ANALYSIS AND PREVENTION OF CHILD EJECTIONS FROM GOLF CARS AND PERSONAL TRANSPORT VEHICLES

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ABSTRACT

United States Consumer Products Safety Commission statistics indicate there are approximately 13,000 golf car related emergency room visits in the United States annually. Of these, approximately 40% involve children (i.e. age < 16) and 50% of these involve a fall from a moving car. Evidence also indicates that many passenger ejections occur during left turns. Children are especially susceptible to ejection because of their small size and reliance upon the hip restraint for stability. While adult ejections have been studied, the present study analyzes mechanisms of child ejection during left turns. Dynamic tests are presented wherein an anthropomorphic Hybrid III 6 year old dummy in the front passenger seat is ejected during a moderate left turn and ejection kinematics are analyzed. An Articulated Total Body (ATB) occupant simulation is also presented, which compares favorably with experimental results. Additional simulations are presented wherein a seatbelt is found to be effective in preventing ejection with minimal belt force requirements. While experimental and simulated occupant dummies do not include muscular reactions, the potentially rapid onset of vehicle acceleration indicates that real occupants, particularly young children, may not have time to react before the ejection process has begun. Results indicate that current hip restraints are not large enough to prevent the ejection of small children during a moderate left turn. Additionally, seatbelts or straps are effective in preventing ejection during driver induced accelerations. The small belt force requirements indicate that seatbelts designed for use in automobiles and meeting Federal Motor Vehicle Safety Standards (FMVSS) may not be necessary. Based on these results, it is recommended that children be prohibited from riding in golf cars without a seatbelt type restraint when driven on golf courses and that seatbelt type restraints be provided for each occupant, especially children, when driving outside the golf course setting.

INTRODUCTION

Research and data compiled across the country indicate that the use of golf cars[1] and Personal Transport Vehicles (PTVs) is rapidly expanding, as are the numbers or injuries related to their use. Recent research conducted by the University of Alabama at Birmingham [1] has indicated that about 1,000 Americans are injured in golf car related accidents each month. Another study completed by the Center for Injury Research and Policy at Nationwide Children's hospital in Columbus, Ohio [2] stated that annual injury rates for golf cars increased 130 percent over 16 years ending in 2006. This study suggested that rules should be in place banning children under 6 years old from riding in golf cars. These studies and their underlying data also indicate that passenger ejection is a dominant mode of injury in golf car and PTV accidents, especially when children are involved. The testing and simulations in the present study investigate the effectiveness and load requirements for preventing ejection of children seated in golf cars.

In addition to golf cars operated on golf courses, resort and retirement communities in the United States, as well as other local municipalities, now allow golf cars and Personal Transport Vehicles (PTVs) on streets as primary means of local transportation [3, 4, 5, 6]. In fact, local transportation of passengers is the express purpose of PTVs. Advertising for many PTVs produced by the major manufacturers (i.e. Club Car, E-Z-Go and Yamaha) specifically indicates that these vehicles are intended for "playing golf or cruising your neighborhood" [7] and "hauling kids" [8] and feature photos of young children riding in the vehicles. In response to the trend of using golf cars and PTVs off the golf course,

[1] While the term ''golf cart'' is used by general public, the manufacturers of those vehicles use the term ''golf car.''

the U.S. National Highway Traffic Safety Administration implemented requirements for safety equipment on Low Speed Vehicles (LSVs) that operate on public roads including mandatory seatbelts for all passengers [9, 10, 11]. However, these regulations define a Low Speed Vehicle as one having a top speed between 32 and 40 kph (20 and 25 mph). As a result, vehicles with top speeds below 32 kph (20 mph), such as golf cars and PTVs remain unregulated.

Golf cars and Personal Transport Vehicles are often substantially similar, are manufactured by the same group of companies, and are virtually indistinguishable to the common observer. However, the manufacturers differentiate these vehicles based on maximum speed and intended usage, which can lead to confusing or ambiguous distinctions. For the purposes of this study, it is sufficient to understand that according to American National Standards Institute (ANSI) standards, the term "golf car" applies to vehicles with a top speed of less than 15 mph that are "specifically intended for and used on golf courses for transporting golfers and their equipment" [12] while "Personal Transport Vehicle" (PTV) applies to vehicles with a top speed of less than 20 mph which are "operated on designated roadways, or within a closed community where permitted by law or by regulatory authority rules" not including golf cars [13].

Previous research performed by Seluga et al [14] and Long et al [15] has demonstrated the ineffectiveness of most hip or handhold restraint systems typically found on existing golf cars and PTVs. In fact, it has been demonstrated that these types of restraints can exacerbate the problem by acting as a tripping mechanism, increasing the likelihood that an ejected occupant will strike the ground head first. Additionally, the documented increase in golf car and PTV injuries is consistent with the data presented by Long et al [15], which indicated an increase in the number of injuries due to increased vehicle usage and the lack of any seatbelt requirements. This study also demonstrated the effectiveness of seatbelts in preventing passenger ejections. Thus, if seatbelts were provided and users exhibited comparable compliance rates to those for automobiles (i.e. approximately 80% [16,17]), then approximately 80% of ejection accidents could be prevented by providing seatbelts.

The debate concerning restraint systems on golf cars and PTVs has had opposing opinions both for and against seatbelts. The opinion that golf cars and PTVs should not have any type of seatbelt system has been primarily put forth by the National Golf Car Manufacturers Association (NGCMA), a non-profit corporation consisting exclusively of golf car manufacturers and organized "to promote the common business interest of its members" [18]. During the 1997 NHTSA rulemaking process related to the newly designated motor vehicle category of "Low Speed Vehicle" (LSV) [9], the NGCMA viewed the seatbelt requirement as "antithetical to the personal safety of drivers and occupants of golf cars" [10] and cited ANSI/NGCMA Z 130.1-1993 [19] which required a Rollover Protective Structure (ROPS) for any golf car containing seatbelts. Additionally, the NGCMA suggested that existing hip restraints do not prevent occupants from jumping or leaping out of golf cars to avoid injury when the car is about to rollover. Accordingly, the NGCMA Golf Course Safety Guidelines [20] state that "use of seatbelts without adequate overhead protection may result in severe injury or death." The investigation by NHTSA regarding the establishment of the "Low Speed Vehicle" (LSV) classification included research of golf car safety; until it was determined that NHTSA would only regulate Low Speed Vehicles intended for on-road use and with a minimum speed of 20 mph. Hence golf cars and PTVs with a maximum speed of less than 20 mph are not currently regulated by any federal agency and the decision to require seatbelts in golf cars and PTVs is left to state and local jurisdictions. It should also be noted that NHTSA in its final ruling concluded that "the conjecture by some commenters that it would be valuable to be able to jump out of an LSV are unsubstantiated speculation that is especially unpersuasive given the volume of data showing that ejection is extremely dangerous and that seatbelts are remarkably effective at preventing ejection" [10].

Accident Statistics

It is estimated that there were, on average, approximately 13,000 golf car related injuries requiring emergency room treatment in the United States per year from 2002 to 2007, not including fatalities that did not involve emergency room treatment. The estimated number of accidents steadily increased from roughly 11,000 in 2002 to over 17,000 in 2007 [21]. Of these, approximately 40% (i.e. over 5,000 per year) involved an ejection from a moving car, representing by far the most common type of accident. In cases where the location of the injury was reported, approximately 70% occurred at sports or recreational facilities (e.g. golf courses) while the remainder occurred at

locations such as private homes or public streets, indicating that these statistics do not make the distinction between golf cars and PTVs that the NGCMA does. When this data is filtered to include only children (i.e. age < 16 years), it is found that this age group is involved in approximately 40% (i.e. over 5,000 per year) of all documented accidents. Furthermore, children are substantially more susceptible to ejection than adults based on the fact that slightly over 50% of child accidents (i.e. over 2,600 per year) involve a fall from a moving car. Of these child ejection accidents, approximately 50% occurred at a sports or recreational facility, while the remaining 50% occurred either at home, on a street, or at some other public property. In light of these statistics, ejections from a moving car represent a significant number of serious golf car and PTV accidents involving children, the reduction of which would significantly improve occupant safety [1,2,22]. It should also be noted that according to the same statistics, approximately 10% of golf car and PTV accidents involve a rollover. Therefore, even if seatbelts did present some increased danger for passengers in rollover events as supposed by the NGCMA, the relative number of ejections accidents to rollover accidents (i.e. approximately 4 to 1) indicates that the addition of seatbelts could still offer an overall improvement of golf car and PTV safety. Furthermore, there are design opportunities available for reducing the number of rollover events [23].

In addition to the statistical injury data, CPSC case narratives also include some details regarding each accident. One common scenario for a passenger ejection accident is when a golf car or PTV, traveling near its maximum speed, is turned to the left. CPSC data from 2002-2007 contains many accident narratives that match this scenario closely, such as "riding with dad in golf cart, dad made a sharp turn and [patient] fell out" or "patient on golf cart at home, brother turned and threw him off cart." Many more of the "fall from cart" type accidents may also involve ejection during a left turn, but the accident narratives are too vague to make this determination in most cases. This theme is repeated in numerous news articles that report many serious head injuries, including some fatalities, that involve both child and adult passengers falling out of a golf car or PTV during a left turn [24, 25, 26, 27, 28, 29].

Current Designs and Standards

The major golf car and PTV manufacturers (i.e. Club Car, E-Z-Go and Yamaha) do not provide seatbelts as standard equipment with their golf cars and PTVs, though personal communications with many authorized dealers indicated that they will provide a seatbelt if the customer requests one. While it may be generally assumed that golf car users on a golf course are not likely to make use of seatbelts due to their need to frequently exit and re-enter the vehicle, the same may not be true for a PTV or a golf car used away from the golf course. In support of this contention, many private communities and municipalities where golf cars and PTVs are used as the primary means of transportation do require seatbelts. Obtaining some form of a seatbelt for a golf car or PTV is not difficult, since most golf car and PTV outfitters offer after market seatbelts [30,31] to meet the market demands for seatbelts that are not being met by the original equipment manufacturers. The community of Palm Desert in California was a pioneer in recognizing the use of golf cars on their roadways and adopted a transportation plan in 1993 requiring seatbelts in golf cars. Some communities, such as Bald Head Island, North Carolina, have recognized the safety benefits of seatbelts but rather than requiring belts on all vehicles, they only recommend that occupants utilize them if present. It should be noted that, contrary to the supposition of the NGCMA that "use of seatbelts without adequate overhead protection may result in severe injury or death," the authors are not aware of any incidences at these or other communities, where the use of a seatbelt had a negative impact on the injury outcomes of a rollover accident.

Unlike the Federal Motor Vehicle Safety Standard (FMVSS) #500 for Low Speed Vehicles, which requires a seatbelt be provided for each intended occupant, neither ANSI standard Z130.1-2004 "Golf Cars – Safety and Performance Specifications" [12] nor ANSI Z135-2004 "Personal Transport Vehicles – Safety and Performance Specifications" [13] require that any seatbelts be provided. In lieu of seatbelts, ANSI Z130.1 and Z135 require "a hand hold or combination hand hold/hip restraint, anchored securely to the [vehicle], creating a barrier to help prevent an occupant from sliding outside of the [vehicle]" [12, 13]. However, these ANSI standards provided neither design requirements nor test procedures to determine the effectiveness of the provided restraints. It has previously been shown experimentally and analytically that the existing restrains, typically no more than 6" tall and 12" long are ineffective for preventing passenger ejections [14, 15]. In addition to the fact that the top of the handhold is often lower than the seated occupant's center of gravity, the location of the handhold (i.e. at

the outboard edge of the seat) is the fulcrum about which an ejected passenger will tend to rotate. As a result, this type of handhold does not provide the passenger sufficient leverage to prevent ejection. Due to the ineffectiveness of these designs, occupant ejections are by far the most common type of golf car/PTV accident. Furthermore, the ANSI standards do not require the manufacturer to provide a recommended minimum occupant age. While both standards require a warning label to be affixed to all vehicles stating "remain fully seated and hold on when in motion," it is highly foreseeable that occupants will not always hold on while the car is in motion, which is especially true with regard to children. Additionally, small children whose feet cannot reach the floor may not have sufficient strength to prevent ejection during a moderate turn.

METHODS

Dynamic Child Dummy Testing

A series of tests were conducted utilizing a 2004 Club Car Villager PTV and a Hybrid III 6 year old dummy weighing 21.4 kg (47 lb). The test vehicle had designated seating positions for four occupants, two facing forward and two facing rearward. In each test, the child dummy was placed unrestrained in the right front seated position with a driver (see Figure 1).

Figure 1: Test vehicle with Hybrid III dummy

The vehicle in each test was brought up to full speed (i.e. approximately 21 kph [13 mph]) by the driver and the accelerator was then released and the car steered into a moderate but easily controllable left turn. In each test the occupant kinematics were recorded with digital video and still images.

Two methods of collecting performance data for the tests were employed. A tri-axial array of accelerometers (IC Sensors 3031-050) was affixed near the vehicle's center of gravity. All accelerometer data were collected following SAE Recommended Practice: Instrumentation for Impact Test – J211/1Mar95. The axis system was in accordance with SAE J1733 Information Report with positive X, Y and Z axes forward, rightward, and downward, respectively. All accelerometer data were collected at 1000 Hz and filtered using a SAE Class 60 filter. In addition to the accelerometer data, vehicle performance data were measured using a GPS-based system (VBOX, Racelogic LTD, Buckingham, England). Three-dimensional speed and positional data were collected at 100 Hz.

Biomechanical Simulations

Three-dimensional computer simulations of the test vehicle and the child dummy were created using the Articulated Total Body (ATB) simulation software [32, 33] for comparison with the experimental results. ATB is a simulation program that models the dynamic response of systems of connected or free bodies such as the human body during a dynamic event. It can be used to model a dynamic environment of surfaces and bodies that interact with one another according to the physical laws of motion and has been used previously to study ejections during motor vehicle accidents [34]. In addition to providing detailed numerical force and motion results, the program also produces graphical depictions of the simulation results.

To simulate the dynamic ejection experiments, a model of the test vehicle was combined with a model of a child dummy occupant based upon the geometry of each. The child occupant model was created using the Generator of Body Data (GEBOD), which is a companion program to ATB that generates a model of the human body for use in ATB simulations [35]. GEBOD utilizes regression equations to calculate the geometric and inertial properties of body segments based on the proportions associated with a 50th percentile child of a given age, height and weight [36]. The relevant geometry of the test vehicle (primarily the seat and hip restraint geometry) was measured directly from the test vehicle. Some of the relevant measurements are shown in Figure 2.

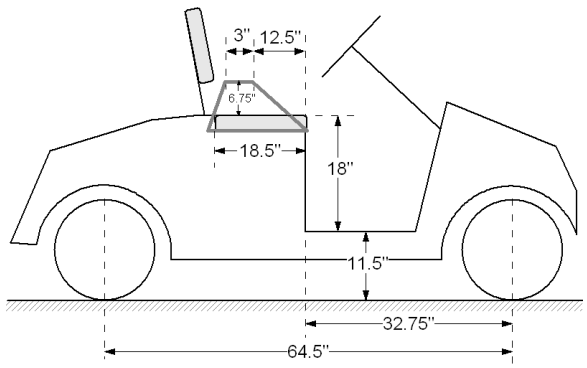

Figure 2: Test vehicle dimensions

The motion of the simulated vehicle was obtained from the experimental vehicle acceleration data described above. The coefficient of friction between the simulated passenger and seat was 0.5 based on averages obtained from testing typical clothing materials on PTV seat surfaces.

The simulations were first conducted with no attachments between the passenger and the vehicle (i.e. occupant not tethered or holding on) for comparison with the dummy experiment. For the purposes of these and all subsequent simulations, ejection was defined as a condition where the passenger's lower torso body segment moved over or around the hip restraint and traveled outside of the car. Next, the simulations were repeated with a spring-damper connection added between the occupant's right hand and the hip restraint, representing an occupant holding onto the hip restraint. These simulations were used to determine the effect of the occupant holding onto the hip restraint. Subsequent simulations were completed with a spring-damper connection between the passenger's left hand and the center of the seat, simulating the occupant holding onto a handhold, strap or the equivalent mounted near the center of the bench seat, though such a handhold was not provided on the test vehicle. Center seat handholds have been previously investigated [14] and these simulations were used to determine the grip and arm strength necessary to prevent child ejection in conjunction with such a device. The necessary grip strength was then compared to typical child strength capabilities to determine if it was feasible for a child occupant to avoid ejection by making use of a central handhold. Finally, additional ATB simulations were created wherein a simulated lap seatbelt was added to determine its effectiveness in preventing ejections and to quantify the belt strength requirements necessary to prevent ejection.

RESULTS AND DISCUSSION

Vehicle Dynamics/Occupant Kinematics

In Test 1 the PTV was brought up to a speed of approximately 21 kph (13 mph) followed by a moderate left turn which produced peak lateral accelerations of approximately 0.6 g (see Figure 3). This peak lateral acceleration was reached approximately 0.5 seconds after the onset of noticeable lateral accelerations. It should also be noted that during the left turn maneuver peak longitudinal decelerations of approximately 0.1 g were developed. The radius of the resulting turn was approximately 20 ft.

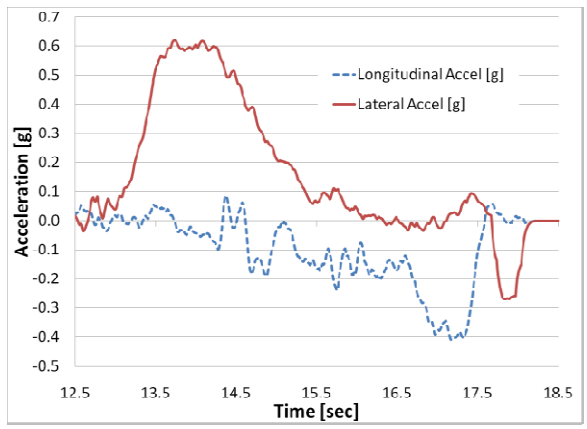

Figure 3: Test 1 recorded vehicle acceleration

The occupant kinematics demonstrated in the test show the child dummy moving laterally initially followed by a combined movement of the dummy moving laterally and forward (see Figure 4).

Figure 4: Test 1 observed occupant kinematics

The hip restraint during the ejection phase acts as a tripping mechanism placing the child dummy into a head first dive onto the asphalt track. Due to the lower inertial properties of the child dummy relative to an adult dummy, the ejection process is of a significantly shorter duration than that observed by the authors in adult ejections. This rapid onset of ejection and subsequent trip produced by the hip restraint leaves the occupant little remedy in avoiding ejection. It should also be noted that due to a child's small stature, an active child would have little opportunity to jump from the vehicle by pushing off the floorboards since the child's feet cannot reach the floorboards.

In Test 2 the PTV was again brought up to a speed of approximately 21 kph (13 mph) followed by a moderate left turn, but in this sequence, one potential driver response to the child dummy ejection was demonstrated. During the turn the driver remained watching the child dummy and at the first observable signs of a potential ejection, the driver commenced maximum effort braking. This maneuver produced peak lateral accelerations of approximately 0.5 g's along a turning radius of 27 ft followed by brake induced longitudinal decelerations of approximately 0.5 g's (see Figure 5).

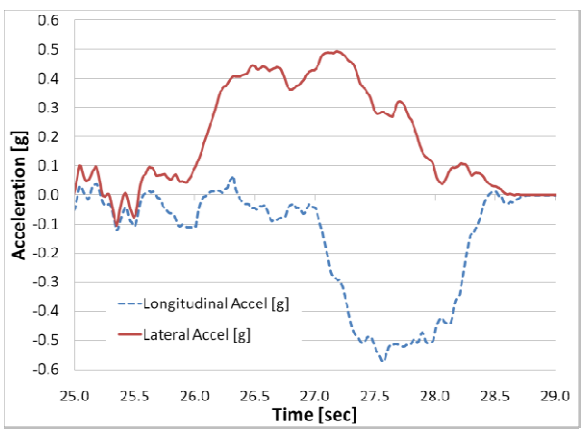

Figure 5: Test 2 recorded vehicle acceleration

Once again, as demonstrated in the previous test, the hip restraint acts as tripping mechanism putting the child dummy into a head first dive onto the test track (Figure 6). Additionally demonstrated in this test is that once the ejection process has started, a braking action by the driver will not prevent an ejection.

Figure 6: Test 2 observed occupant kinematics

These experiments demonstrate the effects of a moderate left turn and the resulting lateral and longitudinal accelerations which act upon a right front passenger and lead to ejection. Passenger ejection is most likely to occur during a left turn, since a right turn will tend to force the passenger to his left, towards the center of the car. Child passengers are especially susceptible to ejection because of their small size and consequent reliance upon the hip restraint to prevent ejection. While the experimental child dummy occupant does not include muscular reactions, the potentially rapid onset of vehicle acceleration (i.e. 0.5 seconds or less) indicates that real occupants, particularly young children, may not have time to react before the ejection process has begun. The results of these experiments indicate that current hip restraints are not large enough to prevent the ejection of small children during moderate left turns. It should be noted that driver ejections, while still possible, are generally less likely due to the fact the driver will inherently anticipate all steering maneuvers and is also able to use the steering wheel as a handhold.

Biomechanical Simulations

<u>Unbelted Occupant</u>

The simulated kinematics of the unbelted occupant ejection show excellent correlation to the experimental dummy results from both tests, as can be seen by comparing Figure 4 and Figure 6 with Figure 7 and Figure 8 (see Appendix A). Both the direction and the timing of the simulated occupant motions match the experiments. In the simulation of Test 1, the unbelted occupant leans and slides towards the passenger side hip restraint, due to the

lateral acceleration generated by the turning vehicle. Next, the occupant rotates over the top and around the front of the hip restraint and is ejected out the passenger side of the vehicle. Following ejection, the occupant's head strikes the ground. It should be noted that although the experimental and simulated dummy rest orientations are somewhat different (i.e. the dummy's feet are facing in different directions after it comes to rest), these differences occur after the impact with the ground. The occupant kinematics during the ejection phase and at ground impact show close correlation.

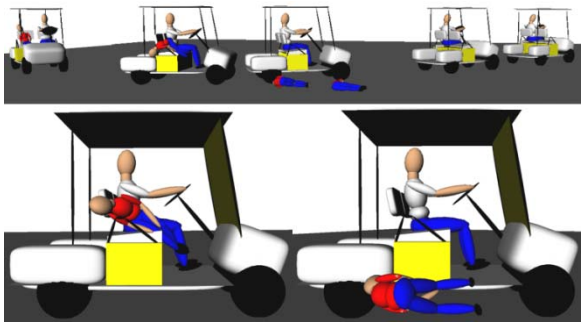

Figure 7: Test 1 simulated occupant kinematics (unbelted and untethered)

In the simulation of Test 2, the unbelted occupant again initially leans and slides towards the passenger side of the vehicle due to the lateral acceleration. Then, as a result of the braking induced longitudinal deceleration, the occupant slides forward, beyond the highest portion of the hip restraint, which is only 3 inches long. Finally, as in Test 1, the occupant rotates over the hip restraint and is ejected out the passenger side of the vehicle, striking his head on the ground.

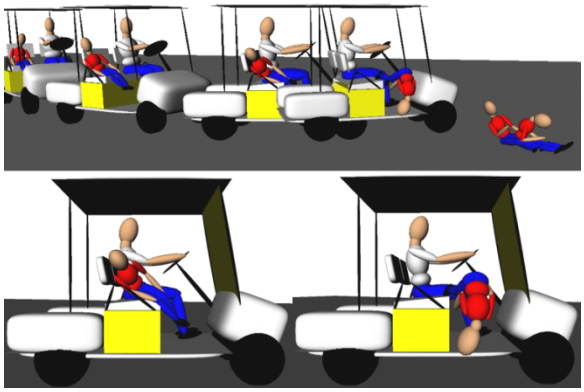

Figure 8: Test 2 simulated occupant kinematics (unbelted and untethered)

The close correlation between the experimental occupant kinematics and the simulated motions indicate that the ATB model can be utilized to accurately simulate golf car and PTV occupant ejection motions. These simulations also reveal that just before impact, the occupant's head has a speed of approximately 15-25 kph (9-15 mph), including a vertical component of velocity of approximately 10-12 kph (6-7 mph) which is equivalent to a fall height of 0.4-.5 meters (1.4-1.5 ft). Research regarding fatal falls from play equipment indicates that children who fall from heights as low as 0.6 meters (2 ft) onto soil or grass can receive fatal head injuries [37]. Thus, the ejection of a child from a golf car or PTV poses significant risk of serious, possibly fatal head injury, especially if the child lands on a paved surface.

Occupant Holding Outboard Hip Restraint

The simulated kinematics of the unbelted occupant holding the outboard hip restraint demonstrated a high risk of ejection, consistent with the findings of a previous study [14]. The ejection process of a child holding onto the hip restraint is depicted in Figure 9.

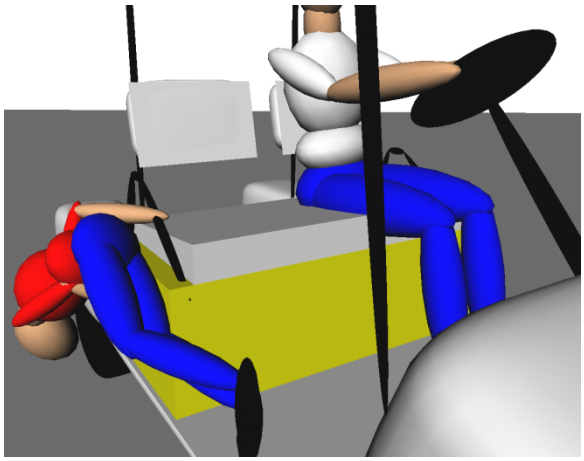

Figure 9: Test 1 simulated occupant kinematics (unbelted and tethered to hip restraint)

As can be seen from the simulated occupant motion, holding onto the hip restraint handhold located at the outboard edge of the seat is ineffective because that point is also the fulcrum about which an ejected passenger will tend to rotate. Therefore, this arrangement requires the occupant to generate large torques about the hand hole to counteract the lateral acceleration forces, which will be difficult since the point of force application (i.e. the outboard handhold) offers very little leverage about the occupant's center of rotation over the top of the handhold. Generating such torques will be difficult for adults and even

more difficult for small children, since they are less likely to be able to attain a "power grip" around the handhold (i.e. fingers flexed around the handhold to form a clamp against the palm) due to its size relative to their hands. Therefore, this type of outboard handhold may not provide the passenger sufficient leverage to prevent ejection, regardless of the occupant's grip strength.

Occupant Holding Central Handhold

The simulated kinematics of the unbelted occupant holding the proposed centrally located handhold demonstrated that with sufficient grip strength, such a handhold could effectively mitigate the risk of ejection (see Figure 10).

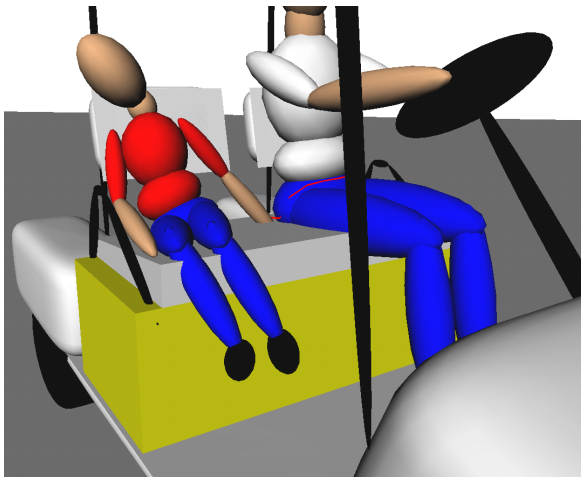

Figure 10: Test 1 simulated occupant kinematics (unbelted and tethered to central handhold)

In this case, the minimum peak hand force required to prevent passenger ejection was simulated for each test. For the simulated 21 kg (47 lb) 6 year old occupant, a peak hand force of approximately 67-107 N (15-24 lb) was required to prevent ejection. It should also be noted that during the simulated left turn, the central handhold caused the occupants left arm to be loaded in tension. Therefore, the only action required of the occupant is to hold onto the handhold, since active shoulder and elbow efforts are not necessary to prevent ejection. Child strength data indicates that children as young as 3-5 years old are routinely capable of hanging from a bar with arms straight for 45-90 seconds [38]. This data indicates that children are capable of supporting roughly half their body weight with each arm under tension when a sufficient handhold is provided, on par with the tensile arm force required to prevent ejection with a central handhold. Since the recorded lateral vehicle accelerations during a left turn last only 3 seconds, it is reasonable to assume that many children would have sufficient strength to hold themselves in a golf car or PTV during a moderate left turn if a centrally mounted handhold were provided. Therefore, a center-mounted left handhold would be an effective countermeasure for mitigating the risk of ejection and seems to be a prudent and inexpensive safety feature that also facilitates compliance with ANSI standard Z130.1. The limitation of such a handhold is that it is not a passive safety device as it does require that the occupant utilize the handhold.

Belted Occupant

Finally, the occupant simulations with a safety belt included demonstrated that a seatbelt is extremely effective at preventing the ejection of even a passive occupant (see Figure 11).

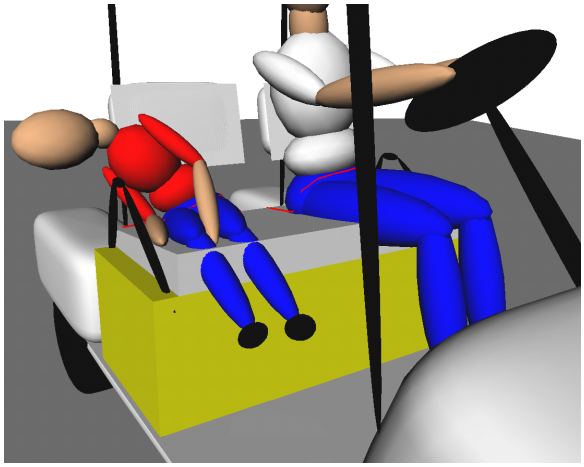

Figure 11: Test 1 simulated occupant kinematics (belted)

This is also consistent with previous dynamic dummy testing [15]. Furthermore, the simulations indicate that the peak force at the inboard seatbelt anchor point is approximately 220-490 N (50-110 lb) for the simulated 21 kg (47 lb) occupant (i.e. approximately 1-2 times the occupant's weight, see Figure 12). Simulated belt forces at the outboard anchor point are negligible. One explanation for the inboard lab belt forces sometimes exceeding the occupant weight is that the geometry of the seatbelt causes the tension to act at non-horizontal angle, requiring larger forces to generate the necessary horizontal loads to prevent ejection. The initial slack in the belt and the resulting magnitude of the interaction between the hip restraint

and the occupant also play a role in how much force must be provided by the seat belt to prevent ejection.

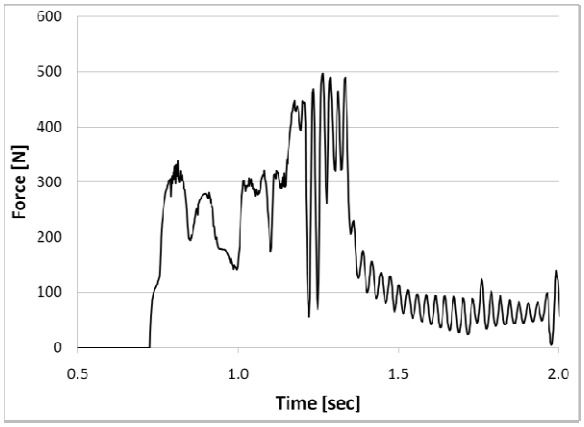

Figure 12: Test 1 Simulated inboard belt force

This belt load is significantly less than the loads experienced by automobile belts during impact events. Therefore, the strength of a golf car or PTV lap belt need not be build to automotive standards to be effective in preventing occupant ejection. Since, if a lap belt is provided, it would be desirable to provide one that could also prevent adult ejections, additional simulations were conducted using a 95 kg (209 lb) 95% simulated adult male occupant to characterize the peak belt loads that would be generated by a larger occupant. These simulations resulted in peak belt loads of approximately 980 N (220 lb), again indicating that an automotive strength belt need not be provided if the goal of the design is to prevent ejections during driver induced accelerations and not to offer protection in collisions. In fact, providing a safety strap that will break free under high acceleration conditions may be more appropriate since the proposed safety strap/belt's purpose is solely to prevent an occupant ejection during a maneuver and not to offer crash protection.

CONCLUSIONS

Summary

The coordinated experimental dynamic dummy testing and biomechanical computer simulation program presented in this study indicate that current golf car and PTV designs create a situation where young passengers are especially susceptible to ejection during moderate left turns. Furthermore, when passengers use the provided outboard hip restraint as a handhold, little protection is provided because the ejected passenger can easily rotate about the hip restraint due to the small size of the hip restraint and the insufficient leverage provided when holding onto the outboard handhold with the right hand. While a previously proposed center-mounted left handhold does offer better ejection protection when used, this feature cannot protect a passive occupant. Therefore, a lap belt restraint, which is extremely effective at preventing ejection, is the best method for preventing child ejections. Furthermore, the lap belt need only withstand minimal forces to prevent ejection during a non-impact event and thus automotive strength seatbelts meeting current Federal Motor Vehicle Safety Standards are not necessary to prevent occupant ejections.

Recommendations

In light of these results, it is recommended that children be prohibited from riding in golf cars without seatbelt type restraints when used on golf courses. If children are allowed to ride on golf cars with no seatbelts then, at the very least, a centrally mounted handhold should be provided to reduce the likelihood of ejection. Furthermore, passive hip restraint effectiveness should be improved on all golf cars and PTVs by increasing the size of the restraint in order to improve occupant retention when a seatbelt is either not provided or not used. When golf cars or PTVs are driven outside a golf course setting, seatbelt type restraints should be provided for all occupants, especially when those occupants are children. The community of Palm Desert in California offers one example of the type of safety rules that should be implemented in local communities.

APPENDIX A: ENLARGED KINEMATICS FIGURES

Figure 4: Test 1 observed occupant kinematics

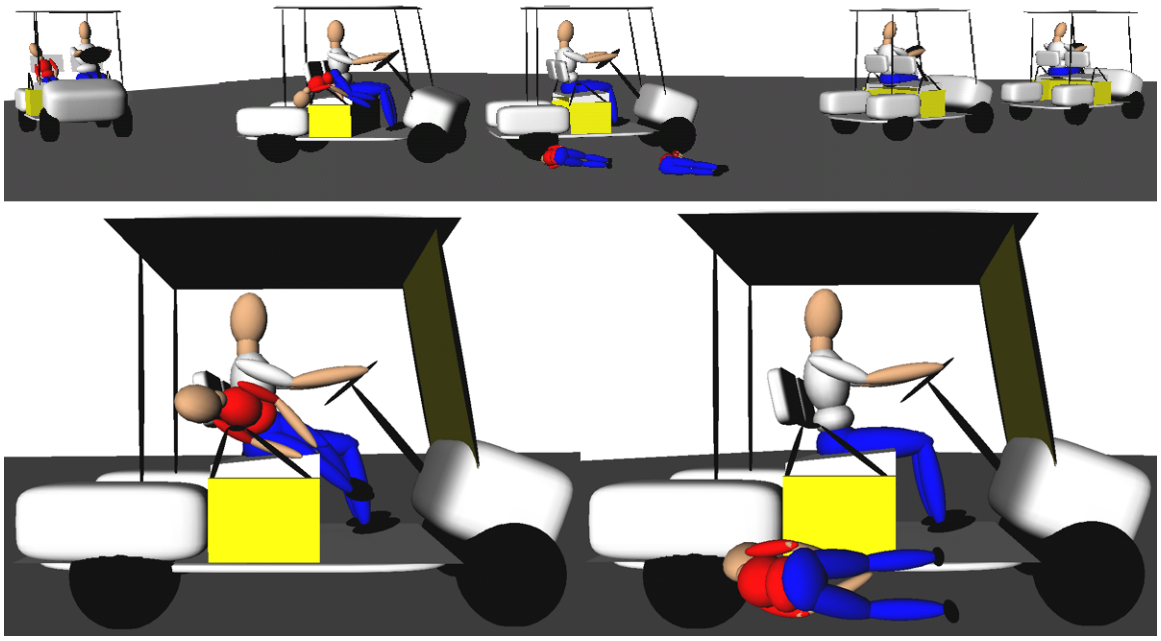

Figure 7: Test 1 simulated occupant kinematics (unbelted and untethered)

Figure 6: Test 2 observed occupant kinematics

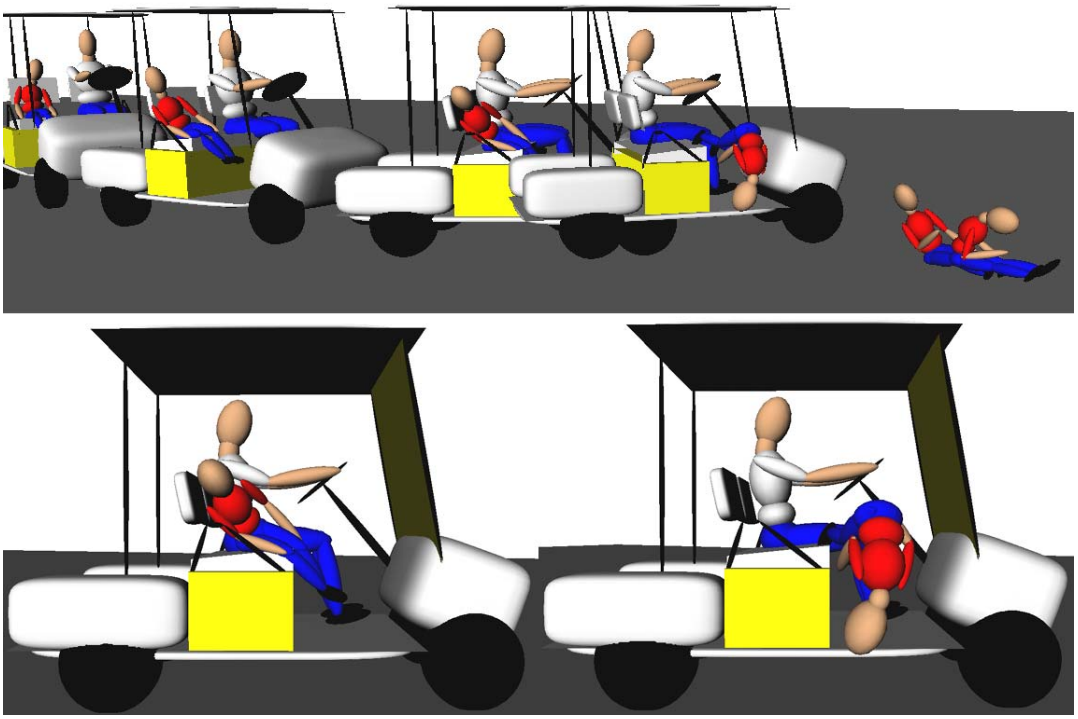

Figure 8: Test 2 simulated occupant kinematics (unbelted and untethered)

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USA AMBULANCE CRASHWORTHINESS FRONTAL IMPACT TESTING

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ABSTRACT

Recent epidemiological studies have identified ambulances as high risk passenger transport vehicles, particularly the rear compartment. It appears in the absence of USA ambulance safety standards or guidelines, non engineer end-users are driving changes in practice and policy in place of independent peer reviewed biomechanical and crash injury outcome data. This study's objective is to compare and analyze frontal crash biomechanical and crashworthiness research for ambulance vehicles, with a focus on application of the real world environment, and development needs for future standards. Frontal impact ambulance crashworthiness tests conducted over past 15 years, were identified and evaluated with a multidisciplinary approach consisting of automotive crashworthiness, emergency medicine, public health and EMS care delivery. Crash test data identified include: 25G to 34 G deceleration sled tests (delta V 20.9 to 32.3 mph); one full crash test of a bullet vehicle travelling at 36 mph crashing into another vehicle, impact Delta V of 30 km/h (18.5 mph) and deceleration of 14Gs to the rear compartment; and three fixed barrier frontal tests at a 40km/h (25 mph) delta V and 25 G impacts. There appeared to be a lack of correlation with real world crash forces in the conduct of the rigid barrier tests. The use of data from side facing occupants was also confounding. Ambulance crashworthiness is a complex system. Clearly demonstrated hazards have been identified in the limited real world crash injury/fatality data and the crash test data available. Testing must be based on meaningful real world parameters such as the forces that occur in actual crashes and the types of injury and fatality hazards to the occupants, so that development of standards and thus the design and construction of ambulance vehicles, can be focused to achieve adequate levels of occupant protection using current crashworthiness methodology already utilized in industry.

INTRODUCTION

There are some unique challenges to the crashworthiness, safety performance analysis and oversight of ambulance vehicles in the USA. Though there has been some very limited research focus on the crashworthiness and occupant protection performance of ambulance vehicles over the past 15 years, there has been no independent review and analysis of the limited work conducted to date. This vehicle safety realm is very much an interdisciplinary field, where the science of crashworthiness and occupant protection safety engineering interacts with acute medical care delivery, clinical ergonomics and also public health, public safety, transportation safety and safety data capture.

EMS is a relatively new industry when compared with other emergency services such as police and fire, and it is an industry that has an unusual history of beginnings within the mortician industry in the USA. The first modern ambulances were hearses, usually a Cadillac, a vehicle in which an occupant could be transported in the recumbent position. In the 1960's, just when general passenger vehicle safety and its occupant safety testing and oversight was rapidly advancing, ambulances transitioned into a box mounted on a truck or van chassis. Thus, largely due to end user and very much non automotive safety factors, ambulances moved away from general passenger vehicle safety oversight in the USA

Additionally, the interior of the box, the rear passenger compartment also became distanced from any technical realms of 'clinical ergonomics'. Reach and access to the patient and patient care equipment, also were without technical or scientific oversight or evidence base. The industry that took on this construction and retrofitting of the rear patient compartment box essentially was the recreational vehicle (RV) industry. That the construction, interior design and layout of the ambulance box in the 1960's

and today resembles features seen in the RV industry is part of that legacy [1to 5, 7 to 13]. Thus, the standard US ambulance vehicle has no overall technical crashworthiness and occupant protection safety performance requirements and oversight. For example, non-crashworthy side facing seating [14 to 19] on a non automotive 2 inch foam cushion bench and an interior layout that has poor or no consideration of the basic principles of operational ergonomics, in that occupants seated and restrained on that bench cannot reach either their patient or their medical or communications equipment.

So whilst the development of clinical emergency care has advanced technologically for example with defibrillation, and other state of the art medical therapies, the vehicle occupant safety issues pertaining to the delivery of EMS care have not kept pace with that advancement of the medical emergency care provided in that environment. Furthermore, despite the large strides the general automotive industry has made in the last 40 years in vehicle occupant protection and passive and active safety, this expertise has yet to be translated substantively to the safety of USA ambulance vehicles. Compounding this also, ambulance vehicles in the USA are a diverse fleet: vans, light and heavy trucks. So there is a spectrum of occupant protection and crashworthiness issues yet to be addressed. Moreover, it remains that there are currently no specific dynamic impact, crashworthiness testing standards for ambulance vehicles in the USA.

Prior to 1999 there were no dynamic safety testing and performance standards for ambulances globally. The first nationally approved safety performance standard was the Australian ASA 4535 in 1999 [20]. This code required dynamic impact testing with use of anthropomorphic crash test dummies (ATD) with a 24 G impact test forward and rear and 10 G laterally.

The CEN1789 [21] followed, implemented in 2000 in Europe and revised in 2006, requiring safety performance testing to 10 G forward, rear, laterally and vertically. Both ASA4535 and CEN1789 are mandated and not voluntary.

Thus ascertaining the safety of EMS transport vehicles (and products in that environment) had remained limited largely to expert opinion and peer evaluation in a piecemeal fashion globally until 1999 in Australia and 2000 in Europe, and still remains so in the USA.

Currently, US ambulances are built by aftermarket ambulance retrofitter/manufacturers, essentially to meet the Ambulance Manufacturing Division (AMD) of the National Truck Equipment Association's own design standards. These AMD 'standards' are essentially developed and overseen by the AMD, and technically outside of automotive safety and crashworthiness engineering oversight. It is similarly the case for the GSA KKK-F [22], purchase specification developed by the General Services Administration (GSA), which defers to the AMD 'standards'.

The GSA KKK-F ambulance vehicle purchase specification guideline is a purchase specification and not a safety performance standard. It does not provide guidelines for any dynamic crash testing – rather simply static tests, as is the case for the AMD 'standards'. Though there is reference to the Federal Motor Vehicle Safety Standards (FMVSS), however in the USA the rear compartment of ambulances have a specific exemption from that standard [23]. Also the GSA KKK is a voluntary specification and compliance is not federally mandated. Furthermore, neither GSA nor AMD write specifications or standards for any other vehicle and clearly AMD is not an independent standardizing body [7 to 11, 13]

Compounding this situation, EMS in the USA has been generally demonstrated in recent years to be a dangerous profession, and vehicle crashes have been shown to be the most likely cause of EMS work related fatalities [24]. The most dangerous part of the ambulance vehicle has been demonstrated in both biomechanical and epidemiological studies to be the rear patient compartment [1 to 5, 25]. It also happens to be the part of the ambulance vehicle that is largely exempt from the USA FMVSS [23].

Thus it is in this setting, of absence of independent comprehensive or meaningful safety performance standards, a poor safety record and piecemeal testing projects conducted essentially without independent automotive safety engineering or national oversight, that this study was embarked upon. Its goal was to critically review the ambulance occupant safety performance testing conducted over the past 15 years. The scope of this study was limited to frontal crash test scenarios and is focused on a methodological review. Detailed analysis of comparative comprehensive test data for these frontal crash tests is the subject of a subsequent review, given the major methodological issues uncovered in this report.

STUDY METHODS FOR ANALYSIS OF FRONTAL COLLISION PERFORMANCE TESTING

A compilation of frontal impact ambulance crashworthiness test studies conducted over the past 15 years was completed. The information compiled was limited to that which was conducted by USA based researchers. Thus the body of research conducted in the early 1990s by Dan Berry in the Ontario Ministry of Transport [26] was not included in this report. This compilation was achieved by an extensive search of peer reviewed papers, reports and electronic online databases and resources in the engineering, EMS and public health fields, and direct contact with those identified who had conducted ambulance crashworthiness testing. The papers and documents identified were evaluated in terms of automotive crashworthiness, emergency medicine and public health and EMS care provision. This evaluation addressed the real world setting of the testing, and the technical occupant protection and crashworthiness issues and challenges regarding the testing performed. This included a full spectrum from whether the tests reflected real world operational environments or vehicle crash situations, as well as configurations of the accelerometers, the nature and applicability of the types of anthropomorphic test devices (ATDs) aka 'crash test dummies' used, and also any ethics issues that pertained to the use of any human subjects. The clinical ergonomics of the rear patient environment and its interaction with the occupant protection issues were also included.

RESULTS

Frontal Collision Tests

Information on ambulance crash testing identified included peer reviewed and published studies in the engineering and medical literature. Society of Automotive Safety Engineers Technical Paper Series, Enhanced Safety of Vehicles Technical Papers, Academic Emergency Medicine, Pre-hospital and Emergency Care and a collection of material forwarded by representatives of National Institute of Occupational Safety and Health (NIOSH) at Morgantown, West Virginia, which included 1 PowerPoint presentation, 21 video clips and 2 documents (one of which was undated and not referenced). However this collection of material did not include the supporting technical data for the testing depicted in the videos. Moreover, this material provided came with disclaimers regards in the validity and accountability of the content. Even the accessible technical data that was available, pertaining to the NIOSH 2003 testing that was described in the SAE 2007 paper [27], which included vehicle accelerometer and crash pulse data, but did not include ATD or restraint data, had this disclaimer. [6]

The publications and documents identified related in total to four test series, three conducted by Levick et al, in 1996, 1999 and 2000, [1-5,7, 10, 28] and one series conducted in 2003 reported by Current et al [27]

Frontal crash tests identified – The four test series conducted are categorized as follows:

- 1996 Levick et al – Deceleration sled – loaded gurney with child ATDs [28]
- 1999 Levick et al – Hyge Accelerator – Rear patient compartment box secured to sled buck – x1 [2, 4]
- 2000 Levick et al – Full vehicle to vehicle crash test – x1 [3, 5]
- 2003 Current et al– Rigid Barrier x3 [27] (references to 29 sled tests, however limited data on the conduct of those tests)

Crash test data obtained for each test from the published documents and additional archival sources are presented and discussed below:

<u>1996 Levick et al Deceleration Sled Tests</u> - A standard ASA 1754 approved sled test rig [28] was modified with a customized welded anchoring mechanism to secure an ambulance gurney. Given that there was no available crash pulse for the forces exerted upon a gurney in an ambulance frontal crash, an approximation was made to utilize the existing crash test pulses used for ASA 1754 child seat testing, as for FMVSS 213 testing. It was understood that this would require validation with instrumented full vehicle testing. However, the resources to achieve that quantitative data were not available at that time, so this was considered the optimal path, given that there were clear uncertainties. This system was designed to produce a deceleration profile to model a standard vehicle full frontal impact to 24G, pulse duration approximately 85 ms, with a deceleration profile as in test data for a 52.7 km/hr sled test (Fig. 1). Test were conducted in October 1996 (Fig. 2), 25G to 34 G deceleration sled tests (delta V 20.9 to 32.3 mph or 33 to 53 km/h), in multiple configurations and restraint devices (as listed below) with 3kg, 9kg and 15 kg child ATDs.

No instrumented ATDs were used. ATD kinematics were recorded only [28]. A standard model 50 Ferno ambulance gurney was tested on this deceleration sled test rig with the following restraint device configurations:

i. an imported specifically designed child restraint blanket
ii. a plexiglas (perspex) cot
iii. infant and child safety seats secured as per described routine patient transport practices
iv. infant and child safety seats secured by prototype device. (Fig. 3)

The testing demonstrated that there was a spectrum of safety performance for the devices, with some catastrophic failures of some devices used in existing ambulance transport practice under the test conditions of the study. Also the testing demonstrated that simple inexpensive modifications to the use of existing devices enhanced their performance in this test environment (Fig. 3.)

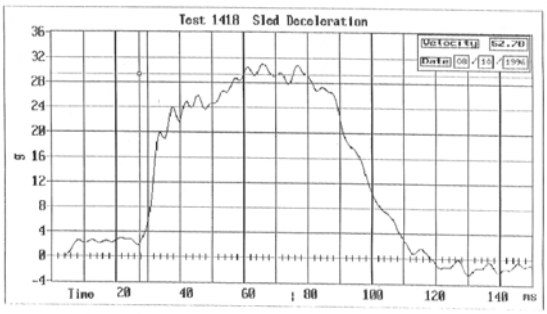

Figure 1. Sample sled deceleration pulse for gurney and non-instrumented child ATD test [28]

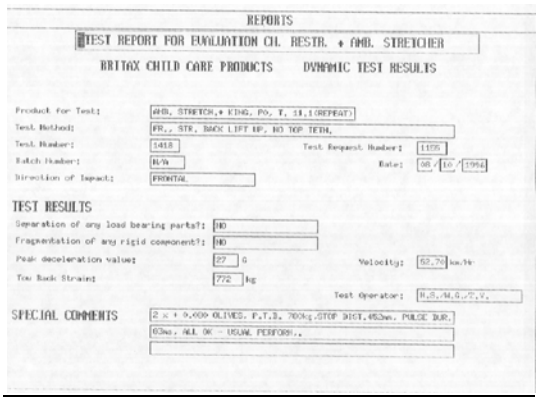

Figure 2. Sample data output for above gurney and non-instrumented child ATD test [28]

Figure 3. Configuration of infant restraint device on the gurney and sled [28]

Identified also were the limitations of conducting crashworthiness performance testing in the absence of testing standards in the ambulance environment. However, the study did demonstrate that interdisciplinary collaboration was key to ensure that the testing reflected real world clinical practices, and also highlighted the importance of determining appropriate quantitative accelerometer parameters that reflected real world ambulance crash impact forces.

<u>1999 Levick et al Hyge Accelerator Sled Test -</u> This test was conducted on the 24 inch HYGE test sled (Fig. 4) located at the Transportation Research Center in East Liberty, Ohio in September 1999. The target sled pulse was 26 G and 30 mph which was approximately the pulse used by the ambulance manufacturer for their 1991 sled test at TRC. *"While it was felt that this pulse was not an accurate representation of the crash pulse for the current chassis on which the ambulance box is mounted, more accurate information on the specific pulse for these vehicles could not be obtained from the chassis manufacturer. Without any information to make an informed decision to change the pulse, the decision was made to use the same pulse that was used in 1991 for the 1999 test. Both the 1999 and 1991 tests used TRC metering pin # 8"*(Crash Test Report Oct 1999). Accelerator sled testing of the ambulance rear patient compartment under frontal impact conditions with a target sled pulse was 26 G at 30 mph (48.3 km/h).

The ambulance box was configured with 2 instrumented and 2 non-instrumented ATDs positioned as in the real world environment.

Figure 4. Configuration of rear patient compartment box on Hyge sled

Two non-instrumented 95th percentile Hybrid-II ATDs were lap belted with the original existing belt systems and positioned in the rear occupant compartment, one on the rear-facing attendant's seat and one on the side-facing bench seat (Fig. 5). A Side Impact Dummy (SID) was unbelted, seated on the front of the side-facing bench seat and positioned next to a passive restraint device. An instrumented Hybrid-III 3 year old child ATD was restrained in a child restraint system, secured to the gurney via a dual belt path.

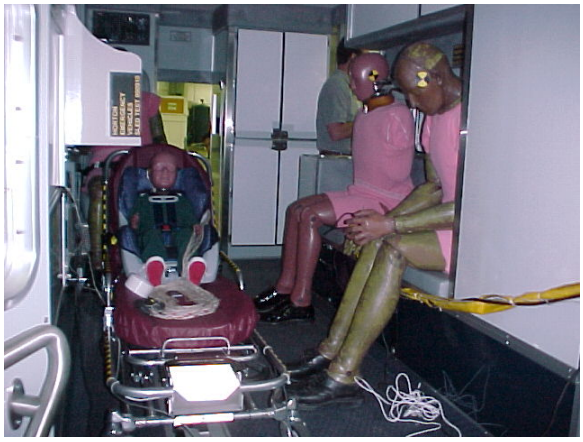

Figure 5. Pre-test configuration of ATDs in box [4]

The actual sled pulse achieved was 34Gs at 34.34 mph (55.27 km/h), and due to separation of the ambulance box from the chassis/sled, the crash pulse imparted to the patient compartment were 20Gs at 20.9 mph (33.64 km/h). The attachment system for the box to the chassis failed, the passive restraint device failed and the SID became a projectile with a measured Head Injury Criterion (HIC) value greater than 1000. The SID also struck other occupants of the rear compartment (Fig. 6).

This study highlighted the need for more research and development in this area. " *Specifically, refinement of the testing procedure to reflect more accurately real world crash conditions, and also modification of the data collection system so that data are not lost during events that occur during impact, should be performed".*

Figure 6. Post-test positions of ATDs in box[4]

The limitations of this study that were identified included:

- *There was data loss from the SID and the patient compartment, which limited the detail of the analysis that could be performed*
- *The vehicle patient compartment used may not have been representative of the fleet of ambulance vehicles on the road.*
- *There was no specific crash pulse or accelerator sled pin designed specifically for this impact environment*
- *There is limited data on the crash configuration for ambulance vehicles to determine which is the most hazardous for injury"*

The recommendations were: *"Full ambulance vehicle crash testing should be conducted of ambulance vehicles which are representative of the current fleet. These tests should be performed under conditions which represent real world crash scenarios so as to ascertain a more accurate set of crash pulses for these vehicles. These pulses are necessary in order for validated sled testing to be conducted so as to advance the understanding of safety initiatives*

required for these unique vehicles. There is also a need to collect the information on crash types that are associated with injury and fatality, including occupant and equipment position and restraint systems in use, so that the appropriate testing schedules can be conducted reflecting real world practice. "

2000 Levick et al Frontal Crash Test – Full vehicle ambulance crash tests were conducted in July 2000 at the Calspan Veridian test site in Buffalo, New York. The test involved a Type III ambulance bullet vehicle travelling at 36 mph (58 km/h) striking the side of van with an impact delta V of 18.5 mph (30 km/h) and deceleration of 14Gs to the rear compartment. The Type III ambulance was configured with accelerometers in the X, Y and Z orientations. Tri-axial accelerometers were placed at the vehicle CG as well as the center of the ambulance module (Fig. 7 & 8). Two accelerometers were attached to the gurney recording acceleration data in the X and Y directions (Fig. 8). This was specifically included so that the forces exerted upon the gurney during this type of vehicle crash could be determined.

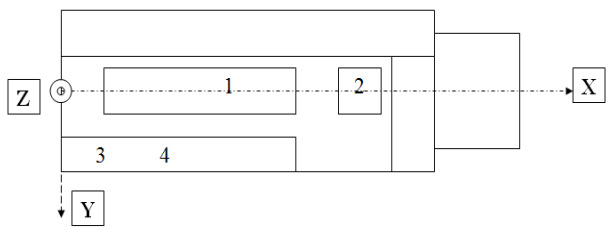

Figure 7. Positioning of lower box accelerometers

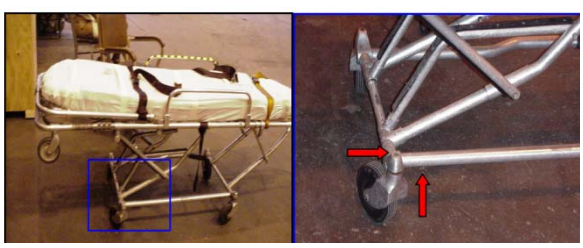

Figure 8. The arrows indicate the positions of the X and Y accelerometers on the stretcher in the 2000 crash tests of Bullet Type III ambulance.

Each of the four ATDs was installed into the Type III bullet ambulance, and were instrumented with tri-axial accelerometers in the head and in the chest. The ATDs were: an instrumented P1-3year old child restrained in child seat on stretcher; P2-95th percentile ATD in rear facing captain's chair with lap belt; P3-5th female unrestrained on squad bench and P4-50^{th,} restrained on squad bench with lap belt (Fig. 9).

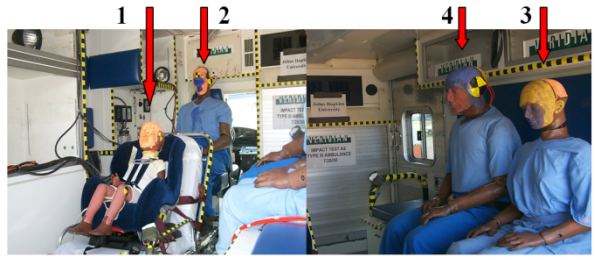

Figure 9. Positioning of the ATDs in the bullet vehicle in the 2000 crash tests [3]

In this test, the child ATD kinematics and injury criteria demonstrated an effective technique for restraint. However the unrestrained ATD (P3) was a risk to both itself and to other occupants. Analysis of high speed films in the ambulance rear cabin revealed life threatening safety hazards despite the fact that vehicle impact accelerations were survivable and occupiable space was preserved.

Figure 10. Initial impact of the bullet Type III ambulance

Figure 11. During the impact of the bullet Type II ambulance

Figure 12. Bullet Type III vehicle post impact

2003 Current et al - Fixed Barrier Frontal Tests - Three fixed barrier frontal impact tests at a 25 mph (40 km/h) delta V and 25 G impacts were conducted in 2003 using Canadian Type III box chassis ambulances (x2 1993, x1 1999 vehicles) with a targeted impact velocity of 48 kph (30 mph). No SID ATDs were used. A number of configurations of harness type restraint systems were tested. The three tests included: a 1993 E350 Type III ambulance with mobile restraint; a 1993 E350 Type III ambulance with mobile restraint and a 1999 E350 Type III ambulance with unrestrained occupant and lap belt only. The findings state "*In addition to an x-axis, or forward component, each of the frontal crash pulses was found to have a significant z-axis, or vertical, component which caused a forward rotation of the patient compartment ranging up to approximately 16.5 degrees. Significant cab-intrusion was observed as a result of the frontal tests that were conducted*."

Of note, the delta V in each of these tests was higher than the impact speed of the vehicles. There were references to some 29 sled runs having been conducted in the documentation provided from Morgantown. However, although 21 video segments were provided, some of which pertained to the rigid barrier tests, comprehensive technical data regarding these tests were not identifiable.

Live human subject testing was depicted in the videos provided in 2007 to the authors, of a vehicle in motion and the human subject wearing a complex harnessing device. The subject was mobile in the vehicle and not seated. No documentation regarding ethics approval was cited. The PowerPoint presentations included some bar charts of measurements. However, no explanatory material available regarding those measurements was provided.

DISCUSSION

Whilst ambulance vehicles in the USA have no requirement or guideline for crashworthiness dynamic impact testing, there have been a number of sled, fixed barrier and full vehicle frontal tests conducted over the previous 15 years. This study highlights the limitations in some of this testing and identifies some confounding aspects of the studies conducted and demonstrates the need not only for formal crashworthiness and dynamic testing standards, but also that testing developed and conducted without comprehensive and collaborative interdisciplinary input from appropriate technical expertise can lead to flawed or misleading results.

The original series of sled test work, of both the isolated gurney sled tests [28] and the rear compartment box Hyge sled test [2,4], highlighted the need for both real world injury data to be integrated into the development of testing profiles. Moreover, there is a need to have full vehicle crash tests conducted to optimally ascertain what ambulance vehicle crash pulses were.

Additionally, challenges were identified in accessing findings of testing conducted by the Morgantown government research team. However, the recommendations were apparently disseminated publically to non automotive audiences [29]. Furthermore, the lack of reference to existing peer reviewed technical publications in the field of ambulance automotive safety occupant protection by the government research team was surprising.

The stated purpose in each of the full vehicle tests was to identify the crash test pulse parameters that could be applied to assess real world crash dynamic performance of ambulance vehicles and their components using a sled test platform. Thus the need for these tests to model the real world scenario as closely as possible was paramount. The difficulties Levick documents in her first two sled test series (1996 and 1999), [1, 2, 4, 28] were how to determine an appropriate sled test crash pulse given that no full vehicle crash test data for the box chassis style of ambulance vehicles was available. Additionally, there was also the confounder of the diverse attachment systems of the rear box to the chassis.

Crash test protocol challenges - The sled tests in the Levick et al 1996 series [28] were conducted modelled on FMVSS 213 (Fig 1 and Fig 13) given that the focus was child patient transport and on the isolated gurney. However, the conundrum of the lack

of full vehicle crash test data was raised and the uncertainty of what the true crash forces were that would be exerted upon the gurney in a real world crash was highlighted. For the Levick et al 1999 Hyge sled test [2,4], the crash test pulse used was the same as that used to test an ambulance box, albeit a different rear compartment box, some years previously. The limitations of this strategy and the important need to acquire real world crash test data to develop true and meaningful crash pulses for this environment was clearly highlighted.

The full vehicle tests conducted by Levick et al in 2000 identified a sample frontal vehicle crash pulse [5], from a 44mph impact speed and a resultant delta V of 18.6 mph, which had a different form to either 213 or 208 (Fig 13).

Current et al [27] carried out crash tests into a full barrier concrete wall as shown in Figure 14. Presumably this was in compliance with the National Highways and Traffic Safety Administration' (NHTSA) FMVSS 208 crash test protocol at 48 km/h (30 mph). The Levick 2000 and Current 2003 pulse are compared with the 213 and 208 pulse below and discussed in more detail below (Fig. 13, 18).

Nature of Barrier - Consensus exists among consumer crashworthiness groups and technical experts in vehicle crashworthiness that an offset crash barrier test is more representative of real world crashes frontal impact crashes [30]. Crashing the full width of a vehicle into a concrete barrier at 90 degrees to the direction of travel (Figs. 14 & 19) results in high decelerations for the occupants and is demanding of the on board restraint systems such as seat belts, pretensioners and air bags. However, such crash tests typically provide little information about occupant intrusion observed in real-world crashes because the loads are distributed across the face of the vehicle. Occupant intrusion is critical to survival rather than testing if the restraint systems fire quickly enough in a highly demanding full frontal crash.

In the case of an offset test (Fig. 15), only one side of the front of the vehicle hits the barrier at a high speed into a crushable aluminium face that simulates the most important characteristics of another striking vehicle. The test is carried out at 64km/h (40mph). The crash forces are concentrated over the 40% overlap of the vehicle's front.

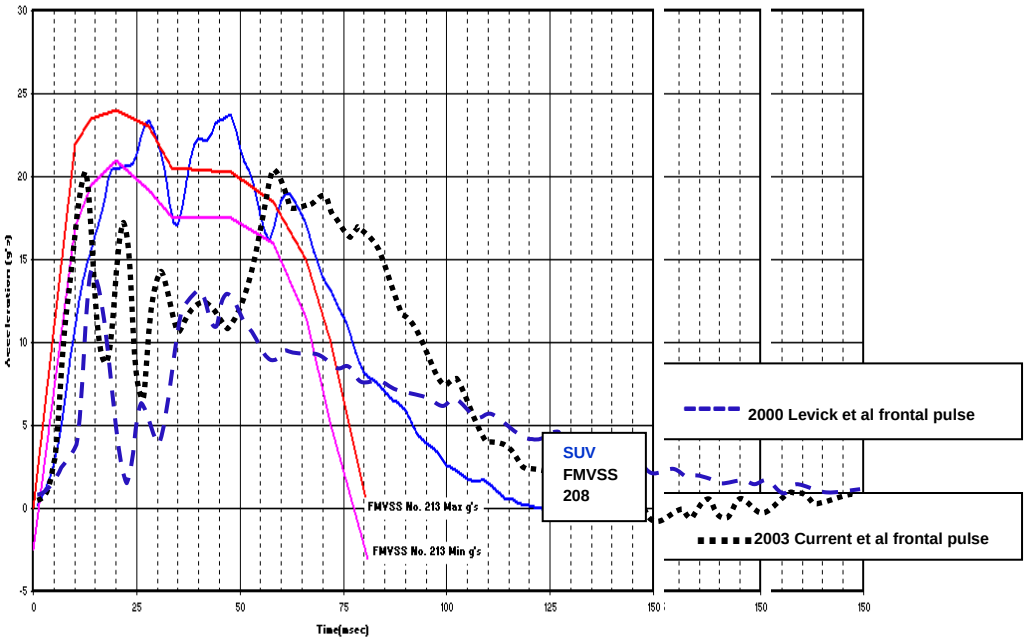

Figure 13. FMVSS 213 and SUV 208 vs 2000 Levick et al frontal crash pulse and 2003 Current et al frontal crash pulse [38]

Because one side of the vehicle is crushed, intrusion into the occupant compartment is more likely than for a full faced 100% barrier impact. The offset deformable barrier test should be on the driver's side where the steering wheel and pedals can increase the risk of injury unless the front of the ambulance is designed to absorb the impact's energy in a realistic way.

Another confounding issue is that the results from either full-width crash tests or offset tests cannot be used to compare vehicle performance across weight classes [31]. The crash energy for heavier vehicles such as the ambulances tested by Current et al [27] is much higher than for a car or SUV. It is well accepted that heavier vehicles can provide better protection to occupants in real world crashes so long as they strike other lighter vehicles. However, such vehicles can also be more aggressive to other smaller crash partner vehicles [33].

Paine et al [32] indicate that an offset crash test into a deformable barrier will highlight any load concentrations that can result from box-section heavy chassis framed structures punching (spearing) into the deformable barrier. Systems designed to achieve better results in a full frontal barrier test, where the frame crushes or buckles against the rigid concrete wall, can be much less effective in an offset deformable barrier test with poor energy dissipation and aggressivity to other road users.

Paine et al [32] also point out a number of other issues why a deformable barrier test is superior to a full frontal crash test in terms of occupant crashworthiness. Large intrusion negates any advantages any restraints may provide for the occupants for ride down and hence survivability.

Though there were no ATDs used in the front cab in the rigid barrier tests by Current et al, Current et al [27] indicate that Ambulance C provides sufficient survival space for the occupant based on two SAE standards J1522 and J833 [34], [35].

Inappropriate standards are being used in this instance to assess the crashworthiness of the crash tested ambulances. Neither SAE J833 nor J1522 are occupant protection or crashworthiness standards. SAE J833 is an ergonomic standard specifying human physical dimensions to be used in construction, general purpose industrial, agricultural tractors, forestry and specialised mining machinery categories. SAE J1522 is the recommended practise for describing the two-dimensional 95th percentile truck driver side view, seat stomach contours for horizontally adjustable seats. These standards are essentially ergonomics standards. To assess risk to occupants of vehicles, it is essential that crash test dummies and generally accepted injury criteria such as those provided by Eppinger et al [36] are used. Any crashworthiness assessment must be injury performance based.

Figure 14. Full barrier Current et al crash tests [27]

Substantial intrusion into the occupant space as shown in Figure 17 reported by Current et al [27] did occur. This intrusion would also have been much greater in a more realistic offset crash into another vehicle of similar mass. Hence, the authors of this paper disagree with Current et al's [27] conclusion in that Ambulance C, deemed by them as providing adequate protection to the occupants, in fact would not in an offset crash test. It would most likely provide inadequate protection. ATD crash dummies and injury measurement instrumentation were not used to assess survivability in the front cab in this test nor was the crash test protocol representative of a real world crash.

Current et al [27] claim that the situation would be worse for van type chassis. Figure 15 shows a Mercedes Sprinter van being crash tested. Note in this test, ATD crash test dummies are being used and an offset crash test is being carried out. Figure 16 shows a photograph of a Mercedes Sprinter ambulance, a model of ambulance used routinely

Figure 15. Offset crash test carried out by DEKRA Germany of a Mercedes Sprinter van

throughout much of Europe and Australasia, in some of the biggest ambulance fleets in the world.

Figure 16 .Mercedes Sprinter van ambulance

This Sprinter vehicle in the USA is distributed under a Dodge or Freightliner distributer. The passive safety provided to the front seat occupants is similar to that provided to occupants in crashworthy vehicles that have undergone rigorous consumer crash test protocols. Additionally, the clinical ergonomics are such that in the rear compartment of this vehicle, there is enhanced access to both the patient and the medical equipment whilst remaining seated and belted when compared to the box chassis design.

However, because there is no crash test protocol for these chassis box ambulance vehicles it is clear that their design and development has resulted in vehicles which are the antithesis of good crashworthy vehicles providing occupant protection for the front seat occupants as well as the rear box occupants.

Figure 17. Crushed front compartment, Current et al [27]

The occupant compartment in the van depicted in Figure 15 shows that despite the severe offset barrier crash, the occupant compartment has been maintained. Note also the air bags provided for decelerating the occupants head and torso.

Compare these photographs with the ones shown in Figure 17. The occupant space is substantially less in the case of a less severe crash test and no airbags are provided for the driver or passenger.

Crash pulses from two tests are shown again in Figure 18 for clarity. The 2003 Current et al [27] crash pulse is supposedly the average of all three barrier tests for the rear box. The 2000 Levick et al test pulse [5] is for the rear box of the bullet vehicle impacting a van ambulance as shown in Figure 18. This Levick et al test represents a real world intersection crash scenario. The target vehicle is a relatively large vehicle. Given that real world crash data suggests that whilst ambulance intersection crashes are associated with the most serious injury and fatality outcomes, the target vehicle is most frequently a passenger car, not a larger vehicle such as a van. Hence, this crash test scenario was set up to reflect the more aggressive crash outcome for the bullet ambulance vehicle. This also highlights that the Current et al [27] crash methodology is distanced from real world impact forces. The impact speed of the Levick et al [5] bullet vehicle was higher than that of the Current et al [27] rigid barrier test vehicle. It can be seen from the comparison pulse diagram in Figure 18, the measured crash forces are substantially higher in the Current et al [27] test and the pulse more severe and over a narrower time window. Note how much less severe the Levick et al pulse [5] is with extended duration to around 0.17 seconds and lower deceleration to about 14 g's peak. Interestingly Figure 13 shows these pulses are biphasic and have a very different configuration to the SUV FMVSS 208 crash pulse.

There is no suggestion that any offset barrier testing was conducted by Current et al, and no offset barrier crash pulse was available for any of the vehicle tests in this study. It would be interesting to overlay the Mercedes Sprinter offset barrier test pulse over these two chassis box ambulance crash pulses, and to analyze the potential occupant outcomes from ATD data in these three scenarios.

Another concern with the test results reported by Current et al [27] are the results from the interior of the rear box in what appear to have been frontal impact tests, possibly mock ups with box facsimile on a sled. The video images reveal some alarming results as shown in Figure 20. This series of images shows a dummy seated in the rear compartment, wearing a harness and sliding sideways during frontal deceleration impacting a cabinet in such a manner that would clearly fracture a human neck and result in serious head injury. There are no reported ATD neck loads or Head Injury Criterion (HIC) results in the 2007 Current et al paper [27]. However, HIC values are reported the 2005 Green et al paper [37], which states *"The use of mobile restraints in an ambulance patient compartment offers the potential to improve significantly the safety and health of EMS worker..... Use of these systems in the fully seated position provides opportunity for improvement over the existing seat belts"*. This appears confusing in the setting of the ATD kinematics. When compared with the findings of Richardson et al [14], Zou et al (Fig. 21) [15] and Stolinski [16 to 19] studies, the severity of the lateral neck loads appear to be potentially injurious for side facing seated ATDs. It is not clear from the representation of the information in the charts [37], what the ATD data was on the side facing squad bench and thus the rationale for the clear recommendations above.

It would be of interest to have access to the detailed ATD data for these 29 tests, and also to conduct the tests with a SID as was done in the Levick et al 1999 [2, 4] test configuration, so that the ATD data would be more realistically representative of the lateral forces exerted on the head and neck and chest of the dummy. Additionally, the validation of the use of ATDs in a standing configuration was not provided. There were video clips of live human subjects in out of seat position and in harness configurations in a moving vehicle. In the absence of the detailed methodology and data, comprehensive and effective analysis of the video footage cannot be completed.

From the occupant biomechanic performance dynamic impact testing conducted by Richardson et al, [14] there are some relatively simple strategies that can address the issues of occupant protection on side facing seating in forward moving vehicles. A simple design fix highlighted to improve the safety of this configuration would be to place lateral protection to support the head and upper body. This would prevent the occupants head and torso from being

forced into extreme lateral flexion and crush of the head and neck.

It is obvious from the above that a paradigm shift in thinking is clearly required in the USA in regards to safety performance evaluation, design and manufacture of ambulance vehicles. Designers and manufacturers need to begin to use the injury performance crash test criteria commonly used throughout the automotive industry to ensure the safety of the front and rear vehicle occupants.

Figure 19. Current et al 2003 rigid barrier test [27]

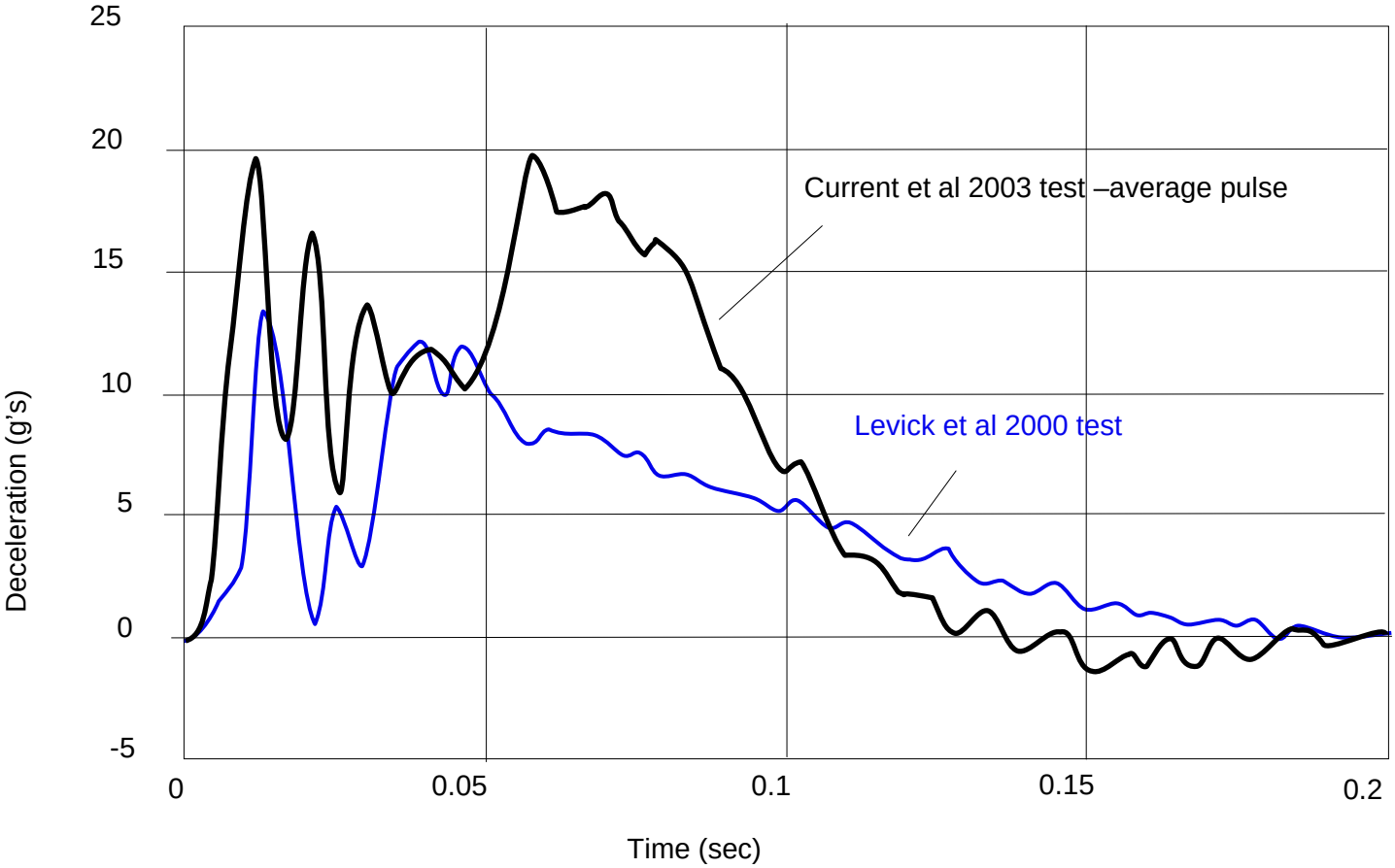

Figure 18 Crash pulses from 2003 Current et al [27] full barrier tests and crash pulse from Levick et al 2000 frontal full vehicle test [5].

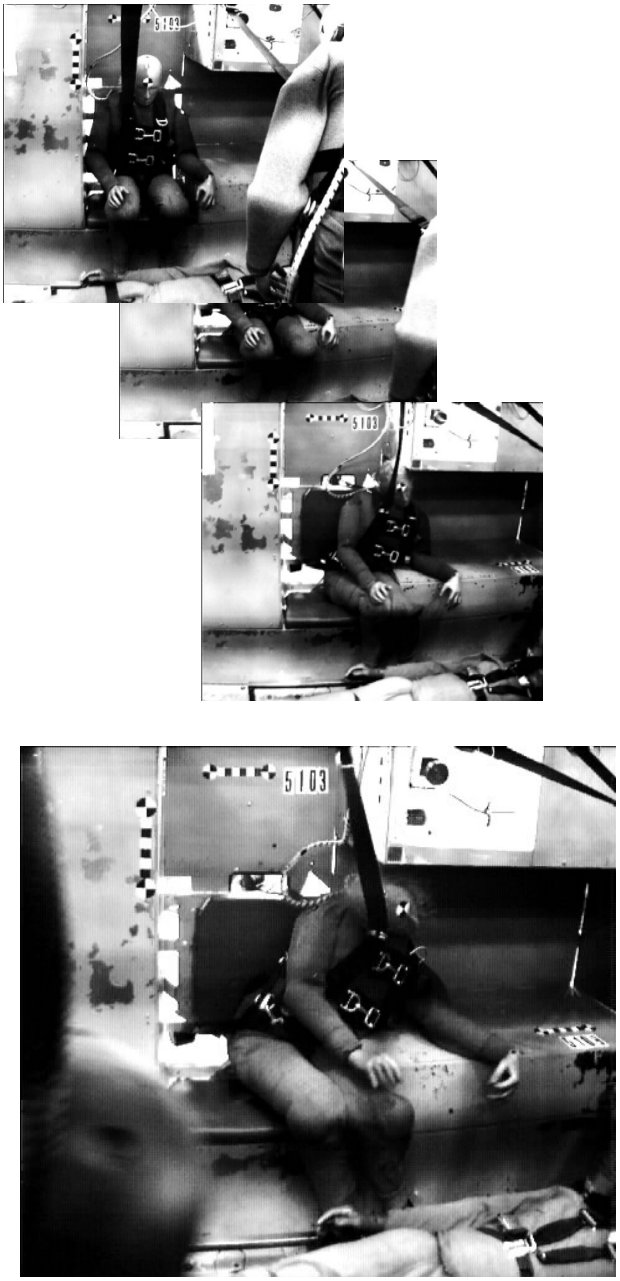

Figure 20. Occupant seat sideways in full harness – Current et al tests. Note how occupant would most likely have received a serious head and neck injury. [37]

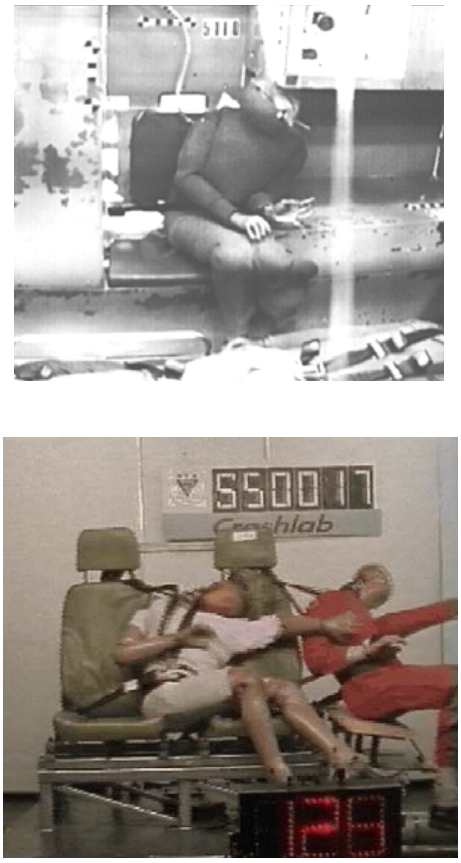

Figure 21. Demonstration of hazards to side facing occupants in a frontal crash, even in absence of cabinetry [37, 14]

CONCLUSIONS

Failure to conduct ambulance crash test scenarios based on real world crash, injury and fatality data and information has resulted in the use of rigid barrier vehicle crash tests generating impact outcomes and profiles that may not be consistent with real world crash events.

Development of ambulance crash testing profiles to form the basis of a testing standard must be driven by appropriate scientific test data that reflects the outcomes seen in the real world environment. Such testing profiles should be overseen by independent experts with a technical background in the relevant fields of population based injury and fatality vehicle crash data, occupant biomechanics, clinical ergonomics, vehicle crashworthiness and vehicle crash testing.

It is apparent from these comparisons, and the previously published fatality data, and crash test data,

that a model to develop crash test pulses for ambulance vehicles must be based on valid testing parameters. As this study demonstrates, test outcomes from rigid barrier testing in the setting of these types of ambulance vehicles may result in confounded and unreliable test models.

In a setting where the funds for such research, as the safety of ambulance vehicles is scarce, focus should be on the most valuable and optimal testing methodologies. Encouraging interdisciplinary collaboration between automotive crashworthiness, ergonomics, emergency medicine, public health and EMS care delivery professionals in this complex field is paramount.

ACKNOWLEDGMENTS

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COMPUTATIONAL ANALYSIS OF A NEAR AND FAR SIDE FRONT OCCUPANT KINEMATICS IN A VEHICLE ROLLOVER WITH DIFFERENT RESTRAINTS

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ABSTRACT

The Volvo XC 70 2001 model is used to conduct the full scale rollover crash test to determine the glazing and roof performance. The biodynamic code MADYMO is used to model the vehicle and its occupant. The acceleration obtained from the full scale rollover test is used to prescribe the motion to the computational model. The front side occupants are 50th percentile Hybrid III ATD's.

A Finite Element belt model is used for the analysis because of its capability to simulate the slip of the occupant under the shoulder belt. The simulation is carried out with different restraint types to quantify the head lateral and vertical excursions. The restraint type includes the conventional three-point system, integrated restraint in which the belt is attached to the seat, and a restraint type in which an extra shoulder belt is added to a conventional and an integrated restraint. The driver and the passenger head kinematics are compared for each restraint type. A comparasion is made for driver and passenger head excursion for different restraint types to demonstrate the effectiveness of each restraint in reducing excursion. The study indicates that an integrated seat belt results in less lateral and vertical head excursion, as compared to the conventional restraint. This study also indicates no significant improvement in reducing head excursion by the addition of an extra shoulder belt compared to a conventional or an integrated restraint.

INTRODUCTION

Seat belts are an important active safety device in a passenger vehicle. Seat belts are intended to reduce injuries to a passenger by preventing the passenger from hitting the interior due to declarative forces. It is estimated that seat belts are responsible for saving 147,246 lives in the period 1975-2001[1]. The lap and shoulder single continuous loop restraint is the most popular seat belt system in the passenger vehicle. This restraint performance is enhanced by the introduction of retractors, webbing grabber, load limiter and pre-tensioners. Three-point restraints play a crucial role in frontal impact by avoiding the secondary impact between the passenger and the vehicle interior. The effectiveness of this restraint during rollover depends on the roof integrity, as the intrusion of the B-pillar tends to move the D-ring generating the slack in the continuous belt loop [2]. The slack in the belt could result in partial or complete ejection causing fatal head and neck injury. Figure 1 shows the fatal complete/partial ejection from different vehicle types. Figure 2 shows the rollover occurrence by vehicle types, which indicates higher rollover propensity for utility vehicles [3].

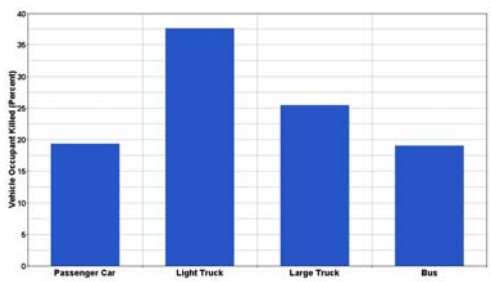

Figure 1. Fatal ejection from different vehicle types.

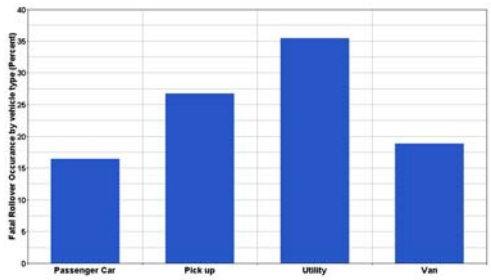

Figure 2. Fatal rollover occurrence by vehicle types.

According to 2001 FARS (Fatality Analysis Reporting System), only eight percent of the vehicles involved in rollover accidents resulted in twenty one percent of the serious injuries and thirty one percent of the fatalities. This makes rollover occupant protection an important research. It mandates a proper understanding of the single loop restraint dynamic behavior during rollover accidents. Several studies were conducted in the past; such as, Arndt et al. [4] conducted a study to correlate restraint slack and occupant excursion. Similarly, Glen Rains et al. [5] demonstrated the influence of a D-ring location on the dummy head excursion using RRT (Rollover Restraint Tester). James F. Pywell et al. [6] demonstrated the effectiveness of a restraint in reducing vertical and lateral head excursion when restraint is integrated with the seat using laboratory test fixture. All these studies are conducted using a laboratory tester with the quasicstatic and dynamic approach. Thorbole et al. [7] in their study demonstrated the effect of gravity on the occupant kinematics when using the laboratory tester compared to the airborne phase of rollovers, when acceleration due to gravity does not result in any relative motion between the vehicle and the occupants.

To address the limitation of a laboratory test to evaluate the performance of different restraints and their configuration, a MADYMO [8] computational model of a full scale rollover test was developed. The objective of this computational study is to compare the head excursion of a far side and near side ATD during the rollover event and to compare the performance of conventional continuous single loop restraints with seat integrated restraints by quantifying the head excursion. This study also quantifies the head excursion with an extra two point restraint added to the three point restraint.

METHODOLOGY

Volvo V70 Remotely Tripped Rollover test

A 2001 Volvo V70 XC, 4-door was used for the full scale trip rollover; as shown in Figure 3.

Figure 3. Test vehicle before rollover.

The vehicle was piloted remotely using a radio control system with the driver in the chase vehicle. The steering servo was capable of providing 11.3 N.m (100in *lbf) of maximum torque. It allowed 4 revolutions at 1000deg/sec maximum. The brake servo allowed 534 N (120 lbf) maximum force, and the throttle allowed 89 N (20lbf). The vehicle was accelerated at full throttle from a complete stop. Prior to approaching the edge of the concrete, a right steer input was initiated followed by a hard left steer input causing the vehicle to yaw counterclockwise and positioning itself approximately parallel to the concrete edge prior to the intended point of trip. The trip mechanism involved a ditch with loose soil 15m (50 feet) long, 0.2m (8 inch) wide and a 0.15m (6 inch) curb height; as shown in Figure 4.

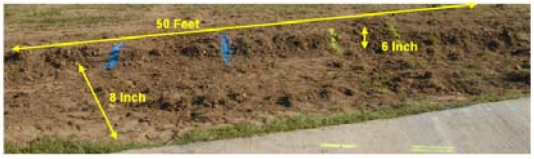

Figure 4. Trip mechanism using lose soil ditch.

The vehicle was instrumented with an IST Motion Master EDR 6DOF stand alone, 6-axis data acquisition system to measure the accelerations and angular rates. The instrument was oriented as per SAE vehicle axis convention and was fixed near the shift stick; as shown in Figure 5.

Figure 5. Instrumentation fixed near shift stick.

Four non-instrumented ATD'S were positioned in the vehicle, two in front and two in the second row; as shown in Figure 6.

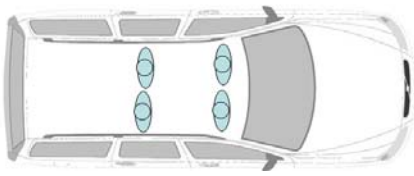

Figure 6. ATD position in the vehicle.

Figure 7 shows linear acceleration data. Figure 8 shows angular velocity data.

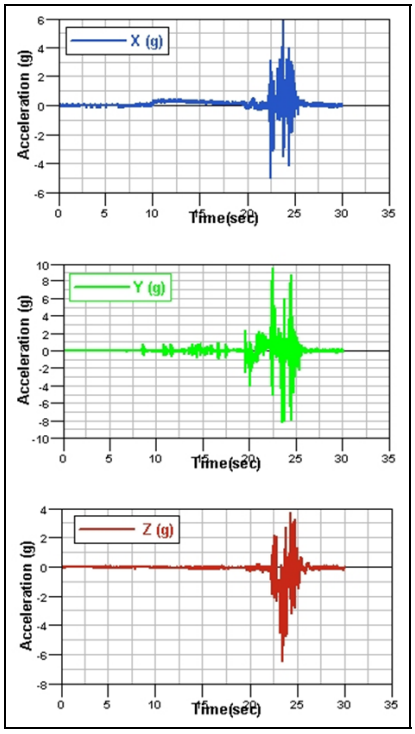

Figure 7. Acceleration data acquired during the test.

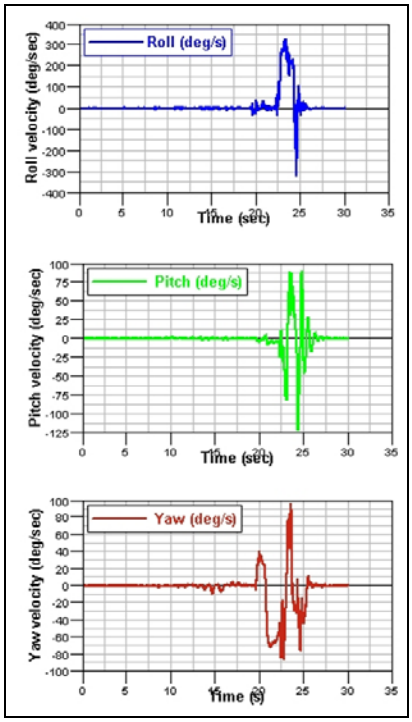

Figure 8. Angular data acquired during the test.

The main intention of this full scale rollover test was to demonstrate the occupant retention capability of modified glazing and door frame. The factory installed tempered glass WSA replaced with laminated glazing with a 7mil clear polyester film applied to the inner surface of the laminated glass. A Hybrid III 5th percentile female dummy was used as a restrained driver with a Hybrid II 50th percentile male dummy as a restrained front passenger. Second row passengers were two unrestrained Hybrid III 5th percentile female dummies. The vehicle motion data acquired during this test was used for the computational analysis intended to evaluate the performance of different restraint in terms of head excursion. Figure 9 shows the rollover sequence from approximately 22.34 sec when the vehicle hit the curb in the ditch. The vehicle rolled once, passenger side leading, without any airborne phase having a 321 deg/sec peak roll velocity. Figure 10 shows the post rollover condition of the vehicle which indicates no failure of the glass except for fractured windshield and back lite.

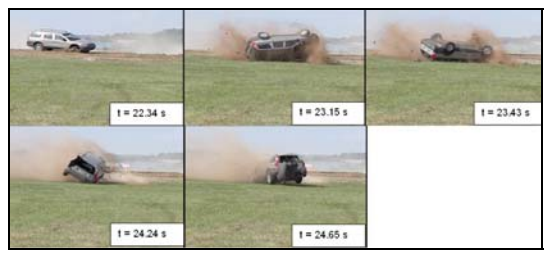

Figure 9. Rollover sequence after vehicle is tripped.

Figure 10. Post rollover vehicle condition.

For the computational analysis the motion data is used from the point where vehicle hits the curb.

Computational Analysis

The biodynamic code MADYMO is used for the kinematic analysis of the front row restrained occupants. This analysis is conducted with the intention of quantifying the front row occupant head excursion with different belt configurations using actual vehicle kinematics as obtained during a full scale rollover test. The data is used from the point where the vehicle hits the curb in

order to reduce the simulation time. MADYMO Version 6.3.1 developed by TASS, running on Intel Quad core Xeon 2.33GHz was used to develop the rollover simulation.

Model Overview - The computational model consists of an ellipsoidal vehicle interior coupled with two Hybrid III 50th percentile male ATD's positioned in the driver and passenger seat. The finite element belt model is used to restrain the occupants. Simulations are conducted for different restraint types to quantify the head excursion.

Interior Geometry - The interior of the vehicle is modeled by measuring the dimensions from the test vehicle. MADYMO ellipsoids are used to create the geometry surface. The interior consists of front seats a second row seat with dash board and steering. Figure 11 shows the modeled interior geometry of the vehicle. The glass is not modeled for this analysis. A free joint is positioned at the location where instrumentation was attached to obtain the vehicle kinematics.

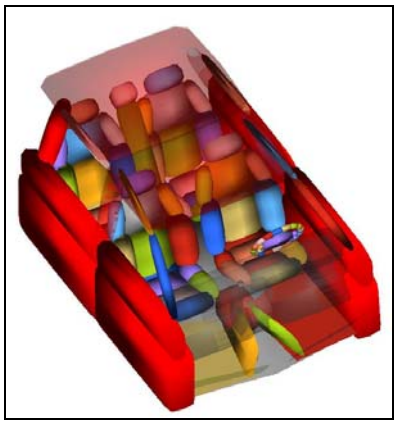

Figure 11. Vehicle interior geometry using ellipsoids.

The standard stiffness characteristics of the seat and the interior are obtained from the application manual of MADYMO [9]. A friction coefficient of 0.2 was used to model contact between occupant and the interior.

Seatbelt – The conventional three-point, single loop belt was modeled, as per location of the D-ring, buckle and floor anchor point in the test vehicle. The D-ring location for the integrated system was assumed on the seat back. The finite element belt in combination with the linear belt segment is modeled to restraint the occupant. The webbing characteristic is obtained from the application manual for MADYMO. A friction coefficient of 0.2 is modeled between the occupant and the belts.

ATD – Hybrid III 50th percentile dummies are used as the driver and the passenger. Initial joint positions of driver's shoulder and elbow are adjusted to replicate steering interaction. No joints in both dummies were locked.

Assembly of Sub-Models – To complete the biodynamic simulation of a rollover accident with different restraints, all of the subsystems as described in the previous section require integration. The ATD's were positioned on the seat and then the restraints were looped around them. The ATD's are allowed to settle down under gravity before they are restrained. Figure 12 shows the complete simulation set up with different restraints.

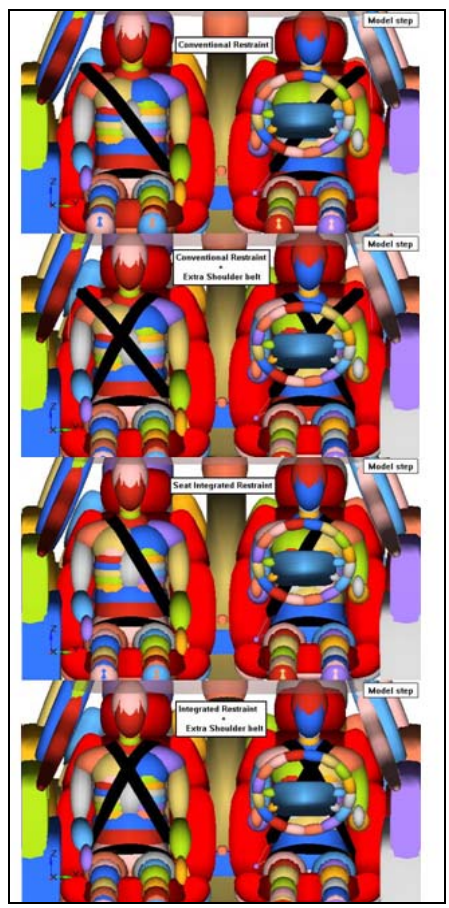

Figure 12. Simulation set up with different restraints.

Response measurement – For each simulation the head excursion of the driver and

the passenger is quantified. This excursion is measured relative to the marker body attached to the vehicle; as shown in the Figure 13. Initially, this marker coincides with the CG of head. The Y displacement provides the lateral excursion relative to this marker, and the Z displacement provides the vertical excursion relative to this marker.

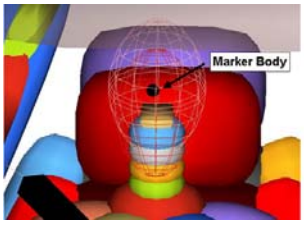

Figure 13. Head excursion measured relative to the marker body.

Simulation time – The actual rollover event was 30 seconds. The simulation motion file is modified to reduce the run time by starting it from the point when the vehicle makes a right turn followed by a hard left turn prior to its trip. The time step used is 10^{-5} with the Euler integration method. The computational time required for this simulation with the FE belt and two dummies was approximately three hours.

RESULTS

The head excursion is quantified relative to the marker body. The head excursion is quantified for two parts of a single rollover event. It is observed that the vehicle completed one roll anticlockwise as seen from the front, followed by additional 40 deg roll, and then fell back on the wheels clockwise in a 40 deg position. The head excursion is reported separately for two phases in a single plot. Figure 14 shows the roll angle of the vehicle with respect to the time and two different phases, as described earlier in this section.

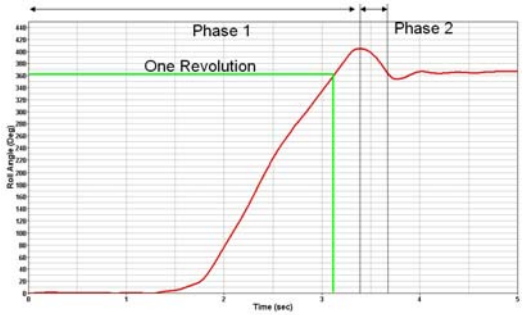

Figure 14. Vehicle roll angle plot during rollover test.

The simulation sequence for each run is reported in the appendix.

Conventional Restraint

Lateral and vertical head excursion is quantified and compared for driver and passenger. Figure 15 shows the lateral head excursion. Figure 16 shows the vertical head excursion for driver and the passenger. The solid blue curve represents the driver, and the dotted red curve represents the passenger. The passenger negative lateral excursion value in the plot is outboard head movement. The driver positive lateral excursion value is an outboard head movement. The positive value of the vertical excursion is an upward movement of the head for both driver and passenger.

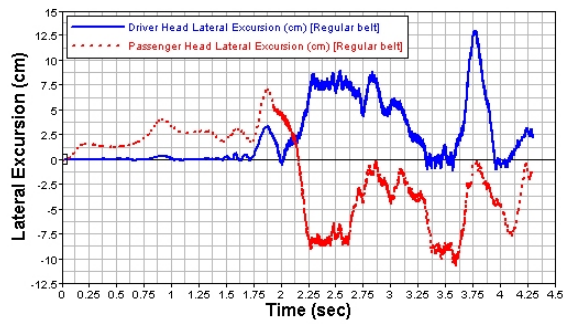

Figure 15. Lateral head excursion for driver and passenger with a conventional belt.

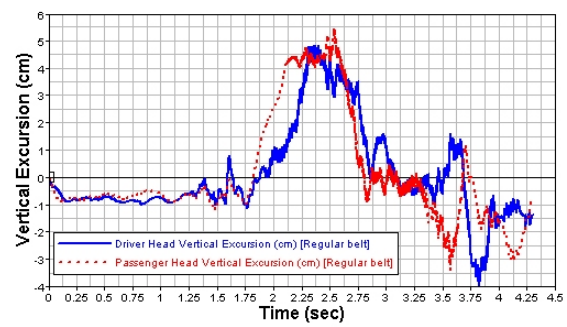

Figure 16. Vertical head excursion for driver and passenger with a conventional belt.

In phase one the peak driver head lateral excursion is 8.57 cm outboard and the passenger head lateral excursion is 8.7 cm. The maximum driver head outboard excursion for phase two is 12.9 cm. The vertical head excursion for driver is 4.7 cm, and 5.25 cm for the passenger. The maximum head lateral excursion occurs in the second phase when the vehicle falls back on the ground after rolling 40 deg about the passenger side. At the peak roll rate the lateral outboard

excursion for the passenger head is 5.2 percent higher than the driver head. The vertical excursion is almost identical. Figure 17 shows the dummy kinematics at peak roll rate.

Figure 17. Driver and passenger kinematics at peak roll rate with conventional restraint.

Seat Integrated Restraint

Figure 18 and Figure 19 show the lateral and vertical head excursion for driver and passenger. The solid blue curve represents the driver and the dotted red curve represents the passenger. The Passenger negative lateral excursion value in the plot is outboard head movement. The driver positive lateral excursion value is an outboard head movement. The positive value of vertical excursion is an upward movement of head for both driver and passenger.

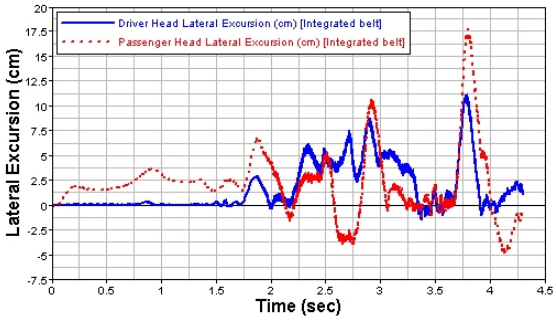

Figure 18. Lateral head excursion for driver and passenger with a seat integrated belt.

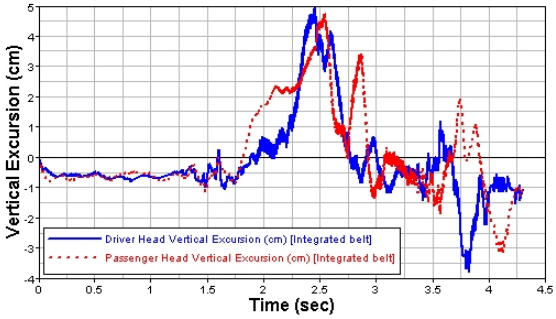

Figure 19. Vertical head excursion for driver and passenger with a seat integrated belt.

The peak driver head lateral excursion in phase one is 8.44 cm outboard and the peak lateral excursion for the passenger is 10.29 cm inboard. Passenger maximum outboard excursion for phase one is 3.46cm. In phase two the passenger head inboard excursion is 17.5 cm and the driver outboard head excursion is 10.8 cm. The peak vertical excursion for the driver in phase one is 4.71 cm, as compared to 5.58 cm for the passenger. At peak roll rate the lateral outboard excursion for the driver head is 5.16 cm and 2.75 cm for the passenger inboards with identical vertical excursion. Figure 20 shows the dummy kinematic at peak roll rate.

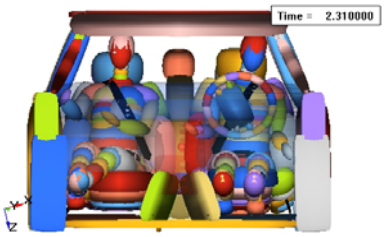

Figure 20. Driver and passenger kinematics at peak roll rate with integrated restraint.

Conventional Restraint Plus Additional Shoulder Belt

In this restraint an additional shoulder harness is added to a conventional restraint, such that the new belt crosses the shoulder belt of the conventional restraint. The top anchor point for the additional belt is on the seat. The bottom anchor point is on the floor. Figure 21 and Figure 22 show the lateral and vertical head excursion for driver and passenger. The solid blue curve represents the driver and the dotted red curve represents the passenger. The sign convention for head excursion is similar, as discussed in the previous section.

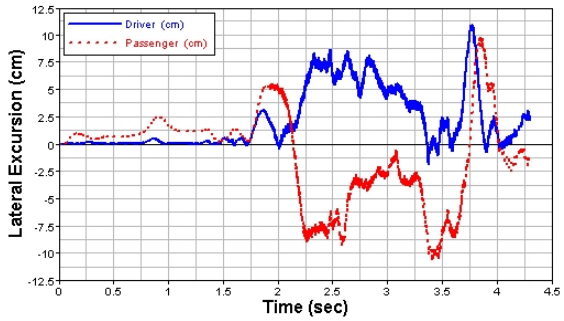

Figure 21. Lateral head excursion for driver and passenger with a five point restraint.

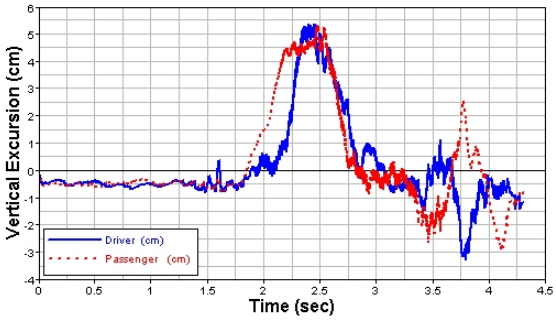

Figure 22. Vertical head excursion for driver and passenger with a five point restraint.

The peak driver lateral excursion in phase one is 8.25 cm outboard and 10.09 cm outboard for the passenger. In the second phase the driver outboard excursion is 10.85 cm and passenger inboard excursion is 9.71cm. The peak vertical excursion for driver and passenger is 5.2 cm in phase one. At peak roll rate the lateral outboard excursion for the passenger head is 23 percent higher than the driver head with similar vertical excursion. Figure 23 shows the dummy kinematic at peak roll rate.

Figure 23. Driver and passenger kinematics at peak roll rate with extra shoulder belt in conventional restraint.

Seat Integrated Restraint Plus Additional Shoulder Belt

In this restraint an additional shoulder harness is added to a seat integrated restraint, such that new belt crosses the shoulder belt of the conventional restraint. The top anchor point for the additional belt is on the seat and the bottom anchor point is on the floor. Figure 24 and Figure 25 show the lateral and vertical head excursion for the driver and the passenger. The solid blue curve represents the driver and the dotted red curve represents the passenger.

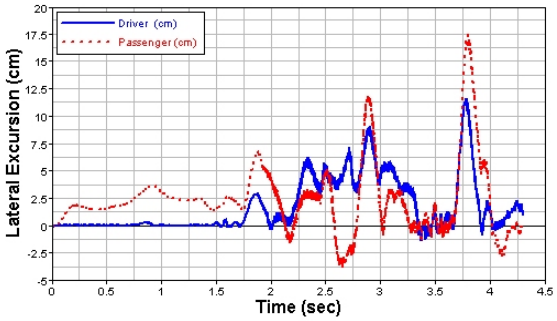

Figure 24. Lateral head excursion for driver and passenger with a five point restraint.

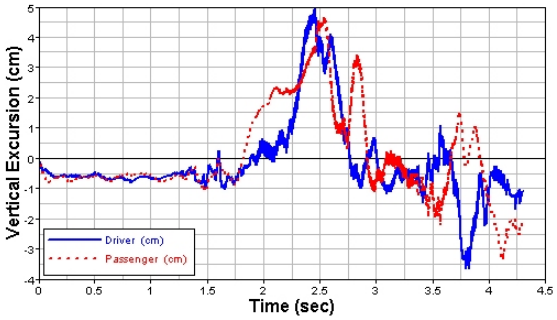

Figure 25. Vertical head excursion for driver and passenger with a five point restraint.

The peak driver lateral excursion in phase one is 8.64 cm outboard and 11.7 cm inboard for the passenger. In the second phase the driver outboard excursion is 11.25 cm and the passenger inboard excursion is 16.9 cm. The peak vertical excursion for driver is 4.8 cm and 4.5 cm for the passenger. At peak roll rate the lateral outboard excursion for the driver head is 4.82 cm and 2.71 cm for the passenger inboards with identical vertical excursion. Figure 26 shows the dummy kinematic at peak roll rate.

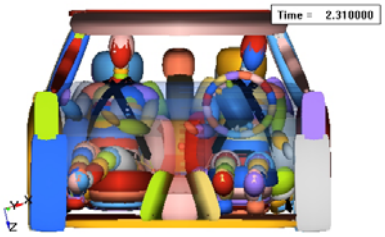

Figure 26. Driver and passenger kinematics at peak roll rate with extra shoulder belt in integrated restraint.

Dynamic Comparison of Different Restraint Types

All the restraint types as described above are compared with each other to identify the dynamic performance of these restraints during this rollover test. The performance is measured in terms of driver and passenger head excursion values. The head excursion is compared at the peak roll rate in phase one, and when the vehicle drops down on its wheels in phase two. Figure 27 shows the comparison of the driver head lateral excursion with different restraint types. This plot clearly indicates 31.4 percent less head outboard excursion for an integrated restraint when compared to a conventional restraint at peak roll velocity. This plot also shows no significant change in lateral outboard excursion with the addition of an extra shoulder strap to a conventional and an integrated restraint. In the second phase integrated restraint results in 15.5 percent less outboard lateral head excursion. Figure 28 shows the driver head vertical excursion comparison which indicates 52.17 percent less vertical excursion with the integrated restraint when compared to the conventional restraint at peak roll rate. This plot also shows no significant change in vertical excursion with addition of an extra shoulder strap to conventional and integrated restraints.

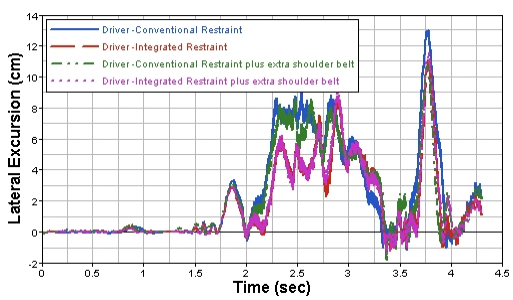

Figure 27. Driver head lateral excursion for different restraints.

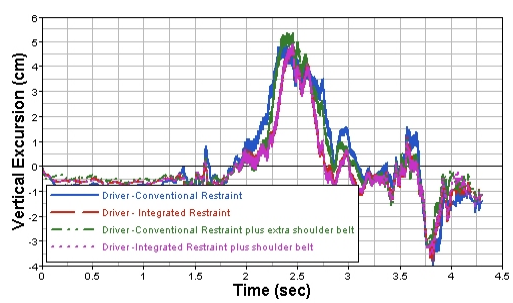

Figure 28. Driver head vertical excursion for different restraints.

Figure 29 shows the lateral head excursion for the passenger which indicates 8.8 cm outboard head lateral excursion for the conventional restraint as compared to 2.8 cm of inboard head excursion with an integrated restraint at peak roll velocity. This plot also indicates that the head stays outboard at a maximum value for 0.25 sec with the conventional restraint. In the second phase the integrated restraint results in 17 cm inboard excursion of the head as compared to 0.4 cm for the conventional restraint. Figure 30 shows the passenger head vertical excursion comparison which indicates 48 percent less vertical excursion with an integrated restraint when compared to the conventional restraint at peak roll rate. This plot also shows no significant change in vertical excursion with the addition of an extra shoulder strap to conventional and integrated restraints.

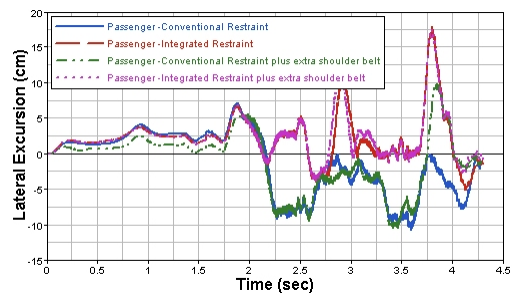

Figure 29. Passenger head lateral excursion for different restraints.

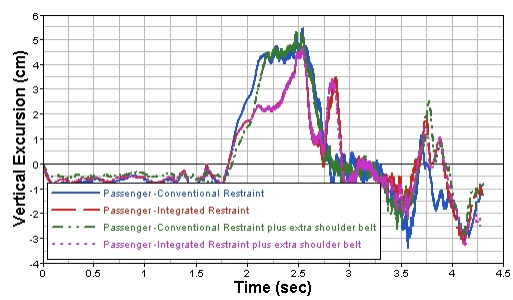

Figure 30. Passenger head vertical excursion for different restraints.

CONCLUSIONS

This study has demonstrated the dynamic comparison of different restraints in terms of head excursion during an actual rollover accident. Front row occupants head lateral and vertical excursions were measured and compared.

The integrated restraint results in less vertical and outboard lateral head excursion as compared

to the conventional restraint at peak roll velocity. As the vehicle start rolling the shoulder belt slip over the shoulder of the driver with the conventional restraint. No slip occurs with the integrated restraint. The addition of an extra shoulder belt to the conventional and integrated restraints does not have any significant effect on the head excursion for this rollover accident. The head excursion of a far side occupant is increased during the second phase of the rollover when the vehicle falls back on the far side wheel.

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[9] "MADYMO Application Manual, Version 6.3.1", Anon., TNO Road Vehicle Research Institute, Delft, Netherlands

APPENDICES

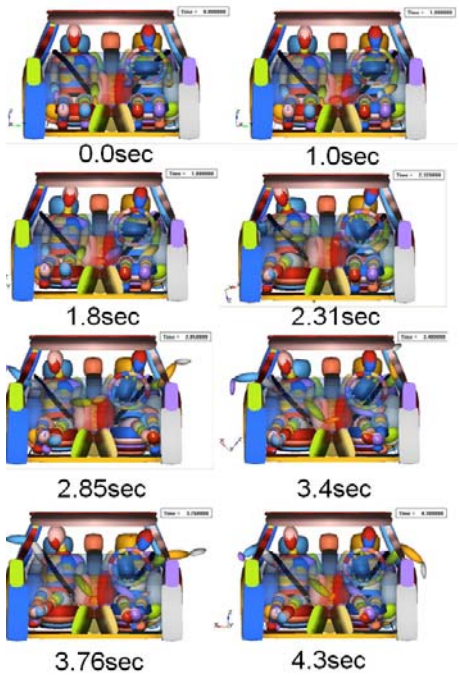

Figure31. Simulation sequence with the conventional restraint.

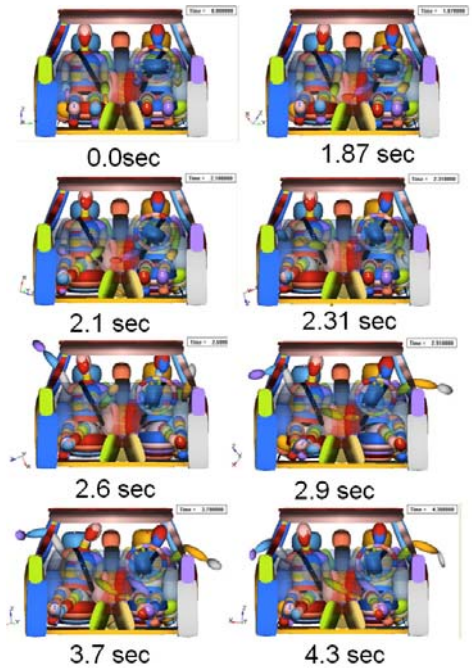

Figure32. Simulation sequence with the integrated restraint.

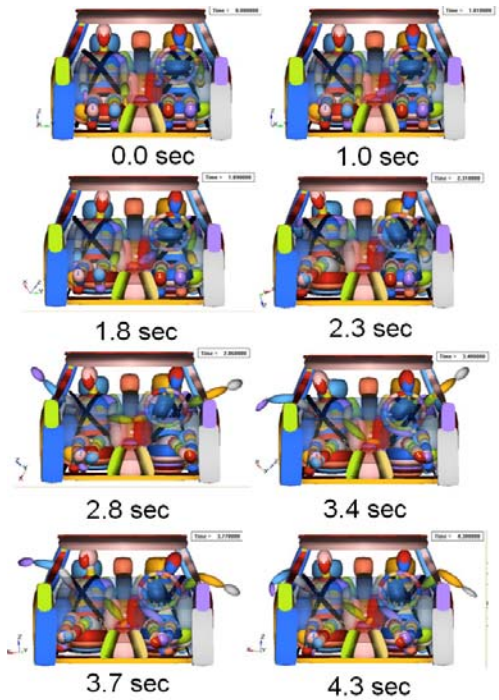

Figure33. Simulation sequence with the conventional restraint plus extra shoulder belt.

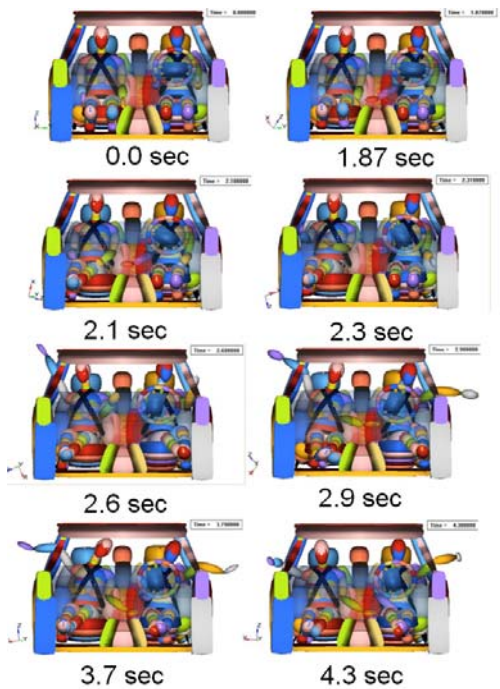

Figure34. Simulation sequence with the integrated restraint plus extra shoulder belt.

VEHICLE ROOF GEOMETRY AND ITS EFFECT ON ROLLOVER ROOF PERFORMANCE

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Paper Number 09-0513

ABSTRACT

The Jordan Rollover System (JRS) provides a realistic, highly controlled, repeatable dynamic test of vehicle roof crush performance under typical rollover conditions [1],[2]. The principal use thus far has been in comparing vehicles' roof crush and injury potential performance in one and two roll events. Because the JRS directly measures the force between the roof and the ground during touchdown, it can be used to measure, assess and optimize occupant protection by adjusting roof geometry, roof structural design and material strength and elasticity, for the least cost and weight.

This study demonstrates that the peak force (load) between the initial leading side roof rail (near side) and the road is roughly four times the vehicle weight (the load-to-weight ratio or LWR) when a vehicle first touches down at around 150º of roll. The force then drops substantially as the vehicle continues to roll over the flat of the roof, in most instances dropping to zero because the vehicle is momentarily airborne. When the vehicle rolls beyond 180º and comes into contact with the side rail opposite to the leading side of roll (far side), the force rapidly rises again. The roof then either collapses or lifts the vehicle center of gravity (COG). The far side rail of a weak roof vehicle that cannot lift the COG may then halt the vehicle's downward fall, imposing even larger forces on the road segment when the vehicle's door and main body structure interact with the roadway. To deal with such forces, a long standing and natural presumption has been to substantially increase the roof strength to weight ratio (SWR), which can result in weight efficiency cost penalties. However, one production vehicle that was tested minimized roof crush without substantially increasing its SWR.

Analysis of the results has found that far side roof crush is strongly related to the difference between the major radius (the maximum distance from the principal axis of rotation to the roof rail) and minor radius (distance from that axis to the center of the roof). Three to four inches, as between cars and LTV's has a significant effect on injury potential. The typical difference in a light truck vehicle LTV is around 15 cm to 25 cm (6" to 10") while in an passenger car it is around 8 cm to 15 cm (3" to 6").

These observations were confirmed by physical tests of strong and weak roofed vehicles. These tests led to the conclusion that a geometry change in the roof to minimize the difference in radius across the roof would reduce the degree to which the far side of a less strong roof had to lift the vehicle as it rolled beyond 180º. A finite element analysis confirmed that for a vehicle of modest roof strength, a structurally strong, rounded roof panel will reduce the far side deformation and intrusion speed by about two-thirds without increasing underlying roof strength. These results were confirmed in JRS testing of current production passenger cars and SUV vehicles and with a "HALO" ™ – High Attenuation Load Offset (U.S. and International Patent Pending Rollover Damage Minimization Device) retrofit kit for SUVs.

INTRODUCTION

In 1967, in an Advanced Notice of Proposed Rulemaking (ANPRM) [3] the National Highway Safety Bureau (NHSB) recognized intrusion as a major factor in occupant survival. Hugh DeHaven's 1952 SAE paper [4] suggested dynamic containment, leading to the FMVSS 208 dolly rollover test. With Franchini in 1969 [5], a general consensus limit of 5" of intrusion evolved. NHSB then initiated the ESV program, the performance specifications that limited roof intrusion in rollover tests to 5" to ensure the preservation of occupant survival space (OSS). When production vehicles of that time failed to meet that criterion in SAE Recommended Practice J996 drop tests at drop heights of 8 cm to 30 cm (3" to 12"), the dynamic intrusion test was abandoned by NHSB. A two-sided quasi static test using a small platen pitched at 10º and rolled at 25º at the A-pillar was proposed with a strength-to-weight ratio (SWR) criterion of 1.5 [6]. When almost all of the production vehicles failed that test, NHSB reduced the

pitch angle to 5º and required that the test be conducted on only one side [7].

In 1989, a NHTSA evaluation showed that the static tests and criteria had no effect on roof strength or rollover casualties. Indeed, a recent paper by Young et al shows how US rollover fatalities continue to increase despite a number of rollover injury mitigation initiatives being introduced over the past two decades [8], [9]. In 1998, NHTSA studied the typical relationship between the FMVSS 216 static and dynamic drop tests with the same orientation. They found that the dynamic drop tests involve 1.6 times the force of the static tests for the same deformation, suggesting an increased SWR criterion of 1.5 times 1.6 or 2.5. Although it was obvious that drop tests ignore the rotational component of a roof-to ground impact (which accounts for substantially increased far-side crush), no alternative test protocol was available to directly measure and evaluate the roof SWR required to limit intrusion in a rollover.

In 2002, the Jordan Rollover System (JRS) was developed to provide a scientific basis for evaluating rollover occupant protection under dynamic conditions. Since that time, about 50 vehicles have been tested in one, two and three roll protocols, most recently with injury interpretation directly from dummy human surrogates. The results of those tests have been published in various conference proceedings [1],[2],[10],[11],[12]. Ratings of dynamic rollover structural performance have been based on NHTSA's 5" occupant survival space, post-crash negative headroom and a 11 km/hr (7 mph) onset of serious head and neck injury. As a body of data, the JRS tests establish relationships between measured parameters, such as crush and crush speed as a function of pitch, impact roll angle, peripheral and translational speed.

The JRS is the first rollover test device that can directly measure force-time histories between the roof and the ground during the roll as a function of roll angle. That force is also a function of the dynamic strength of the roof and, sometimes at high-roll angles, the body, the weight of the vehicle, and the dynamic extent of roof crush.

This paper presents plots of this load-to-weight ratio (LWR) and the interior intrusion measured on each side of the roof as a function of roll angle for 5 current model passenger cars and 5 current model LTVs. All of which were JRS tested with the same two roll protocol. Vehicle responses are compared and interpreted in the Discussion and Results sections.

A principal geometric conclusion was validated by designing an SUV retrofit kit to improve rollover occupant protection in weak-roofed vehicles. The kit was JRS tested to deal with the immediate concerns for rollover casualties in commercial, industrial and government off-road and rural undeveloped or poorly-maintained road operations.

METHODS

The JRS is versatile in that it can provide repeatable dynamic data under almost any realistic rollover protocol. A dynamic test is the best way to rate rollover crashworthiness performance. The fixture with a mounted vehicle is shown in Figure 1.

Figure 1. Jordan Rollover System (JRS) Test Rig.

Descriptions of how the test rig functions are described elsewhere [2], [13]. The vehicle is mounted to towers as on a spit through the COG and its axis of rotation. The vehicle is simultaneously rotated and released as a roadbed moves under it. The test is commenced from an almost vertically oriented position to the roadbed similar to that shown in Figure 1.

During the simultaneous rotation and fall, the vehicle strikes the moving roadbed below on the leading side of roll (near side) at the roof rail at the prescribed roadbed speed, vehicle angular rate, drop height and impact pitch angle. After striking the near side the vehicle continues to roll and strikes the side opposite to the leading side being the far side. The vehicle is then captured. The motions of the vehicle and roadway are coordinated so that the touchdown conditions can be controlled and thus repeated within a narrow range that was considered acceptable in other crash test protocols used by IIHS and NCAP [14],[15].

A 50th percentile Hybrid III Anthropomorphic Test Dummy (ATD) is used to monitor head and neck loading in the driver seat position. String potentiometers are used to measure roof intrusion and intrusion rates, as well as the ATD's motion. High speed cameras also record vehicle and ATD motions. The ATD is setup by the FMVSS 208 protocol.

Measured parameters included: the roll angle and rate, the pitch angle and its variation, the dummy motion relative to the seat through a string pot to the dummy buttocks, the intrusion of both sides of the roof, and the forces between the vehicle roof, the roadbed and the towers.

In a rollover crashworthiness study of ten current production vehicles (5 passenger cars and 5 light trucks), the relationship of the forces between the ground and the roof and the deformation of the roof as a function of roll angle was investigated. The tests were conducted by the Center for Injury Research and funded by the Santos Family Foundation through the Center for Auto Safety. The vehicles were supplied by State Farm Insurance Company.

DISCUSSION

Generic SWR vs. Dynamic Injury Potential

A comparison of SWR ratings and dynamic ratings from a companion ratings paper [16] is shown in Figures 2 and 3. The slope of the lines represents a reduction in the injury risk rating comparable to the IIHS study. It is also worth noting that the risk of passenger and SUV vehicles at essentially the same SWR also varies greatly.

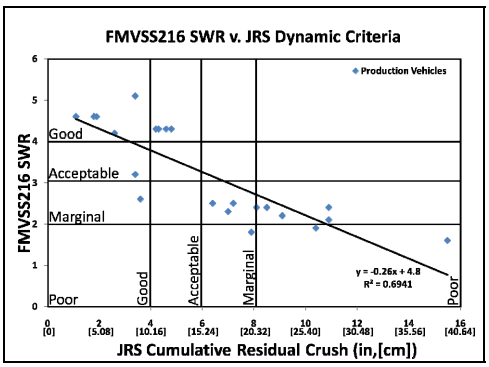


Figure 2. JRS Cumulative Residual Crush

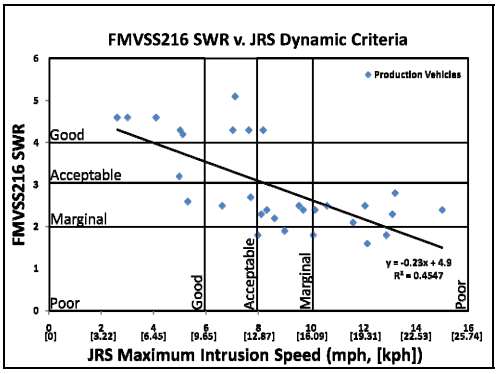


Figure 3. JRS Maximum Intrusion Speed

Since the JRS tests can be carried out with instrumented ATD's it is possible to individually measure the roof crush effects on various injury criteria of different vehicle roof geometric, structural and material designs. In other words a dynamic based rating system can resolve the disparities and reflect real world injury potential.

RESULTS

This section provides detail about the relationship between road load measurements as a function of roll angle and the resulting roof crush on the near (leading side of roll) and far (opposite to leading side of roll) sides. Figure 8 has an insert orienting the reader to the position of the vehicle at each peak load when seen from the ¾ view from the front. In this case the near side (passenger side for US vehicles, since all JRS tests are passenger side leading) peak road load is shown at ~155 degrees after first contacting at about 145 degrees as shown at the beginning of roof crush and road load. Similarly, the peak far side road load occurs at about 200 degrees and the loading affecting roof deformation ends when the peak roof crush occurs at about 210 degrees. After that point the road is recording the force that is loading the vehicle body in the area around the window sill to fender area. Notice in this case that the peaks are both about four times the vehicle weight.

The deformation of the roof is measured with string potentiometers and confirms the accuracy with video tracking software in the two interior camera recordings. As shown in Figure 4 and 5, the string potentiometers are placed at the center of the vehicle and are attached to the A-pillar on both the driver and passenger sides of the vehicle and to the B-Pillar on the driver's side. The reason for no additional string potentiometers is the Hybrid III dummy kinematics interfere with transducers. If additional data is required it can come from the video tracking software for any point on the interior. String potentiometers are reliable and have an accuracy of about one quarter of a centimeter (one tenth of an inch). However, the tracking software adds confirmation and the ability to resolve the radial displacement into rectilinear coordinates. Since the measurements of interest are in the order of 15 cm (6") of displacement, the error in measurement of the string potentiometer is at least an order of magnitude less.

Figure 4. Vehicle Interior String Potentiometers

Figure 5. String Potentiometers to A Pillar

The study focuses on the detail available from the five passenger cars and five LTVs shown in Figures 6 and 7. They are all shown in their post test conditions after JRS tests with identical two roll protocols, first at 5 degrees and the second at 10 degrees of pitch.

Characteristics affecting roof crush comparisons

Comparisons show dramatic differences in roof crush between vehicles of similar FMVSS 216 SWR class and between passenger cars and LTV classes. What factors in addition to SWR affect vehicle roof crush performance is not clear at this point in time.

As indicated in the last section of this paper, a geometry change to "roundness" produced spectacular results. Four factors have been identified which could affect the dynamic but not the static test results: 1) the geometry as described by the difference in ratio of the major and minor radius (the "roundness" of the roof) for a particular vehicle; 2) the geometry as described by the longitudinal rake of the windshield and roof as well as the front of the hood between different vehicles; 3) the structural section configurations and joint design; and 4) the construction material's elasticity. The specific effect of each, if any, on injury potential performance is a future effort.

Figure 6. JRS Post Test Two Roll 5 Passenger Vehicles.

Figure 7. JRS Post Test Two Roll 5 LTV Vehicles.

Comparisons between similar SWR LTVs

Consider the roof crush performance of two LTV vehicles by the same manufacturer shown in Figures 9 and 10. The Honda CRV has a SWR of 2.6 and the Ridgeline SWR is 2.4. Notice that the roof crush in the CRV is half that of the Ridgeline in roll 1 at 5 degrees of pitch and in Roll 2 at 10 degrees of pitch. The peak roof intrusion speed is shown in Figures 11 and 12 where the chart starts at 175 degrees to highlight far side vehicle response. These plots show that when there is a significant force beyond the time of peak roof crush

(about 210º of roll), it comes from the lower side of the upper vehicle structure contacting the road segment. To the extent that the force no longer crushes the roof laterally it is irrelevant to roof performance.

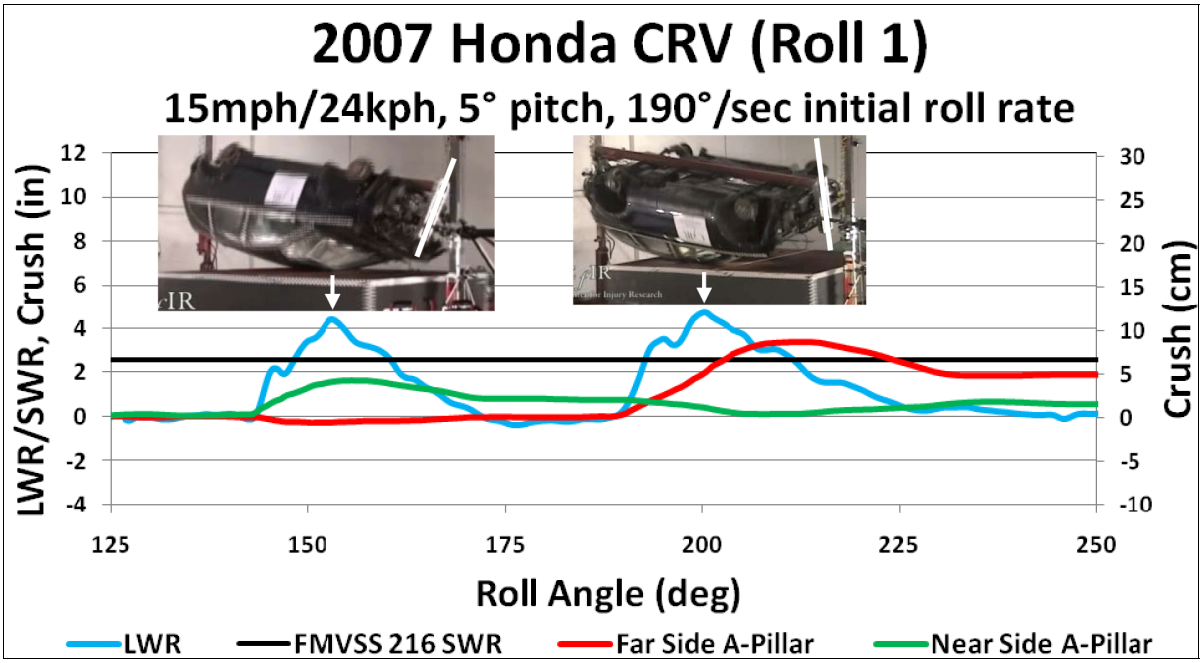


Figure 8. 2007 Honda CRV Test Results with Actual Vehicle Positions at Peaks.

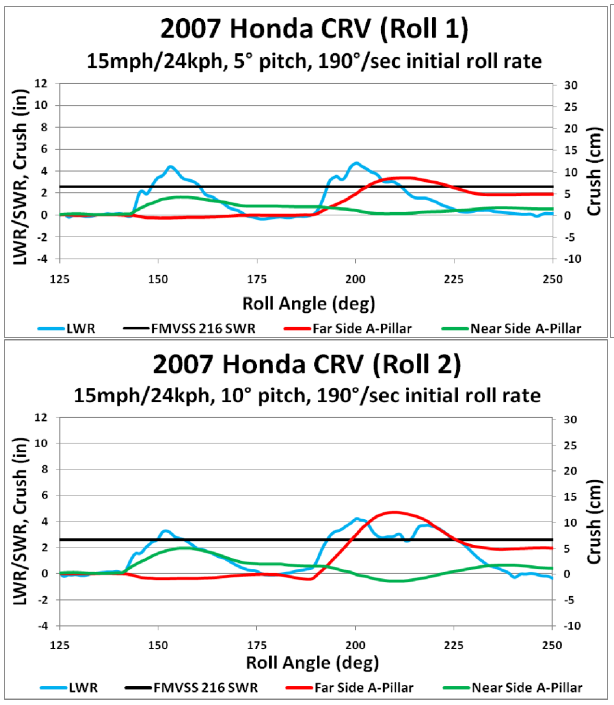


Figure 9. CRV Roof Crush vs. Roll Angle.

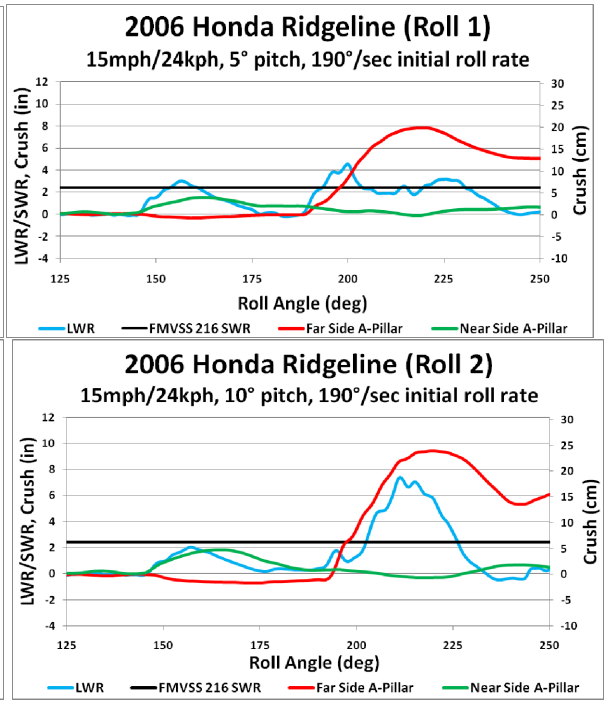


Figure 10. Ridgeline Roof Crush vs. Roll Angle.

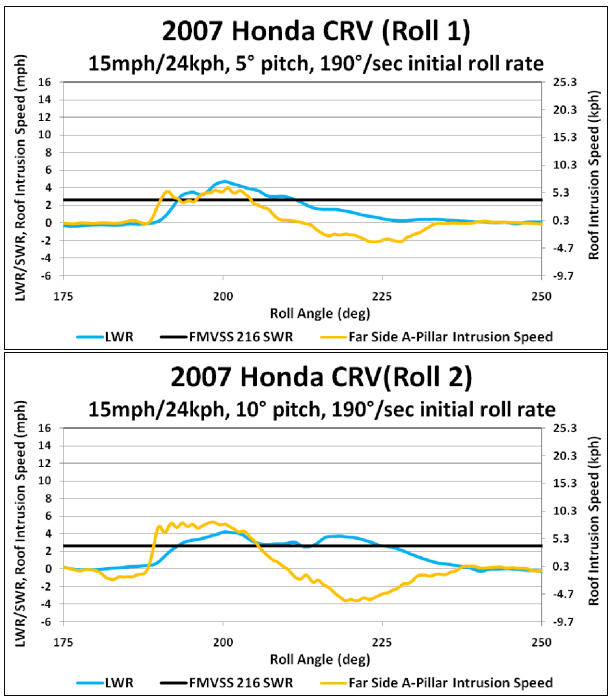


Figure 11. CRV Peak Roof Instrusion Speed.

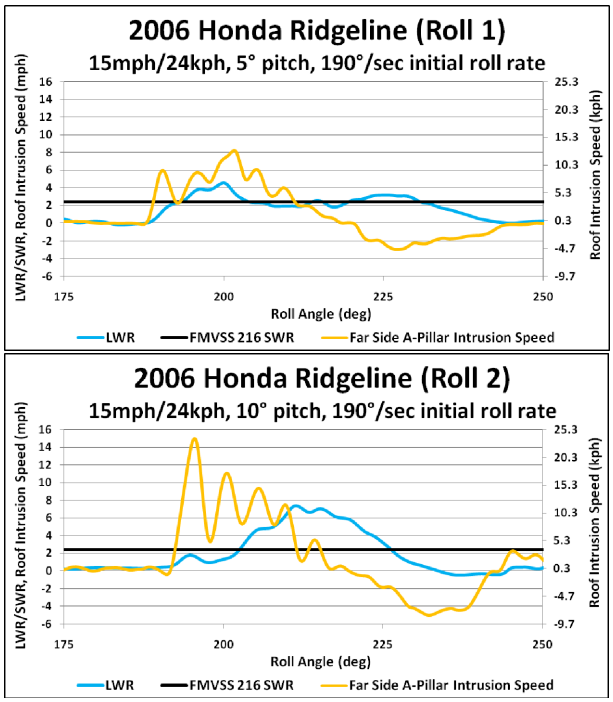


Figure 12. Ridgeline Peak Roof Instrusion Speed.

Comparisons Between Autos of Substantially Different SWR

The roof crush versus roll angle performance of two passenger cars, a VW Jetta with an SWR of 5.1 and a Pontiac G6 with an SWR of 2.3, is shown in Figures 13 and 14. Notice that the roof crush in the first 5 degree roll of the VW is one third of that of the G6 and the residual roof crush is 40% of peak value versus 75% of the peak value in the G6. In Roll 2 at 10 degrees of pitch the peak and the residual intrusion values are the same for both, but the cumulative residual for the Jetta is only about 9cm (3.5") compared to 18 cm (7") on the G6. The peak roof intrusion speed is shown in Figures 15 and 16, where the chart starts at 175 degrees to highlight far side vehicle response.

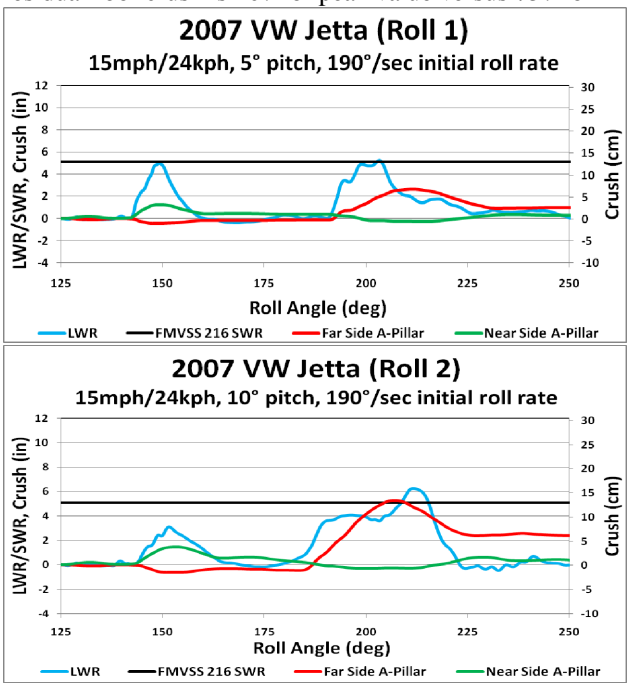


Figure 13. Jetta Roof Crush vs. Roll Angle.

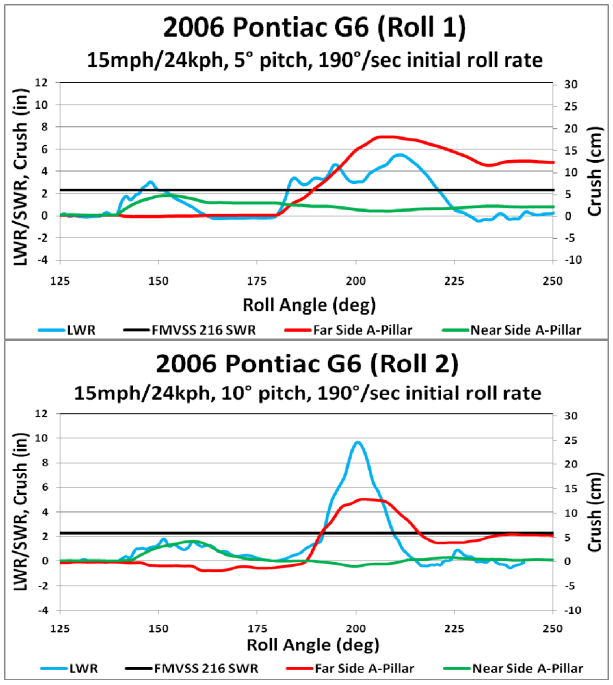
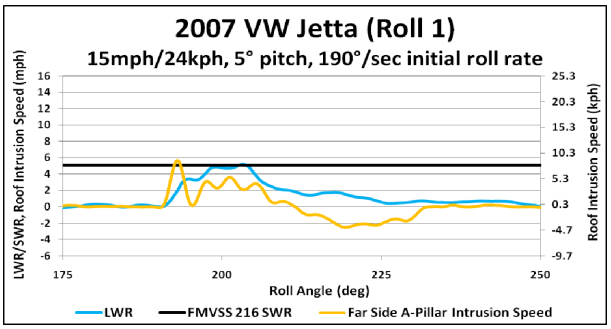


Figure 14. G6 Roof Crush vs. Roll Angle.



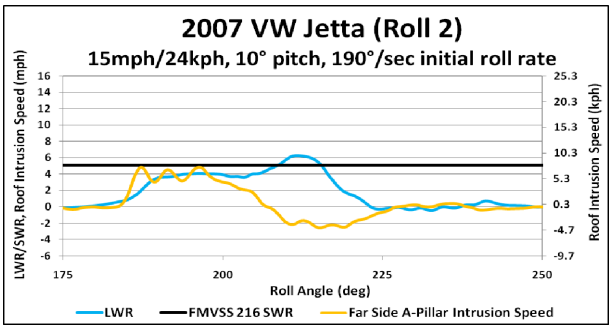
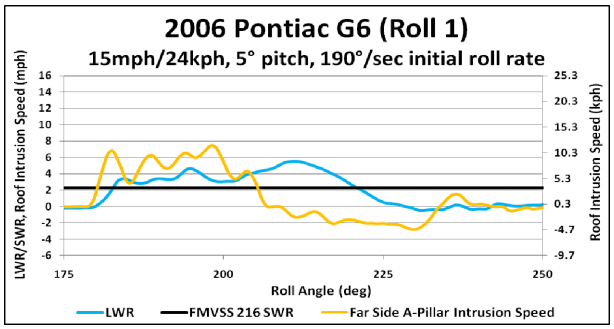


Figure 15. Jetta Peak Roof Instrusion Speed.



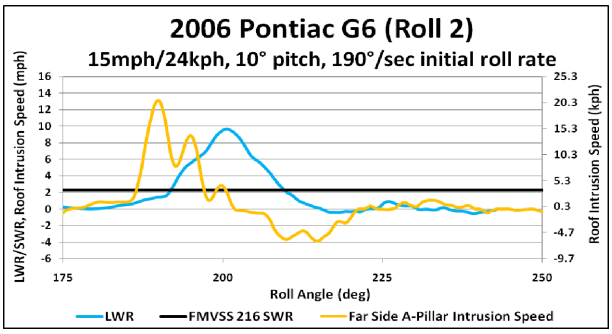
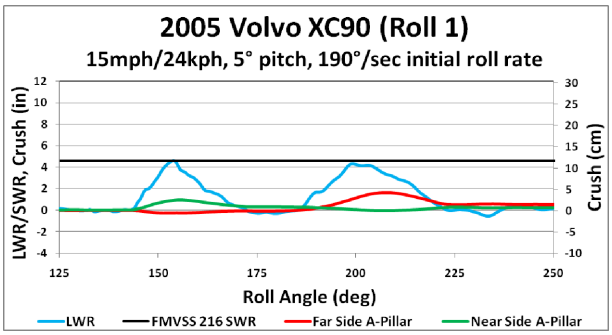
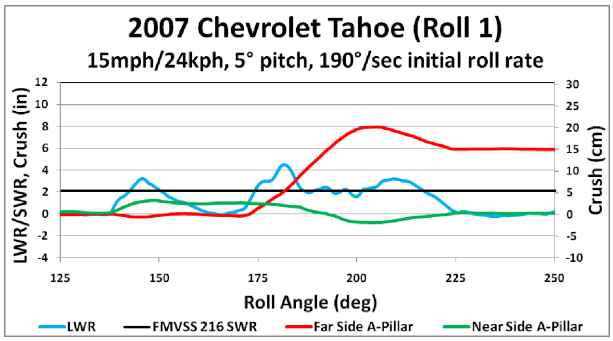


Figure 16. G6 Peak Roof Instrusion Speed.

Comparisons Between SUVs of Substantially Different SWR

The roof crush versus roll angle performance of two SUVs, an XC-90 with an SWR of 4.6 and a Chevrolet Tahoe with an SWR of 2.1, is shown in Figures 17 and 18. Notice that the roof crush in the first 5 degree roll of the XC-90 is one fourth of that of the Tahoe and the residual roof crush is 3 cm (1") versus 15 cm (6") in the Tahoe. In Roll 2 at 10 degrees of pitch the peak and the residual intrusion values are about 5 cm (2") compared to 15 cm (6") and the cumulative residual for the XC-90 is only about 5 cm (2") compared to 28 cm (11") on the Tahoe. Note that the near side damage in the second roll on the Tahoe first erected the far side to some degree before the rotational impact component collapsed it. The peak roof intrusion speed is shown in Figures 19 and 20, where the chart starts at 175 degrees to highlight far side vehicle response.





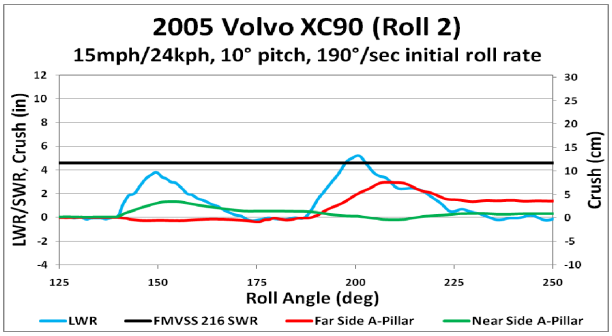


Figure 17. XC90 Roof Crush vs. Roll Angle.

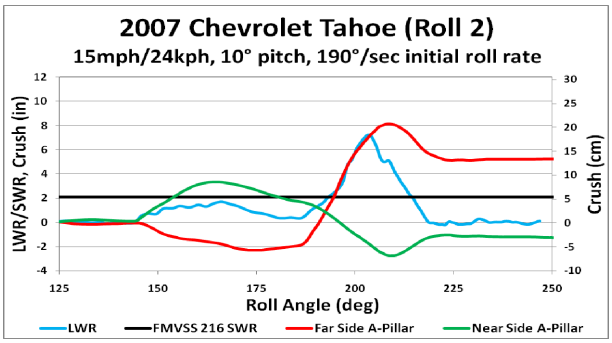


Figure 18. Tahoe Roof Crush vs. Roll Angle.

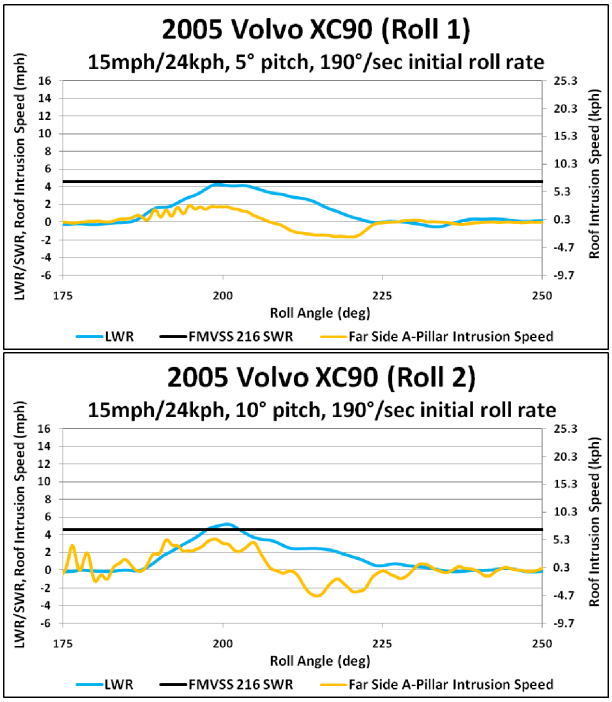


Figure 19. XC90 Peak Roof Instrusion Speed.

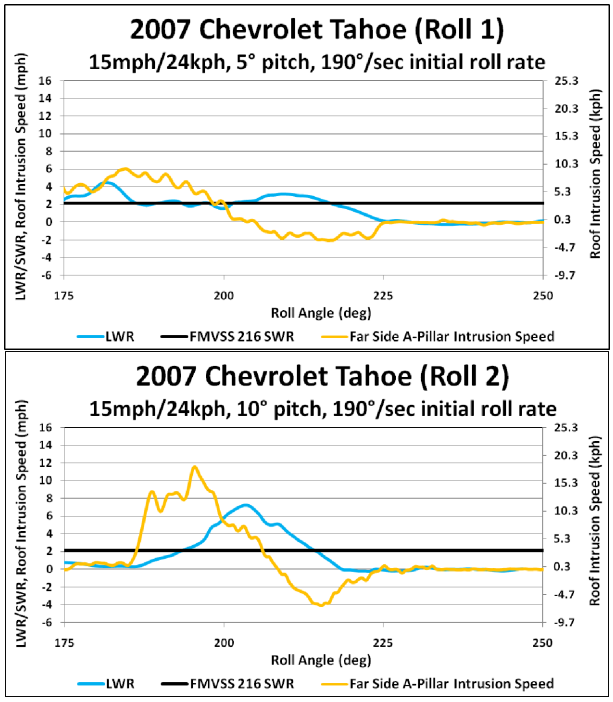


Figure 20. Tahoe Peak Roof Instrusion Speed.

Comparisons between a passenger car and an SUV of similar SWR

The roof crush versus roll angle performance of an SUV, the Jeep Grand Cherokee and a passenger car, the Chrysler 300 both with an SWR of about 2.5 but grossly different geometry, is shown in Figures 21 and 22. The peak and residual roof crush in the first 5 degree roll of both vehicles is about the same. In Roll 2 at 10 degrees of pitch the peak and the residual intrusion values are about 23 cm (9”) and 15 cm (6”) for the Cherokee compared to 13 cm (5”) and 5 cm (2”) for the 300. The cumulative residual for the Cherokee is about 28 cm (11”) compared to 18 cm (7”) on the 300. The peak roof intrusion speed is shown in Figures 23 and 24, where the chart starts at 175 degrees to highlight far side vehicle response.

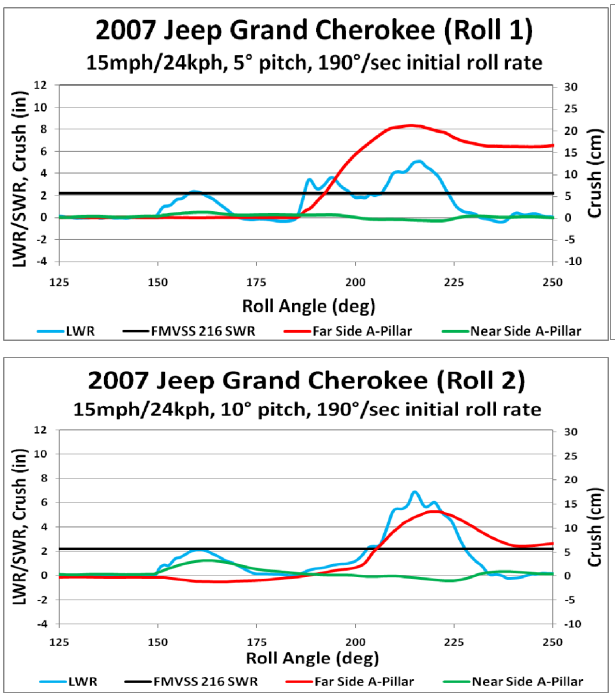


Figure 21. Cherokee Roof Crush vs. Roll Angle.

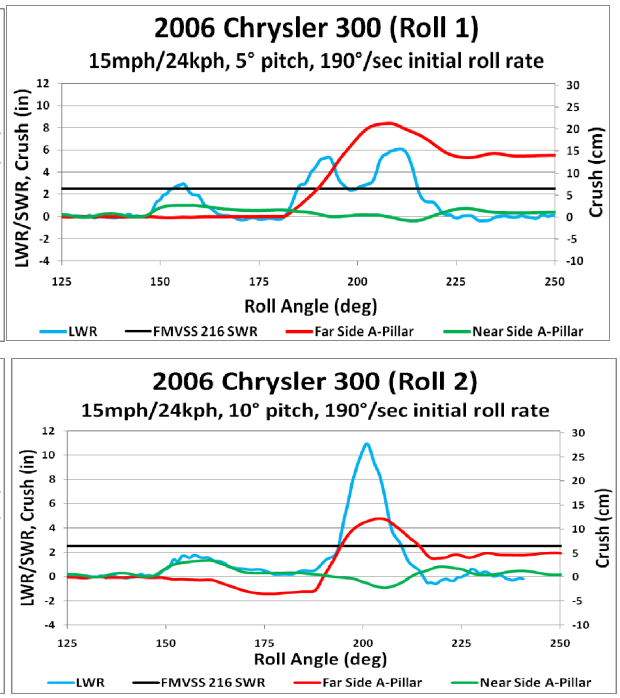


Figure 22. 300 Roof Crush vs. Roll Angle.

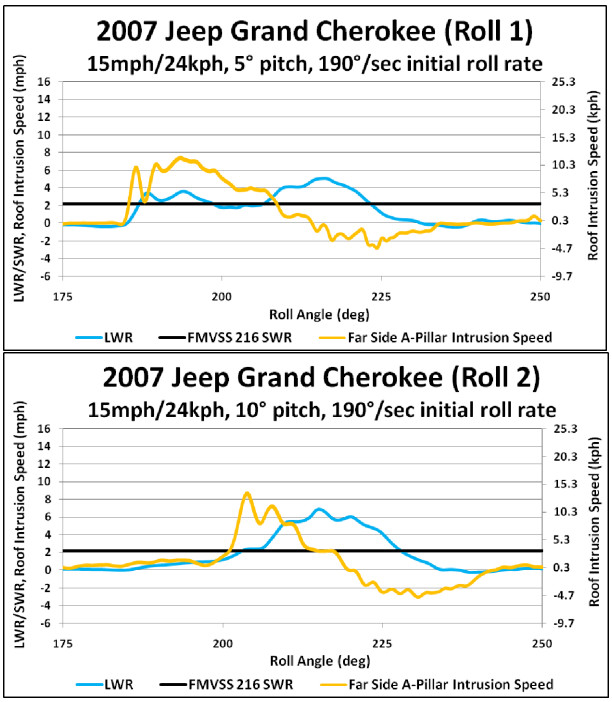


Figure 23. Grand Cherokee Peak Roof Instrusion Speed.

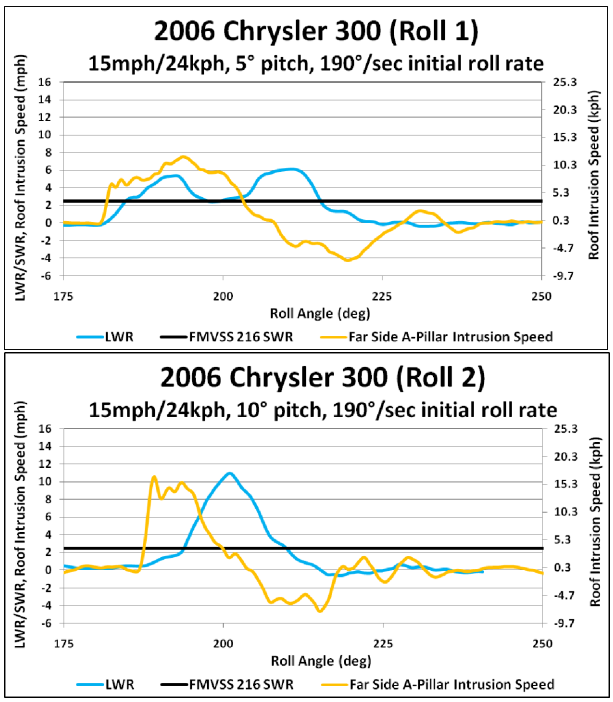


Figure 24. 300 Peak Roof Instrusion Speed.

Geometric performance validation

Operations on unpaved road surfaces, such as U.S. Border Patrol operations, vehicle operations in theaters of war, energy and metals exploration and mining businesses, use production pick-up trucks, SUVs and buses for transportation. Consistent with the 10% fatality and serious injury performance of these vehicles in the mainly on-road private consumer usage, the frequency and injury risk of off road operation is also high. In consideration of their occupational health and safety requirements and liability for on-the-job injury,

operators have established a voluntary rollover crashworthiness standard minimizing roof crush.
One solution for available production pick-up trucks is to design an external roll cage mounted in the pickup bed and extending over the cab [17]. Roll cages installed on the interior of SUV's interfere with the rollover activated window curtain airbags and are generally insufficiently padded, cumbersome and awkward for entry and exit, riding comfort and frontal safety as shown in Figure 25.

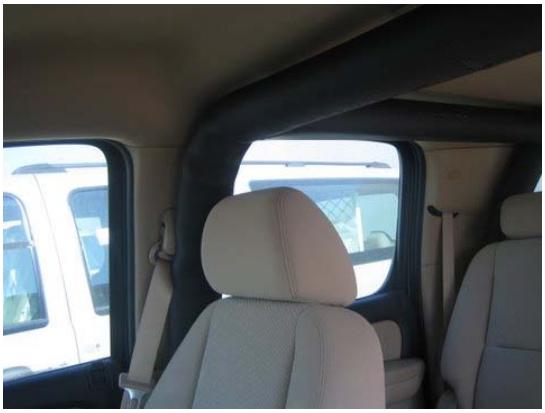


Figure 25. Internal Roll Cage.

The systems appear to employ the intrusion criteria formulated by Franchini in 1968 [5] and a blunt strategy of strengthening the roof well above what is accepted as industry best practice that has demonstrable good rollover crashworthiness, e.g. the Volvo XC-90. Because rollovers involve many impact orientations the accepted solutions are in some instances massive, unyieldingly rigid and cargo space consuming.

The availability of the continuous time history of the forces between the vehicle roof and the roadbed spawned the development of a geometric roof design to evenly distribute the roof load during road contact, equate and minimize near and far side roof crush and thus reduce the risk of occupant injury at minimum cost and weight. The first application has been to develop an acceptably styled, universal retrofit kit for production vehicles to achieve state-of- the-art occupant protection at minimum production and installation cost. Most of the vehicles in use today have strength to weight ratio (SWR) roofs as measured by the U.S. FMVSS 216 test of 1.8 to 2.4. Figure 26 and 27 are pictures of a 1993 Jeep Grand Cherokee (JGC) (4400 lbs., SWR=2.3) before and after a one roll 10 degree JRS test.

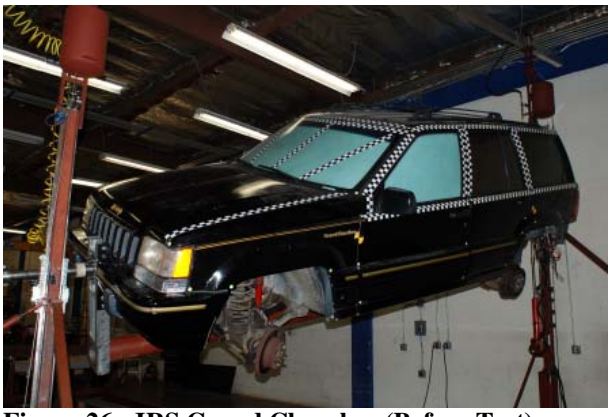


Figure 26. JRS Grand Cherokee (Before Test).

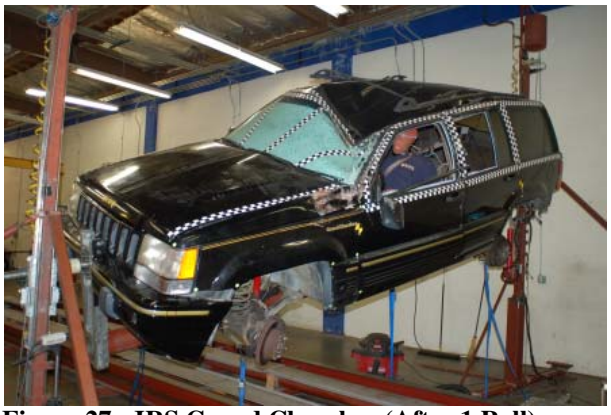


Figure 27. JRS Grand Cherokee (After 1 Roll).

The results of this one roll JRS test are shown in Figures 32 and 33. The far side A Pillar crush was close to 30 cm (12"). The far side A Pillar intrusion speed was over 16 km/p (10 mph).

The HALO ™ system, which was developed in early 2008, is shown in Figure 28. The structure was initially designed for the 1993 Jeep Grand Cherokee (JGC), which has one of the lowest "roof strength to vehicle weight ratios" and one of the worst rollover crash characteristics in terms of occupant injury potential as demonstrated on the JRS and shown in Figure 27.

Figure 28. HALO ™ Roof Damage Minimization Device

Several forms of evidence show how well HALO ™ works including physical crash testing, computer based finite element analysis (FEA), and photogrammetric 3D analysis. Two similar 1993 Jeep Grand Cherokees were tested on the JRS with the same protocol. The HALO ™ reduced dynamic roof intrusion at the A-Pillar by more than 27 cm and at the B Pillar by more than 16 cm. Roof intrusion speed was also reduced from 16 km/h to 1.6 km/h at the A-Pillar and from 12.4 km/h to 1.1 km/h at the B-Pillar. The interior camera view for each test at peak loading is shown in photos from the testing video in Figures 30 and 31. The Hybrid III dummy experienced axial neck loading of around 10 kN (1 ton) in the production vehicle versus only 1 kN (equivalent to standing on your head) in the Jeep with HALO ™.

A Finite Element analysis from Friedman Research Corporation of the first configuration indicated a reduction in far side intrusion at the A pillar from 30 cm (12") to 10 cm (4") with increased near side intrusion to 10 cm (4"). The initial design was tested on two different vehicles before the final design was achieved. Illustrations of this analysis are shown in Figure 32.

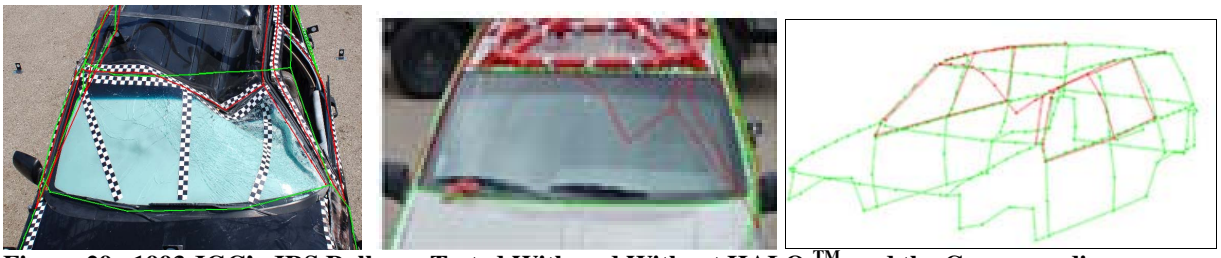


Figure 29. 1993 JGC's JRS Rollover Tested With and Without HALO ™ and the Corresponding Photogrammetric 3D Analysis.

Figure 30. Interior of a 1993 JGC Without HALO ™

Figure 31. Interior of a 1993 JGC With HALO ™

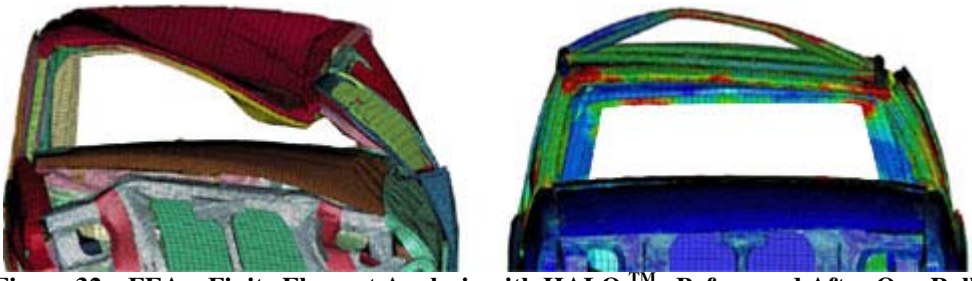


Figure 32. FEA – Finite Element Analysis with HALO ™, Before and After One Roll.

Two derived versions of a retrofit kit have been developed. The primary difference in an SUV is an internal buttress' at the B-pillars for applications to vehicles with SWR's of less than 2.5. The system creates and supports a strong round roof a few inches forward of the B-pillar. This has two effects. The round roof (or attachment) causes the impact and rolling force load on the roof from the road, to be constant (distributed equally) from near to far side. Locating and supporting the strong round roof forward of the B-pillars transfers and relieves a portion of the load at the A-pillars (and distributes across the header), which are traditionally weak (because of the FMVSS 216 test conditions). Another 1993 Jeep was fitted with a HALO ™ and JRS tested again and the exterior views are shown in Figures 33 and 34. Very little change occurred in the structure, even after 2 test rolls. The data from the production JGC and the results for the three rolls with the final HALO ™ design are shown in Figures 35 through 42.

Figure 33. JGC with HALO ™ Before Testing.

Figure 34. JGC with HALO ™ After 2 Test Rolls.

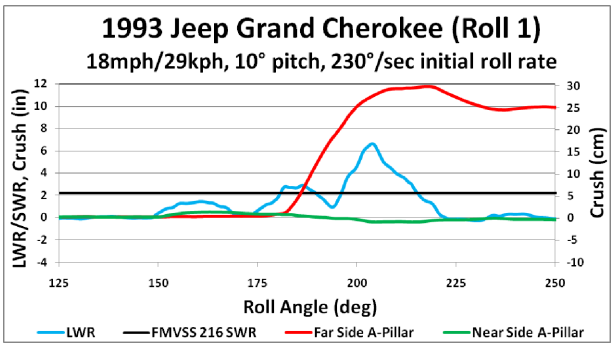


Figure 35. JGC Roof Crush vs. Roll Angle.

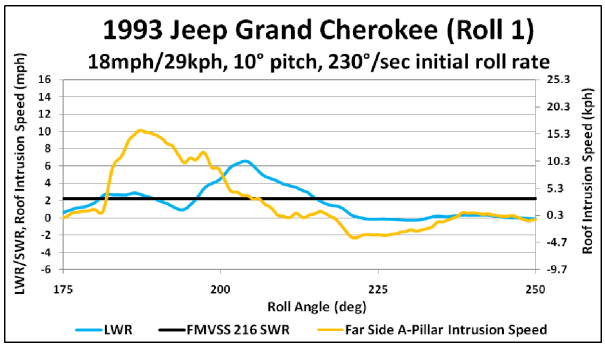


Figure 36. JCG Peak Roof Instrusion Speed.

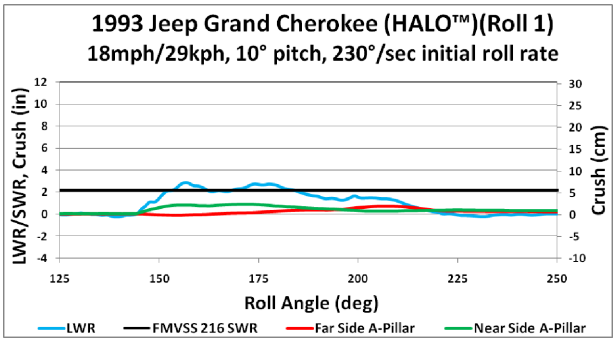


Figure 37. JGC w/HALO ™ Roll 1 Roof Crush

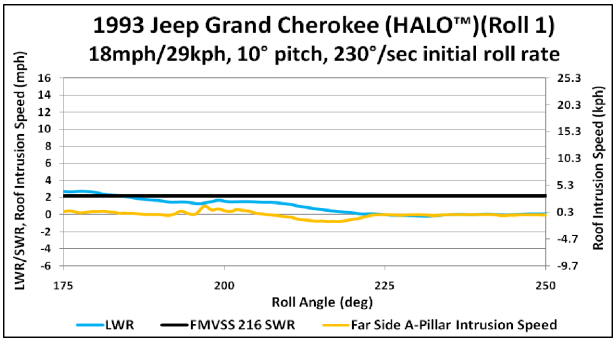


Figure 38. JGC w/HALO ™ Roll 1 Intrusion Speed

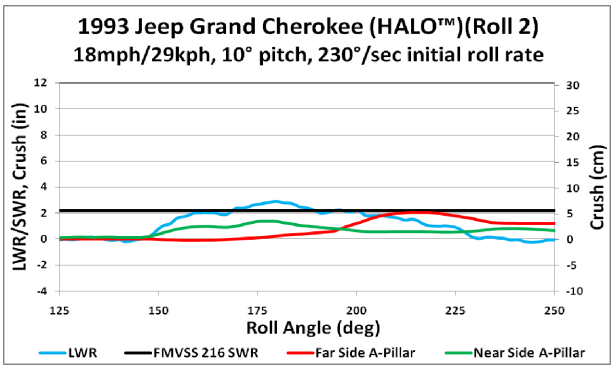


Figure 39. JGC w/HALO ™ Roll 2 Roof Crush

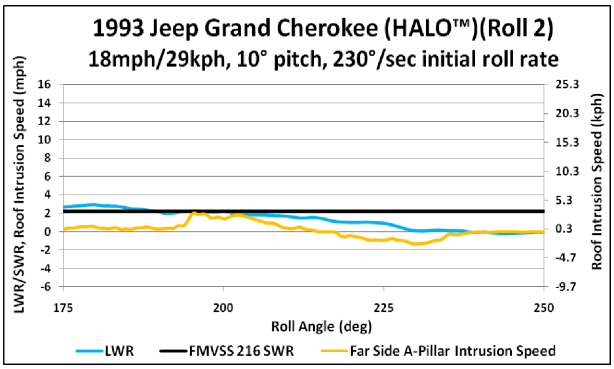


Figure 40. JGC w/HALO ™ Roll 2 Intrusion Speed

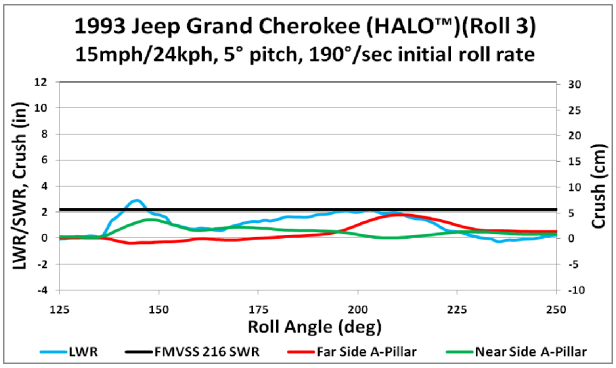


Figure 41. JGC w/HALO ™ Roll 3 Roof Crush

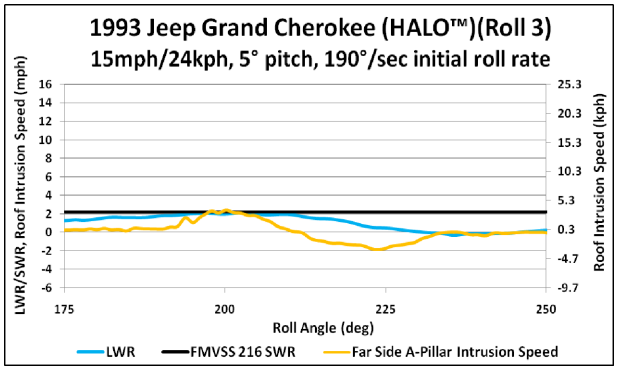


Figure 42. JGC with HALO ™ Roll 3 Intrusion Speed

CONCLUSIONS

- The geometry of a vehicle roof has a significant effect on the performance of that vehicle during a rollover and can be changed with little addition of weight.
- The geometry *alone* cannot compensate for fundamental weaknesses in the pillars
- Geometry alone can improve the performance of vehicles with relatively weak A-Pillar/Headers with reasonable B-Pillar strength.
- A vehicle's dynamic rollover characteristics largely determine the typical roof touchdown pitch orientation. Many vehicles with good FMVSS 216 SWR at 5 degrees of pitch are half as strong at 10 or more degrees of pitch. Therefore the touchdown pitch orientation of a FMVSS 216 compliant roof may or may not collapse unless its performance at 10 degrees of pitch has been assessed.
- A vehicle's roof contact pitch orientation strongly affects its injury potential performance in terms of roof crush and intrusion velocity.

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