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ABSTRACT

In this study, U.S. accident data was analyzed to determine interior contacts and injuries for front-seated occupants in rollovers. The injury distribution for belted and unbelted, non-ejected drivers and right front passengers (RFP) was assessed for single-event accidents where the leading side of the vehicle rollover was either on the driver or passenger door. Drivers in a roll-left and RFP in roll-right rollovers were defined as near-side occupants, while drivers in roll-right and RFP in roll-left rollovers were defined as far-side occupants.

Serious injuries (AIS 3+) were most common to the head and thorax for both the near and far-side occupants. However, serious spinal injuries were more frequent for the far-side occupants, where the source was most often coded as roof, windshield and interior. Based on the injury sources for both situations, head injuries seem to occur from contact with the roof, windshield (in particular for unbelted occupants) and pillars, while thoracic injuries resulted from contact with steering assembly and the interior.

The field injury data was compared with the Hybrid III responses obtained from simulated mathematical rollovers to better understand occupant kinematics and injury biomechanics. These simulations were validated using laboratory tests. The laboratory tests included the FMVSS 208 dolly rollover, the ADAC corkscrew, curb and soil-trips, bounce-overs and fall-overs.

Based on the mathematical simulations, the kinematics of the front far-side occupant differed from that of the near-side. For the belted far-side occupant, the torso often slipped out of the belt which allows excursion towards the near-side occupant. For the belted near-side occupant, the shoulder belt remained on the upper body during the initial roll phase. The occupant nonetheless moved up and outwards and the head could contact the roof-rail and header areas depending on the rollover condition simulated. The near-side occupant's head crossed the window plane more frequently than the head of the far-side occupant. Dummy kinematics from the simulation help explain the frequency of serious head and thorax injuries reported in the field. Field data analysis and mathematical simulations are useful in understanding injury biomechanics and providing guidance for future testing.

INTRODUCTION

Rollover accidents are a significant safety issue. NHTSA (2000) reported that, for years 1992 to 1998, there was an average of about 227,000 rollover crashes per year. These rollovers resulted in 9,063 fatalities per year and over 200,000 non-fatal injuries per year. With respect to fatalities per registered vehicle, rollovers were found to be second to frontal crashes in their level of severity. As countermeasures are developed and as the vehicle crashworthiness is improved for frontal impacts, the number of fatalities in frontal accidents will be reduced. Rollovers are thus likely to become even more significant.

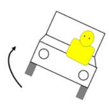
Various tests have been developed to evaluate the kinematics of occupants in a simulated rollover environment. These tests include the FMVSS 208 dolly tests (Orlowski *et al*, 1985), the ADAC corkscrew, curb and soil-trip tests (Thomas *et al*, 1989; Cooperider *et al*, 1998), and fall-overs (Deley, 1987; Bardini *et al*, 1999). Mathematical models were developed and validated using the results of the test data.

The objective of this study was to compare the kinematics and injury responses of far-side and near-side front occupants in rollovers. The frequency of serious injuries and their injury sources were assessed using accident data and correlated with the dummy kinematics from laboratory tests and mathematical models. This information provides inputs for the development and assessment of mathematical models of occupant kinematics in rollovers.

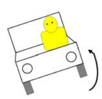
METHODS

DATA: The data was obtained from the National Automotive Sampling System/ Crashworthiness Data System (NASS-CDS). NASS-CDS consists of police reported tow-away traffic crashes in the US. This database is a representative sample of about 5,000 crashes per year. Statistical sampling weights are provided, so that results can be extrapolated to represent US crash experience. The data includes detailed information from the NASS investigation teams. For this study, the data consists of rollover accidents that occurred in the years 1992 through 1998.

ROLL DIRECTION: In a trip-over accident, the vehicle can either roll right or left along its longitudinal axis.



Roll left represents a roll with the driver side leading. From a driver's perspective, the vehicle is rolling counter-clockwise.



Roll right occurs when the right front passenger side is leading during the roll. From a driver's perspective, the vehicle is rolling clockwise.
Cases with unknown roll direction were removed from the analysis.

OCCUPANTS: In this analysis, the occupants were divided into far-side and near-side adult front passengers.

- Far-side – Far-side occupants were defined as persons older than 12 years old and consisted of drivers in a roll-right vehicle and right front passenger in a roll-left vehicle. In the 92-98 database, there were a total of 801,719 far-side occupants.
- Near-side – Near-side occupants were defined as persons older than 12 years old and consisted of drivers in a roll-left vehicle and right front passenger in a roll-right vehicle. In the 92-98 database, there were 876,521 near-side occupants.

EJECTION: Ejection can either be complete, partial or unknown. Partial ejection also includes ejection with unknown degree. Cases with unknown ejection were removed from the analysis.

INJURIES: The injuries were classified using the NASS-93 system. In this study, an Injury Severity Score (ISS) was calculated for each injured driver. ISS was chosen since it was shown to correlate well with mortality. The ISS was grouped as "> ISS 12".

INJURY SEVERITY: Serious injuries included injuries with an AIS ≥ 3

OCCUPANT KINEMATICS

All tests were conducted with belted dummies in the driver and right front passenger seating positions. The kinematics of the occupants were obtained from the film analysis of onboard cameras placed inside the occupant compartment or outside on the hood. However, due to limited camera coverage any 'out-of-view' data was complemented by occupant kinematics obtained from validated mathematical models using MADYMO. The models were also used to confirm the occupant kinematics for various perspectives and to compare belted and unbelted occupant responses.

MODELING

PC-Crash is commonly used to reconstruct real-world accidents. In this study, PC-Crash software was initially used to correlate mathematical models with test conditions (Fig. 1). MADYMO was then used to model the detailed suspension of the vehicles. The vehicle kinematics obtained in MADYMO were then correlated with the test data (Fig. 2). The occupant kinematics were correlated with test prescribed motion model. In general, a good correlation was found (Fig. 3).

Once the belted models were correlated to the test, seatbelt components were removed for both occupants and subjected to same rollover conditions. The results from these two sets were used for occupant kinematic comparison for belted and unbelted situations.

Roll Angle Comparison for Test and Simulation (deg/s)

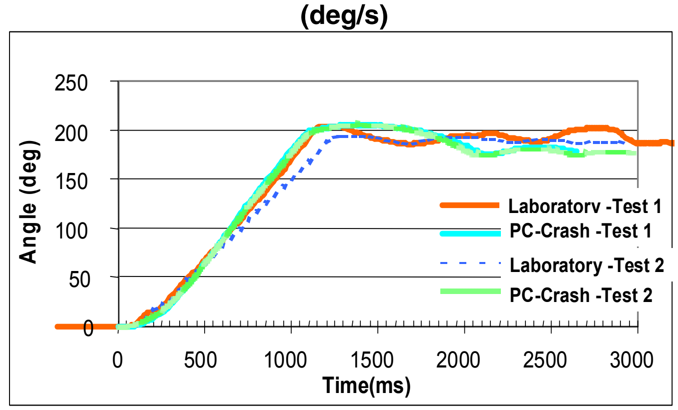


Figure 1. ADAC Corkscrew Vehicle Roll Angle Obtained from Laboratory Tests and PC-Crash Simulation.

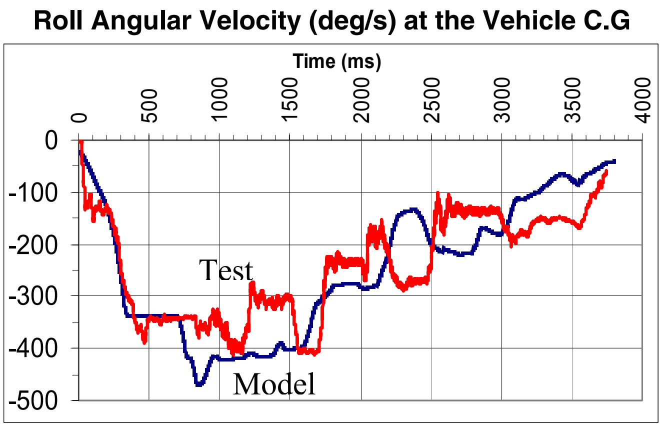


Figure 2. FMVSS 208 Vehicle Roll Rate (deg/s) Obtained from Laboratory Tests and MADYMO Simulation.

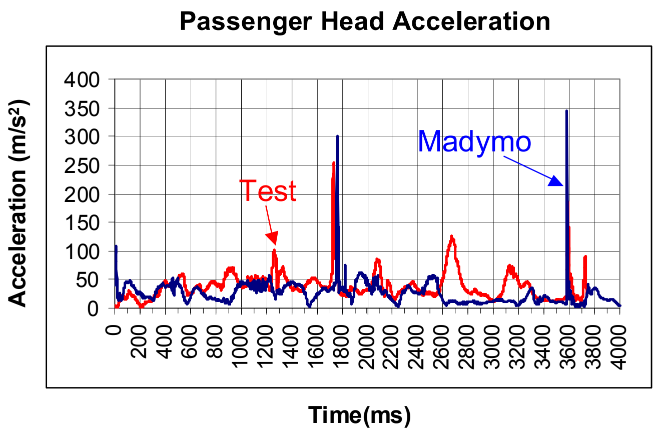


Figure 3. FMVSS 208 Occupant Head Acceleration Obtained from Laboratory Tests and MADYMO Simulation.

NORMALIZING FIELD DATA

To compare the field injury results between different categories, the data was normalized:

- Occurrence: Occurrence is the number of occupants (or injuries) in a particular category divided by the total number of exposed occupants (or injuries).
- Rate: Rate is the ratio between the number of seriously injured occupants and the total number of exposed occupants.
- Risk: Risk is the number of serious injuries divided by the number of occupants.

RESULTS

ACCIDENT DATA: Occupant injuries in a rollover depend on the seating location of the occupant and the vehicle roll direction. The kinematics of near and far-side occupants may differ depending on the roll direction. To investigate the effect of roll direction, the front adult occupants were divided into near-side and far-side. The distribution between near and far-side occupants was similar, at 100,215 per year and 109,565 per year respectively (Table 1). Of these, 71.4% and 70.3% were belted respectively. For the belted group, the ratio of ejected per non-ejected was 1.9 per 100 for the far-side occupants and 2.2 per 100 for the near-side. For the unbelted group, the ratio was higher for far-side than near-side occupants at 34.0 per 100 and 30.1 per 100 respectively ($p<0.05$).

Table 1. Incidence per Year of Far-side and Near-side Occupants by Belt Usage and Ejection Status

	Far-Side		Near-Side	
Ejection	**Belted**	**Unbelted**	**Belted**	**Unbelted**
None	69,703	20,991	75,154	24,687
Complete	1,311	7,137	1,639	7,419
Unknown	587	486	194	472

Figure 4 shows the occurrence of all and seriously injured (ISS > 12) near and far-side adult front passengers by rollover types. The rate for an occupant to be seriously injured is also given. Occupants (all and seriously injured) were most frequently involved in a trip-over, at a similar occurrence of 60% for both far-side and near-side occupants. Fall-overs resulted in an occurrence of 14.6% for far-side and 11.1% for near-side occupants. The rate to be seriously injured was higher for far-side occupants (4.9 per 100 exposed) than near-side occupants (4.0 per 100). For far-side occupants, the rate was highest for climb-over events and collision with other vehicles, while it was greatest for bounce-over events for near-side occupants.

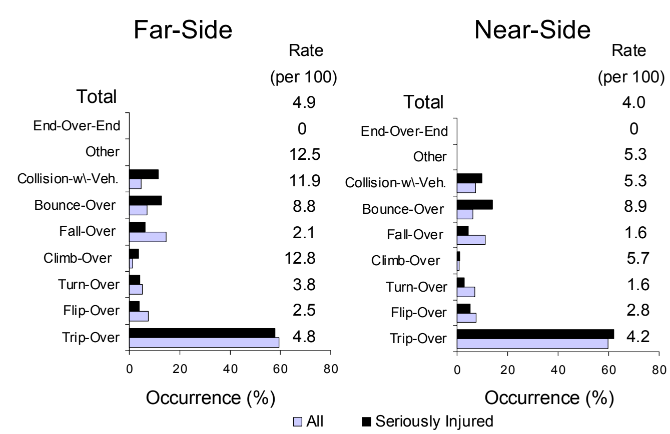


Figure 4. Distribution of All (ISS 0-75) and Seriously Injured (ISS > 12) Far-side and Near-side Occupants by Roll Type

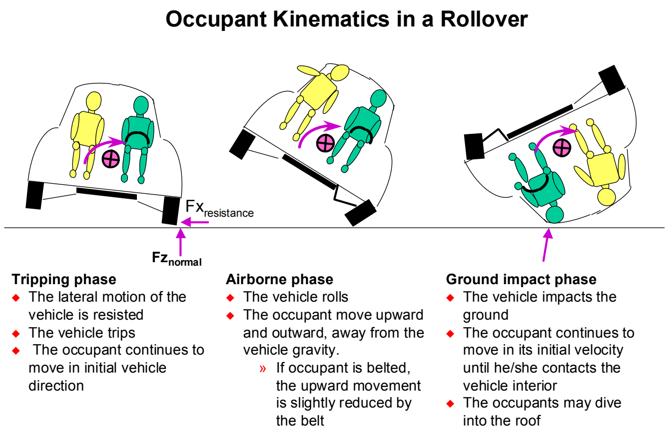


Figure 5. Schematics of Occupant Kinematics in a Rollover

During the initial roll, the occupant kinematics varies based on the sitting location and the vehicle roll direction. Figure 5 depicts the various kinematics for the near-side and far-side occupants in a rollover about the longitudinal axis of a vehicle. The far-sided occupant has more energy than the near-sided occupant due to a larger radius.

Figure 6 shows the distribution of belted/unbelted near-side and far-side occupants when ejected and non-ejected. For ejected occupants, serious injuries were most frequent to the head and thorax, while they were most common in the head, thorax, spine and in the extremities for non-ejected occupants.

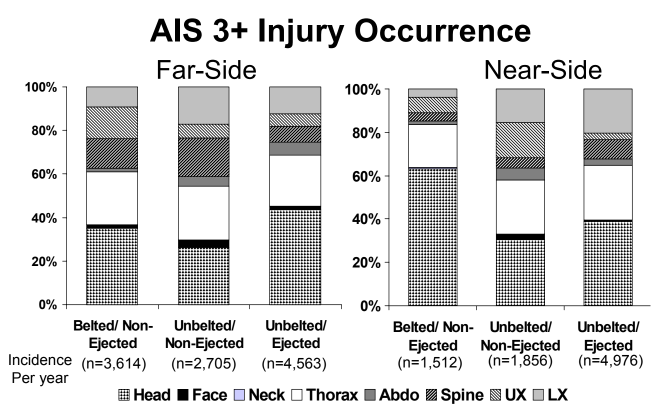


Figure 6. Distribution of AIS3+ Injuries Far-side and Near-side Occupants by Ejection Status and Belt Usage

The risk for serious injuries was assessed for non-ejected near and far-side occupants. The results are shown in Table 2. For belted and unbelted non-ejected drivers, the risk for all serious injuries was higher for far-than near-sided occupants (Z= 17.4 for belted and Z=17.1 for unbelted, $p < 0.01$). Furthermore, the risk of serious injuries was higher for unbelted occupants than belted drivers (Z= 29.3 for far and Z=21.9 for near-sided, $p < 0.01$). The risk for serious head injuries is higher for far than near-sided drivers (Z=3.0 for belted and 3.4 for unbelted, $p < 0.05$).

Table 2. Risk of AIS3+ Injuries for Non-Ejected Far-side and Near-side Occupants by Belt Usage

	Risk of AIS 3+ Injuries per 1000 Exposed Occupants	
	Belted/Non Ejected	
	Far (n= 69,703 per Year)	Near (n= 75,154 per Year)
Head	18.2	12.7
Thorax	12.5	4.0
Neck/ Spine	7.2	0.9
All	51.8	20.1
	Unbelted/Non Ejected	
	Far (n= 20,991 per Year)	Near (n= 24,687 per Year)
Head	33.9	22.8
Thorax	32.0	18.8
Neck/ Spine	23.0	3.6
All	128.9	75.2

Table 3. Frequency of Serious Injury Sources for Non-Ejected Far-side and Near-side Occupants by Belt Usage

Injury Sources for Non-Ejected Adult Occupants				
	Far-side		Near-side	
	Belted	Unbelted	Belted	Unbelted
AIS 3+ Head				
Roof	90%	35.5%	85.8%	57.3%
Windshield		38.6%	4.6%	14.0%
Pillars	6.7%	11.7%	4.8%	26.1%
Window		4.2%		
Other	3.3%	10.0%	4.8%	
AIS 3+ Thorax				
Steering	6.8%	62.0%	15.1%	74.0%
Interior	84.2%	22.0%	67.0%	21.2%
Panel		9.4%		
Belt	2.4%		8.6%	
Other	3.2%	3.5%	9.4%	4.9%
AIS 3+ Spine				
Roof	76.7%	47.7%		
Windshield		26.2%		
Interior	12.6%	12.2%		
Window		10.8%		
Other	13.7%	3.2%		

The frequency of injury sources for non-ejected near-side and far-side occupants have been tabulated for serious head, thorax ad spinal injuries (Table 2). For the belted occupant, more than 85% of the sources for head injuries were coded as roof. The remaining sources consisted of pillars and windshield. For the unbelted occupant, roof/pillar contacts were also frequent as well as windshield and window contacts. For thoracic injuries, the frequency of contact with the steering assembly was more frequent for the unbelted occupant than the belted. For the belted, interior contact was more significant. Sources for serious spinal injuries were only available for far-side occupants. These sources included the roof (in particular for belted drivers), windshield, interior and window.

MATHEMATCAL SIMULATION DATA: The kinematics of the front occupants were assessed using validated models of various roll direction. In the laboratory rollover conditions, the predominant vehicle motion was roll around the longitudinal axis (due to lateral velocity input). However, in real-world cases, rollovers are three dimensional (3-D) with vehicle forward velocity contributing to kinematics as well. This phenomenon may alter the occupant kinematics in the field as compared to the 'ideal' laboratory conditions. ADAC corkscrew, bounce and pitch-over were rollover conditions where the 2-D kinematics are more field relevant.

For simplicity, occupant kinematics can be split into three general phases. First is the lateral contact phase, second roll initiation and air-born or rigid-body motion phase, and the last, multiple ground contact phase. Each of these phases plays a significant role with different rollover characteristics. For example, the first two phases are influenced by tire, wheel and suspension characteristics for the vehicle and occupant initial position (or 'out-of-position' due to pre-roll motion). Understanding these two phases is important to predict an impending rollover and for rollover-sensor development. The third phase may be important from the standpoint of vehicle structural deformation, ejection and occupant to exterior and interior contact loads.

Occupant head acceleration data correlated to the test results. The present model does not necessarily capture all the structural deformation, but is sufficiently accurate for parametric studies. The next few sections describe the head trajectory for belted and unbelted occupant kinematics. Note that from figure 3, in general, resultant occupant head accelerations are less than typical frontal impact and as such corresponding HIC values tend to be less as well.

In both test and simulations, standard frontal 50^{th} percentile Hybrid III ATD is used. One main consideration for this is due to upper and lower limb biofidelity as well as appropriate distribution of mass and moment of inertia in comparison to other devices.

Phase 1 and 2: An example of belted driver head trajectory in a lateral curb trip is shown in figure 7. The roll is such that the driver's side is leading. Lateral displacement refers to head target clearance from the driver side window. Due to initial tripping phase, the suspension is loaded and the vehicle body and the belted occupant continued to move reaching point B. After this stage, the vehicle body starts to rotate and displacement increases between head and window until point C.

At point C, the dummy inertia is overcome and it starts to rotate about the vehicle center of gravity (CG), taking an active part in the rollover. Point D represents the building up of Coriolis force on the occupant, at approximately 350 ms. Head vertical displacement is in the order of 80-100 mm at this stage and if the occupant is 'out-of-position,' there may be a likelihood of head to interior contact in the region of upper B-pillar or side rails. This points to possible contact injuries seen in the field data. Once airborne, occupant and vehicle tend to move in tandem with slight delay. This is shown by increased displacement from D back to E.

Belted Driver Head Trajectory Phase-1 & 2

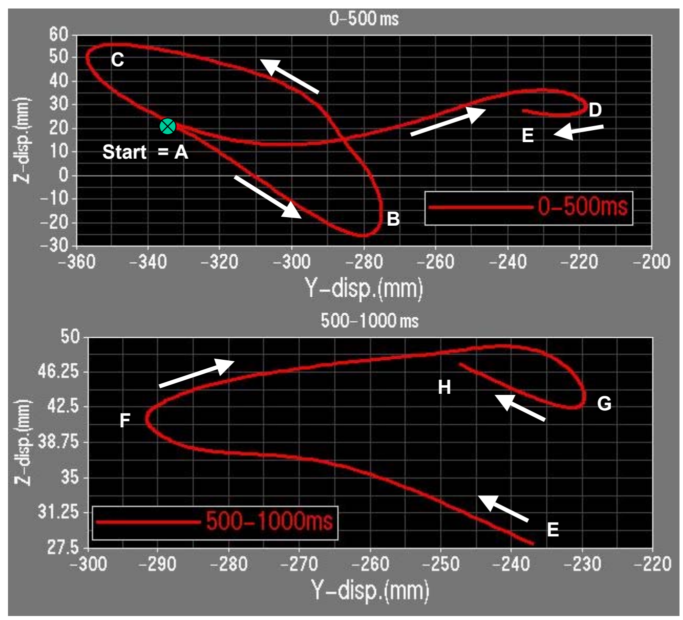
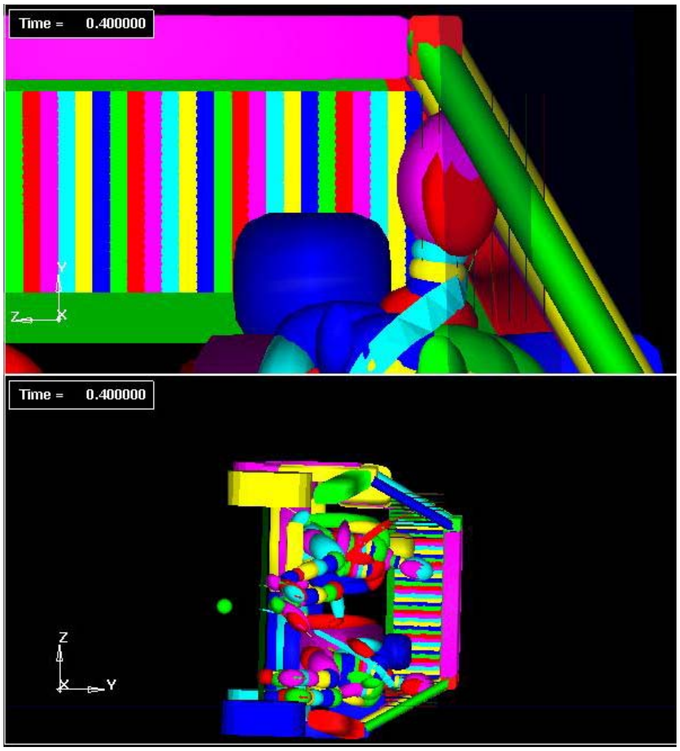


Figure 7. Head trajectory for Belted Drivers in a Lateral Curb Trip Test 0-1000ms.

Head trajectory for the Phase 2 is also shown in figure 7. The trajectory follows points E through H. At the end of Phase-2, the rigid body rollover is completed, as the vehicle lands on its leading edge wheels and the occupant experiences deceleration. In turn, the ATD develops relative velocity both with respect to the moving vehicle frame as well as exterior ground surface. This combined vehicle occupant kinematics may lead to further contact forces and thus potential head and torso injuries. This is accompanied by the start of potential partial ejection for belted and unbelted. For example, the FMVSS-208 Madymo model depicts the velocities between the driver head and the side window/B-pillar. These velocities were up to 4 km/h for belted and up-to 12 km/h for unbelted occupants.

Vehicle & Belted Driver Head



Kinematics at T=400 ms

Figure 8. Belted driver head trajectory in a 48 km/h FMVSS-208 Madymo simulation at 400 ms.

Phase-3: In the last phase beyond first quarter turn, the vehicle may undergo structural deformation and the occupant may be either partially or completely ejected due to centrifugal forces via glass openings. It is also seen that the vehicle momentarily becomes stationary in contact with the ground and the occupant continues to move building relative velocities that are higher than in the airborne phase. This may lead to multiple contacts of head, torso and limbs mainly with the upper A-pillar, roof rail, side-rail and B-pillar roof-rail joint for the driver. Note: Detailed head trajectories are shown in the appendix.

DISCUSSION

In this study, the distribution of front occupants involved in a rollover was assessed by roll direction, belt usage and ejection status using NASS-CDS data for years 1992 to 1998. Near-side occupants were defined as drivers in a roll-left and right front passenger (RFP) in a roll-right rollover accident, while drivers in a roll-right and RFP in a roll-left rollovers were defined as far-side occupants.

For both belted and unbelted occupants, the risk to be seriously injured was higher for far than near-side occupant data. For the far-side occupants, the risk was highest for climb-over events and collision with other vehicles, while it was greatest for bounce-over events for near-side occupants.
For unbelted occupants, the ratio of ejected occupants per non-ejected was higher for far-side than near-side occupants. For both near and far-side ejected occupants, serious injuries were most common in the head and thorax.

In the non-ejected group, the risk to be seriously injured was higher when the occupants were unbelted. The risk was also higher when the occupants were far-sided than near-sided. When belted and non-ejected, the risk to sustain an AIS 3+ spinal, head and thoracic injury was higher for far than near-side occupants ($Z=3.37$ for spine; $Z=9.91$ for head and $Z=4.63$ for thorax, $p < 0.05$). For far-side/non-ejected occupants, the ratio of AIS 3+ injury risk was about 3 times higher for spinal and thoracic injuries when the occupant was unbelted than when belted. These results support the benefit of belt usage in a rollover accident.

In this study, various mathematical tools were used to evaluate vehicle and occupant kinematics. PC-Crash was used to simulate the laboratory tests. PC-Crash was found sufficient for A to B comparison. For more detailed analysis, MADYMO was used. MADYMO uses the multi-body lumped mass parameters approach. With MADYMO, a better hysteresis model was obtained for loading and unloading. In the future, it may be necessary to use Finite Element Analysis (FEA) to better understand the dynamic response of the vehicle. A FEA model will improve the simulation of suspension and tire models for impulse loading.

Occupant motion is very complex. A good correlation was obtained between the MADYMO model and the laboratory tests until the vehicle first contacts the ground. Taking the prescribed vehicle motion from the laboratory tests increased the correlation to the complete event. Occupant kinematics, such head-to-vehicle displacement and velocity, are useful to understand the injuries observed in the field and to develop safety countermeasures.

The Madymo model, in general, captures the location of the head and torso contacts seen in the laboratory tests which corresponds to similar ‘zones’ in the field data analysis. The primary areas are front upper A-pillar/header, side rails and B-pillar/roof rail joint for the driver. For the occupant, it is the roof area near the vehicle lateral center and B-pillar/roof rail joints of the passenger side. Side window up or down situation was not explicitly studied in the model. However, most cases in the laboratory test conditions, the side window was broken upon contact with the ground and exterior objects, which are beyond the scope of controls in a test environment.

It is also clear from the head trajectory figures for belted and unbelted drivers that the ‘kinematic-zone’ for belted is clearly smaller than for unbelted drivers. This makes it much more challenging to design inflatable restraint systems that provide complete coverage as well as timely deployment and inflation of such devices in a rollover situation for unbelted occupants.

ACKNOWLEDGMENTS

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Appendix

Figure 9. FMVSS-208 Driver Head Trajectory (Complete Event)

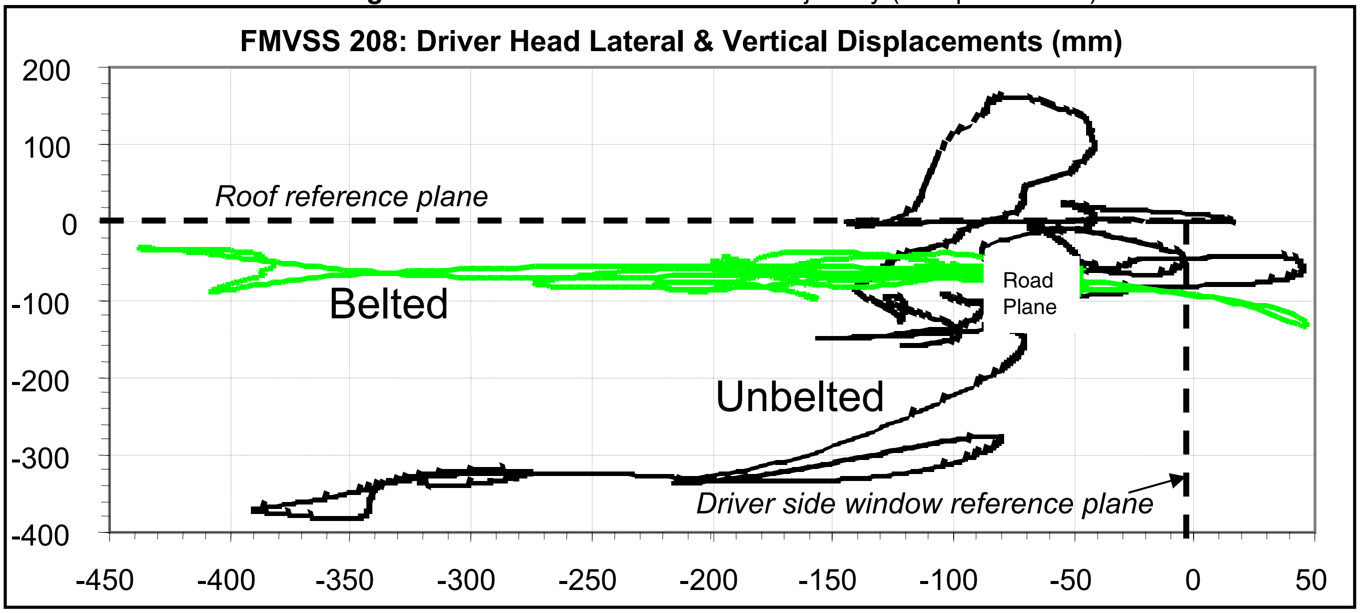
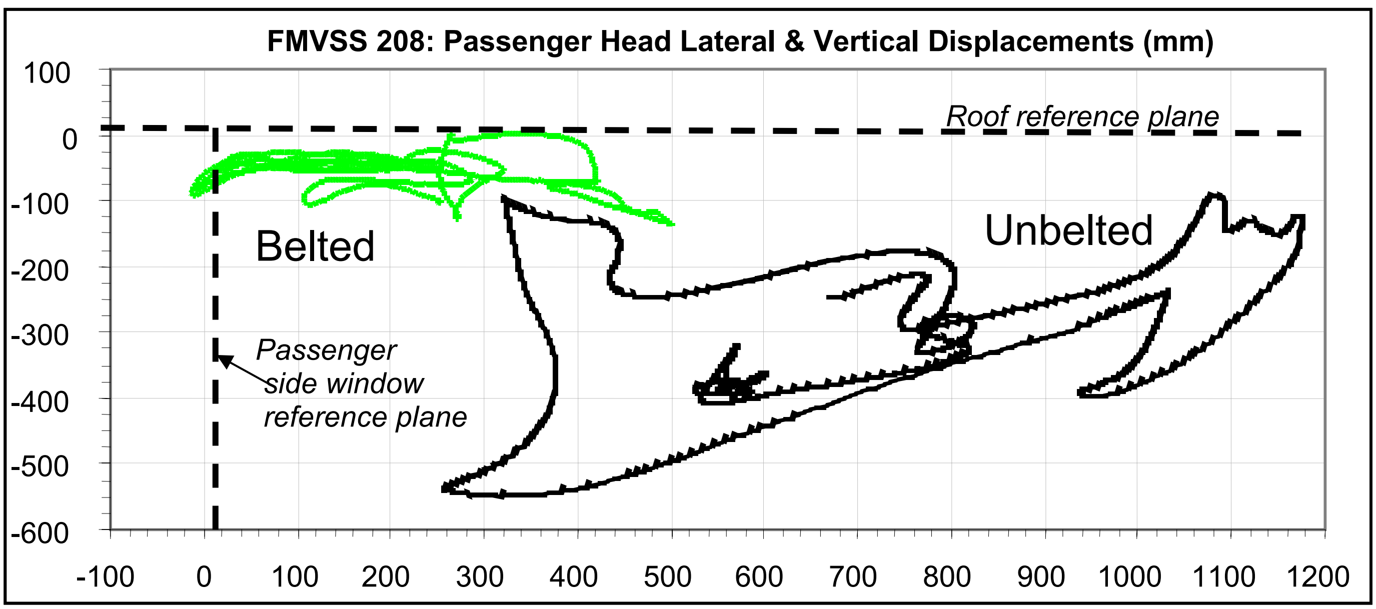


Figure 10. FMVSS-208 Right Passenger Head Trajectory (Complete Event)



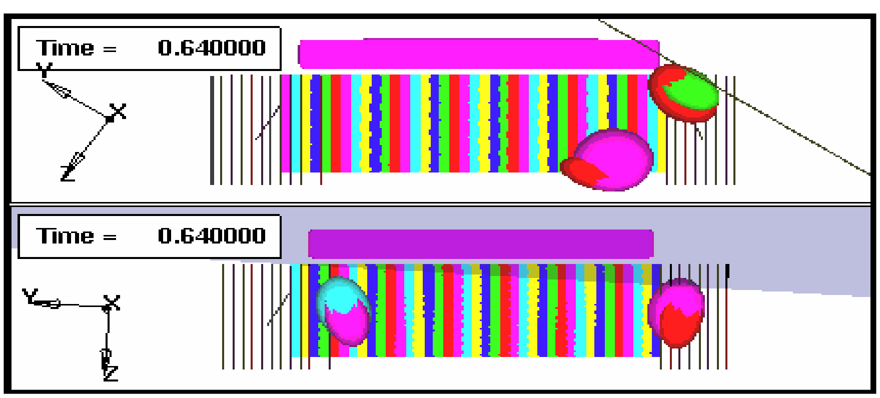


Figure 11. FMVSS 208 Unbelted and Belted
Driver and Right Front Passenger Head Kinematics at T=640ms