Analyzing the influence of median cross-section design on highway safety using vehicle dynamics simulations

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\textbf{ABSTRACT}

Although vehicle dynamics simulations have long been used in vehicle design and crash reconstruction, their use for highway design is rare. This paper investigates the safety of highway medians through iterative simulations of off-road median encroachments. The commercially available software CarSim was used to simulate over one hundred thousand encroachments, representing the entire passenger vehicle fleet and a wide range of encroachment angles, departure speeds, steering inputs, and braking inputs. Each individual simulation output was then weighted using data from previous studies to reflect the probability of each specific accident scenario occurring in a real-life median encroachment. Results of this analysis illustrate the relative influence of median cross-section geometry on the resulting accident outcomes. The simulations indicate that the overall safety of a highway median depends on the occurrence of both vehicle rollover and median crossover events, and the cross-section shape, slope, and width are all shown to greatly affect each of these incidents. An evaluation of the simulation results was conducted with vehicle trajectories from previous experimental crash tests. Further assessment of the aggregate simulation results to actual crash data was achieved through comparison with several databases of crash statistics. Both efforts showed a strong agreement between the simulations and the real-life crash data.

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1. Introduction

At the end of 2004, there were an estimated 6.18 million motor vehicle accidents reported in the United States (NHTSA, 2004a). Nearly half of these incidents led to personal injury, and a total of 42,636 fatalities were documented. This fatality count has remained relatively unchanged for more than a decade and equates to one death on the highway every 12 min.

From an engineering perspective, highway safety can generally be improved in two ways. The first is through improved vehicle design, while the second is through improved design of the roadway and roadside. 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 passengers in a crash. Although these advances in vehicle safety technology have been shown to decrease fatalities, more transportation-related deaths can be prevented through improved roadside design, including the median on divided highways.

In relation to the present study, installation of a longitudinal median barrier has been shown to reduce the severity of median-related crashes. The American Association of State Highway and Transportation Officials’ (AASHTO) Roadside Design Guide (AASHTO, 2006) contains median barrier warrant criteria for divided highways. A negative consequence of installing median barrier is that crash frequency has been shown to increase (Donnell and Mason, 2006). If the AASHTO median barrier warrants are not met, highway designers have little guidance to consider the safety consequences of median cross-section design decisions. It is hypothesized that different median type, width, and cross-slope configurations may increase the propensity of vehicles encroaching into the median to rollover. On the other hand, alternative median cross-section designs may increase the likelihood of vehicles entering the opposing travel lanes after encroaching into the median. These tradeoffs are addressed in the present study.

To analyze these safety tradeoffs, it is costly to reconstruct a median on an existing highway and subsequently perform physical testing of the new median in an observational study. Alternatively, a cross-sectional study of different median cross-sections could be evaluated to determine the safety tradeoffs (single versus...
multi-vehicle crashes) associated with different geometries. Such an approach would be predicated on significant variation in median cross-section designs across a sample of roadways. Graham et al. (2009) found that little variability exists among state transportation agencies with respect to median cross-section design standards on rural divided highways. As such, vehicle dynamic simulations of new or alternative median cross-section designs on rural divided highways can overcome these limitations in a cost-effective and timely manner.

For the past 40 years, vehicle dynamics software packages have been used to aid in vehicle performance analysis and accident reconstruction. While some of the early versions of this software, including Highway Vehicle Object Simulation Model (HVOSM) (McHenry, 2009) and Vehicle Human Environment (HVE) (EDC, 2009), were used to aid in highway design, the use of multi-body vehicle simulation to study proposed roadway design changes remained relatively rare until the late 1990s.

In 1997, Chrstos and Heydinger published a study in which the Vehicle Dynamics Analysis Non Linear (VDANL) and Vehicle Dynamics Models for Roadway Analysis and Design (VDM RoAD) software packages were used to predict the dynamics of a 1994 Ford Taurus. Results from this study showed a very realistic trend, both in the linear and non-linear range of the vehicle response, when compared to experimental data. Similarly, Steffan and Moser (2004) used a program called PC-CRASH to reconstruct rollover crashes. When compared to real-life crash test data, the model showed good agreement.

Further testing involving vehicle dynamics simulations was carried out by the Federal Highway Administration (FHWA)/National Highway Traffic Safety Administration (NHTSA), National Crash Analysis Center (NCAC) in 2008 (Marzougui et al., 2008). In this study, simulations with the HVE software package were compared with physical testing of a pickup truck and small passenger vehicle. Using cable barriers designed to meet crash testing criteria established in the National Cooperative Highway Research Program (NCHRP) 350 study (Ross et al., 1993), this investigation examined the occurrence of barrier underrides that was reported in crash data. Simulation results were strikingly similar to the physical test data obtained from high speed video footage and vehicle sensors. And while significant challenges remain for modeling the soil–tire interaction experienced during off-road excursions, this study further proves that the simulation of gross vehicle motion is representative of physical off-road crash tests.

This study aims to investigate the safety of earth-divided, traversable rural highway medians without longitudinal median barriers by simulating median encroachments for several different vehicle classes, initial speeds, and encroachment angles. Different design characteristics of the median, including cross-section shape, slope, width, and their relative effect on the vehicle response during the encroachment are also investigated.

In the simulations, the CarSim (Mechanical Simulation Corporation, 2009) software was used. Benekohal and Treiterer’s study (1998) was one of the first to use CarSim to perform simulations for highway design analysis of traffic patterns on the highway in both normal and stop-and-go driving scenarios. Today, CarSim is one of the most widely used vehicle dynamics simulation packages in industry. CarSim was also selected for use in the present study due to its ability to easily interface with external MATLAB and Simulink scripts and for its ease of customizing roadway cross-sections, specific vehicle geometries, and driver inputs. While it is not possible to completely validate any software package for all ranges of vehicle dynamics, it is appropriate to compare the merits of one software package to another. In particular, compared to most software packages and assumptions used for crash reconstruction in median environments and the subsequent legal analyses (Brach, 2005), the models used in the CarSim software in general include aspects affecting vehicle motion neglected by most software. For example, many software systems neglect the steering effects due to suspension deflection (e.g. suspension kinematics and compliance) or neglect suspension deflection entirely. Many crash reconstruction analyses neglect how the vertical load on the tire will change the tire’s steering forces within a turn or change the tire’s camber angle, which in turn neglects how roll-induced weight shift affects a vehicle’s steering ability. These factors are included in the standard CarSim models used in this study. However, one factor ignored by all software that is commercially available is how the deformation of the soil surface can modify the tire forces (Li and Sandu, 2007). This can be important for soil-tripped rollover, trajectories through very loose or wet soils, etc. Although this study does not include the ability to predict tire forces under large soil movement near the tire, an analysis (discussed later) of vehicle trajectory assuming a non-deformable surface is utilized along with experimentally measured thresholds of soil-tripped rollover to infer the occurrence of this specific behavior.

The remainder of this paper discusses details of a specific study using vehicle dynamics simulations to examine the safety of highway medians. Section 2 presents a methodology for a simulation-based safety analysis of highway medians, including post-processing analysis techniques. Section 3 presents the main outcomes of the simulations. Section 4 analyzes the outcomes of the simulations, specifically considering the influence of several median design factors. This portion of the paper also presents a design tool for highway engineers to use. Section 5 discusses the comparison of the simulation results to real-world data, while the last section presents the conclusions from the study.

2. Methodology

2.1. Methodology for simulations

To evaluate the safety of each median, several thousand simulations were run in an attempt to create a realistic dataset that best represents the range of median encroachment outcomes on an actual highway. The following method was iteratively used for the simulations in this study:

Step 1: define the median cross-section.
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.

Seven different vehicles, seven initial speeds, seven encroachment angles, three steering inputs, and two braking inputs from the driver were considered for each median cross-section simulated in this study. Details of each step and the simulation parameters are provided in the following sections.

2.1.1. Step 1: define the median cross-section

To define the median cross-section, both on and off-road cross-sections and friction maps were created in CarSim. This study initially used a 60-ft (18.29 m) wide V-shaped median with a slope of 6%:1V, and a 2.4-m wide inside (or median side) shoulder with a grade of 4% as laid out in the Pennsylvania Department of Transportation’s design standards (PennDOT, 2002). Additional medians of varying slope and width were then examined including: 40-ft (12.19 m) wide V-shape with 6:1 slopes, 60-ft (18.29 m) wide V-shape with 5:1 slopes, 60-ft (18.29 m) wide trapezoidal shape with 5:1 slopes, and 80-ft (18.29 m) wide V-shape median with 10:1 slopes. These represent the most common rural divided high-
way median cross-section standards used by state transportation agencies in the United States (Graham et al., 2009).

2.1.2. Step 2: choose the vehicle

CarSim allows nearly every parameter of the test vehicle, from geometric configurations to inertial properties, to be user-defined. This study uses vehicle parameters obtained by averaging data collected in the 1998 New Car Assessment Program (NCAP) (Heydinger et al., 1999). Although this survey is more than a decade old, the collected in the 1998 New Car Assessment Program (NCAP) (Heydinger et al., 1999). Although this survey is more than a decade old, the average distributions within the vehicle fleet change slowly. The primary vehicle parameters used in this study include sprung mass, wheel base, track width, center of gravity (CG) location, and inertial properties. Values for each were obtained by averaging across each vehicle class from the NCAP (Hamblin, 2007), and Table 1 shows a summary of these parameters.

2.1.3. Step 3: establish the initial conditions

This study only varied the vehicle’s initial speed and departure angle upon encroachment. All other vehicle states, including roll, pitch, and sideslip, were initially set to zero. The RSAP Engineer’s Manual provided a range of speeds and encroachment angles and their respective likelihood of occurring on the highway. The angles varied from 2.5° to 32.5° in 5° increments, and speeds ranged from 8 to 88 km/h (5–55 mph) in 16 km/h (10 mph) increments, also including 115 km/h (70 mph) (Mak and Sicking, 2003). These speeds and angles were chosen to best represent the vast range of conditions under which a roadside encroachment could occur.

2.1.4. Step 4: determine the driver’s actions

The driver’s actions during an encroachment are almost always unknown, and thus the most likely scenarios for driver intervention must be inferred. This study considers two generic scenarios that represent active driver input: (1) steer the vehicle to the center of the median (median recovery) and (2) attempt a return to the roadway by steering to the edge of the pavement on the original travel lane shoulder (road recovery). The third steering scenario was a “no steer” condition in which the driver is modeled to take his/her hands completely off of the steering wheel. To implement these situations, the vehicle in the CarSim driver model was directed to each of these three representative target point trajectories. Fig. 1 shows a plan view of these targeted steering paths.

Due to the specific encroachment angle and speed combination, the driver’s attempt to recover to the shoulder edge, or even to the middle of the median, may not be physically possible. However, it must be noted that the steering inputs were defined in a way that simulates the driver’s reaction and subsequent attempt to direct the vehicle to a particular target point, whether or not the vehicle actually reaches that target point or not. In fact, in most of the simulations with high speeds and large encroachment angles, the target paths defined by the chosen steering input are different from the actual trajectory of the vehicle during the encroachment due to the severe vehicle dynamics of these maneuvers.

The braking was generically defined to be either a light braking (defined as 5 MPa of pressure at the cylinder) or hard braking (defined as 15 MPa), both with a simulated antilock braking system (ABS) subsystem included with the CarSim vehicle model. Each steering–braking combination was simulated for all possible vehicle-speed-angle runs tested, for a total of six driver actions simulated for each vehicle-speed-angle run.

2.1.5. Step 5: run the simulation

An external MATLAB script was used to automate the simulation process by defining the median cross-section, vehicle, initial conditions and driver’s actions before the simulation was started. The simulation was then run using a time step of 0.002 s, and the output variables were stored in a MATLAB structure file for post-processing and subsequent analysis. Each scenario was simulated for a total of 16 s, or up until the moment rollover was detected and confirmed, whichever happened first. The typical simulation took 16–17 s to run on a 3 GHz, Pentium 4 Dell Dimension 8300 desktop computer. Thus, to comprehensively simulate one typical median cross-section design, it took about 9 h.

2.1.6. Step 6: summarize the outputs and repeat

The simulation process was repeated for each possible combination of vehicle, initial speed, encroachment angle, and driver actions. Ultimately, 2058 simulations were run for each median cross-section tested. For the 54 medians simulated, a total of 111,132 simulations were conducted, resulting in a wide range of possible crash scenarios.

2.2. Data post-processing

Although the vehicles chosen for this study represent the vehicle population on the highway, certain vehicles are more common than

<table>
<thead>
<tr>
<th>Vehicle class</th>
<th>Sprung mass (kg)</th>
<th>Wheel base (m)</th>
<th>Track width (m)</th>
<th>Front axle to CG (m)</th>
<th>CG height (m)</th>
<th>Ixx (kg m²)</th>
<th>Iyy (kg m²)</th>
<th>Izz (kg m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger small</td>
<td>969</td>
<td>2.524</td>
<td>1.446</td>
<td>1.021</td>
<td>0.519</td>
<td>392.6</td>
<td>1612.2</td>
<td>1798.8</td>
</tr>
<tr>
<td>Passenger large</td>
<td>1403</td>
<td>2.679</td>
<td>1.468</td>
<td>1.277</td>
<td>0.585</td>
<td>632.3</td>
<td>2749.7</td>
<td>2893.3</td>
</tr>
<tr>
<td>Pickup small</td>
<td>1409.4</td>
<td>2.948</td>
<td>1.424</td>
<td>1.396</td>
<td>0.620</td>
<td>571.25</td>
<td>3142.75</td>
<td>3326.25</td>
</tr>
<tr>
<td>Pickup large</td>
<td>1885.8</td>
<td>3.425</td>
<td>1.619</td>
<td>1.581</td>
<td>0.684</td>
<td>940.5</td>
<td>5344</td>
<td>5642.25</td>
</tr>
<tr>
<td>SUV small</td>
<td>1718.5</td>
<td>2.683</td>
<td>1.496</td>
<td>1.350</td>
<td>0.688</td>
<td>803.33</td>
<td>3367</td>
<td>3522.17</td>
</tr>
<tr>
<td>SUV large</td>
<td>2251.1</td>
<td>3.032</td>
<td>1.579</td>
<td>1.628</td>
<td>0.767</td>
<td>1157.25</td>
<td>5960.75</td>
<td>6111</td>
</tr>
<tr>
<td>Van</td>
<td>1847.5</td>
<td>2.947</td>
<td>1.589</td>
<td>1.480</td>
<td>0.698</td>
<td>992.33</td>
<td>4410.67</td>
<td>4617.83</td>
</tr>
</tbody>
</table>

Table 1

Vehicle parameters.
others. Likewise, certain initial speeds and encroachment angles are far more likely to occur than others. To better represent the likelihood of each specific encroachment occurring in real-life median encroachments, a post-processing weighting method that factors in the relative probability of each occurring on a highway was implemented.

To obtain a probability estimate of each vehicle class appearing on the highway, the 2001 National Household Travel Survey (U.S.DOT, 2004) was used. It was assumed that the probability of accidents for each class is equal to the representation of each vehicle class on the road. This assumption is based on highway travel data reported by FHWA (2007) and NHTSA (2007). By combining the exposure data from FHWA and crash data from NHTSA, the crash rate (crashes per 100 million vehicle-miles traveled) was nearly uniform for passenger cars, pick-up trucks, SUVs, and vans. As such, each vehicle class was assigned a weighting factor equal to its frequency of appearing on the highway, and the results are summarized in Table 2.

Although the statistics in the aforementioned travel survey may appear dated, a more recent distribution produced in a 2006 study (White, 2007) showed comparable data. Passenger cars consisted of 54% of the roadway population, while SUVs, vans, and pickup trucks collectively held 39.5%. Motorcycles, buses, and truck combinations accounted for the remaining vehicles on the road.

Similarly, probabilities for the occurrence of each encroachment angle and speed were obtained from the RSAP Engineer’s Manual (Mak and Sicking, 2003), thereby producing weighting factors for all possible speed and angle combinations. These are summarized in Table 3.

Since there is no prior study that incorporates the probability of the driver’s actions, the steering and braking inputs were weighted evenly across all runs. Although certain actions by the driver are more probable than others, there is presently no data regarding this issue available. Thus, this methodology is devised in a way such that, as data quantifying the driver’s likelihood to react in a particular manner becomes available through naturalistic studies, appropriate weighting factors can be assigned to each specific steering and braking input.

The total weighting factor used for each individual simulation in this study is then a product of the individual weighting factors for each parameter used in the simulation (see Eq. (1)). For example, a crash scenario involving a large passenger vehicle (50.1% of vehicles on the road) departing the roadway at an angle of 12.5° and a speed of 56 kmph (representing 5.13% of departures), the total weighting factor would be: $0.501 \times 0.0513 = 0.0257$. This quantity indicates that of all the crash scenarios on the highway, this specific one occurs 2.57% of the time.

$$\text{total weighting factor} = \text{vehicle weighting factor} \times \text{speed and angle combination weighting factor}$$ (1)

3. Simulation outcomes

After incorporating the weighting factors into the simulation data to better represent the probability of each specific crash scenario (vehicle, speed, departure angle, and driver actions combined), the relative influence of the median cross-section on accident causation was investigated. More specifically, instances of vehicle rollover and the end locations of all simulations were monitored. As shown below, median design is fundamentally a tradeoff between rollover events, cross median collisions, and vehicles entrapped in the median.

3.1. Vehicle rollover

One of the primary causes of death on the highway is vehicle rollover. With the drastic increase in sport utility vehicles (SUVs), the amount of rollover incidents is on the rise. In 2004, the National Highway Traffic Safety Administration (NHTSA, 2004a) reported that SUVs contributed to 36% of the total 9053 fatal rollovers on the highway. In another 2004 study, NHTSA (2004b) predicted that 90% of all rollovers are due to a tripped phenomenon. Although it is not possible to differentiate rollovers occurring in the median versus to the right of the traveled way, these statistics indicate that 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 roadway.

A disadvantage to using vehicle dynamics simulation programs to model these rollover situations is that there are currently no commercial software packages that correctly predict deep soil–tire forces and hence soil-tripped rollover. However, in 2004, some general criteria for soil-tripped rollover were recently published in an experimental study (Kroninger et al., 2004), where rollover was consistently observed to occur when the vehicle exhibited a sideslip greater than 45° at a speed greater than 32.187 kmph (20 mph). We adopt the same criteria in the simulations in order to classify soil-tripped rollovers.

After applying this designation for rollover to the simulation results for each vehicle class, the scenarios that exhibited rollover during the off-road trajectory were recorded. Fig. 2 displays the

<table>
<thead>
<tr>
<th>Vehicle class weighting factors.</th>
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<tbody>
<tr>
<td>Vehicle</td>
</tr>
<tr>
<td>Small passenger</td>
</tr>
<tr>
<td>Large passenger</td>
</tr>
<tr>
<td>Small pickup</td>
</tr>
<tr>
<td>Large pickup</td>
</tr>
<tr>
<td>Small SUV</td>
</tr>
<tr>
<td>Large SUV</td>
</tr>
<tr>
<td>Van</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Speed and encroachment weighting factors.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial speed (kmph)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>24</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>56</td>
</tr>
<tr>
<td>72</td>
</tr>
<tr>
<td>88</td>
</tr>
<tr>
<td>115</td>
</tr>
</tbody>
</table>
resulting distribution of rollover scenarios, for all of the simulated medians, and filtered by vehicle class. As to be expected, and in agreement with existing crash statistics (NHTSA, 2004a,b), the small SUV category experiences more than twice the number of rollovers as a small passenger vehicle.

3.2. Final resting locations

Although vehicle rollover is a primary concern during highway median encroachments, a second catastrophic occurrence must be considered as well. This event, referred to as a median crossover, is an incident in which the vehicle encroaching into the median ultimately enters the opposing lanes of traffic, thus risking the possibility of a high-speed, head-on collision with oncoming vehicles. Several researchers have shown that median crossover crashes are more severe than other median-related crashes (Donnell et al., 2002; Miaou et al., 2005). To examine the occurrence of median crossovers, the final resting location of the vehicles was extracted from the simulation data. For clarity purposes, Fig. 3 shows the resting positions for 250 vehicles that did not rollover during the simulation. As can be seen in the figure, several vehicles traversed the median and entered the opposing lane of traffic before coming to a rest. The overall proportion of these median crossover events will be discussed further in Section 4.

3.3. Design ratio

Even though the rollover and crossover data is by itself useful, it does not provide a clear understanding of the tradeoffs that may exist when designing a median. To provide more insight into these tradeoffs, a ratio of those simulation runs in which the vehicle crossed into the opposing lane to those which exhibited rollover was created (see Eq. (2)).

\[
\text{ratio} = \frac{\text{number of median crossovers}}{\text{number of rollovers}} \quad (2)
\]

This ratio presents the data in a means useful to highway designers. For example, if one specific median design has a 2:1 ratio of crossovers to rollovers, and a second median has a 4:1 ratio, the designer knows that the vehicles will be twice as likely to rollover in the first median than in the second. At the same time, the second design will be twice as likely to experience a median crossover and thus a head-on collision. For a median crossover crash to occur, however, a vehicle traveling in the opposing travel lanes must be present.

4. Discussion

In an attempt to determine the influence of the median cross-section on the vehicle response during a median encroachment, simulations were run with varying median cross-section shape, slope, and width. All 2058 possible combinations of inputs (vehicle, speed, angle, steering, and braking) were tested for each median.

4.1. Influence of median cross-section

For the initial test of the median cross-section, the five median profiles in question were:

1. 6H:1V, 60-ft wide, V-shape.
2. 6H:1V, 40-ft wide, V-shape.
3. 5H:1V, 60-ft wide, V-shape.
4. 5H:1V, 60-ft wide, trapezoidal shape.
5. 10H:1V, 60-ft wide, V-shape.

Fig. 4 shows the resulting rollover scenarios as a function of the median cross-section. These results indicate that the shape, slope, and width of the median all influence rollover occurrence. Looking specifically at the rollover instances for the two 5H:1V, 60-ft wide medians, Fig. 4 also shows that the trapezoidal cross-section led to...
20.6% of the rollovers, whereas the similar V-shape median resulted in 23.7% of the rollovers.

Upon investigation of the median crossovers from the vehicle dynamics simulations, the 5H:1V, 60-ft wide trapezoidal median resulted in 58 of the possible 355 median crossover occurrences (3.45% of all simulated scenarios), whereas 74 were accounted for by the 5H:1V, 60-ft wide V-shape median. As such, the trapezoidal median was better at containing the vehicle, reducing the number of crossover events by 21.6% when compared to the V-shape median. From these results, it appears that a 5H:1V, 60-ft wide trapezoidal median can reduce the probability of median crossover crashes when compared to the similar V-ditch design in the event of an off-road incursion. But, in order to draw a general conclusion, further simulation of trapezoidal medians with various slopes and widths needs to be conducted.

As expected, the medians with the steepest cross-slopes (5H:1V) resulted in the highest frequency of rollover incidents. The narrowest median (40-ft wide) exhibited 14.6% of all the rollover incidents, which is the lowest of all the medians simulated, but this is due to the shorter length of traversal and hence larger number of vehicles that experience median crossover, many of which rollover thereafter (which is not captured in these results). The effects of median slope and width are presented in further detail below.

4.2. Influence of median slope

Since the median cross-section was shown to have a large effect on the vehicle response in Section 4.1, the influence of median slope alone was investigated. A 60-ft wide, V-shape median with varying slope was considered. The evaluated slopes ranged from 4H:1V to 10H:1V, in increments of 1 ft horizontal (4H:1V, 5H:1V, etc.). Fig. 5 shows the resulting rollover scenarios in these simulations, sorted by the median upon which they were simulated.

In general, the shallower sloped medians resulted in fewer rollover scenarios than steeper slopes, but when examining the occurrence of median crossovers, the opposite trend appeared. Presenting the design tradeoff (discussed in Section 3.3) in Fig. 6, it is evident that a flatter median side-slope will lead to a smaller number of rollovers, but at the cost of increasing the likelihood of an encroaching vehicle to enter the opposing lane of traffic, and henceforth risking a head-on collision.

4.3. Influence of median width

To investigate the influence of median width, all 2058 possible scenarios were analyzed for a 6H:1V sloped, V-shape median with varying width. The widths tested ranged from 40 (12.19 m) to 76 ft (23.16 m), in increments of 6 ft (1.829 m). Fig. 7 indicates that the widest median resulted in the highest number of rollovers.

Using the same ratio of median crossover to rollover, Fig. 8 shows that a vehicle entering a 40-ft wide median is almost twice as likely to enter the opposing lane as a vehicle on any other median width tested. These results again portray an obvious trade-off between vehicle rollover and entrance into the opposing lane.
Due to the longer distance within the median, and thus a greater chance of a soil-tripped phenomenon occurring, wider medians led to more rollovers. At the same time, the longer traversal distance (i.e., median width) prevented cross-median crashes.

5. Comparison of simulation results to real world data

An evaluation of the simulation results was conducted by comparing the CarSim outputs both with vehicle trajectory data from full-scale experimental testing and with statistics compiled from several crash studies.

5.1. Trajectory comparison

In 2006, testing of a 2000 Chevrolet C2500 pickup truck was performed at the Texas Transportation Institute (TTI) Proving Grounds Research Facility. A 120-ft long, 6H:1V V-shaped median was constructed for the test. The truck departed the roadway surface at a speed of 101.2 km/h (62.9 mph) and with an encroachment angle of 24.7°. Although this test involved a high-speed barrier impact, the vehicle traveled over 13 ft across the median before impacting the barrier 0.520 s later.

After digitizing high speed video footage, the vehicle’s lateral and vertical trajectories from the full-scale test were obtained. As seen in Fig. 9, the overall trajectories in the simulation data matched well this individual crash scenario.

Looking at the angular displacement data between the TTI test and the CarSim predictions, further evaluation of the simulation results was conducted. Fig. 10 shows the resulting comparison between the roll and yaw angles for the two tests. As seen in the figure, both of these outputs from CarSim matched very closely with the real-life test.

Although this one trajectory does not illustrate the entire range of steering behavior, vehicles, and median cross-sections that were considered in this study, it does provide a means of evaluating the model in one specific case. Due to the lack of experimental data, it is standard practice in the vehicle dynamics community to use one, or very few, trajectories to infer key behaviors of a vehicle. And while correlation does not imply causation, it does reinforce the model’s ability to predict the naturally occurring vehicle response during a median encroachment. Further evaluation of the aggregate simulation results is discussed in the following section.

5.2. Statistical comparison

As the trajectory comparison presented in Section 5.1 only assesses one encroachment scenario, crash statistics found in both the 2004 (NHTSA, 2004a) and 2005 NHTSA Traffic Safety Facts (NHTSA, 2006) were used to further compare the overall results from the simulations to real-life data. In 2005, the NHTSA reported that of all reported highway crashes, 2.6% experienced rollover after departing the roadway. The CarSim simulations, which predicted rollover 2.46% of the time, deviated by a mere 5.38% from the published statistics. The NHTSA statistics do not differentiate between rollovers occurring to the left or right of the traveled way; however, these statistics provide a basic means of evaluating the simulation predictions.

Reported crash data from the 2004 Traffic Safety Facts, reported that of all rollover situations on the roadway that year, 94% were for passenger vehicles. The remaining 6% consisted of commercial vehicle rollovers. As the CarSim experiments were only run for passenger vehicles, the resultant rollover percentages for all vehicle classes add up to 100%. As a result, the simulation rollover percentages were adjusted to add up to a total of 94%, to parallel the NHTSA data and eliminate any possible error due to inconsistency. When these figures were modified, the results matched the crash statistics well. As shown in Fig. 11, this corrected rollover data for all vehicle classes simulated differs from the crash statistics by less than 8.5%, and in the majority of the cases, less than 4%. As such, these simulation results are closely correlated with the data published by the NHTSA.
While the data presented above offers a means for evaluating the rollovers exhibited during simulation, the median crossover results must be verified as well. The NCHRP 22-21 (Graham et al., 2009) study provided statistical data for both median crossover and rollover occurrences for several median types on rural divided highways. These statistics were stratified according to the median slope and width characteristics. After extracting the data that pertained to the medians that were simulated, Figs. 12 and 13 show the resulting comparison between the two data sets.

As shown in Figs. 12 and 13, 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. The lack of correlation between the simulation and reported crash statistics in the 2:1 to 4:1 cross-slope category is likely due to the small proportion of medians with slopes in this category (less than 20 miles [32 km]). The simulation results from the remaining groups deviated from the NCHRP 22-21 statistics by a maximum of 16.6%, and in most cases, this discrepancy was less than 12%. But, even with these differences in the actual numerical data, the general trends presented by the simulations are confirmed with the crash statistics. 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 confirms that the general tendency of a median to experience a crossover event is preserved in the simulations.

6. Conclusion

This paper presented a means of analyzing the influence of median cross-section on the safety of highway medians through the implementation of vehicle dynamics simulations. A methodology for the simulations was introduced, in which the vehicle, speed, encroachment angle, steering and braking inputs were all varied to evaluate their respective effects on vehicle behavior. Each individual run was assigned a weighting factor to better represent the likelihood of that particular scenario occurring in a real-life highway median encroachment.

The median cross-section was found to have a significant effect on the vehicle response within the median. Median shape, slope, and width were all found to be important in predicting both median crossover incidents and in-median rollovers.

There is one main safety tradeoff between designing a median to prevent vehicular rollover and designing it with the intention of preventing median crossovers. From the simulation data, general trends depicted the relationship between a design parameter (median shape, width, etc.) and the frequency of both rollovers and cross-median crashes. For instance, when all other design variables are held constant, as the median width is increased, the frequency of rollover increased (see Fig. 7).

The accuracy of the simulation results was examined by considering both full-scale experimental crash testing and published crash statistics. Both comparisons resulted in great agreement between the real-life tests and simulation data. Fig. 14 displays the statistical data against the simulation data on a scatter plot. By drawing a line of perfect correlation, the overall fidelity of the simulations, compared to the published crash statistics (NHTSA, 2004a; Graham et al., 2009), can be seen on one figure.

The authors feel that the effects of soil deformation present the largest discrepancy in the simulated physics of a median incursion, particularly near the moment of rollover of a vehicle. Thus, the exact locations and moments of rollover are expected to have some error. And even if the physics are correct, there remains large uncertainty in the driver’s steering action during an incursion. Both are a challenge to all vehicle simulation software packages used for crash analyses of vehicle’s departing the road surface. The agreement between the simulations used herein with national and site-specific crash statistics suggests that simulations, even if their results are approximate, still have predictive value. These two phenomena deserve further study, and assuming future work progresses understanding of tire forces or driver behavior, the methodology presented herein allows straightforward modification of results once these behaviors are better known.
Future work will examine several crash factors not considered in this study including: encroachments into medians with non-zero horizontal or vertical curvature, encroachments into the shoulder, how driver reactions to barrier placement may affect rollover/impact outcomes, and how driver inputs other than the “zero-input” case affect barrier impact geometries. Additionally, updates to the simulation will be analyzed to improve the fidelity, the most significant modifications being the inclusion of soil–tire interactions that can directly predict the occurrence of soil-tripped rollover, and the incorporation of results from naturalistic driving studies that will provide data to assign weighting factors for the driver’s actions.

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