Sensitivity Analysis on the Influence of Vehicle Factors on the Kinematic Response of a Mid-Sized Male Crash Dummy During a Simulation of a Controlled Rollover Crash.

Stephen A. Ridella, Cezary Bojanowski

Abstract Previous analysis of the mechanisms of rollover injured occupants concluded that vehicle deformation, crash and occupant factors may have contributed to the likelihood of these injuries, particularly those to the cervical spine. This study uses parametric analysis of a computer simulated rollover crash to show how certain vehicle and crash factors may influence the kinematics of a mid-sized male crash dummy model and the risk of injury.

A previously validated finite element model of a mid-sized sedan was subjected to a simulated, repeatable rollover crash test. Nine different vehicle and crash parameters were varied from nominal positions and results generated for dummy kinematics, injury measures such as Head Injury Criterion (HIC) and upper neck forces and moments, and maximum roof deformations. Over 90 simulations were run and statistically analyzed using analysis of variance techniques to determine factors most influencing dummy and vehicle responses.

Of all parameters simulated, the pitch angle, defined as the forward angle of the vehicle relative to its longitudinal axis, influenced the dummy's head and neck injury measures the most, accounting for 50% of the response in some cases. Drop height, roll angle, and roof geometry had significant influence on the maximum roof deformation. Identifying the most influential vehicle and crash factors in the model may lead to changes in vehicle design to minimize vehicle rollover crash response and the risk of occupant injury.

Keywords CRIS, drop height, intrusion, parametric analysis, pitch angle, rollover

I. INTRODUCTION

According to the National Highway Traffic Safety Administration (NHTSA), fatalities attributed to a rollover involved crash in the United States have decreased from 11,433 in 2005 to 7,659 in 2011 [1]. Despite these reductions, the percentage of fatalities of occupants in passenger vehicles involved in rollover crashes relative to all crash fatalities in passenger vehicles remained at 25% over the same time period. Rollover crash injury has been extensively studied by many researchers. There has been a significant amount of analysis of the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) data base in recent years by researchers attempting to correlate various factors of rollover crashes with the risk of injury. Reference [2] analyzed NASS-CDS for association of roof crush on risk of head and spine injury as well as death for belted adults in rollover crashes after controlling for vehicle type, rollover severity (number of rolls), occupant age and occupant gender. They found that the risk of sustaining an AIS 3+ spine injury nearly doubled for as little as 8cm-15cm of roof crush compared to no roof crush, but interestingly only increased to an odds ratio of 2.69 for roof crush levels more than 30cm. However, the mortality risk at 30 cm of roof crush was 7 times the risk when little (< 3cm) of roof crush was noted. Others [3-4] examined multiple years of the NASS-CDS data to determine factors associated with increased risk of injury in rollover crashes. Both papers published extensive comparisons of vehicle and occupant factors that may contribute to risk of rollover crash injury. Reference [3] found a similar result regarding roof intrusion as a predictor of moderate to severe spine injury. They also found that 35% of the cases with spinal injury had little or no roof intrusion. Reference [5] examined rollover injuries of belted, unejected occupants involved in pure rollover (no other planar crash) crashes in both NASS-CDS and the Crash Injury Research and Engineering Network. From the NASS-CDS data they found that cervical spine fractures accounted for nearly 20% of all serious (AIS 3+) injuries for those occupants. Roof intrusion greater than 30 cm

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was noted in over 35% of the spine injured cases, however, 27% of the occupants were considered obese (Body Mass Index > 30). Additional analysis of NHTSA's Crash Injury Research Engineering Network (CIREN) for cervical spine cases showed that both vertical and lateral roof intrusion at the injured occupant location are related to the level of cervical spine injury, especially in cases where there are 2 roof inversions of the vehicle during the crash.

While the field crash databases give some ability to review the circumstances of a particular rollover crash, they lack the ability to look at how an actual rollover crash occurs. Field data takes into account all rollover cases where actual testing can look at a specific crash mode in a controlled environment. A variety of test conditions have been developed to assess vehicle and occupant motions as a result of vehicle rollover. Two recent studies attempted to create a repeatable rollover crash condition. References [6-7] have shown that they can perform a full vehicle, repeatable, laboratory rollover test that has independent control of lateral velocity, drop height, roll angle and rate, and vehicle pitch angle. Another test device, the Controlled Rollover Impact System, or CRIS, reported by [8], uses a tractor-trailer system to carry and transport a vehicle, rotating on its longitudinal roll axis, before "releasing" the vehicle onto the ground or pavement at any part of the vehicle (roof, wheels, etc.) designated. CRIS may be used to evaluate a number of important parameters in a rollover event such as roll rate, drop height and impact location, lateral velocity and roof strength. Reference [9] ran a series of production and roll-caged passenger cars using the CRIS fixture and measured Hybrid III neck load (belted dummy) during the rollover event. The results indicated that the stiffer roll-caged roofs did not offer any protection from prevention of roof crush as neck loads on the dummy were similar between production and roll-caged vehicles.

Given that a rollover crash is a chaotic and often unrepeatable event and that test methods can only analyze one condition at a time, computer simulation offers some advantages in analyzing the vehicle and occupant responses. Modeling allows parametric changes to be made that are prohibitively expensive to test while maintaining a consistent baseline of occupant and vehicle behavior for comparison. There have been many attempts to simulate rollover crashes using both rigid body and finite element methods too numerous to describe in this paper. In more recent years, there have been significant efforts to use computer modeling to understand the interaction of occupant kinematics and vehicle characteristics during rollover to assess injury potential. Reference [10] assessed dynamic roof crush as it interacted with a crash dummy through computer modeling while Reference [11] documented a process for simulating vehicle kinematics and occupant responses in three laboratory-based rollover tests. Occupant responses to the vehicle kinematics were described by a model of the 50th percentile male Hybrid III dummy as well as the Total Human Model for Safety (THUMS) finite element human model. The research examined the sensitivity of the dummy and human model to changing test, vehicle and restraint conditions and demonstrated that increased roof strength and enhanced seat belt systems may not completely eliminate the risk of neck injury in certain rollover crashes. Reference [12] published on an extensive parametric analysis of vehicle (roll, pitch and yaw angles, roll rate and drop height) and occupant factors (size and position) with respect to their ability to predict the vehicle and occupant responses. Using a combined finite element and rigid body model analysis, [12] showed that the drop height was a significant predictor of the vehicle roof crush and the occupant risk for injury.

The modeling studies to date have focused on specific rollover conditions and have not systematically studied the interactions of crash, vehicle, occupant and restraint parameters on the potential for injury that has been well documented in rollover crash data studies. This paper intends to address some of those concerns by subjecting a vehicle model, previously validated for roof strength performance, to determine sensitivity of occupant and vehicle response through an analysis of vehicle crash and structural parameters. A model of the previously described CRIS system will be used to validate occupant motion in a previously run CRIS test and determine how that model could be used for assessing vehicle crash and structural parameters as well as some occupant parameters on occupant response. Identifying the parameters most responsible for occupant response may be further used in simulation and testing to identify potential vehicle countermeasures to reduce the incidence and severity of occupant rollover injury.

II. METHODS

Vehicle Finite Element and CRIS Test Model

One of the purposes of this paper is to demonstrate the validation of a computer model of the proposed

Controlled Rollover Test System test. A series of CRIS tests were run by Exponent Failure Analysis Associates using the 1999 Ford Crown Victoria and a 50th percentile male, Hybrid III crash test dummy as the occupant [9]. The Hybrid III dummy was placed in the driver's seat, wearing the production three-point continuous-loop, sliding latch plate restraint system. The seat back was in an upright position at an angle of 29 degrees measured on the front surface of the seat back 10 inches above the seat cushion. The seat belt was placed on the dummy with proper routing and no slack in either the lap or shoulder belt. The CRIS is a machine that is designed to release a translating vehicle, rotating about its principal longitudinal axis, at a controlled orientation and from a desired drop height. A diagram of the CRIS, its primary components and initial test conditions are shown in Figure 1 as the vehicle is impacting the ground.

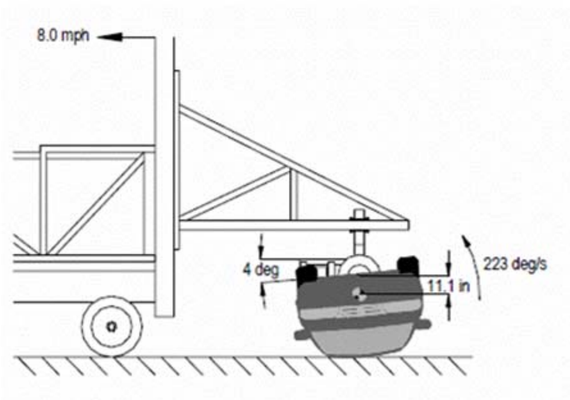

Fig. 1: Schematic of the Controlled Rollover Impact System (CRIS) and initial impact conditions for test 51502 [8-9]

Physical testing was conducted using a 1999 Ford Crown Victoria with a body-on-frame construction, but the numerical simulations were performed using a finite element model for a 2001 Ford Taurus. The reason for this is that the Taurus finite element model was the closest available FE model to the Crown Victoria. A 2001 Ford Taurus finite element model (FEM - version 4) developed by the National Crash Analysis Center (NCAC) at George Washington University was obtained directly from the NCAC [13]. The model contains 921,793 nodes and 973,351 elements describing 802 individual parts. The FEM model was developed in LS-DYNA version 970 and extensively validated for frontal and side crash conditions as well as FMVSS No. 216, the quasi-static roof crush regulation prescribed by NHTSA. Reference [14] documented the roof crush resistance of the Taurus model relative to the FMVSS 216 test. The good roof crush resistance force versus displacement correlation between the Ford Taurus test and model in the FMVSS No. 216 test was one of the determining factors in choosing this vehicle for the CRIS study.

For consistency, a comparison between roof crush resistance forces of the Ford Taurus and Crown Victoria when tested to the FMVSS No. 216 requirement was plotted and shown in Figure 2. The roof structure of the Ford Taurus is very representative of the roof structure of the vehicle involved in the rollover tests. This comparison shows relatively close agreement between the two vehicles (Figure 2). The Taurus simulation is initially stiffer than either vehicle test, however the final plateau force for all three results is quite similar at the 80 mm displacement level. Assuming that the Crown Victoria and the Taurus are manufactured using the same steel for the A-, B- and C-pillars, then the dynamic roof-crush behavior should be similar. Thus from a roof-crush-resistance aspect, the Taurus appears to be a good surrogate for the Crown Victoria.

The Crown Victoria impacted the ground at a 4 degree angle and the impact point was located just above the A pillar as shown in Figure 1. To capture the same vehicle to ground impact parameters in the computer simulation model as in the test, a series of simulations were run using the Ford Taurus FEM where inertial properties of the Taurus model were modified to match the Crown Victoria properties. The initial CRIS Taurus FEM vehicle orientation is shown in Figure 3.

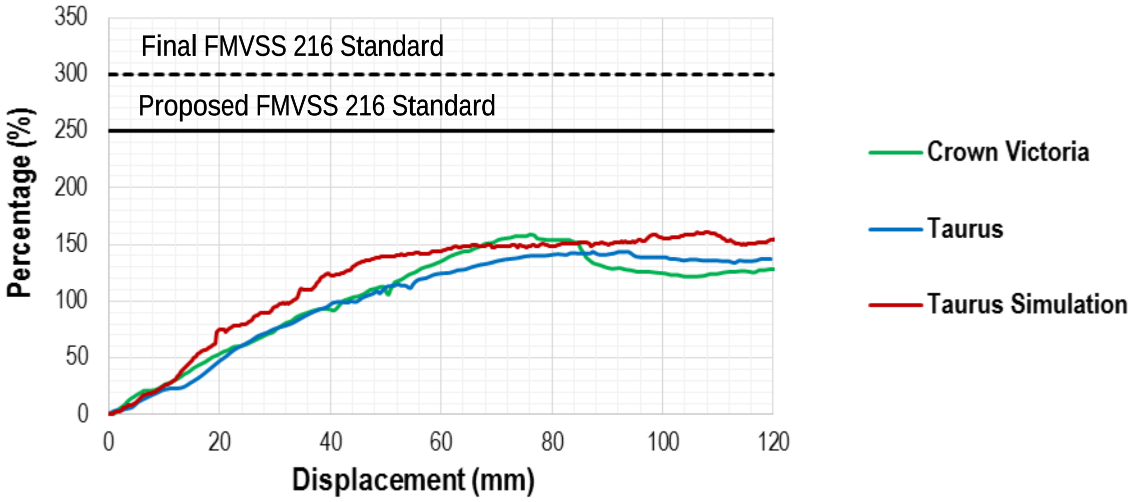

Fig. 2. Resistance Forces versus Roof Crush for Crown Victoria, Ford Taurus and Ford Taurus simulation compared to the proposed and enacted resistance force thresholds in FMVSS 216.

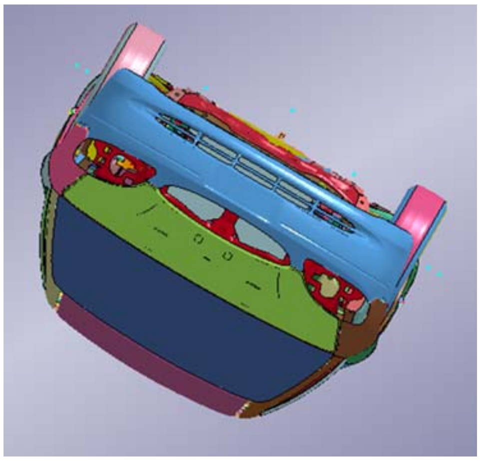

Fig. 3. Front View of 2001 Ford Taurus FEM Just Prior to Release from CRIS System

Parametric Analysis of the CRIS Model

Nine independent vehicle and crash parameters were incorporated into the model. The parameters are given in Table 1. Seven of these parameters were simple substitution of values (t1-t7) from the baseline parameter value. Pillar thickness variation was done for both pillars and roof rail thickness variations were done across both sides and the header (Figure 4) and done in increasing thickness only to approximate increased roof strength without adding significant mass to the vehicle. The material variation (showing increasing stiffness) is shown in Figure 5 and was taken from estimated material parameters adapted from [14]. The roof morphing and seat back angle variations required separate models (9 combinations) to account for possible interaction of roof to seat during simulations. The drop height, roll and pitch angles are varied around the parameters of the original CRIS test for the Crown Victoria. LS-OPT was used to control model parameter combinations. A total of over 90 variations were analyzed. The NCAC has recently developed a new detailed finite element model of the Hybrid III 50th percentile dummy used for frontal crash simulations. The model consists of 397,491 elements, 228,650 nodes and 365 material models. The computational time step is fixed at 0.5 µs. No variations to the dummy position (other than noted in t9) or the seat belt were performed. Dummy output parameters were taken as follows: Peak head CG resultant acceleration, Head Injury Criterion (HIC), upper neck axial force (Fz), upper neck bending moment (My), and Combined Neck Injury Criteria (Nij). Vehicle output parameters taken were as follows: peak intrusion of occupant compartment in three measurements. Two diagonals across first row occupant compartment indicate intrusion at driver or passenger sides. Vertical intrusion through vehicle centerline was also measured as well as vertical acceleration of vehicle CG. Analysis of variance (ANOVA) and

Global Sensitivity Analysis (GSA) was performed to assess the contribution of each input variable variation to the variance in occupant and vehicle response.

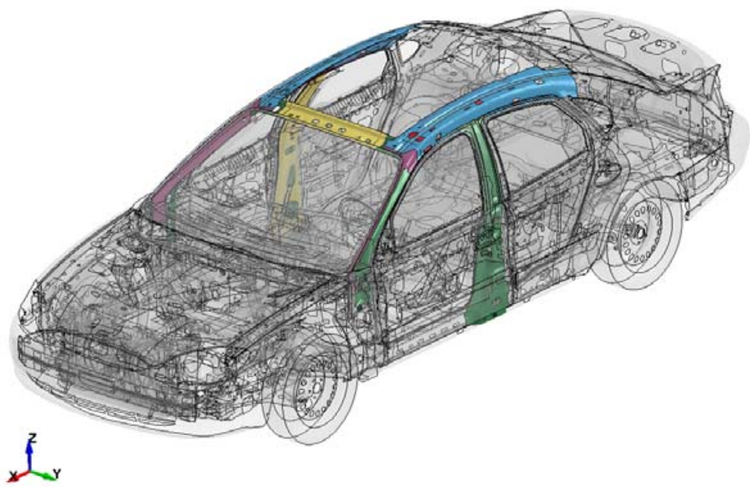

Fig. 4. Taurus Model Showing Locations of Pillar and Roof Rail Variations

TABLE I
VEHICLE AND TEST PARAMETERS USED IN SIMULATIONS

Parameter	Variations
A Pillar Thickness (t1)	Baseline, +25%, +50%
B-Pillar Thickness (t2)	Baseline, +25%, +50%
Roof Rail Thickness- Driver Side (t3)	Baseline, +25%, +50%
Material Change Parameter (t4)	Baseline, intermediate, boron steel (Figure 5)
Drop Height (t5)	11.1 in (28.2 cm), 13.1 in (33.3 cm), 15.1 in (38.4 cm)
Roll Angle (t6)	46 degrees, 49 degrees, 52 degrees (to horiz plane)
Pitch Angle (t7)	+3 degrees(forward), 0 degrees, -3 degrees (rearward)
Seat Position (t9)	29 degrees, 26.5 degrees, 24 degrees
Full Roof Morphing Parameter (t12)	No morph, +0.5 in (1.25cm), +1.0 in (2.54 cm)

III. RESULTS

CRIS Model Validation

The CRIS test series described in [9] had a limited set of data collected relative to the vehicle and the dummy thus the validation of the model has some limitations. Figure 6 shows the residual crushed profile (plastic deformation) from two different views. No external crush or internal intrusion measurements were taken in the test, however, several important observations may be noted. The driver side A-pillar is severely crushed both vertically and laterally in both test and model. Buckling of the roof as the B and C-pillars have collapsed is also noted in both and appears quite similar.

Dummy kinematics appear to be similar between model and test. Figure 7 shows dummy head orientation for both test (left) and model (right) as the dummy is interacting with the roof during the initial crush phase of the test. Dummy responses from the CRIS test were confined to head accelerations and neck forces and moments. The neck force and moment results are shown in Figure 8. The peak neck axial forces were around 11kN for the test and about 12.5kN for the simulation, however the timing of peak neck loads are quite similar. For both CRIS test and the model, the peak neck bending moment (My) approaches 80 N-m (uncorrected My), at similar times in the event. The corrected moment for the occipital condyle in the test is about 20 percent less.

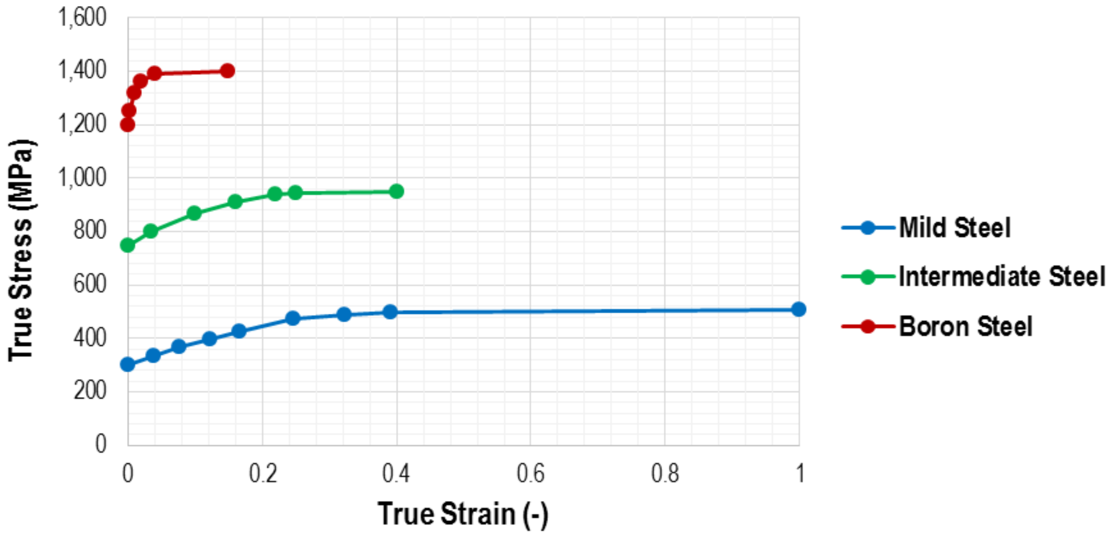

Fig. 5. Steel Stress-Strain Variants Used in Taurus A, B, Roof Rail Model

Fig. 6. Qualitative crush comparison of production Crown Victoria (top) from test 51502 and modified Taurus model (bottom) subjected to same input conditions adjusted for same touchdown location.

Parameter Analysis Results

As the simulations were carried out, it became clear that the vehicle and occupant responses were highly non-linear as parameters were varied. This makes the use of a linear analysis of variance (ANOVA) a less reliable analysis tool. Hence, all parametric variance results will be reported for the Global Sensitivity Analysis since GSA allows for non-linearity in the responses. The parameters were varied using design of experiments approach and D-Optimal point selection. It assures good coverage of multidimensional space of parameters and minimizes errors of fitting surfaces into the responses. For brevity, a vehicle response and an occupant response analysis will be shown followed by an overall parameter analysis summary. Figure 9 shows a GSA output graph for the driver side roof crush response as the parameters were varied. Referring back to Table 1, the t7 parameter, vehicle pitch angle, accounted for almost half of the roof crush response followed by roof

Fig. 7. Qualitative comparison of dummy head orientation just after touchdown for production Crown Victoria (left) from test 51502 and modified Taurus model (right) subjected to same input conditions adjusted for same touchdown location.

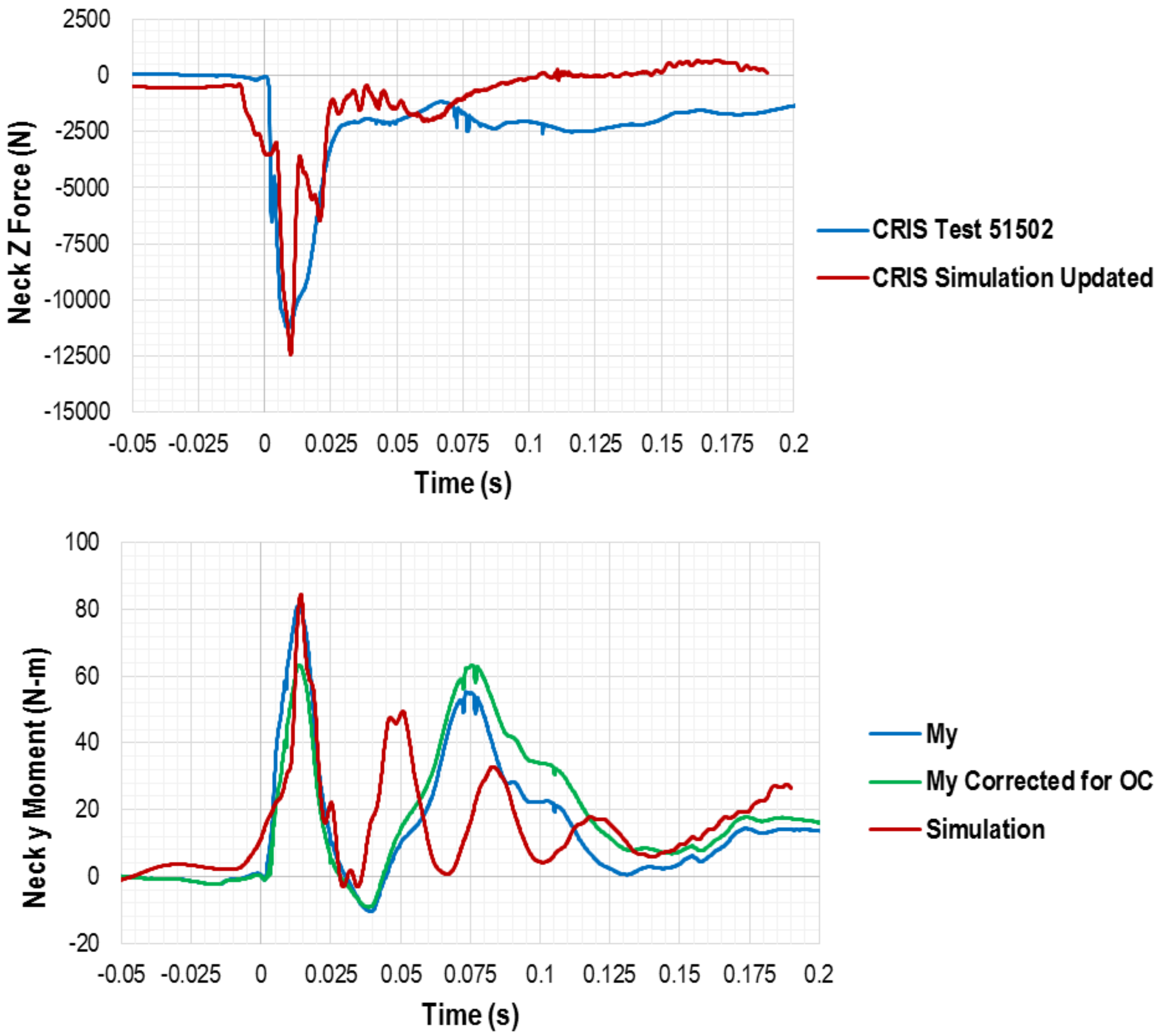

Fig. 8. Comparison of FEM dummy model neck force (top) and moment results (bottom) to CRIS test.

stiffness (modified by changing material parameters) and roll angle. Pitch angle is the fore-aft angle the vehicle longitudinal axis makes with the ground.

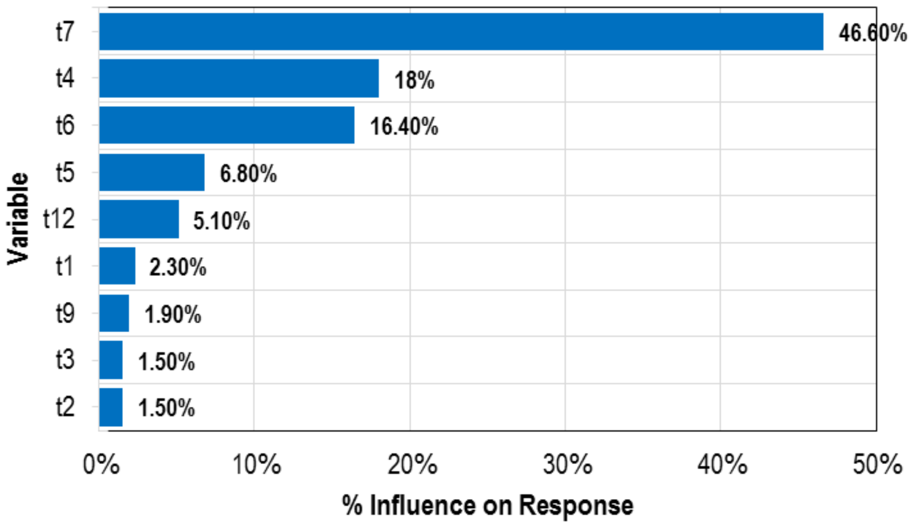

Fig. 9. Global sensitivity Analysis (GSA) plot of parameter contribution to the driver side roof crush response.

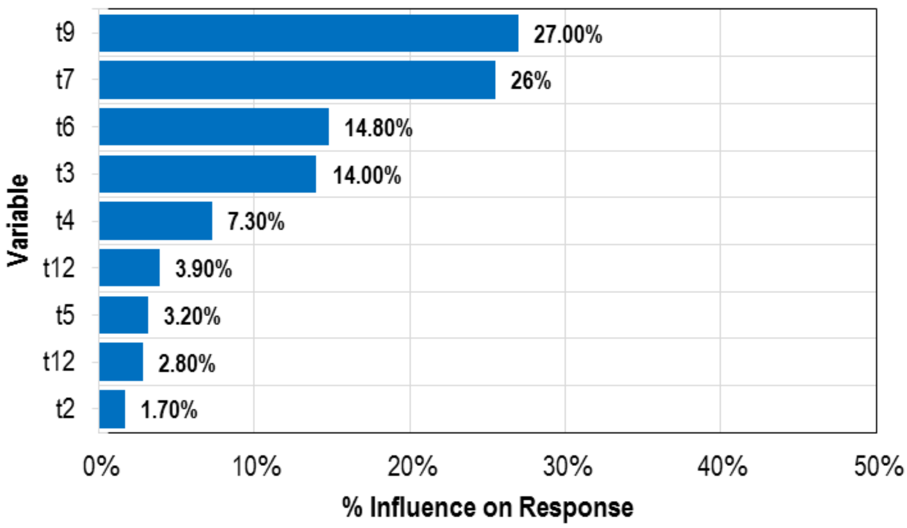

Figure 10. GSA plot of parameter contribution to the dummy axial neck force response.

Seat position accounts for 27% of the neck response, pitch angle accounts for 26% while, roll angle roof rail thickness and drop height account for the majority of the remaining response. A similar chart is observed for the neck moment results also. Figure 11 shows the entire parameter variation and GSA results as a cumulative plot and the composition of influence each parameter has on a given vehicle or dummy response. The longer the bar for the variable (lower plot), the greater influence it has on the response. It can be seen that vehicle pitch angle (t7), vehicle roll angle (t6), seat position (t9) and drop height (t5) have significant influences on the responses. Overall, pitch angle accounts for about one-fourth of the overall vehicle and occupant responses, followed again by roll angle and seat position. Drop height had its largest influence on the centerline roof crush response. Pillar thicknesses (t1 and t2) each accounted for less than 5% of the total response. Material stiffness variations accounted for about 8 % of the total response. The morphing variable (t12) had its largest effect on the passenger side roof crush but hardly any effect on the driver side roof crush.

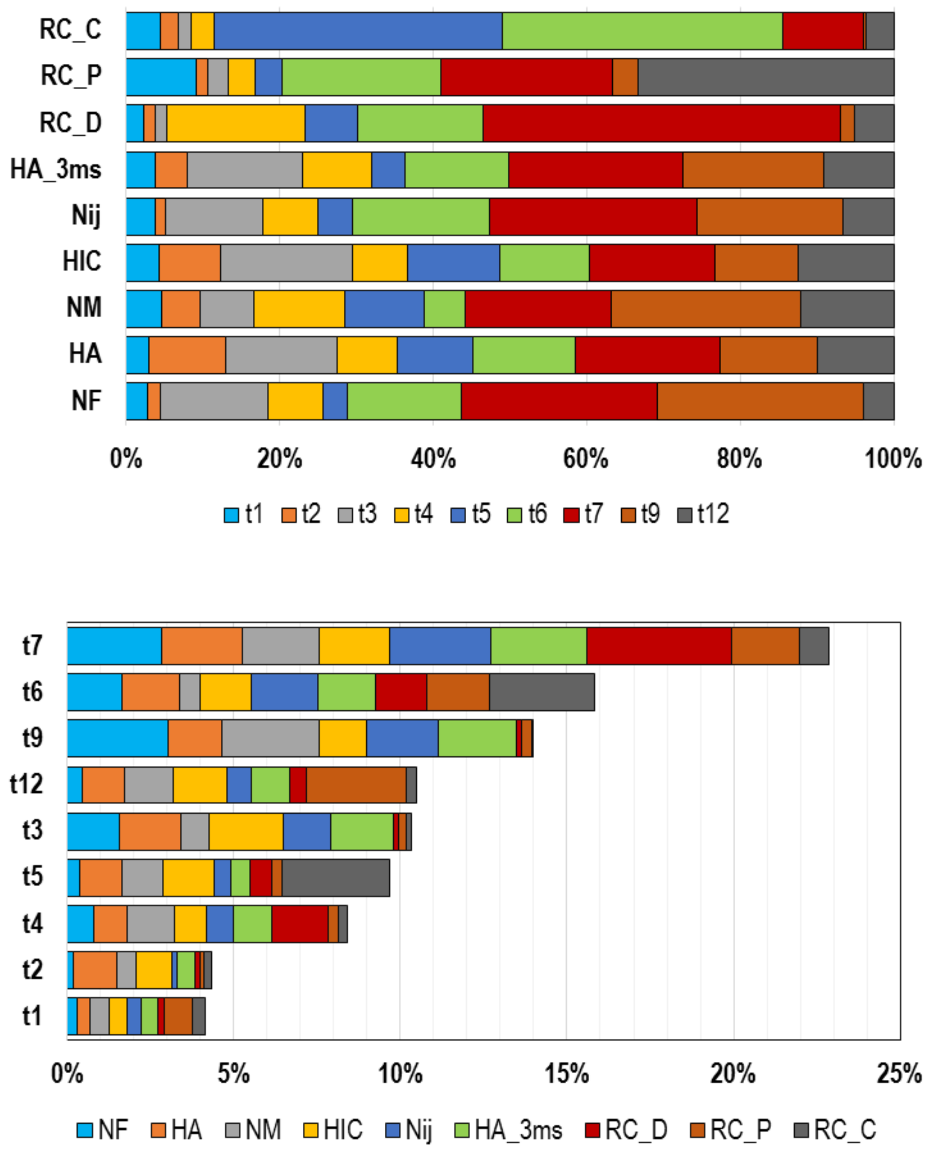

Fig. 11. Cumulative GSA plots of parameter contribution to all dummy and vehicle responses. (NF = neck axial force, HA = peak head acceleration, NM = upper neck bending moment, HIC= Head Injury Criterion, Nij = Neck injury criteria, HA_3ms = 3ms clip for peak head acceleration, RC_D = roof crush driver side, RC_P = roof crush passenger side, RC_C = roof crush center of vehicle)

IV. DISCUSSION

Efficacy of chosen models

This study takes an important step towards understanding how vehicle and crash parameters may influence the vehicle and occupant response in a simulation of a controlled rollover crash test condition. The repeatable and controllable CRIS test system [8] is an ideal system to model since one can accurately prescribe initial conditions that produce consistent results while allowing for parameter variation that can provide insight into what parameters are most influential. In this study, a FEM vehicle model was shown to be valid for overall crush response and occupant injury measures. In the vehicle response evaluation section it was shown that the roof deformation patterns between the FEM and the CRIS test are very similar. The good correlation between the test and FEM simulation of the overall roof deformation patterns, the occupant's head impact points with the roof and the similar peak neck axial force and moment indicate the confidence to use finite element models selected to simulate the CRIS test event and its variations in this study. Finally, most rollover simulation studies [11-13] have used a model of a sports utility vehicle in their analysis while this study chose to use a mid-sized passenger sedan to add further challenge and to define responses in a different vehicle class.

Explanation of parameters chosen and their effects

The variations of model and crash conditions were selected based on previous research and parameters that have been hypothesized to be important in vehicle and occupant responses. The A-Pillar, B-Pillar and Roof Rail thicknesses (parameters t1, t2 and t3) were intended to add stiffness to the roof structure without changing material characteristics. The material change variable, t4, added increasingly stronger steel characteristics to the model without changing gauge thickness of the steel. When the boron steel characteristics were added to the model, the overall strength-to-weight ratio (SWR) of the model increased to nearly 3.0. This result is compliant with current FMVSS 216 standard threshold. Increased roof strength has been shown to reduce overall crush and intrusion. For this study, the structural changes had less effect than the crash parameters on the occupant and vehicle responses. The material change (stiffness) accounted for about 8 percent of the response and the roof rail thickness scale factor (t3) contributed to about 10% of the variations in responses. Pillar thickness scale factors (t1, t2), had little effect on the occupant responses while having some effect on the vehicle vertical crush response. Reference [15] described rollover injuries in belted, unejected occupants relative to roof intrusion from single vehicle rollover crashes in the National Automotive Sampling System- Crashworthiness Data System (NASS-CDS) database. The analysis indicated that the maximum severity of head, neck (cervical spine and/or spinal cord) and face injury was significantly related to the amount of roof intrusion into the occupant compartment and the remaining post-crash headroom in the vehicle. Stronger/stiffer roofs may limit intrusion during rollover thus mitigating occupant contact. The proximity of the dummy's head to the roof and the CRIS test method may limit the effect a stronger roof may have since space is limited in this particular vehicle model.

Drop height, pitch angle and roll angle were chosen based on previous work by [13]. That study ran over 1300 simulations of a combined rigid body dummy/FEM vehicle simulation of a rollover event varying these and other variables. It found that the drop height was the most significant predictor of the vehicle roof crush and the occupant risk for injury. It had prescribed an initial occupant vertical velocity as a surrogate for drop height, thus ensuring that vertical velocity was increased linearly. The current study did not find drop height as significant a predictor of occupant response. Drop height was a direct input variable in the initial set-up of the current study and the variation (from 11-15 inches or 28-38 cm) was chosen to maximize effect. The lack of strong effect may be due to vehicle variations between studies (sport utility versus passenger vehicle). In this study, parameters are physically changing (compared to a forced parameter in [13]). Changing the pitch angle in the current study has the effect of raising the CG as well as changing the roll angle. The changing roll angle effect likely changes the impact location of the roof to the ground increasing the likelihood of occupant head to roof (or other structure) contact.

The effect of changing seat position (t9) and roof morphing (t12) analysis produced interesting results, albeit based on somewhat unrealistic conditions. The morphing features in modern FEM pre-processors allow for small changes in element sizes without pre-stressing elements or requiring extensive model adjustments. Added length to elements in the roof to make it taller was thought to increase headroom (roof-to-head distance). Changing seat position angle was thought to create a similar increase in headroom. The contribution of these two parameters to the vehicle and occupant response was 14% and 10% respectively. It was found that the roof often "bottomed" out on the top of the driver's headrest (seat was made very stiff) thus this could have negated any effects. Also, the initial roof strength of the Taurus model had a 1.5 SWR (compliant with previous version of FMVSS 216) and the severity of the test overwhelmed the effect of the variables. Stronger roofs are already being seen in more recent vehicle roof strength tests reported by NHTSA and the Insurance Institute for Highway Safety (IIHS) where SWRs over 4 and sometimes 5 have been consistently reported.

Limitations

The use of the Hybrid III 50th percentile male crash test dummy model may have masked some effects of the parameters chosen. The axial stiffness of the Hybrid III neck is much higher than for humans and could have provided an unrealistic injury risk. The 12kN loads observed in the model validation study are nearly three times the threshold risk for a severe neck injury. Others have used human models in their rollover simulations and reported differences in injury potential relative to dummies [11]. Also, the CRIS test method, while repeatable, may be less sensitive to parameter variation as the dummy is not allowed to rotate or translate until the vehicle is released. Alternatively, the range in the variation for some parameters may not have been great enough to demonstrate significant effects.

V. CONCLUSIONS

This study has provided important results to understand rollover crash and injury response better. Crash data analysis provides the perspective of where injuries are occurring, but cannot derive causal relationships between vehicle parameter/responses and occupant injury. Simulation studies and analysis techniques have improved significantly to allow for assessing potentially important crash and vehicle characteristics that may get a step closer to causal relationships.

The main conclusions of this study are:

1) A vehicle finite element model, representing a passenger car in a repeatable, rollover crash test conditions may provide insight into how vehicle and crash parameters affect response. Proper validation of the model provides confidence that the model has merit and that parameter variations give meaningful results.

2) A variance-based global sensitivity analysis was an effective tool to determine the contribution of vehicle and crash parameters on the vehicle and occupant responses. Reducing the opportunity for the occupant to strike his/her head on the vehicle's interior components could reduce the risk of neck injury that has been identified as the most common injury sustained by belted, unejected occupants in pure rollover crashes.

3) The variables that contribute the most to the occupant and vehicle structural response (pitch angle, roll angle, and drop height) have the effect of determining where and with what force the vehicle roof impacts the ground. This information could help in identifying vulnerable areas in vehicle structures and designing countermeasures for vehicles that can mitigate intrusion and occupant contact to the roof.

4) The assessment of occupant factors and vehicle restraint factors was not performed in this study. Restraint assessment such as seatbelt pretensioners or other novel seat belt configurations as well as occupant variation (size, position, stiffness) may play as important a role in understanding injury causation and mitigation.

VI. ACKNOWLEDGEMENT

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