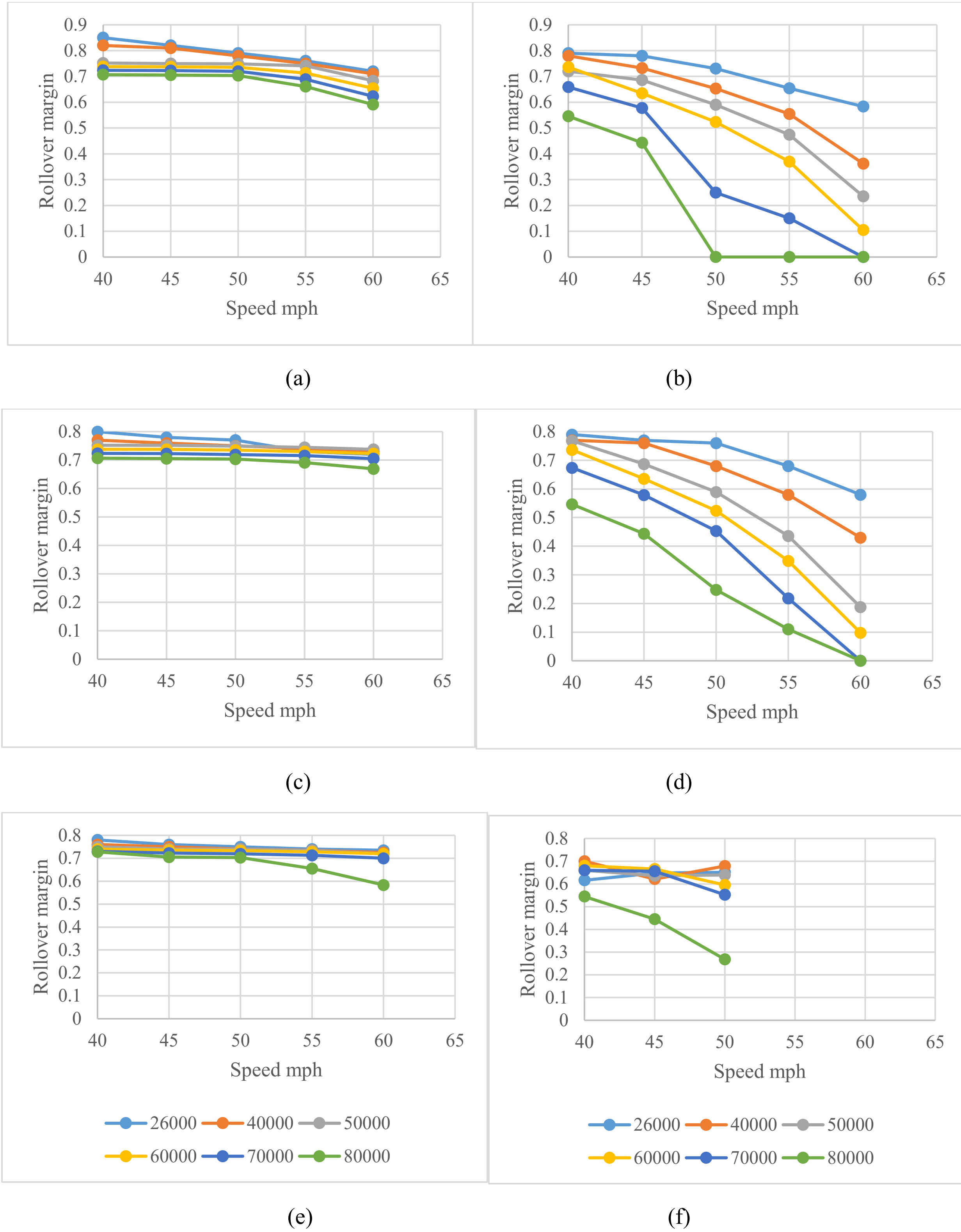


Figure 6.3 The impact of truck speeds with different gross weights on rollover safety margins for moderate-sharpness and sharp curves on dry (a, b), wet (c, d), and snowy roads (e, f)

6.3 Multiple Regression Models

Two models were developed for truck SMs and RMs. For each model, three equations were established according to the road surface conditions (dry, wet, and snowy). In total, six equations were presented to be used in the design framework of speed limits. The predictors were the operating speed, truck weight, grade, curve radius, superelevation, and curve angle. Tables 6.3 and 6.4 illustrate the results of the models in terms of SMs and RMs, respectively.

Table 6.3 Skidding margin multiple regression models for dry, wet, and snowy road conditions

Skidding margins model for dry road surfaces				
Variable	**Estimate**	**T-Statistic**	**Standard Error**	**P-value**
Constant	0.787	20.150	0.036	<0.001
SE	0.006	2.957	0.008	0.003
Speed Mph	-0.005	-13.648	0.008	<0.001
Radius ft	$1.108 * 10^{-4}$	11.054	0.008	<0.001
Angle degree	-0.001	-4.844	0.008	<0.001
Model Fit Statistics				
Adjusted R-squared	**0.746**			
F-statistic	**185.2**			
P-value	**< 0.001**			
The model equation: $SM_{Dry} = 0.787 + 0.006\, SE - 0.005S + 1.108 * 10^{-4}R - 0.001Angle$				
Skidding margins model for wet road surfaces				
Variable	**Estimate**	**T-Statistic**	**Standard Error**	**P-value**
Constant	0.492	9.425	0.052	<0.001
Grade %	0.029	-2.739	0.006	0.006
SE	0.008	-4.428	0.003	0.003
Speed Mph	-0.005	-9.850	0.006	<0.001
Radius ft	$1.069 * 10^{-4}$	8.729	0.001	<0.001
Angle degree	$-6.638 * 10^{-4}$	-2.575	0.002	
Model Fit Statistics				
Adjusted R-squared	**0.746**			
F-statistic	**79.14**			
P-value	**< 0.001**			
The model equation: $SM_{Wet} = 0.492 + 0.008SE + 0.029G - 0.005S + 1.069 * 10^{-4}R - 6.638 * 10^{-4}Angle$				
Skidding margins model for snowy road surfaces				
Variable	**Estimate**	**T-Statistic**	**Standard Error**	**P-value**

Constant	0.131	7.118	0.018	<0.001
SE	0.005	5.490	0.009	<0.001
Grade %	0.010	4.392	0.002	<0.001
Speed Mph	-0.002	-12.189	0.001	<0.001
Radius	$4.676 * 10^{-4}$	11.813	0.003	<0.001
Weight lb	$-1.279 * 10^{-7}$	-11.610	0.007	<0.001
Angle degree	$-2.736 * 10^{-4}$	-3.292	0.008	0.001
Model Fit Statistics				
Adjusted R-squared		**0.73**		
F-statistic		**132.1**		
P-value		**< 0.001**		
The model equation: $SM_{Snowy} = 0.131 + 0.005SE + 0.010G - 0.002S + 4.676 * 10^{-5}R - 1.279 * 10^{-7}Weight - 2.736 * 10^{-4}Angle$				

All considered variables in the table were found to be statistically significant at the 95th percentile confidence level. The parameters were interpreted from the models assuming all else was controlled. The regression analyses yielded significant inferences regarding the impact of each variable to better understand the realistic truck performance when cornering as referred to previously

Table 6.4 Rollover margin multiple regression models for dry, wet, and snowy road conditions

Rollover margins model for dry road surfaces				
Variable	**Estimate**	**T-Statistic**	**Standard Error**	**P-value**
Constant	1.068	10.581	0.010	<0.001
SE	0.028	5.572	0.005	<0.001
Grade %	0.521	4.277	0.012	<0.001
Speed Mph	-0.009	-10.024	0.009	<0.001
Radius ft	$2.247 * 10^{-4}$	10.506	0.002	<0.001
Weight lb	$-4.344 * 10^{-6}$	-10.119	0.004	<0.001
Angle degree	-0.003	-5.660	0.004	<0.001
Model Fit Statistics				
Adjusted R-squared	**0.761**			
F-statistic	**157.9**			
P-value	**< 0.001**			
The model equation: $RM_{Dry} = 1.068 + 0.028\,SE + 0.521G - 0.009S + 2.247 * 10^{-4}R - 4.344 * 10^{-6}Weight - 0.003Angel$				

Rollover margins model for wet road surfaces				
Variable	**Estimate**	**T-Statistic**	**Standard Error**	**P-value**
Constant	0.993	15.088	0.065	<0.001
Speed Mph	-0.012	-11.653	0.010	<0.001
Radius ft	$2.472 * 10^{-4}$	14.028	0.001	<0.001
Weight lb	$-3.374 * 10^{-6}$	-7.175	0.004	<0.001
Angle degree	-0.002	-4.990	0.004	<0.001
Model Fit Statistics				
Adjusted R-squared	**0.744**			
F-statistic	**185.5**			
P-value	**< 0.001**			
The model equation: $RM_{Wet} = 0.993 - 0.012S + 2.472 * 10^{-4}R - 3.374 * 10^{-6}\,Weight - 0.002Angle$				

Rollover margins model for snowy road surfaces				
Variable	**Estimate**	**T-Statistic**	**Standard Error**	**P-value**
Constant	0.968	14.650	0.066	<0.001
Speed Mph	-0.007	-5.837	0.001	<0.001
Radius ft	$9.540 * 10^{-4}$	4.421	0.002	<0.001
Weight lb	$-1.883 * 10^{-6}$	-3.473	0.005	<0.001

Angle degree	-0.003	-6.130	0.005	<0.001
Model Fit Statistics				
Adjusted R-squared	**0.644**			
F-statistic	**53.93**			
P-value	**< 0.001**			
The model equation: $RM_{Snowy} = 0.968 - 0.007S + 9.540 * 10^{-5}R - 1.883 * 10^{-6}\ Weight - 0.003Angle$				

In Table 6.4, R is the curve radius, S is the truck operating speed in mph, SE is the curve superelevation, G is the grade profile (+ve means upgrade and –ve is downgrade), Angle is the curve angle, and Weight is the truck gross weight in lbs.

It is clear from Tables 6.3 and 6.4 that the developed equations vary with the statistically significant factors for SMs and RMs. Operating speed has the highest impact on the lateral and roll stability of trucks among all considered factors. The results were in line with several studies since they showed that greater operating speed significantly increased skidding and rollover probability (Chen et al., 2018; XU et al., 2013). This indicated that adjusting the operating speed would be vital for truck drivers to maintain the truck in the desired trajectory and avoid any stability issues. The superelevation has a significant impact on the SMs opposed to rollover probability. Several studies (Alrejjal and Ksaibati, 2021b; Alrejjal et al.,2021b; Chen and Chen, 2010; You et al., 2012) reported that in terms of roll stability, superelevation does not alleviate the impact of lateral acceleration to assist in rollover prevention. However, the models demonstrate their impact for skidding events. It assists trucks to avoid veering off the curve since it counterbalances the centrifugal forces developed while cornering (Alrejjal and Ksaibati, 2022).

Increasing the radius decreases the potential of a skidding and rollover event, and their margins increase. However, grade impact was significant only in the dry condition mode. This is because trucks are more vulnerable to rollover in this road condition compared with other road surfaces. From another perspective, the impact of grade in SM models is critical when the road surfaces are wet and snowy. This supports the above claim that when assessing truck performance and stability, both safety margins should be considered since side friction demand and lateral acceleration acting on truck tires develop concurrently according to the road conditions. Figure 6-4 explains how SMs and RMs change for a wide range of curve radii at different speeds on dry, wet, and snowy road surfaces. The dashed red line represents the zero point that represents the impending skidding and rollover points. RM reached zero before the SM, and the impact of different speeds is more significant for SM on snowy road conditions. In low friction conditions, trucks start to skid at speeds of 50 and 60 mph even on a relatively larger curve radius (Figure 6.4 [f]). Therefore, truck drivers should be more cautious and accommodate their speeds according to the challenging road conditions. Figure 6.5 displays the truck weight impact on safety margins on the considered road surfaces at a wide range of speeds. One of the prominent inferences obtained is that the influence of different weights is more distinctive on RMs compared with SMs on all road conditions. Truck drivers with high weights should be more careful of rollover crashes rather than skidding and runoff crashes. Consequently, speed limits should be modified based on the truck weights and road surface conditions to avoid skidding and rollover events.

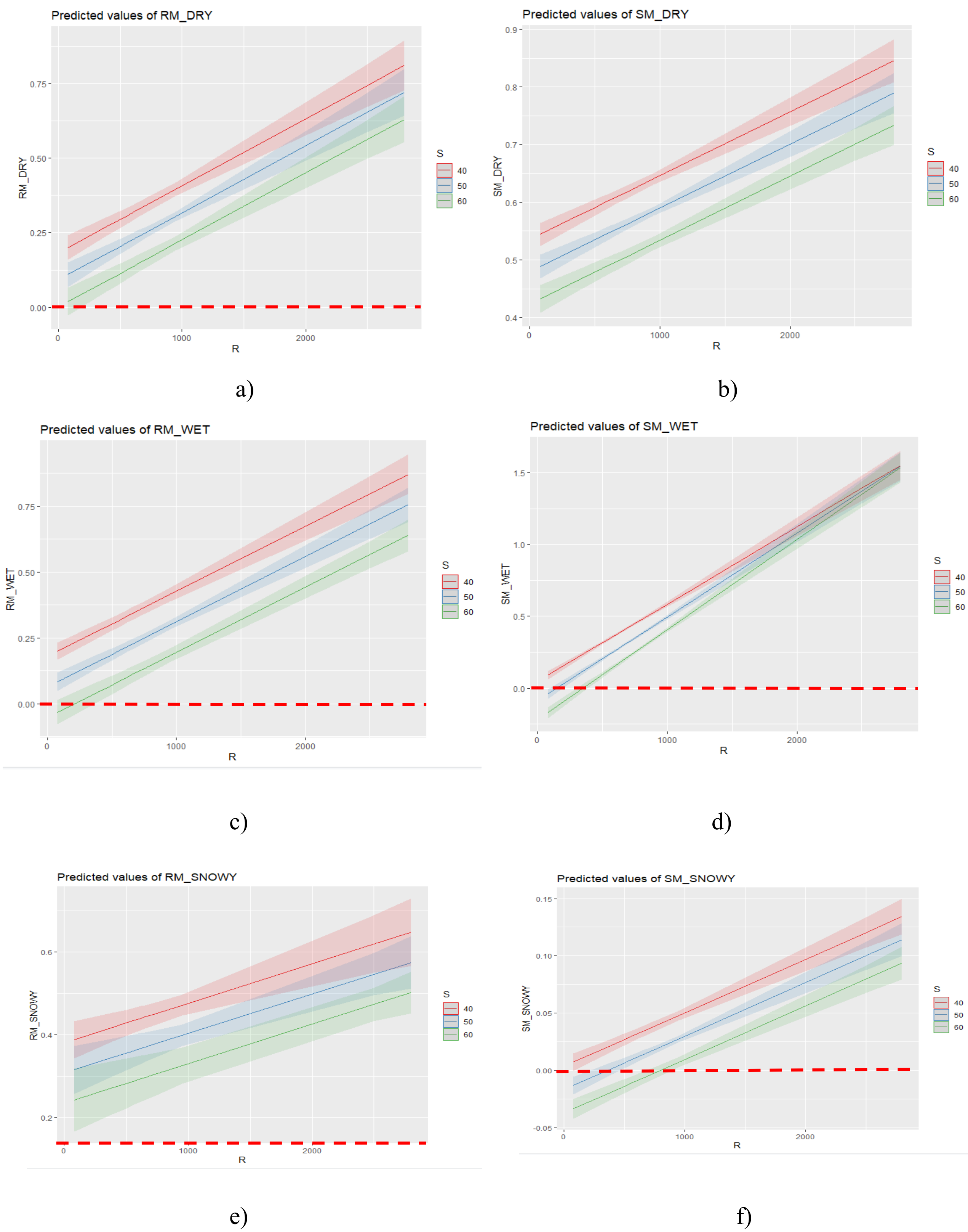


Figure 6.4 The impact of truck speeds (S) with different curve radii (R) on SM and RM on dry (a, b), wet (c, d), and snowy roads (e, f) (The red dashed line represents the skidding and rollover point, safety margin = 0)

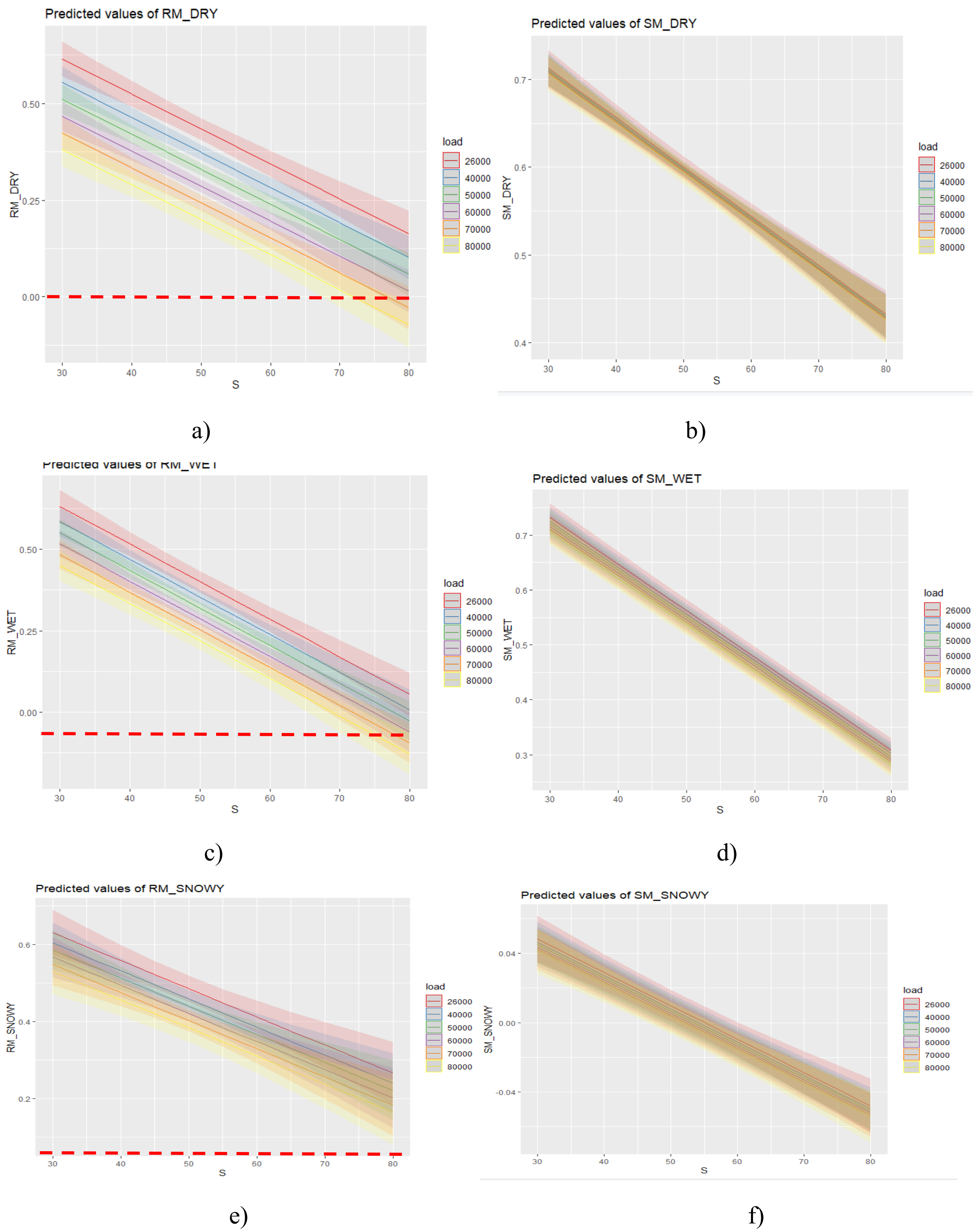


Figure 6.5 The impact of truck gross weights in lbs with different speeds (S) on SM and RM on dry (a, b), wet (c, d), and snowy roads (e, f) (The red dashed line represents the skidding and rollover point, safety margin = 0)

6.4 Speed Limits Design Procedure

A new framework for designing speed limits on a combined curve is proposed in this paper following an iterative process as shown in Figure 6.6 and summarized as follows:

- An initial operating speed is selected for the horizontal curve.
- The curve parameters (R, angle, G and SE) are selected for the considered curve.
- Identify the gross weight of the truck.
- Insert all these factors in the models based on the road surface conditions.
- Determine the SMs and RMs corresponding to the inputs.
- Check the least value of safety margins between SMs and RMs.
- Conduct risk analysis for the safety margin value. A previous study reported that the skidding and rollover risk status can be categorized into four groups: Safe state when SM or RM >= 0.4, Warning state when SM or RM is between 0.4 and 0.2, Risky state when SM or RM is between 0.2 and 0, and skidding or rollover state when RM=0 (Qu et al., 2018).
- By evaluating the SM and RM state, the design is deemed acceptable when SM/RM is greater than 0.4 or lower operating speed by 5 mph is selected and the procedure is repeated through the framework.

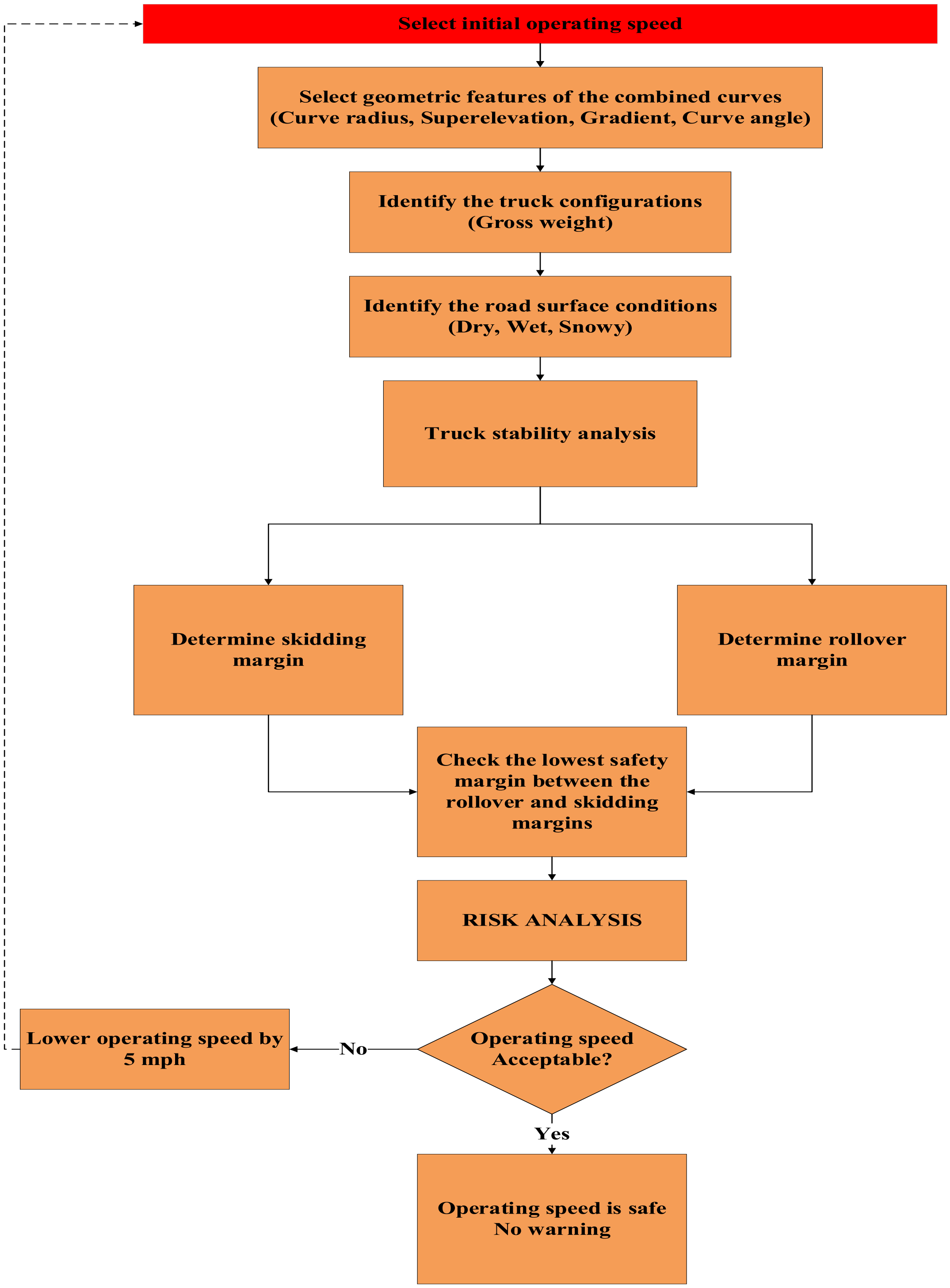


Figure 6.6 Speed limit assessment framework

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Wyoming's roads are characterized by challenging mountainous terrain and adverse weather conditions. This poses safety concerns. On the challenging mountainous curves, the risk is greater because they consist of a combination of horizontal curves and vertical alignment/curves. Designing such alignment is challenging with the appropriate design speed due to many complex components that should be considered as challenging terrain and different vehicle characteristics. Besides, vehicle performances vary under adverse road surface conditions and severe crosswinds. The Green Book (The American Association of State Highways and Transportation Officials (AASHTO) (2011b) considers a simplified approach (point-mass model) to estimate the appropriate speed limit based on the radius of horizontal curves. This method considers an unsprung (rigid) model for the vehicles, which is independent of vehicle dimensions and features. Also, it represents the vehicle as a point and assumed to be on a planar surface instead of a three-dimensional surface (having a combined horizontal and vertical curve). This approach does not account for multiple dynamic and kinetic parameters that vary when vehicles are traversing a horizontal curve.

By using multi-body vehicle dynamic simulation modeling, this research has overcome the limitation to evaluate vehicle stability in terms of skidding and rollover at various operating speeds. This was achieved to identify safe speed limits along curved mountainous road sections with challenging conditions. Several critical variables were considered, such as the operating speeds, geometric characteristics (curve radius, curve grade, curve angle, and superelevations), and vehicle types and configurations (CG payload height and gross weight). Due to the harsh winters in Wyoming, adverse weather conditions were considered in the simulation, including dry, wet, and snowy road surface conditions as well as the impact of severe crosswinds. The results revealed that the impact of crosswind parameters (speed and direction) changes based on the curve features and truck configurations. Further, the research provided the critical wind speeds and directions that truck drivers should be cautioned about to avoid rollovers. Among all considered factors, operating speed has the highest impact on the lateral and roll stability of vehicles. The superelevation has minimal impact on rollover probability as opposed to the SMs. Including various payloads for trucks, the study highlighted how truck performance varies on combined curves. Speedy behaviors coupled with high gross weights would be more hazardous for drivers. Considering all these factors in the design policy of speed limits on combined curves provides a better understanding of vehicle skidding and rollover events reflecting real-world scenarios.

This study filled the gap in the literature regarding the impact of these key factors on vehicle stability and how to assign appropriate speed limits on these challenging sections. Although the qualitative impact of the considered key factors is likely known, this study provided a quantitative-based approach to capture the impact of these factors with their interactive effect on vehicle stability. The results of the multiple regression model quantify the impact of these factors on lateral and roll stability of vehicles. It provided new insights regarding the impact of various interactions between the factors, particularly when applying brakes.

This research has many potential applications. It formed the basis for offering guidelines regarding the design of road sections with combined (horizontal and vertical) alignments and the implementation of safety countermeasures on existing curved roads. The study offered a holistic design framework for safe vehicle speeds on combined curves with respect to lateral and roll stability.

7.2 Recommendations and Future Studies

Although many issues throughout the research were resolved, several areas can be addressed for future studies. More critical scenarios involving cornering may be considered. For instance, lane changing scenarios while cornering is hazardous under adverse weather conditions. Also, platooning situations that involve a multitude of vehicles closely following each other is risky when cornering. For validation purposes, conducting a few field tests reflecting the conducted scenarios is needed in the future. For the developed models, additional key factors ought to be included in the investigation. They consist of the roadside parameters, driver fatigue, and distractions. Furthermore, this research only considered the roll stability of the five-axle tractor-semitrailer on the horizontal curves combined with vertical slopes. Therefore, the lateral and roll stability related to various truck types with more alignment combinations, such as the compound horizontal curves and reverse horizontal curves on upgrades and downgrades, should be investigated in further research.

It is recommended that advanced safety data analysis methodologies be applied to control for bias and obtain more accurate results. Such methods include non-parametric methods, hierarchal modeling methods, machine learning methods, Bayesian methods, and those that accommodate spatial correlations. Additionally, employing real-time data for evaluating safety data of mountainous roads would result in more accurate inferences to identify surrogate safety measures. Furthermore, linking real-time weather data and truckload data with crash data may improve the predictive power of the risk assessment process. This will lead to proposing safety countermeasures based on better-informed decisions and, thus, save lives.

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9. APPENDIX A: Multibody Vehicle Dynamic Simulation Output for Passenger Cars

Time (s)	Lateral Force on 1st Axle	Lateral Force on 2nd Axle	Lateral Force on 1st left tire	Lateral Force on 2nd left tire	Lateral Force on 1st Right Tire	Lateral Force on 2nd Right Tire	Vertical Force on 1st Axle	Vertical Force on 2nd Axle	Vertical Force on 1st left tire	Vertical Force on 2nd left tire	Vertical Force on 1st Right Tire	Vertical Force on 2nd Right Tire
0	-3.245	2.54	-6.526	0.454	3.281	2.086	10180.385	8831.757	4842.607	4660.818	5337.778	4170.939
0.025	33.546	-0.539	-184.223	-104.244	217.769	103.705	9077.824	8846.166	4295.525	4441.382	4782.299	4404.784
0.05	49.368	29.717	-142.713	-103.826	192.082	133.543	6756.025	8854.222	3186.882	4341.215	3569.143	4513.007
0.075	51.63	64.781	-85.937	-85.527	137.567	150.309	4805.393	8778.516	2292.387	4310.703	2513.006	4467.813
0.1	52.004	87.189	-66.489	-65.056	118.493	152.245	4265.825	8434.74	2082.413	4168.089	2183.412	4266.651
0.125	59.776	80.99	-75.569	-25.457	135.345	106.447	4369.769	6571.112	2113.152	3258.03	2256.618	3313.082
0.15	65.729	59.889	-86.304	29.482	152.033	30.407	3980.01	4328.267	1892.635	2151.597	2087.376	2176.67
0.175	62.129	49.37	-86.074	87.653	148.204	-38.283	3330.153	3232.965	1584.435	1612.34	1745.719	1620.626
0.2	57.689	56.908	-92.798	165.523	150.487	-108.616	3010.416	3216.242	1443.499	1604.597	1566.917	1611.645
0.225	84.971	49.915	0	209.636	84.971	-159.721	596.784	2923.577	0	1477.469	596.784	1446.108
0.25	0	55.689	0	204.488	0	-148.8	0	2185.545	0	1133.579	0	1051.966
0.275	0	52.015	0	204.479	0	-152.464	0	1799.282	0	950.355	0	848.927
0.3	0	52.697	0	236.493	0	-183.796	0	1845.063	0	973.624	0	871.439
0.325	64.066	148.085	-85.738	270.011	149.804	-121.926	1993.132	1700.62	836.726	1060.168	1156.406	640.452
0.35	131.993	167.408	-277.517	167.88	409.51	-0.472	6173.522	687.844	2938.242	685.499	3235.28	2.345
0.375	144.289	153.087	-461.194	232.964	605.482	-79.877	9813.062	1370.879	4793.967	989.457	5019.095	381.422
0.4	89.195	121.551	-541.622	473.632	630.817	-352.081	9970.679	3700.303	4972.408	2047.34	4998.271	1652.963
0.425	49.362	39.89	-432.748	695.894	482.11	-656.004	8020.097	6464.741	3969.114	3232.446	4050.982	3232.295
0.45	53.214	7.977	-344.198	581.066	397.412	-573.089	7831.79	6957.171	3774.595	3348.246	4057.195	3608.925
0.475	76.262	74.688	-331.378	412.567	407.64	-337.88	8239.524	5960.228	3922.565	2948.207	4316.959	3012.021
0.5	99.422	107.531	-319.829	425.316	419.251	-317.785	8226.323	6431.981	3916.353	3231.994	4309.97	3199.987
0.525	103.208	98.447	-308.361	453.61	411.569	-355.164	8031.846	7624.838	3844.257	3738.468	4187.59	3886.37
0.55	97.86	104.7	-302.871	379.49	400.731	-274.79	7881.503	7676.174	3798.102	3743.658	4083.402	3932.516
0.575	95.018	121.511	-304.545	313.262	399.563	-191.752	7890.422	7290.397	3831.467	3617.733	4058.955	3672.664
0.6	90.461	121.277	-315.721	305.805	406.182	-184.528	8065.202	7577.115	3946.085	3775.445	4119.117	3801.67
0.625	79.797	110.788	-335.045	291.793	414.842	-181.004	8347.188	7914.847	4108.108	3929.445	4239.08	3985.402
0.65	67.94	99.473	-356.681	259.105	424.621	-159.632	8674.333	7882.386	4284.022	3919.356	4390.311	3963.03
0.675	56.731	89.102	-376.317	234.077	433.048	-144.975	8986.597	7800.841	4443.591	3896.572	4543.006	3904.269

0.7	45.329	78.384	-391.677	217.674	437.006	-139.291	9238.431	7835.337	4566.914	3929.246	4671.517	3906.091
0.725	33.154	66.616	-402.429	201.625	435.583	-135.009	9434.487	7938.142	4662.892	3990.324	4771.595	3947.818
0.75	19.938	54.587	-410.428	183.941	430.366	-129.353	9618.696	8084.271	4758.37	4069.305	4860.327	4014.966
0.775	5.818	42.707	-417.698	163.775	423.516	-121.068	9823.694	8265.241	4867.964	4164.152	4955.73	4101.089
0.8	-8.574	30.919	-424.539	139.924	415.965	-109.005	10048.728	8467.816	4987.279	4269.174	5061.449	4198.642
0.825	-22.757	19.145	-430.175	111.468	407.418	-92.323	10284.135	8679.204	5110.933	4378.361	5173.201	4300.843
0.85	-36.731	7.474	-434.21	78.08	397.479	-70.606	10531.821	8894.098	5241.135	4489.627	5290.686	4404.471
0.875	-50.654	-4.048	-436.78	39.72	386.126	-43.768	10797.312	9114.45	5380.797	4604.427	5416.515	4510.023
0.9	-64.531	-15.55	-437.953	-3.759	373.422	-11.792	11079.386	9344.126	5528.498	4724.616	5550.888	4619.51
0.925	-78.218	-27.069	-437.449	-52.462	359.231	25.393	11368.671	9584.94	5679.086	4850.701	5689.586	4734.239
0.95	-91.252	-38.698	-433.29	-106.458	342.038	67.76	11616.766	9836.908	5808.23	4982.411	5808.536	4854.497
0.975	-103.705	-50.371	-425.054	-165.714	321.349	115.343	11823.949	10099.167	5917.285	5118.984	5906.664	4980.183
1	-116.06	-61.925	-415.243	-229.971	299.183	168.046	12031.096	10369.305	6025.991	5258.988	6005.105	5110.317
1.025	-128.161	-72.989	-405.757	-298.138	277.596	225.15	12224.433	10624.111	6126.592	5390.22	6097.841	5233.892
1.05	-139.452	-82.951	-396.409	-366.144	256.956	283.193	12364.524	10813.846	6199.977	5488.291	6164.547	5325.555
1.075	-149.806	-91.76	-387.221	-429.241	237.415	337.481	12449.37	10961.494	6245.734	5565.63	6203.636	5395.863
1.1	-159.322	-99.467	-378.798	-484.223	219.476	384.756	12490.829	11085.589	6269.44	5630.677	6221.389	5454.913
1.125	-167.796	-105.794	-371.137	-528.205	203.341	422.411	12474.847	11150.588	6263.908	5665.257	6210.939	5485.331
1.15	-174.764	-110.58	-363.464	-558.49	188.7	447.91	12367.006	11121.223	6212.756	5652.538	6154.25	5468.684
1.175	-179.967	-113.818	-354.957	-573.753	174.99	459.935	12143.09	10986.448	6102.941	5586.53	6040.149	5399.917
1.2	-183.693	-115.656	-345.75	-574.71	162.057	459.054	11823.728	10752.748	5943.772	5469.556	5879.956	5283.192
1.225	-186.363	-116.496	-336.488	-564.239	150.125	447.743	11468.434	10455.345	5764.902	5319.223	5703.532	5136.122
1.25	-188.923	-117.121	-329.005	-547.067	140.081	429.946	11155.087	10164.695	5606.227	5171.514	5548.86	4993.182
1.275	-192.188	-118.289	-324.544	-527.614	132.356	409.324	10919.347	9935.472	5486.866	5054.905	5432.48	4880.568
1.3	-196.26	-120.337	-323.016	-508.647	126.757	388.31	10757.062	9774.616	5405.256	4973.393	5351.806	4801.223
1.325	-201.12	-123.369	-323.833	-491.341	122.713	367.972	10650.968	9667.697	5352.872	4919.85	5298.096	4747.847
1.35	-206.682	-127.365	-326.287	-475.951	119.605	348.586	10580.787	9596.571	5319.471	4885.099	5261.316	4711.472
1.375	-212.799	-132.23	-329.721	-462.281	116.922	330.051	10528.462	9544.967	5295.814	4860.813	5232.648	4684.153
1.4	-219.307	-137.834	-333.615	-449.968	114.308	312.134	10480.949	9500.864	5275.149	4840.78	5205.799	4660.084
1.425	-226.13	-144.039	-337.684	-438.64	111.554	294.601	10430.703	9456.945	5253.5	4821.166	5177.203	4635.779
1.45	-233.181	-150.71	-341.773	-427.987	108.592	277.277	10374.68	9409.763	5229.191	4800.119	5145.489	4609.644
1.475	-240.401	-157.726	-345.831	-417.782	105.429	260.057	10312.763	9358.444	5202.066	4777.116	5110.698	4581.329
1.5	-247.733	-164.98	-349.873	-407.869	102.14	242.889	10246.285	9303.478	5172.727	4752.347	5073.558	4551.13
1.525	-255.158	-172.382	-353.936	-398.148	98.777	225.766	10176.946	9245.846	5141.99	4726.271	5034.955	4519.575
1.55	-262.645	-179.851	-358.071	-388.556	95.426	208.705	10106.199	9186.533	5110.562	4699.356	4995.637	4487.177

1.575	-270.104	-187.32	-362.256	-379.054	92.151	191.734	10035.03	9126.309	5078.924	4671.971	4956.106	4454.338
1.6	-277.49	-194.732	-366.487	-369.615	88.997	174.884	9963.956	9065.687	5047.32	4644.355	4916.636	4421.331
1.625	-284.759	-202.038	-370.757	-360.221	85.998	158.183	9893.157	9004.958	5015.826	4616.638	4877.331	4388.32
1.65	-291.866	-209.198	-375.042	-350.856	83.176	141.658	9822.621	8944.257	4984.423	4588.867	4838.198	4355.39
1.675	-298.768	-216.176	-379.317	-341.505	80.549	125.329	9752.257	8883.618	4953.051	4561.044	4799.206	4322.573
1.7	-305.428	-222.944	-383.558	-332.156	78.131	109.212	9681.972	8823.029	4921.649	4533.147	4760.323	4289.882
1.725	-311.809	-229.477	-387.743	-322.799	75.934	93.321	9611.7	8762.46	4890.172	4505.148	4721.528	4257.313
1.75	-317.642	-235.758	-391.725	-313.424	74.083	77.665	9541.409	8701.884	4858.586	4477.017	4682.823	4224.867
1.775	-322.82	-241.773	-395.461	-304.024	72.641	62.251	9471.093	8641.282	4826.858	4448.723	4644.236	4192.559
1.8	-327.353	-247.501	-398.941	-294.589	71.587	47.089	9400.76	8580.646	4794.964	4420.236	4605.796	4160.41
1.825	-331.344	-252.916	-402.27	-285.104	70.927	32.189	9332.308	8519.976	4764.121	4391.533	4568.187	4128.443
1.85	-335.158	-258.008	-406.131	-275.564	70.973	17.556	9282.99	8459.319	4744.075	4362.607	4538.915	4096.713
1.875	-338.719	-262.819	-410.751	-266.004	72.032	3.184	9261.529	8399.113	4738.151	4333.545	4523.378	4065.568
1.9	-341.728	-267.36	-415.833	-256.469	74.105	-10.891	9263.655	8340.414	4743.471	4304.719	4520.184	4035.695
1.925	-343.863	-271.833	-420.894	-247.259	77.031	-24.574	9280.222	8291.399	4755.232	4281.024	4524.99	4010.376
1.95	-344.493	-276.796	-425.239	-239.162	80.746	-37.634	9302.475	8269.598	4769.001	4271.576	4533.473	3998.022
1.975	-343.304	-282.17	-428.458	-232.539	85.153	-49.631	9324.976	8274.811	4781.969	4275.255	4543.007	3999.555
2	-340.402	-287.454	-430.519	-227.319	90.116	-60.135	9345.951	8297.74	4793.206	4287.134	4552.745	4010.607
2.025	-335.863	-292.06	-431.442	-223.185	95.579	-68.875	9365.85	8328.122	4803.015	4302.118	4562.836	4026.004
2.05	-329.48	-295.516	-431.189	-219.748	101.708	-75.768	9385.691	8358.793	4812.013	4316.706	4573.679	4042.087
2.075	-321.128	-297.522	-429.718	-216.652	108.59	-80.869	9406.086	8386.417	4820.579	4329.242	4585.507	4057.175
2.1	-310.864	-297.906	-427.068	-213.629	116.204	-84.278	9427.021	8410.373	4828.73	4339.376	4598.29	4070.997
2.125	-298.325	-296.569	-423.049	-210.449	124.724	-86.121	9448.083	8431.332	4836.219	4347.384	4611.864	4083.947
2.15	-282.948	-293.432	-417.365	-206.938	134.416	-86.494	9468.784	8450.255	4842.709	4353.678	4626.075	4096.578
2.175	-264.439	-288.424	-409.863	-202.988	145.424	-85.436	9488.767	8467.918	4847.908	4358.556	4640.859	4109.362
2.2	-242.822	-281.435	-400.569	-198.467	157.747	-82.968	9507.887	8484.786	4851.64	4362.166	4656.248	4122.62
2.225	-218.169	-272.329	-389.539	-193.252	171.37	-79.077	9526.176	8501.066	4853.848	4364.542	4672.328	4136.523
2.25	-190.158	-261.034	-376.638	-187.221	186.48	-73.813	9543.765	8516.855	4854.549	4365.666	4689.217	4151.189
2.275	-158.553	-247.306	-361.78	-180.263	203.228	-67.043	9560.813	8532.266	4853.779	4365.492	4707.034	4166.775
2.3	-123.437	-231.034	-345.042	-172.264	221.606	-58.77	9577.457	8547.314	4851.577	4363.969	4725.88	4183.345
2.325	-84.918	-212.093	-326.513	-163.135	241.595	-48.958	9593.793	8561.947	4847.979	4361.062	4745.814	4200.886
2.35	-42.75	-190.346	-306.102	-152.784	263.352	-37.562	9609.926	8576.128	4843	4356.756	4766.926	4219.372
2.375	3.234	-165.681	-283.765	-141.138	286.999	-24.542	9626	8589.865	4836.623	4351.058	4789.377	4238.807
2.4	52.871	-137.989	-259.624	-128.147	312.495	-9.842	9642.016	8603.205	4828.813	4343.981	4813.203	4259.224
2.425	107.196	-107.178	-233.201	-113.764	340.397	6.586	9657.874	8616.212	4819.5	4335.548	4838.374	4280.663

2.45	168.327	-73.214	-203.492	-97.972	371.819	24.758	9673.456	8628.947	4808.488	4325.713	4864.969	4303.233
2.475	234.816	-35.992	-171.276	-80.729	406.092	44.738	9688.687	8641.453	4795.604	4314.347	4893.083	4327.106
2.5	305.077	4.668	-137.398	-61.954	442.474	66.622	9703.538	8653.755	4780.805	4301.358	4922.733	4352.397
2.525	378.423	48.996	-102.249	-41.572	480.672	90.568	9718.021	8665.863	4764.184	4286.756	4953.837	4379.108
2.55	454.834	97.168	-65.891	-19.527	520.725	116.695	9732.159	8677.785	4745.889	4270.614	4986.27	4407.172
2.575	533.849	149.301	-28.352	4.218	562.202	145.083	9745.981	8689.525	4726.06	4253.008	5019.921	4436.516
2.6	615.173	205.332	10.306	29.56	604.867	175.773	9759.463	8701.085	4704.818	4234.006	5054.645	4467.079
2.625	699.234	265.179	49.879	56.411	649.354	208.768	9772.633	8712.477	4682.277	4213.684	5090.356	4498.793
2.65	785.917	328.718	90.275	84.678	695.642	244.04	9785.552	8723.708	4658.512	4192.085	5127.04	4531.622
2.675	875.089	395.765	131.395	114.229	743.695	281.535	9798.251	8734.774	4633.565	4169.226	5164.686	4565.548
2.7	966.503	466.102	173.076	144.914	793.427	321.189	9810.733	8745.674	4607.469	4145.128	5203.264	4600.546
2.725	1056.077	539.532	213.551	176.609	842.526	362.924	9765.024	8756.397	4537.337	4119.842	5227.687	4636.556
2.75	1152.059	616.259	255.919	209.44	896.14	406.819	9741.454	8766.084	4474.633	4093.851	5266.821	4672.233
2.775	1256.428	696.005	300.19	243.417	956.239	452.587	9799.343	8773.235	4466.302	4068.457	5333.041	4704.779
2.8	1362.741	777.569	344.303	277.912	1018.438	499.657	9881.471	8780.134	4475.76	4044.038	5405.712	4736.097
2.825	1466.618	853.782	387.348	309.029	1079.27	544.752	9950.764	8706.1	4480.056	3955.405	5470.708	4750.695
2.85	1567.681	941.398	429.772	346.528	1137.91	594.87	9992.702	8732.529	4471.169	3929.378	5521.533	4803.15
2.875	1665.496	1036.233	471.503	385.91	1193.994	650.323	10009.971	8814.59	4450.493	3938.722	5559.478	4875.868
2.9	1758.214	1131.258	511.472	423.114	1246.742	708.144	10014.198	8893.837	4422.246	3947.104	5591.952	4946.733
2.925	1849.79	1222.12	549.997	456.343	1299.793	765.777	10015.523	8945.25	4390.689	3940.441	5624.834	5004.808
2.95	1941.283	1308.47	587.675	486.432	1353.608	822.038	10018.517	8968.77	4358.619	3918.58	5659.898	5050.19
2.975	2032.233	1391.39	624.397	514.571	1407.837	876.819	10023.419	8974.304	4327.178	3886.666	5696.242	5087.637
3	2121.889	1472.081	660.006	541.679	1461.883	930.402	10028.795	8971.476	4296.496	3850.253	5732.299	5121.223
3.025	2209.587	1551.231	694.363	568.22	1515.224	983.011	10033.21	8966.266	4266.367	3813.217	5766.843	5153.048
3.05	2295.157	1629.1	727.477	594.348	1567.68	1034.752	10036.694	8961.478	4237.018	3777.517	5799.676	5183.961
3.075	2378.671	1705.455	759.391	619.937	1619.28	1085.518	10040.895	8957.322	4209.276	3743.37	5831.619	5213.952
3.1	2459.956	1779.042	790.046	644.767	1669.91	1134.274	10046.476	8952.714	4183.462	3710.174	5863.014	5242.54
3.125	2538.562	1848.57	819.35	668.777	1719.212	1179.792	10053.424	8946.764	4159.563	3677.511	5893.861	5269.253
3.15	2614.125	1916.014	847.28	692.022	1766.845	1223.992	10061.369	8939.42	4137.439	3645.384	5923.93	5294.036
3.175	2686.745	1981.414	873.818	714.523	1812.927	1266.891	10069.863	8931.219	4116.86	3613.97	5953.003	5317.248
3.2	2755.691	2044.799	898.3	736.29	1857.391	1308.509	10078.552	8922.673	4097.575	3583.447	5980.977	5339.226
3.225	2818.444	2106.198	920.78	757.33	1897.665	1348.868	10087.22	8914.126	4079.466	3553.949	6007.754	5360.176
3.25	2878.398	2164.984	942.095	777.044	1936.302	1387.941	10095.674	8905.754	4062.551	3525.642	6033.124	5380.112
3.275	2935.775	2220.801	962.361	795.104	1973.415	1425.697	10103.978	8897.71	4046.83	3498.706	6057.148	5399.004
3.3	2990.526	2274.625	981.576	812.52	2008.95	1462.105	10112.229	8889.933	4032.298	3473.076	6079.931	5416.857

3.325	3042.577	2326.308	999.718	829.208	2042.858	1497.1	10120.485	8882.258	4018.894	3448.537	6101.591	5433.721
3.35	3091.878	2375.753	1016.773	845.116	2075.105	1530.636	10128.775	8874.605	4006.537	3424.949	6122.238	5449.655
3.375	3138.401	2422.903	1032.739	860.225	2105.662	1562.678	10137.098	8866.962	3995.162	3402.257	6141.936	5464.705
3.4	3182.131	2467.732	1047.627	874.532	2134.504	1593.199	10145.442	8859.347	3984.731	3380.451	6160.711	5478.896
3.425	3223.061	2510.201	1061.457	888.045	2161.604	1622.156	10153.785	8851.774	3975.23	3359.541	6178.555	5492.233
3.45	3261.188	2550.309	1074.252	900.775	2186.936	1649.535	10162.11	8844.245	3966.661	3339.545	6195.449	5504.7
3.475	3296.515	2588.059	1086.037	912.732	2210.478	1675.327	10170.401	8836.753	3959.031	3320.478	6211.37	5516.276
3.5	3329.009	2623.41	1096.822	923.927	2232.187	1699.483	10178.648	8829.285	3952.351	3302.347	6226.298	5526.938
3.525	3358.766	2656.342	1106.663	934.372	2252.103	1721.971	10186.844	8821.823	3946.628	3285.161	6240.216	5536.661
3.55	3385.728	2685.571	1115.559	944.093	2270.169	1741.478	10194.983	8814.318	3941.868	3268.928	6253.115	5545.39
3.575	3409.873	2712.256	1123.525	953.181	2286.348	1759.075	10203.06	8806.661	3938.114	3253.694	6264.946	5552.967
3.6	3431.277	2736.852	1130.614	961.675	2300.664	1775.177	10211.068	8798.965	3935.401	3239.499	6275.667	5559.466
3.625	3449.289	2759.387	1136.36	969.576	2312.929	1789.811	10216.179	8791.329	3931.625	3226.33	6284.554	5564.999
3.65	3463.237	2779.895	1140.243	976.907	2322.994	1802.988	10214.96	8783.729	3924.153	3214.182	6290.807	5569.546
3.675	3474.987	2798.315	1143.31	983.721	2331.677	1814.594	10212.934	8775.934	3916.798	3203.154	6296.136	5572.78
3.7	3485.503	2814.491	1146.122	990.007	2339.381	1824.484	10213.518	8767.563	3911.739	3193.231	6301.778	5574.332
3.725	3494.802	2826.826	1148.693	994.655	2346.11	1832.171	10217.626	8753.306	3909.445	3180.486	6308.182	5572.821
3.75	3502.521	2836.299	1150.894	998.311	2351.627	1837.988	10224.559	8735.544	3909.54	3166.339	6315.019	5569.205
3.775	3508.307	2844.58	1152.609	1001.85	2355.698	1842.73	10232.923	8719.613	3911.446	3154.19	6321.477	5565.423
3.8	3511.794	2851.869	1153.701	1005.213	2358.093	1846.656	10241.543	8707.401	3914.608	3145.024	6326.936	5562.377
3.825	3512.901	2858.536	1154.111	1008.73	2358.79	1849.806	10249.853	8698.448	3918.632	3138.447	6331.221	5560.001
3.85	3511.741	2864.114	1153.831	1012.074	2357.91	1852.04	10257.811	8691.463	3923.314	3133.622	6334.497	5557.842
3.875	3508.459	2868.187	1152.845	1015.006	2355.614	1853.181	10265.628	8685.272	3928.594	3129.849	6337.033	5555.423
3.9	3503.268	2870.512	1151.24	1017.399	2352.027	1853.113	10273.52	8679.127	3934.483	3126.72	6339.037	5552.407
3.925	3496.272	2870.989	1149.049	1019.206	2347.223	1851.783	10281.595	8672.701	3940.999	3124.073	6340.596	5548.627
3.95	3487.522	2869.667	1146.289	1020.479	2341.233	1849.187	10289.842	8665.946	3948.142	3121.902	6341.7	5544.044
3.975	3477.045	2866.569	1142.973	1021.239	2334.072	1845.33	10298.184	8658.944	3955.891	3120.259	6342.293	5538.685
4	3464.867	2861.786	1139.113	1021.521	2325.754	1840.266	10306.532	8651.809	3964.219	3119.206	6342.313	5532.603
4.025	3451.032	2855.37	1134.726	1021.347	2316.306	1834.023	10314.832	8644.629	3973.109	3118.784	6341.722	5525.845
4.05	3435.607	2847.355	1129.843	1020.733	2305.765	1826.622	10323.106	8637.45	3982.596	3119.002	6340.509	5518.448
4.075	3418.661	2837.781	1124.485	1019.683	2294.176	1818.098	10331.387	8630.289	3992.698	3119.847	6338.688	5510.442
4.1	3400.257	2826.668	1118.667	1018.189	2281.59	1808.479	10339.677	8623.143	4003.394	3121.291	6336.284	5501.852
4.125	3380.459	2814.081	1112.4	1016.281	2268.059	1797.8	10347.965	8616.009	4014.642	3123.302	6333.324	5492.707
4.15	3359.336	2800.057	1105.696	1013.942	2253.64	1786.115	10356.235	8608.88	4026.401	3125.847	6329.835	5483.033
4.175	3336.958	2784.649	1098.572	1011.189	2238.386	1773.46	10364.455	8601.756	4038.632	3128.898	6325.822	5472.858

4.2	3313.394	2767.908	1091.047	1008.028	2222.347	1759.88	10372.585	8594.632	4051.307	3132.424	6321.278	5462.208
4.225	3288.721	2749.892	1083.142	1004.468	2205.579	1745.424	10380.627	8587.505	4064.401	3136.398	6316.226	5451.107
4.25	3263.034	2730.677	1074.882	1000.534	2188.152	1730.143	10388.606	8580.374	4077.898	3140.792	6310.709	5439.582
4.275	3236.43	2710.319	1066.295	996.226	2170.135	1714.093	10396.558	8573.237	4091.779	3145.575	6304.779	5427.662
4.3	3209.001	2688.883	1057.403	991.554	2151.598	1697.329	10404.512	8566.098	4106.024	3150.719	6298.488	5415.378
4.325	3180.838	2666.508	1048.232	986.597	2132.605	1679.911	10412.487	8558.959	4120.608	3156.197	6291.879	5402.762
4.35	3152.008	2641.961	1038.797	980.743	2113.21	1661.218	10420.495	8551.859	4135.502	3162.025	6284.993	5389.833
4.375	3122.533	2616.029	1029.104	974.648	2093.428	1641.381	10428.54	8544.763	4150.713	3168.287	6277.827	5376.476
4.4	3092.515	2589.581	1019.198	968.405	2073.316	1621.175	10436.619	8537.665	4166.262	3174.955	6270.358	5362.709
4.425	3062.069	2562.739	1009.114	962.035	2052.955	1600.703	10444.727	8530.607	4182.101	3181.953	6262.626	5348.654
4.45	3031.317	2535.585	998.881	955.533	2032.436	1580.051	10452.86	8523.602	4198.145	3189.191	6254.715	5334.411
4.475	3000.384	2508.221	988.529	948.924	2011.855	1559.298	10461.018	8516.636	4214.307	3196.583	6246.711	5320.053
4.5	2969.39	2480.723	978.093	942.209	1991.297	1538.513	10469.205	8509.688	4230.512	3204.05	6238.693	5305.639
4.525	2937.849	2453.123	967.24	935.39	1970.609	1517.732	10475.347	8502.769	4245.236	3211.546	6230.11	5291.223
4.55	2904.746	2425.581	955.329	928.535	1949.417	1497.046	10474.47	8496.425	4254.994	3219.391	6219.476	5277.034
4.575	2871.303	2398.625	943.126	921.91	1928.177	1476.715	10469.868	8492.027	4262.385	3228.485	6207.483	5263.542
4.6	2838.423	2372.569	931.116	915.669	1907.307	1456.9	10464.371	8490.731	4269.367	3239.575	6195.004	5251.156
4.625	2806.471	2346.455	919.456	909.058	1887.015	1437.397	10459.449	8489.312	4276.739	3250.136	6182.71	5239.176
4.65	2775.54	2320.433	908.172	902.12	1867.368	1418.314	10455.544	8487.969	4284.649	3259.926	6170.895	5228.043
4.675	2745.594	2295.618	897.266	895.569	1848.328	1400.049	10452.443	8490.914	4293.015	3271.8	6159.428	5219.114
4.7	2715.752	2272.107	886.775	889.422	1828.977	1382.686	10449.797	8499.023	4301.655	3286.301	6148.141	5212.721
4.725	2686.348	2249.416	876.63	883.354	1809.719	1366.062	10447.381	8511.146	4310.398	3302.761	6136.983	5208.384
4.75	2657.842	2226.97	866.807	877.048	1791.035	1349.921	10445.216	8525.55	4319.146	3320.246	6126.07	5205.304
4.775	2630.211	2204.352	857.271	870.298	1772.94	1334.054	10443.37	8540.754	4327.838	3337.974	6115.532	5202.781
4.8	2603.294	2181.345	847.941	863.028	1755.353	1318.318	10441.83	8555.831	4336.437	3355.47	6105.393	5200.361
4.825	2576.492	2157.924	838.191	855.25	1738.301	1302.674	10440.508	8570.373	4344.936	3372.559	6095.572	5197.814
4.85	2550.456	2134.225	828.734	847.088	1721.722	1287.137	10439.263	8584.325	4353.347	3389.264	6085.915	5195.061
4.875	2525.111	2110.369	819.549	838.621	1705.562	1271.748	10437.932	8597.796	4361.639	3405.673	6076.294	5192.123
4.9	2500.444	2086.485	810.633	829.928	1689.811	1256.557	10436.411	8610.93	4369.777	3421.856	6066.634	5189.074
4.925	2476.414	2062.705	801.951	821.078	1674.462	1241.627	10434.666	8623.846	4377.742	3437.848	6056.924	5185.998
4.95	2453.07	2039.151	793.574	812.13	1659.496	1227.021	10432.72	8636.615	4385.526	3453.652	6047.195	5182.964
4.975	2430.471	2015.928	785.461	803.132	1645.009	1212.796	10430.614	8649.274	4393.119	3469.246	6037.495	5180.028
5	2408.802	1993.122	777.719	794.123	1631.083	1198.999	10428.389	8661.854	4400.499	3484.603	6027.891	5177.251
5.025	2387.968	1970.794	770.301	785.154	1617.666	1185.64	10426.102	8674.356	4407.657	3499.679	6018.445	5174.677
5.05	2367.991	1949.15	763.206	776.274	1604.784	1172.876	10423.791	8686.783	4414.58	3514.43	6009.212	5172.354

5.075	2348.964	1928.26	756.464	767.526	1592.5	1160.734	10421.476	8699.152	4421.245	3528.817	6000.231	5170.335
5.1	2330.929	1908.199	750.101	758.953	1580.828	1149.246	10419.158	8711.464	4427.623	3542.808	5991.534	5168.656
5.125	2313.934	1888.384	744.134	749.925	1569.8	1138.459	10416.829	8723.741	4433.687	3556.398	5983.142	5167.342
5.15	2298.011	1869.607	738.578	741.151	1559.434	1128.457	10414.483	8736.02	4439.429	3569.624	5975.054	5166.396
5.175	2283.204	1852.007	733.453	732.74	1549.751	1119.267	10412.11	8748.242	4444.838	3582.414	5967.271	5165.827
5.2	2269.57	1835.628	728.792	724.711	1540.779	1110.918	10409.704	8760.368	4449.881	3594.703	5959.823	5165.665
5.225	2257.123	1820.511	724.583	717.084	1532.539	1103.427	10407.258	8772.398	4454.515	3606.448	5952.743	5165.949
5.25	2245.882	1806.58	720.83	709.878	1525.053	1096.702	10404.769	8784.346	4458.707	3617.628	5946.062	5166.718
5.275	2235.871	1793.672	717.545	703.121	1518.326	1090.551	10402.235	8796.21	4462.44	3628.236	5939.796	5167.974
5.3	2227.095	1782.206	714.734	696.839	1512.362	1085.367	10399.654	8808.004	4465.712	3638.279	5933.942	5169.724
5.325	2219.574	1772.156	712.401	691.033	1507.172	1081.123	10397.024	8819.769	4468.521	3647.759	5928.503	5172.009
5.35	2213.316	1763.517	710.548	685.702	1502.768	1077.815	10394.342	8831.522	4470.855	3656.669	5923.486	5174.852
5.375	2208.253	1756.251	709.161	680.831	1499.093	1075.419	10391.611	8843.256	4472.709	3665	5918.902	5178.256
5.4	2204.378	1750.298	708.228	676.406	1496.15	1073.892	10388.834	8854.955	4474.086	3672.747	5914.748	5182.209
5.425	2201.66	1745.632	707.737	672.428	1493.923	1073.204	10386.015	8866.604	4475	3679.915	5911.015	5186.689
5.45	2200.01	1742.165	707.647	668.856	1492.363	1073.309	10382.853	8878.19	4475.271	3686.518	5907.582	5191.672
5.475	2199.171	1739.834	707.839	665.672	1491.332	1074.162	10377.949	8889.71	4474.06	3692.583	5903.889	5197.126
5.5	2199.073	1738.592	708.298	662.871	1490.776	1075.721	10370.88	8901.119	4471.187	3698.15	5899.693	5202.97

10. APPENDIX B: Multibody Vehicle Dynamic Simulation Output for Semi-trailer Truck

Time	Vertical Force on 1st left tire	Vertical Force on 2nd left tire	Vertical Force on 3rd left Tire	Vertical Force on 4th left Tire	Vertical Force on 5th left Tire	Vertical Force on 1st Right Tire	Vertical Force on 2nd Right Tire	Vertical Force on 3rd Right Tire	Vertical Force on 4th Right Tire	Vertical Force on 5th Right Tire
0	24461.6	31011.9	64787.8	37197.3	34216.8	29704	27541.8	57998.9	38995.3	32654.1
0.025	25738.8	41074.2	51611.8	37623	36413.2	27946.3	43716.5	54846.4	38243.3	36740.4
0.05	24220.2	45748.9	41115.4	36831.8	37457.2	28661.3	55413.3	50617.7	36606.1	37021
0.075	24207.7	43659.9	40922.2	37203.5	37417.8	28842.5	56302.8	53550.5	36136	36136
0.1	24615.3	42559.1	43430.9	37278.1	37162.7	28188.1	54607.9	55432.8	36092.7	35782.5
0.125	25448.3	45335.5	46392.7	36954.4	36896.2	27087.1	52386.6	53335.1	36642.4	36426.8
0.15	26183	48495	48794.8	36716.2	36749.8	26213.9	50010.8	50143.5	37740.1	37653.3
0.175	26080	49065.3	49169	36711.2	36766.9	26239.2	49128.6	49044.7	38699	38657.2
0.2	25425.7	47710.3	47914.6	36869.4	36906.7	26789.2	50216.5	50266.4	39060.3	39004.5
0.225	24473.4	45150.2	45414.8	36983.8	36982.4	27592.3	52806.2	52934.3	38769.2	38667.7
0.25	24208.1	43800.4	44061.6	36813.6	36775.7	27871.6	54321.2	54444.5	38143.4	37999.2
0.275	24524.6	44030.5	44278.8	36346.6	36296.4	27650.9	54216.6	54294.8	37709.1	37555.7
0.3	25193.5	45660.7	45883.5	35772.1	35741.2	27057.7	52517.7	52531	37737.9	37615.1
0.325	25778	47204.8	47379.3	35381.4	35388.3	26607.1	50476.9	50434.2	38139.9	38066.5
0.35	25805.5	47375.6	47509.6	35321.9	35361.6	26679.2	49696.3	49629	38592.2	38555.5
0.375	25398.2	46217.6	46343.5	35527.2	35575.2	27102.6	50396.8	50356.9	38796.1	38761
0.4	24832.5	44488.7	44653.2	35822.4	35850.6	27640.1	52032.9	52056.1	38669.1	38601.7
0.425	24629.9	43761.8	43984.4	35947.1	35945.5	27781.6	53182.3	53270.2	38375.2	38267.5
0.45	24813	44231.8	44502.9	35821.6	35798.5	27559.5	53258.6	53379.4	38182	38050.5
0.475	25271.6	45751.7	46033.9	35607.7	35586.6	27090.6	52289.3	52402.9	38261.2	38136
0.5	25623	47068.7	47320.4	35517.3	35520.1	26759.5	51217.7	51298.9	38558.6	38462.8
0.525	25618	47300.2	47505.5	35655.1	35686.9	26793.5	50899.8	50947.6	38871.1	38805.1
0.55	25337.8	46531.4	46700.5	35994.1	36043.1	27091.1	51515.3	51548.9	39015.2	38960.1
0.575	24994.2	45350.9	45514.2	36318.2	36366.4	27447.3	52559	52598.7	38904.1	38837.6

0.6	24908.6	44783.9	44964.8	36399.9	36437.8	27546.3	53127	53181.7	38607	38520.8
0.625	25096.7	45106.5	45309.6	36209.5	36229.6	27385	52920.3	52980.5	38309.4	38203.8
0.65	25460.9	46083.1	46291.1	35893.6	35908.4	27067.8	52002.1	52051.7	38142.7	38034
0.675	25702.2	46822.3	47012.5	35674.9	35704.6	26867.1	51114.3	51142.1	38122.2	38031
0.7	25686.9	46818.2	46981.1	35690.8	35745.1	26901.6	50812.9	50821.5	38171.8	38104.8
0.725	25483.8	46121	46268.5	35928.3	36000.6	27108.2	51160.4	51167.2	38186.9	38133.2
0.75	25249.1	45275.3	45435.1	36229.8	36302.9	27318.4	51788.6	51813.6	38123.2	38064.3
0.775	25192.9	44994.9	45189.4	36408.4	36466.8	27331.9	52134.7	52189.7	38006.9	37929.1
0.8	25336.9	45439.9	45674.4	36398.9	36437.5	27154.5	51969.6	52051.8	37902.3	37804.3
0.825	25578.2	46361.1	46618.1	36292	36319.8	26889	51440.9	51535.6	37866.2	37759.5
0.85	25722	47078.6	47330.4	36246.4	36279.5	26735.9	51026.7	51114.8	37901.2	37801.4
0.875	25705	47218.6	47444.4	36369.1	36419.3	26761.7	51004.6	51073.4	37962.7	37878.9
0.9	25577.7	46841.5	47037.2	36646.3	36714.2	26911.2	51373.9	51422.4	37996.9	37927
0.925	25455.3	46323.4	46502.5	36938.6	37014.1	27058.5	51800.1	51835.5	37965.9	37899
0.95	25466.4	46158.2	46338.6	37100.1	37169.7	27060.2	51902.1	51934.7	37867.8	37792.3
0.975	25614.6	46490.9	46682.7	37080.5	37137.1	26918.4	51587.2	51622.3	37727.9	37639.1
1	25795.6	47068.4	47267.1	36940	36986.7	26731.1	51037	51073.3	37574.1	37476.3
1.025	25884.1	47466	47658.3	36816.7	36864.1	26623.8	50610.5	50641.3	37425.9	37329.1
1.05	25853.7	47473.9	47647.7	36827.8	36886.6	26630.8	50489.9	50509.1	37297.6	37210.4
1.075	25746.2	47123.8	47291.6	36987.1	37060.4	26710.6	50628.6	50643.6	37194.1	37118.1
1.1	25650.4	46718.7	46902.2	37211.7	37293.6	26774.8	50790.9	50818.9	37112.4	37041.7
1.125	25665	46637	46829.8	37393	37472.4	26735.3	50740.9	50773.4	37044.1	36968.8
1.15	25780	46953.1	47159.6	37472.1	37539.5	26603.3	50447.2	50485.8	36974	36886.6
1.175	25911.2	47458.3	47682.1	37474.7	37528.6	26465	50093.8	50144.6	36892.4	36792.1
1.2	25981.3	47851.8	48084.1	37481.7	37528.3	26397.5	49895.1	49954.5	36799.6	36692.1
1.225	25977.6	47975.9	48202	37569.6	37618.3	26412.6	49923.6	49981.3	36708.6	36601.7
1.25	25933.9	47862.2	48072.4	37754.2	37811.3	26479.4	50129.2	50176.5	36636	36535.3
1.275	25913.1	47696.8	47892.5	37983.6	38048.6	26538.4	50303	50337.2	36588.4	36493.4
1.3	25976	47718.9	47908.5	38178.9	38245.1	26518.4	50243.2	50268.6	36552.4	36457.8
1.325	26095.2	47966.2	48158.8	38291.1	38350.9	26433.6	49975.2	49999.4	36501.8	36401.2

1.35	26206.3	48292.5	48492.6	38323.8	38372.8	26343	49654.8	49684.4	36409.9	36299.7
1.375	26262.1	48521.1	48726.7	38325.7	38365.5	26293.8	49445.3	49482	36270.2	36151.4
1.4	26260.8	48567.6	48772.4	38354.2	38390.7	26291	49397.7	49438.3	36102.2	35979.6
1.425	26232.3	48452.7	48651.3	38440.7	38479.6	26310.4	49460.5	49500	35941.3	35819.9
1.45	26214.8	48311.5	48504	38574.3	38617.7	26312.7	49492.2	49527.5	35816.5	35698.6
1.475	26255.6	48324.9	48515.9	38708.9	38762.9	26253.6	49360.9	49393.9	35728.7	35617.4
1.5	26331.1	48508.4	48704.4	38800.8	38877.1	26161.4	49115.6	49151.8	35651.6	35556.1
1.525	26400.7	48762.8	48967.5	38856.9	38932.6	26073.3	48865.3	48909.8	35571.3	35474.1
1.55	26436.2	48967.9	49179.6	38899	38965.4	26019.9	48717.6	48771.5	35473.2	35365.6
1.575	26441.1	49064.3	49277.1	38957.3	39021.4	26003.6	48698.1	48757.6	35361	35249.5
1.6	26440.1	49071.3	49278.6	39051.5	39119.5	26002.1	48760.6	48819.7	35257.4	35147.7
1.625	26457.6	49068	49266.6	39176.2	39250.4	25990.8	48806.4	48859.8	35183.6	35078.4
1.65	26517.8	49152.6	49343.1	39304.5	39383.8	25949.9	48718.3	48764.8	35141.2	35040.2
1.675	26599.2	49320.9	49506.7	39410.9	39492.1	25893.3	48533.8	48576.1	35114.1	35014.6
1.7	26675.4	49523	49707.8	39484.6	39563.8	25841.4	48330.1	48373.2	35076.5	34975.2
1.725	26726.6	49685.9	49871.8	39532.8	39608.3	25810.8	48186.6	48234.3	35010	34904.7
1.75	26753.7	49775	49961.3	39573.9	39646.6	25799.8	48127.6	48180.9	34914.6	34805.6
1.775	26773.9	49808.9	49993.1	39624.1	39696.7	25792.7	48115.5	48172.1	34807.5	34697.4
1.8	26805.7	49838.6	50018.5	39689.1	39764.5	25772.2	48086.7	48143.3	34712.1	34604
1.825	26865.1	49912.3	50087.7	39763.4	39842.7	25735.2	47981.7	48036.7	34642.5	34537.8
1.85	26943.2	50037.9	50210.7	39836.7	39918.8	25690.4	47807.6	47862.3	34595.9	34494.4
1.875	27014.2	50189.1	50362.9	39901.4	39983.9	25643.6	47615.2	47673.5	34557.2	34456.6
1.9	27064.9	50324.6	50503	39957.2	40037.8	25606.2	47461.8	47528.6	34508.9	34406.9
1.925	27095.6	50423.1	50607.7	40009.8	40087.6	25578.1	47373	47450.9	34443.5	34339.1
1.95	27116.2	50494.7	50684.8	40066.2	40141.9	25548.6	47329.8	47418.4	34366.7	34260.3
1.975	27138.7	50593.1	50763.2	40129.9	40205.4	25506.4	47300.2	47383.8	34292.5	34186
2	27168.1	50733.4	50881.1	40201	40277.7	25446.9	47241.6	47311.8	34234.3	34129.7
2.025	27200.1	50904.4	51059.6	40277.6	40356.7	25374.9	47127.9	47209.8	34197.6	34096.3
2.05	27225.9	51085.6	51249.5	40358.2	40440.1	25301.6	46984.4	47077.8	34177.2	34079.9
2.075	27239.4	51246.9	51409.9	40439.8	40524	25237.1	46846.5	46942.4	34160	34066.1

2.1	27241.5	51367.9	51526.5	40516.7	40602	25183.7	46731.8	46827.2	34130.7	34038.9
2.125	27234.3	51453	51607.6	40582.2	40667	25140.7	46635	46730.2	34080.4	33989.2
2.15	27225.7	51523.8	51674.3	40631.2	40714.5	25101.3	46534.5	46628.9	34010.1	33918.6
2.175	27218.2	51599.7	51745.1	40662.9	40744.4	25064.1	46407.3	46499.6	33928.8	33836.9
2.2	27209.9	51685.9	51824.9	40681.1	40760.9	25031.8	46246.1	46335.2	33846.7	33755.1
2.225	27195.3	51771.9	51903.5	40691.5	40769.8	25010.5	46064.3	46150.4	33771.1	33680
2.25	27168.8	51841.7	51965.3	40698.8	40775.3	25005	45886.7	45971.7	33702.7	33612.2
2.275	27128.9	51886.1	52002	40712.2	40786.1	25015.6	45734.4	45821.4	33640.5	33549.8
2.3	27078.1	51909.8	52018.5	40735.1	40805.1	25037.8	45613.9	45706.6	33584.7	33492.8
2.325	27021.5	51927.6	52030	40761.8	40826.4	25065.8	45518.2	45620.1	33535.3	33441
2.35	26961.9	51955	52051.3	40787	40844.7	25096.5	45435.9	45549.9	33494.6	33397
2.375	26899.1	51998.1	52087.4	40827.9	40856.6	25130.8	45360.6	45489	33479	33365.5
2.4	26831.6	52050	52130.5	40875.7	40869.9	25170	45296.3	45440.6	33488.8	33354.1
2.425	26754.5	52097.4	52167	40914.8	40906	25219	45255.2	45417	33514.3	33384.1
2.45	26663.6	52127.6	52184.5	40941.6	40931.9	25280.9	45249	45430.4	33546.2	33421.8
2.475	26564.5	52133.5	52175.5	40944.1	40926	25349.9	45279.8	45482.3	33571.9	33446.7
2.5	26449.8	52111.1	52134.8	40908.1	40880.1	25426.5	45338.1	45561.4	33587.1	33460.5
2.525	26318.5	52059.7	52059.6	40834	40798.1	25500.5	45420	45661.2	33606.4	33481.6
2.55	26181	51964.1	51934.2	40727.6	40686.3	25576.2	45496.1	45751.3	33651.3	33531.6
2.575	26041.4	51809.4	51745.4	40591.6	40545.8	25662.8	45549.6	45816.9	33733.9	33621.7
2.6	25895.9	51594.2	51495	40421.6	40370.2	25771.7	45603.9	45884.3	33852.5	33748.2
2.625	25737.5	51318.4	51186.2	40207.6	40147.6	25908.2	45695.7	45994.2	33993.6	33895.7
2.65	25561.6	50993.4	50831.9	39944.6	39872.7	26071.6	45856.7	46179.8	34148.1	34054.9
2.675	25369.3	50637.2	50448.5	39639	39553.4	26255.5	46092.7	46446.5	34320.2	34231.5
2.7	25059.7	50265.7	50048.8	39307.9	39209	26411	46387.7	46776.3	34526.9	34444.8
2.725	24707.9	49886.3	49636.1	38970.9	38860.3	26515.1	46718.4	47143.3	34787.3	34715.3
2.75	24458.3	49494.6	49199.2	38640.1	38519.2	26749.2	47077.1	47529.3	35109.6	35051
2.775	24281.3	49075.2	48731.5	38310.1	38178	27069.3	47476.7	47944.7	35481	35436.9
2.8	24186.6	48614.9	48237.3	37962.4	37816.1	27490.6	47932	48416	35875.2	35844.7
2.825	24130.8	48114.3	47721.2	37579.6	37415.6	27963.6	48443.4	48954.8	36269.9	36251.5

2.85	24087.4	47272.3	47185.9	37154.8	36971.4	28442.3	48852.2	49548.9	36657.9	36651.6
2.875	24036.1	46577.9	46562.7	36684.8	36480.9	28883.5	49317.2	50166.8	37038.4	37044.6
2.9	23952.9	46063.1	45503.2	36157	35927.8	29263.3	50058.9	50496	37399.6	37416.4
2.925	23820.3	45543.6	44967.7	35593.1	35333	29568.7	50804.9	51306.9	37759.2	37789.6
2.95	23627.5	45052.9	44610.1	35045.8	34760.4	29803.9	51603.4	52311.6	38169.4	38221.6
2.975	23384.2	44618.1	44206.1	34588.1	34303.1	29992	52508	53326.9	38706.9	38788.5
3	23110.1	44142.1	43698.2	34239.2	33963.9	30154.1	53422.8	54277.5	39375.9	39506.8
3.025	22826.4	43586.8	43105.6	33940	33673.9	30302	54277.2	55158.2	40123	40310.6
3.05	22550.4	42982.3	42470.7	33600.2	33335.1	30446	55075	55984.4	40860.8	41099.8
3.075	22293.2	42364.8	41824.3	33148.1	32873.8	30596.7	55841.1	56775.6	41518.1	41798.5
3.1	22058.7	41741.2	41170.9	32563.5	32274.2	30763.6	56590	57542.1	42076	42391.4
3.125	21846.1	41092	40488.4	31876.8	31574.5	30952.7	57318.8	58278	42565.4	42916.9
3.15	21652.9	40395.2	39750.4	31141.1	30833	31165.2	58016.5	58972.7	43038.6	43433.2
3.175	21476.2	39642.5	38952.2	30398.8	30093	31398	58680.8	59624.4	43539.1	43985.5
3.2	21312.4	38848.8	38113.8	29665.6	29367.4	31645	59320.9	60249.2	44086.3	44589.6
3.225	21157.7	38039.5	37266.6	28935.3	28645.6	31899.9	59957	60874.6	44677.6	45239.1
3.25	21007.2	37235.6	36434.6	27889.5	27910.1	32158.5	60611.4	61528.3	45123	45921.2
3.275	20861.9	36438	35618.9	27080.9	27110	32413.9	61294.3	62218	45761.9	46621.2
3.3	20713	35629.6	34803.2	26473	25998.8	32672	61999.7	62926.3	46706.2	47143.6
3.325	20558.6	34809.9	33983.2	25833.4	25348	32930.6	62734.1	63662.9	47669	48156.1
3.35	20395.4	34002.3	33184.1	25167	24738.1	33186.2	63531.3	64473.7	48650.4	49260.3
3.375	20221.4	33241.5	32446.7	24476.3	24027.6	33434.6	64430.2	65404.7	49654.5	50296.3
3.4	20037.9	32529.5	31766.9	23735	23242.4	33676.3	65428.7	66448.5	50653.1	51293.2
3.425	19849.7	31847.8	31110.4	22941.5	22413.4	33915.2	66488.9	67557	51642.7	52286.8
3.45	19660.7	31169.5	30444.1	22113.8	21563.4	34155	67574.8	68680.9	52642.1	53292.6
3.475	19472.9	30469.3	29741.7	21266.3	20703.9	34398	68662	69790.9	53665.1	54321.6
3.5	19287.3	29731.3	28991.7	20403.6	19833.7	34644.9	69733.8	70869.6	54710.4	55378
3.525	19104.7	28950.8	28192.1	19526.7	18953.3	34895.6	70780.5	71911.5	55764	56444.8
3.55	18926	28129.6	27348.6	18636.8	18050.7	35149.3	71798.9	72918.2	56804.8	57509.5
3.575	18752	27275	26470.9	17719.7	17119.8	35404.7	72788.5	73892.9	57829.8	58557.7

3.6	18571.1	26395.5	25571.9	16776.2	16162.5	35651.7	73749.8	74836.1	58829.4	59577.2
3.625	18389.1	25502.9	24659.6	15810.3	15185.2	35888.8	74679.9	75750.1	59800.8	60563.3
3.65	18212.9	24602.8	23741	14833.5	14195.6	36124.2	75582.3	76636.2	60742.6	61519.5
3.675	18042.9	23702.3	22819.1	13855.8	13201.5	36357.5	76459.1	77499.9	61658.9	62453.4
3.7	17878.4	22807.4	21907.6	12886.8	12220.3	36587.7	77314.4	78338.1	62554.9	63363.1
3.725	17734	21945.2	21034.4	11929.3	11256	36803.8	78128.4	79135.2	63438	64254.8
3.75	17627.9	21147.8	20258.1	10982.8	10304.7	36996.4	78838.4	79845.3	64311.3	65134.1
3.775	17565.2	20462.3	19592.6	10046.1	9357.4	37165.3	79431.9	80433.6	65177.7	66011.6
3.8	17544.7	19908.4	19043.8	9111.3	8411.7	37312.6	79911.8	80883.5	66046.9	66891.1
3.825	17562.4	19486.4	18662.5	8175	7469	37439.5	80274.1	81183.9	66921.8	67770.1
3.85	17613.1	19191.8	18407.7	7235.9	6521.5	37547.9	80521.2	81381.4	67804.4	68656.4
3.875	17728.9	19015.5	18266.7	6299.3	5570	37633.2	80663.1	81483.6	68692.9	69553.7
3.9	17961.1	18948.9	18231.7	5357.2	4638.6	37751.8	80679.7	81471.1	69595.9	70439.6
3.925	18243.4	19063.3	18379.3	4488	4043.2	37903.5	80482.9	81254.1	70502.6	71529.1
3.95	18423.3	19182.5	18525.5	3868.8	3246.9	38088.2	80395.4	81174.9	71639.3	72483.2
3.975	18134.9	18453.5	17815.7	3119.9	2434.7	38431	81243.8	82083.4	72471.9	73170.4
4	17481.4	17148.4	16540.2	2428	1751.4	38687.9	82749	83659.2	73091.2	73733.6
4.025	16861.7	15752.4	14757.2	1879.2	1212.1	38788.4	84193.2	87692.6	73647.5	74297
4.05	16649.4	14466.9	14730.8	1434.5	780.7	38857.9	84670.7	91259.8	74332.9	75022.8
4.075	16844.6	13566.6	14302.6	989.2	352.8	39002.4	84237.4	92659.8	75135.4	75888.4
4.1	17239.3	13063.7	13800.6	496.9	0	39235.3	83517	91861.3	75973.7	76810.8
4.125	17806.8	12683.6	13046.9	0	0	39604.6	82733.8	89976.7	76617.9	77881.4
4.15	18194.1	11975.6	12043.4	0	0	40216.6	82608.2	89094.5	77242.9	78482.1
4.175	18162.6	11226.7	11270.4	0	0	40691.2	83561	90271.3	77416.1	78503.3
4.2	17881.7	10577.4	10824.4	0	0	40899.1	85003	93165.6	77064.7	78006.3
4.225	17691.4	10056.7	10756.3	0	0	40980.5	86069.1	96373.7	76169.4	76999.2
4.25	17783.3	9652.7	10782	0	0	41079.4	86281.3	98322	75248.8	76019.1
4.275	18174.3	9292.1	10577.5	0	0	41271.2	85774.5	98325.6	74710.6	75476.5
4.3	18738.6	8861	9972.8	0	0	41653.5	84960.2	96810	74539.7	75328.8
4.325	19132.9	8164.1	8950.5	0	0	42126.8	84190.3	95076.8	74450	75249.9

4.35	19165.8	7222.7	7878.2	0	0	42467.7	84062.8	94415.6	74159.9	74935.6
4.375	18888.8	6362.9	7034.5	0	0	42602.1	84541.8	95052.2	73599	74319.5
4.4	18511.5	5668.4	6515.4	0	0	42548.2	85116.2	96411.1	72941.7	73601
4.425	18282.4	5367	6413.9	0	0	42419.3	85465.3	97628.9	72455.2	73071.6
4.45	18267.1	5083.2	6294.5	0	0	42369.9	85409.5	98048.3	72305.3	72893
4.475	18368.4	4857.7	6131.5	0	0	42444	85161.5	97824.8	72465.6	73052.8
4.5	18451.2	4625.2	5838.6	0	0	42618.1	85153.2	97623.5	72784.1	73366.1
4.525	18402.1	4298.6	5427.8	0	0	42842	85530.4	98114.5	73112.5	73675.8
4.55	18241.4	3846.8	5002.1	0	0	43033.4	86151.9	99449.7	73356	73895.8
4.575	18088.8	3317.8	4648.6	0	0	43186.4	86717.2	101194.7	73547.8	74071.9
4.6	18060.9	2793.4	4389	0	0	43339.2	87003.8	102681.9	73790.5	74308.3
4.625	18175.2	2334.8	4181.2	0	0	43525.8	86996.4	103491.1	74130.3	74651.3
4.65	18381.6	1958.6	3956.3	0	0	43747.1	86892.4	103690.4	74499	75022.8
4.675	18618	1609.6	3661.5	0	0	44025.1	87440.3	103695.9	74756.5	75271.1
4.7	18729.1	1333.1	3274.5	0	0	44312.8	88149.6	104021.5	74774.6	75264.4
4.725	18654.6	929.4	2844.3	0	0	44494.5	89292.4	104802.9	74557.7	75015.9
4.75	18480.6	473.1	2397.9	0	0	44564.2	90586	105763.9	74209.3	74644.4
4.775	18308.3	15.3	1918.5	0	0	44568.6	91552.6	106403.7	73871.8	74303.7
4.8	18182.3	0	1398.9	0	0	44541.8	91997.4	106352.2	73636.6	74084.3
4.825	18075.4	0	863.4	0	0	44508.9	91948.9	105625.2	73496.7	73967.4
4.85	17927.6	0	339.7	0	0	44466.5	91749.1	104562	73381	73868
4.875	17699.1	0	0	0	0	44393.7	91810	103680.3	73205.7	73692.6
4.9	17403.2	0	0	0	0	44274.7	92307.1	103406.1	72939.1	73411
4.925	17099.7	0	0	0	0	44114.8	93056	103506.6	72641	73098.4
4.95	16851.7	0	0	0	0	43935.4	93647.7	103580.8	72416.8	72875
4.975	16683	0	0	0	0	43724.4	93780.6	103275.7	72322.7	72797.1
5	16529.8	0	0	0	0	43423.7	93415.2	102531.3	72339.1	72836.6
5.025	16349.6	0	0	0	0	43100	92831.1	101638.7	72399	72911.3
5.05	16171.8	0	0	0	0	42838.1	92392.2	100972.2	72437.1	72945.6
5.075	16027.8	0	0	0	0	42673.9	92346.3	100778.8	72416	72905.1

5.1	15952.7	0	0	0	0	42599.3	92617.3	100959.5	72353.7	72817.5
5.125	15965.7	0	0	0	0	42579.1	92924.8	101203.8	72306.6	72750.6
5.15	16051.5	0	0	0	0	42572.8	93027.5	101254.7	72328.5	72762.8
5.175	16183	0	0	0	0	42552.1	92877.4	101071.7	72457	72888.3
5.2	16419.7	0	0	0	0	42528.1	92644.3	100852.2	72632.2	73058.8
5.225	16686.4	0	0	0	0	42525.3	92582.7	100876.7	72770.9	73184.7
5.25	16910.9	0	0	0	0	42483.5	92797.4	101260.8	72826.7	73220.9
5.275	17107.8	0	0	0	0	42371.8	93182.7	101887.4	72825.2	73201.6
5.3	17304.9	0	0	0	0	42169.4	93488.7	102483.1	72838.9	73207.2
5.325	17527.2	0	0	0	0	41871.9	93505.1	102820.2	72927.9	73300.1
5.35	17761.3	0	1501.1	0	0	41511.4	93175.9	103175.3	73091.4	73473.7
5.375	17958.6	0	2914.7	0	0	41161.9	92398.1	103698.7	73314	73712.4
5.4	18136.6	0	3757.7	0	0	40877.6	91233.4	104199.6	73652.4	74083.1
5.425	18337.1	0	4273.3	0	0	40663.6	89883.8	104591.3	74009.5	74473.9
5.45	18587	0	4768.9	0	0	40497.2	88351.1	104788.6	74322.3	74813.2
5.475	18892.6	2222	5400.8	0	0	40362.6	87088.9	104668	74528.7	75032.9
5.5	19214.1	3911.6	6574.3	0	0	40279.5	85922.1	104167.5	74637	75150.5
5.525	19527.6	5117.3	8631.5	0	0	40219.2	84652.8	103512.8	74739.7	75273.2
5.55	19818.7	6821.2	9290.1	0	0	40164.2	83516.1	102466.6	74836.9	75398.2
5.575	20116.2	7657.6	9762.6	0	0	40108.7	82755.3	100914.5	74981.9	75581.5
5.6	20412.7	8337.6	10054	0	0	40023.1	81696.2	98872.4	75128.7	75762.6
5.625	20673.6	8998.3	10446.5	0	0	39877	80699.4	96518.1	75197.8	75848.3
5.65	20868.1	9714	11115.1	0	0	39658	79975.2	94244.3	75114.9	75767.3
5.675	20976.5	10488.1	11979.2	0	0	39367.6	79638	92432.8	74870.5	75502.8
5.7	20995.5	11441.8	13013.3	0	0	39008.5	79517	91246.3	74528	75130
5.725	20936.9	12605	14173.2	0	0	38581.3	79360.4	90587.2	74183.9	74777.9
5.75	20822.7	13729.6	15378.4	0	0	38093.7	79153.3	90152.1	73966.2	74575.2
5.775	20679.5	14764.6	16554	0	0	37563.9	78792.3	89602.5	73971	74602.6
5.8	20522.1	15738	17597.5	0	0	37015	78233.4	88733.1	74216.1	74884.8
5.825	20311.5	16645.5	18494.9	0	0	36462.9	77571.2	87503	74638	75347.1

5.85	20051.3	17539.4	19280.4	0	0	35888.2	76892.4	86035.2	75121.2	75861.3
5.875	19781.3	18461.8	20015.6	0	0	35329.9	76281.6	84512	75550.2	76303.5
5.9	19548	19442.6	20781.4	3757.1	0	34812.5	75792	83081.8	77439.2	76402.9
5.925	19361.6	20617.2	21758.9	7186.3	4479.9	34364.4	75577.9	82188.3	78393.5	77549.6
5.95	19193.3	22195.4	23334.7	9205.2	8960.3	33990.5	75963.5	82666.8	77305.2	78415.4
5.975	19048.8	24106.8	25550.4	9397.6	8914.4	33683.9	77019.4	84851.8	74411	75216.1
6	19016	25818	27726.6	8576.5	7590.7	33504.6	78182.7	87395.5	70480.6	70510.1
6.025	19185	26674.3	28755.3	7996.6	7097.2	33530.7	78185.8	88138.9	67317.6	67320.4
6.05	19543.9	26376.7	28261.7	8536.3	7933.8	33747.5	76506.2	85951	66121.6	66528.5
6.075	19987.5	25185.4	26540.1	9913.6	9474.6	34056	74044.3	81436.3	66215.7	67091.2
6.1	20375.8	23396.6	23905.6	11189.6	10815	34326.8	71798.9	76234.4	66242.3	67317.6
6.125	20625.4	22165.3	21992.4	11820.2	11370.7	34533.8	70412.6	72211	65368.7	66355.4
6.15	20743.6	22082.7	21484.9	11815.1	11222.8	34586.1	70319.1	70545.5	63645.7	64334.6
6.175	20699.1	22961	22389.3	11631.8	10896.1	34453.6	71140.8	71543	61649.6	62039.6
6.2	20542.8	24076.3	23931.6	11771.1	10977.5	34246.5	72383.9	73409.1	60069.3	60299
6.225	20291.9	25137.8	25087	12558.1	11811.8	34047.1	73973.1	75346.6	59300.8	59564.2
6.25	20237.3	26245	26155.5	13904.5	13279.1	33661	74476.1	76444	59353.3	59788.5
6.275	20502.5	27285.3	27367.2	15422	14913.6	33278.6	73482.5	75160.9	59860.5	60496.6
6.3	20871.5	28486	28121.9	16742.2	16301.4	33018.9	72003.7	72960.9	60432.6	61192.9
6.325	21080.2	29494.1	28988.2	17755.1	17303.8	32868.5	70812.7	71514.1	60932.4	61711.3
6.35	21039.9	30103.8	29705.2	18404.7	17884.2	32781	70293.5	71148.3	60772.1	61473.6
6.375	20848.9	30436.8	30145.5	18621.4	18023.6	32718	70433.8	71453.1	59943.3	60525.3
6.4	20565.5	30590.2	30316.6	18697.5	18049.9	32655.2	70961.8	72041.2	58904.8	59395
6.425	20330.3	30867.4	30539.7	18808.8	18159.3	32440.7	71404.1	72435.4	58032.6	58502.4
6.45	20388.9	31200.2	30762.1	18981.5	18366.4	32232.8	71007.4	71905.5	57473.2	57985.9
6.475	20683.3	31411.7	30855.2	19179.4	18608.1	32192.4	69948	70679.4	57186.2	57766.6
6.5	20988.5	31531.1	30886.3	19347.4	18804.9	32255.3	68793.9	69404.2	57025	57658.8
6.525	21146.7	31490.8	30806.4	19445.1	18903.3	32365	68006.9	68576.5	56834.4	57485.1
6.55	21151	31233.7	30553.1	19478.2	18916.2	32476.9	67739.4	68345.7	56554.2	57186.9
6.575	21077.3	30641.8	29995.8	19462.8	18871.5	32603.2	67768.4	68453.1	56200.4	56795.6

6.6	21013.4	30164.1	29562.3	19419.1	18799.5	32760.7	67990.7	68769.7	55845	56402.6
6.625	21039.6	30280.5	29716.5	19336	18696.9	32756	68210.8	69069.4	55596.1	56135.8
6.65	21145.9	30758.5	30217.1	19273	18627.2	32651.5	68196.4	69111	55486.5	56033.1
6.675	21233.3	31262.7	30724.2	19363	18725.6	32561.6	68101	69042.2	55590.6	56168.9
6.7	21245.8	31579.4	31026	19571.6	18950.3	32527.2	68087.1	69035.6	55956	56577.9
6.725	21173.8	31631.3	31063	19841.6	19228.2	32541.9	68262.1	69216.9	56490	57145.6
6.75	21004.2	31496.6	30921.9	20051.2	19431	32593.3	68813.9	69786.3	56973.3	57639.7
6.775	20792.9	31282.9	30707.9	20107.5	19468.6	32658.4	69533.4	70526.9	57271.4	57928.8
6.8	20684.8	31230.8	30648.8	19979	19319.2	32676.4	70026	71027.8	57391.7	58034.1
6.825	20696.3	31359.9	30750.1	19589.7	18920.3	32637.6	70145	71125.7	57433.3	58073
6.85	20751.9	31377.8	30722.3	19068.8	18401.1	32630.6	69968.1	70897.6	57487.6	58140.8
6.875	20781.9	31160.8	30452.5	18606.5	17944.3	32683.3	69706.6	70574.9	57631.3	58304.4
6.9	20747.6	30576.8	29825.9	18272.9	17625	32791.9	69533.3	70356.5	57831.5	58530
6.925	20656.4	29766.7	29002.9	18018.6	17375	32956.4	69461	70277.8	58001	58711.7
6.95	20564.1	29109	28364.1	17752.1	17095.5	33083.2	69548.6	70401.9	58083.1	58781.1
6.975	20522	28839.2	28133.2	17423.4	16742.2	33121.3	69682.4	70601.5	58082.1	58754.6
7	20528.4	28936.2	28268.9	17089.8	16388.7	33085.9	69810.4	70796.8	58094.4	58746.6
7.025	20534.2	29170	28524.8	16871.6	16163.1	33039	69972.1	71002.4	58236.5	58890.3
7.05	20504	29329.1	28685.5	16849.5	16144.3	33021.3	70199.1	71244.1	58562.9	59240.3
7.075	20423.6	29325.2	28672.1	16987.9	16287	33041.2	70549.5	71590.3	59029.9	59738.6
7.1	20309.3	29212.9	28550.3	17151.7	16447.2	33089.2	70994.1	72026.2	59514.5	60245.5
7.125	20217	29095	28429.5	17203.7	16484.7	33139.4	71410.7	72436.9	59896.2	60631
7.15	20173.7	29074.4	28407.8	17055.9	16317.4	33168.8	71708.5	72727.4	60123.5	60848.6
7.175	20169.5	29104.2	28429.5	16699.9	15946.6	33186.9	71853.7	72854.3	60216.2	60931.5
7.2	20182.1	29041.4	28347.1	16246.9	15490.1	33228.4	71869.5	72835.4	60256.1	60974.3
7.225	20187.3	28762.6	28040.2	15823.5	15074.4	33321.4	71819.7	72740.6	60326.5	61062.4
7.25	20171.4	28258.9	27512.7	15489.1	14751.5	33452.4	71746.7	72629.1	60455.6	61214.8
7.275	20147.2	27681.1	26929.6	15224.1	14491.9	33583.8	71685	72554.6	60616.4	61390.9
7.3	20130.6	27219.8	26489.2	14972.2	14234.5	33673.7	71653.2	72543.5	60761.1	61534.8
7.325	20125.2	26980.2	26287.6	14701.4	13949.4	33706.2	71670.5	72612.1	60867.4	61627

7.35	20118.1	26958.4	26290	14433.7	13666.5	33693.1	71773.9	72769.1	60960.3	61704
7.375	20089.7	27061.6	26393.2	14228	13451.8	33658.5	71996.7	73016	61096.3	61833.7
7.4	20025.8	27159.2	26505.9	14134.5	13357.5	33627.4	72315.6	73364.6	61325.6	62072.5
7.425	19936.7	27189.3	26544	14153.4	13381.4	33609.6	72679.6	73749	61656.2	62424.1
7.45	19847.9	27169.6	26518.1	14235.4	13468.1	33600.7	73025.1	74089.3	62044.8	62835.5
7.475	19782.1	27149.7	26486.9	14283.5	13515.7	33593.6	73295	74341.1	62417.4	63223.2
7.5	19744.7	27152.8	26480	14211.6	13438	33588.8	73473.1	74499.3	62698.6	63508.1
7.525	19724.6	27149.2	26466.2	14004.8	13223.9	33596.9	73579.9	74584.9	62864.5	63670.6
7.55	19705.7	27069.3	26372.4	13699.5	12915.3	33632.1	73641.5	74620.4	62939.8	63742.9
7.575	19679	26861.8	26146.7	13360.2	12579.3	33699.3	73668.8	74615.9	62973.6	63780.2
7.6	19647.1	26537.9	25803.8	13040.6	12268.2	33787.5	73655.6	74571.9	63011.7	63828.2
7.625	19618.8	26169	25422.3	12761	11998	33874.3	73596.4	74491.1	63074.7	63902.7
7.65	19599	25844.2	25096.7	12516.2	11758.8	33940.2	73503.8	74394.4	63159.4	63994.8
7.675	19582.5	25618.3	24883	12294.4	11537.9	33978.2	73410.8	74316.7	63253.8	64089.1
7.7	19557.1	25494.2	24780.1	12095.2	11336.1	33994	73375.3	74311.7	63352.2	64181.6
7.725	19511.8	25443.4	24752.7	11931	11168.6	33998.7	73447.1	74419.9	63462.8	64285.5
7.75	19445.1	25430.9	24759.8	11821.8	11052.8	34001.6	73628	74632.7	63604	64421.9
7.775	19366.6	25430.9	24771.7	11793.3	10995.2	34006.8	73876.6	74901.1	63807.5	64604.9
7.8	19290.9	25437.2	24782.1	11811.7	11001.5	34014.4	74134.6	75164.7	64053.2	64843.1
7.825	19228.2	25456.2	24800	11849.4	11043.6	34024.5	74358.6	75382.3	64308.7	65115.8
7.85	19178.3	25484.2	24824.3	11870.1	11062.8	34041	74537.7	75548.2	64549.9	65367.2
7.875	19134	25492.3	24827.6	11830.6	11017.1	34071.1	74684.6	75678.1	64737	65554.6
7.9	19088	25441.7	24770.8	11728.8	10909.4	34121.3	74813.8	75787.9	64856.6	65670.9
7.925	19037.6	25315.3	24636.4	11577.7	10754.8	34192.2	74929.6	75881.9	64920.4	65731.5
7.95	18986	25115.6	24427.5	11396.6	10572.8	34277	75022.1	75951.4	64947.3	65757.4
7.975	18937.7	24867.4	24171.2	11204	10381.6	34364.3	75074.7	75982.7	64958.4	65769.6
8	18894	24606	23905.5	11013.8	10193.7	34444.5	75084.5	75976.9	64969.2	65782.4
8.025	18851	24358	23658.7	10835.1	10016.9	34513.1	75069.4	75955.1	64987.1	65801.7
8.05	18802	24134.9	23442.7	10675	9857.2	34571	75062.3	75951.6	65014.4	65828.6
8.075	18741.7	23937.2	23257.2	10539.4	9720.8	34621.5	75098.2	76000	65052.1	65864

8.1	18670	23764.1	23098.6	10433.3	9612.9	34666.9	75197.7	76117.6	65102.4	65911.1
8.125	18593.5	23617.4	22966.7	10358	9536	34709	75359.1	76297.6	65169.1	65975.2
8.15	18520.4	23499.9	22862.2	10311.2	9488	34749.5	75561.6	76515.2	65255.6	66060.7
8.175	18456	23410	22782.1	10286.3	9462.7	34789.9	75779.4	76741.7	65362.3	66168.4
8.2	18401.1	23337.2	22716.1	10274.1	9450.6	34833.8	75994.2	76958.3	65483.7	66292.3
8.225	18353.4	23264.8	22647.9	10269.2	9445.4	34885	76200.8	77161	65609.9	66421.3
8.25	18309.6	23175.2	22560.7	10255.1	9430.8	34946.2	76402.9	77355.4	65730.4	66543.4
8.275	18268.3	23058.7	22442.5	10217.5	9392.7	35017.4	76604.4	77545.7	65828.8	66642
8.3	18230.2	22913.9	22293	10157.3	9332.5	35095.5	76803	77729.7	65901.8	66714.2
8.325	18197	22746.4	22121.2	10077.5	9253.3	35176	76988.5	77901.4	65954.6	66765.9
8.35	18169	22565.6	21937	9981.6	9159.2	35254.8	77152.1	78053.1	65993.5	66804.1
8.375	18144.7	22379	21748	9876	9056.5	35329.3	77292.3	78183.4	66026.1	66837
8.4	18121.2	22190.1	21557.8	9767.9	8952.3	35398.9	77415.6	78299.8	66059.3	66871.3
8.425	18098.2	22003.4	21371.9	9663.7	8852.3	35461.5	77530.5	78411.3	66096.9	66910.4
8.45	18081.2	21841.7	21213.4	9562.5	8755.5	35511.5	77628.7	78510.1	66142.9	66957.8
8.475	18070.8	21717.6	21094.7	9462.9	8660.1	35549.3	77708.3	78593.4	66199.6	67015.7
8.5	18067	21637.9	21021.8	9363.6	8564.9	35575.3	77767.7	78659.1	66270.1	67087.2
8.525	18069.2	21602.9	20994.4	9263.3	8468.8	35590.8	77807.6	78706.2	66357	67175.4
8.55	18076.3	21610.1	21009.2	9160.4	8370.4	35597.9	77828.6	78734.3	66462.2	67282.4
8.575	18096.2	21684.1	21090	9053.6	8268.7	35599.3	77818.6	78730.3	66587.1	67409.7
8.6	18128.1	21801.8	21213.4	8941.6	8162.8	35596.9	77789.4	78705.7	66731.8	67558
8.625	18154.7	21922.6	21338	8822.5	8050.7	35584.1	77757.8	78676.6	66894.6	67725.1
8.65	18169.6	22012.2	21429.9	8693.8	7929.9	35574.4	77742.2	78661.6	67071.5	67906.6
8.675	18168.2	22051.2	21469.5	8553.9	7796.4	35572.5	77753.9	78672.8	67257	68095.4
8.7	18156.2	22042.3	21460.3	8401.2	7647.1	35577.5	77786	78703.9	67446	68284.2
8.725	18144.8	22009.1	21425.9	8234.3	7482.7	35585	77825.3	78742.7	67633.2	68469.2
8.75	18135.4	21967.1	21382.4	8055.1	7306.3	35594.7	77879.3	78797	67817.3	68650.5
8.775	18129.7	21923	21336.2	7867.5	7121.7	35605.1	77942	78860.6	68000.2	68830.4
8.8	18129.6	21881.5	21291.9	7676.7	6934.1	35616	78005.9	78925.7	68185.9	69013.2
8.825	18135.9	21846.8	21253.8	7487.4	6748.2	35627.1	78066.4	78986.9	68377.4	69203

8.85	18149.1	21821.9	21224.9	7302.2	6566.6	35637.7	78119.9	79041.2	68575.8	69400.4
8.875	18174.6	21808.2	21207.4	7121.8	6389.8	35647.1	78165.5	79088	68779.7	69603.9
8.9	18214.3	21806.3	21202.3	6946	6217.2	35659.8	78204.2	79129.2	68986.5	69810.5
8.925	18263.3	21821.8	21215.6	6774.3	6050.5	35670.9	78238	79167.2	69194	70015.4
8.95	18313.8	21849.4	21242	6607.1	5889	35671.5	78273.6	79208.7	69400.8	70218.5
8.975	18359.9	21877.2	21269.1	6444.8	5732.3	35662.2	78308.9	79250.8	69605.5	70419.7
9	18393.3	21894.4	21286	6287.7	5580.6	35642.7	78343.7	79292.4	69806.5	70617.6
9.025	18400.1	21895	21286.2	6135.2	5433.3	35605.9	78378.5	79333.7	70001.2	70809.3
9.05	18384	21880.5	21270.5	5986.4	5289.2	35557	78414.3	79374.5	70186.4	70991.2
9.075	18354.9	21860.7	21247.7	5841.1	5147.9	35499.9	78453.5	79416.1	70359.9	71160.9
9.1	18324.9	21840.9	21222.5	5700.1	5010.4	35444.3	78498.5	79459.7	70521.1	71318.1
9.125	18298.4	21823.3	21196.3	5565.2	4878.8	35396.4	78546.2	79501.7	70670.7	71463.8
9.15	18279.1	21799.8	21171	5438.7	4755.5	35361.7	78590.1	79539.1	70810.4	71599.9
9.175	18270.4	21759.4	21146.7	5322.5	4642.3	35344.2	78613.4	79571.1	70940.8	71727.4
9.2	18273.5	21717.6	21101	5216.3	4539.1	35344.8	78631	79584	71060.4	71844.2
9.225	18288.3	21677.2	21048.9	5120.2	4479.8	35358.6	78646.6	79578.8	71164.5	71968.3
9.25	18307.5	21631.8	20996.5	5032.6	4400.5	35383.1	78667.2	79586.6	71249.5	72053.5
9.275	18317.5	21559.6	20923.3	4959	4321.2	35422.7	78722.9	79638.7	71311.7	72099.4
9.3	18323.2	21476.8	20842	4900.6	4255	35461.6	78801	79716.6	71354.2	72124.9
9.325	18337.6	21413.9	20781.8	4856.5	4204.3	35491	78868.6	79783.9	71383.2	72141.6
9.35	18363.2	21385.8	20757	4827	4168.3	35510.3	78907	79821.6	71405.7	72155.8
9.375	18402.8	21383.8	20759.3	4816.3	4149.3	35521.5	78920.2	79834.4	71425.3	72168
9.4	18451.2	21419.2	20800	4824.2	4148	35526.4	78900.5	79815.2	71443	72179.5
9.425	18497.8	21486	20873.1	4850.6	4163.8	35511.2	78842.7	79759.2	71454.7	72186.4
9.45	18529.6	21562.2	20956.7	4914.1	4208.1	35475.9	78770	79690.1	71453.3	72175.7
9.475	18541.8	21628.9	21031.5	5007.5	4280.8	35430.2	78708.1	79633.1	71417.8	72129.3
9.5	18532.3	21672.5	21082.8	5122.3	4375.7	35381.1	78673.4	79602.9	71338.3	72041.5
9.525	18507.6	21687.8	21104	5256.4	4489.4	35335	78669.6	79601	71217.7	71913.7
9.55	18481.3	21684.6	21104.1	5411	4686.9	35298.5	78676	79604.9	71059.9	71779.3
9.575	18459.5	21674	21094.6	5587.4	4888.8	35274.6	78684.4	79606.6	70862.3	71621.5

9.6	18445.5	21666.6	21087.9	5760.6	5058.6	35262.7	78694.9	79607.9	70649.1	71408.4
9.625	18442.6	21663.4	21084.3	5914.6	5204	35261.5	78696.7	79598.5	70416.7	71167.5
9.65	18451.9	21662.2	21080.8	6061.3	5348.5	35267.4	78677.4	79565.1	70185.9	70938.8
9.675	18474.5	21664	21079	6217	5504.7	35277.3	78630.8	79503.1	69983.3	70744
9.7	18514.8	21675.4	21087.9	6384.5	5671.6	35291.3	78549	79407.8	69817.4	70586.1
9.725	18566.8	21699.8	21113.7	6551.4	5835.8	35305.8	78444.3	79296.1	69676.6	70451.1
9.75	18620.2	21759	21178.6	6702.4	5981.7	35312.3	78344.8	79197.8	69544.2	70321.2
9.775	18666.1	21851	21279.5	6829.8	6102.6	35309.6	78273.2	79134	69411	70188
9.8	18697.7	21957.4	21395.3	6939.4	6206.1	35298.3	78235.4	79106.7	69283.1	70060.2
9.825	18711.8	22054.1	21498.9	7045.8	6308.7	35280.9	78224.6	79104	69176.1	69956.1
9.85	18709.4	22122.7	21571	7159.7	6425	35260	78223.3	79106.1	69102.5	69884.5
9.875	18695.7	22158	21607	7280.9	6549	35237.3	78215.1	79097.4	69057.9	69843.1
9.9	18681	22172.6	21621.5	7396.3	6666.3	35215.9	78202	79082.9	69023.6	69810.6
9.925	18671.2	22185.8	21634.5	7490.3	6760.5	35198.8	78193.1	79073.6	68977.2	69762.8
9.95	18666.1	22203.9	21652.6	7555.3	6825.1	35184.1	78189.2	79070.1	68905.9	69686.9
9.975	18668.4	22226	21673.6	7598.4	6868.2	35172.6	78182.9	79063.7	68813	69589.3
10	18679.7	22248	21692.5	7637	6908.4	35163.9	78166.1	79044.2	68714.6	69488.2
10.025	18702.1	22267.9	21707.6	7688.5	6963	35158	78130	79003.4	68627	69400.9
10.05	18732.4	22289.4	21718.8	7760.5	7038.5	35153.5	78072.3	78938.7	68555.7	69331.7
10.075	18765	22318.2	21735.7	7849.1	7129.5	35148.3	78011	78868.5	68493.6	69270.9
10.1	18794.3	22355.6	21773.8	7943.9	7225.1	35140.6	77959.9	78821.5	68427.5	69203.8
10.125	18815.4	22403.1	21825.9	8037	7317.8	35129.9	77933.6	78806.9	68348.5	69121.7
10.15	18825.8	22452.6	21878.6	8128.3	7408.7	35116.6	77936.2	78819.3	68257.8	69027.7
10.175	18825.3	22491.5	21918.4	8223	7504.2	35101.8	77952.2	78841	68164.1	68932.5
10.2	18816.6	22508.9	21934.8	8325.7	7608.6	35086.7	77963.8	78854.4	68075.7	68844.7
10.225	18804.3	22506.8	21930.5	8435.1	7720.2	35071.9	77965.4	78854.9	67994.2	68764.9
10.25	18791.3	22496	21917.1	8543.8	7830.6	35057.7	77959.4	78846.5	67913.5	68685.4
10.275	18779.3	22483.5	21902.6	8642.8	7930.1	35043.5	77948.1	78833.1	67825.1	68596.6