NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Vehicle Performance Division
Washington, D.C. 20594

February 27, 2012

SIMULATION STUDY: BIOMECHANICS

1. ACCIDENT

LOCATION:	Interstate 95 (I-95) New England Thruway, at Mile Marker 3.2, in New York, Bronx County, New York
VEHICLE 1:	1999 Prevost H3-45 56-Passenger Motorcoach
OPERATOR:	World Wide Travel of Greater New York Ltd.
DATE:	March 12, 2011
TIME:	Approximately 5:38 a.m. EST

NTSB #: HWY-11-MH-005

2. GROUP

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3. ABSTRACT

The New York City motorcoach accident resulted in 15 fatalities and 17 injuries ranging from minor to serious. The accident involved a quarter turn rollover and secondary collision with a stationary sign pole structure, which intruded into the occupant compartment. Structural intrusion was the primary cause of injury and death; however questions were raised whether passenger seat belts might have been a mitigating factor, if they had been available. A computer simulation study (MADYMO, release 7.2) was developed to explore the potential effects of passenger restraints.

The results of the MADYMO simulation showed that unrestrained occupants were vulnerable to injury during the bus overturn due to impacts with other occupants and impacts with interior surfaces. Occupants were then in close contact with the window and sidewall structure adjacent to the ground at the end of the simulation. As a result, unrestrained occupants were also vulnerable to ejection if window integrity was lost. Simple variations in seating configuration such as seat orientation and armrest position greatly affected kinematics and injury predictions. After the bus overturned, unrestrained occupants were piled on top of one another in the region beside the window between the seats and the luggage racks. This position placed the occupants in a position vulnerable to injury given the intrusion that followed from the secondary impact with the sign pole structure.

In the simulation, lap/shoulder belted occupants were contained within their seating compartments. Occupants seated on the far side of the roll (opposite the side near the ground) were able to partially escape the shoulder harness during the roll sequence, which then placed them in a position closer to the floor of the bus rather than closer to the luggage racks, reducing their vulnerability during intrusion at the window level later in the impact sequence. Near side occupants remained in a more upright position during the simulation, making them potentially more vulnerable to impact and intrusion of the sign pole structure. Simulated injury levels for the motorcoach rollover by itself were low for all lap/shoulder belted occupants.

The study did not simulate the impact with the stationary sign stanchion structure nor the resulting intrusion. The actual event roll sequence and impact with the ground was not replicated. Instead, the accident case was based on the vehicle dynamics simulation and an estimate of ground impact forces based on the National Highway Traffic Safety Administration (NHTSA) roof strength crash tests done according to the United Nations Economic Commission for Europe (UN-ECE) Regulation No. 66, referred to in this report as "R66"[1]. The simulation did not represent the actual occupant positions, sizes or gender in the accident. The results provide general information about occupant kinematics and injury potential based on the accident simulation.

4. INTRODUCTION

Rollovers only represent 3% of all collisions but account for 32% of all fatalities in passenger vehicles. Statistics reveal that passengers involved in rollover crashes are more likely to suffer serious injuries than those in other types of crashes.[2] NHTSA reported that rollovers are the most dangerous crash type for all classes of light vehicles, when measured based on fatalities or incapacitating injuries to the occupants.[3] This result occurs because of the relatively

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[1] "Uniform Provisions Concerning the Approval of Large Passenger Vehicles with Regard to the Strength of Their Superstructure", UN-ECE Regulation No. 66, http://www.unece.org/trans/main/wp29/wp29regs61-80.html.

[2] Johnson AK, Knapton DA. Occupant Motion During a Rollover Crash. National Highway Safety Administration, DOT HS-806 646, November 1984.

[3] An Experimental Examination of Selected Maneuvers that may Induce On-Road, Untripped Light Vehicle Rollover – Phase 1-A of NHTSA's 1997-1998 Vehicle Rollover Research Program, DOT HS 809 357, August 2001.

low percentage of rollover crashes and the high percentage of fatalities associated with those crashes. Other research indicates that belted occupants typically experience a lower fatality rate than unbelted occupants due to the reduced risk of full or partial ejection.[4] Despite the reduced fatality rate when belted, head impacts still occur due to the dynamics of the vehicle and the restrained occupant kinematics. Similarly, 60% of the fatalities resulting from rollovers were to ejected occupants, while more than 70% of those killed were not restrained.[5] Clearly, rollovers in passenger vehicles have been extensively studied in the past. The occupant kinematic patterns and injury patterns resulting from rollover crashes are well known. According to the NPRM[6] on motorcoach occupant protection published on August 18, 2010, NHTSA found that between 1999 and 2008, 54 fatal motorcoach crashes occurred resulting in 186 fatalities. When looking at the most harmful event for these fatal motorcoach crashes, 44% are rollovers, while 33% are involved in multivehicle crashes and 19% involve impacts with roadside hardware.

In 1985 and 1990, General Motors conducted several rollover and drop tests on light vehicles to determine the influence of roof strength on injury mechanisms to the unrestrained[7] and belted dummy.[8] They concluded that in general the rotational force dictates the position of the dummy, resulting in an upright position with the head upwards and outboard for the belted dummy. Unrestrained, the dummy lifted off the seat and remained in the roof or upper door region as the vehicle rolled. The dummy only moved from this position if a significant force was applied to the vehicle such as a tire to ground impact as the vehicle continued to roll. According to this work, roof strength had no effect on the predicted head injury because the injury was dependent on the dummy's head being in the region near to the roof crush (for example, roof crush needed to be directly above the driver's head to cause injury, which wasn't always the case). In general, the significant factors affecting injury potential were the orientation of the body at impact and the proximity of the occupant to the portion of the vehicle undergoing the high change in velocity. The researchers also stated that safety belts prevented ejection and impacts with the vehicle interior but did not minimize head or neck loads for dummies in the area of a ground impact.

The roll event alone does not tell the whole story. Research indicates that the circumstances of the rollover accident sequence have a profound effect. A recent presentation at

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[4] Moffatt EA, Cooper ER, Croteau JJ, Parenteau C, Toglia A. Head Excursion of Seat Belted Cadaver, Volunteers and Hybrid III ATD in a Dynamic/Static Rollover Fixture. Society of Automotive Engineers, SAE Paper 973347, 1997.

[5] "Runge takes the hot seat in SUV debate", Automotive Engineering International (ISSN 0098-2571), April 2003, Volume 111, Number 4.

[6] Notice of Proposed Rulemaking (NPRM), "Federal Motor Vehicle Safety Standards; Motorcoach Definition; Occupant Crash Protection," which was published at 72 Federal Register 50958 on August 18, 2010.

[7] Orlowski KF, Bundorf RT, Moffatt EA. Rollover Crash Tests – The Influence of Roof Strength on Injury Mechanics. Society of Automotive Engineers, SAE Paper 851734, 1985.

[8] Bahling GS, Bundorf RT, Kaspzyk GS, Moffatt EA, Orlowski KF, Stocke JE. Rollover and Drop Tests – The Influence of Roof Strength on Injury Mechanics Using Belted Dummies. Society of Automotive Engineers, SAE Paper 902314, 1990.

the 2011 Crash Injury Research and Engineering Network's (CIREN) annual meeting discussed single vehicle, multiple event rollover crashes focusing on light vehicles.[9] The CIREN presentation focused on the importance of looking at multiple event rollover crashes instead of single event rollovers that do not involve a secondary planar event. The researchers found that a collision with a fixed object, such as a tree, bridge, traffic barrier or non-breakaway pole, is typically the most severe and the last event in a rollover sequence. They also found that single vehicle, multiple event rollovers accounted for a large majority of both the fatal rollover cases (65.6%) and occupant fatalities (73.6%). Digges and Eigen[10] research was similar, and found that rollovers involving planar events with severe damage have injury rates that are two to three times higher than an equivalent rollover without the planar event.

The objectives of the present study were to create an occupant simulation representative of the accident sequence, to evaluate injury potential during the roll, and to evaluate occupant kinematics relating to their position at the time of the secondary planar impact into the non-breakaway pole structure. Unrestrained and lap/shoulder belted restraint conditions were evaluated.

5. METHODS

5.1. Software

MADYMO is a MAthematical DYnamic MOdeling software package that is used to solve crash engineering problems. For this simulation, MADYMO release 7.2 was employed. The multi-physics simulation program has capabilities for combining both multibody and finite element analysis techniques.

5.2. Coordinate System

The coordinate system was such that the positive x-axis pointed toward the front of the vehicle. The positive y-axis pointed toward the left side of the vehicle and the positive z-axis pointed upward, towards the roof of the vehicle.

The base coordinate system of the MADYMO occupant model lies within the pelvis, Figure 1. The coordinate system was established such that the positive x-axis pointed anteriorly. The positive y-axis pointed laterally to the occupant's left and the positive z-axis pointed proximally (toward the head). Each body segment had a local coordinate system associated with it. The orientation of each segment's coordinate system was fixed locally to the segment but may vary globally relative to the segment's position in space.

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[9] Crandall J, Bose D, Show G, Sochor M, Lockerby J, Bollapragada V, Kerrigan J, Mutter K, Single Vehicle Multiple Event Rollover Crashes: NASS and CIREN Analysis, http://www.nhtsa.gov/DOT/NHTSA/NVS/CIREN/Presentations/2011/UVA-CIREN-Sep2011.pdf on November 14, 2011.

[10] Digges K, Eigen, AM, Injuries in Rollovers by Crash Severity, 20th International Technical Conference on the Enhanced Safety of Vehicles, Lyon, France, 2007.

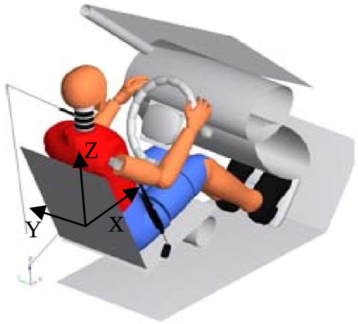

Figure 1: The coordinate system for the occupant's pelvis.

5.3. Simulation Set-up

Two rows of seats within the motorcoach near the center of gravity were simulated representing a small portion of the motorcoach interior. Occupants were placed in the second row of seats, so they were largely confined between the two rows of seats. There were no constraints fore or aft of the two rows of seats, so the occupants could escape the simulation (one occupant in one simulation did escape forward of the first row of seats). The simulations evaluated various configurations including the longitudinal seat offset, the armrest position, number of occupants in the row, occupant seating position, and restraints. Although the occupants in the New York City accident were both male and female and of various sizes, for simplicity the occupants in the simulation were all represented by 50th percentile adult male dummies.

The center of gravity of the motorcoach, the location of the floor, luggage racks, seat spacing, aisle width and other physical characteristics of the bus were established in MADYMO to best represent the dimensions of the accident bus and the characteristics determined during the vehicle dynamics simulation. Although dimensionally accurate, the material properties for many of the interior surfaces were not known. As a result, generic material properties were assigned to the interior surfaces to reflect generic materials such as seats, sidewalls, windows, luggage racks, floor and armrests. These material properties were consistent over all the simulations performed.

5.3.1 Simulation Conditions

Initially, a Design of Experiments (DOE) was developed to better understand the range of performance based on changes to the initial conditions. These changes included the severity of the impact of the sidewall onto the ground, the position of the bus at the time of the impact, the positions of the armrests (up or down) and the restraint condition for the occupant (unrestrained or lap/shoulder belted). These conditions were evaluated for both a near side and a far side occupant seated alone in the second seat row of the simulation. Initial results showed that the factors were not balanced, meaning that some conditions had little effect, while others, when coupled with the dynamics of the bus, could expose occupants to injury or position occupants in a vulnerable position such that a secondary impact, such as the pole intrusion, could cause substantial harm. These single occupant results are summarized in the results section, for reference.

Based on these initial simulations and the preliminary results, it was determined that for most occupants, the simulated motorcoach roll event by itself, was not causing the fatal injuries seen in the accident bus. Occasionally, occupant impacts to the side wall occurred from a combination of impact pulse and occupant position that resulted in an elevated injury measure. This situation was also seen in the NHTSA rollover crash tests. In the 2009 test, for example, the unrestrained dummy traveled laterally out of the seating compartment and the dummy's head impacted the overhead luggage resulting in a head injury criteria measure of 1458.[11] High neck compression forces were also recorded.

Thus, the plan for the simulation was modified. Instead of a DOE, several simulations were developed to look at the factors that change occupant kinematics and injury measures. Of particular interest were the conditions that may place occupants in a position vulnerable to secondary impacts. These conditions included: seat row occupancy (single occupant or four occupants); seat row alignment (alignment of the dual seats on either side of the aisle, including directly aligned, 33% offset and 50% offset); seating location (side of the bus and window/aisle seat), and restraint condition (unrestrained or lap/shoulder belted). These simulations were all run with the armrests in the up position in order to maintain a controlled "unrestrained" position. Preliminary results from the initial simulations showed that the armrests in the down position restrained the occupant pelvis for a short period of time, which may not provide a truly "unrestrained" condition.

5.3.2 Initial Occupant Positioning

Each 50th percentile adult male dummy was centered on the seat and a pre-simulation was run to ensure proper positioning. For consistency, the report will refer to the occupants as A, B, C and D, as seated from left to right facing forward. Occupant A is shown in pink, B in orange, C in blue and D in green. The bus rolled onto its right side and therefore, occupant A is the far side occupant and occupant D is the near side occupant. Still images showing these occupants in various conditions (except the seat offset of 33% and 50%) are shown in Figure 2 through Figure 5.

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[11] Peschman E, Winkelbauer D, Final Report on the ECE Regulation 66 Based Research Test of Motor Coach Roof Strength 2000 MCI 102-EL3 Series Motorcoach NHTSA No: MY0800, October 1, 2009, ECE 66-MGA-2009-001.

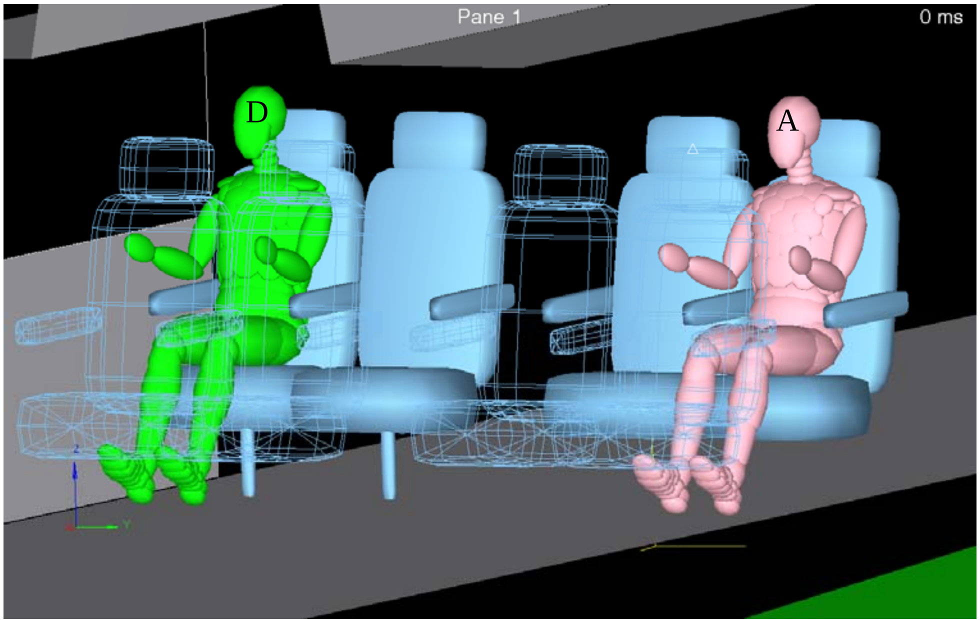

Figure 2: A still image showing the positioning of occupants A and D with the seat armrests in the down position. Front row of seats shown in wireframe to provide a clear view of the occupants in the second row of seats.

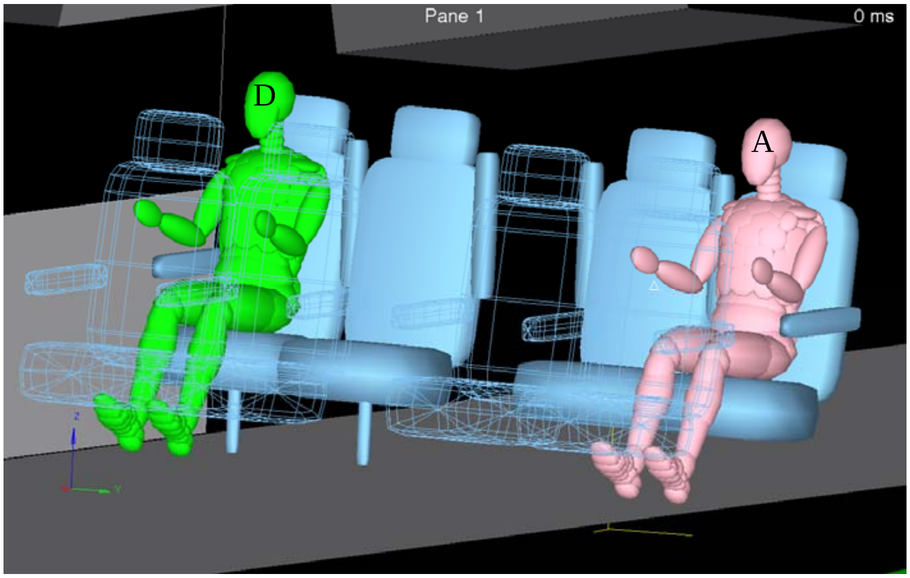

Figure 3: A still image showing the positioning of occupants A and D with the seat armrests in the up position. Front row of seats shown in wireframe to provide a clear view of the occupants in the second row of seats.

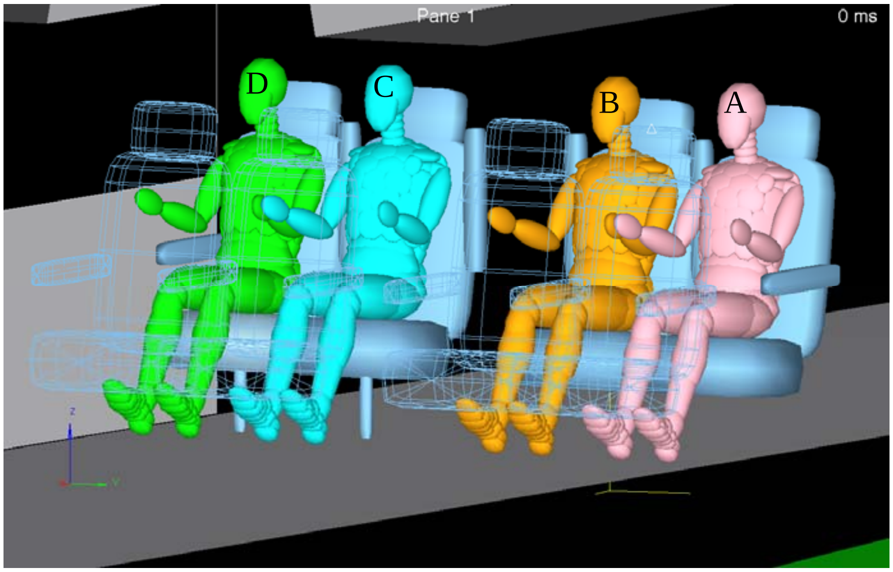

Figure 4: A still image showing the positioning of occupants A, B, C and D with the seat armrests in the up position. Front row of seats shown in wireframe to provide a clear view of the occupants in the second row of seats.

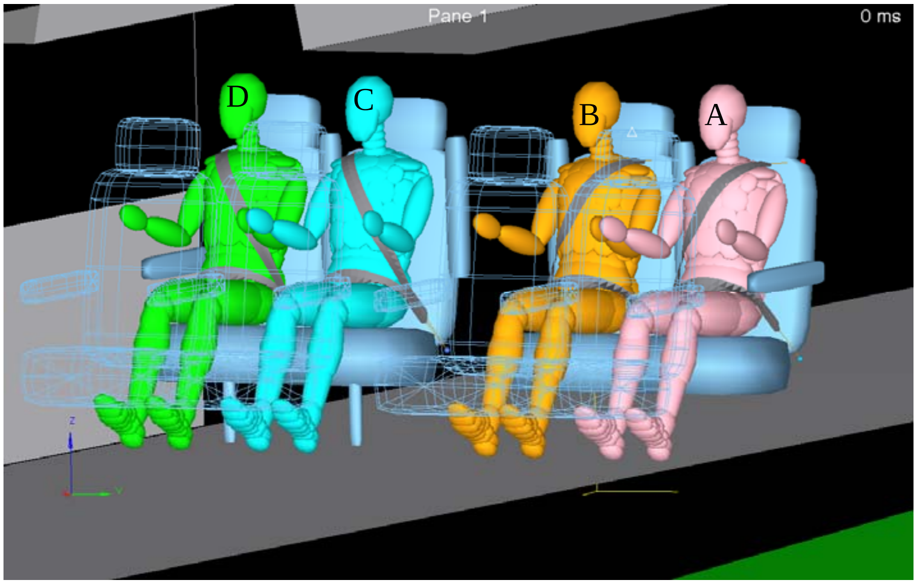

Figure 5: A still image showing the positioning of occupants A, B, C and D with the seat armrests in the up position and restrained with lap/shoulder belts. Front row of seats shown in wireframe to provide a clear view of the occupants in the second row of seats.

5.4. Bus Motion

The MADYMO simulations needed a defined bus motion. This input was developed in two parts. The first part represented the bus as it struck the guardrail and rolled, and was generated using a separate vehicle dynamics simulation as described in section 5.4.1. The second part was an extension of the final roll and impact with the ground, as described in section 5.4.2, and with further details in Section 5.5.

5.4.1 Vehicle Dynamics Simulation

The vehicle dynamics[12] were modeled in TruckSim.[13] The interaction with the guardrail was modeled with the assistance of Simulink.[14] The vehicle dynamics simulation was limited to roll angles less than 90 degrees and therefore ended prior to the impact with the ground. At the end of the vehicle dynamics simulation, the roll rate was approximately 100 deg/sec. For comparison, an estimate of the roll rate in the NHTSA R66 crash tests based on video analysis showed a roll rate of around 50 deg/sec. The faster roll rate as compared to the R66 test used in the simulation was considered reasonable because the R66 test was more severe in two other respects. First, the R66 impact was onto a hard surface, and second, the bus was on an elevated platform, allowing the bus to rotate more than 90 degrees prior to impact. In contrast, the accident vehicle rolled onto its side on a grassy surface while coming into contact with a guardrail at the bus's lower right side.

The position, orientation and acceleration time history of the bus based on the vehicle dynamics simulation are shown in Figure 6 through Figure 8. Note that the vehicle dynamics simulation uses a coordinate system relative to the roadway. The positive X axis is the forward motion of the bus, positive Y is laterally to the left, and positive Z is vertically upwards. The position and orientation time histories were used as the vehicle motion in MADYMO. The vehicle simulations did not, however, include the final impact with the ground. The TruckSim program capabilities are limited to vehicle dynamics and not external impact to the body of the vehicle.

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[12] HWY-11-MH-005 Vehicle Dynamics Study.

[13] TruckSim Mechanical Simulation. TruckSim is a software tool for simulating and analyzing the dynamic behavior of medium to heavy trucks, buses and articulated vehicles. http://www.carsim.com/products/trucksim/index.php on November 29, 2011.

[14] MATLAB Simulink. http://www.carsim.com/products/supporting/simulink/index.php on November 29, 2011.

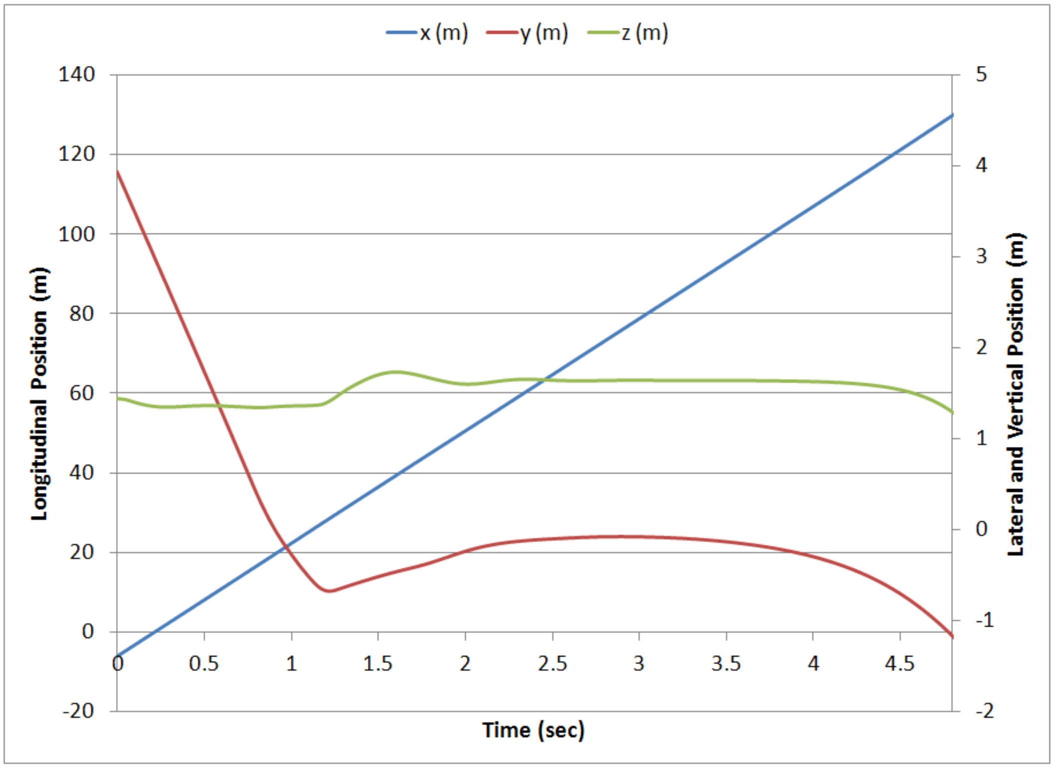

Figure 6: The position time history of the motorcoach based on the vehicle dynamics simulation, measured at the bus cg relative to the road surface near the start of the simulation.

Figure 7: The orientation time history of the motorcoach based on the vehicle dynamics simulation.

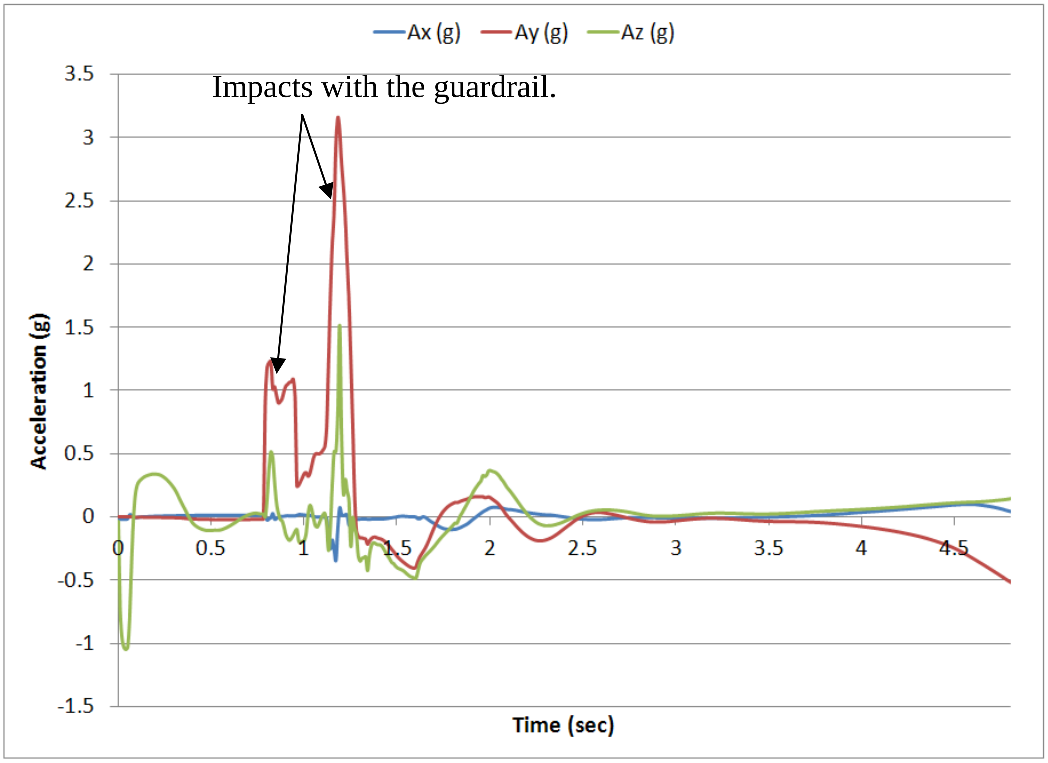

Figure 8: The linear acceleration time history of the motorcoach cg based on the vehicle dynamics simulation (note that the vehicle dynamics simulation did not include the bus sidewall to ground impact).

5.4.2 Extension of Bus Motion

This time history data was extended to include a short period of time with the bus decelerating while on its right side and stopping its motion due to impact with the ground. This extension of the data was needed so that the occupants could be exposed to the final deceleration event, which greatly affected their final rest position. Ending the simulations at the end of the TruckSim data left the occupants in a position where the right side of the bus was just beginning to contact the guardrail and ground; vulnerability of the occupant's position after the roll could not be fully evaluated.

The vehicle dynamics motion was extended from 4.8 seconds to 5.48 seconds. For the first 0.2 seconds of the data extension, the position and orientation data were extended linearly at the same rate as the motion prior to the end of the vehicle dynamics data. After approximately, 0.2 seconds, the bus's roll angle was approximately 90 degrees. Since the accident bus's orientation and lateral and vertical position changed little after initial contact with the ground, these values were then held constant while the longitudinal position of the bus was continued, but at a deceleration of 0.5 G, which approximated the friction of a vehicle sliding on its side.

It was necessary to generate an impact with the ground for inclusion in the MADYMO simulation, since it was not included in the vehicle dynamics model. This impact was applied as an acceleration pulse when the bus orientation was in the rolled position. Accelerations measured in the NHTSA R66 crash tests were used as a basis for the ground impact input to the MADYMO simulation. Two acceleration pulses were developed to represent the high and low accelerations measured in the NHTSA R66 crash tests. These pulses are discussed in greater detail in the following section. Ultimately, only the high pulse was used in the final simulations.

5.5. NHTSA Testing

The National Highway Traffic Safety Administration (NHTSA) conducted a series of full scale crash tests to evaluate motorcoach structural integrity, occupant kinematics, restraint systems and injury mechanisms. This testing involved a full scale frontal crash test, three tests similar to Economic Commission for Europe (ECE) R66 and two additional tests addressing roof strength based on the school bus standard FMVSS 220. The testing based on FMVSS 220 will not be addressed in this report.

5.5.1 Full Scale Frontal Crash Test

On December 14, 2007, NHTSA conducted a full scale frontal impact barrier test of a 2000 MCI 102EL3 Renaissance motorcoach. The bus had 54 passenger seats, was 45 feet long and 12 feet 6 inches tall. The total weight of the test vehicle was 42,720 lbs. The bus was equipped with a variety of seats including American Seating seats without belts, MCI/Amaya/FAINSA seats with both lap belts and lap/shoulder belts and Freedman Seating seats with lap/shoulder belts.

The impact speed was set at 30 mph into a rigid barrier with a full overlap. Twenty two dummies were on the test vehicle including 17 hybrid III 50th percentile males, 3 hybrid II 5th percentile females and 3 hybrid III 95th percentile males. The actual impact speed was recorded at 30.36 mph with a dynamic crush of 6.5 feet and a peak deceleration of 10g at 125 msec into the crash (Figure 9). This pulse was viewed as a potential worst case scenario for the deceleration of the bus when impacting the non-breakaway light pole. Ultimately, this pulse was not used in the simulation, as will be explained in a later section addressing occupant kinematics and positioning that created vulnerability to secondary impacts.

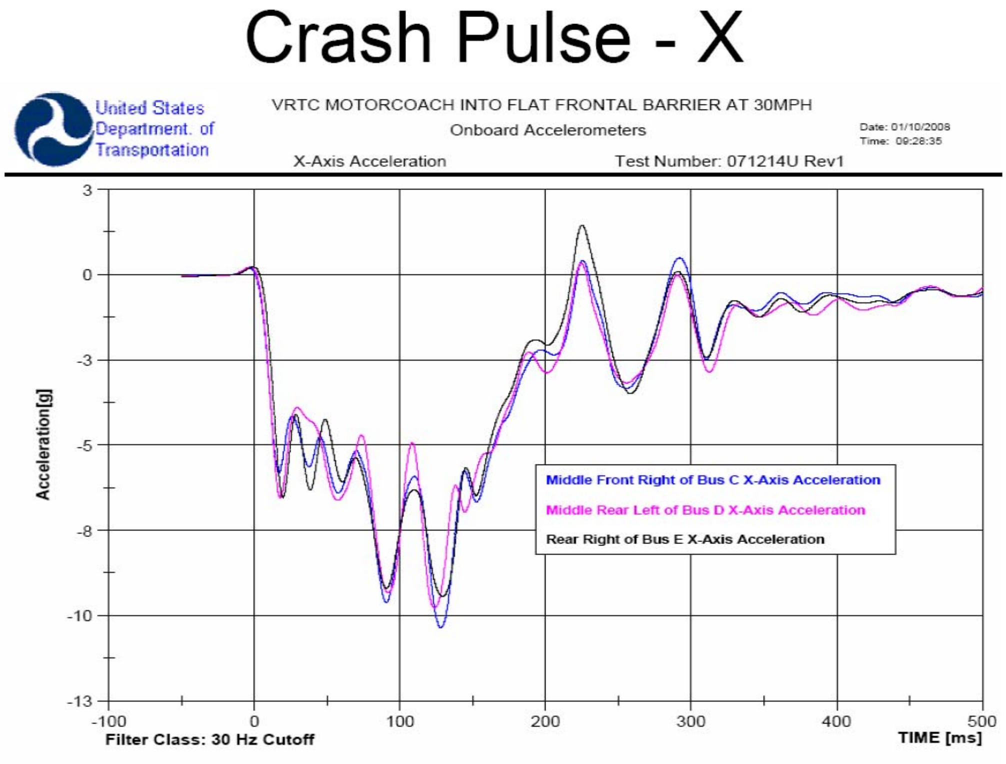

Figure 9: The recorded and filtered crash pulse in the x-direction from the 2007 full scale frontal barrier test.[15]

5.5.2 Economic Commission for Europe (ECE) R66 Complete Vehicle Test

In accordance with the August 2007 Motorcoach Safety Action Plan, NHTSA purchased a 1992 Motor Coach Industries (MCI) model MC-12 and a 1991 Prevost model LeMirage motorcoach for testing. Both coaches were 40 feet long but had visible construction differences and different window dimensions. The ECE R66 test method tips the bus sideways off a 31.5 inch platform onto a hard surface. The impact typically occurs at the intersection between the sidewall and the roof (referred to as the "roof rail"), and at an angle greater than 90 degrees due to the elevated platform. The buses were instrumented with accelerometers along the roof and at the floor of the bus. The average acceleration near the top of the bus was 7.59 g for the MCI bus and 8.20 g for the Prevost bus.[16] An additional test was conducted on a 2000 MCI 102-EL3 series motorcoach, which was a newer and heavier motorcoach.

In order to recreate the decelerations experienced by the dummies in the first two tests, as opposed to the direct loading at the roof rail, the accelerations measured at the floor were examined for both the 1992 MCI and the 1991 Prevost buses. Due to the orientation at impact,

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[15] Motorcoach Safety Research Motorcoach Crash Test, Docket Number NHTSA-2007-28793, Report Date January 23, 2008.

[16] Motorcoach Roof Crush/Rollover testing Discussion Paper, NHTSA, Docket No. NHTSA-2007-28793, March 2009.

accelerations in both the y and z axes were examined at all three locations along the length of the buses.

The maximum accelerations at three locations along the bus floor are shown in the tables below. The range in maximum acceleration in the y axis was between 3.6 G – 6.9 G. The range in maximum acceleration in the z axis was between 3.7 G – 13.2 G.

Table 1: Ranges in floor level acceleration: Prevost 1991

Location	Y acceleration (max) G	Z Acceleration (max) G
Front	4.8	13.2
Middle	3.8	4.7
Rear	6.9	3.7

Table 2: Ranges in floor level acceleration: MCI 1992

Location	Y acceleration (max) G	Z Acceleration (max) G
Front	5.2	10.0
Middle	3.6	6.7
Rear	4.1	12.3

5.5.2.1.Simplified Pulse Shape

The accelerometer at the front of the Prevost bus recorded the highest accelerations while the accelerometer at the middle of the Prevost bus recorded the lowest accelerations. These two acceleration positions were used to represent the high and low acceleration at the floor location.

Since the loading to the accident bus was primarily to the side of the bus not at the intersection of the sidewall and the roof rail, as in the ECE R66 test, a resultant acceleration was calculated for the floor accelerations at the front and middle of the 1991 Prevost coach. In order to calculate the resultant acceleration, raw accelerometer data was obtained from the NHTSA website for this crash test. The data was then filtered using the CFC60 filter, as done for the NHTSA reports, and the resultant acceleration in the y-z direction was calculated. This resultant was then applied in the y-direction only as that was the main direction of loading. Although the accelerations were recorded for about 2 seconds after ground impact, the main portion of the acceleration pulse lasted for approximately 0.3 seconds with some rebound contributing forces afterwards. An example of the acceleration time history in the y-direction and the y-z resultant acceleration on the 1991 Prevost at the front floor location are shown in Figure 10 and Figure 11. (Note that impact with the ground occurred at approximately 0.5 seconds in the plot.)

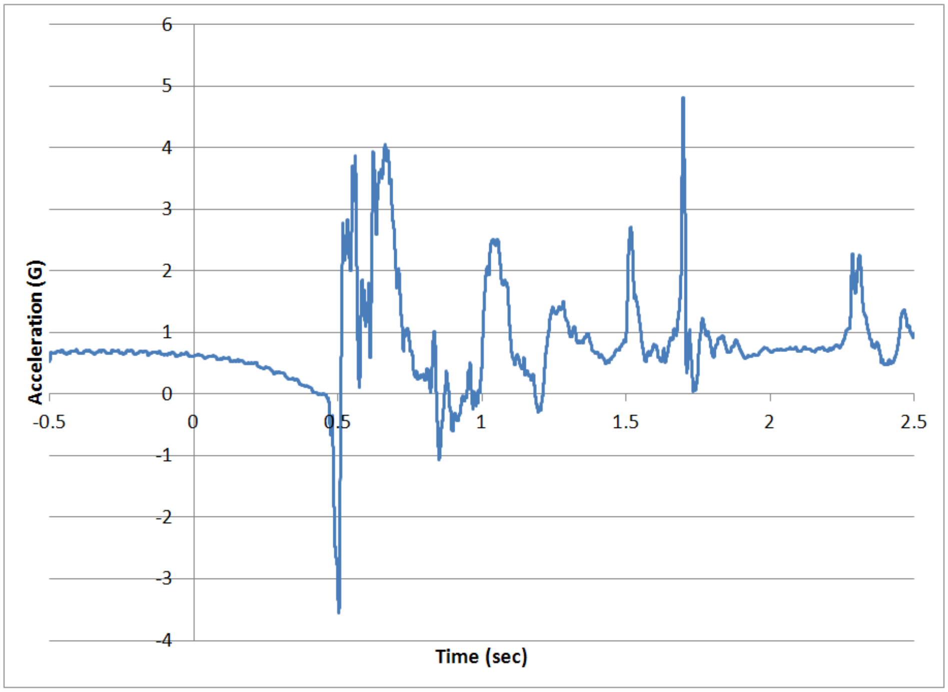

Figure 10: The accelerations measured at the front template location on the floor in the y axis on the 1991 Prevost LeMirage motorcoach.

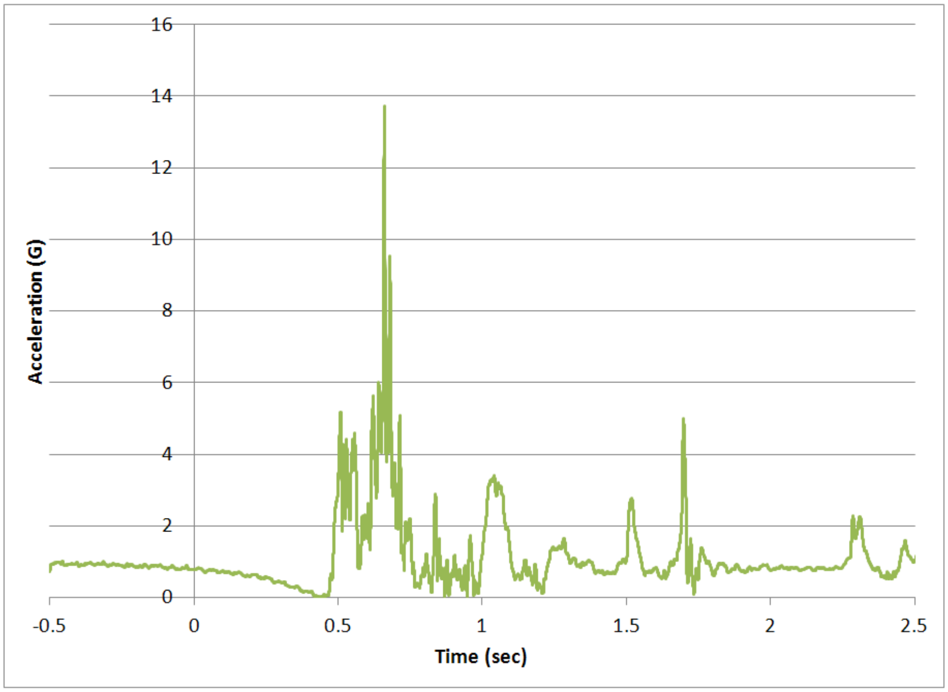

Figure 11: The resultant accelerations at the front template location on the floor in the y-z direction on the 1991 Prevost LeMirage motorcoach.

Simplified triangular pulse shapes were created to best represent the resultant accelerations and the change in velocity at the front and mid position of the bus. The resultant accelerations along with the simplified pulse and the calculated change in velocity for the resultant acceleration and the simplified acceleration are shown in Figure 12 and Figure 13. For consistency, the duration of the pulse and the time to peak was held constant for both pulses.

Ultimately, based on the results of the initial simulations in the design of experiments, the simple triangular pulse estimated from the front of the Prevost motorcoach was used for all the simulations.

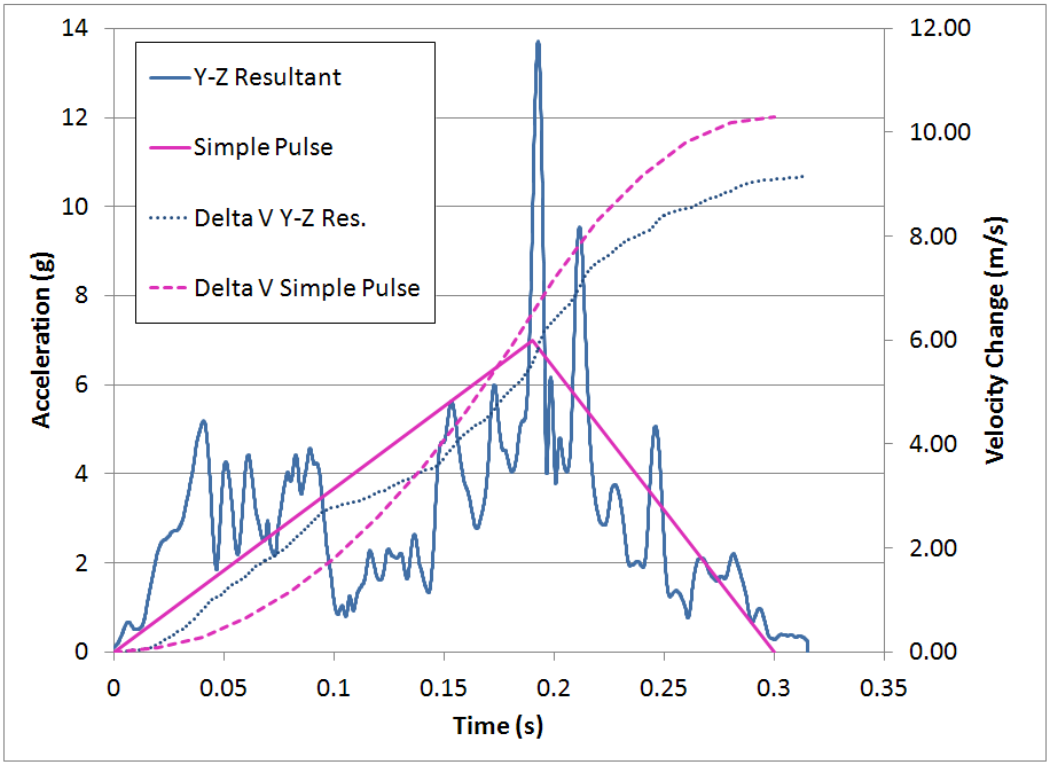

Figure 12: The simple triangular pulse representing the resultant acceleration and the velocity change at the front of the 1991 Prevost.

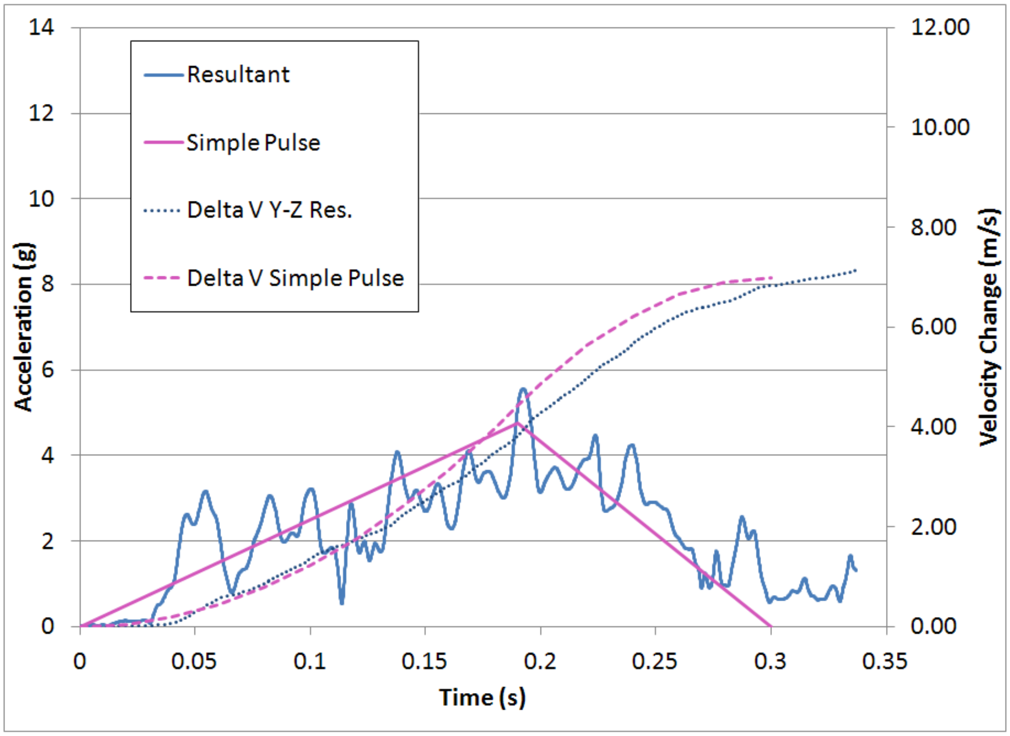

Figure 13: The simple triangular pulse representing the resultant acceleration and the velocity change at the middle of the 1991 Prevost.

5.6. Injury Criteria

Injury criteria focused on the head, neck and chest. The 36 ms head injury criterion (HIC) was the measure for head injury (critical value = 1000). Neck injury measurements included the Nij (critical value = 1.0) and also axial tension (critical value = 4170 N) and axial compressive (critical value = -4000 N) forces. Chest compression (critical value = 63 mm) and acceleration (critical value = 60 g) were evaluated for chest injury.

6. RESULTS AND DISCUSSION

6.1. Injury Criteria

A summary of the injury measures is shown in Table 3. Injury values above the limit are highlighted in yellow. Those values near the injury criteria limit are marked with an orange type.

6.2. Occupant Motion and Injury Measures

6.2.1 Unrestrained

In general, in the unrestrained condition, simulated occupants moved, uncontrolled, in the direction of the roll. In this accident scenario, the roll was extremely slow with an initial impact into the guardrail that caused the occupants to initially move toward the right side of the bus. The occupant's initial position, the orientation of the armrests, the position of the far side seats relative to the near side seats, and the number of occupants in the seat row all affected the kinematics and the injury values.

6.2.1.1.Single Occupant, Far Side

The far side occupant crossed the width of the bus and in this seating configuration, the occupant's head impacted the sidewall (Figure 14) and window structure. This impact did not result in a high HIC value but rather in a high compressive load in the occupant's neck. Both the Nij in the compression-flexion direction and the axial compressive force were above injury limits. High neck compressive forces and Nij compressive loads were also seen in the 1991 Prevost R66 test, the 2000 MCI R66 test and the 1992 MCI R66 test for the front unrestrained passenger.[17] Photographs showing the final rest positions for the three unrestrained passengers in the NHTSA R66 tests are shown in Figure 15, Figure 16, and Figure 17. (Note that the passenger in the NHTSA test started in the far side aisle seat, not the far side window seat as in this MADYMO simulation. In addition, the roll direction was toward the driver's side. In the present study, the roll direction was toward the passenger side.)

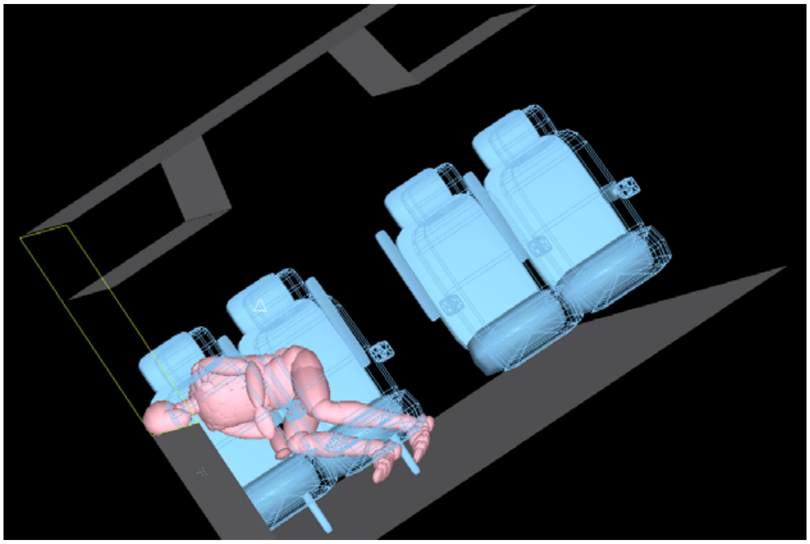

Figure 14: A still image from the simulation showing the far side occupant (occupant A) as the sole occupant in the seat row. The unrestrained occupant crossed the width of the motorcoach and the occupant's head impacted the sidewall and window structure. (T=1.56 seconds)

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[17] Hansen J, Janovicz M, Final Report on the ECE Regulation 66 Based Research Test of Motor Coach Roof Strength 1991 Prevost LeMirage NHTSA No: CM0801, May 20, 2008, ECE 66-MGA-2007-002; ECE 66-MGA-001; ECE 66-MGA-2009-001.

Figure 15: Post-Test View of Front Unrestrained Test Dummy (1991 Prevost LeMirage). The image has been rotated and flipped such that the occupant motion appears to be in the same direction as the accident vehicle's roll.

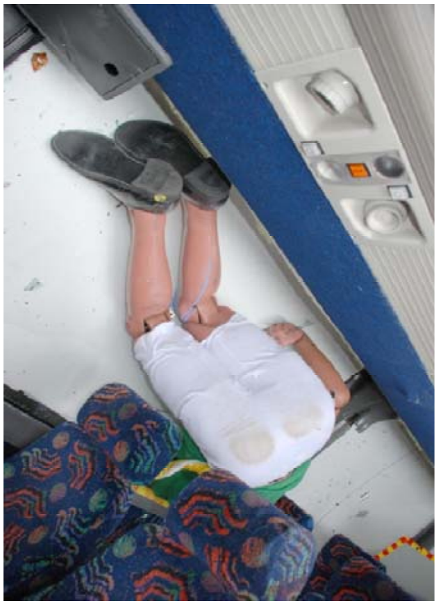

Figure 16: Post-Test View of Front Unrestrained Test Dummy (2000 MCI 102-EL3). The image has been rotated and flipped such that the occupant motion appears to be in the same direction as the accident vehicle's roll.

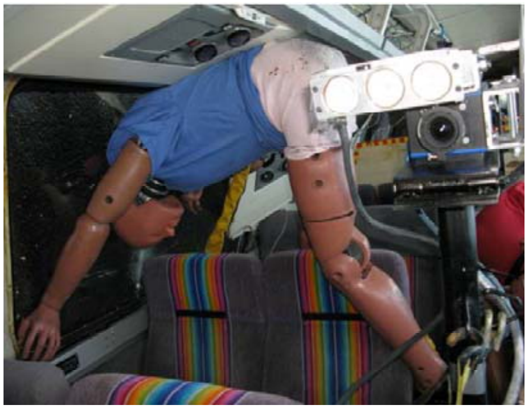

Figure 17: Post-Test View of Front Unrestrained Test Dummy (1992 MCI MC-12). The image has been rotated and flipped such that the occupant motion appears to be in the same direction as the accident vehicle's roll.

6.2.1.2.Single Occupant, Near Side

The near side occupant (occupant D) generally stayed in the same position throughout the rollover sequence. This occupant did interact with the sidewall and the window during the roll, as can be seen in Figure 18. Injury values were low for this occupant when seated alone in the seat row.

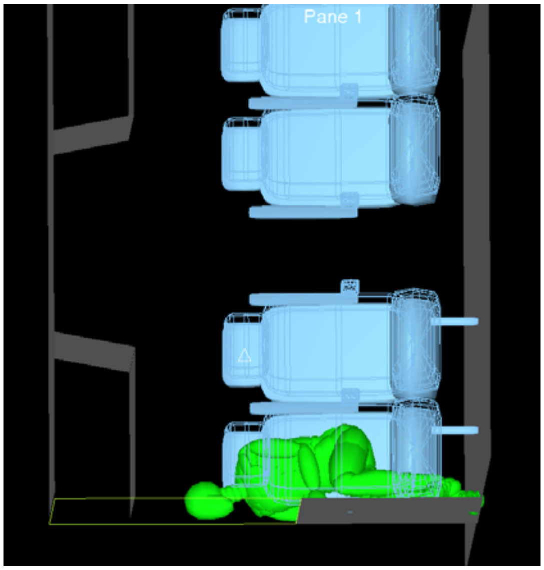

Figure 18: A still image from the simulation showing the near side occupant (occupant D) as the sole occupant in the seat row. Note that the bus is rolled onto its right side in this image. (T=5.17 seconds)

6.2.1.1.Fully Occupied Row

In the accident motorcoach, some of the seats on one side of the aisle were offset with respect to the seats on the other side of the aisle. Three different seat configurations were explored during the simulation with four occupants in a single seat row. The first configuration aligned the far side seats directly with the near side seats. The 33% offset condition placed the far side seats 1/3 of the distance between the seats forward of the near side seats. The 50% offset condition placed the far side seats ½ of the distance between the seat rows forward of the near side seats.

As mentioned earlier, the occupants moved toward the right side of the bus in the direction of the roll. The seat offset had a large affect on the motion of the far side occupants, and in turn created a variety of occupant impact orientations and associated range of injury values. Neck axial compression was high for the far side aisle seated occupant (occupant B) in all seat offset conditions, but was also high for the far side window occupant (occupant A) and the near side aisle seated occupant (occupant C) in some configurations. In the 33% offset condition, occupant B also had a high HIC value at about the same time as head contact occurred with the side wall in the single occupant simulations.

Figure 19 highlights the chaotic motion of the occupants out of their seating positions during the roll. Only the near side window seated occupant (occupant D) stayed close to the original seating position. However that position, despite not showing elevated injury measures in this simulation, was most vulnerable to impacts from other occupants. This occupant was also closest to the ground, making this position also vulnerable to ejection if the window integrity were lost.

Intrusion from the light pole structure compromised the region between the seat headrests and the luggage racks. Figure 19 further shows the vulnerability of various portions of the body, depending on the seat configuration and the number of occupants in a seat row, to secondary impacts including intrusion.

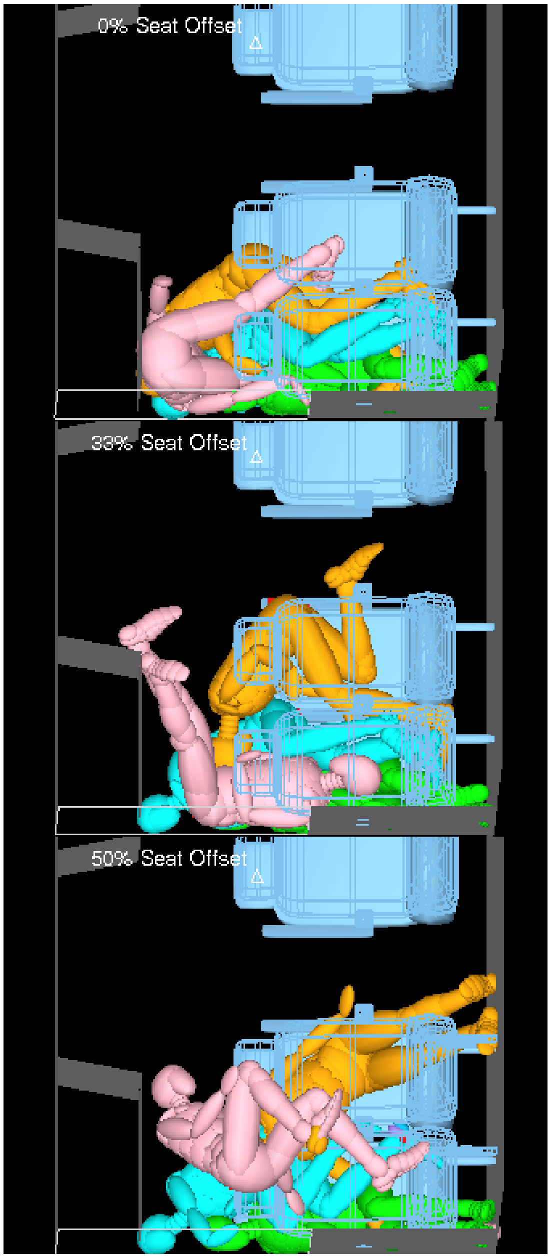

Figure 19: A still image showing the three offset conditions at the end of the simulation. The no offset condition is at the top, 33% offset is in the middle and 50% offset is at the bottom. (T=5.4 seconds)

6.2.2 Lap/Shoulder Belted

6.2.2.1. Fully occupied Row

Occupant motion was controlled in the lap/shoulder belted condition (Figure 20). Limited initial lateral motion still occurred, but the restraints kept the occupants in the original seating location throughout the accident sequence. The upper body of the far side occupants did slip out of the shoulder harness during the roll sequence. The occupant seated at the far side window seat (occupant A) escaped the shoulder harness prior to the far side aisle seated occupant (occupant B). Likely, this occurred because the aisle seated occupant's lower body rotated into the aisle causing some rotation of the upper body, which engaged the shoulder harness for a longer duration. The window seated occupant's (occupant A) lower legs interacted with the seat cushion and reduced upper body rotation, contributing to a more direct lateral motion, and occupant A thus escaped the harness earlier in the simulation.

The rear seat passenger's upper body also slid from the shoulder harness during the NHTSA R66 tests with both MCI buses. The final rest positions for these two passengers can be seen in Figure 21 and Figure 22. (The seats failed in the 1991 Prevost test. Therefore motion of the occupant out of the harness was not examined.) Note that the simulation view shown in Figure 23 was rotated and flipped to facilitate comparison to the NHTSA R66 tests.

The final rest position at 5.4 seconds in Figure 20 of the lap/shoulder belted condition clearly shows that the restraints served to control the occupant motion and keep the occupants in their original seat. The restraints also prevented occupant motion into the window region and the region of the luggage racks. Similar results were seen in the NHTSA R66 tests of the lap/shoulder belted occupants. Injury values were also low for the simulated lap/shoulder belted occupants throughout the roll sequence.

Although the impact with the pole structure was not simulated, final rest positions for the occupants highlight the potential risk to unrestrained occupants during the initial roll sequence and also during any subsequent secondary impact. The pole structure intrusion and interaction with occupants was not simulated due to the lack of known parameters and that the intrusion zone is clearly associated with severe traumatic injury.

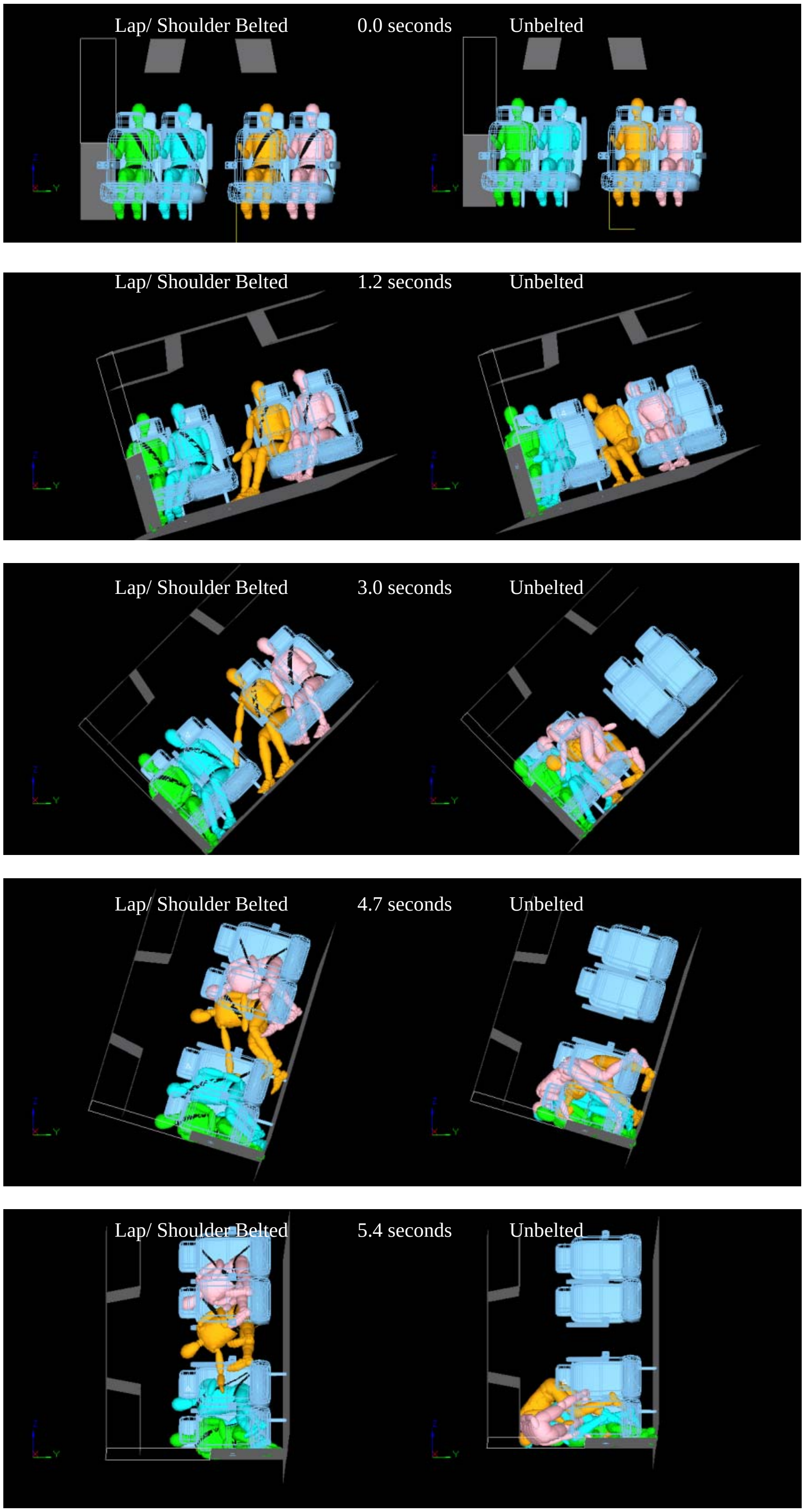

Figure 20: A comparison the lap/shoulder belted condition (left) with the no offset, unrestrained condition (right) at five positions in time.

Figure 21: Post-Test View of Rear Restrained Test Dummy (1992 MCI MC-12). The image has been rotated and flipped such that the occupant motion appears to be in the same direction as the accident vehicle's roll.

Figure 22: Post-Test View of Rear Restrained Test Dummy (2000 MCI 102-EL3). The image has been rotated and flipped such that the occupant motion appears to be in the same direction as the accident vehicle's roll.

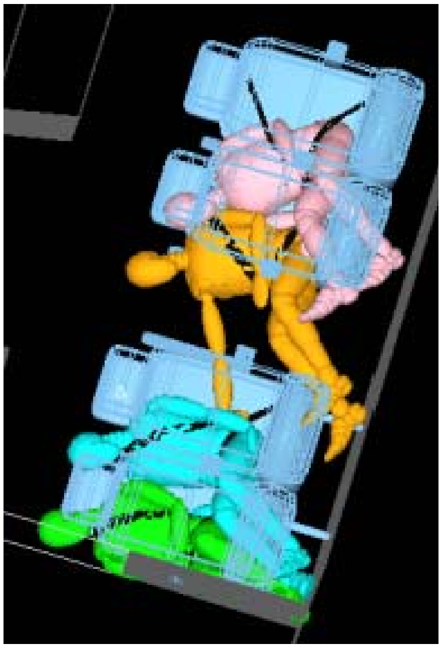

Figure 23: A still image showing the simulation at 4.7 seconds for the lap/shoulder belted occupants. (The pink occupant is still the far side occupant.)

7. SUMMARY

The results of the MADYMO simulation showed that unrestrained occupants were vulnerable to injury during the bus overturn due to impacts with other occupants and impacts with interior surfaces. Occupants were then in close contact with the window and sidewall structure adjacent to the ground at the end of the simulation. As a result, unrestrained occupants were also vulnerable to ejection if window integrity was lost. Simple variations in seating configuration such as seat orientation and armrest position greatly affected kinematics and injury predictions. After the bus overturned, unrestrained occupants were piled on top of one another in the region beside the window between the seats and the luggage racks. Every occupant's head was in this region and far side occupants had a large portion of their thorax and pelvis in the region between the tops of the seat backs and the luggage racks. This position placed the occupants in a position vulnerable to injury given the intrusion that followed from the secondary impact with the sign pole structure, which intruded in the region between the tops of the seat backs and the luggage racks.

In the simulation, lap/shoulder belted occupants were contained within their seating compartments. Occupants seated on the far side of the roll (opposite the side near the ground) were able to partially escape the shoulder harness during the roll sequence, which then placed them in a position closer to the floor of the bus rather than closer to the luggage racks, reducing their vulnerability during intrusion at the window level later in the impact sequence. Near side occupants remained in a more upright position during the simulation, making them potentially more vulnerable to impact and intrusion of the sign pole structure. Simulated injury levels for the motorcoach rollover by itself were low for all lap/shoulder belted occupants.

Future work could focus on a detailed finite element model representing the structure of the motorcoach and the interior components in more detail. This model could enable a detailed reconstruction of the ground impact and impacts between occupants and the interior motorcoach surfaces.

Table 3: A summary of the injury values for all conditions tested.

Condition	Occupant	HIC-36	Chest Accel (g)	Chest Deflection (mm)	Nij (T-E)	Nij (T-F)	Nij (C-E)	Nij (C-F)	Neck Axial Tension (N)	Neck Axial Compression (N)
3pt belts	A	44.5	21.7	9.1	0.25	0.14	0.16	0.17	1293.9	-981
	B	19.4	20.1	15.9	0.24	0.12	0.15	0.18	1296.9	-1103.3
	C	21	21.4	10.7	0.31	0.08	0.09	0.16	899.7	-784.6
	D	8.5	20.5	5.5	0.17	0.07	0.07	0.13	898.8	-753.4
No Seat Offset	A	214.2	21.8	16.2	0.19	0.16	0.36	1.1	826.9	-5733.9
	B	205.7	26.5	21.1	0.25	0.17	0.6	0.91	1380.5	-4730.4
	C	453.4	19.2	21.5	0.14	0.08	0.22	0.56	383.8	-2962.9
	D	113.5	30.9	3.7	0.5	0.12	0.14	0.2	1537.5	-960.36
33% Seat Offset	A	98.8	13.6	2.5	0.19	0.2	0.87	0.5	617.7	-4187.6
	B	1940	10.7	1.7	0.13	0.11	0.12	0.82	615.2	-4625.2
	C	114.1	15.4	6.7	0.14	0.08	0.19	0.8	476.2	-4385.4
	D	143.1	30.2	5	0.17	0.15	0.14	0.28	1231.8	1160.3
50% Seat Offset	A	75.8	11.5	6.6	0.18	0.62	0.09	0.07	3871.9	-362
	B	350.9	13.5	1.6	0.25	0.17	0.44	0.94	1137.4	-4850.8
	C	193	11.9	7.9	0.22	0.07	0.36	0.77	627.3	-3744.1
	D	175.2	33.8	5.2	0.23	0.13	0.1	0.25	874.4	-1145.6
Single Occupant										
Armrest Up	A	103.7	30.9	1.9	0.15	0.09	0.76	2.42	647.7	-12122
Armrest Down	A	502.8	24.8	6.2	0.15	0.15	1.11	1.36	691.8	-5363.1
Armrest Up	D	137.8	25.1	1.6	0.13	0.05	0.11	0.27	579.6	-1118.4
Armrest Down	D	112.3	21.5	3.0	0.13	0.04	0.05	0.18	341.0	-837.7