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ANALYZING HIGHWAY MEDIAN SAFETY THROUGH VEHICLE DYNAMICS SIMULATIONS

A Thesis in

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by

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Abstract

This thesis presents an analysis of highway median safety through the use of dynamic simulations of vehicles. The commercially available software CarSim® was used to simulate several thousand off-road median incursions. Various contributing factors, including median cross-section geometry, vehicle type, and driver intervention, and their respective influence on accident causation, were investigated.

The results from the simulations presented in this work offer design guidance for highway engineers. The simulations indicate that overall safety of a median depends on the occurrence of both vehicle rollover and median crossover incidents. Based on this data, as the design engineer develops a new median, they can optimize a particular median geometry to prevent rollover or crossover events. Further results provide bumper height traces which allow engineers to design barriers at specific heights and at particular offsets within the median to maximize safety in the event of an off-road excursion.

To validate the simulation, vehicle trajectories from previous full-scale experimental crash tests, provided by The Texas Transportation Institute, were considered. Further verification of the aggregate simulation results was carried out by comparing them to statistical data from both the National Highway Traffic Safety Administration Traffic Safety Facts and the National Cooperative Highway Research Program Project 22-21. Both validation efforts produced strong agreement between the simulation results and the real-life crash data.

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Chapter 1

Introduction

As more people are continually travelling on the nation's highways each year, the chance of a motor vehicle accident is consequently rising as well. As a result, greater emphasis is being placed on transportation safety in today's society than ever. In addition to the great strides that have been taken to increase the safety of the vehicles on the highway, several actions have been made to make the highways themselves safer for the passengers.

In recent years, The United States Department of Transportation (DOT) has made great progress in the highway safety realm with its research and ground-breaking technologies. As a result, the number of injuries and fatalities on the nation's highways has been steadily declining. In 2007, the total number of fatalities on all of the highways in the nation was the lowest it had been since 1994 [1] and the fatality rate, defined as the number of deaths per 100 million vehicle miles traveled, was at its all time lowest. In an effort to further increase the safety of all travelers on the nation's highways, this thesis investigates the safety of highway medians by simulating median encroachments for several different vehicle classes, initial speeds, encroachment angles, and anticipated driver interventions.

1.1 Motivation

During the 2004 calendar year, an estimated 6.18 million automobile accidents were reported to the police. More than 2.78 million, or roughly 45%, of these incidents led to personal injury and 42,636 lives were lost, an increase of 2,000 over the preceding decade [2]. This fatality rate, encompassing 0.7% of all total crashes, is a bit misleading. Compared to the total number of crashes reported, the number of deaths seems very low. But, looking at this number closer, it leads to an average of 117 people killed each day in a motor vehicle accident. Ultimately, this means that every 12 minutes, there is one life lost due to an automobile accident.

One of the major causes of death during a highway accident is vehicle rollover. With the dramatic increase in sport utility vehicles (SUVs) over the past decade, the number of rollover incidents has been steadily on the rise. Due to their center of gravity being much higher than passenger cars, SUVs contributed to 36% of all fatal rollovers documented on the highway in 2004, compared to the 16% for passenger cars. Furthermore, of all the passenger injuries recorded during 2004, injuries due to SUVs rolling over were more than three times as common as those due to passenger cars rolling [2].

The 2004 National Highway Traffic Safety Administration (NHTSA) Traffic Safety Facts [2] indicated that there were 9053 fatalities due to rollover incidents on the highways. Of all the fatalities on the highway that year, rollovers accounted for 21.2%. This number was up 16.9% from the 7741 rollover deaths reported in 1994, clearly reflecting the increased SUV population on the road. But, even though the SUVs contribute to the largest number of rollovers during highway accidents, there are greater dangers during an off-road excursion. In 2004, the NHTSA predicted that 90% of all rollovers are due to a tripped phenomenon [3]. Once the vehicle departs the roadway, the chances for a tripped effect increase greatly. Several factors, including the sloped terrain, soil-tire force interaction, and the penetrating nature of the tire on soft ground, contribute to this greater likelihood of the vehicle rolling over once it has left the pavement. At this point, it is apparent that action must be taken to help prevent these tripped rollovers, and ultimately save lives on the highway.

1.2 Prevention of Highway Fatalities With Safer Vehicles

Several different approaches have been taken to help reduce the amount of deaths on the highway. For years, automobile manufacturers have concentrated on protecting the vehicle occupants in the event of a crash. Safety features, such as front and side air bags, seat belts, and active stability systems, have been developed to protect the passengers. In 2008, a projected 83% of all people travelling on the highway reported wearing their seat belts [4]. This vast increase was estimated to have saved 2,700 lives alone.

Additionally, the NHTSA recently released a statement saying that all new vehicles must be equipped with electronic stability control (ESC), beginning with the 2012 model line [5]. By mandating ESC to be on all production vehicles (heavy trucks in excess of 10,000 lbs. excluded), the amount of rollovers seen on the highway is expected to reduce greatly, possible by as large as 84%. Estimates predict that more than 10,000 fatalities and 238,000 injuries will be prevented with this new policy.

Although these advances in vehicle safety technology are projected to lead to a huge decrease in fatalities, by improving the safety of the actual highway in addition to the safety of the vehicles, even more transportation related deaths can be prevented.

1.3 Using Vehicle Dynamics Simulations for Highway Median Safety Analysis

With today's fast improving technology, computer simulations are becoming more commonly used in place of physical testing. For at least four decades, vehicle dynamics simulation packages have been used to aid in vehicle design, performance analysis, and accident reconstruction for forensic applications. Even though some of the early simulation software, including HVOSM [6], PC-Crash [7], and HVE [8], were used to aid in highway design, the use of multi-body vehicle dynamics simulations to evaluate proposed changes to highway medians remains relatively rare.

Historically, to evaluate possible design changes for a highway median, including alterations of the median geometry and placement of an in-median barrier, an extremely large budget was needed. Additionally, several years were needed to collect and analyze crash data in order to observe any changes in statistical trends.

With the results of this study, highway engineers can assess design changes in a cheap and timely manner by simulating the vehicle response during a median encroachment. Proposed alterations can be evaluated through these simulations, revealing the results of the new design, and in some instances, producing undesirable results that would have otherwise gone unnoticed. Furthermore, pros and cons can be weighed between two (or more) proposed new design features, and the best possible median design will surface.

This study considers several different variables in a median encroachment, including different vehicles, varying speeds and encroachment angles, and simulates them in an attempt to analyze the safety of highway medians. Different design characteristics of the median, including cross-section shape, slope, and width, and their relative effect on the vehicle response during the incursion are also investigated. Additionally, both bumper height and vehicle position throughout the incursion are evaluated as a means of analyzing roadway safety design features, such as location and height of cable barriers that could potentially be installed within the median.

For this thesis, a relatively new software package called CarSim [9] is used for the simulations. It was selected because it is the most widely used vehicle dynamics software in industry and it is easy to interface with external MATLAB and Simulink scripts. The software also has an advanced graphic user interface (GUI) allowing the user to easily build customized roadway profiles, define specific vehicles, and control the driver's steering, accelerator and braking inputs. More detail on CarSim and its capabilities is discussed in Section **2.3**.

1.4 Outline of Remaining Sections

The remainder of this thesis discusses the use of vehicle dynamics simulations to examine the safety of highway medians and is organized as follows. Chapter 2 introduces several previous studies in which vehicle dynamics simulations were used for accident reconstruction on the highway. Earlier studies that analyzed highway safety are also documented in this segment of the thesis. Chapter 3 presents a methodology for the simulation-based safety analysis of highway medians that was used in this study. The results for the entire batch of simulations are displayed in Chapter 4. Several influencing factors, including median profile, vehicle type, and driver inputs, and their respective effects on the in-median vehicle response are also outlined here. The resulting median design guidance derived from the data is addressed in Chapter 5. Validation and verification of the simulation results were conducted and the results are presented in Chapter 6. Validation testing was carried out with both full-scale crash test trajectories and crash statistics. Chapter 7 investigates the influence of the driver's actions throughout the median incursion. The relative importance the driver model in these simulations is also discussed here. The final chapter presents the conclusions derived from this thesis and the goals for future work.

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Chapter 2

Literature Review

Historically speaking, vehicle dynamics simulations have been used for several vehicle design and testing applications for at least three decades. Through simulation, engineers can easily evaluate new designs, both on the component and system level, without ever building a prototype. Although full-scale prototype testing remains the true test of any product, simulations can be used for the initial evaluation of the new design, thus eliminating several potential problems that may arise, and ultimately leading to a more refined design that can be built and tested as a prototype. In the long run, these simulation toolsets greatly reduce both time and cost for the entire design process.

2.1 Historical Use of Vehicle Dynamics Simulations for Accident Reconstruction

In recent years, vehicle dynamics simulation packages have been used for accident reconstruction as a means for analyzing both vehicle and highway safety. Various software programs, such as Vehicle Dynamics Analysis Non Linear (VDANL) [1], Human Vehicle Environment (HVE) [2], Highway Vehicle Object Simulation Model (HVOSM) [3], and PC-Crash [4] are often used for reenacting the vehicle response during a crash. Based on the data gathered at the scene of the incident, these programs were used to recreate the event and thus complete a full analysis of the accident causation in an attempt to prevent similar crashes.

Chrstos and Heydinger published a study [5] in which VDANL and Vehicle Dynamics Models for Roadway Analysis and Design (VDM RoAD) simulation programs were used to predict the dynamics of a 1994 Ford Taurus. Final outcomes of the simulations were compared to experimental data, showing great agreement in both the linear and non-linear range of the vehicle response for both programs (see Figure **2.1**).

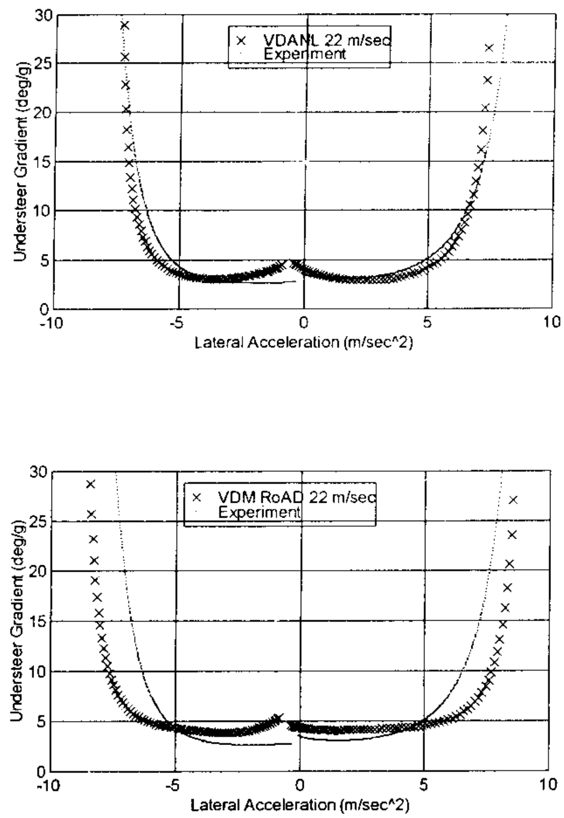

Figure **2.1** – Comparison of Understeer Gradient in Simulation and Real-Life Testing

In 1996, MacInnis Engineering Associates Ltd. completed a validation study [6] of PC-Crash [4], successfully comparing the simulation results to the trajectories and end locations experienced during full scale crashes. A more recent study, published by Steffan and Moser [7], used PC-Crash for accident reconstruction, particularly of rollover incidents. This study incorporated all major contributors of rollover events, including accurate vehicle geometries and extensive models for tire forces and moments, suspension, and fixed object impacts. Again, the results from PC-Crash were verified with full scale crash test data.

2.2 Previous Studies Analyzing Highway Safety

Over the years, there have been numerous studies analyzing, and improving upon, the safety of our nation’s highway system. This research encompasses everything from evaluating median barrier impacts to rollover events, in which both current and newly proposed highway designs are considered.

In 1993, the National Cooperative Highway Research Program (NCHRP) presented guidelines for crash testing of highway barriers in their NCHRP 350 [8] report. Crash tests for three different types of vehicles, including a 700 kg compact car, 820 kg small passenger car, and 2000 kg pickup truck, were conducted at a nominal speed of 100 kmph (62 mph). The resulting guidelines from this study are widely accepted and implemented in the realm of highway design.

In the third edition of their Roadside Design Guide, the American Association of State Highway and Transportation Officials (AASHTO) published median barrier warrant criteria for divided highways [9]. Another investigation that same year [10] investigated the influence of longitudinal median barriers on the resulting accidents associated with those sections of highway. Although the severity of the median-related crashes was reduced for those medians which contained barriers, the corresponding frequency of crashes was shown to increase. But, this rise in the crash rate is also suspected to be a result of the median cross-section itself. Different configurations (shape, slope, width, etc.) are speculated to have a large effect on the likelihood of vehicles encroaching upon the median, and at the same time, other median geometries are thought to alter the propensity of vehicles traversing the entire median and entering the opposing travel lanes. Although vehicle rollover seems as though it would be the most severe crash event experienced during a highway median encroachment, several research studies [11] [12] have indicated median crossovers, which often lead to head on collisions with oncoming traffic, can be even more dangerous than rollovers.

In 2009, the NCHRP 22-21 study [13] investigated several different median cross-sections of divided highways in a number of states across the nation. This survey of medians analyzed crash data for several different median widths and slopes, as well as medians with and without barriers. The effects of the median cross-section on the resulting accident rate (accidents per miles-years traveled) were presented in statistical form. Even though each state transportation agency provides their own design standards for median cross-sections of rural divided highways, the authors found that little variation exists between the crash data from state to state.

2.2.1 Highway Safety Analysis Using Vehicle Dynamics Simulations

One of the first studies to employ CarSim as the vehicle dynamics software package in a highway design analysis was Benekohal and Treiterer's investigation into traffic patterns on the highway [14]. Both normal driving conditions and stop-and-go scenarios were simulated with CarSim by varying the average speed, density, and volume of the traffic population. Speed, steering, vehicle trajectory, and braking outputs from the simulation of traffic propagation were compared to real-life traffic data, and after a regression analysis of each of these output variables, an R-squared value of 0.98 or better proved to verify the simulation outcomes.

A more recent study created an in-depth driver vehicle module (DVM) to predict the driver's response in various crash situations on the highway [15]. This work, published by the Federal Highway Administration (FHWA), merged a simulation created in VDANL [1] with a computational driver model which attempted to predict the human driver's cognitive processes during the emergency driving situations. Although this study provides useful results, the DVM was only created for passenger cars and Class 8 tractor trailers.

In 2008, testing which incorporated vehicle dynamics simulations was conducted by the FHWA/National Highway Traffic Safety Administration (NHTSA) National Crash Analysis Center (NCAC) [16]. Simulation work was performed with HVE [2], evaluating off-road crashes involving a large passenger, pickup truck, and small passenger vehicle. Using cable barriers that were designed in accordance with the guidelines established in the NCHRP 350 study [8], the NCAC closely examined the cases in which vehicles actually went beneath the cable barriers. As these barrier under rides were becoming more frequent in real life crashes, concern grew in the median design community, as these scenarios often led to fatalities. Comparing the simulation results to high speed video footage and vehicle sensor data obtained during full scale testing, a significant correlation between the two datasets was present.

2.2.2 Shortcomings of Vehicle Dynamics Simulations for Off-Road Conditions

As described in the previous sections, vehicle dynamics simulations have been repeatedly validated for dynamic testing on the roadway surface. But, this is not the case for off-road driving. One of the biggest obstacles in predicting the vehicle response for these off-road conditions is modeling the interaction between the ground surface and the tires. As a vehicle leaves the road surface and travels on soft ground, the tires have a tendency to sink into the ground surface. This deep penetrating nature of the tires on soft ground leads to large differences in tire forces during the vehicle traversal. As the vehicle departs the road surface and, in most cases, exhibits some degree of sideslip, the sidewall forces of the tire tend to build up as the vehicle slides over the soft ground. These forces are often great enough to lead to a tripped rollover, and since 90% of all rollover incidents are due to a tripped phenomenon [23], their inclusion in simulation models is imperative. This lack of an accurate soil-tire model is perhaps the biggest downfall of using vehicle dynamics simulations for predicting off-road vehicle behavior. There have been decades of research conducted in this realm, and several studies have drawn valid conclusions on this matter [17] [18] [19] [20] [21] [22], but to this date, there are no commercially available vehicle dynamics software packages which have validated their tire models for deep soil traversal.

2.2.3 Shortcomings of Accident Reconstruction

One of the major downfalls of recreating highway accidents for a safety analysis is the current dependence on crash reports. Although forensics experts can deduce a great deal of information from inspecting the crash site, there is still a fair amount that remains questionable. In a 1989 publication [24], Day and Hargens conclude that there are many contributory factors of the accident which must be inferred from the final outcomes of the crash. Due to these uncertainties, assumptions must be made which will result in the "most likely" crash scenarios. Often times, crash statistics are used to increase the accuracy of these assumptions, but even still, there are still several specific actions that took place during the real-life crash which cannot be inferred and thus, will not be incorporated into the ensuing reconstruction.

Another key shortcoming of accident reconstruction is that it is difficult to infer the driver's intervention prior to, and throughout, the crash. Again, these driver actions must be ascertained from the final outcome of the incident. Most previous studies of this nature neglect the driver's inputs in their reconstructive simulations, and similarly, full scale crash testing seldom incorporates any steering input during the vehicle's excursion. The vehicle is merely driven off the roadway at the desired angle of encroachment and then left to follow its natural path without any input at the steering wheel. As will be shown in detail in Chapter 7, this unknown, or even purposely neglected, steering input greatly affects the entire vehicle response during the accident and thus cannot be ignored.

2.3 Overview of CarSim Software

A relatively new software package from Mechanical Simulation Corporation called CarSim [25] was used for the simulation work in this study. Previous work towards this study [26] included a thorough survey of all commercially available software packages that could possibly be used for the simulations. In the end, CarSim was selected because it is easily interfaced with MATLAB and Simulink code, and is easy to customize each test parameter of concern.

2.3.1 Features of CarSim

Although CarSim was originally developed for the dynamic simulation of vehicles, the models have been updated over the years to reflect the advancing vehicle technologies, thus incorporating several new features in the software. The latest version of CarSim allows the user to simulate, and animate, any custom vehicle test, with the ability to output over 700 variables for post-process analyzing. The mathematical models used to calculate the vehicle dynamics during the simulation contain many typical vehicle parameters, which are frequently measured during real-life testing [25]. To increase their accuracy, these math models are based on real-life test data tables provided by notable companies across the world, including Calspan Corporation [27], Anthony Best Dynamics [28], and Morse Measurements [29].

CarSim also gives the user the option of choosing between several different models for each test parameter. For instance, there are six tire models (including the TNO Delft-Tyre and Pacejka 5.2 Magic Formula models) that are included with the software [25]. The user can pick which model they desire to use, or even create their own model, and then run the simulation. Where this becomes of particular interest for this study is the various algorithms that can be chosen to model the human driver. The user has four different models to choose from including "open loop steer control" and "driver path follower." The first method lets the user define the steering wheel angle at a certain time during the simulation while the latter defines a target path that the driver intends to follow, and then interpolates the steering input that will best lead to the vehicle following the desired path.

CarSim also allows the user to create any custom road, from rural, four lane divided highways to race tracks, upon which the vehicle will be simulated. The user has the ability to build customized three-dimensional terrain profiles, for both on-road and off-road conditions, complete with friction coefficients for each surface. The simulations can be further tailored with CarSim's ability to define custom test events and conditions. Acceleration, speed, braking, and steering are just some of the aspects of the simulation that can be controlled during the simulation. Additionally, initial values for over 200 different variables can be imported into the simulations, thus allowing virtually any desired scenario to be simulated.

2.3.2 Validation of CarSim Simulations

As the CarSim algorithms are constantly being updated to account for changing vehicle technologies, constant validation testing is needed. Numerous studies have been conducted over the years, comparing the outputs from CarSim to full-scale vehicle (and component) testing, and in the majority of cases, the simulation predictions are in close agreement with the full-scale results [30] [31] [32] [33].

In 2007, Jen and Lu published a study [32] in which CarSim was used to validate the outputs from a newly built kinematics and compliance (K&C) test machine at the Industrial Technology Research Institute in Taiwan. At first, steady-state cornering conditions were considered both in simulation and on the K&C rig. After these tests were proven to agree, dynamic handling testing ensued. Again, the results from these full scale dynamic experiments were shown to closely match the simulation outputs.

Another study, published by Yu and Johnson in 2008 [33], utilized CarSim to predict the overall effects of a power steering failure. After defining the vehicle in CarSim to mimic the test vehicle used in this study, several different steering inputs were defined with CarSim's "driver path follower" driver model. This led to a variety of steering angles and lateral accelerations experienced by the vehicle during the simulation. Data analysis from this study displays that the outputs from the simulation strongly correlated with the full scale vehicle testing results under the same steering and acceleration conditions.

As with any simulation software package, there are always going to be strengths and weaknesses. Perhaps the biggest shortcoming of CarSim is the lack of validation for off-road simulations. As stated above, the software has been tested for simulations on the roadway, even with wet and icy split-mu surfaces. But, the verification of CarSim for median encroachments, specifically off-road conditions is missing. As a result, this study discusses multiple approaches to validate the CarSim model for these off-road simulations. Chapter 6 describes the methods used to compare the simulation results from this study with both full-scale vehicle testing and published crash statistics [13] [34] [35], and presents the results from these findings.

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Chapter 3

Methodology for Simulation-Based Safety Analysis

To evaluate the safety of each median in this study, several thousand simulations were run in an attempt to create a realistic dataset. Seven different vehicles, seven initial speeds, seven encroachment angles, three steering inputs, and two braking inputs from the driver were considered for each simulated median. By altering the aforementioned variables, these median encroachment simulations incorporate several contributory factors seen in real-life accidents on the highway.

3.1 Methodology for Simulations

The methodology used to analyze the safety of highway medians with vehicle dynamics simulations is described in the following six steps:

Step 1: Define the median profile
Step 2: Choose the vehicle
Step 3: Establish the initial conditions
Step 4: Determine the driver's actions
Step 5: Run the simulation
Step 6: Summarize the outputs and repeat

External codes, which iteratively used the six step method above, were created in MATLAB to perform the simulations in batches. Each of these steps is explained in detail in the following sections.

3.1.1 Step 1: Define the Median Profile

Within CarSim, the roadway profile can be defined in a custom manner, allowing the user to simulate any median geometry desired. The X-Y horizontal geometry (top view), centerline elevation (vertical profile of the road itself), and off-centerline elevation (shoulder, median, berms, etc.) can all be defined here. Figure **3.1** shows the screen in CarSim where the roadway is built.

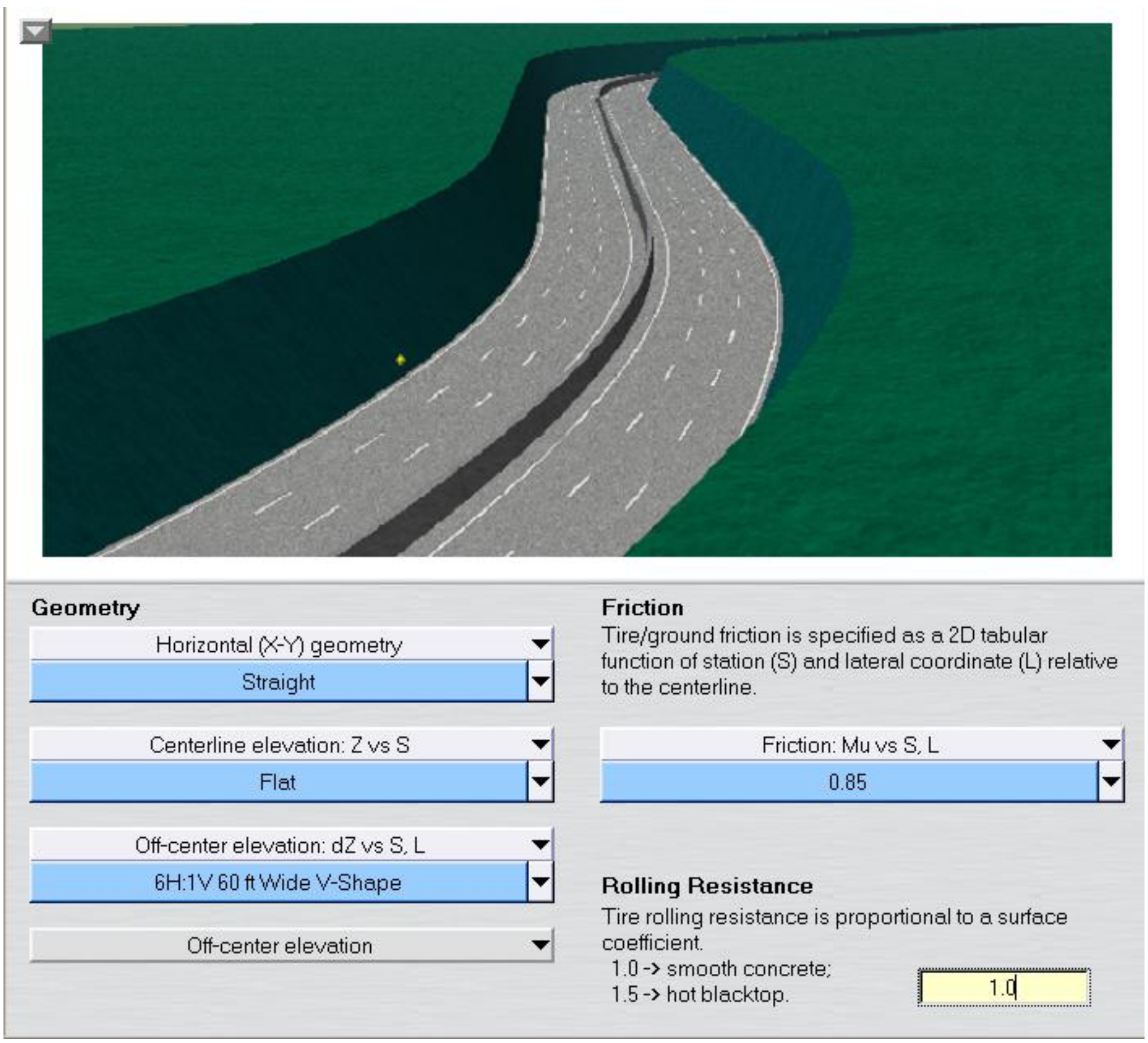

Figure **3.1** – Custom Roadway Build in CarSim

This study initially used an 18.29 m (60 foot) wide V-shaped median with a slope of 6H:1V. The road itself was given a 2% crowned slope and a 2.4 m wide shoulder with a grade of 4%, based on The Pennsylvania Department of Transportation's design standards. Figure **3.2** shows the design plan for this typical median, taken from the PennDOT standards [1].

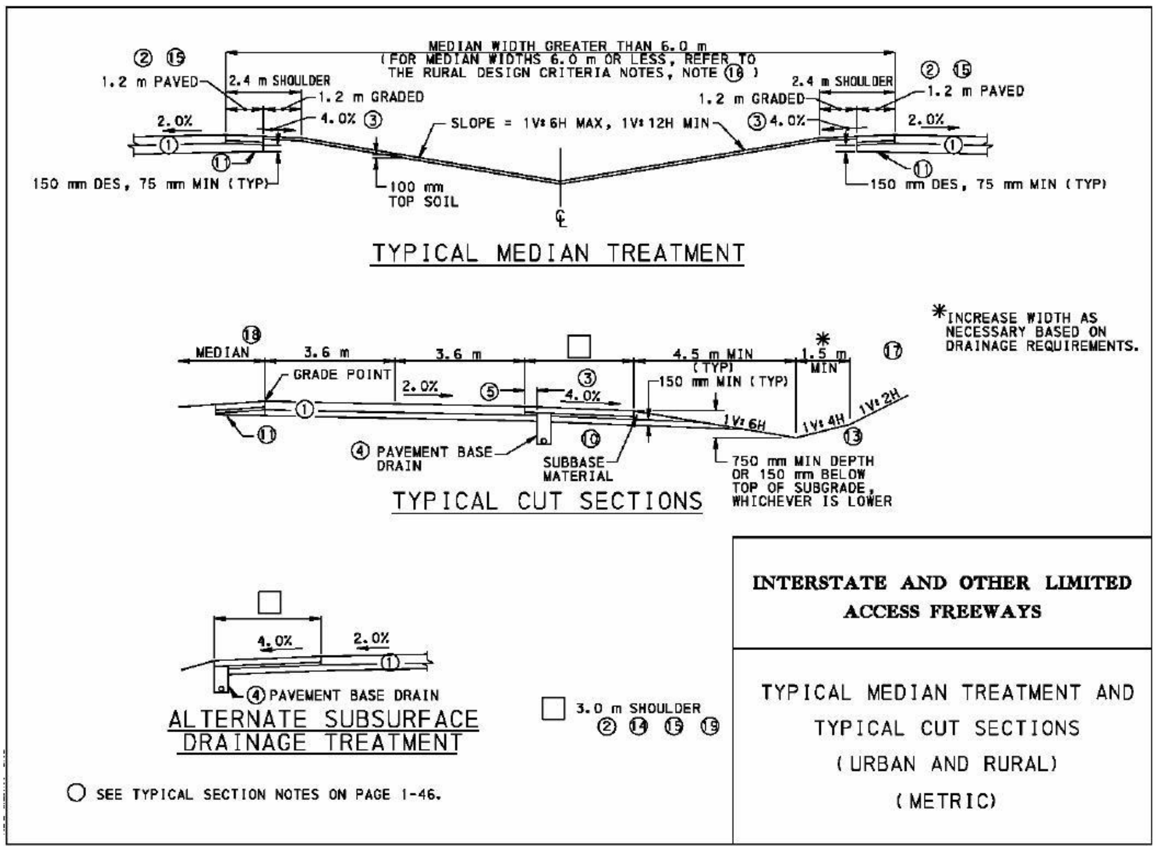

Figure **3.2** – 6H:1V V-Shape Median Cross-Section

The highway was assumed to be flat and straight, with the edge of the shoulder as the lateral zero line and the height of the roadway at the edge of the travel lane to be the vertical datum line. The simulations initialized the vehicle in the left travel lane of the roadway, with a lateral offset of -4.2m.

Based off of the PennDOT standards, several points of interest within the roadway profile were declared here as well. As stated above, the shoulder edge of the original travel lane was declared to be the zero point. The median swale point, opposing shoulder edge, and edge of opposing travel lane were also marked. Figure **3.3** shows a detailed diagram with each of these landmarks labeled.

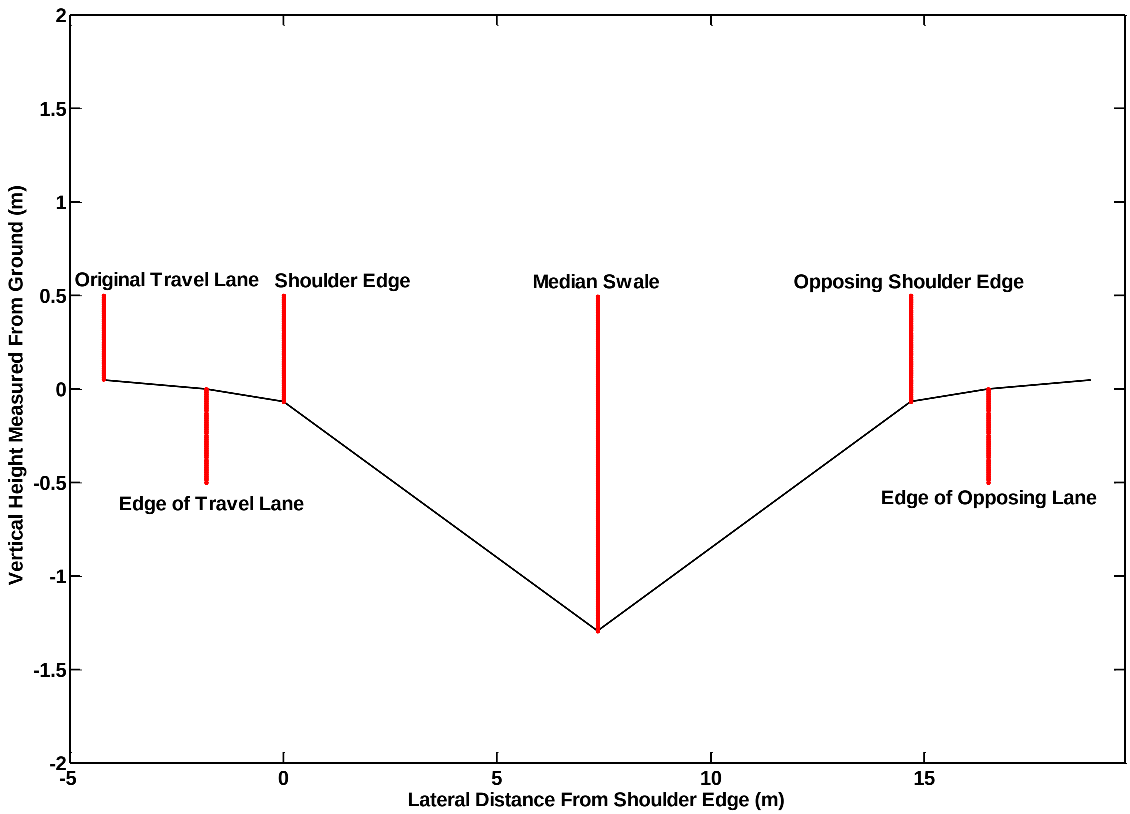

Figure **3.3** – Reference Points Within the Median

Additionally, the friction between the tires and the ground surface was also customized here. The pavement was assumed to be dry asphalt, and thus received a friction value of 0.85, and the grass 0.3. The entire roadway profile, including both on and off-road profiles complete with the friction maps, was created with an external

MATLAB script (see Appendix A) and then input into CarSim when the simulations were run.

3.1.2 Step 2: Choose the Vehicle

To define the vehicle to be simulated, CarSim allows nearly every parameter of the vehicle, from geometric configurations to inertial properties to be user-defined. Figure **3.4** shows the main screen used to define custom geometric parameters of the vehicle chassis being simulated.

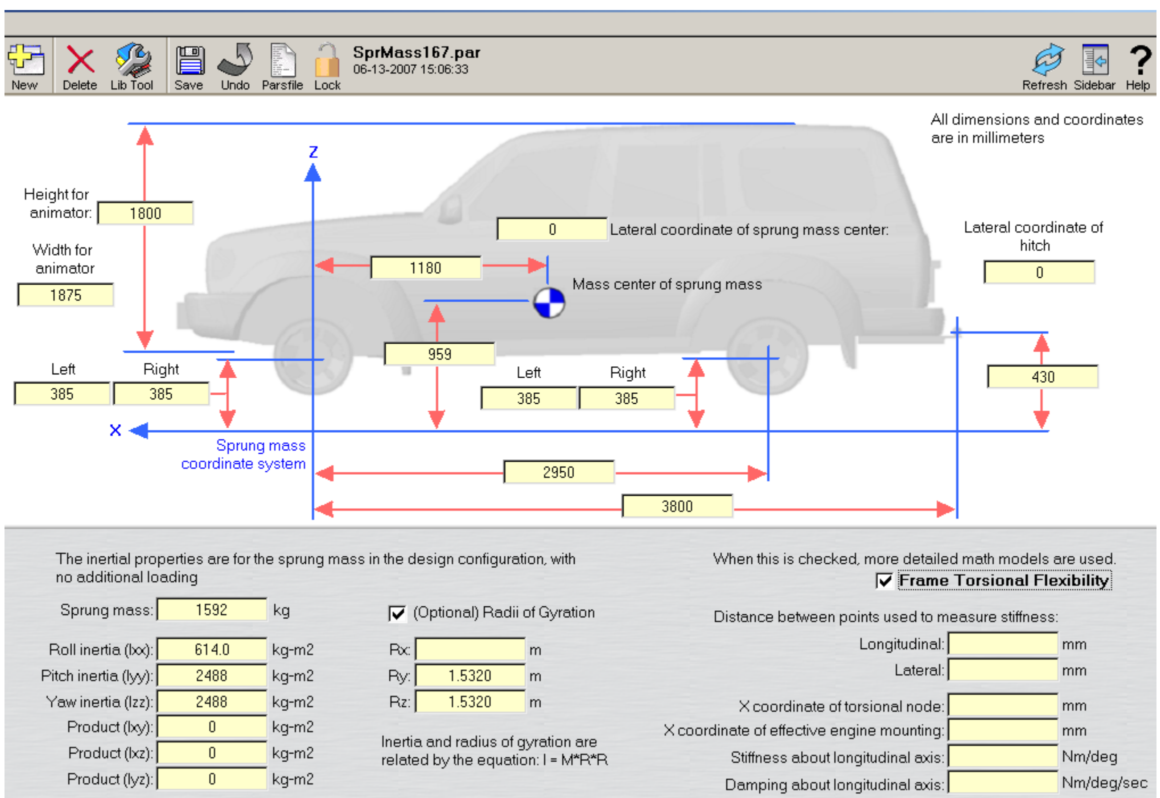

Figure **3.4** – Custom Vehicle Parameters in CarSim

This study used vehicle data collected during the 1998 New Car Assessment Program (NCAP) conducted by the National Highway Traffic Safety Administration (NHTSA) [2]. Although this survey is more than a decade old, its results were closely matched during a more recent assessment performed by the National Cooperative Highway Research Program (NCHRP) in 2003 [3]. This study, published as the NCHRP's Roadside Safety Analysis Program (RSAP) Engineer's Manual, used vehicle distributions that were very similar to those in the 1998 NHTSA study, suggesting that the average composition of the vehicle fleet changes slowly.

Using the data from the NCAP, average values for sprung mass, wheel base, track width, center of gravity location, and inertial properties were calculated for each vehicle class in the study. In the same manner as the roadway was defined, these vehicle parameters were assigned to the individual simulation run via an external MATLAB script that ran before CarSim was initialized (see Appendix A). Table **3.1** shows a summary of these parameters that is henceforth used to characterize the vehicles simulated in this study [4].

Table **3.1** – Vehicle Parameters Used in Simulations

Vehicle Class	**Sprung Mass (kg)**	**Wheel Base (m)**	**Track Width (m)**	**Front Axle to CG (m)**	**CG Height (m)**	I_{xx} **(kg-m^2)**	I_{yy} **(kg-m^2)**	I_{zz} **(kg-m^2)**
Passenger Small	969	2.524	1.446	1.021	0.519	392.6	1632.2	1798.8
Passenger Large	1403	2.679	1.468	1.277	0.585	632.3	2749.7	2893.3
Pickup Small	1409.4	2.948	1.424	1.396	0.620	571.25	3142.75	3326.25
Pickup Large	1885.8	3.425	1.619	1.581	0.684	940.5	5344	5642.25
SUV Small	1718.5	2.683	1.496	1.350	0.688	803.33	3367	3522.17
SUV Large	2251.1	3.032	1.579	1.628	0.767	1157.25	5960.75	6111
Van	1847.5	2.947	1.589	1.480	0.698	992.33	4410.67	4617.83

Although several other dynamic properties of the vehicle and its subsystems can be specified, the simulations performed in this study use the default values found in CarSim. These characteristics that are generalized include aerodynamic properties, suspension kinematics and compliance, tire properties, and steering system geometries.

3.1.3 Step 3: Establish the Initial Conditions

Prior to starting the simulations, the initial conditions must be specified. In CarSim, the vehicle states can be initialized to any custom value. There are over six hundred output variables that CarSim is capable of calculating during the simulation. Each of these properties can be set to any desired value before the simulation is run. Figure **3.5** shows where the initial conditions are defined inside CarSim.

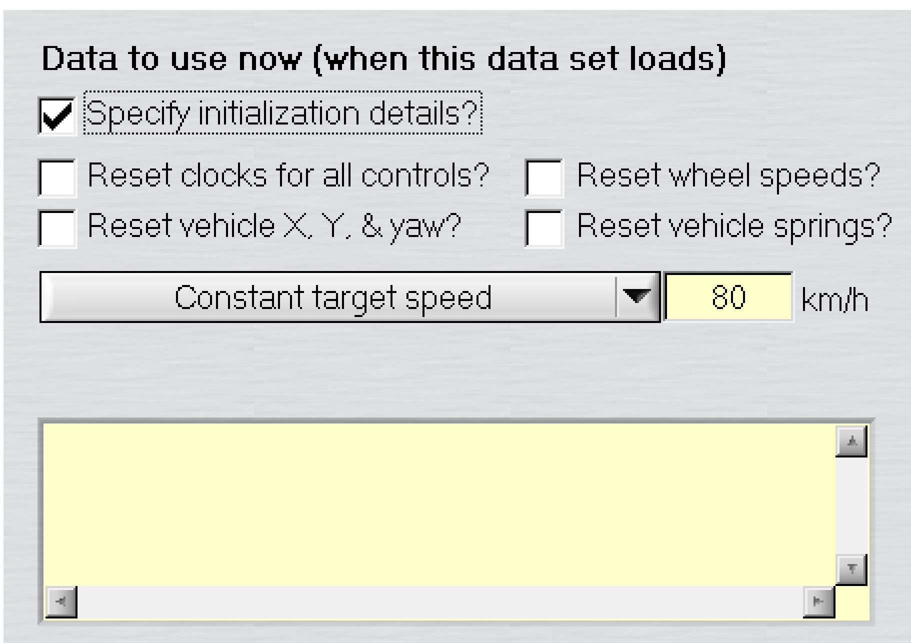

Figure **3.5** – Setting Initial Conditions in CarSim

The simulations used in this study only varied the vehicle's initial speed and departure angle upon encroachment of the median. The encroachment angle of the incursion was defined by setting the initial yaw angle of the vehicle prior to running the simulation (see Appendix A). The vehicle velocity was assumed to be purely in the longitudinal direction (directed along the longitudinal axis of the vehicle, not in the direction of the road) and it was also defined before activating CarSim. All other vehicle states, including steering angle, roll, pitch, and sideslip, were initialized to be zero.

The values for initial vehicle speeds and encroachment angles under consideration were obtained from the RSAP Engineer's Manual [3]. The speeds varied from 8 to 88 kmph in 16 kmph increments (5 to 55 mph in 10 mph increments) and also included 115 kmph (70 mph). The encroachment angles varied from 2.5° to 32.5° in 5° increments. As the Engineer's Manual produced statistical data from real-life driving conditions (including the relative likelihood of each of them occurring), these speeds and angles were used in the simulation setup. These probabilities, and their incorporation into this study, are discussed further in Section **3.2**.

3.1.4 Step 4: Determine the Driver's Actions

Where the vehicle type, speed, and encroachment angle in a median incursion are fairly easy to characterize, the most unpredictable variables are the driver's actions. They are almost always unknown in these instances, and thus generalizations must be inferred for the most likely modes of driver intervention. The simulated vehicles were assumed to have an automatic transmission, thus eliminating the shifting and clutch engagement/disengagement variables in the experiment. This decreased the amount of emphasis on driver skill and ability, as the driver was no longer able to control the engine speed (as is possible with a manual gearbox). As a result, only the steering and braking inputs were varied in the simulations.

These experiments consider two generic scenarios that represent the driver actively giving a steering input. The first, and most aggressive, suggested that the driver made a full attempt to return to the roadway. This "road recovery" steering input was defined to direct the vehicle to the edge of the shoulder on the original travel lane.

Slightly less aggressive was the "median recovery" steering input, which assumed that the driver makes an effort to steer the vehicle to the center of the median. The third steering scenario implemented in these simulations was a "no steer" condition. Rather than forcing the steering input to be zero during the simulation, and thus giving the impression that the driver held the steering wheel at zero input for the duration of the crash, the driver is modeled to take his/her hands completely off of the steering wheel and let the vehicle follow its natural path throughout the incursion. Figure **3.6** shows a top view of these three steering inputs overlaying the roadway. Defining lines (shoulder edge, lane edge, and swale point) are also labeled for further clarity.

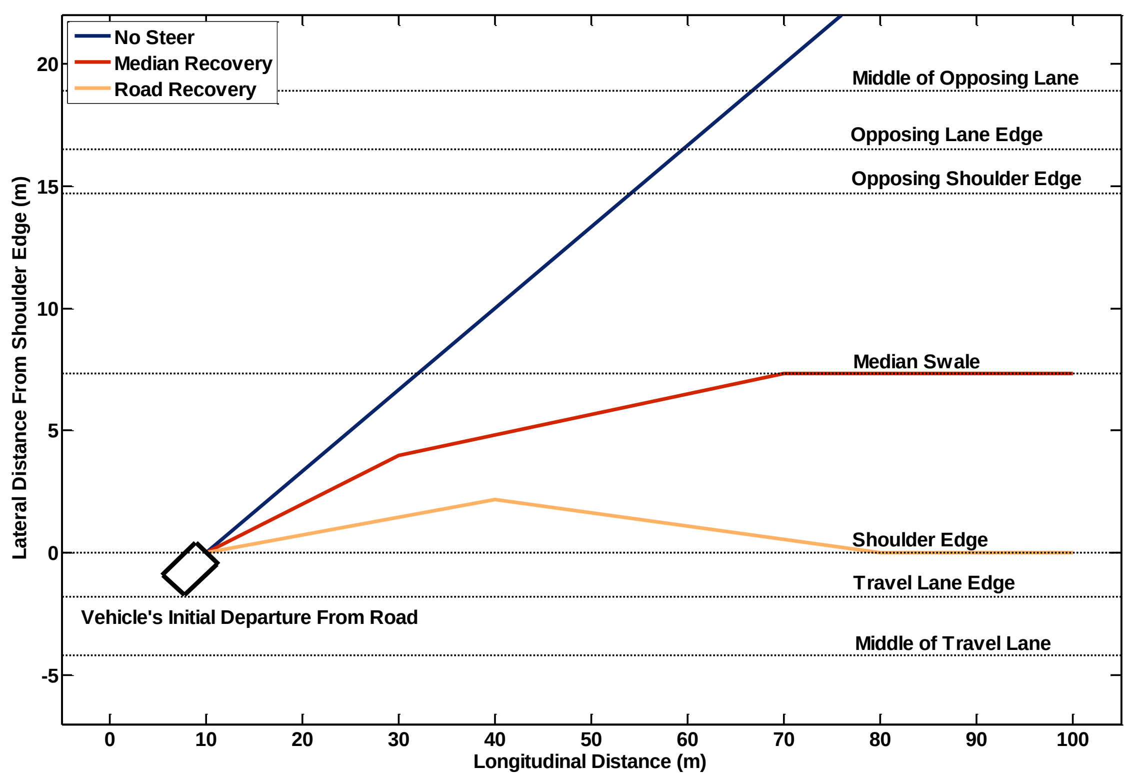

Figure **3.6** – Steering Inputs Used In Simulations

To implement these situations, the CarSim driver model was used to follow the desired path. Representative target point trajectories, toward which the vehicle was directed in the simulation, were created with the “Driver Path Follower” steering control feature. Figure **3.7** shows this customized target path in CarSim. As can be seen here, the preview time and lag can also be customized to account for driver experience, fatigue, or any other inferred distractions (eating, talking on the phone, etc.). For this study, the preview time was set to be 1 second and the lag was 0 seconds, which were default values in CarSim for the average driver ability.

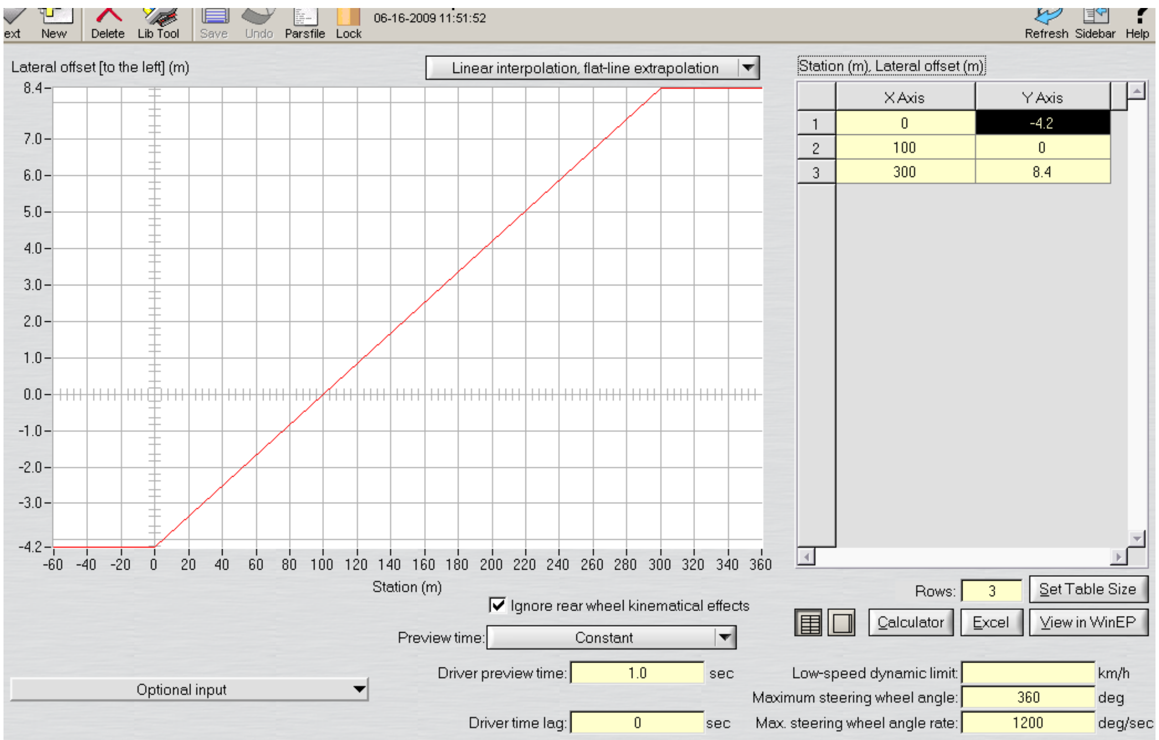

Figure **3.7** – Driver Path Follower in CarSim

It must be noted that these target paths may not actually be attained during the simulation. Due to the particular angle and speed at which the vehicle departs the roadway, the vehicle’s ability to recover to the shoulder edge, or even to the middle of the median, may not be physically possible. These steering inputs are defined solely in a way to simulate the driver's attempt to direct the vehicle to a particular target point, not whether the vehicle actually reaches that point or not. In reality, most of the simulations that contain high speeds and large encroachment angles have target paths that differ greatly from the actual trajectories of the vehicle during the incursion due to the severe vehicle dynamics of these maneuvers.

Now that the steering inputs have been laid out, the other driver variable that needs to be considered is braking. The braking was generically defined to be either a light braking (defined as 5 MPa of pressure at the cylinder) or hard braking condition (15 MPa). It can be assumed that at the instant the driver realizes that their vehicle has departed the roadway, they will apply the brakes. Thus, the possibility of zero braking was not simulated. Additionally, as the majority of passenger vehicles on the road today have an Anti-Lock Braking System (ABS) onboard, each of the simulated vehicles were also assumed to have ABS [5].

Each steering-braking pair was simulated, for a total of six possible driver actions for each vehicle-speed-angle combination. Once again, the driver's actions were established in a MATLAB script prior to running the simulation (see Appendix A).

3.1.5 Step 5: Run the Simulation

To run the batch of simulations, a MATLAB script was created to automate the process (see Appendix A). The median profile, including the friction map, was loaded first. After this, the code automatically loaded the vehicle, initial conditions, and driver's actions before the simulation itself was started.

With all these values in place, CarSim was then initialized. The simulation was run, using a time step of 2 microseconds, for up to 16 seconds. If rollover was experienced, the internal CarSim model terminated itself at that point, as the data is invalid once rollover has occurred. With no rollover, the simulation ran for the full 16 second period. All of the output variables from the test were stored in a MATLAB structure file for analyzing and post-processing. The typical simulation took about 7 seconds to run on a 3 GHz, Pentium 4 Dell Dimension 8300 desktop computer.

3.1.6 Step 6: Summarize the Outputs and Repeat

This six step simulation process, illustrated in Figure **3.8** below, was implemented with a loop in the MATLAB script as discussed in the previous section. Within the loop, every possible combination of vehicle, initial speed, encroachment angle, and driver actions were simulated for each roadway profile tested. Ultimately, 2,058 simulations were run for each median. For the 54 medians simulated, a total of 111,132 simulations were conducted, resulting in a wide range of possible crash scenarios.

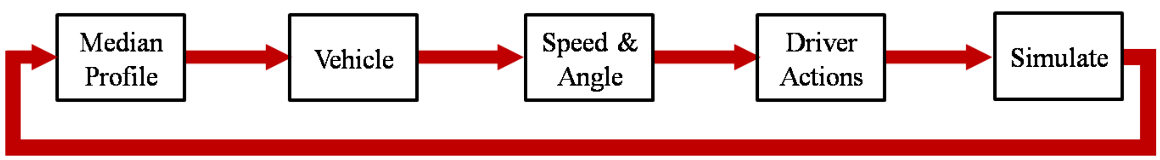

Figure **3.8** – Overall Simulation Process

Although these simulations represent a vast array of possible incursions on real-life highways, statistical data obtained from previous studies was used to aid in the accuracy of the simulations. To better mimic the likelihood of each specific encroachment occurring in real-life, a post-processing weighting method, based on the RSAP Engineer's Manual [3], was implemented. This method is discussed in detail in the following section.

3.2 Individual Simulation Weighting Factors

Each individual scenario simulated in CarSim represented one specific vehicle trajectory during a highway median incursion. However, based on field data and forensic reports of actual crashes, some of these situations are far more likely to occur than others. In an attempt to recreate a more realistic summary of results that closely parallels real-life crash instances, a post-processing weighting method was devised.

Although the vehicles chosen for this study (discussed in Section **3.1.2**) were shown to be an accurate representation of the vehicle population on the highway, certain vehicles are far more common than others. In a similar manner, certain vehicle speeds and encroachment angles at the moment of departure from the roadway are more common in actual median incursion events. For example, more vehicles travel down the highway at 115 kmph (70 mph) than at 8 kmph (5 mph). Thus, it makes sense to favor the simulations that are run at the faster speed over those performed at the slower speed. To help quantify exactly how much each specific scenario should be weighted, data was taken from both the RSAP Engineer's Manual [3] and the 2001 National Household Travel Survey (NHTS) [6].

3.2.1 Weighting Factors Assigned According to Vehicle Class

The probability of each vehicle class appearing on the highway was extracted from the NHTS [6]. It was then assumed that the number of accidents for each vehicle class was proportional to the percentage of each vehicle appearing on the road. Therefore, all vehicles were expected to run off the road at an equal rate, and thus for example, SUVs were not taken to crash into the median more frequently (per capita) than passenger cars, or vice versa. The resulting weighting factors assigned to each vehicle class are summarized in Table **3.2**.

Table **3.2** – Vehicle Class Weighting Factors

Vehicle Class	Weighting Factor
Small Passenger	0.089
Large Passenger	0.501
Small Pickup	0.090
Large Pickup	0.101
Small SUV	0.063
Large SUV	0.063
Van	0.093

Although this NHTS data may seem a bit outdated, similar data was published in 2006 (and then updated in 2007) by Pavement Interactive [7]. Trucks and busses were found to consist of 38.7% of the highway population and the remaining automobiles completed the remaining 61.2%. The Federal Highway Administration (FHWA) classifies SUVs and vans as light trucks, which comprised 92% of the truck and bus population. FHWA found that 54% of the vehicles on the roadway were deemed to be passenger cars, compared to the 59% published in the NHTS study. Additionally, Pavement Interactive found SUVs, vans, and pickup trucks to collectively comprise 39.5% of the highway population, whereas they accounted for 41% according to the NHTS.

3.2.2 Weighting Factors for Speed and Encroachment Angle

Using data from the RSAP Engineer's Manual [3], probabilities for the occurrence of the vehicle's initial speed were obtained. Data for the encroachment angles during median incursions were also gathered from this document. By multiplying these probability values for speed with those for the encroachment angles, weighting factors for each possible speed-angle combination were produced. The tabulated results are displayed in Table **3.3**.

Table **3.3** – Speed and Encroachment Angle Weighting Factors

		Encroachment Angle (deg)						
		2.5	**7.5**	**12.5**	**17.5**	**22.5**	**27.5**	**32.5**
Initial Speed (kmph)	**8**	0.0002	0.0005	0.0005	0.0003	0.0002	0.0001	0.0002
	24	0.0049	0.0119	0.0118	0.0088	0.0057	0.0034	0.0042
	40	0.0151	0.0364	0.0359	0.0268	0.0174	0.0104	0.0127
	56	0.0215	0.0519	0.0513	0.0382	0.0248	0.0149	0.0181
	72	0.0205	0.0494	0.0488	0.0364	0.0236	0.0142	0.0173
	88	0.0152	0.0367	0.0362	0.027	0.0176	0.0105	0.0128
	115	0.02	0.0484	0.0478	0.0356	0.0231	0.0139	0.0169

3.2.3 Total Weighting Factor for the Individual Crash Scenario

Since there have not been any prior studies that quantify the driver's intervention during a median incursion, no statistical data regarding the probability of each of the driver inputs could be gathered. As a result, the steering and braking inputs were weighted evenly across all runs.

The total weighting factor assigned to each particular simulation was simply a product of the individual weighting factors for each parameter used in the simulation. For example, for an incursion involving a large passenger vehicle (weighting factor of 0.501) traveling at a speed of 56 kmph and departing the roadway at an angle of 12.5° (collectively weighted by 0.0513), the total weighting factor would be: 0.501 x 0.0513 = 0.0257. This quantity clearly shows that of all the crash scenarios on the highway, this specific case occurs 2.57% of the time.

[1] (2002). *Design Manual, Part 2, Highway Design, in 13M.* Pennsylvania Department of Transportation: p. 1-24.

[2] Heydinger, G. J., Bixel, R. A., Garrott, W. R., Pyne, M., Howe, J. G., & Guenther, D. A. (1999). *Measured Vehicle Inertial Parameters - NHTSA's Data Through November 1998:* SAE 1999-01-1336.

[3] Mak, K. K., & Sicking, D. L. (2003). *NCHRP 492 - Roadside Safety Analysis Program (RSAP) - Engineer's Manual. 2003.* Washington, D.C.: Transportation Research Board.

[4] Hamblin, B. C. (2007). *Vehicle Rollover Prediction From Low Order Dynamic Models or Varying Terrain Encountered During Median Traversal.* University Park: The Pennsylvania State University.

[5] *Anti-Lock Braking System (ABS).* Retrieved June 16, 2009, from U. S. Department of Transportation National Highway Traffic Safety Administration: http://www.nhtsa.dot.gov/cars/problems/Equipment/absbrakes/page1.html

[6] (2004). *2001 National Household Travel Survey: Summary of Travel Trends.* U.S. Department of Transportation.

[7] White, G. (2007). *Trucks and Buses*. Retrieved June 16, 2009, from Pavement Interactive: http://pavementinteractive.org/index.php?title=Trucks_and_Buses

Chapter 4

Simulation Results and Discussion

Using the weighting factors developed in Section **3.2** for each individual simulation run, the data from the entire batch of simulations is analyzed in this section. Simulations for 54 different median cross-sections were conducted, and the results discuss the relative effect of altering certain characteristics of the median profile, including cross-section shape, slope, and width.

4.1 Simulation Outcomes

After performing the 2,058 simulation scenarios (vehicle, speed, encroachment angle, steering and braking combinations) for each median, two main events were considered in the post-processing data analysis: vehicle rollover and cross-median crashes. A ratio between these two severe occurrences and its value to highway design engineers is also presented in Section **4.1.3**.

4.1.1 Vehicle Rollover

One of the primary concerns with median design is the increasing number of rollovers incidents seen during median encroachments over the past several decades [1]. Perhaps the biggest difficulty of using vehicle dynamics software to simulate off-road excursions is their inability to model deep soil-tire forces. Currently, there are no commercially available software packages that can determine deep soil-tire forces in the context of vehicle chassis dynamic simulations, and thus predict a soil-tripped rollover. As 90% of all rollover incidents are due to a soil-tripped phenomenon [2], this difficulty would appear to present a large problem with the simulations.

Fortunately, a tripped rollover phenomenon can be inferred from the simulations during the post-processing of the vehicle trajectory data. An experimental study, published in 2004 by Kroninger, et al. [3], established criteria for a soil-tripped rollover. During this test, rollover was consistently observed when the vehicle exhibited a sideslip greater than 45°, while travelling at a speed greater than 32.187 kmph (20 mph). After imposing these limits on the simulation data, those scenarios which did exhibit rollover were separated from those which did not exhibit rollover. After filtering the rollover cases for all five medians listed above, Figure **4.1** shows the resulting distribution, sorted by vehicle class. As to be expected, the small SUV vehicle class experienced roughly twice the number of rollovers as both of the passenger vehicle classes. A total of 2734 rollovers were found in simulation, with small SUVs accounting for 541 (19.8%) of them.

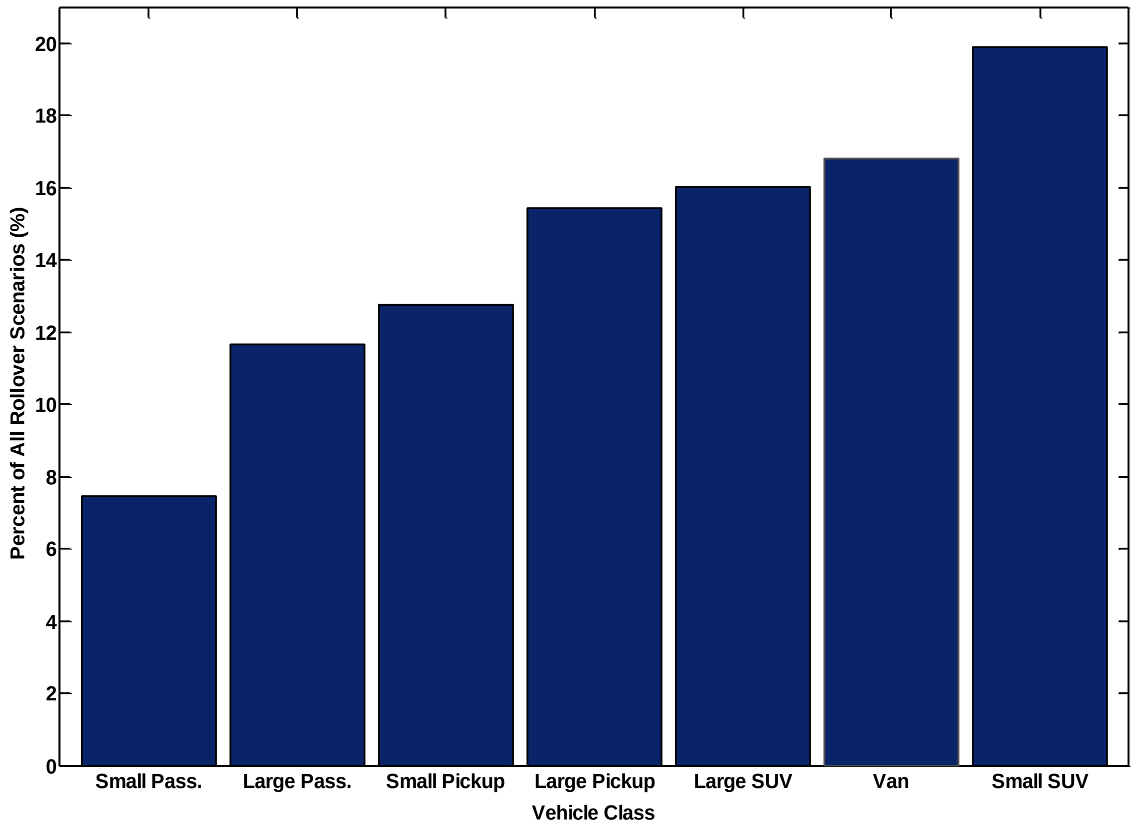

Figure **4.1** – Rollover Cases for Each Vehicle Class

4.1.2 Median Crossover

While crash statistics indicate that vehicle rollover is a leading cause of deaths on the highway, there is a second major contributor to median fatalities. This event, called median crossover, is a catastrophic occurrence in which the vehicle traverses the entire median and encroaches upon the opposing lanes of traffic. In this case, there is a possibility of a head-on collision with oncoming vehicles, which in many cases is even more disastrous than a rollover incident.

To investigate the occurrence of median crossovers during the simulations, the vehicle position was monitored throughout the incursion. For all scenarios in which rollover did not occur, the location at which the vehicle came to rest was obtained from the simulation data. Figure **4.2** shows the resting location of several vehicles, overlaying a top view of the median. As can be seen in the figure, all of the locations appearing above the opposing lane shoulder edge represent vehicles which crossed the median and entered the opposing lanes of traffic before coming to a rest. For clarity purposes, the figure only shows the resting location for 250 of the simulation runs.

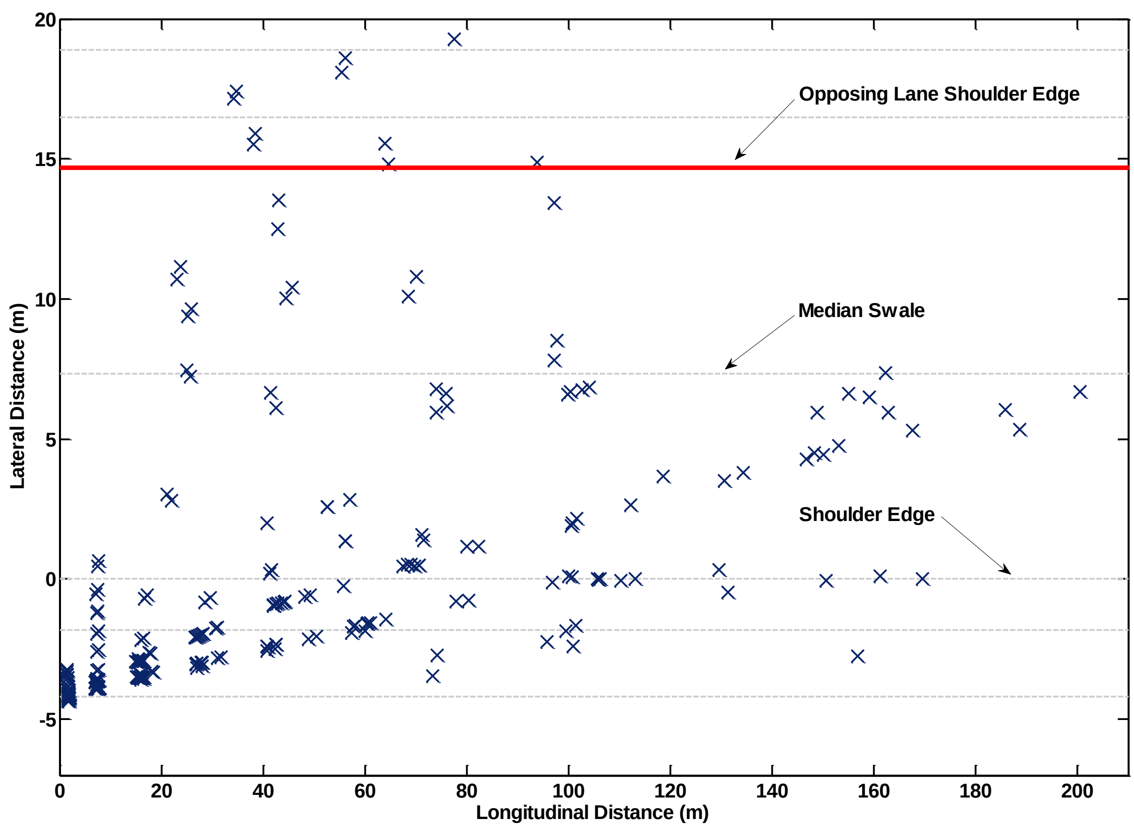

Figure **4.2** – End Locations of For Vehicles That Did Not Roll Over

4.1.3 Design Ratio: Median Crossovers to Rollover Incidents

The two primary causes of death during an incursion into a traversable highway median are vehicle rollover and head-on collisions. Even though the simulation results provide sufficient information about the occurrence of rollover and median crossover incidents, the data does not provide a clear understanding about the possible tradeoffs between the two crash modalities that may exist when designing a median.

To provide insight into these possible tradeoffs, a ratio between the two factors was created. This ratio, defined as the number of crossover incidents per every rollover (see Eq. **4.1**), presents both data sets in a meaningful manner to the highway designers. For example, if one specific median design leads to 300 crossover events and 150 rollovers, and another leads to 400 crossovers and 100 rollovers, the design ratios for those medians would be 2:1 and 4:1 respectively. At first, it would appear that, with the lower number of rollover incidents, the second median was indeed safer. But, by calculating this ratio, it is seen that although rollovers are prevented, the risk of a head-on collision following a crossover event was increased. The ratio tells the design engineer that, with the second median, the vehicles running off the roadway will be twice as likely to experience a median crossover, and thus a head-on collision. The tradeoff between the two main catastrophic events during an off-road highway median incursion is now clearly presented.

$$\boldsymbol{Ratio = \frac{Number\ of\ Median\ Crossovers}{Number\ of\ Rollovers}} \qquad (\mathbf{Eq. 4.1})$$

4.2 Influence of Median Geometry

Our investigation into the influence of median geometry on accident causation concentrated on three of the main geometric characteristics of the highway median: cross-section shape, median slope, and median width. Both V-shape and trapezoidal ditch profiles were analyzed, while the median slopes ranged from 4H:1V to 10H:1V and the widths varied from 40 feet to 76 feet. The findings from each of these investigations are presented in the following sections.

4.2.1 Median Cross-Section Shape

To investigate the influence of median cross-section shape on the resulting vehicle response during an off-road median encroachment, five different median configurations, which are listed in Table **4.1**, were tested. All 2,058 different vehicle-speed-angle-steering-braking combinations were simulated for each of the five medians. After the simulations were completed, the rollover and crossover instances were recorded. Figure **4.3** (next page) shows the resulting rollover scenarios for each simulated median.

Table **4.1** – Initial Batch of Medians Simulated

Median Number	Cross-Section Characteristic		
	Slope	**Width**	**Shape**
1	6H:1V	60 ft.	V-Shape
2	6H:1V	40 ft.	V-Shape
3	5H:1V	60 ft.	V-Shape
4	5H:1V	60 ft.	Trapezoidal
5	10H:1V	60 ft.	V-Shape

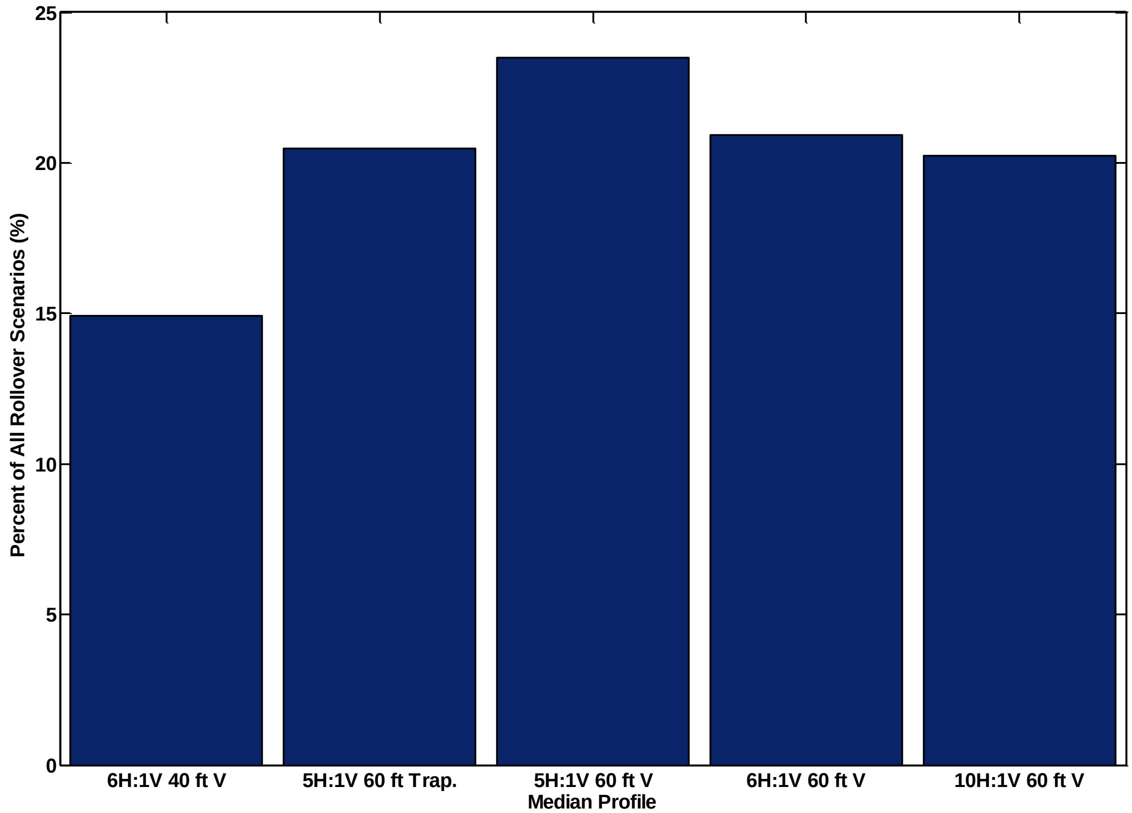

Figure **4.3** – Effect of Median Cross-Section on Vehicle Rollover

The results presented here indicate that, as expected, all three median characteristics – cross-section shape, slope, and width – influence the occurrence of both vehicle rollover and median crossover. Median slope and width will be discussed in further detail in the following sections.

Considering only the two 5H:1V, 60 foot wide medians, Figure **4.3** dictates that, for the same array of simulation conditions, a trapezoidal cross-section median would lead to fewer rollovers than an identical median with a V-shape profile. Specifically, of the total 355 median crossovers experienced for the five medians simulated, 58 occurred on the trapezoidal median, whereas 74 were accounted for by the similar V-shape median. By examining Figure **4.4**, the trapezoidal median also resulted in a lower ratio of crossovers to rollovers, thus producing a smaller quantity of crossovers.

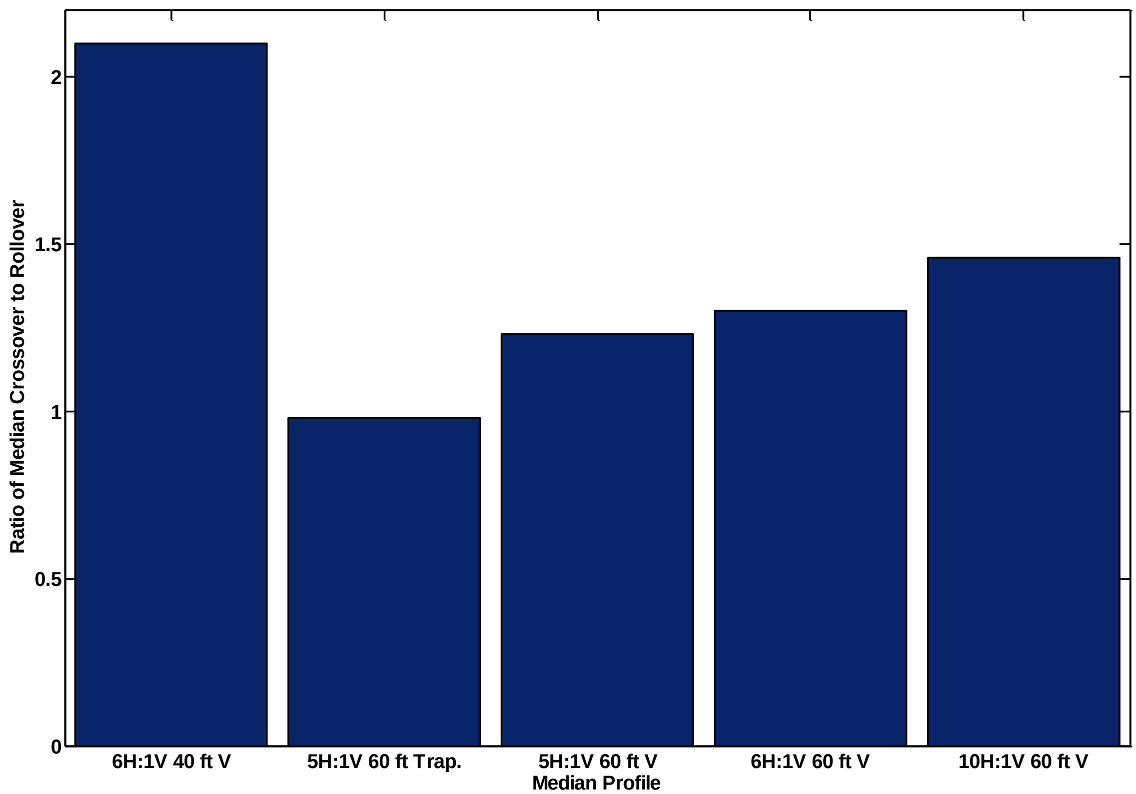

Figure **4.4** – Effect of Median Cross-Section on the Design Ratio

Another safety factor that was considered in this study was the severity of the vehicle dynamics throughout the median incursion. Specifically, the vehicle's yaw rate, roll angle, and sideslip angle were examined, as extreme values for these vehicle states could lead to a violent ride for the passengers, and ultimate result in injury. When these three variables were extracted from the simulation data for the two 5H:1V, 60 foot wide medians, the values for all three were much lower for the trapezoidal median than they were for the V-Shape profile. Figure **4.5** shows these variables for an incursion involving a small SUV traveling at 115 kmph, departing the roadway at an angle of 12.5°, with the driver attempting a median recovery, and applying a light braking condition. As indicated by the legend, the red lines represent the V-shape median, while the blue lines show these variables for the trapezoidal median.

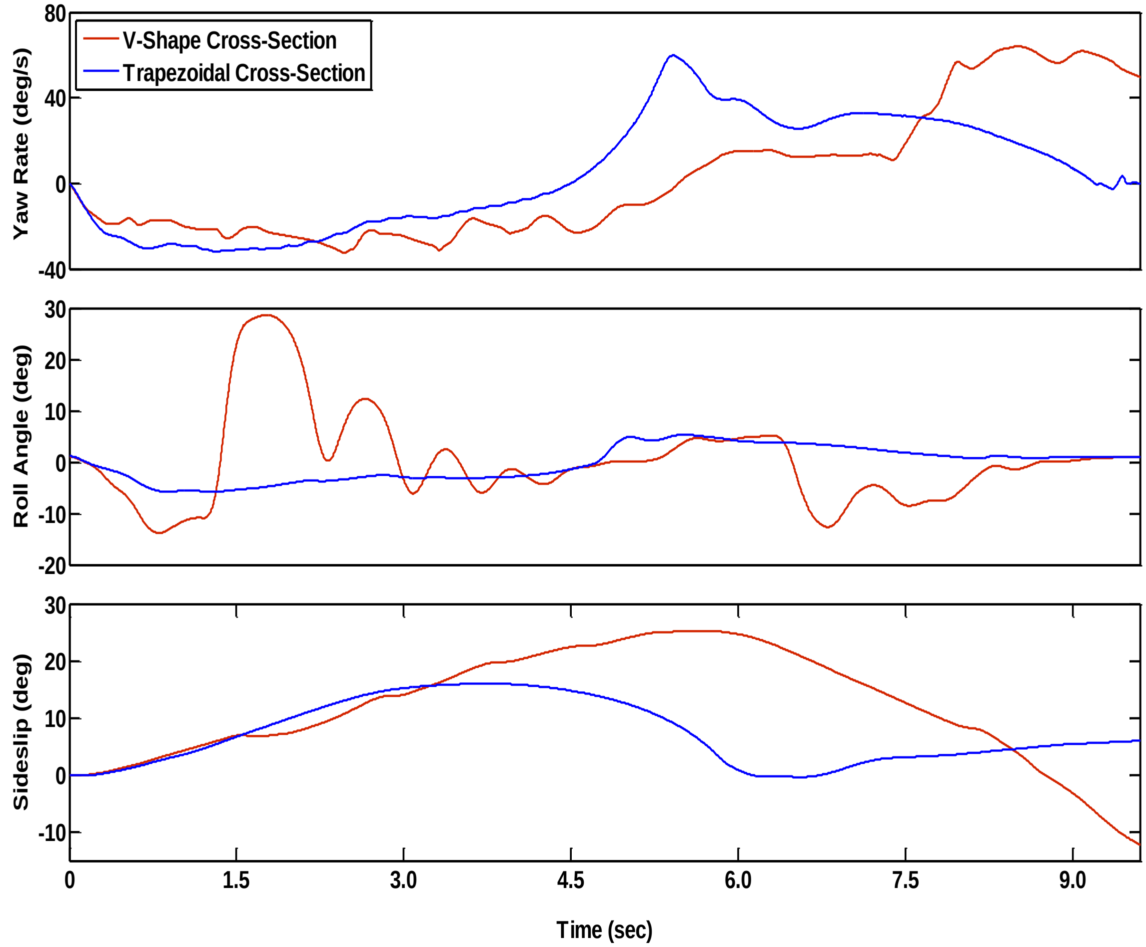

Figure **4.5** – Effect of Median Cross-Section on Vehicle States

As can be seen, the vehicle experienced a much less severe off-road excursion with the trapezoidal cross-section. In fact, in this particular case, the vehicle roll reached a maximum of 28.6° for the V-shape median, while the similar scenario for the trapezoidal median only experienced a maximum roll of 5.8°. This difference in the vehicle states ultimately shows that not only does a trapezoidal cross-section reduce both rollover and crossover incidents, but it also might lead to a much less aggressive and violent incursion.

Even though these results suggest that a trapezoidal median profile will be safer that a V-shape cross-section in the event of an off-road incursion, the trapezoidal profile was only simulated for one specific slope-width combination. To draw an all-encompassing conclusion, further simulation testing of various trapezoidal medians, and then comparison to its V-shape profile counterpart, needs to be conducted.

The overall results from this investigation into median cross-section shape are summarized in Table **4.2**. As seen here, for the same 2,058 simulated scenarios, the median geometry has a significant effect on accident causation.

Table **4.2** – Effect of Median Profile on Accident Causation

Median Slope	**Median Width**	**Median Shape**	**Rollovers**	**Crossovers**	**Ratio**
6H:1V	40 ft	V-Shape	37 (14.6%)	79 (22.3%)	2.14
5H:1V	60 ft	Trapezoidal	52 (20.6%)	58 (16.3%)	1.12
5H:1V	60 ft	V-Shape	60 (23.7%)	74 (20.8%)	1.23
6H:1V	60 ft	V-Shape	53 (20.9%)	69 (19.4%)	1.30
10H:1V	60 ft	V-Shape	51 (20.2%)	75 (21.1%)	1.47
Total			**253**	**355**	**1.40**

4.2.2 Median Slope

Since the median geometry was found to have an impact on the vehicle response in the previous section, the relative effect of median slope on accident causation was investigated. In order to analyze the influence of median slope alone, a 60 foot wide, V-shape median was considered with several different slopes being considered. The evaluated slopes ranged from 4H:1V to 10H:1V in increments of one unit horizontal (4H:1V, 5H:1V, 6H:1V, etc.).

Just as in the investigation of the median cross-section shape in the previous section, there were two main incidents considered in this analysis: vehicle rollover and median crossover. After applying Kroninger's threshold criteria for soil-tripped rollover events, the more aggressive slopes (4H:1V and 5H:1V) were found to result in a higher number of rollovers than the more modest slopes (9H:1V and 10H:1V). Figure **4.6** shows the resulting distribution of rollovers experienced during the simulations.

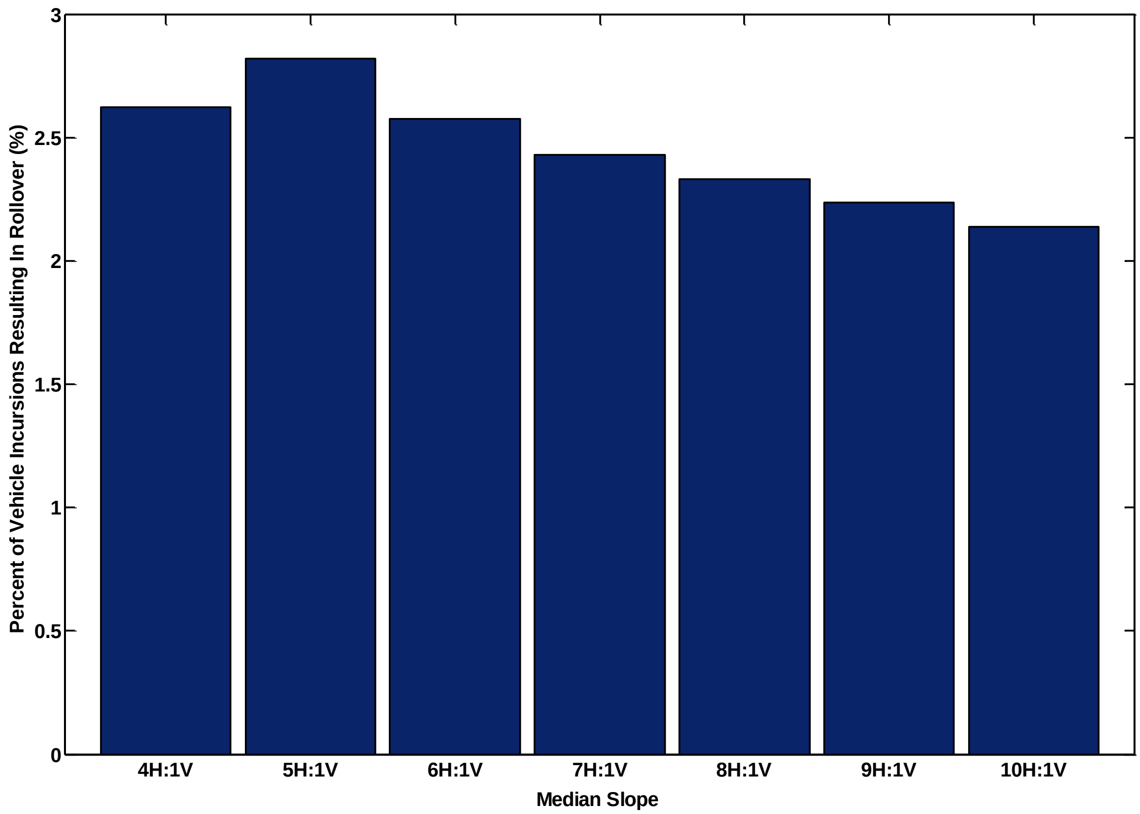

Figure **4.6** – Effect of Median Slope on Vehicle Rollover

Figure **4.7** presents the design tradeoff between median crossovers and rollovers. The lower values for the ratio between the two events give the impression that the steeper sloped medians reduce the likelihood of vehicles traversing the median. However, this trend is largely due to the larger amount of rollovers experienced with the steeper medians. Looking to Table **4.3**, the number of crossover events was actually higher for the steeper median slopes. In fact, a 10H:1V sloped median is shown to exhibit 24.1% fewer rollovers and 9.86% fewer crossovers than its 5H:1V counterpart. The summary provided in this table suggests that, based on the simulations conducted in this study, a more gradually sloped median profile will reduce the frequency of both rollover and crossover incidents in the event of an off-road median incursion.

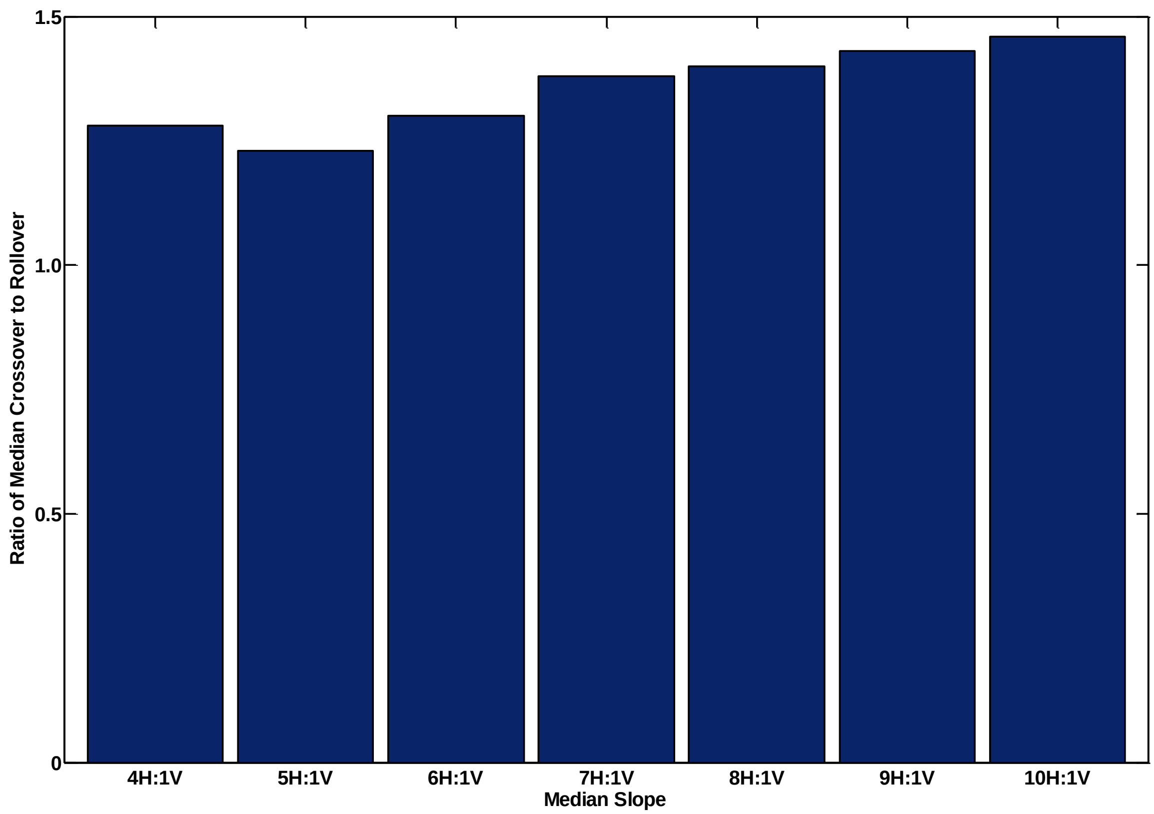

Figure **4.7** – Effect of Median Slope on Crossover to Rollover Ratio

Table **4.3** – Effect of Median Slope on Accident Causation

Median Slope	Rollovers	Crossovers	Ratio
4H:1V	54 (15.3%)	69 (14.5%)	1.28
5H:1V	58 (16.4%)	71 (14.9%)	1.23
6H:1V	53 (15.0%)	69 (14.5%)	1.30
7H:1V	50 (14.2%)	69 (14.5%)	1.38
8H:1V	48 (13.6%)	67 (14.1%)	1.40
9H:1V	46 (13.0%)	66 (13.9%)	1.43
10H:1V	44 (12.5%)	64 (13.5%)	1.46
Total	**353**	**475**	**1.35**

4.2.3 Median Width

After the investigation into the effect of median slope on the vehicle response was completed, a similar analysis was conducted for medians of varying width. To isolate the median width variable by itself, a 6H:1V sloped, V-shape median was considered for all the runs. The width of the median was then varied from 40 feet (12.19m) to 76 feet (23.16m) in 6 feet (1.829m) increments. Again, the main events of concern were vehicle rollover and median crossover. When all of the median widths had been simulated for every test scenario, the 76 foot wide median emerged with the highest number of rollover events. 3.21% of the simulated incursions led to a rollover event for this particular median, whereas the narrowest median (40 foot wide) only experienced 2.09% of incidents leading to rollover. Figure **4.8** illustrates the general trend that as the median width increased, so did the number of rollovers.

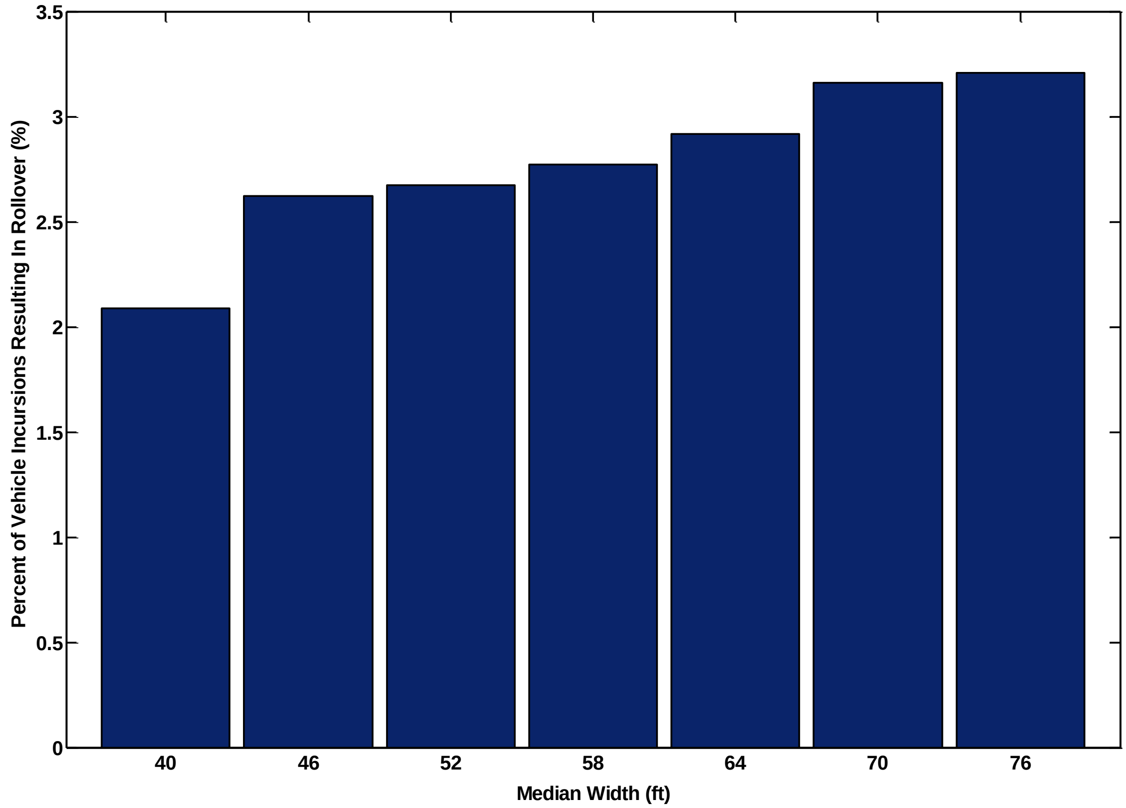

Figure **4.8** – Effect of Median Width on Vehicle Rollover

The initial impression given by this figure is that, with the lower number of rollovers, the 40 foot wide median would be the ideal choice. But, when considering the ratio of crossovers to rollover events, the 40 foot wide median experienced nearly twice as many median crossover events as any other median width tested. Showing this trait in Figure **4.9**, it is evident that a narrower median does reduce the number of rollovers, but at the cost of allowing the vehicle to enter the opposing lane. This will result in an increased probability of a head-on collision. The results show that as the median width increases, the crossover to rollover ratio decreases. Due to the larger distance within

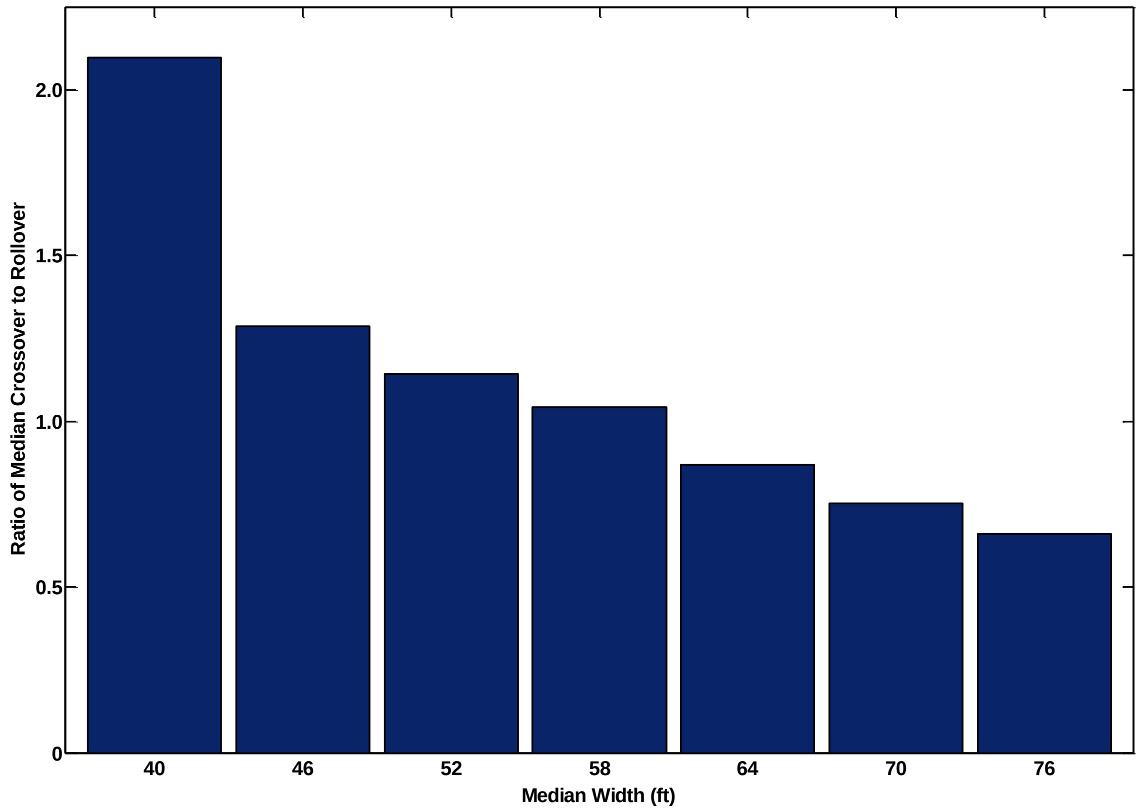

Figure **4.9** – Effect of Median Width on Crossover to Rollover Ratio

the median, the potential for a crossover event subsequently decreases. At the same time, the longer traversable distance leads to a longer period of time in which a soil-tripped rollover can occur. These results, summarized in Table **4.4**, clearly portray the tradeoff between vehicle rollover and crossover incidents which must be considered when designing a new highway median.

Table **4.4** – Effect of Median Width on Accident Causation

Median Width	**Rollovers**	**Crossovers**	**Ratio**
40 ft	43 (10.8%)	90 (21.1%)	2.10
46 ft	54 (13.5%)	70 (16.4%)	1.29
52 ft	55 (13.8%)	63 (14.8%)	1.14
58 ft	57 (14.3%)	59 (13.8%)	1.04
64 ft	60 (15.0%)	52 (12.2%)	0.87
70 ft	65 (16.3%)	49 (11.5%)	0.75
76 ft	66 (16.5%)	44 (10.3%)	0.66
Total	**400**	**427**	**1.07**

[1] (2006) *Traffic Safety Facts 2005: A Compilation of Motor Vehicles Crash Data from the Fatality Analysis Reporting System and the General Estimates System*. Washington, D.C.: National Highway Traffic Safety Administration.

[2] (2004). *Vehicle Dynamic Rollover Propensity Project Overview*. Washington, D.C.: National Highway Traffic Safety Administration.

[3] Kroninger, M., Lahmann, R., Lich, T., Schmid, M., Guttler, H., Huber, T., et al. (2004). *A New Sensing Concept for Tripped Rollovers:* SAE 2004-01-0340.

Chapter 5

Guidance for a Safer Median Design

Now that the respective effects of median cross-section slope and width have been analyzed, general guidance is provided for the design of safe median profiles on a divided highway. As presented in the previous sections, the main tradeoff in the design of traversable medians is between rollover and crossover events. That is, the highway engineer must choose between a median design that is intended to minimize vehicle rollover, or one which aims to prevent vehicles from traversing the median and entering the opposing lanes of traffic. Additionally, for medians which will contain a longitudinal cable barrier, a major concern is where to install the barrier, and at what height to place the cables, in order to maximize the safety of the vehicles departing the roadway. The following sections explore these issues.

5.1 Overall Data Trends

This analysis compares the rollover and crossover tendencies of each specific median slope-width profile against all the other medians simulated. All 2,058 scenarios were run for each of the 49 possible slope-width combination medians, and three main sets of data were extracted from the simulation results; instances of vehicle rollover, median crossover events, and the trajectory which the vehicle followed during the incursion.

Table **5.1** displays the rollover data for all of the simulated slope-width combination medians. As seen in the table, the general trends predicted in Sections **4.2.2** and **4.2.3** were preserved: as the slope became less steep while the median width was constant, the rollover probability decreased. Additionally, as median width increased for a constant slope, the likelihood for a vehicle to roll over also increased. The rollover probabilities from this investigation are organized below and presented in a manner which highway engineers can easily reference.

Table **5.1** – Rollover Percentages for Every Simulated V-Shape Median Profile

		Median Width (ft)						
		40	**46**	**52**	**58**	**64**	**70**	**76**
Median Slope	**4H:1V**	1.99%	2.48%	2.53%	2.58%	2.72%	2.87%	2.92%
	5H:1V	2.19%	2.72%	2.77%	2.82%	2.96%	3.16%	3.26%
	6H:1V	2.09%	2.62%	2.67%	2.77%	2.92%	3.16%	3.21%
	7H:1V	1.90%	2.38%	2.38%	2.48%	2.58%	2.77%	2.82%
	8H:1V	1.85%	2.28%	2.33%	2.38%	2.53%	2.67%	2.72%
	9H:1V	1.75%	2.19%	2.19%	2.28%	2.38%	2.53%	2.58%
	10H:1V	1.65%	2.09%	2.09%	2.14%	2.28%	2.38%	2.48%

The same process was carried out for the cross-median events. Again, the same trends from Sections **4.2.2** and **4.2.3** were observed: for a constant median width, the change in slope had a minimal effect on the likelihood for the simulated vehicle to traverse the entire median. Furthermore, as the width increased for a constant sloped median, the amount of cross-median encroachments occurring was drastically reduced. Regardless of the slope, the narrow 40 foot wide medians were nearly twice as likely to exhibit rollover than the wider medians. The tabulated probability values are presented in Table **5.2**.

Table **5.2** – Cross-Median Percentages for Every Simulated V-Shape Median Profile

		Median Width (ft)						
		40	**46**	**52**	**58**	**64**	**70**	**76**
Median Slope	**4H:1V**	3.69%	2.82%	2.58%	2.38%	2.09%	1.90%	1.70%
	5H:1V	3.94%	3.01%	2.67%	2.48%	2.19%	2.04%	1.85%
	6H:1V	3.94%	3.06%	2.72%	2.58%	2.28%	2.14%	1.90%
	7H:1V	3.79%	2.92%	2.58%	2.48%	2.14%	1.99%	1.80%
	8H:1V	3.74%	2.87%	2.58%	2.38%	2.14%	1.94%	1.75%
	9H:1V	3.64%	2.82%	2.48%	2.33%	2.04%	2.38%	1.70%
	10H:1V	3.50%	2.72%	2.43%	2.24%	1.99%	1.80%	1.65%

Although this guidance in median design provides useful information about each median characteristic, the tradeoff between rollover incidents and crossovers is still not obvious. To help resolve this issue, the design ratio of median crossovers to rollovers for all medians is presented in contour form in Figure **5.1**. Each of the contours in the figure represents a dividing line which separates the median slope-width combinations by their respective ratio between median crossovers and vehicle rollovers. Figure **5.1** now provides a tool for highway engineers to determine the projected rate of crossovers versus rollovers based off of simulation data. For example, if the median is designed such that rollover incidents and crossover crashes are equally as likely, then the slope and width can then be chosen based on the information presented in the above figure by following the contour line corresponding to the ratio of 1.

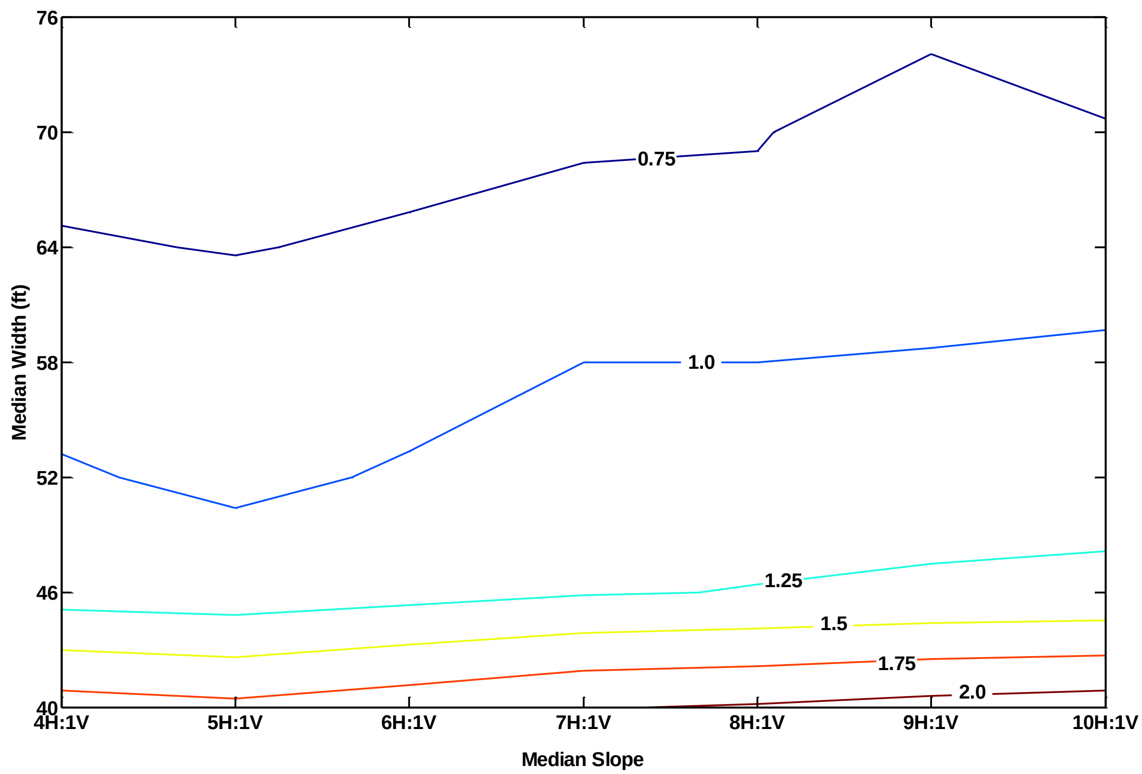

Figure **5.1** – Ratio of Crossover to Rollover Contours

Additionally, when examining the vehicle trajectories, even more information about the median profile's ability to entrap the encroaching vehicle can be gathered. The percentage of all vehicles simulated which passed through a certain area of the median was recorded. First, these vehicle populations were sorted by the median slope upon which the simulation took place. The data was normalized per unit width of the median in a way such that the zones of each median were consistent no matter what the median width was. This avoided the issue that a 30 foot offset could exist at either the down slope, back slope, or swale point, depending on the median width. The resulting traces, showing in Figure **5.2**, show that as the vehicles approach the median swale, more vehicles are entrapped on the down slope for a less aggressive median slope. The 10H:1V and 9H:1V median slopes respectively resulted in 58.4% and 60.6% of the vehicles reaching a particular offset on the down slope, compared to the respective 71.2% and 75.1% for the 5H:1V and 4H:1V slopes.

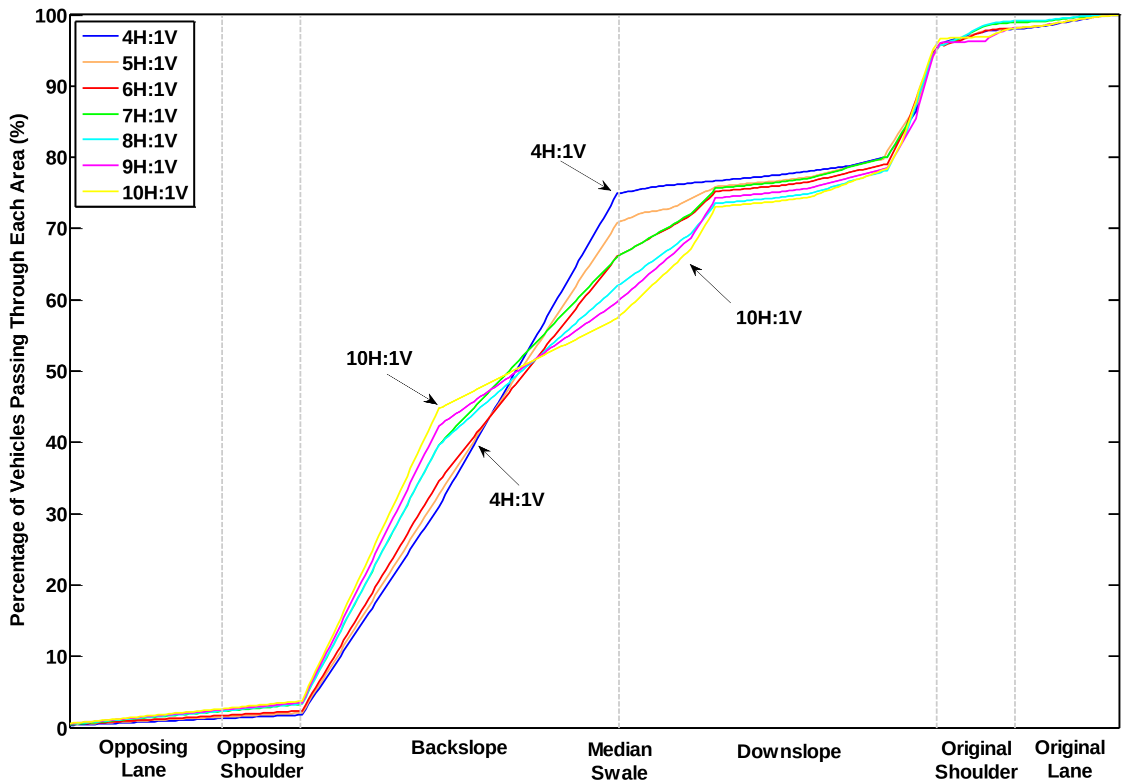

Figure **5.2** – Vehicle Population for Medians of Varying Slope for All Widths

Once the vehicles continue onto the back slope, the trend flips such that the steeper sloped medians have more success at stopping the vehicle. For the 10H:1V and 9H:1V medians, 44.8% and 42.7% of all simulated vehicles reach an offset halfway across the back slope, compared to the 33.4% and 31.0% seen on the 5H:1V and 4H:1V slopes. By the time the vehicles reach the opposing shoulder edge (which is the point at which a median crossover occurs), the traces converge again, resulting in the population of cross-median crashes for these medians which was reported in Table **5.2**.

After the data was sorted per median slope, the same analysis was conducted, this time organizing the data by median width. Again, the traces were normalized per unit width, so the relative zones of each median were consistent regardless of median width. Figure **5.3** shows the resulting distributions of vehicles throughout the incursion.

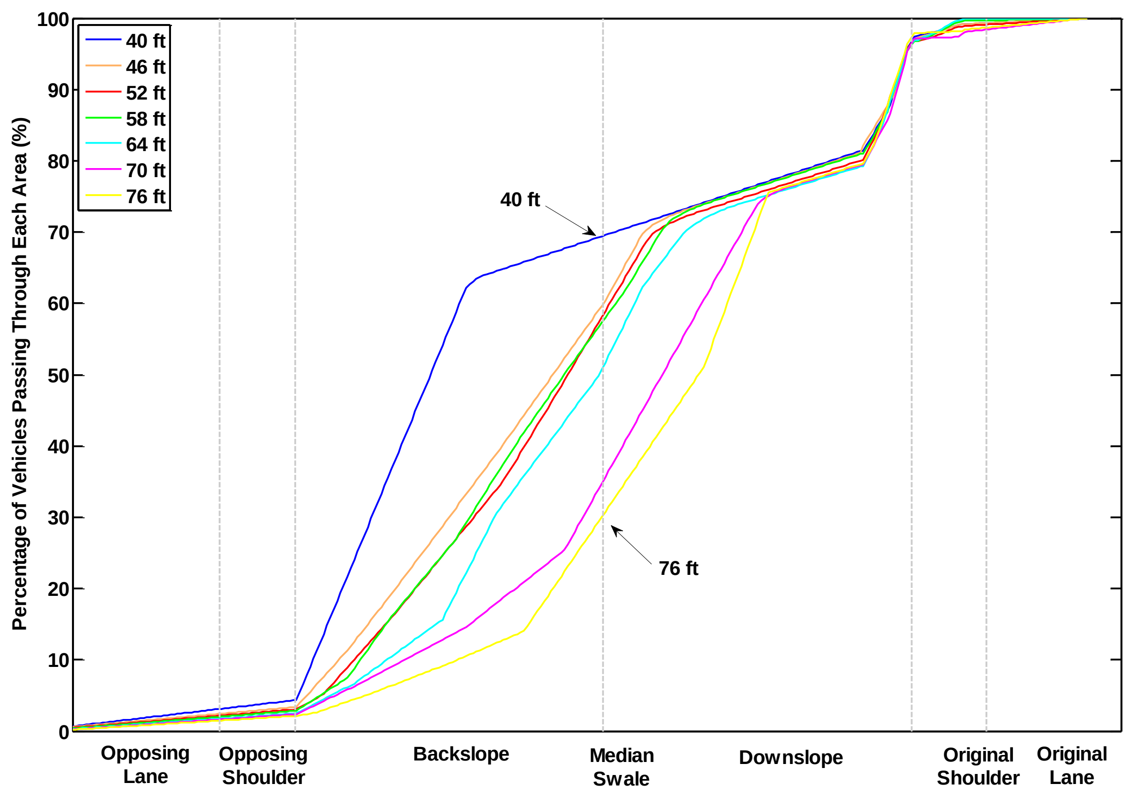

Figure **5.3** – Effect of Median Width on Vehicle Trajectories for All Slopes

For the simulations performed, the larger median widths successfully entrapped more vehicles within the median. As the vehicles traveled along the down slope, a series of parallel traces is seen. At various points within the down slope, the individual traces started to deviate, and by the time the vehicles reached the swale point, a large gap between the 40 foot wide and 76 foot wide medians emerged. 62.4% of the vehicles on the 40 foot wide median reached this point, where only 30.1% of the vehicles passed through on the 76 foot wide median. As the vehicles traveled up the back slope, the resulting traces for the normalized median width began to reconvene.

By arranging each of these traces according to the driver's steering input, this convergence can be explained. In certain cases, most often those in which the driver gives the median recovery steering input, the vehicles are passing through the median swale point and then they are turning back towards the swale as the driver attempts a median recovery. This explains the large gap in vehicle population seen on the back slope which then converges at the opposing shoulder edge. Figure **5.4** shows the distribution of vehicle locations for the 40 foot and 76 foot medians sorted by steering input.

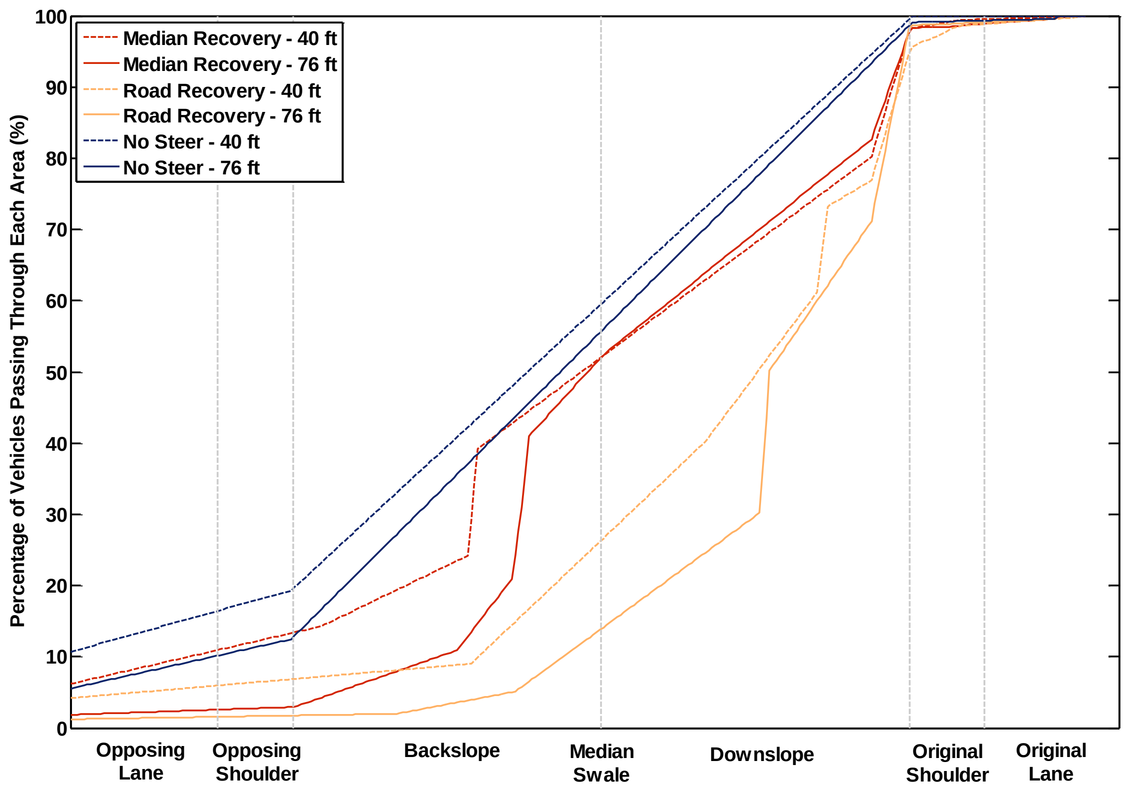

Figure **5.4** – Effect of Steering Input on Vehicle Trajectories

The sudden drops in the vehicle population are due to vehicles reaching that specific offset, but not reaching the next reference point considered. It can be inferred that these spikes are indicative of the vehicles turning back towards the original travel lane, and thus becoming entrapped within an area of the median that they had previous traversed. As seen in Figure **5.4**, these instances occur for the median recovery and roadway recovery steering inputs. Since the driver is not attempting to steer the vehicle at all, the no steer condition has no effect on the vehicle steering back towards the original travel lane. These findings clearly show that the driver's steering input is a large factor in the resulting trajectory of the vehicle during an off-road median encroachment. A more in-depth investigation into the effects of driver intervention is discussed is Chapter 7.

5.2 Barrier Placement and Cable Height

In an attempt to prevent median crossovers, median designs will sometimes employ a barrier within the median. The three typical types of barriers used are concrete barriers, W-beam guardrails, and guard cable barriers. A study conducted by the South Carolina Department of Transportation (SCDOT) at the end of 2003 [1] concluded that of these main barrier designs, the three strand cable barriers were the safest and most appropriate for reducing the amount of vehicles that could potentially traverse the median. However, while designing these cable barriers, the placement of the barrier and the height of the cables themselves must be considered carefully.

In most cases, the vehicle bumpers are going to impact the barrier first, and with the increase of SUVs and large pickup trucks on the highway, the range of bumper heights is rapidly expanding. The lowermost point of the bumper, deemed the bumper clearance height, was, on average, 0.230m for passenger cars and 0.444m for SUVs [2]. As a result of these incompatibilities, the existing cable barriers were no longer effective at preventing catastrophe on the highway. In certain instances, these incompatible bumpers led to the vehicles under-riding the barrier, and at times the vehicles were actually sliced by the cables (see Figure **5.5** [3]).

Figure **5.5** – Vehicle Being Sliced By Cable Median Barrier

To help reduce these horrific events, the bumper position was considered in a post-processing analysis. The trajectories calculated in CarSim are at the vehicle’s center of gravity, thus the bumper position must be inferred. This study employed a market survey of a large portion of the 2009 model line to estimate the average bumper height (with respect to the CG) for each vehicle class. Several different manufacturers and models of passenger cars, SUVs, pickup trucks, and vans were considered to best represent the overall population of vehicles on the highway. Ground clearance, or ride height, data was obtained from the websites of the various different vehicle manufacturers. This data was tabulated and the results can be found in Appendix B.

More times than not, the difference between the ground clearance and bumper clearance value was specific to each individual vehicle design. As a result, the bumper

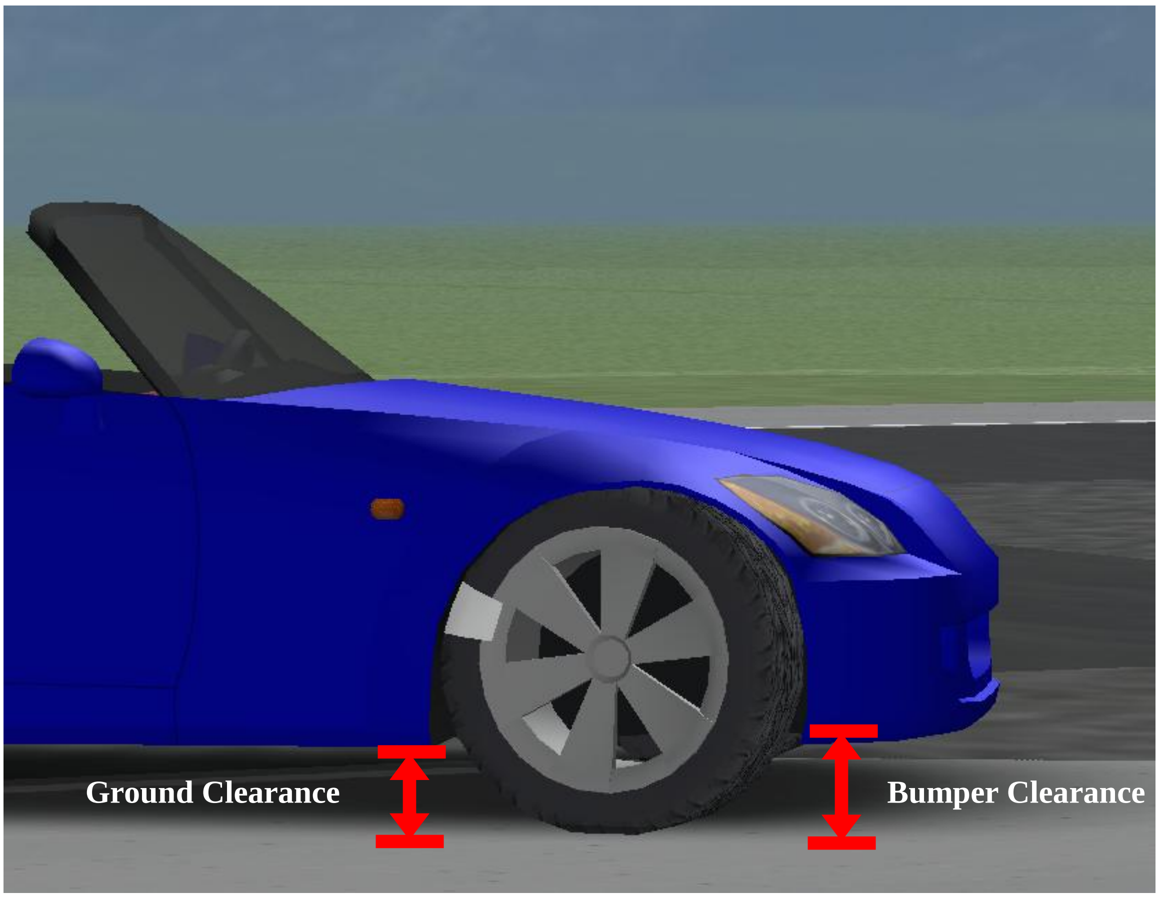

Figure **5.6** – Bumper Clearance and Ground Clearance Definitions

clearance, measured from the ground surface to the bottom of the bumper, of each of these surveyed vehicles was determined through repeated measurements in a parking lot. When these measured bumper clearances were plotted against the ground clearance data in Figure **5.7**, a linear trend between the two values emerged.

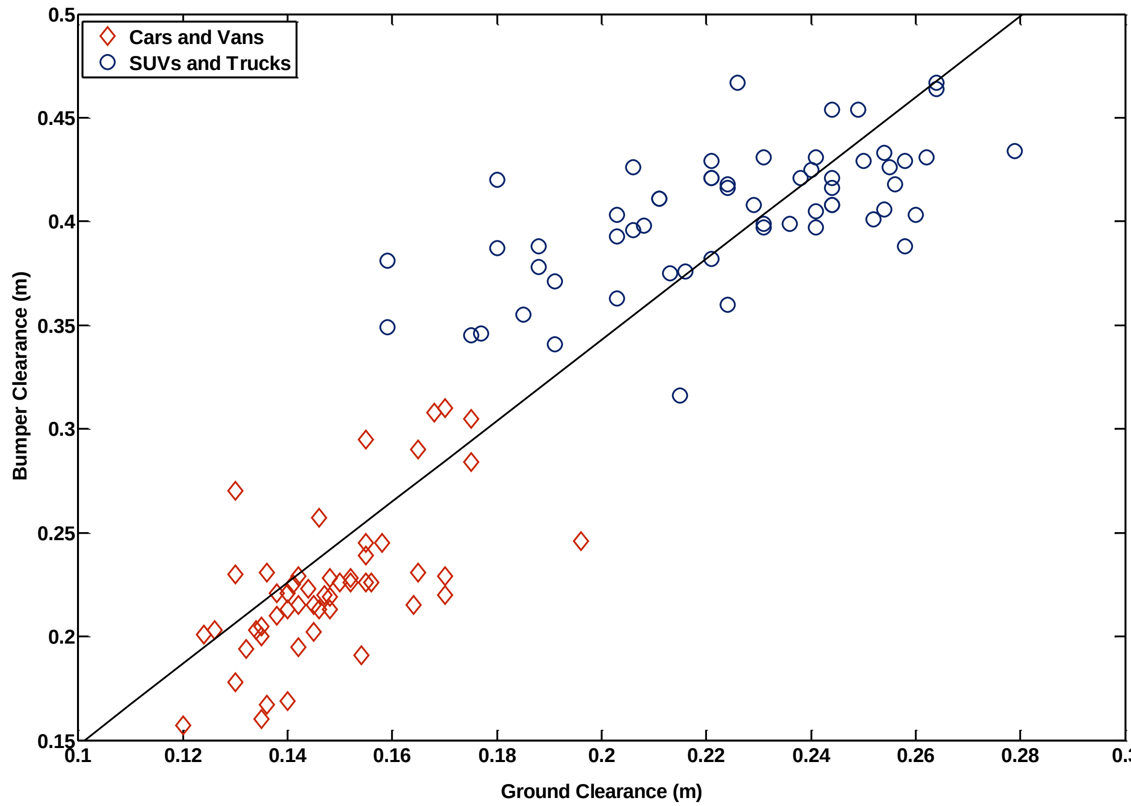

Figure **5.7** – Bumper Clearance Measurements vs. Ground Clearance Data

By considering any point along this line, the bumper clearance for each vehicle class can be inferred from the average ground clearance data calculated from the manufacturer websites. When compared to other bumper height surveys [2], these results are strikingly similar. Using these new bumper clearance values, the average distance between the bumper and the vehicle's CG was easily calculated. This value was then subtracted from the vertical displacement data (output at the CG), resulting in position data for the bottom of the bumper throughout the entire simulation.

As a means for evaluating the validity of these position values, the initial range of all bumper clearance heights was considered. After the previously defined weighting factors were applied to each vehicle class, the resulting distribution is shown in Figure **5.8**. The bimodal distribution seen here is an accurate representation of vehicles on a real-life highway. The first mode corresponds to the population of passenger cars and vans, whereas the second mode is indicative of the SUV and truck population. The two modes are separated by about 8 inches (20.5 cm), reflecting a great deal of incompatibility amongst bumpers on the highway today.

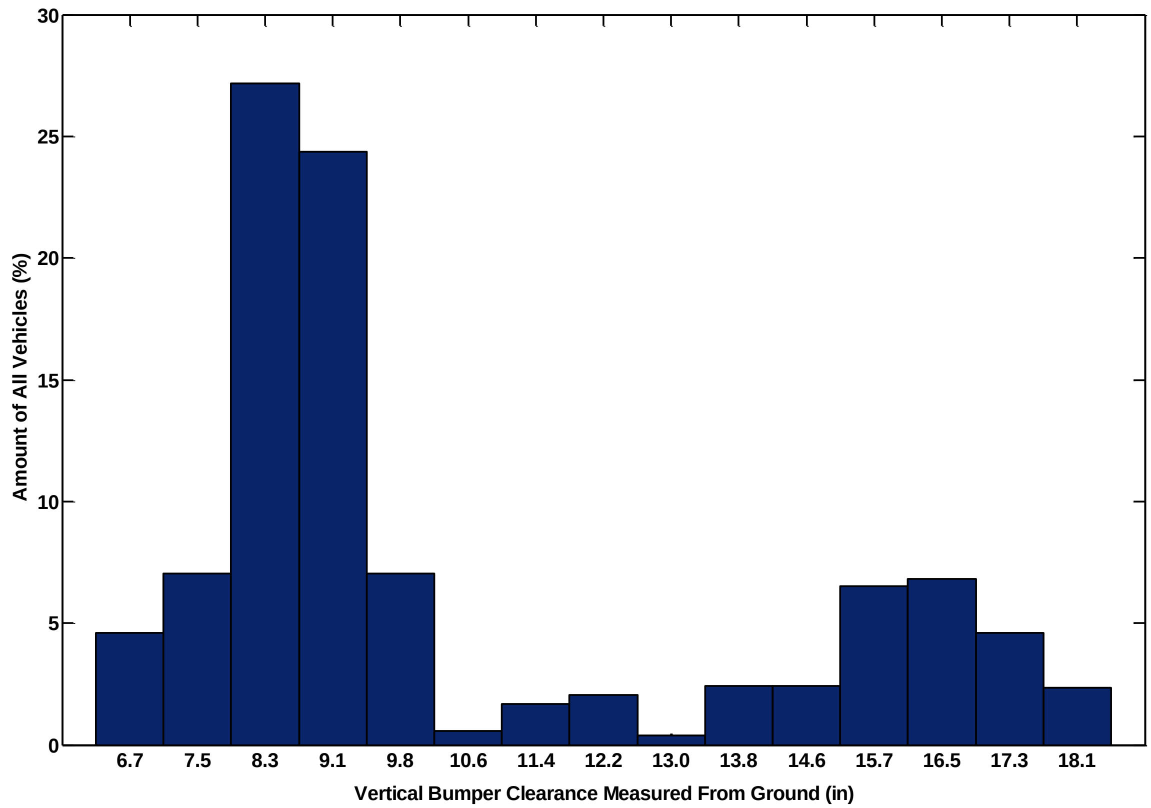

Figure **5.8** – Distribution of All Bumper Clearance Heights on the Highway

In practice, the term “bumper height” is commonly accepted to be the distance from the ground surface to the top of the bumper [4]. As such, the height of the bumpers themselves was also measured in a parking lot and then average values were taken across each vehicle class. By adding this resulting mean to the position of the bottom of the bumper, position traces for the “bumper height” were calculated throughout the vehicle trajectory.

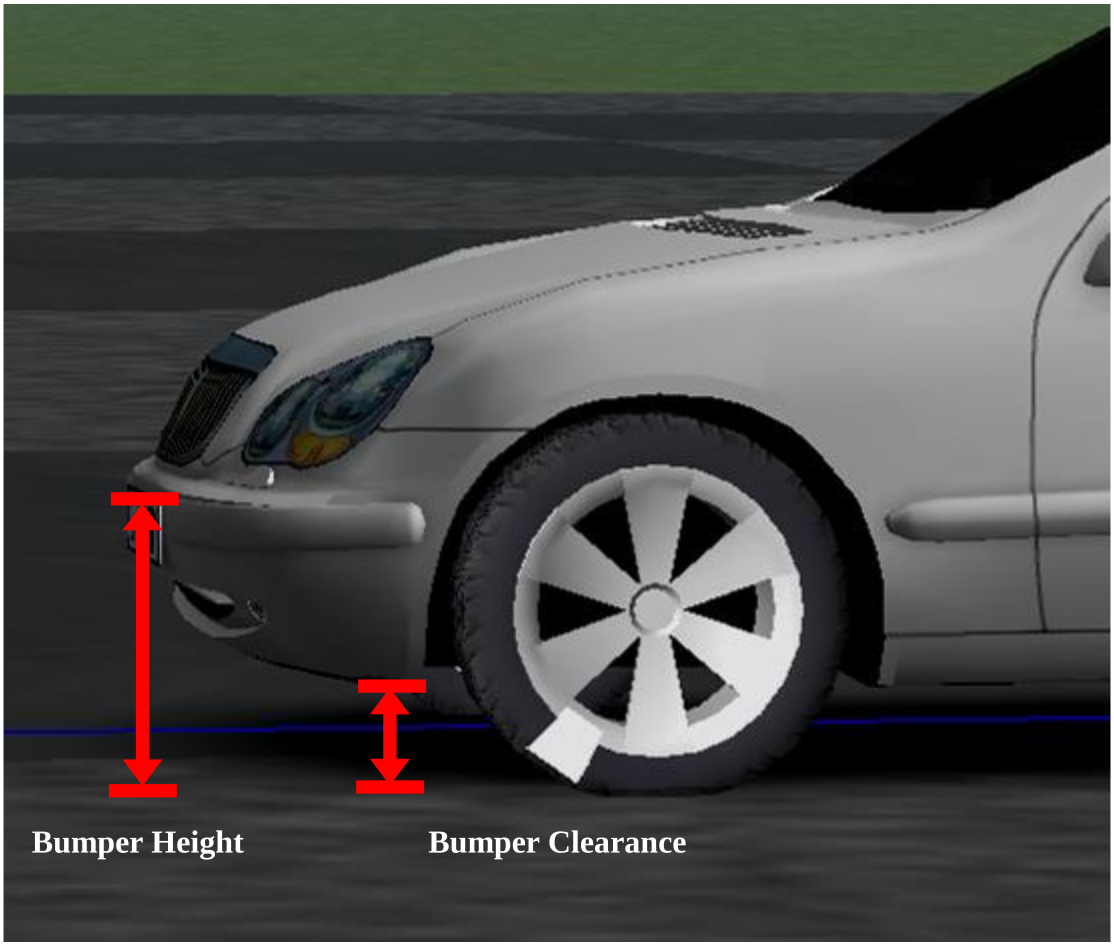

Figure **5.9** – Bumper Height Definition

After applying the individual weighting factors to each of the 111,132 simulations, a weighted distribution of bumper heights was generated at several different locations within the median, including: when the vehicle was at the edge of the original travel lane, the shoulder edge, at the median swale, and at several intermediate points within the down slope. These bumper traces are useful in the design of median barriers, as the entire population of vehicle bumpers is presented at certain offsets from the shoulder. Figure **5.10** displays these distributions overlaying a V-shape median profile. As shown in the figure, the initial bimodal distribution converges to a single model by the time the vehicle passes the edge of the shoulder. This phenomenon is most likely due to the suspension differences between a SUV and passenger car. Typically, SUVs have softer suspensions than passenger cars, resulting in a larger range of travel for the vehicle chassis. Thus, when the SUVs traveled down the median slope, their suspensions compressed, lowering their bumper height closer to that of the passenger car experiencing the same encroachment conditions. Bumper traces representative of a small SUV and small passenger vehicle are also shown in Figure **5.10**. These trajectories utilize the same initial simulation conditions and driver inputs in an attempt to isolate the effect of the vehicle class alone. When the two vehicles reached median swale, their respective bumper traces crossed. In this specific case, the vehicle bounced severely once it reached the swale point, and eventually the entire vehicle even became airborne.

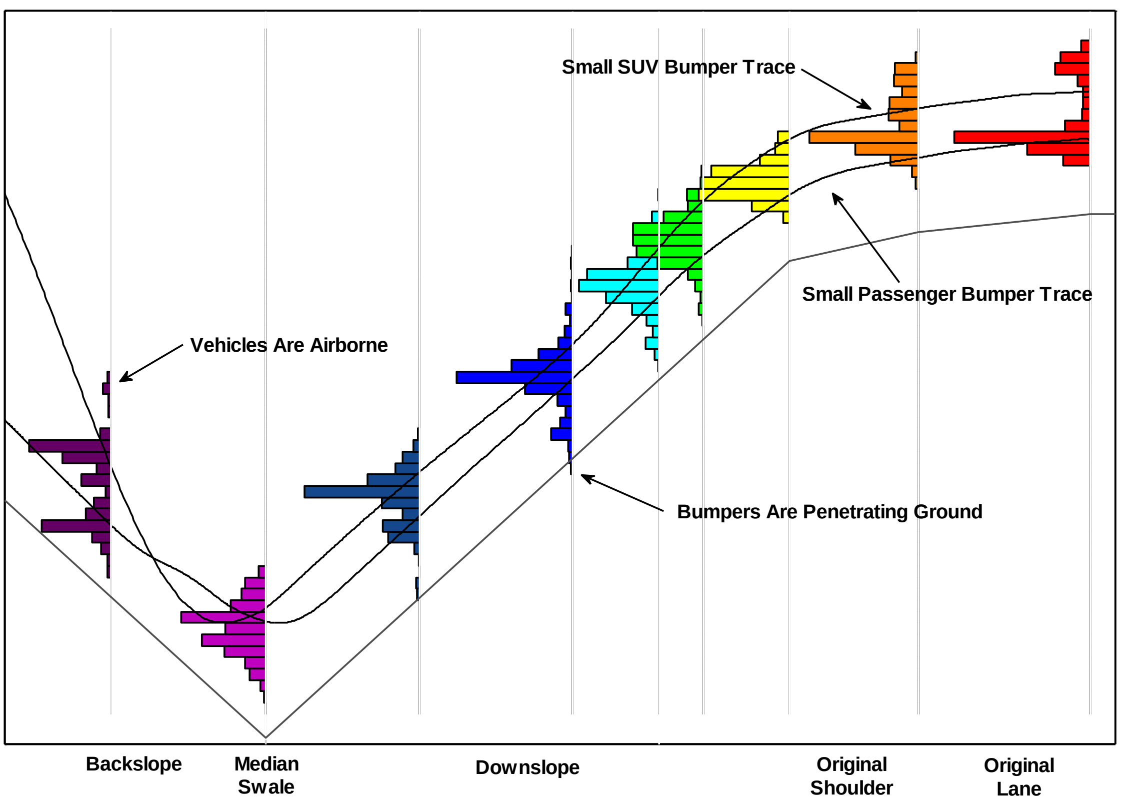

Figure **5.10** – Bumper Height Distributions at Various Locations Within the Median

In some instances, as the vehicle departed the paved shoulder, and continued on the median down slope, the suspension would be compressed so greatly that the front bumper would actually impact the ground. As seen in Figure **5.10**, some of the vehicles that impacted the ground surface even penetrated the ground lightly with the front edge of their bumper. Figure **5.11** captures this occurrence during playback of the CarSim surface animator.

Figure **5.11** – Bumper Penetrating the Ground Surface

Whether the vehicle bumpers penetrated the slope or not, as the vehicles continued through the median, the two modes appeared to separate again. Once the swale point was reached, several bumpers impacted the back slope at roughly the same height. This consistency is reinforced due to the fact that this is the point where the small passenger and small SUV bumper traces (shown in Figure **5.10**) intersected. After this point, major differences between all the vehicles emerged. For example, some vehicles bounced off the back slope before coming to a rest safely within the median whereas other vehicles became airborne and most likely rolled over thereafter.

Taking this analysis one step further, the mode value of bumpers was considered at the same offsets from the highway shoulder. As there were shown to be great inconsistencies between SUV/pickup and passenger car bumper heights, a resulting bimodal distribution of bumper heights was observed. Traces for these two modes of bumper heights were produced for both the bumper top (commonly referred to as bumper height) and bumper bottom (bumper clearance). These trajectories, shown for a 60 foot wide 6H:1V sloped V-shape median in Figure **5.12**, portray the most likely vertical position for both the top and bottom of the bumper for all vehicles on the highway. With these four traces of data, the highway engineer can determine both the barrier location and height of the cables that will be most effective at retaining and redirecting the vehicle in a safe manner.

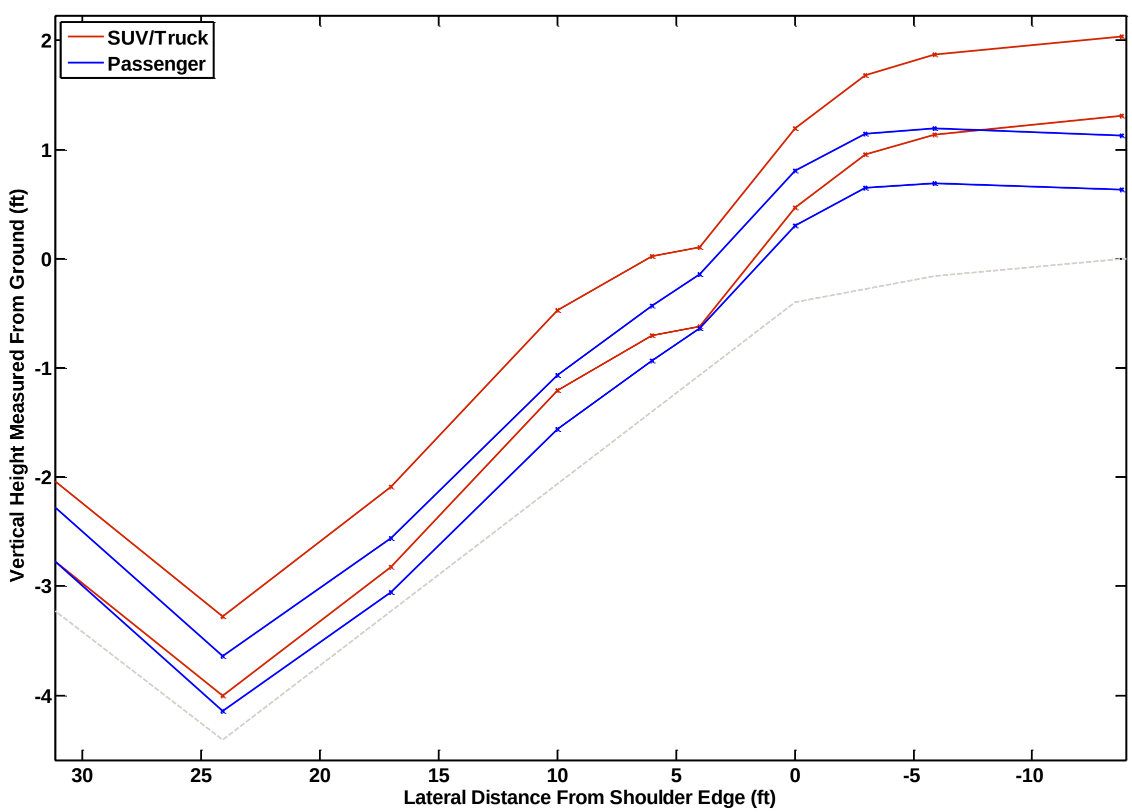

Figure **5.12** – Bumper Height and Clearance Modes During the Median Encroachment

[1] Zeitz, R. (2003). *Low-Cost Solutions Yield Big Savings*. Retrieved January 28, 2008, from Turner Fairbank Highway Research Center: http://www.tfhrc.gov/pubrds/03nov/11.htm

[2] (2006). *Lower/Upper Bumper Reference Line.* International Organization of Motor Vehicle Manufacturers Pedestrian Safety GRSP Informal Group.

[3] Paben, J. (2008). *Photos of Crash Scenes Where Cable Median Barriers Were Involved*. Retrieved June 30, 2008, from The Bellingham Herald: http://blogs.bellinghamherald.com/media/blogs/jared/cable2.jpg

[4] (2007). *Chapter 4501-43 Maximum Height of Bumpers.* Retrieved July 9, 2009, from LAWriter: Ohio Laws and Rules: http://codes.ohio.gov/oac/4501-43

Chapter 6

Validation and Verification

Validation and verification of the simulation work done for this thesis was conducted by comparing simulated results to data traces recorded during full scale experimental tests by other researchers. The data collected from this test was also compared to the results obtained through simulation of the same aggregate test conditions. Further validation efforts were carried out through comparison of the simulation results with statistical correlations obtained through outside studies.

6.1 Full-Scale Experimental Testing

In 2006, a collaborative study between the Texas Department of Transportation and the Federal Highway Administration [1] included full scale crash testing of a 2000 Chevrolet C2500 pickup truck in their test number 452106-3. Acceleration and angular displacement data was recorded with onboard sensors at a rate of 10 kHz. Although this was a test involving a barrier impact, the vehicle traversed 13.25 feet across the median before the collision occurred. Digitization of high speed video footage provides the vehicle trajectory during the encroachment, and indicates that the barrier impact took place at 0.520 seconds.

6.1.1 Test Conditions

Testing was performed at the Texas Transportation Institute (TTI) Proving Grounds Research Facility in College Station, TX. At the proving grounds, a 120 foot long, 6H:1V V-shape median was constructed with compacted soil (see Figure **6.1**). Slight headwinds, ranging from 4 to 7 mph, were also present at the time of the test.

Figure **6.1** – Median Profile for Full Scale Crash Testing

A 2000 Chevrolet C2500 pickup truck with a static weight of 4621 lbs. (2096 kg) was used as the test vehicle. The vehicle's wheelbase and track width were 131.9 in (3350 mm) and 63 in (1600 mm) respectively. Additional vehicle parameters are given in Appendix C.

Using a cable tow and guidance system, the test vehicle departed the roadway at an initial speed of 62.9 mph (101.2 kmph) and an encroachment angle of 24.7°. Upon reaching the edge of the roadway surface, just prior to continuing down the slope, the cable was released and the vehicle was free to traverse the median and impact the barrier. For the validation work presented here, the first 0.520 seconds from the time the vehicle reached the edge of shoulder until the moment of impact are used.

6.1.2 Comparison of Simulation Results to Full Scale Testing

To obtain the vehicle trajectory, high speed video footage from the crash test was digitized. A total of 52 data points were obtained during the 0.520 seconds elapsed prior to the barrier impact. As longitudinal position is not really of importance, only the lateral and vertical traces were considered. The full scale vehicle was determined to be at the edge of the shoulder at time t=0, and as a result, the simulation data from CarSim was offset so the time stamp t=0 corresponded to when the simulated vehicle was at the same distance. Figure **6.2** shows the ensuing trajectories in the YZ plane for both the full-scale test and the simulated vehicle.

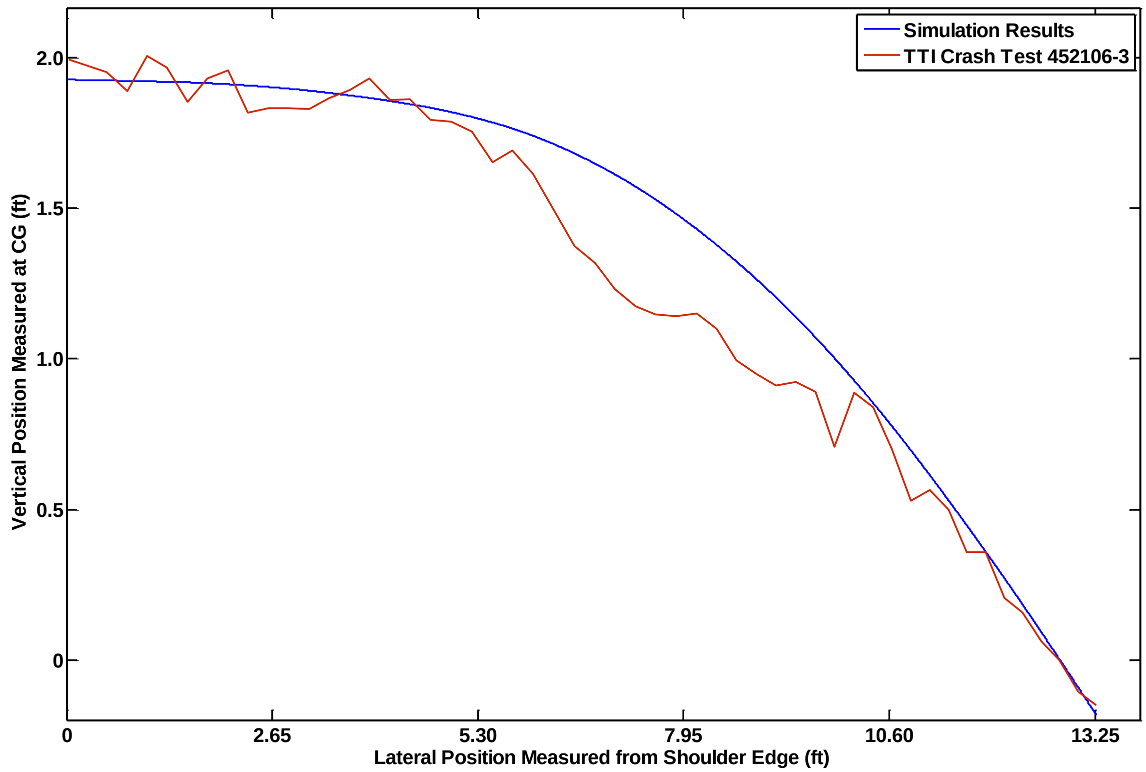

Figure **6.2** – Vehicle YZ Trajectories for CarSim and Crash Test Results

As seen in the figure, the overall trend of the simulation data matched this individual crash scenario rather well. When the vehicle reached a lateral distance of 5.3 feet, or roughly halfway through the trajectory, the two sets of data started to diverge slightly. At a lateral offset of 10 feet, the traces again merged, and the two coincided very well for the remainder of the trajectory.

Further comparisons were drawn for angular displacement data between the simulation and crash test. The roll and yaw angle outputs from CarSim, seen in Figure **6.3** and Figure **6.4** respectively, matched very closely with the real-life test. Large discrepancies between the two tests emerged when the pitch angle was examined.

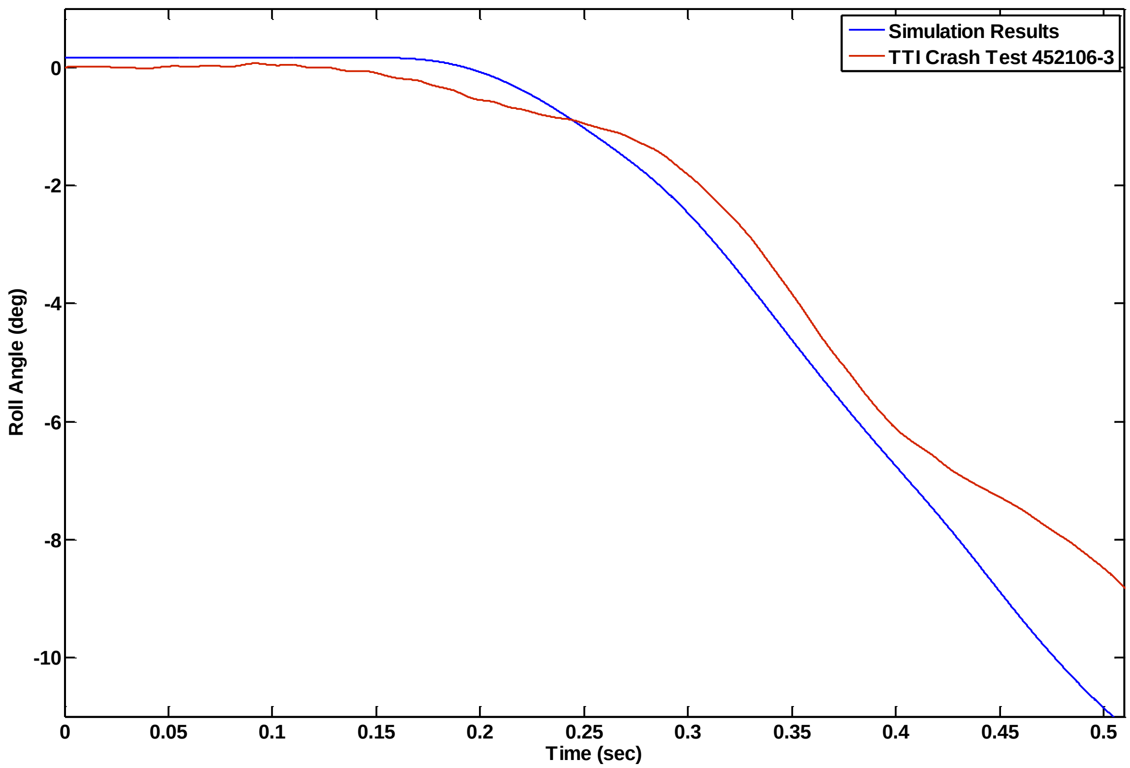

Figure **6.3** – Roll Angle for CarSim and Crash Test Results

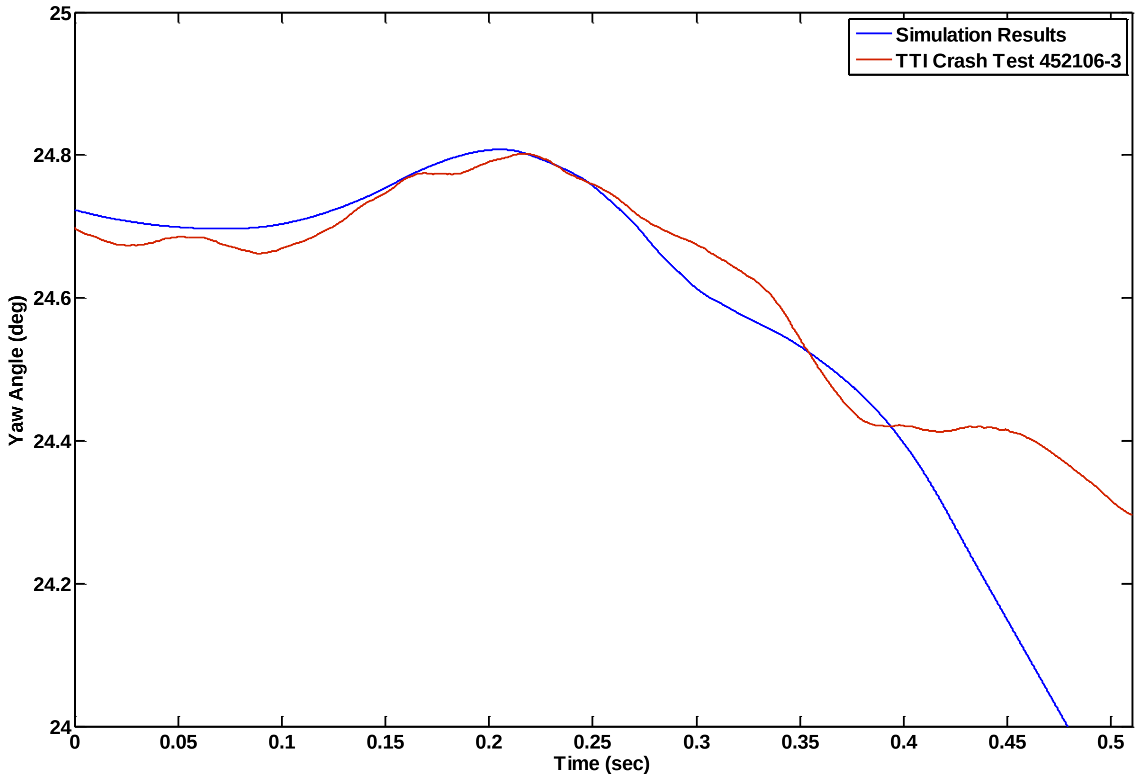

Figure **6.4** – Yaw Angle for CarSim and Crash Test Results

The comparison of pitch angle between both datasets is shown in Figure **6.5**. Around 0.225 seconds, the simulations started deviating from the crash test data. By the end of the encroachment, the difference between the two sets of angle data was over 6°.

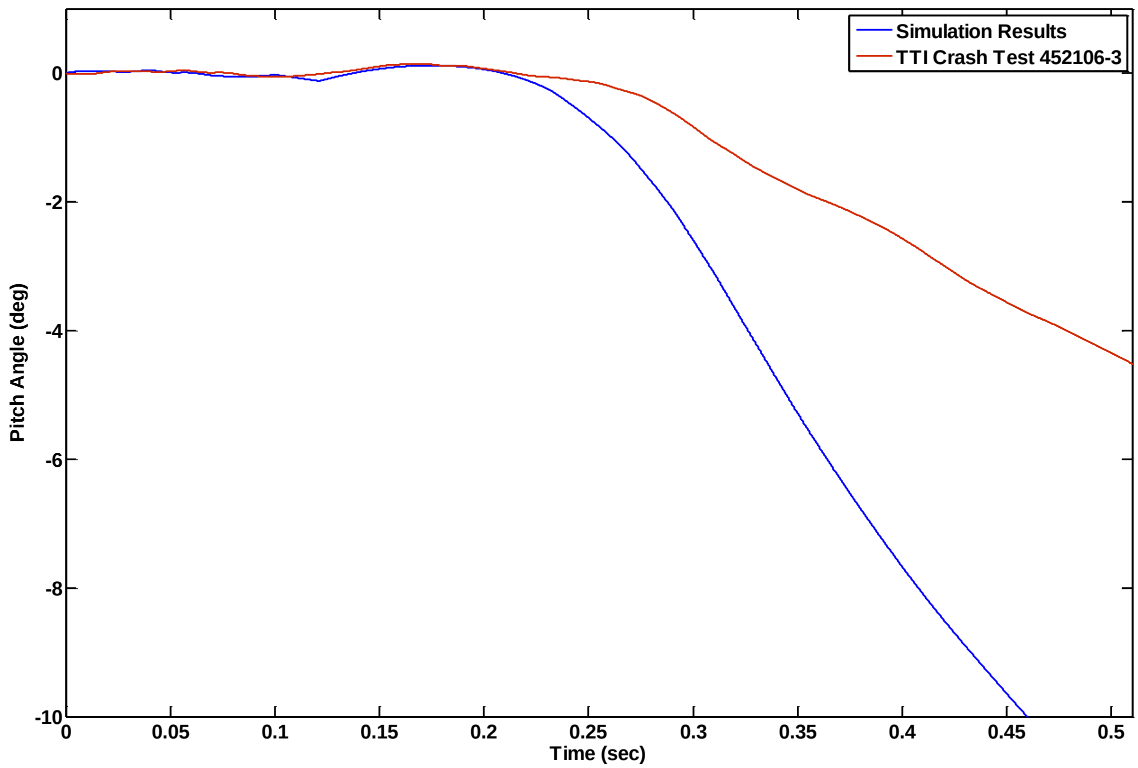

Figure **6.5** – Pitch Angle for CarSim and Crash Test Results

When examining the vehicle's suspension in high speed video footage from the experimental test, this relatively large difference in pitch angle data can be best explained as follows. As the vehicle was being accelerated, the tires and/or front suspension were being loaded by the cable-tow system. When the cable was released at the moment the vehicle reached the edge of the shoulder, the suspension appeared to be rebounding, thus forcing the front of the vehicle upwards and decreasing the vehicle's pitch. The vehicle then became airborne as it traveled down the slope, and remained airborne until impact (see Figure **6.6**). This airborne effect would also lead to a lower pitch angle than if the vehicle were driving on the sloped surface. Although these phenomena lead to discrepancies in pitch angle, they would not have any noticeable effect on the roll or yaw angle, thus explaining why pitch, and only pitch, angle data did not match closely.

Figure **6.6 –** Fully Airborne Vehicle During Experimental Crash Test

Several of the assumptions made for the accident reconstruction could be additional causes of these differences in vehicle pitch. When the test vehicle was built in CarSim, the overall dimensions, weight, and inertial properties were the only parameters adjusted. The remaining features of the test vehicle, including suspension characteristics and tire inflation pressures, were defined with the default “Pickup: Full Size” in CarSim, and were most likely different from the actual values for the full-scale test vehicle. As the vehicle traverses down the embankment, these attributes have a great effect on the amount of suspension displacement that will occur, and thus have a resulting effect the vehicle’s pitch angle throughout the encroachment. Furthermore, as seen in both simulation and real-life testing, the vehicles may become completely airborne once they leave the roadway and travel down an embankment. In addition to affecting the vehicle pitch angle, these suspension differences would also be a contributory factor to whether the vehicle became airborne or remained on the ground surface.

6.2 Statistical Validation

Although the full-scale experimental testing provides a great source for validating the CarSim results for off-road median incursions, comparing the overall simulation results and trends with crash statistics leads to a means of comprehensively verifying the entire set of simulations.

6.2.1 Rollover Verification

The 2005 NHTSA Traffic Safety Facts [2] concluded that of all the reported accidents, 2.6% of them led to rollover events. This batch of simulations contained a total of 111,132 runs (2,058 runs per median x 54 medians). There were a total of 2734 rollover incidents, representing 2.46% of all the crashes simulated. Comparing the measured 2.6% statistic from NHTSA to the simulation result of 2.46%, the simulation results deviated by a mere 5.38%. This close correlation to the percentage of real-life rollover incidents goes to validate the simulations performed in this study.

Additionally, in 2004, the Traffic Safety Facts [3] reported that the breakdown of rollover incidents per vehicle class went as follows: 36% for SUVs, 25% for pickups, 17% for vans and 16% for passenger cars. When grouping the simulation results into the four aforementioned categories, SUVs accounted for 35.9% of all rollover cases, while 28.2% was contributed by pickups, 16.8% for vans, and 19.1% for passenger cars. Again, the values obtained with the simulations (shown in Figure **6.7**) are in correlation with this data published by the NHTSA, thus providing another means of validating the work performed in this study.

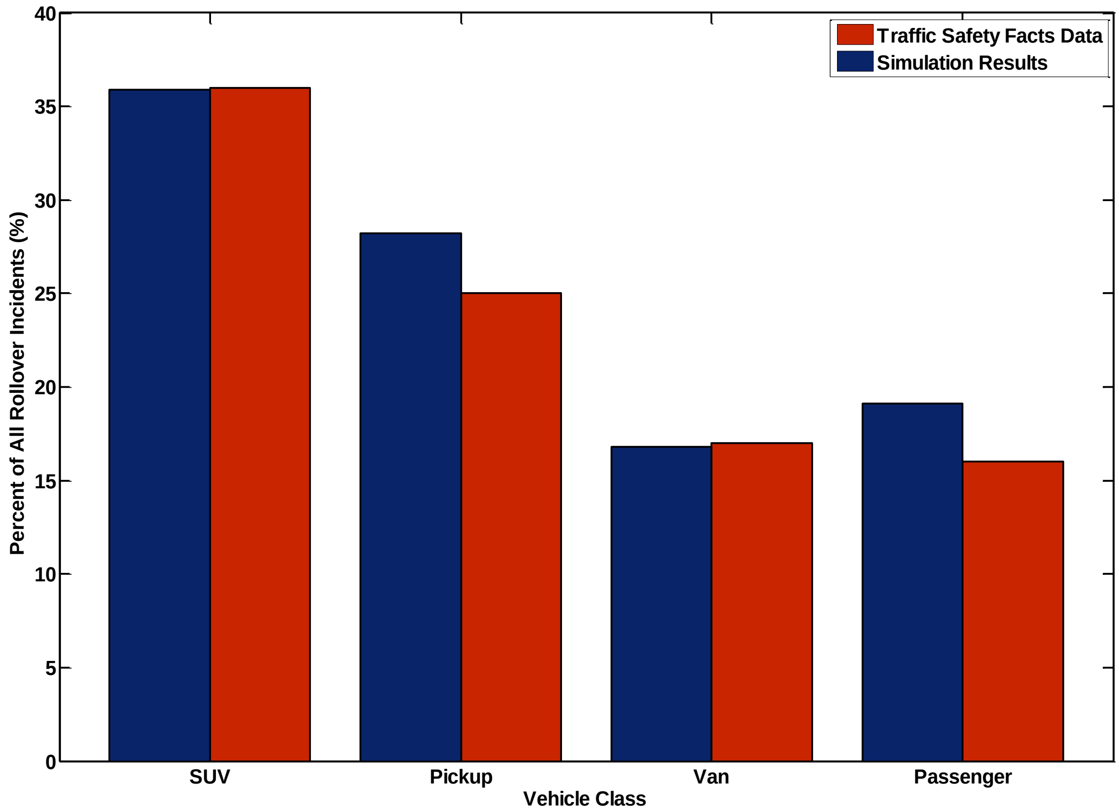

Figure **6.7** – Comparison of Rollover Data for Each Vehicle Class

As can be seen in the figure, the simulations closely compare to the real-life data from the 2004 Traffic Safety Facts, with the SUV and van vehicle classes matching extremely well. The simulations predicted that passenger cars would roll 3.1% more often, and pickups 3.2% more, than the crash statistics showed. These discrepancies are most likely due to the fact that the NHTSA figures only sum up to a total of 94%. It can be inferred that 94% of the rollovers recorded were for passenger vehicles, while the remaining 6% consisted of commercial vehicles, most likely heavy trucks and busses. As the CarSim experiments were only run for passenger vehicles, the resultant percentages reflect 100% of the roadway population.

Because of this difference, totals for the simulations were then modified to add up to the 94% reported in the Traffic Safety Facts. The previously used weighting factors (reported in Table **3.2**) were altered to reflect the population of vehicles on the highway used by the Traffic Safety Facts. After these adjustments were made, the SUVs now contributed to 35.1% of all rollover cases, while passenger cars, pickup trucks, and vans respectively accounted for 15.6%, 27.1%, and 16.3%.

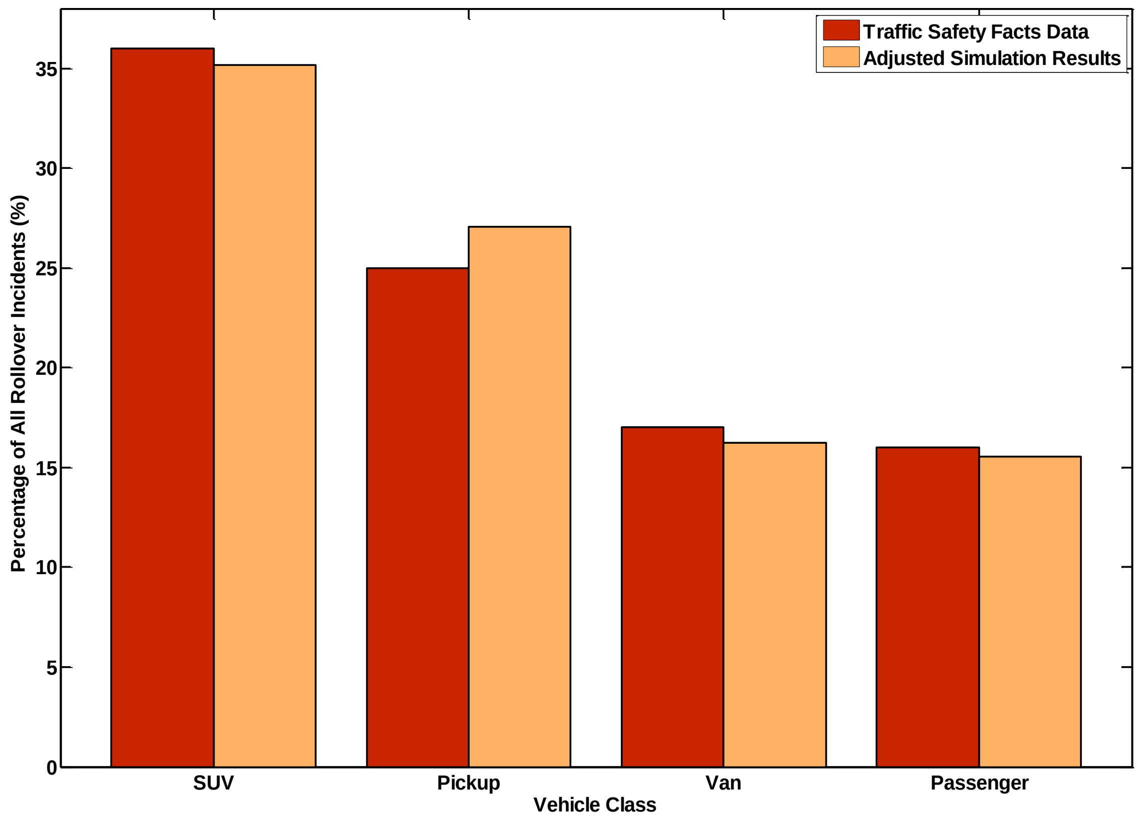

Figure **6.8** – Adjusted Rollover Data for Each Vehicle Class

As seen in Figure **6.8**, once the simulation data was weighted and modified to add up to 94%, the CarSim results are an exceptionally good match with the real-life crash statistics. The difference between the two data sets is summarized in Table **6.1**. As can be seen in the table, with the bus and heavy truck data eliminated, the rollover data for all the vehicle classes simulated differ from the crash statistics by less than 8.5%, and in most of the cases, less than 4%. It can now be said that these values are in very close correlation with this data published by the NHTSA, thus further validating the work performed in this study.

Table **6.1** – Simulation Rollover Data Compared to 2004 NHTSA Traffic Safety Facts

Vehicle Class	NHTSA Traffic Safety Facts	Adjusted Simulation Results	Percent Difference
SUV	36.0%	35.1%	2.5%
Pickup	25.0%	27.1%	8.4%
Van	17.0%	16.3%	4.1%
Passenger	16.0%	15.6%	2.5%

6.2.2 Median Crossover Verification

In addition to the rollover results validated in the previous section, the median crossover data from the simulations must be verified as well. For this portion of the cross-verification, results from the NCHRP 22-21 [4] study were used. This study provides statistical data for the occurrence of both cross-median collisions and vehicle rollover. These statistics were arranged according to the median slope and width characteristics, and data not pertaining to medians evaluated during this study was ignored. Comparing these datasets, the simulation results were in agreement with the real-life statistics again.

The NCHRP 22-21 data sorted the median slopes into the following categories: 2:1 to 4:1, 4:1 to 6:1, 6:1 to 8:1, and 8:1 to 10:1. Similarly, the median widths were grouped as such: 31 to 50 feet, 51 to 65 feet, and 66 to 80 feet wide. In agreement with these groupings, the simulation data was combined into the same median profile denominations. Figure **6.9** shows the resulting comparison between the two data sets, based on the slope of the median simulated.

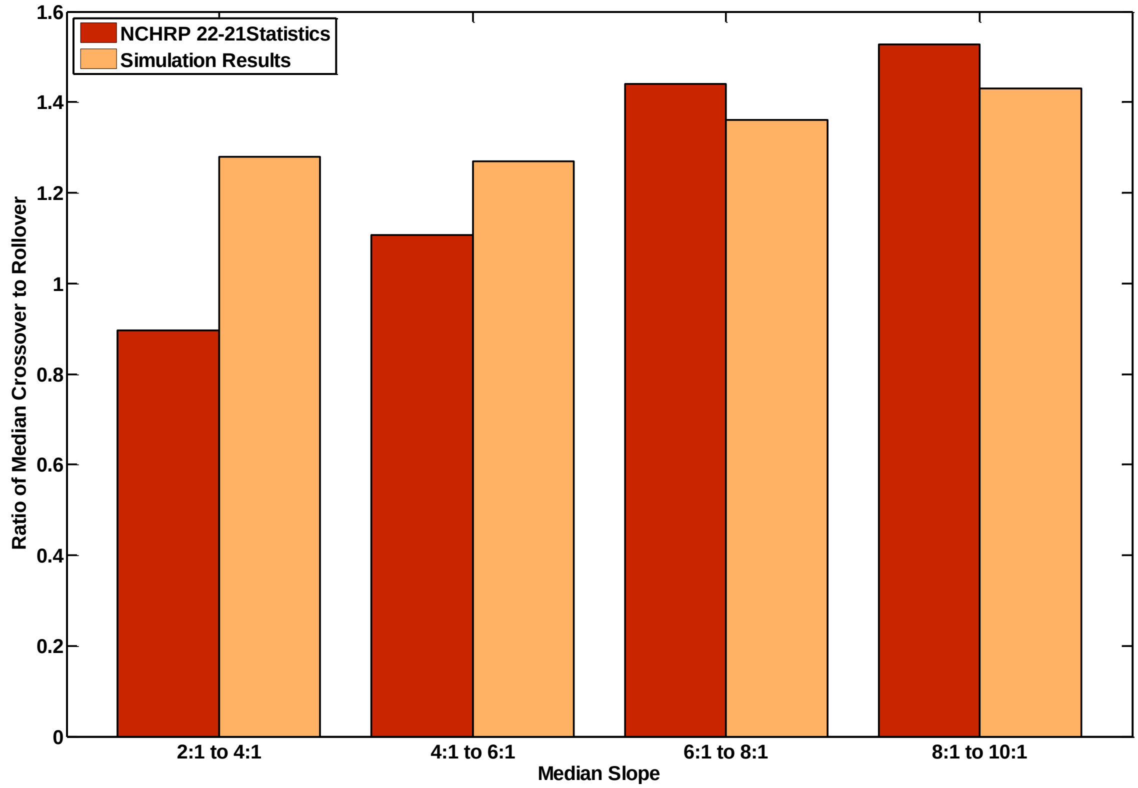

Figure **6.9** – Comparison of Crossover to Rollover Ratio for Each Median Slope

With the exception of the 2:1 to 4:1 median slope subset, all of the remaining simulation results strongly resemble the reported crash statistics, deviating by less than 15%. The discrepancy in the 2:1 to 4:1 range between the two data sets is most likely due to the tiny number of accidents that were reported in the NCHRP data. Less than 20 miles (32 km) of highway were surveyed in this category, compared to the 344 miles of highway in the 6:1 to 8:1 slope bracket. Hence, the number of accidents reported may not be statistically significant. Additionally, another reason for this lack of correlation could be that of the medians within the 2:1 to 4:1 range, only the 4:1 slopes were simulated in our study. As shown in Section **4.2.2**, generally speaking, a steeper slope will lead to a larger number of rollovers. From this, it can be inferred that if the 2:1 and 3:1 sloped medians were indeed simulated, there would be a greater rollover rate for that range of slopes. Thus, the crossover to rollover ratio would decrease, leading to a better match with the crash statistics.

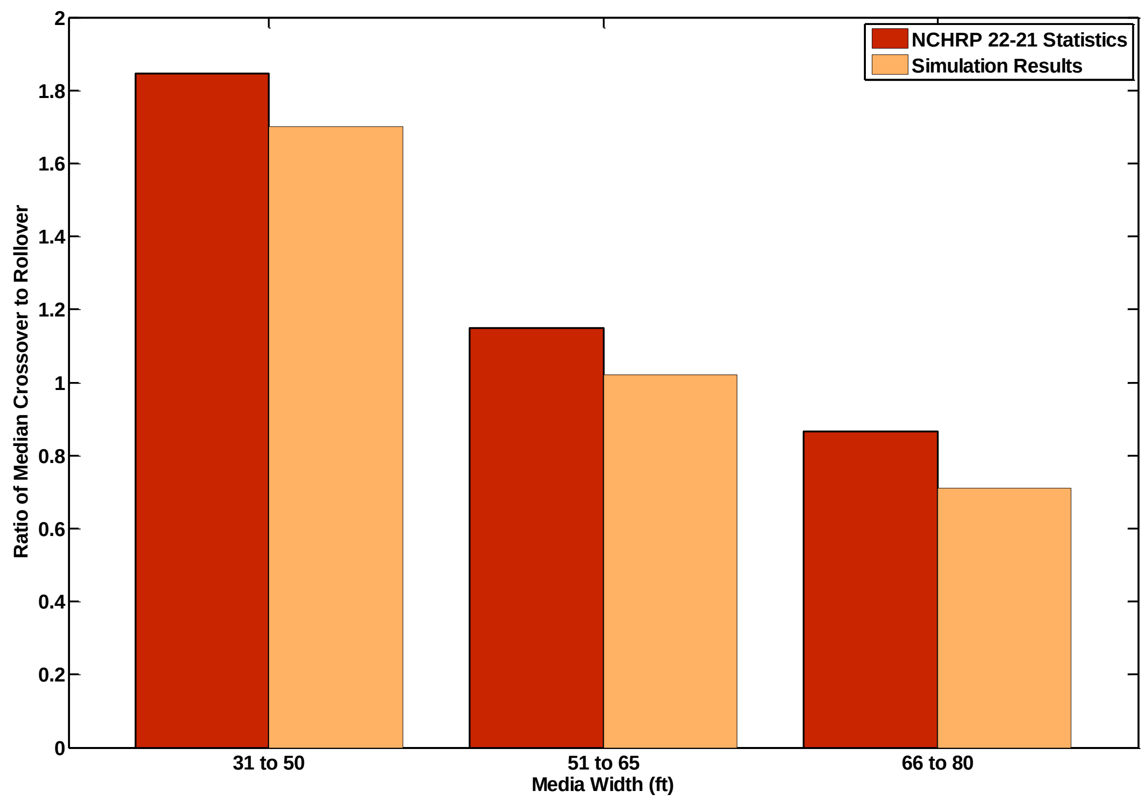

Figure **6.10** – Comparison of Crossover to Rollover Ratio for Each Median Width

Presenting the results from the simulations and crash statistics, based upon the width of the median, Figure **6.10** again shows a close correlation between the two sets of data. The simulation results deviated from the NCHRP statistics by a maximum of 16.6%. But, even with these differences in the actual numerical data, the general trends closely match: as median width increased, crash data clearly shows that the number of crossovers decreased and the number of rollovers increased. Likewise, as the median slope was flatter, the crash data verified that the number of crossovers increased and the number of rollovers decreased. This comparison, summarized in Table **6.2**, validates that the experimentally measured tendency of a median to experience a crossover event is preserved in the simulations.

Table **6.2** – Crossover to Rollover Ratio for Simulations and NCHRP 22-21 Statistics

Median Width (ft)	Median Slope	NCHRP 22-21	Simulation Results	Percent Difference
ALL	2:1 to 4:1	0.896	1.280	42.8%
	4:1 to 6:1	1.107	1.270	14.8%
	6:1 to 8:1	1.440	1.360	5.54%
	8:1 to 10:1	1.527	1.430	6.34%
31-50	ALL	1.847	1.695	8.24%
51-65		1.148	1.016	11.5%
66-80		0.866	0.723	16.6%

The overall fidelity of the simulations, compared to the published crash statistics from the NHTSA and NCHRP studies, is presented in Figure **6.11**. By plotting the crash statistics versus the simulation results, and drawing a line of perfect correlation, the error in the simulations is reflected in the resulting distance from this line. As displayed here, the simulation results show great agreement with both sets of real-life crash data.

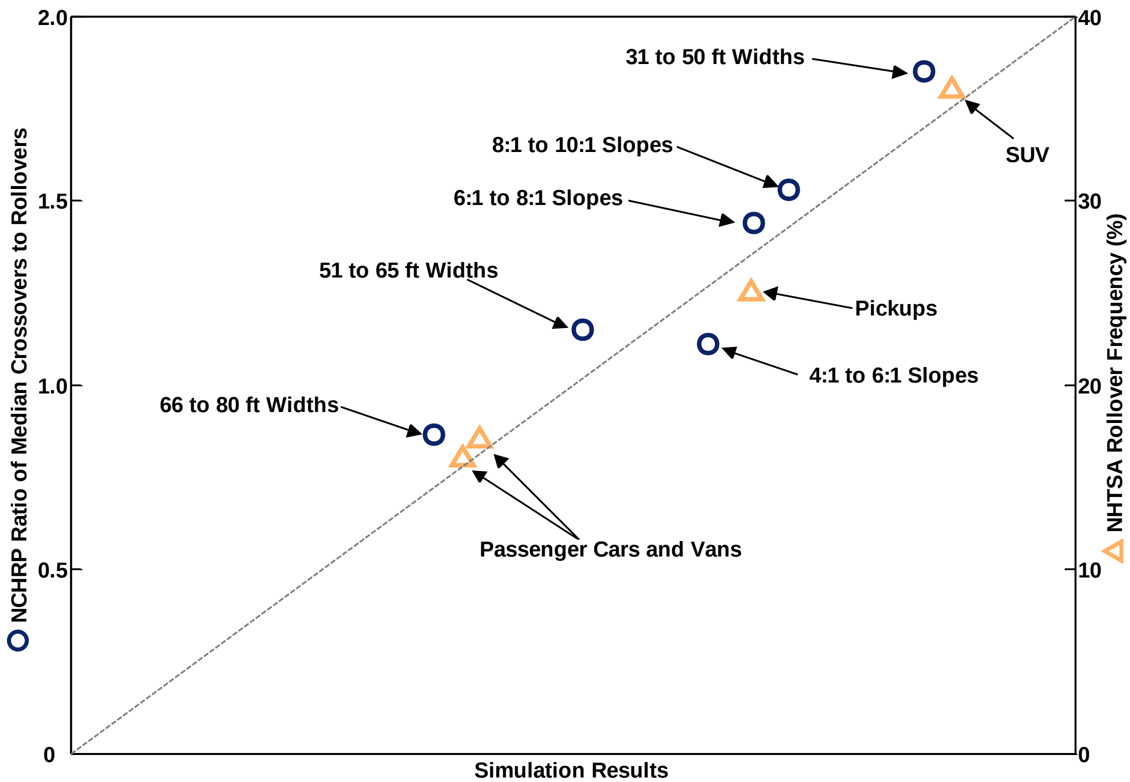

Figure **6.11** – Fidelity of Aggregate Simulation Results

[1] Sheikh, N.M., Bligh, R.P., Menges, W.L. (2007). *Crash Testing and Evaluation of F-Shape Barriers.* College Station: Texas Transportation Institute. FHWA/TX-08/0-5210-3.

[2] (2006) *Traffic Safety Facts 2005: A Compilation of Motor Vehicles Crash Data from the Fatality Analysis Reporting System and the General Estimates System*. Washington, D.C.: National Highway Traffic Safety Administration.

[3] (2004). *Traffic Safety Facts: 2004 Data.* Washington, D.C.: National Highway Traffic Safety Administration: p. 1-12. DOT HS 809 911.

[4] Graham, J. L., et al. (2009). *NCHRP Project 22-21: Median Cross-section Design for Rural Divided Highways.* Washington, D.C.: Transportation Research Board of the National Academies.

Chapter 7

Effect of Driver Input on Vehicle Response

As stated in Chapter 3, the driver's input during a median incursion is the most unknown aspect of the crash scenario. In most previous studies of this nature, the driver's input is neglected, but results from this test presented in Section **5.1** indicate that the driver intervention is a primary factor in accident causation and hence cannot be ignored. Thus, a more in-depth investigation into the influence of the driver inputs was conducted.

7.1 Influence of Driver's Actions

To illustrate the importance of the driver's actions, the same vehicle, speed, and encroachment angle was simulated on a 6H:1V, 60 foot wide V-shape median. Each successive run implemented a different input from the driver. In Figure **7.1** below,

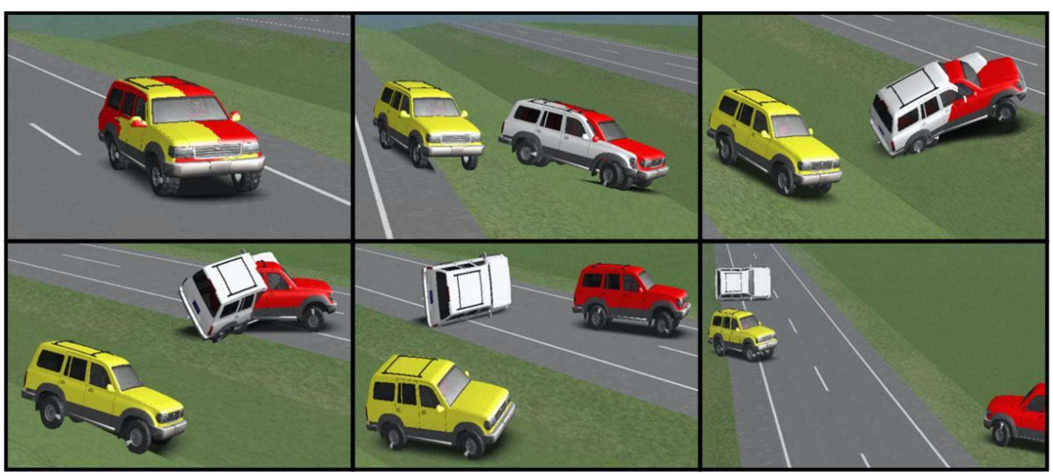

Figure **7.1** – Influence of Steering Input on Vehicle Response a simulation run is shown for a small SUV departing the roadway at an angle of 12.5°, and with an initial speed of 88 kmph (55 mph). The white vehicle simulates the road recovery steering input, the red vehicle has the median recovery, and the yellow vehicle has the no steer condition. As can be seen in the figure, there are extreme differences in the vehicle response between these three scenarios even though the only differing factors were the driver inputs. One vehicle exhibited rollover, another led to a median crossover event, while the third crossed both lanes of oncoming traffic and came to a rest on the far shoulder of the opposing lane.

Although the screenshots from the CarSim animator shown in Figure **7.1** depict the vast differences in vehicle response for varied driver inputs, more is revealed when examining the full dataset for these simulations. Vehicle roll angle and sideslip are shown in Figure **7.2** and Figure **7.3** respectively. Again, the results here are drastically different with the only variable factor being the driver input.

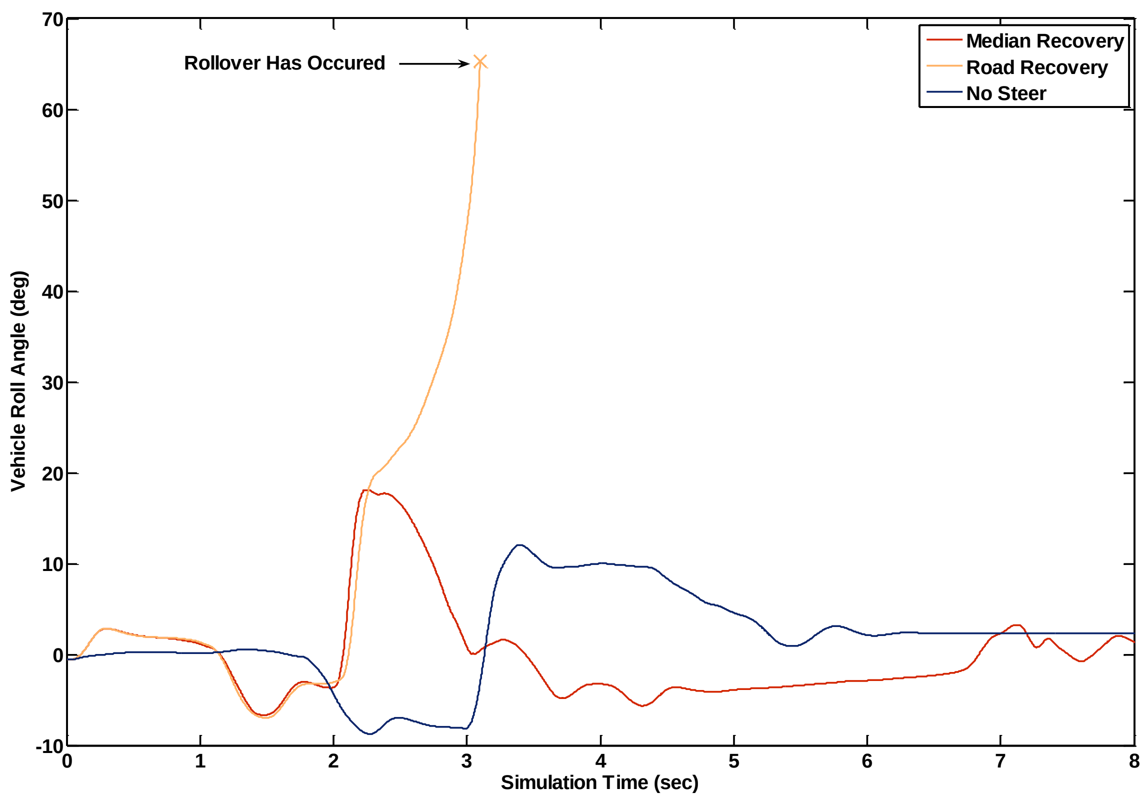

Figure **7.2** – Influence of Steering Input on Roll Angle

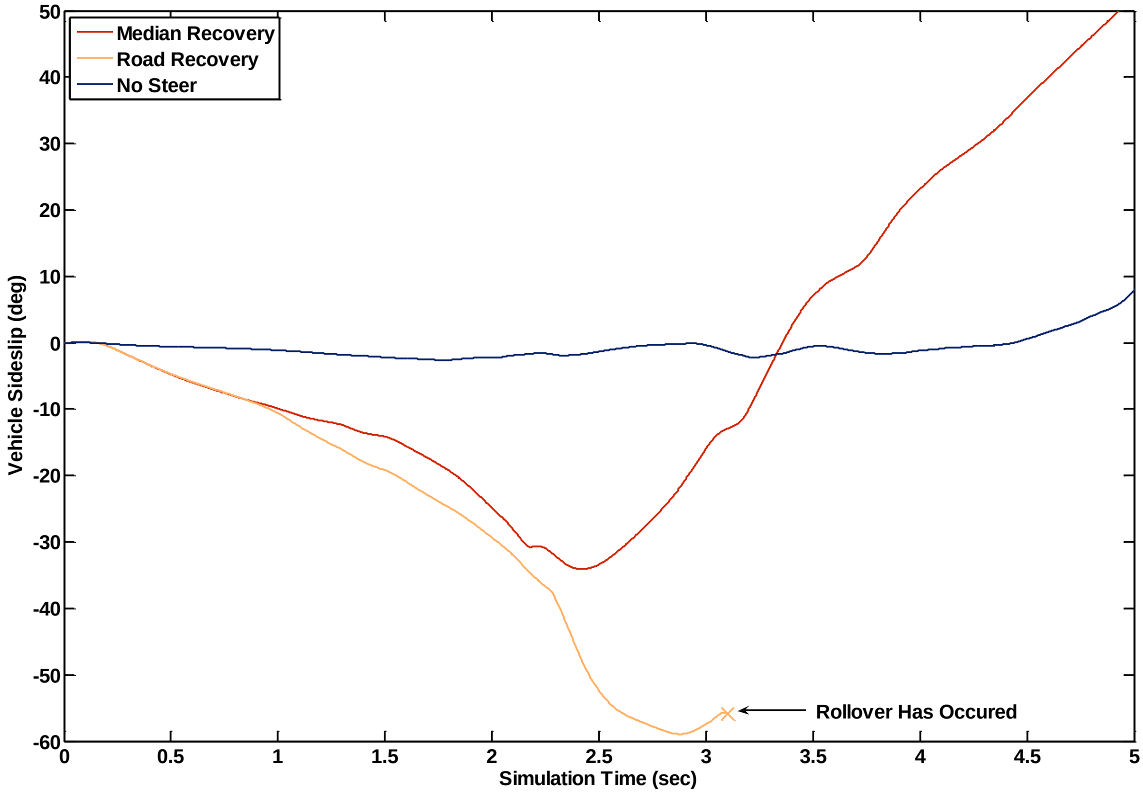

Figure **7.3** – Influence of Steering Input on Sideslip

After this investigation of the driver's influence on the vehicle response during an individual scenario, the entire batch of 111,132 simulations was analyzed. Examining all the instances of rollover, and organizing them by steering input, the results show the influence of each steering input. As expected, the most aggressive steering input (road recovery) led to the highest number of rollovers. 61.4% of all rollovers documented in this study were simulation runs that implemented the road recovery steering input. Compared to the 33.2% for median recovery, and the mere 5.31% for the no steer condition, the road recovery steering resulted in almost twice as many rollovers as the median recovery. Figure **7.4** displays the resulting distribution for all vehicle rollovers detected in the simulations per steering input.

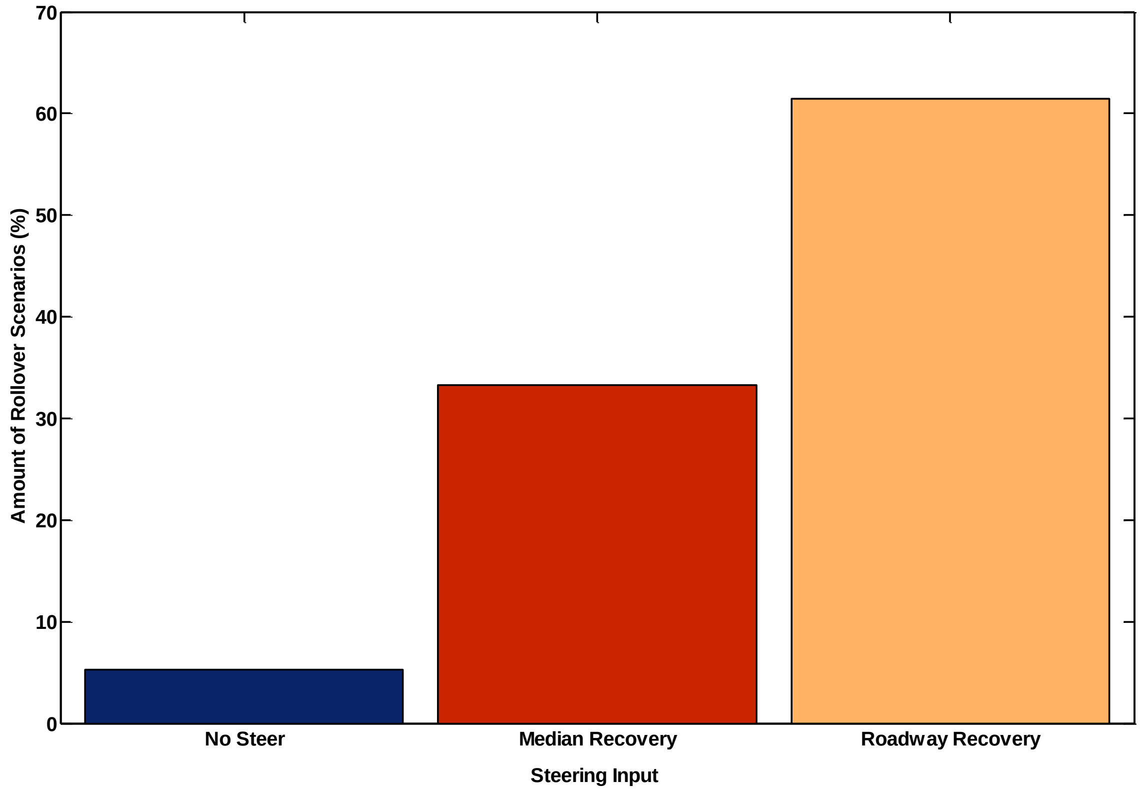

Figure **7.4** – Influence of Steering Input on Vehicle Rollover

To further illustrate the effects of the driver's intervention during a median encroachment, Figure **7.5** displays the resting locations of the vehicles which did not rollover. It is obvious that if the driver does not steer the vehicle in any manner, the vehicle will most likely traverse the entire median and thus result in a median crossover. The following results from this portion of the analysis were observed:

- The majority of the vehicles which were given a road recovery steering input came to rest in the original travel lanes.
- The median recovery steering input led to most vehicles coming to rest within the median.
- The greatest number of vehicles ending up in the opposing lanes of traffic was for encroachment scenarios with the no steer input.

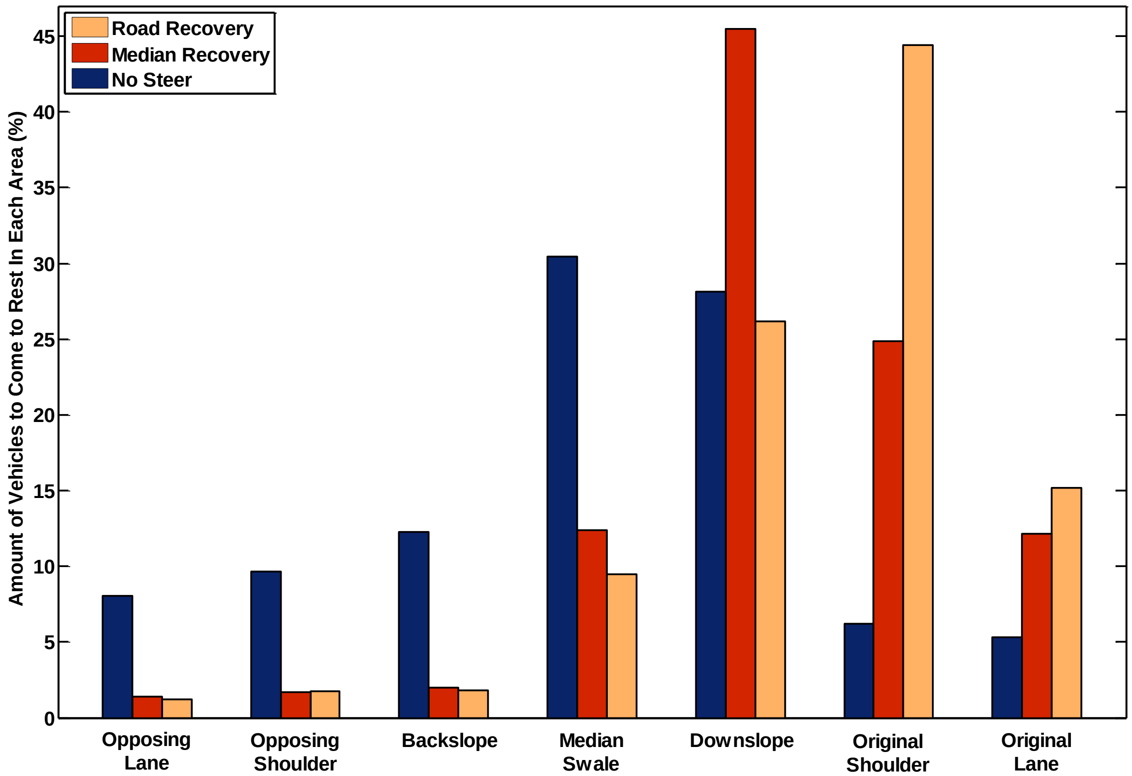

Figure **7.5** – Influence of Steering Input on Vehicle Resting Location

At this point, it is clear that the driver's input during a median encroachment event has an enormous impact on the in-median vehicle response. These findings indicate that these inputs are primary contributing factors to vehicle rollover and median crossover incidents and thus, they cannot be ignored when utilizing vehicle dynamics simulations as an aid for highway median design.

7.2 Importance of Driver Model

As explained in Section **3.1.4**, the steering input in CarSim is defined through target point trajectories which represented the three different steering scenarios. In addition to the differences in the actual target points, the algorithm used to calculate the steering input from these target points has a large influence as well. This was observed when the CarSim software used in this study was upgraded from version 6.05 to version 7.01b.

When CarSim was updated from version 6.05 to version 7.01b, there were several changes, both microscopic and macroscopic, in the driver models between the two versions of the software. Both of these versions implement a driver model based on MacAdam's closed loop model [1]. This application of optimal preview control incorporates both the preview time and physical delay in the driver's reaction due to neuromuscular coordination. Figure **7.6** shows a block diagram, representing the preview control system which MacAdam applied to modeling the human driver. Here, T* and τ represent the preview time and transport lag respectively associated with the driver.

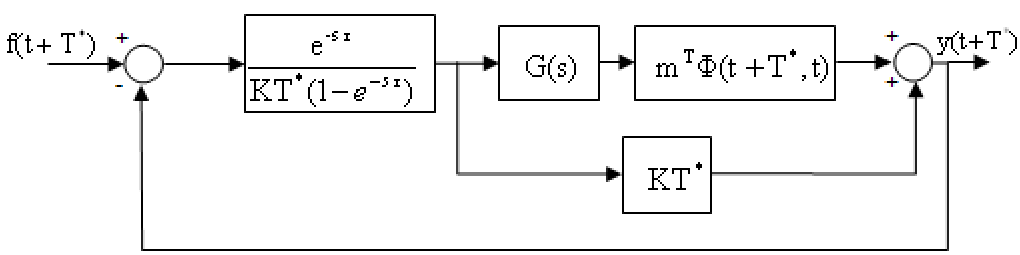

Figure **7.6** – MacAdam's Optimal Preview Control Model for the Human Driver

The primary difference from version to version of CarSim is that the older version applies a step function when modeling the driver's steering corrections as the vehicle deviates off its target path. The new version interpolates the error between the target and actual vehicle trajectories, smoothing out the differences. This ultimately leads to a much more realistic steering input during the incursion.

To investigate the effect that this updated driver model has on the simulation results, the entire set of 111,132 simulations was re-simulated with CarSim 7.01b. The aggregate distributions of both rollover and crossover events were relatively unchanged from those instances resulting from simulation with CarSim 6.05. The newer software version predicted rollover 2.46% of the time compared to the 2.41% predicted by the older version. Similarly, 3.40% of the simulations in CarSim 7.01b led to a median crossover, while crossovers were seen in 3.55% of the runs CarSim 6.05. On the whole, there were ultimately no significant changes in the results between the two software versions, but when individual cases were scrutinized, several discrepancies in the vehicle response throughout the encroachment emerged.

To illustrate the different vehicle responses caused by the updated driver models, one specific simulation is examined. Using a 60 foot wide, 6H:1V sloped V-shape median, a small SUV was simulated with both versions of CarSim. The vehicle was traveling at 88 kmph (55 mph), encroached the median at an angle of 32.5°, and the driver was modeled to attempt a median recovery with light braking applied during the incursion. Figure **7.7** shows the resulting vehicle trajectory from this investigation.

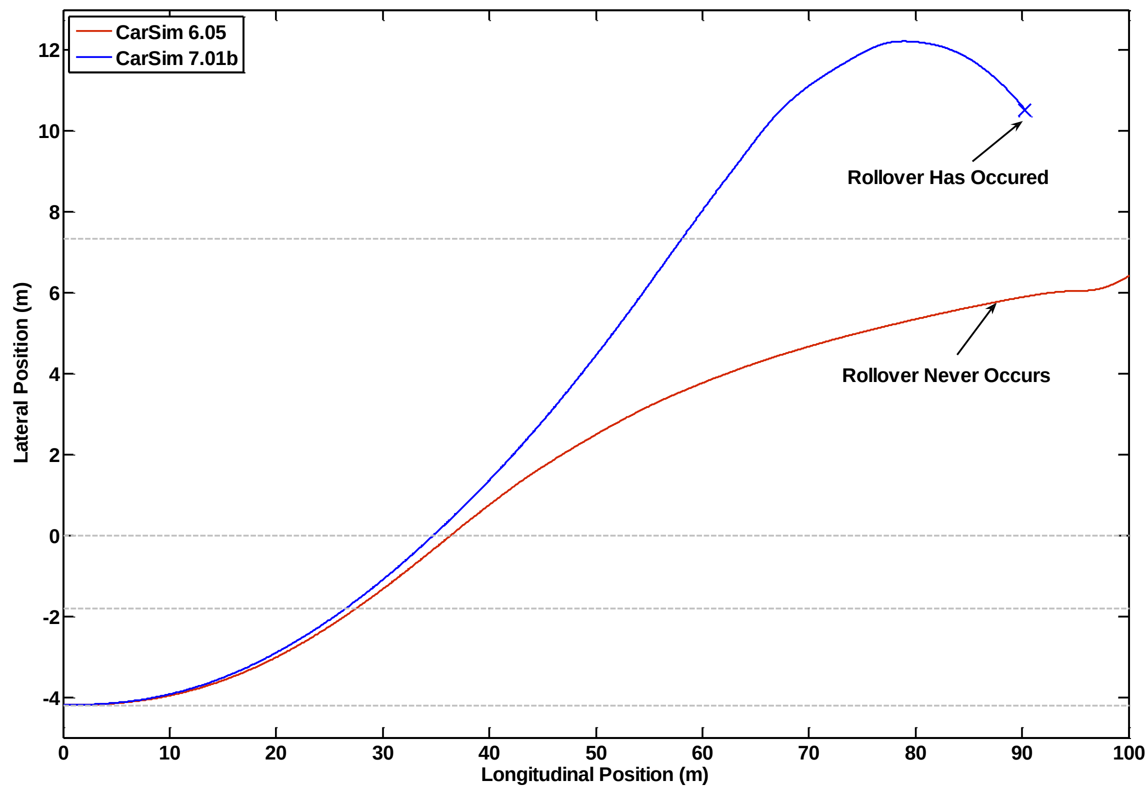

Figure **7.7** – Vehicle Trajectories for Different Driver Models

As seen here, the differences between the two vehicle responses are significant. The CarSim 7.01b simulation, represented by the blue line, passes the target point in the median swale and travels up the back slope before coming to a rest. The CarSim 6.05 simulation, represented by the red line, came to a rest even before the swale point. Additional differences can be observed when examining the vehicle sideslip during the trajectory. After applying the designation for rollover (discussed in Section **4.1.1**), Figure **7.8** shows that the CarSim 7.01b simulation led to rollover, whereas the identical run in CarSim 6.05 did not. These huge differences go to further demonstrate the importance of incorporating an accurate driver model within vehicle dynamics simulations.

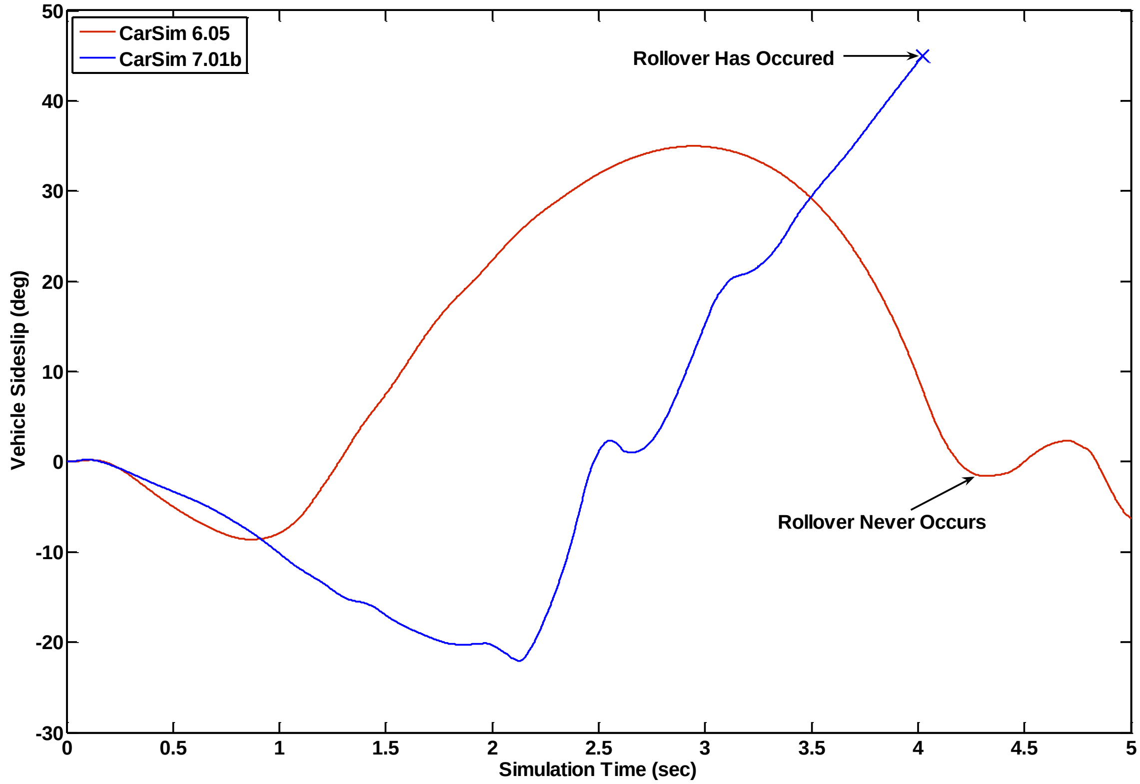

Figure **7.8** – Vehicle Sideslip for Different Driver Models

[1] MacAdam, C. C. (1981). *Application of an Optimal Preview Control for Simulation of Closed-Loop Automobile Driving.* IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-11, No 6.

Chapter 8

Conclusions

This thesis discussed a means of analyzing highway median safety through the use of vehicle dynamics simulations. In an attempt to design a safer median, a total of 111,132 different median encroachments were simulated with CarSim software. A methodology for these simulations was presented, in which seven different vehicles, seven initial speeds, seven encroachment angles, and six driver inputs were incorporated for each median profile tested. Each possible combination of the aforementioned experimental parameters was simulated to create a vast array of possible crash scenarios. But, in order to better represent the likelihood of each particular scenario occurring in a real-life highway median encroachment, each individual run was assigned a weighting factor based on probability statistics from previous studies [1] [2] [3]. The conclusions from this study, including deductions for the investigation into median safety and the importance of the human driver model, are presented in the remainder of this chapter.

8.1 Median Safety

In the analysis of median safety, the median cross-section was found to have a significant effect on the vehicle response within the median. Each characteristic of the median profile, including shape, slope, and width, were all found to have a sizeable importance in predicting both median crossover incidents and in-median rollovers. General trends emerged from the simulation data, providing a great deal of insight into the relative effect of a change in each median parameter. A more aggressive slope was shown to lead to more rollover scenarios, and a lower ratio of cross-median events to rollovers. But, when looking at the raw numbers for the median crossovers, the aggressive slopes were actually shown to increase the frequency of these events as well. The smaller ratio for the steeper medians was solely due to the larger number of rollovers. In the same manner, the investigation into the effect of median width revealed that a wider median would lead to more rollovers, due to a greater traversable distance in which a potential soil-tripped phenomenon could arise. Furthermore, a narrow median resulted in a greater probability of a cross-median event occurring. This is expected, due to the shorter distance that was needed to be covered for the crossover to occur. Examining the data carefully, the narrow medians (40 and 46 feet wide) exhibited nearly twice as many crossovers as the wider medians (70 and 76 feet wide). From these results, it is apparent that there is a clear tradeoff between designing a median to prevent against rollover events, or designing it with the purpose of cutting down on median crossovers.

To provide a clear understanding of the tradeoffs of selecting one median design over another, general guidance for a safer median design was provided in Chapter 5. The resulting data, presented for every median slope-width combination that was simulated, offered the percentage of all simulated encroachments which led to a rollover situation, and similarly displayed the resulting percentages for the crossover events in a second table. These two tables presented the two major catastrophic events on the highway in a useful means for highway design engineers. By combining these two sets of data and producing a contour plot for the resulting ratio between median crossovers and vehicle rollover, Figure **8.1** (previously shown as Figure **5.1**) offers a tool for to help the engineers choose the “best” design for the intentions of that particular median.

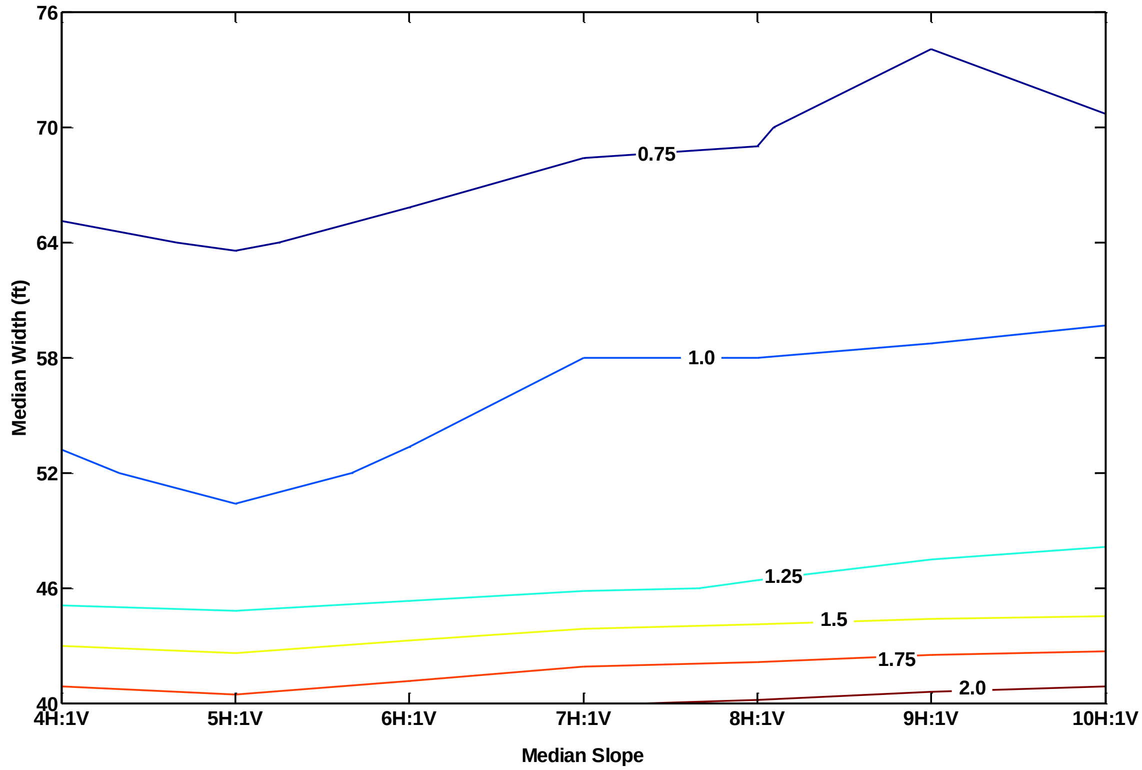

Figure **8.1** – Ratio of Crossover to Rollover Contours

The accuracy of the simulations was evaluated by comparing the results to data from both full-scale experimental crash testing and published crash statistics. Compared to the TTI test, the simulation's trajectory, roll angle, and yaw angle data matched closely. Throughout the run, only the pitch angle data showed noticeable discrepancies. When examining video footage from the test, the truck's suspension appeared to be initially compressed by the cable system which pulled the vehicle. The differences in pitch angle data are most likely accounted for by this initial suspension displacement and the assumptions made in the vehicle subsystem models used in the simulation. When evaluating the aggregate simulation results with crash statistics from previous studies, the frequency of simulated rollovers matched closely with those reported in real-life. The crossover to rollover ratio data was also compared to crash statistics from the NHTSA Traffic Safety Facts and NCHRP 22-21 study. Figure **8.2** (previously shown as Figure

6.11) shows the resulting comparison between the two sets of data, again showing great agreement between the simulation results and real-life crash data.

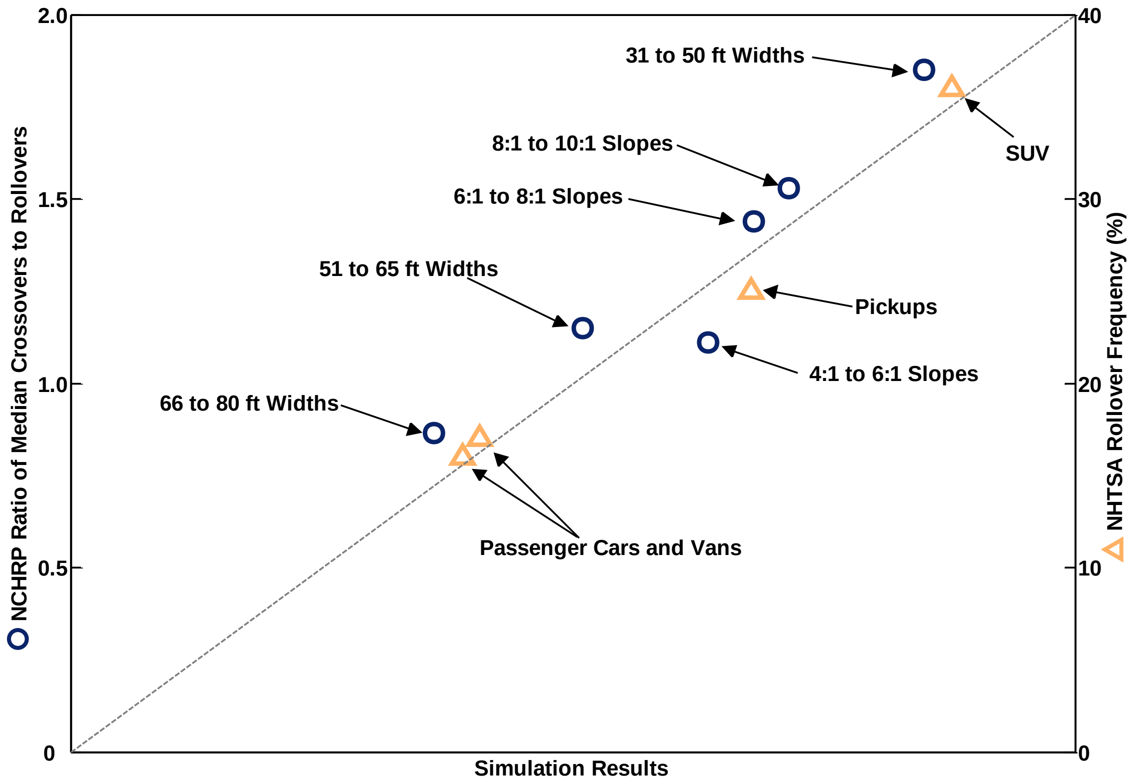

Figure **8.2** – Fidelity of Aggregate Simulation Results

In regard to the placement and height of a possible in-median barrier, a complete analysis of the vehicle bumper height distributions throughout the encroachment was conducted. The vertical heights at several offsets from shoulder were shown to initially have a bimodal distribution (representing the SUV and passenger car population) while still on the roadway. Then, due to suspension differences, as the vehicles traveled down the median slope, the two modes converged into one until just prior to the median swale point. As seen in Figure **8.3**, (previously shown as Figure **5.10**), the distribution then began to diverge again, and the two modes of data reappeared. Several vehicles were shown to impact the ground surface, and in some cases, even penetrate the soil with their bumpers. Furthermore, vehicles were shown to impact the swale point with such great force that, when traveling on the back slope, they became completely airborne. Considering all simulations, whether the vehicle traveled down the median smoothly, impacted the ground, or became airborne, traces for the overall modes for bumper height (top of bumper) and clearance (bottom of bumper) were provided. These trajectories provide another tool for highway designers, as they can clearly see the height of the majority of vehicle bumpers if there were to place a barrier at any corresponding offset.

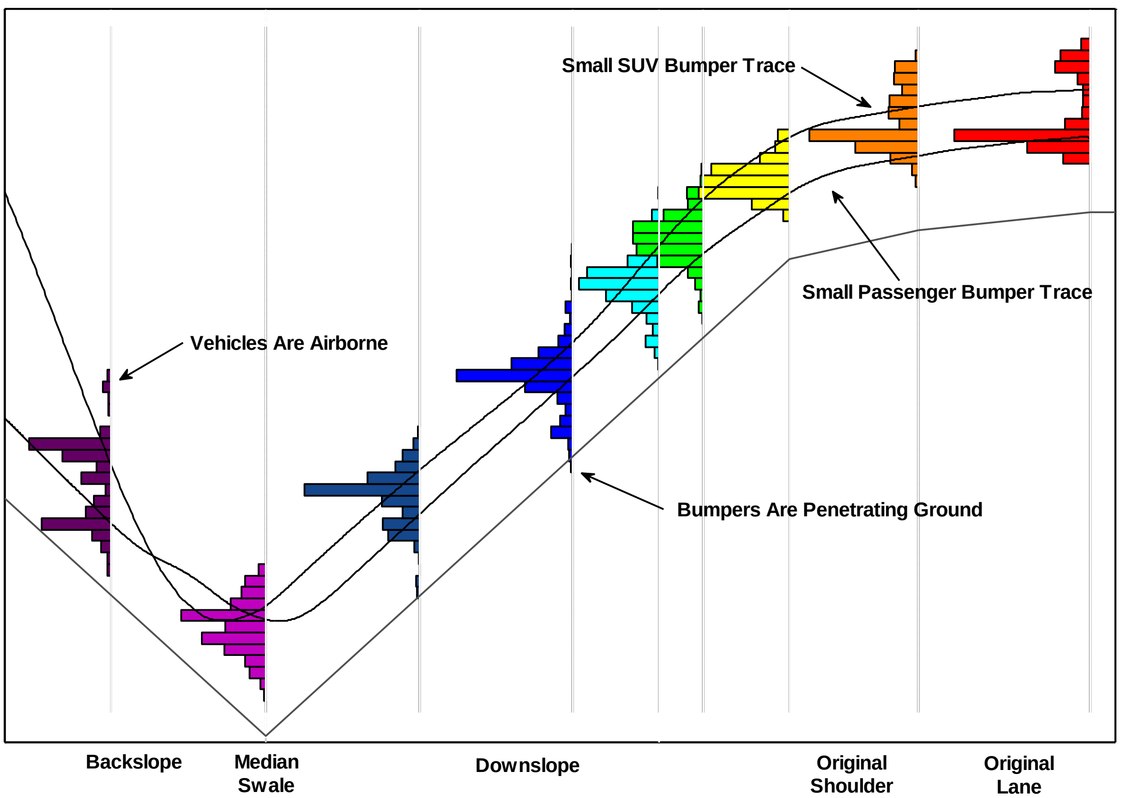

Figure **8.3** – Bumper Height Distributions at Various Locations Within the Median

8.2 Influence of Driver Intervention

Results shown in Chapter 7 indicate that the driver's actions have a significant effect on the vehicle trajectory within the median. Figure **8.4** (previously shown as Figure **7.4**) alone indicates that by attempting to steer the vehicle back onto the roadway, the driver is 12 times more likely to induce rollover than if they were to completely let go of the steering wheel. Closer examination of the effect of the driver revealed that differences in the driver model itself can also lead to vast discrepancies in the results for the same encroachment conditions. In this study, even an updated version of the same software model led to minor inconsistencies in the dataset. The CarSim v7.01b driver model, although based on only a slightly updated interpolation algorithm, was shown to result in different outcomes for some encroachments simulated with the older CarSim v6.05. These results make apparent the need to incorporate an accurate, and validated, driver model when using vehicle dynamics simulations for roadway design.

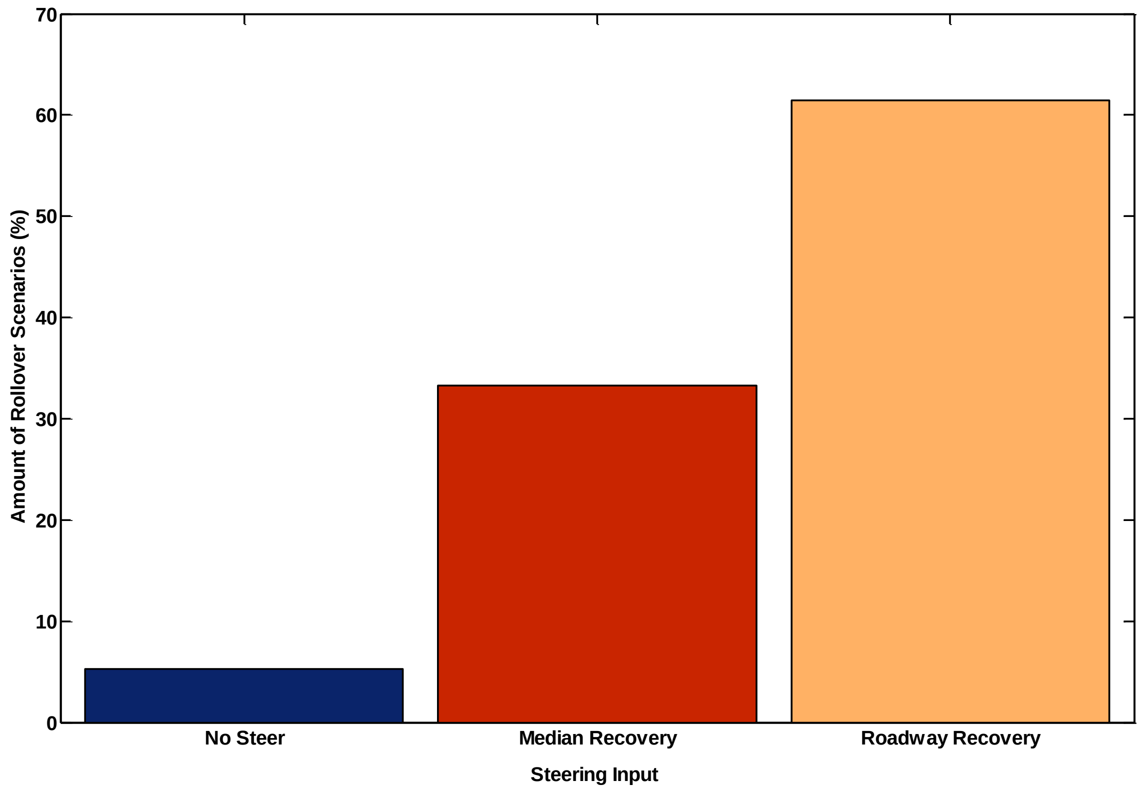

Figure **8.4** – Influence of Steering Input on Vehicle Rollover

8.3 Future Work

While this simulation study encompassed several different facets of median encroachments, there are still many more worth investigating. To continue this analysis of median safety, future work will examine several of the crash factors that were not under consideration in this study. For instance, at the time of encroachment, the initial sideslip, roll, and pitch of the vehicle were all taken to be zero. In reality, if a sudden change in dynamic behavior (ie. a tire blowout) was the cause of the vehicle encroaching upon the median, these variables will most likely not be zero. These cases of non-zero initial values for these vehicle states need to be investigated, as these variables have the potential to alter the vehicle trajectory, and rollover tendency, greatly.

Additionally, more accurate vehicle models will be incorporated in the simulations. For this study, a lumped vehicle model was used, with only the mass, wheel base, track width, and inertial parameters being specified. The remaining characteristics, including tire diameter, inflation pressure, and suspension properties, were held constant across each simulated vehicle class. Although these default characteristics in CarSim are based on real-life test data, by further customizing the parameters to model specific vehicles, the overall fidelity of the simulations will increase.

Another need for future work lies in the addition of more median geometries. For instance, this study only investigated trapezoidal medians briefly. Although the results showed a decrease in both rollovers and cross-median activity, without conducting simulations for all possible slope-width combinations of trapezoidal medians and comparing the results to the V-shape counterpart medians, an absolute conclusion cannot be drawn. Additionally, medians with non-zero horizontal (ie. a curved roadway) and/or vertical curvature (ie. the two directions of traffic lanes are not at same vertical height) need to be considered as well.

Although the results presented in Chapter 5 provide a valuable set of tools for the highway designer, they do not provide any means of cost-benefit analysis. For example, the results shown here can tell the engineer that by changing the design of an existing median, the amount of rollovers will be reduced by 2%. But, that only presents the benefit of the design change. The cost still remains a mystery. By incorporating a full cost-benefit of altering the median design (ie. this new design will save 20 lives annually, but will cost 20 million dollars to install), a better toolset can be provided for the design engineers.

Finally, updates to the simulation code itself will be analyzed to improve their fidelity. As stated in Section **2.2.2**, one of the biggest downfalls of vehicle dynamics simulations is their inability to properly model soil-tire interactions, and thus soil-tripped rollover. Although the Kroninger study [4] provides guidelines which help detect these rollover events, updating the software to account for these forces will allow for soil-tripped rollovers to be directly predicted. This would undoubtedly lead to a better understanding of this phenomenon and thus a more accurate prediction for off-road vehicle rollover.

Further additions to the simulation work would include an investigation into how the driver would react differently if there was or was not a barrier installed within the median. Unless the driver were asleep at the wheel, they are almost guaranteed to make an attempt to avoid impacting the barrier. Results shown in Chapter 7 conclude that the driver's intervention during a median encroachment has a significant effect on the vehicle response within the median. Thus, the driver reacting differently in the cases where a barrier existed in the median would more likely affect the rollover and impact outcomes. Current barrier impact studies usually only conduct crash tests with a frontal impact and assume the "no steer" condition that was implemented in this study. But, as shown in this simulation work, several vehicles spun around or experienced heavy sideslip, and in the event of a barrier impact, they would either impact with their rear bumper, or even worse, sideswipe the barrier. Possible means for investigating this aspect would be to incorporate Penn State's fully immersive driving simulator, and perform several simulation runs with the barrier versus no barrier condition being altered. As the simulator is driven with CarSim software, implementation would take minimal additional work, and after subjects are chosen for the experiment, testing could immediately ensue.

8.4 Final Thoughts

The preliminary 2008 NHTSA Traffic Safety Facts [5] estimate that the number of fatalities on the highway is about 3,000 fewer than the previous year, indicating that the measures being taken to increase highway safety are indeed helping. Between equipping vehicles with highly advanced safety features, designing vehicles that are less prone to rollover (SUVs in particular), and designing safer medians for the nation's highways, the death total was projected to be 31,110 for the period from January 2008 to October 2008. Although this number is still high, the average death rate decreased from

113 to 102 per day. This decrease is indicative of an increase in safety of both the vehicles and roadways. And while the numbers appear to be on the decline, there are still means to make the fatality count decrease even further. Just as former United States Secretary of Transportation Mary E. Peters proclaimed [6], “For the second year in a row, we are seeing historic lows in deaths on our nation’s roads. While we are encouraged by these declines, our work is not nearly complete in making our safe transportation network even safer.”

[1] Mak, K. K., & Sicking, D. L. (2003). *NCHRP 492 - Roadside Safety Analysis Program (RSAP) - Engineer's Manual. 2003.* Washington, D.C.: Transportation Research Board.

[2] (2004). *2001 National Household Travel Survey: Summary of Travel Trends.* U.S. Department of Transportation.

[3] White, G. (2007). *Trucks and Buses*. Retrieved June 16, 2009, from Pavement Interactive: http://pavementinteractive.org/index.php?title=Trucks_and_Buses

[4] Kroninger, M., Lahmann, R., Lich, T., Schmid, M., Guttler, H., Huber, T., et al. (2004). *A New Sensing Concept for Tripped Rollovers:* SAE 2004-01-0340.

[5] (2008). *Traffic Safety Facts: Early Estimate of Motor Vehicle Traffic Fatalities From January to October 2008*. Washington, D.C.: National Highway Traffic Safety Administration.

[6] Echols, S. (2008). *U.S. Secretary of Transportation Mary E. Peters Announces New Data Showing Record Low Highway Fatalities; Americans Safer than ever on the Nation's Roads, Rails, and in the Skies*. Retrieved June 17, 2009, from U.S. Department of Transportation Office of Public Affairs: http://www.dot.gov/affairs/dot17508.htm

Appendix

Appendix A Location of MATLAB Codes

The MATLAB codes used to define all of the simulation inputs and initiate CarSim can be found on Dr. Brennan's research group server in the following directory: Z:/Projects/Old_Projects/NCHRP_22_21_Median_Design/CarSim_Code. They are also saved locally on the Dell Dimension 8300 desktop computer in 323 Leonhard Building. The following m-files will be needed:

- *script_median_profile* – defines the median cross-section profile
- *script_road_friction* – defines the friction map for on and off-road conditions
- *script_vehicle_inputs* – loads the vehicle parameters defined in Section **3.1.2**.
- *script_driver_inputs* – loads the driver inputs
- *script_braking* – defines the hard and light braking conditions
- *script_steering* – defines the road recovery, median recovery, and no steer conditions using the CarSim "Driver Path Follower"
- *script_run_CarSim* – defines the initial speed and yaw angles, loads CarSim, and runs the simulation

The MATLAB codes used to post process the data are also found on Dr. Brennan's server, and can be found in the following directory: Z:/Projects/Old_Projects/NCHRP_22_21_Median_Design/Post_Process_Code. Additionally, all of the raw and post-processed data files for this study are found on the server as well.

Appendix B Vehicle Bumper Survey

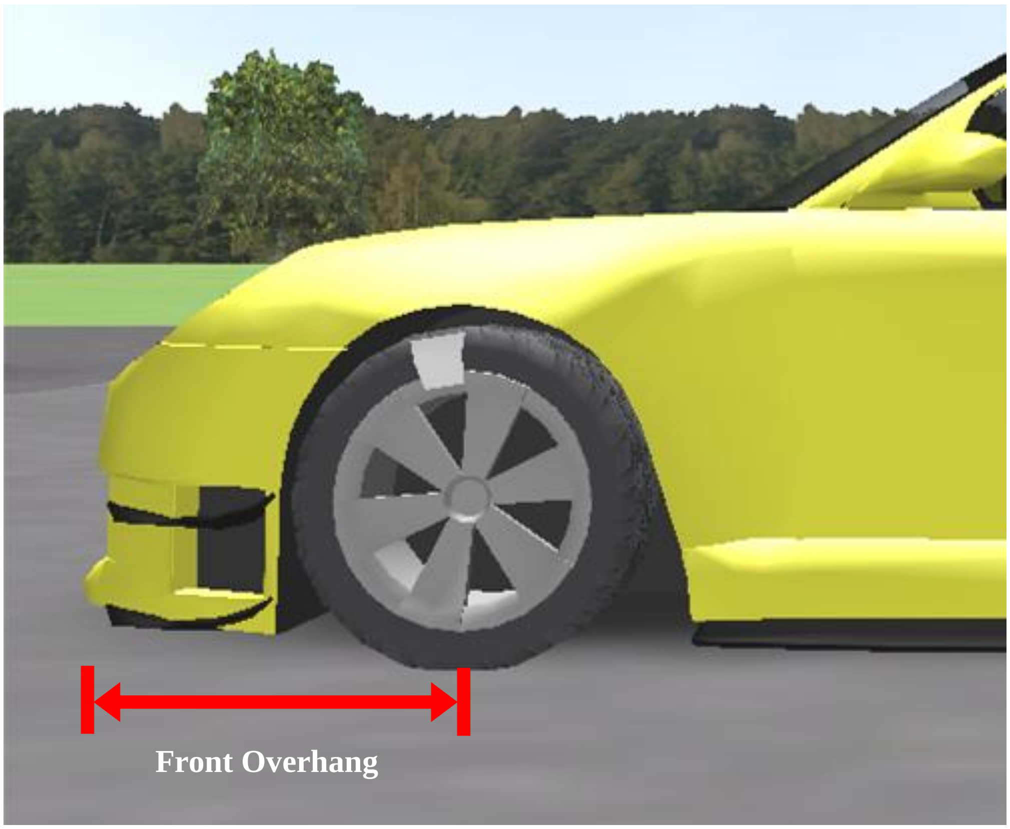

Figure **B.1** – Front Overhang Distance on Vehicle

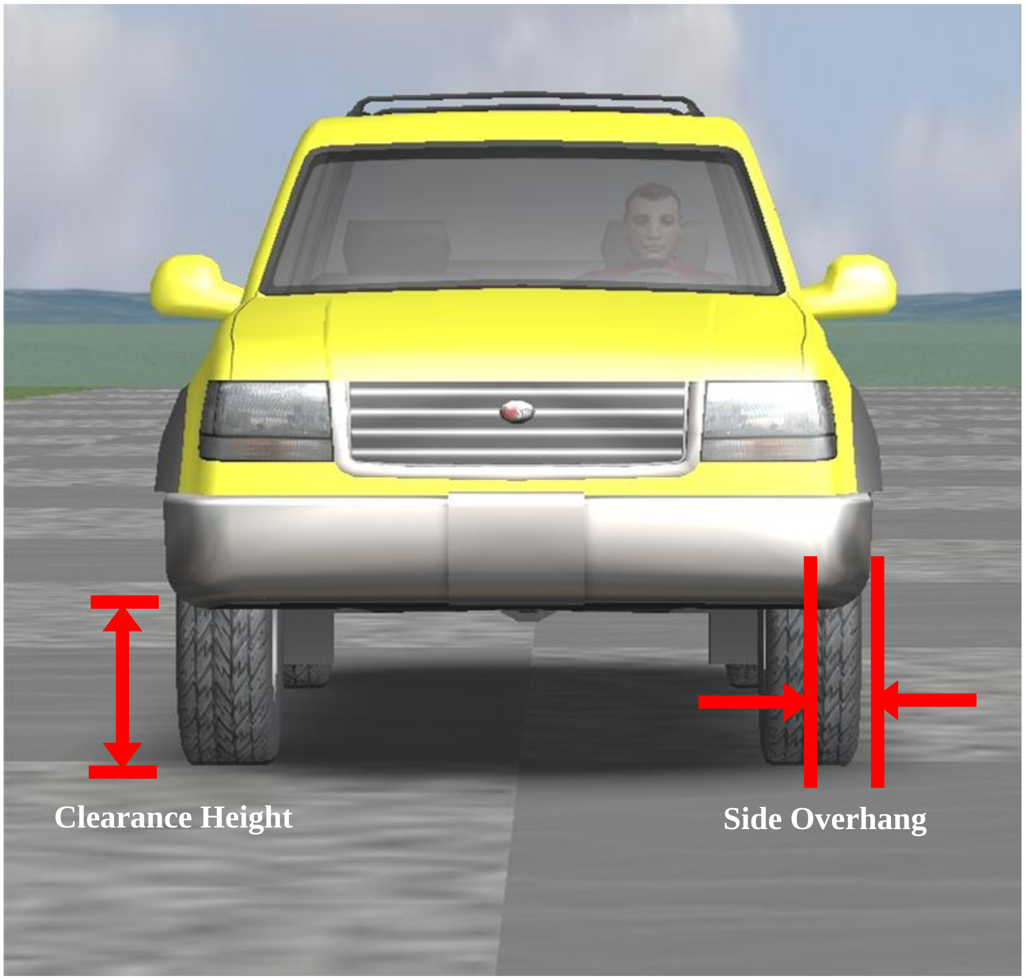

Figure **B.2 –** Side Overhang and Bumper Clearance Distances on Vehicle

Table **B.1** – Small Passenger Vehicle Bumper Positions

Small Passenger			
Vehicle	**Front Overhang**	**Side Overhang**	**Clearance Height**
Acura TSX	0.911	0.130	0.226
Audi A4	0.792	0.126	0.215
BMW 1-Series	0.752	0.105	0.215
BMW 3-Series	0.762	0.128	0.202
Chevrolet Malibu	0.919	0.136	0.220
Chevy Cobalt	0.898	0.109	0.229
Chrysler PT Cruiser	0.826	0.112	0.231
Dodge Caliber	0.890	0.114	0.246
Ford Focus	0.836	0.118	0.226
Honda Civic	0.894	0.127	0.220
Honda S2000	0.760	0.139	0.160
Kia Spectra	0.864	0.119	0.239
Mazda 3	0.855	0.113	0.191
Mazda MX-5	0.763	0.114	0.167
Mercedes-Benz C-Class	0.859	0.123	0.203
Nissan 350Z	0.732	0.140	0.169
Nissan Altima	0.796	0.123	0.221
Pontiac G5	0.889	0.112	0.231
Pontiac Vibe	0.892	0.123	0.257
Saab 9-3	0.865	0.138	0.194
Saturn Astra	0.859	0.132	0.219
Subaru Impreza	0.898	0.122	0.228
Toyota Corolla	0.849	0.121	0.229
Volkswagen Jetta	0.788	0.121	0.221
Volvo S40	0.808	0.118	0.205
Average	**0.838**	**0.123**	**0.215**

Table **B.2** – Large Passenger Vehicle Bumper Positions

Large Passenger			
Vehicle	**Front Overhang**	**Side Overhang**	**Clearance Height**
Acura TL	0.885	0.129	0.228
BMW 7-Series	0.924	0.121	0.201
Cadillac DTS	1.068	0.156	0.200
Chevrolet Corvette	0.875	0.133	0.157
Chevrolet Impala	1.042	0.133	0.223
Chrysler Sebring	1.013	0.136	0.245
Dodge Charger	1.016	0.146	0.230
Dodge Viper	0.975	0.178	0.178
Ford Taurus	1.129	0.130	0.213
Honda Accord	1.065	0.128	0.215
Kia Amanti	1.100	0.132	0.245
Mazda 6	1.035	0.126	0.210
Mercury Grand Marquis	1.226	0.189	0.225
Mercury Sable	1.133	0.128	0.226
Nissan Maxima	0.997	0.136	0.226
Pontiac G6	0.974	0.140	0.203
Pontiac Grand Prix	1.015	0.127	0.213
Saab 9-5	1.036	0.135	0.195
Toyota Camry	1.015	0.123	0.213
Average	**1.028**	**0.138**	**0.213**

Table **B.3** – Small Pickup Truck Bumper Positions

Small Pickup			
Vehicle	**Front Overhang**	**Side Overhang**	**Clearance Height**
Chevrolet Colorado	0.861	0.128	0.399
Dodge Dakota	0.975	0.172	0.388
Ford Ranger	0.889	0.137	0.393
GMC Canyon	0.861	0.141	0.425
Honda Ridgeline	0.840	0.136	0.398
Isuzu i-290	0.808	0.128	0.375
Mazda B-Series	0.846	0.137	0.360
Nissan Frontier	0.839	0.140	0.421
Toyota Tacoma	0.894	0.147	0.431
Average	**0.868**	**0.141**	**0.399**

Table **B.4** – Large Pickup Truck Bumper Positions

Large Pickup			
Vehicle	**Front Overhang**	**Side Overhang**	**Clearance Height**
Chevrolet Avalanche	0.908	0.145	0.467
Chevrolet Silverado	0.924	0.160	0.429
Dodge Ram	0.899	0.147	0.387
Ford F-150	0.892	0.151	0.421
GMC Sierra	0.901	0.148	0.431
Lincoln Mark LT	0.837	0.151	0.406
Nissan Titan	0.847	0.147	0.429
Toyota Tundra	0.849	0.152	0.464
Average	**0.882**	**0.150**	**0.429**

Table **B.5** – Small SUV Bumper Positions

Small SUV			
Vehicle	**Front Overhang**	**Side Overhang**	**Clearance Height**
Acura RDX	0.871	0.140	0.349
BMW X3	0.820	0.165	0.363
Ford Escape	0.809	0.127	0.376
Honda CR-V	0.894	0.127	0.355
Honda Element	0.852	0.119	0.345
Infiniti EX35	0.885	0.105	0.371
Jeep Compass	0.876	0.146	0.396
Jeep Liberty	0.744	0.141	0.396
Jeep Wrangler	0.719	0.265	0.454
Kia Sportage	0.761	0.135	0.316
Mazda CX7	0.901	0.135	0.346
Nissan Xterra	0.819	0.140	0.401
Saturn Vue	0.903	0.145	0.378
Subaru Forester	0.931	0.126	0.381
Toyota RAV4	0.835	0.128	0.341
Average	**0.841**	**0.143**	**0.371**

Table **B.6** – Large SUV Bumper Positions

Large SUV			
Vehicle	**Front Overhang**	**Side Overhang**	**Clearance Height**
Cadillac Escalade	1.049	0.137	0.418
Chevrolet Equinox	0.953	0.124	0.408
Chevrolet Suburban	1.073	0.170	0.397
Chevrolet Tahoe	0.992	0.164	0.397
Chevrolet TrailBlazer	0.951	0.152	0.416
Chrysler Pacifica	1.008	0.169	0.382
Dodge Durango	0.963	0.147	0.420
Ford Expedition	1.092	0.150	0.421
Ford Explorer	1.002	0.163	0.411
GMC Acadia	0.993	0.141	0.388
GMC Envoy	0.998	0.148	0.403
GMC Yukon	1.092	0.147	0.467
Honda Pilot	1.031	0.137	0.403
Hyundai Veracruz	1.017	0.138	0.433
Jeep Commander	0.866	0.155	0.418
Jeep Grand Cherokee	0.853	0.282	0.411
Kia Sorento	0.990	0.141	0.408
Lincoln Navigator	1.086	0.149	0.434
Mazda CX9	1.062	0.141	0.416
Mercury Mountaineer	1.003	0.160	0.408
Nissan Pathfinder	1.002	0.150	0.429
Pontiac Torrent	0.953	0.124	0.426
Saturn Outlook	1.043	0.137	0.405
Toyota 4Runner	0.998	0.168	0.431
Toyota FJCruiser	0.991	0.145	0.421
Toyota Highlander	0.998	0.142	0.399
Toyota Land Cruiser	1.005	0.165	0.426
Toyota Sequoia	1.016	0.151	0.454
Average	**1.003**	**0.153**	**0.416**

Table **B.7** – Van Bumper Positions

Van			
Vehicle	**Front Overhang**	**Side Overhang**	**Clearance Height**
Chevrolet Uplander	0.910	0.122	0.290
Chrysler Town & Country	0.903	0.145	0.295
Dodge Grand Caravan	0.936	0.145	0.270
Honda Odyssey	0.937	0.132	0.284
Kia Sedona	0.890	0.150	0.308
Nissan Quest	0.937	0.131	0.310
Toyota Sienna	0.948	0.146	0.305
Average	**0.923**	**0.139**	**0.295**

Appendix C TTI Crash 452106-3 Test Vehicle Parameters

Table **C.1** – Test Vehicle Parameters

Year	2000		Wheelbase	3350 mm		Left Front Mass	589 kg
Make	Chevrolet		Front Track	1590 mm		Right Front Mass	590 kg
Model	C2500		Rear Track	1610 mm		Left Rear Mass	439 kg
			Overall Length	5470 mm		Right Rear Mass	487 kg
Tire Size	245/75R16		CG Height	415 mm		Total Mass	2096 kg
Front Inflation	50 psi		Overall Height	1820 mm			
Rear Inflation	80 psi		Bumper Height	635 mm			
			Ride Height	415 mm			

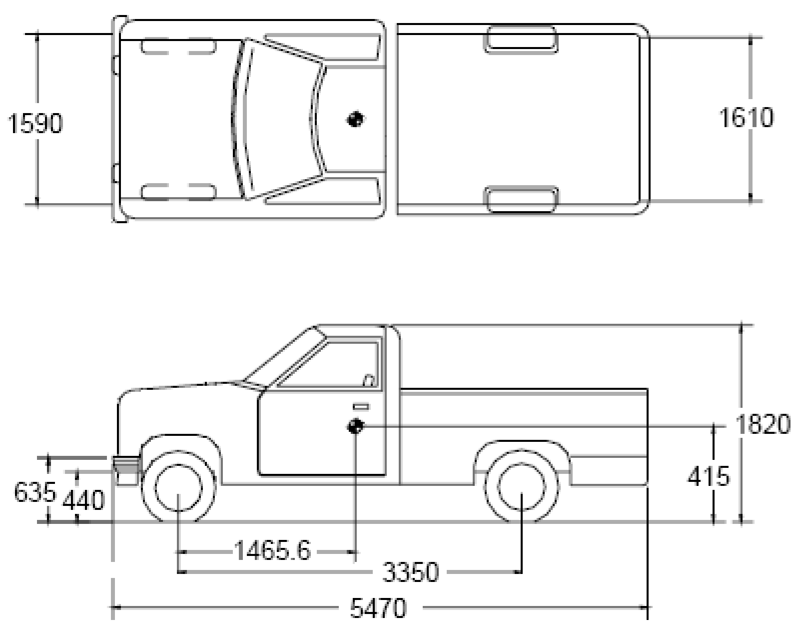

Figure **C.1** – 2000 Chevrolet C2500 Dimensions

Appendix D NCHRP 22-21 Crash Statistics

Table **D.1** – Preprocessed NCHRP 22-21 Crash Data

Median Profile					Rates (Crashes/Mile/Year)							
Width	Slope	Sites	Length (mi)	Mile - Years	Total Accident Rate	Median Related Accident Rate	CMC Rate	NCMC Rate	Rollover Rate	Barrier Hit Rate	Fixed Object Accident Rate	Other Median Related Rate
31 to 50	2:1 to 4:1	2	1	6	10.17	4.5	0.17	0	0.33	0	2.67	1.33
		3	1.5	9	1.56	0.44	0.11	0	0.22	0	0.11	0
		5	2.5	15	10.87	4.73	0.33	0.13	0.6	0	2.8	0.87
	4:1 to 6:1	3	1.5	9	6.89	4	0.11	0.22	0.78	0	1.44	1.44
		1	0.5	3	2.33	1	0	0.67	0	0	0.33	0
		44	27.43	157.17	7.48	3.3	0.15	0.06	0.38	0.25	1.55	0.92
		10	4.79	23.97	2.71	0.46	0.04	0.04	0	0	0.38	0
	6:1 to 8:1	4	3.49	17.95	8.86	3.34	0	0.06	0.22	1.89	0.61	0.56
		83	60.13	317.15	6.04	2.16	0.06	0.03	0.26	0.48	0.76	0.58
		31	20.79	103.97	5.29	1.03	0.05	0	0.11	0	0.57	0.31
		6	5.97	29.85	9.01	1.71	0	0.03	0.54	0	0.7	0.44
		1	1	5	4.8	1.4	0	0	0	1.2	0	0.2
	8:1 to 10:1	6	6	30	15.2	4.5	0	0	0.17	2.23	0.63	1.47
		2	1.89	9.45	4.23	2.43	0	0	0.11	1.8	0.11	0.42
		49	43.72	219.62	6.93	2.7	0.03	0.01	0.2	1.45	0.44	0.57
		30	22	109.99	6.89	1.21	0.11	0.02	0.3	0	0.45	0.33
		6	6.03	30.15	6.9	1.63	0.03	0.03	0.33	0	1.03	0.2
		1	1	5	2.8	1	0	0	0	0.8	0.2	0
51 to 65	2:1 to 4:1	1	0.5	3	2	0.33	0	0	0	0	0	0.33
		2	1	6	5.17	2.17	0	0.17	0.33	0	0.67	1
		8	4	24	2.42	0.79	0	0	0.21	0	0.29	0.29
		3	1.5	9	4.11	0.67	0	0	0.33	0	0.22	0.11
	4:1 to 6:1	88	43.61	244.06	2.37	0.67	0.04	0.03	0.18	0	0.2	0.22
		30	15.4	86.48	3.94	1.26	0.08	0.02	0.2	0.09	0.47	0.39
		120	60	360	2.09	0.63	0.02	0.01	0.16	0	0.18	0.27
		1	1	5	4.4	0.8	0	0	0.4	0	0.2	0.2
		9	4.5	27	4.85	1.19	0.04	0	0.15	0	0.48	0.52
	6:1 to 8:1	105	60.92	324.1	4.49	1	0.02	0.02	0.17	0	0.37	0.4
		43	22.77	122.86	4.15	1.38	0.04	0.02	0.15	0.15	0.48	0.54
		97	50.98	300.9	1.85	0.54	0.02	0.02	0.15	0	0.15	0.2
		2	2	10	26	7	0	0	0.5	1	2.9	2.6
	8:1 to 10:1	49	37.17	190.37	5.05	1.1	0.03	0.01	0.29	0	0.4	0.37
		21	13.31	69.03	4.84	1.84	0.01	0.01	0.12	0.8	0.35	0.55
		26	13.5	80	1.88	0.53	0.01	0	0.11	0	0.2	0.2
		7	6.72	33.6	19.11	4.55	0.18	0	0.18	0.98	1.76	1.46
		3	3	15	11.87	2.73	0.2	0	0.13	0	0.93	1.47
66 to 80	2:1 to 4:1	4	2	12	2.67	0.67	0	0	0.17	0	0.25	0.25
		2	0.97	4.84	5.58	2.06	0	0	0.21	0	1.65	0.21
	4:1 to 6:1	9	4.99	28.95	2.25	1	0.03	0	0.21	0	0.31	0.45
		4	3.01	15.56	8.42	3.86	0	0	1.61	0.96	1.09	0.19
		19	16.11	80.56	4.43	1.22	0.05	0.02	0.61	0	0.41	0.12
	6:1 to 8:1	7	5.55	29.25	1.57	0.24	0.03	0	0.07	0	0.1	0.03
		20	15.8	78.99	6.89	2.66	0.01	0	0.58	0.41	1.1	0.56
		87	82.19	410.95	4.57	1.16	0.02	0.01	0.68	0	0.33	0.12
		3	3	15	10	3	0	0	0.27	0.6	0.93	1.2
		9	9	45	4.4	1.2	0.13	0.02	0.64	0	0.2	0.2
	8:1 to 10:1	6	6.01	30.05	0.6	0.17	0	0	0.17	0	0	0
		17	14.98	74.9	8.37	3.39	0	0	0.41	0.87	1.28	0.83
		83	78.16	390.82	3.45	0.94	0.03	0.01	0.48	0	0.3	0.14
		4	4	20	8.8	3.35	0	0	0.45	0.85	1.1	0.95
		16	16.02	80.1	7.12	1.75	0.02	0.02	0.37	0	0.67	0.65

Table **D.2 –** NCHRP 22-21 Crash Data Summary

Median Width (ft)	Median Slope	Mile-Years	Rollovers	Crossovers	Rollover Rate	Crossover Rate	Cross to Rollover Ratio
ALL	**2:1 to 4:1**	88.840	26.006	33.838	0.404	0.362	0.896
	4:1 to 6:1	1040.75	271.894	493.958	0.389	0.430	1.107
	6:1 to 8:1	1810.97	597.782	1048.109	0.342	0.492	1.440
	8:1 to 10:1	1388.08	435.347	835.573	0.328	0.500	1.527
31-50	**ALL**	1101.27	286.678	692.297	0.290	0.535	1.847
51-65		1910.40	338.817	959.200	0.371	0.425	1.148
66-80		1316.97	705.535	759.981	0.436	0.378	0.866