USA AMBULANCE CRASHWORTHINESS FRONTAL IMPACT TESTING

Nadine Levick
EMS Safety Foundation (1)
USA
Raphael Grzebieta
Injury Risk Management Research Center (2)
University of New South Wales
Australia
Paper Number 09-0471

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.)

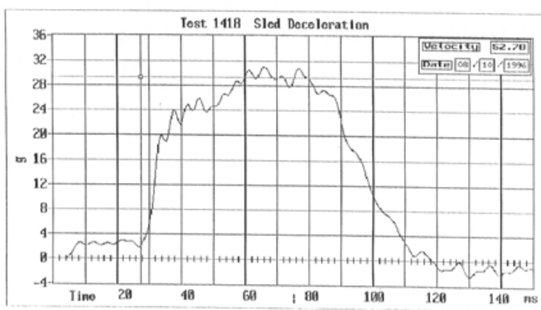
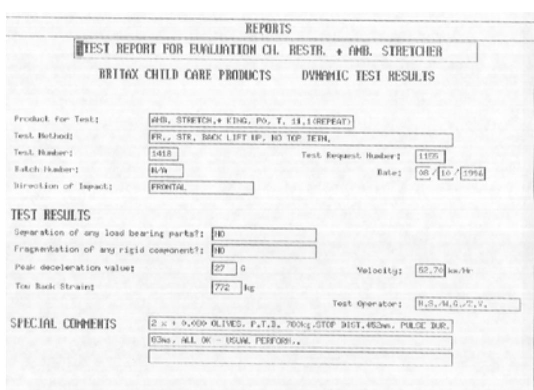


Figure 1. Sample sled deceleration pulse for gurney and non-instrumented child ATD test [28]



REPORTS

TEST REPORT FOR EVALUATION CH. RESTR. + AMB. STRETCHER

BRITAX CHILD CARE PRODUCTS DYNAMIC TEST RESULTS

Product for Test: AMB. STRETCH.+ KING. PO. T. 11.1(REPEAT)
Test Method: FR., STR, BACK LIFT UP, NO TOP TETH.
Test Number: 1418 Test Request Number: 1155
Batch Number: N/A Date: 08/16/1996
Direction of Impact: FRONTAL

TEST RESULTS

Separation of any load bearing parts?: NO
Fragmentation of any rigid component?: NO
Peak deceleration value: 27 G Velocity: 52.70 km/hr
Tow Back Strain: 772 kg
Test Operator: N.S./M.G./T.V.

SPECIAL COMMENTS 2 x + 0.600 OLIVES. P.T.D. 700kg.STOP DIST.452mm. PULSE DUR. 63ms. ALL OK - USUAL PERFORM..

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.

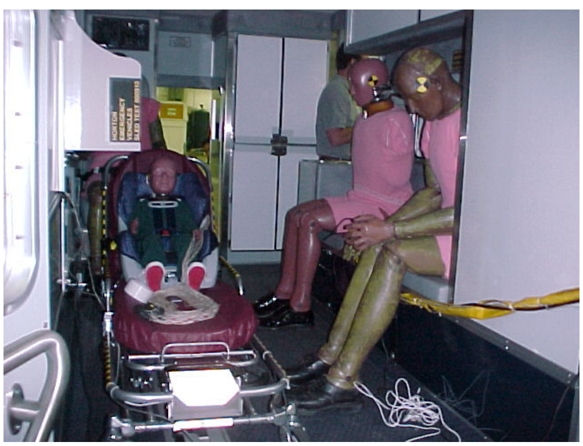


Figure 5. Pre-test configuration of ATDs in box [4]

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.

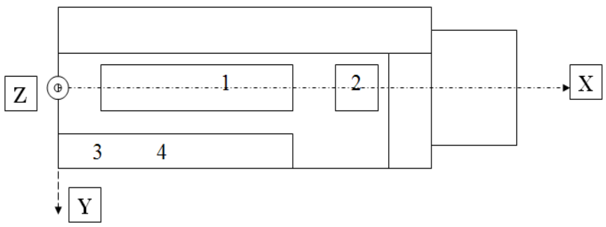


Figure 7. Positioning of lower box accelerometers

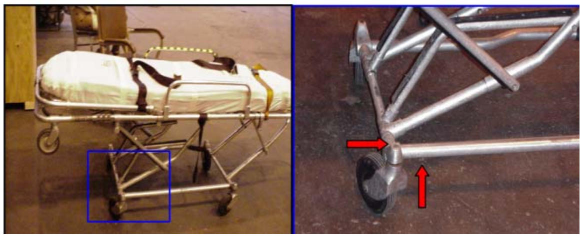


Figure 8. The arrows indicate the positions of the X and Y accelerometers on the stretcher in the 2000 crash tests of Bullet Type III ambulance.

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 P4-50th, restrained on squad bench with lap belt (Fig. 9).

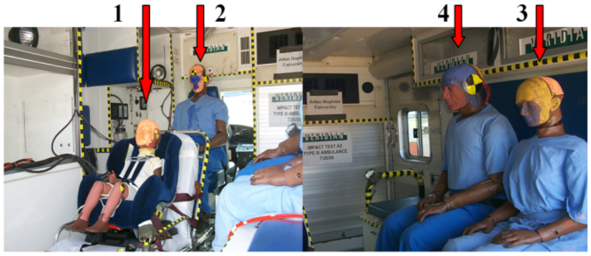


Figure 9. Positioning of the ATDs in the bullet vehicle in the 2000 crash tests [3]

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).

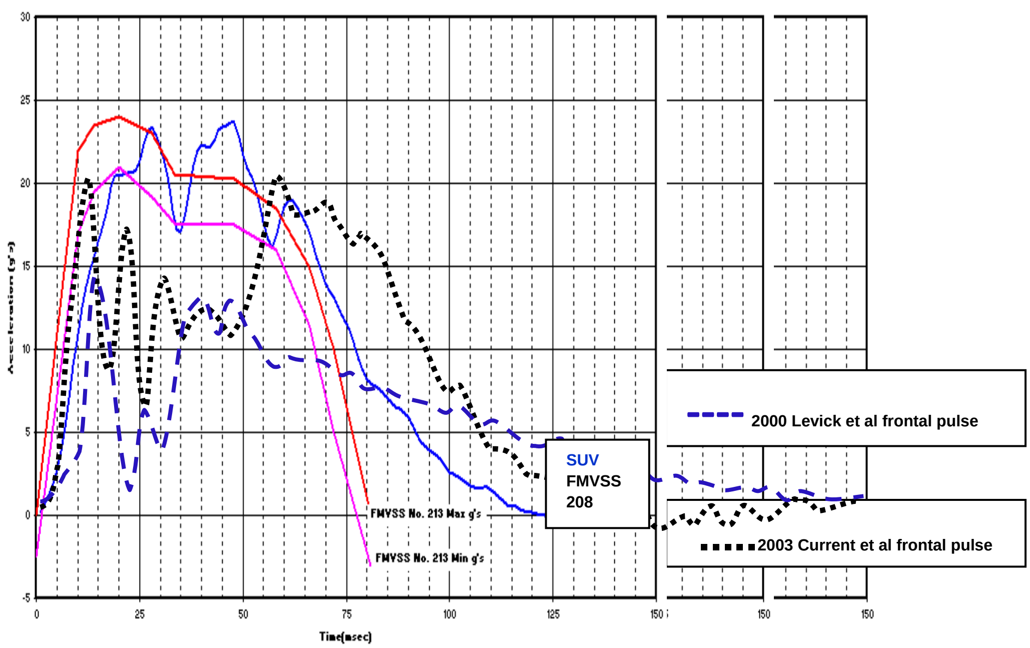


Figure 13. FMVSS 213 and SUV 208 vs 2000 Levick et al frontal crash pulse and 2003 Current et al frontal crash pulse [38]

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.

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]

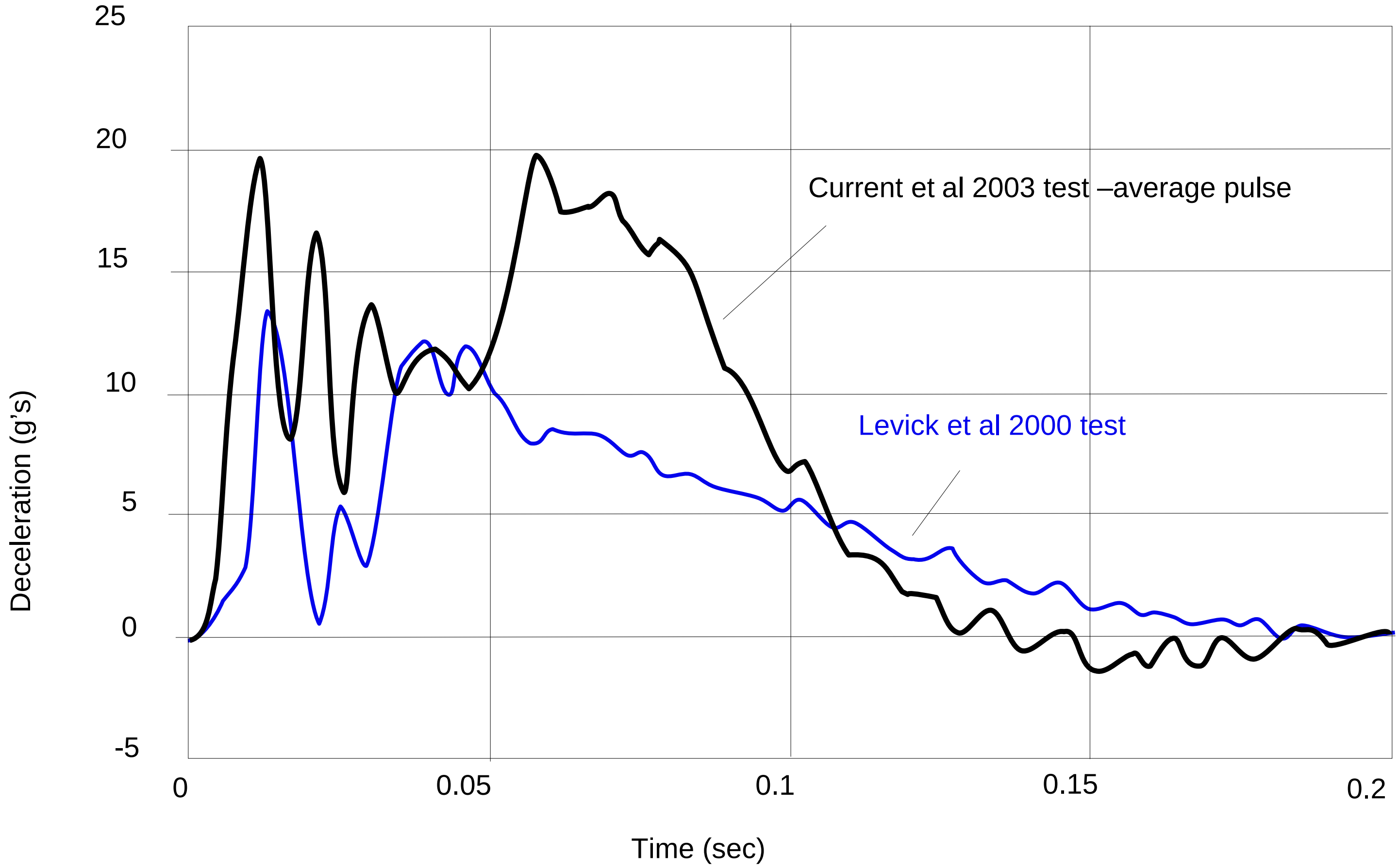


Figure 18 Crash pulses from 2003 Current et al [27] full barrier tests and crash pulse from Levick et al 2000 frontal full vehicle test [5].

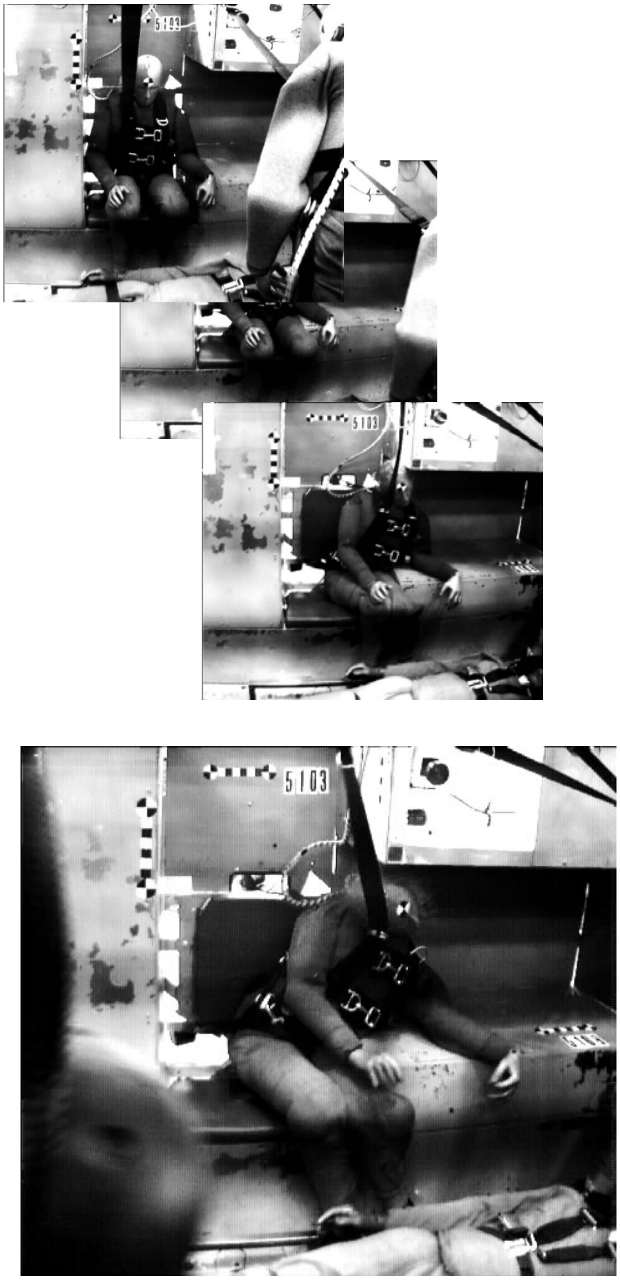


Figure 20. Occupant seat sideways in full harness – Current et al tests. Note how occupant would most likely have received a serious head and neck injury. [37]

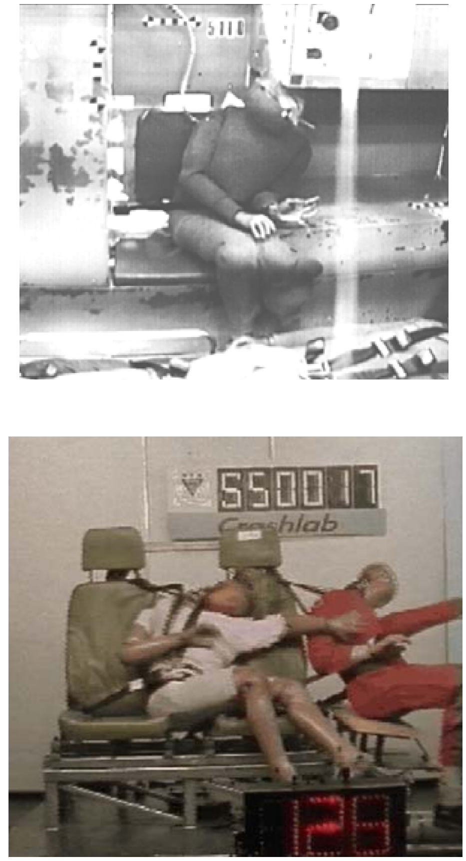


Figure 21. Demonstration of hazards to side facing occupants in a frontal crash, even in absence of cabinetry [37, 14]

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

The authors would like to acknowledge the many collaborators who have assisted in compiling and critiquing this information. Particular thanks for the support of the EMS providers and agencies who have been instrumental in procuring the vehicles for many of these tests and who have shared their time and thoughts to assist the authors.

CONTACT

Nadine Levick MD, MPH, Emergency physician and interdisciplinary researcher.
email: nlevick@attglobal.net
web: www.objectivesafety.net

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