

UTILIZATION OF VEHICLE DYNAMIC SIMULATIONS AS PREDICTORS OF HIGHWAY SAFETY

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ABSTRACT

Safety is a crucial consideration in the design of roadways, yet formal tools to study roadway safety prior to implementation are often quite limited. As a possible new tool, this work investigates the iterative use of vehicle dynamic simulations to study vehicle-roadway interaction in order to optimize highway design for safety. Following a discussion of the history and accuracy of vehicle dynamic simulations, a methodology of roadway geometry analysis is presented. This methodology is motivated by an example scenario studying the safety of a depressed median of a rural highway when there is an in-median incursion. The vehicle type, vehicle speed, vehicle trajectory, and in-median corrective maneuvers are all varied in a simulation-based analysis to evaluate their respective effects on vehicle behavior. Simulation outputs including vehicle orientation, trajectory and instabilities are useful in understanding the effects of cross-section characteristics on vehicle safety.

INTRODUCTION

Vehicle dynamic simulation software is a crucial tool in vehicle design and safety, and has been in use for many decades in three primary application areas:

1. Automotive designers who utilize simulations to predict possible problems with new or existing vehicle designs,
2. Government agencies who rely on simulation software to determine whether a new vehicle is safe and to analyze testing protocols, and
3. Forensic engineers who use simulations to pinpoint the chain of events in an accident.

This study considers adding yet another facet of application of vehicle dynamic simulation:

4. Highway design engineers who use simulations to predict relationships between roadway geometry and resulting crash types and incident rates.

The development of vehicle dynamic simulations over the past several decades has progressed along many parallel lines

in each of the application areas mentioned above, but the goal in all cases is to use simulations to alleviate the cost, time, safety, and availability concerns associated with experimental testing. Some of the most complex simulations are those in the area of vehicle design where simulations are used to aid in vehicle setup, stability analysis, and performance. Modern examples of software focusing primarily on this area of implementation include CarSim®, TruckSim®, HVOSM® and VDANL® [1-4]. Many of these programs have been extended in the past several years, allowing them to perform other tasks such as accident reconstruction. Another line of development of vehicle simulation software programs were programs originally developed with a specific goal of aiding in accident reconstruction, for example PC Crash® and HVE® [5, 6]. Many of these accident-reconstruction software packages today are fully capable of simulating extensive off-road and on-road driving scenarios even apart from the crash event itself. Thus, there appear to be several converging capabilities across vehicle dynamics analysis and crash-reconstruction software. This convergence presents a new and powerful toolset to the roadway designer.

The goal of this study is to introduce and demonstrate vehicle dynamic simulations as a new tool to study vehicle-roadway interaction with the goal to improve vehicle and roadway safety. Unlike many safety studies dealing with roadway geometry that utilize crash statistics to evaluate design choices, simulation software allows the highway engineer to perform accident free “what-if” studies on possible roadway designs, and justify the final design choices using quantitative and qualitative metrics specifically focused on vehicle safety [7-10].

The remainder of this paper provides details about vehicle dynamic simulations with specific focus on an example safety study of a median design. Section 2 provides a brief history of vehicle dynamics. Section 3 explains basic principles of vehicle dynamics, while Section 4 discusses experimental validation. Section 5 presents a methodology of simulation-based safety analysis. Section 6 discusses results of the simulations as applied to a specific study on the impact of

median geometry on the safety of median traversal. Conclusions summarize the main results.

HISTORY OF DYNAMIC SIMULATIONS

Simulations as discussed in the context of this work can be thought of as complex numerical algorithms that are designed to simulate Newtonian dynamics. To recognize the possible complexity of simulations, one only needs to consider how simulations function. Vehicle simulations utilize numerical solvers to predict vehicle behavior given three items:

1. A set of system inputs (steering, braking, throttle inputs) and constraints (road geometry and friction),
2. The differential equations describing the vehicle behavior, typically derived from laws of physics and physical and geometrical constraints of the vehicle, and
3. Initial conditions of the vehicle system as represented by initial conditions on the governing differential equations.

An overview of simulation technology can be found in [11-15].

The dominant usage of vehicle simulations today remains the study of vehicle handling and response. While numerical dynamic models of vehicle behavior have been presented in literature as far back as the 1950's, their usage was generally limited by the inability to solve the often complex equations of motion on limited computing hardware [16]. Since the development of low-cost personal computing the past several decades, simulations are commonplace in the study of vehicle motion. Indeed, as computational capabilities have increased, so has the development of more complex and realistic vehicle simulations [17-19]. For example, in [17], Day recounts the state-of-the-art in simulation programs of the late 1980's, summarizing respective strengths and weaknesses of various simulation programs at that time. The choices were clearly partitioned between either vehicle dynamics applications or crash-reconstruction applications in the form of impact simulations. By the 1990's, the convergence of impact-analysis type software and vehicle dynamics was facilitated by the availability of finite element modeling, better inclusion and understanding of tire and impact forces, better analysis of tripping/furrowing effects, and better validation of tire models for large variations in camber and normal force. Simulations emerged that were able to model rollover behavior from the initial trajectory as the vehicle leaves a roadway, through an off-road segment into a rollover situation. Today, road profile and similar 3D effects have been incorporated into most commercial simulation environments with claims of close fidelity between simulation-predicted vehicle behavior and experimental measurements [17, 20].

The concept of applying vehicle dynamics software to the analysis of off-road vehicle behavior is gaining recent popularity. For example, some have used simulations to study driver response to roadway departure [21]. Others have concentrated on off-road ride comfort [22] and some have focused on friction influences due to water or snow [23]. While these applications are diverse, few people to date have looked specifically at the use of vehicle dynamics to analyze and optimize the roadway design itself.

Highway engineers have been using simulation programs for decades as a means to calculate a cost versus benefit value

for changes in roadway designs or the addition of a barrier. Such programs usually use accident data to estimate encroachment frequency, accident frequency, accident severity and the resulting cost of the accident, including both injury cost and the cost to repair any damaged obstructions. Such cost/benefit programs have progressed over the years to include updated encroachment data, accident data and to improve the program's user interface in hopes of increasing usage. The Texas Transportation Institute released the ABC program in the mid-1980's; a cutting-edge program at the time for it used the then-recent results of the Cooper encroachment study [8]. The Federal Highway Administration modified TTI's ABC® program to make it more user friendly and improve the crash severity models and released it in 1988 as the Benefit/Cost Analysis Program (BCAP). BCAP® is most well known because it was used to develop the guidelines outlined in the 1989 AASHTO Guide Specifications for Bridge Railings. Continual refinement and a push for fewer required inputs led to the development of ROADSIDE®, published as an appendix in the 1996 Roadside Design Guide [24]. But the program proved to be too oversimplified to adequately model roadside incursions. The National Cooperative Highway Research Program recognized ROADSIDE®'s shortfalls, so funded a project to develop a replacement program. The resulting software, the Roadside Safety Analysis Program (RSAP) was produced by the Texas Transportation Institute and included in the updated Roadway Design Guide [25]. While case studies of the RSAP® program show some correlation between model predictions and accident data, the program relies mostly on accident history as inputs, making it difficult to update the program to account for changes in the vehicle fleet [7]. Further, because of the focus on accident statistics and correlation, the program is not capable of including variations in driver input and the resulting changes in dynamic response due to steering.

VEHICLE DYNAMICS

At highway speeds, a vehicle's motion is very complex, but is primarily governed by the forces generated at the tires of the automobile due to tire-road interaction. If forces are known, one can apply either Newtonian force/moment balances or can use Lagrange methods to derive equations of motion which are readily simulated in various commercial numerical solvers.

In many vehicle dynamics studies, only three degrees of freedom – the yaw rate, the lateral velocity, and the roll angle – are studied. Each is illustrated in Fig. 1 along with the Society of Automotive Engineers (SAE) vehicle-fixed coordinate system that is employed in the remainder of this paper [26]. While other motions will obviously affect vehicle behavior, these three are usually chosen for study primarily because they best predict vehicle handling and safety at highway speeds. For example, under certain situations or vehicle setups, the yaw and lateral degrees of freedom can be coupled in a manner that produces an unstable lateral skid response or highly oscillatory fishtailing behavior. The roll angle is an important measure as it denotes the onset to rollover.

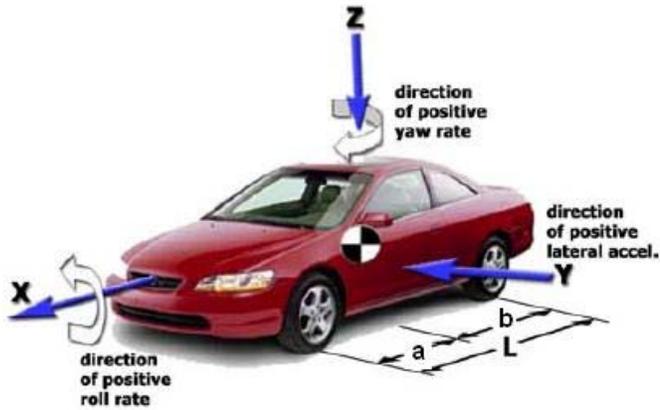


FIGURE 1: DEGREES OF FREEDOM OF A VEHICLE DEFINED IN SAE VEHICLE COORDINATE SYSTEM

For simplicity in representing the equations of motion, vehicle positions, velocities, and accelerations are generally measured using coordinate systems fixed to the vehicle center-of-gravity (C.G.). This study uses the SAE standard coordinate system, where velocities are measured from the vehicle C.G. to motion of the road as evidenced directly under the C.G. When needed, positions of the vehicle are obtained by transforming these velocities to a separate, earth-fixed coordinate system [27].

If considering only yaw, lateral, and roll motions of the vehicle, there will be at least three differential equations of motion governing the vehicle's behavior. Further equations may arise if additional energy storage mechanisms are considered, for example suspension deflection, tire deflection (vertically and laterally), etc.

THE VALIDITY OF VEHICLE DYNAMIC SIMULATIONS

Full validation of any simulation's ability to predict behavior of all types of severe off-road vehicle crash-like maneuvers would be exceedingly difficult, expensive, and dangerous. However, partial confirmation of a simulation's accuracy can still be obtained in several ways. The first method is a controlled experiment that examines simulation accuracy situation-by-situation. This method is increasingly gaining attention, for example the project initiated by NCHRP Project 22-24, FY 2007, the "Development of Verification and Validation Procedures for Computer Simulation Used in Roadside Safety Applications" [28]. The second method is to directly measure all physical parameters on a vehicle piece-by-piece, then reconstruct the system virtually to ensure exact kinematic representation in the simulation model. This method is employed by [29]. The final method of partially confirming a complex, nonlinear simulation of vehicle behavior is to analyze a much simpler usage and representation of the model. This is discussed below.

In the author's previous research [30], simplified vehicle models were developed and compared experimentally to measured data. Data was captured on a DGPS/IMU equipped test vehicle at the Pennsylvania Transportation Institute test facility, and the resulting time-domain fits of various models versus measured data are shown in Figs. 2-4 [31]. Even though the simulation models were quite simple, the match between simulation predictions and measured data is quite good.

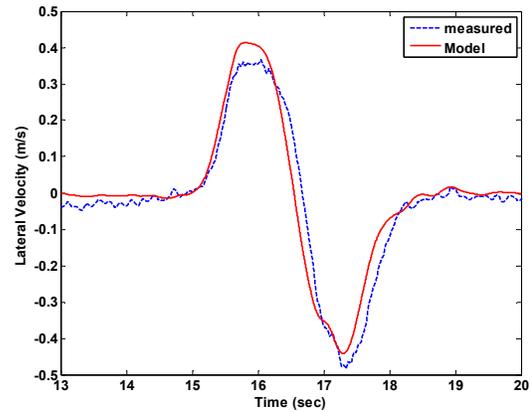


FIGURE 2. LATERAL VELOCITY RESPONSE

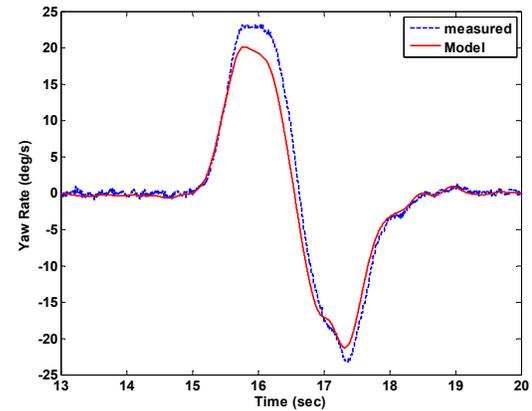


FIGURE 3. YAW RATE RESPONSE

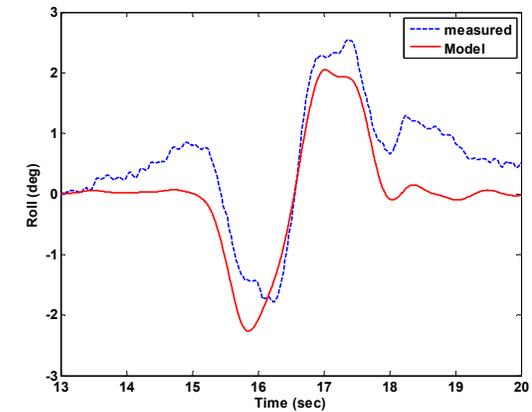


FIGURE 4. ROLL ANGLE RESPONSE

Commercially-available vehicle dynamics simulations contain dynamic representations that are far more complex than plotted in Figs. 2-4. For example, the model mismatch in Fig. 4 is largely due to the uneven profile of the testing roadway area [32]. Although the testing was performed on an area of the testing facility that appeared level, small terrain disturbances proved to have large effects on the dynamics of the vehicle. The data was corrected for terrain variation by performing the same lane change maneuver at low speeds and subtracting the roll angle measured at low speeds from the measured data at the normal test speed. A comparison of the raw and corrected roll angles is shown in Fig. 5.

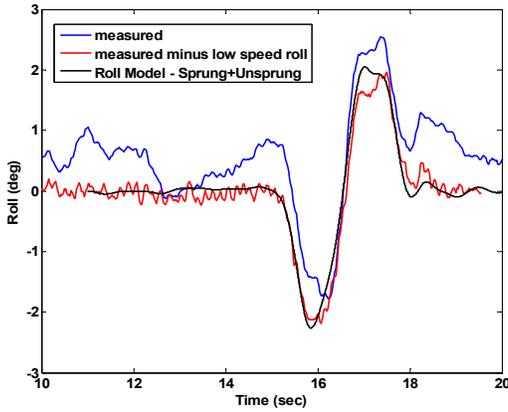


FIGURE 5: LANE CHANGE ROLL RESPONSE WITH AND WITHOUT TERRAIN COMPENSATION

By including known terrain variation and a suspension model, a better fit can be obtained not only for this relatively planar simulation, but also for uneven roadway surfaces typical of highway road geometries. Additionally, matches can be obtained for tires undergoing a large deal of skidding by including non-linear tire models, braking forces, changing road friction profiles, etc. These advanced modeling capabilities are common in modern vehicle simulation software. Validation of these capabilities is beyond the scope of this work; however, further detail can be obtained from references [14, 17-19, 33-39].

In the remainder of this study, a more complex, non-linear vehicle simulation model (commercially-available via CarSim®) will be used to analyze vehicle-roadway interaction. The intent of this study is to illustrate a method of roadway safety analysis based on vehicle dynamics simulation.

SIMULATIONS OF VEHICLES DURING MEDIAN ENCROACHMENTS

Methodology

To illustrate the use of vehicle simulations to examine roadway geometry effects, a study was done to investigate parameters that affect the dynamics and location of a vehicle during median encroachments. The goal of the study was to arrive at a “best” median profile given a variety of vehicle and driver inputs representative of incursion conditions recorded on rural divided interstate highways. For a given median profile, the vehicle simulation parameters were varied to represent the range of incursion events, including changing the vehicle type, encroachment angle, departure speed, type of corrective steering input and level of brake input.

Several different parameters representing variability in median profiles were used in this study including changing the width of the median or the slopes of the front and back slope. All medians studies were based on the standard V-type median profile described by the Pennsylvania Department of Transportation, a profile also employed by a majority of state DOT’s [40].

Vehicle parameters were obtained by averaging the vehicles tested during NCAP testing in 1998[41], the last year that NHTSA published a database of vehicle parameters, and breaking them into the types listed in Table 1. The resulting averaged vehicle parameters matched distributions used in similar studies [8]. Parameters of interest included mass,

wheel base, track width, CG location and inertial parameters for all three axes. A summary of the vehicles used is shown in Table 1 below.

TABLE 1. VEHICLE PARAMETERS USED IN STUDY

Car	Sprung Mass (kg)	Wheel Base (m)	Track Width (m)	Front Axle to CG (m)	CG Height (m)	Ixx (kg-m ²)	Iyy	Izz
Passenger Small	969	2.5	1.4	1.0	0.52	393	1632	1799
Passenger Large	1403	2.7	1.5	1.3	0.59	632	2750	2893
Pickup Small	1409	2.9	1.4	1.4	0.62	571	3143	3326
Pickup Large	1886	3.4	1.6	1.6	0.68	941	5344	5642
SUV Small	1718	2.7	1.5	1.4	0.69	803	3367	3522
SUV Large	2251	3.0	1.6	1.6	0.77	1157	5961	6111
Van	1847	2.9	1.6	1.5	0.70	992	4411	4618

Encroachment angle and departure speed were selected to be representative of events recorded from previous incursion reconstruction studies [8]. These studies presented frequency of encroachments at given angles and speeds. The angle varied from 2.5° to 32.5° in 5 degree increments, and speed varied in increments of 16 km/hr from 8 km/hr to 88 km/hr and also included 115 km/hr data.

Driver inputs were chosen to model the range of inputs a driver may chose during a median encroachment. The driver’s steering is represented by the standard previewed lag model wherein the driver’s reaction is modeled as a proportional to a time delayed look-ahead error. This model requires a reference lateral position or target road placement at which the driver is attempting to steer. The three steering inputs included a target of returning to the left shoulder of the roadway, a target of the middle of the median and a no steering case. Braking was varied between hard and light braking with ABS brakes used in both situations. Braking inputs in CarSim® are defined by the pressure applied to the brake system. In this study, hard braking was defined to be 15 MPa while light braking was defined to be 5 MPa.

The CarSim® software used for this study can easily be integrated with MATLAB® to perform multiple simulations. For this study, a total of 7 vehicles, 7 encroachment angles, 7 speeds, 3 steering inputs and 2 braking inputs were simulated for a total of 2058 simulated encroachments per profile. Each of the parameters were written into a separate input parsing file, which was then read by the CarSim® software as initial conditions or inputs during the median incursion. Outputs of the simulations, including vehicle position, tire forces, angles of orientation, speed and accelerations were saved in an output file for each simulation for later post-processing using custom MATLAB scripts.

Weighting

Some vehicles and incursion situations are far more common than others, so to better represent real world conditions and the frequency of different types of median incursions, each simulation was weighted based on three variables: vehicle type, encroachment angle and initial speed. The encroachment angle and speed frequencies were taken

from the Engineer's Manual for the Roadside Safety Analysis Program. The distribution of vehicle type were found in the 2001 National Household Travel Survey, prepared for the U.S. Department of Transportation [8, 42]. Table 2 contains information about the encroachment angle and speed distribution, and Table 3 has the vehicle frequency breakdown.

TABLE 2. WEIGHTING FACTOR FOR DEPARTURE ANGLE AND SPEED COMBINATION (ALL VALUES ARE $\times 10^{-4}$)

		Departure Angle (deg)						
Speed		2.5	7.5	12.5	17.5	22.5	27.5	32.5
km/hr	8	2	5	5	3	2	1	2
	24	49	119	118	88	57	34	42
	40	151	364	359	268	174	104	127
	56	215	519	513	382	248	149	181
	72	205	494	488	364	236	142	173
	88	152	367	362	207	176	105	128
	115	200	484	478	356	231	139	169

TABLE 3. WEIGHTING FACTOR FOR VEHICLE TYPE

Vehicle	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

The driver inputs of steering and braking were all equally weighted due to the lack of information available from accident reports about driver inputs.

In the final location plots, the 'weight', or likelihood, for each situation is indicated visually by the size of the marker marking the end location, with a large marker indicating a more common occurrence. The linewidth of each marker in the plot was set equal to 500 times the frequency of the given simulation. To better understand the relationship between terrain and vehicle response, end locations were condensed into histogram plots of lateral distance from the roadway edge. To produce histograms that clearly illustrate the frequency of an event, each simulation was replicated by a whole number factor proportional to the weighting if the inputs, and then the entire plot was normalized to produce results in percentages of likelihood of a vehicle coming to rest at a certain location.

Results

While the simulations have the capability to output over 500 different variables, there are only a few primary variables of interest when considering the overall dynamics of vehicles during off-road incursions. Of particular interest was the forward and lateral velocity of the vehicle, the yaw and roll angle of the vehicle and the path traveled.

While CarSim® has been validated for on-road maneuvers, the off-road validation is not as strong [15, 33].

Currently, no commercially available software on the market can accurately model rollover behavior through the point of vehicle body contact with the ground, and very few have the ability to account for soil penetration or tire furrowing. Part of this weakness is due to the lack of a comprehensive soil deformation model which would include lateral forces upon the tires that could lead to a tripped rollover. To correct for this shortfall, a post-processing step was used to monitor the value of the vehicle's velocity and sideslip angle, β , the angle between the heading and the velocity vector of the vehicle. Previous studies have shown through experimental testing of induced rollovers, that a threshold of 45° sideslip and a minimum speed of 32.187 km/hr (20 mph) will lead to a soil tripped rollover [43, 44]. During the post-processing, if a vehicle experienced 45° sideslip while the vehicle speed was above 32.187 km/hr, the traversal was marked as a rollover event. Due to the unpredictable nature of rollover accidents, any trajectory data after the onset of rollover was ignored in later calculations that attempted to predict the end locations of vehicles.

Plotting end locations of each situation provides an understanding of where vehicles have traveled since leaving the roadway. Fig. 6 shows the end locations of all simulations run on a 18.29m wide median with a 6H:1V front and back slope. Note that the axes are not equally proportioned.

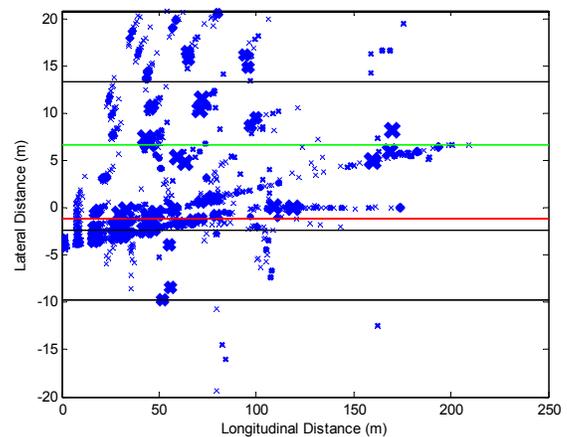


FIGURE 6. FINAL POSITIONS FOR ALL SIMULATIONS ON 18.89m 6H:1V MEDIAN

The horizontal lines across the plot indicate the roadway edges and the middle of the median. The shoulder of the original travel lane ends at 0 lateral offset. Any simulations that resulted in the vehicle traveling past the opposing lanes of traffic were ignored since this study is focused on median design, not the right roadside.

As previously described, a post-processing step was added to monitor vehicle sideslip angle and vehicle velocity for conditions that are conducive to vehicle rollover. The location where rollover was initiated is shown in Fig. 7.

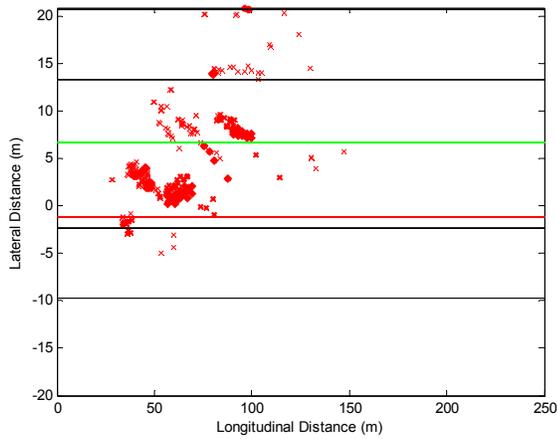


FIGURE 7. INITIATION POINT OF ROLLOVER IN SIMULATIONS ON 18.89M 6H:1V MEDIAN

To clarify the relationship between parameters across several profiles, each profile investigated was divided into seven sections across its width regardless of the width or slope, as shown in Fig. 8.

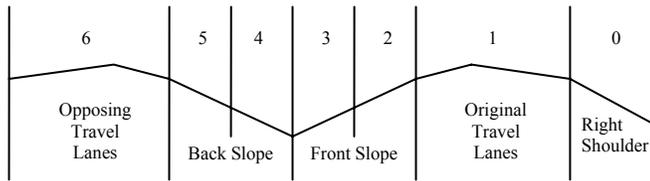


FIGURE 8. PROFILE ZONES

A sensitivity analysis was performed on all five variables of interest: steering input, braking input, initial speed, encroachment angle and vehicle type. While all variables have an impact on the behavior of the vehicle during an incursion, some clearly had a more significant impact. When comparing end locations of the vehicle subject to the light and hard braking inputs, it was noted that the hard braking situations were simply a “shadow” of the light braking situations in the sense that the hard braking simulations were shifted slightly behind the corresponding simulation that received only light braking. Of all variables investigated in this study, aggressiveness of braking input seemed to have the least impact on vehicle behavior. The results from examining encroachment angle and speed were very predictable: vehicles with higher speeds traveled further longitudinally, and vehicles with larger encroachment angles and no steering input traveled the furthest laterally.

The driver’s steering input had a very large impact on the severity of the dynamics of the vehicle during the median traversal. The situations with no steering input, in general, traveled the furthest laterally. While most of the situations that received a steering input made it to the target position, either the middle of the median or the roadway edge, some resulted in a rollover or uncontrolled situation. Some situations that included a steering input did not result in the vehicle coming to a rest at the target location, but rather, the vehicle lost control and began skidding as a result of the steering input. Fig. 9 shows the same final position plot as Fig. 6, but distinguishes between the three different steering inputs.

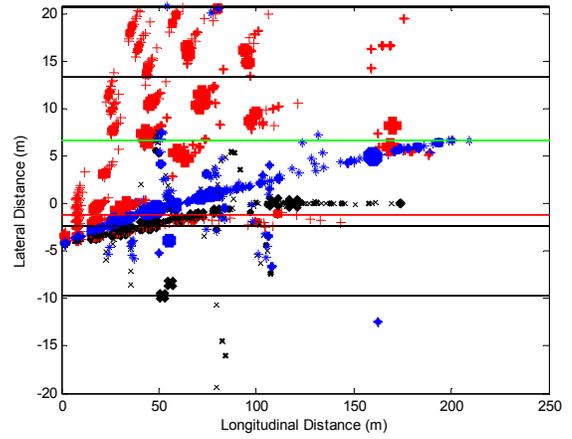


FIG. 9: FINAL POSITIONS ON 18.89M 6H:1V MEDIAN WITH STEERING INPUT DISTINCTIONS

Vehicle type had a large impact on the final location of the vehicle after incursion. Larger vehicles, such as pickup trucks, SUV’s and vans all traveled further laterally than passenger vehicles. Fig. 10 shows a categorization of end locations for each vehicle type throughout the seven zones.

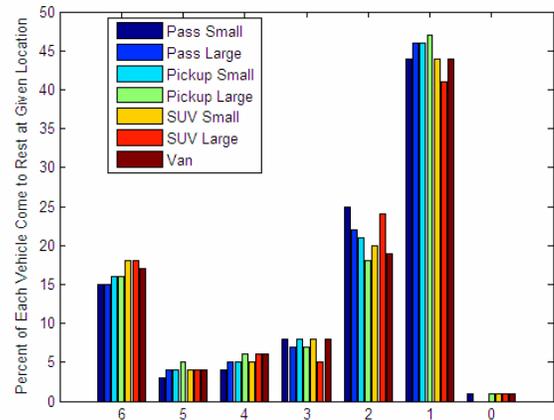


FIG. 10: PERCENT OF VEHICLE TYPE TO COME TO REST ACROSS 18.89M 6H:1V MEDIAN

The values are normalized as percentages of all incursions for a given vehicle type. As seen in the zone six distribution, there is a slight trend in the data indicating that larger vehicles are more likely to enter the opposing lanes of traffic than their smaller counterparts. As the vehicle fleet continues the shift towards larger vehicles, the relationship between vehicle size and lateral excursion into a median gains importance in redesigning the nation’s roadways and roadsides.

PROFILE STUDY

Two important factors were considered during a study of median profiles: width and slope. Each was varied independently to isolate the effects of each. The same 2058 simulations were run over all profiles. The profiles were compared by examining the end locations of vehicles that did not rollover and the location of rollover initiation for vehicles that did rollover.

Varying Width

A representative median with shoulder characteristics matching the typical median from the Pennsylvania Department of Transportation and a 6H:1V front and back slope was varied in width from 12.19m (40ft) to 23.16m (76ft) in 1.83m (6ft) increments. The end locations of each simulated median incursion were recorded and weighted as described above. All medians were then compared by plotting the percentage of vehicles to come to a rest in certain lateral zones, such as the front slope, back slope and opposing lanes. Results are shown in Fig.11.

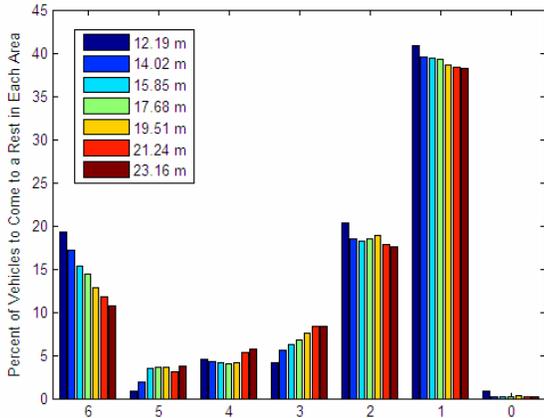


FIG. 11: PERCENT OF VEHICLES TO COME TO REST ACROSS PROFILES OF VARYING WIDTH

It is clear from the data that as the width of the median increases, fewer vehicles traverse the entire median and enter the opposing lanes of traffic. This is as expected.

But what is not expected is the influence of median width on the initiation of a rollover event. The widest median, at 23.16m, results in a relatively high number of rollover situations when the vehicle leaves the roadway, and again when passing through the bottom of the v-shape. The narrowest median causes rollover in contrasting locations, the front slope and in opposing traffic. Since the goal of this study is to arrive at the ‘best’ median design, one that limits rollover accidents and prevents cross median collisions, the overall frequency of each was compared across medians of varying width. Fig. 12 shows the rollover frequency for the seven medians of varying width.

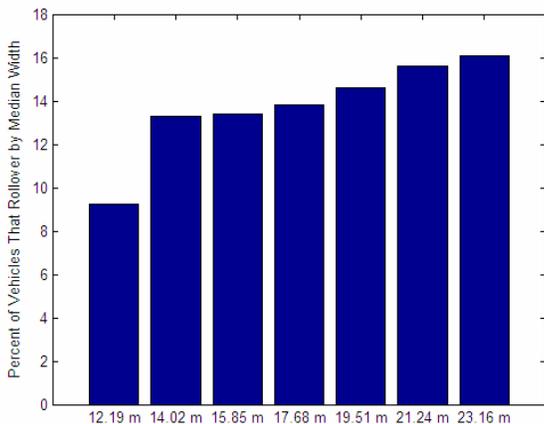


FIG. 12: PERCENT OF ENCROACHMENTS THAT RESULT IN ROLLOVER FOR MEDIANS OF VARYING WIDTH

While it appears that a narrow median would be a good design in terms of limiting rollover accidents, Fig. 10 showed that narrow medians result in a high percentage of vehicles crossing into opposing traffic. Further, incursions are not correctly simulated after traveling past the opposing lanes of traffic, so the rollover frequency on narrow medians may be underrepresented.

To balance the two worst case scenarios, of rolling over and entering oncoming traffic, a ratio between rollovers occurring in the median and vehicles either entering oncoming traffic lanes or rolling over in the opposing lanes was determined. The breakdown of events formulating this ratio are shown in Eq. 1.

$$\text{ratio} = \frac{\# \text{ of Rollovers in Opposing Lanes} + \# \text{ Vehicles Entering Opposing Lanes}}{\# \text{ of Rollovers in Median}} \quad (1)$$

For medians of varying widths, this ratio is shown in Fig. 13.

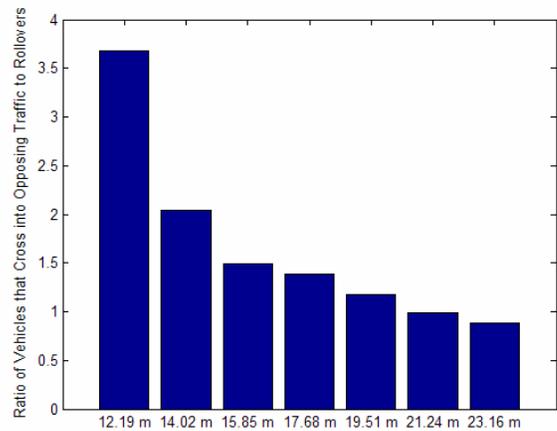


FIG. 13: RATIO BETWEEN VEHICLES ENTERING OPPOSING LANES AND VEHICLES ROLLING OVER

A vehicle entering a median 12.19m in width is over 3.5 times more likely to cross into oncoming traffic than rollover in the median. So even though the rollover frequency for a narrow median is low, the vehicle still carries a high likelihood of being involved in an accident.

As previously mentioned, a motivating factor for comparing median profiles of different shapes is to understand how a trend of increasing vehicle size affects median safety. The simulations that were identified as potentially leading to a rollover were grouped by median width in Fig. 12. These events were then sorted by the vehicle type to determine how vehicle geometry affects rollover propensity during a median traversal. Fig. 14 shows the breakdown of rollover frequency by vehicle.

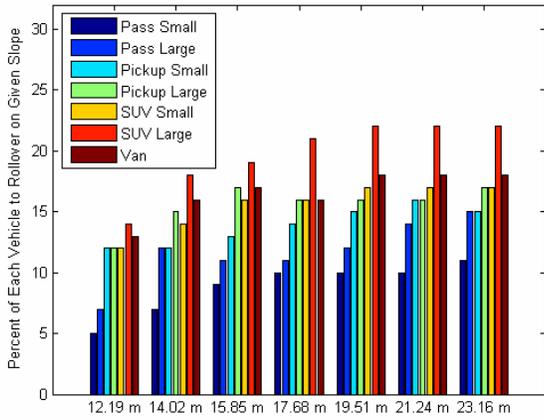


FIG. 14: ROLLOVER FREQUENCY BY VEHICLE FOR MEDIANS OF VARYING WIDTH

It is clear that the larger vehicles have a much higher likelihood of rolling over compared to passenger cars. This trend is evident across medians of any width.

Varying Slope

Similarly to the varying width investigation, a representative median with shoulder characteristics matching the typical Pennsylvania Department of Transportation 18.89m wide median was altered to vary the front and back slope from a 4H:1V to a 10H:1V slope in 1H increments. The end locations of each simulated median incursion were recorded and weighted as described above. All medians were then compared by plotting the percentage of vehicles to come to a rest in certain lateral zones, such as the front slope, back slope and opposing lanes. All seven median profiles were plotted on the same graph, Fig. 15.

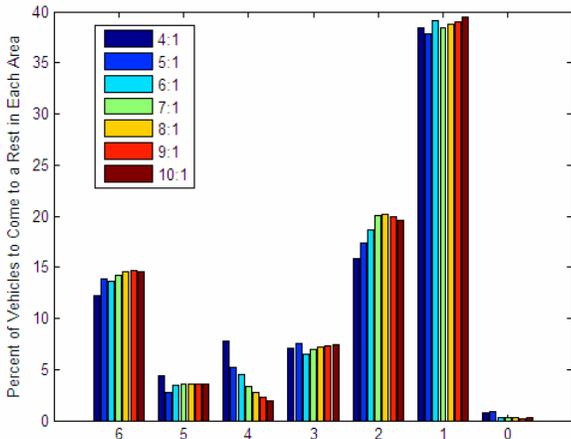


FIG. 15: PERCENT OF VEHICLES TO COME TO REST ACROSS PROFILE OF VARYING SLOPE

The end locations do not show an obvious trend to indicate that one slope profile is more preferred over another, but a closer look at the situations that would likely lead to a rollover situation provide better proof that a safety improvement occurs for a slope no steeper than 7H:1V, as seen in Fig. 16.

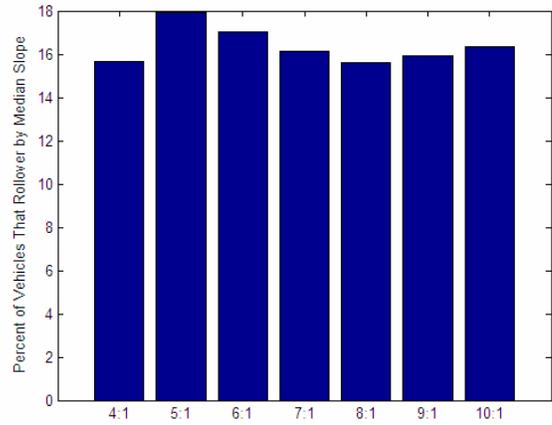


FIG. 16 :PERCENT OF ENCROACHMENTS THAT RESULT IN ROLLOVER FOR MEDIANS OF VARYING SLOPE

An 8H:1V slope has the lowest rollover frequency, followed closely by a steep 4H:1V slope. Again, to balance the two worst case situations, the ratio between the likelihood of a vehicle entering oncoming traffic and the likelihood of vehicle rolling over in the median was calculated for each slope as in Eq. (1). The resulting ratios are shown in Fig. 17.

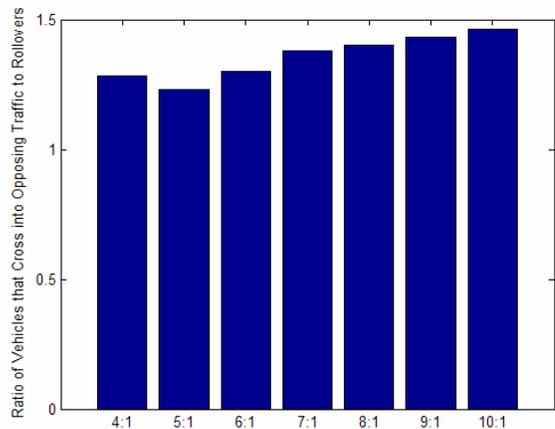


FIG. 17 : RATIO BETWEEN VEHICLES ENTERING OPPOSING LANES AND VEHICLES ROLLING OVER

This comparison indicates that the 5H:1V slope has the lowest opposing lane entry versus rolling over ratio, however, it also has the highest rollover likelihood, although there is not a large difference between all the simulated slopes.

For each median of varying slope, rollover frequency was examined for the different vehicle types used in the simulation study. The results were quite similar to that seen in the study of varying median width: that larger vehicles are more likely to rollover regardless of the slope of the median encountered.

CONCLUSIONS

The work presented here was a preliminary study of the use of vehicle dynamics simulations for roadway design. The commercially available vehicle dynamic simulation software, CarSim®, was used as a tool to study the effect of highway median width and slope on vehicle stability. This study was initiated as part of an effort to arrive at a more informed view of highway design.

The results indicate tradeoffs in the size and slope of median profiles versus the type of accidents observed: narrow medians produce a high likelihood of a cross median collision, yet produce fewer rollover accidents.

In regard to slope variations, there is not a large difference in outcomes versus slope. An 8H:1V front and back slope leads to an incrementally fewer number of rollover accidents. This suggested change away from the commonly implemented 6H:1V slope might be a reflection on the increased number of light trucks and SUV's on the roadways.

When considering vehicle type, this study indicates that light trucks such as SUV's, pickup trucks and minivans carry the highest rollover probability, regardless of median width or slope. This trend existed for all medians studied.

To determine the "best" median design, other factors are needed to supplement the above conclusions. Traffic volume will affect the likelihood that a vehicle crossing into opposing lanes of traffic will be involved in an accident.

Ultimately, comparison of rollover to cross-median collisions requires a weighted safety analysis. This safety tradeoff is necessary because vehicles are designed to withstand head-on and side impacts, and thus a cross median collision may be favorable to a severe rollover accident. The safety and cost outcomes of both accident types as well as the relative impact of each type of accident are needed to truly quantify whether a median design is the 'best' in regard to vehicle safety. This work is ongoing.

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