CRASHWORTHINESS ANALYSIS OF THREE PROTOTYPE AMBULANCE VEHICLES

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ABSTRACT

This paper is an evaluation of the predicted safety performance of three USA prototype ambulance vehicles with aftermarket structural modifications. Expected safety performance was analyzed using existing and established automotive safety principles. Information on design and construction of the vehicles was identified, and evaluated via application of basic engineering crashworthiness principles and laws of physics, with a specific focus on countermeasure design for reducing harmful loading and injury causation potential in crashes or sudden decelerations. Data sources used for the analysis included: vehicle specifications, inspections, photographs, crash tests and published crashworthiness and injury mitigation literature.

Results demonstrated poor vehicle structural integrity and crashworthiness for these aftermarket modified ambulance vehicles. Assessed crashworthiness performance and occupant protection do not appear optimized even for the minimally structurally modified van. Current interior design features (seat design, patient transport device design, head strike zones and restraint systems) and layout, demonstrated predictable serious crashworthiness and occupant protection hazards.

These are projected findings, rather than actual crashworthiness tests – however this is the first comparative automotive safety evaluation of prototype ambulance vehicles. This is key information for a major fleet of vehicles globally which has had minimal automotive safety attention or input to date.

From this study it appears there are major deficiencies in safety design of these prototypes. Emphasis on a passenger compartment that has crashworthy features, effective seat design, based on existing literature and a clear focus on occupant human factors and equipment location and anchors, could provide for major safety enhancements for ambulance vehicles. There is need for vehicle safety researchers, ambulance industry and vehicle designers to recognize and apply these existing principles to reduce current failures in an important and essential service that appears to have a poor safety record, considerably below that of other passenger (Maguire 2003, Ray 2005, Levick 2006) and also other commercial vehicles (FMCSA).

INTRODUCTION

Emergency Medical Service (EMS) vehicles, ambulances, are an unusual vehicle in the transportation system for a number of reasons – they carry passengers in a number of orientations, are part of an emergency response system, are built primarily as aftermarket modifications to existing vehicles or have a 'box' secured to a light or heavy truck chassis (all conducted outside of the existing automotive safety infrastructure), and are also occupational environments for the EMS providers. However, in the USA ambulance vehicle safety is addressed outside of the Federal Motor Vehicle Carrier Safety Administration system – in regards to crash events and outcome data collection and hence do not share the same comprehensive safety oversight of other commercial vehicles.

Capture of safety performance of these vehicles is at best scant – and rudimentary at a national level and has been demonstrated to be incomplete (McGuire 2003). The data that has been published highlights that ambulances are associated with high crash fatality and injury rates per mile traveled and that compared to other emergency vehicles (Becker 2003) have high occupant fatality rates and that also compared to trucks have almost double the percentage of occupant fatalities. It is recognized that the hazards are greatest for occupants of the rear compartment (Becker 2003).

Given this background and the existing, albeit scant, biomechanical and crashworthiness data that have been published – the issue of identifying crashworthiness and occupant hazards has been raised in a number of sectors.

One response to this safety performance challenge has been for a spectrum of people to attempt to address the occupant safety and crashworthiness of these vehicles and largely on an individual level . However, as well intentioned as these initiatives have been , they have primarily involved small teams of Emergency Medical Service end users and after market manufacturers and had very minimal, if any, input from key and recognized automotive safety expertise, and very minimal application of in depth understanding of automotive safety and crashworthiness principles.

EMS is a relatively new industry, an industry that has an unusual history of beginnings within the mortician industry. The first modern ambulances were hearses, usually a Cadillac station wagon, a vehicle in which an occupant could be transported in the recumbent position. Proximity and access to the patient was not a challenge in that environment, which was very compact. However over the past 50 years ambulance vehicles in the USA have become larger and larger – and transitioned from the intact automotive passenger vehicle to the truck chassis with an after market 'box' or a modified van with an aftermarket elevated roof. What should be kept in mind is that these vehicles, related largely to how they are operated, are vehicles at high risk of crash and thus it would seem prudent that the safety and crashworthiness of these vehicles be optimized.

How safe are EMS vehicles and to what standards are they designed and tested? Despite the large strides that the general automotive industry has made in the last 30 years in the safety of passenger vehicles, this expertise has not yet been translated substantively to the safety of ambulance vehicles. There are few safety standards and no crash safety test procedures or guidelines that provide occupant protection in ambulance vehicles in the USA. Limited safety testing requirements were established in Europe in 1999 (CEN 1789). Australia has had the ambulance restraint standard ASA 4535 in place since 1999, and it is the most stringent globally (AS/NZS 4535). Thus ascertaining the safety of EMS transport vehicles (and products in that environment in the USA) remains limited largely to sparse expert opinion and peer evaluation, often by non automotive safety engineering expertise and in a piecemeal fashion.

EMS has been generally demonstrated recently to be a dangerous profession, and vehicles crashes have been shown to be the most likely cause of a work related fatality in EMS (Maguire 2003). The most dangerous part of the ambulance vehicle has been demonstrated in both biomechanical and epidemiological studies to be the rear patient compartment (Becker 2003, Levick 2000-2006), which currently is a part of the ambulance vehicle that is also largely exempt from the USA Federal Motor Vehicle Safety Standards (FMVSS). Also, unfortunately, no reporting system or database exists specifically for identifying ambulance crash related injuries and their nature, so specific details as to which injuries occurred and what specifically were the mechanisms which caused them are scarce, and there is not yet a national system for this data capture in the USA.

What we do know is that ambulances have high crash fatality rates per mile, well above those of passenger vehicles, or even when compared to similar sized vehicles (Ray 412).- and there is approximately one ambulance crash fatality per week in the USA, and a number of serious injuries for each fatality, with over 4,000 reportable crashes per year (Becker 941).

There has been a limited number of peer reviewed automotive safety engineering tests conducted for the EMS environment in Sweden (Turbell 1980), Australia (Best 1993, Levick 1998), and the USA (Levick 2000-2001). That which has been conducted has clearly identified some predictable and largely preventable hazards, particularly pertaining to intersection crashes and the hazards of the rear patient compartment, demonstrating the benefit of use of existing restraints for occupants, the importance of over the shoulder harnesses for the recumbent patient and firmly securing all equipment (Best 1993, Levick 1998-2006). These studies also identify hostile and hazardous interior surfaces of the rear compartment, as well as a need for head protection.

Many fatal and injurious ambulance crashes occur at intersections – either with the ambulance being struck with a side impact (more likely on its right side) or frontal impact. Failure to stop at an intersection for all vehicles is an extremely high risk practice. Lack of use of seatbelts by EMS personnel is cited frequently in the literature as a predominant cause for the high injury and fatality rates for occupants in EMS crashes (Becker 2003). The hazards resulting from the failure to secure equipment in the patient compartment, which has also been found to cause serious injury in the event of a collision has also been documented. This is supported by the engineering data from ambulance safety research involving crash tests (Levick 2001), as well as insurance and litigation records. With ambulance crashes being identified in the USA as the highest cause of patient adverse event mortality and serious morbidity (Wang 2007).

The very recently developed American National Standards Institute/American Society of Safety Engineers Z15.1 Fleet Safety Standard (ANSI/ASSE 2006) is possibly the only nationally approved fleet safety standard that is now applicable to the safety management of EMS vehicle fleets. It requires that the vehicles be crashworthy and safe – yet, in the USA there are no crashworthiness standards for these vehicles. The only USA guideline is the GSA KKK purchase specification, which does not provide for guidelines for dynamic crash testing – rather simply static tests. It is likely that the implementation of ASSE/ANSI standard will enhance the data collected regarding EMS vehicle safety, and hopefully provide more emphasis on EMS vehicle safety generally and assist in bringing EMS vehicle safety more inline with state of the art automotive safety practices.

Complexity of the Vehicle

A primary challenge to determining a dynamic safety testing profile in EMS is that of a spectrum of occupant orientations and structural crashworthiness performance of the rear compartment. The rear compartment is an environment containing a combination of occupant positions, for health care providers and the patient and any family members and also a large amount of different types of medical equipment, such as cardiac monitors and oxygen cylinders.

Complexity of the Activities in the vehicle environment

The rear compartment is also an environment where health care activities, access to equipment and communications are all undertaken. So that the design and crashworthiness features need to consider these activities – even though it has been described that emergency life saving procedures are only required in less than 5% of EMS transports.

Crashworthiness and Occupant Protection Systems

The principles of crashworthiness and occupant protection have been well described in foundation papers such as the original Dehaven publications (DeHaven 1952) and more recently Tingvall's landmark vision zero paper (Tingvall 1998). There is extensive engineering literature on the principles behind crashworthiness and occupant protection. These principles are reviewed in both the Rechnitzer (Rechnitzer 2000) and Grzebieta (Grzebieta 2006) papers which address these fundamental approaches that underpin the analysis undertaken in this paper.

Design Principles for Injury Mitigation upon Impact

i. Reduce the exchange of energy -
ii. Provide energy absorption (maximize the stopping distance) –
iii. Ensure compatible interfaces –
iv. Manage the exchange of energy –
v. Provide a survival space

Based on the above design principles, and the extensive body of automotive safety literature and existing real world ambulance crash data, in addition to any dynamic or impact test data for similar ambulance design and performance – an analysis of the anticipated crashworthiness performance strengths and weaknesses of the selected prototype vehicles was conducted by the multidisciplinary team. The analysis is one based on these principles and is supported by evidence from the real world and crash test data that is available.

ANALYSIS OF THE THREE AMBULANCE PROTOTYPES BASED ON THESE FUNDAMENTAL PRINCIPLES OF AUTOMOTIVE IMPACT MECHANICS

Approach

The three vehicles used in this study reflect a spectrum of the vehicles that have been designated by their designers as safety prototypes for ambulance transport in the USA. They were developed and designed essentially by end users and after market manufacturers, with limited, if any input, from key recognized automotive safety expertise and infrastructure. Expected safety performance was analyzed using existing and established automotive safety principles in addition to relevant published crashworthiness literature. Information on design and construction of the vehicles was identified, and evaluated via application of basic engineering crashworthiness principles and laws of physics, with a specific focus on countermeasure design for reducing harmful loading and injury causation potential in crashes or sudden decelerations. Data sources used for the analysis included: vehicle specifications, inspections, photographs, actual real world crash information for similar vehicle construction, crash tests and published crashworthiness and injury mitigation literature.

The Three Vehicles – All three vehicles have been developed by end users with support of an after market ambulance manufacturer, of which there are some 56 in the USA, largely all members of the NTEA (ref)

Vehicle X - A modified van, with an elevated roof
Vehicle Y - A chassis with aftermarket box
Vehicle Z - A chassis with aftermarket box

The vehicle X - is a standard van which had undergone structural modifications to the body and interior modifications to the seating and some equipment anchors, in addition to some change in arrangement of cabinetry and some additional electronics for collision avoidance.

Vehicle Y – is a truck chassis with an aftermarket box – and a spectrum of seating arrangements, with a spectrum of restraint approaches. This vehicle also has and some additional electronics for collision avoidance.

Vehicle Z - is also a truck chassis with an aftermarket box – and a spectrum of seating arrangements, with a spectrum of restraint approaches.

The following types of features were evaluated for each vehicle, and rated by the multidisciplinary team on a 5 level scale of estimated safety or protective performance based on the fundamental principles of crashworthiness - a score of five stars being the best expected performance and a score of one star being the lowest expected performance. There were no negative score designations. One star was the lowest score achievable. Features analyzed included: Rear passenger compartment construction, Seating design Squad bench design, Head strike areas, Hostile interior structures, Restraint systems, Netting and any Impact tested components

Study Findings

Results demonstrated poor vehicle structural integrity and crashworthiness for these aftermarket modified ambulance vehicles both theoretically and the related vehicle crash data and from the controlled crash test data. Assessed crashworthiness performance and occupant protection do not appear optimized even for the minimally structurally modified van.

The real world crash data demonstrated some complete disruption of the rear compartment 'box' in the type Y and Z vehicles (Figs 1a and 1b) , and some disruption of the vehicle compartment integrity related to the aftermarket modifications to the roof of the vehicle of the type X style.

Figure 1a. and 1b. Examples of real world crash outcomes for the rear passenger compartment (EMS Network)

Figure 1b. Image of the ambulance's right side (EMS Network)

Published crash test data confirmed these findings for both frontal and side impacts (Figs 2a and 2b.).

Figure 2a. and 2b. An example of crash test outcome at 44 miles/hr closing speed for a chassis/box configuration. Figure 2a. Immediately after impact, chassis/box ambulance on its side.

Figure 2 b. The struck vehicle has been righted to demonstrate the intrusion to the rear passenger compartment. (crash and impact test photos provided by the author)

For vehicles Y and Z there were also concerns raised regarding the nature of the attachment of the 'box' to the chassis and the potential for the rigidity this system to increase the transfer of energy to the rear compartment occupants.

Additionally, there was liberal use of netting in a these vehicles – even though no testing of the nature of the netting material or its performance under impact conditions was referenced by any manufacturer. In studies conducted by the project SUPPORT team and the author – the characteristics of appropriate netting structure and dynamic impact performance has been evaluated, as well as an optimal design to allow for adequate human factors issues. (Fig 3.)

Figure 3. Dynamic testing of a netting device, by Project SUPPORT design team and the Author

Regarding the layout of the vehicles – Patient (P) was recumbent toward the left side of center of each vehicle, Occupant (A) was in the rear facing Captains chair, Occupant (B) and (C) were on the squad bench positions, and Occupant (D) was in an alternate position on the left hand side of the rear compartment or at the forward end of the squad bench. The

Figure 4. Interior cabinetry and seating design

Evaluations of the anticipated crashworthiness of these components are outlined in Table 1. below, with the 1 to 5 scale representing the anticipated degree of crashworthiness, one being the lowest score and 5 being the highest achievable score.

Table 1. Features analyzed

	Vehicle X	Vehicle Y	Vehicle Z
Rear passenger compartment construction	***	*	*
Seating design	***	**	**
Squad bench design	*	*	*
Head strike areas			
Patient –P	***	***	***
Occupant- A	**	**	**
Occupant- B	**	**	**
Occupant –C	**	**	**
Occupant -D	**	**	**
Hostile interior structures	***	**	**
Restraint systems	**	**	**
netting	**	**	**
Impact tested components	*	*	*

DISCUSSION

The features described in these study vehicles had numerous concerns – the five major area of concern.

1. For study vehicles Y and Z - being a non crashworthy structure of the rear passenger box, with non crashworthy connections of the passenger box to the chassis and in the setting of vehicle X, the van, compromising the potential integrity of the passenger compartment by removing and replacing the roof.

2. The persistence of the 'squad bench' in all vehicles with minimal if any occupant protection related to this structure and of variable degrees of potential failure of occupant protection based on its design and construction.

3. An interior environment where access to the equipment or the patient was severely limited due to the layout of the rear compartment with many hostile surfaces

4. All vehicles were designed using harness systems in side oriented seating positions in the rear passenger compartment, even though there is published literature suggesting that this is hazardous (Richardson et all 1999, Zou et al 1999). Additionally, there was no evidence that any of these harnessing systems had undergone any meaningful, if any, dynamic impact testing.

5. Rear compartment interior design features, (Fig. 4) particularly in and around the seating positions, where there were cabinetry and rigid structures that were potential hazards to seated occupants, and arm rests where there were potential hazards of a side facing occupant being struck in the liver or spleen region in a frontal impact.

By contrast there are some excellent examples of vehicles that are in use in EMS outside of the USA. The vehicles used by NSW Ambulance in Australia (NSW Ambulance) or the vehicles used in Sweden and Norway – some of which are similar to the Australian vehicles – are essentially retrofitted intact automotive industry manufactured vans without any structural modifications performed and with close involvement of the original automotive manufacturing expertise – rather than primarily being performed by an aftermarket manufacturer and in relative isolation of the automotive safety engineering industry. Neither the Australian vehicles nor the Swedish or Norwegian vehicles have a squad bench nor the after market structural vehicle modifications that can potentially decrease crashworthiness integrity that were seen in study vehicles X, Y and Z.

It remains a sad irony that the design and crashworthiness features and occupant protection for the rear compartment of vehicles carrying laundry and packages is essentially little different from a dynamic impact crashworthiness perspective than for these chassis box combination or retrofitted ambulance vehicles carrying our emergency providers, patients and next of kin in the USA.

The failure to address the design of these vehicles based on accepted published and peer reviewed automotive safety literature, and in isolation of the extensive global expertise in automotive safety, human factors and ergonomics, remains a serious concern for this aspect of the EMS system.

CONCLUSIONS

Ambulance vehicle design and crashworthiness features should be driven by accepted automotive safety principles, practice and science. In the USA in a setting of high crash rates, documented high rear occupant compartment injury and fatality rates, a complex occupant and emergency care environment, and the absence of prescribed dynamic crashworthiness test procedures for ambulances – a comprehensive application of existing knowledge in vehicle impact dynamics and automotive safety performance principles should be applied by appropriately skilled experts in the field of crashworthiness and automotive safety. These findings in this study are projected findings, rather than actual crashworthiness tests – however this is the first comparative automotive safety engineering evaluation of prototype ambulance vehicles by recognized automotive safety expertise.

This is key information for a major fleet of vehicles globally which has had minimal automotive safety attention or input to date. Clearly the optimal approach to ascertain crash performance of these vehicles in addition to inspection of real world vehicle crash sites and vehicles is to conduct appropriate vehicle crash tests – with crash test dummies, anthropomorphic test devices (ATDs) which are properly configured for the unusual occupant positions that are routine in the ambulance environment and also – given the high frequency of 'roll-over' of these vehicles in crash situations to conduct rollover tests of these vehicles in addition to side impact testing (Levick 2000-2006) which would demonstrate the impact performance and any failures of these vehicles.

From existing published USA research, and crash information - side impact crash performance for the box style vehicles (vehicle Y and Z) is very poor, and frontal impact also results in poor occupant protect for the rear compartment of these vehicles. From this study it appears there are major deficiencies in the safety design of these prototypes. The issue of placing occupants in a non automotive safety engineered 'box' construction for a passenger compartment is fundamentally unacceptable given the current knowledge in automotive safety design and performance and the existing data on crash out comes for these vehicles.
Emphasis on effective seat design, based on existing automotive safety literature and a clear focus on occupant human factors and equipment location and anchors, could provide for major safety enhancements for ambulance vehicles. There is need for vehicle safety researchers, ambulance industry and vehicle designers to recognize and apply these existing principles to reduce current system failures in an important and essential service that has a poor safety record well below that of passenger vehicles and other commercial vehicles.

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