Review of injury mitigation strategies and methods of assessment for passenger vehicle rollover crashes in Australia

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Abstract

Rollover crashes are one of the most severe crash modes for passenger vehicle occupants in Australia. They produce a wide range of injury patterns due to their ballistic and chaotic nature. Thus, multiple injury mitigation strategies are required to protect occupants against the large variety of potential loading and impact scenarios. Many strategies (e.g. side curtain airbags and upper interior head protection) have been employed to reduce the occurrence of injuries in rollover crashes with varying success. Recent epidemiological research regarding serious and fatal head, spine, and thoracic injury in pure rollover crashes has identified distinct injury patterns and characteristics. Further, the relationships between these injury patterns and specific occupant, vehicle, and crash factors have also been identified. This work reviews current and proposed injury mitigation techniques specific to pure rollover crashes in light of these recent findings and attempts to identify the types of injuries that each strategy would be most effective at reducing. The injury characteristics previously identified serve as a basis from which to evaluate the estimated effectiveness that particular countermeasures and injury mitigation strategies might have for the Australian passenger vehicle fleet. The findings will provide an up-to-date review with specific focus on Australian rollover characteristics that can be used to inform future regulatory and consumer rating tests.

Introduction

Crashes involving rollover have a higher rate of fatal and serious injury than planar crashes in Australia and the United States (US) (Fréchède, McIntosh, Grzebieta, & Bambach, 2011; National Center for Statistics and Analysis, 2007). While the majority of research efforts concerning rollover take place in the US, the characteristics and patterns of rollover crashes and injury outcomes are similar for Australia (Bambach, Mitchell, Mattos, Grzebieta, & McIntosh, 2014). The total number, as well as the rate, of occupants involved in rollover crashes has decreased significantly over the last ten years in New South Wales; however, the rate at which occupants are seriously or fatally injured in rollover crashes has not decreased proportionately (Bambach et al., 2014).

The body regions that most commonly sustain serious injuries in pure rollover crashes are the head, spine, and thorax (Bambach et al., 2014; Mattos, Grzebieta, Bambach, & McIntosh, 2013a). These injuries are caused by the interaction between the occupant and the vehicle interior or exterior environment. It is generally accepted that head and spine injuries are primarily due to direct impact between the head and interior roof structure (Bambach, Grzebieta, Mcintosh, & Mattos, 2013; Foster et al., 2012; Mattos et al., 2013a). In the case of partial ejection the head is exposed to impacts with the ground surface which further increases the risk of injury. Thorax injuries have been reported to occur primarily due to interaction with the vehicle door in oblique-type loading scenarios and are not likely related to the amount of intrusion of the roof or door (Bambach, Grzebieta, & McIntosh, 2013). The omnidirectional nature of the loading conditions during a rollover result in the occupant experiencing a combination of vertical and lateral accelerations which current restraint systems are not designed for.

Advances in vehicle safety technology continue to provide more and better means of reducing occupant injury during a crash through active and passive means (Young, Grzebieta, Rechnitzer, Bambach, & Richardson, 2006), yet no regulatory or consumer rating tests evaluate the performance of passive or active safety features specifically for the rollover crash mode in Australia. Vehicle design, driven by regulatory testing and consumer demand (O'Neill, 2009), has been the primary driver in the recent decline of occupant fatality rates in Australia and the US (Anderson & Searson, 2015; Farmer & Lund, 2015; Newstead, Watson, & Cameron, 2010). Additionally vehicle manufacturers are meeting enhanced requirements more quickly and more widely than ever before (Park, Rockwell, Collins, Smith, & Aram, 2015). It is, thus, advantageous to continue to expand the scope of compliance and consumer rating tests to include new safety technologies, promote innovation, and deliver a greater level of safety.

Methods

This study is a review of injury prevention strategies for rollover crashes that have been identified in the literature. Each strategy is described and its relationship to injuries specific to the head, spine, or thorax is noted. Methods of testing and evaluation are also recommended and the expected benefit of each countermeasure is identified. Current standards or consumer tests are provided as examples where applicable.

The countermeasures reviewed in this work are limited to features that aim to prevent injury during the rollover crash. Therefore, technologies such as electronic stability control that aims to prevent a crash or E-call that aims to provide better post-crash care are not discussed.

Results and Discussion

Four approaches for mitigating head, spine, and thorax injury in rollover crashes were identified from the literature. These are summarised along with their estimated effect on reducing injury to a particular body region in Table 1, where injury is described using the Abbreviated Injury Scale (AIS) (AAAM, 2008). The mitigation of head and spine injuries in rollover crashes requires the use of many different countermeasures and strategies. Thoracic injuries, on the other hand, would benefit the most from an advanced restraint system.

Table 1. Injury risk management objectives for rollover crashes

Strategy	**Estimated injury reduction**[1]		
	Head	**Spine**	**Thorax**
Rollover restraints	Up to 30 % AIS 3+ (Mattos et al., 2013a)	Up to 50 % AIS 3+ (Bambach, Grzebieta, Mcintosh, et al., 2013)	Up to 90 % AIS 3+ (Bambach, Grzebieta, & McIntosh, 2013)
Structural performance	Up to 66 % AIS 3+ (Bambach et al., 2014; Mattos et al., 2013a)	Up to 39 % AIS 3+ (Bambach, Grzebieta, Mcintosh, et al., 2013; Bambach et al., 2014)	Likely unaffected (Bambach, Grzebieta, & McIntosh, 2013; Bambach et al., 2014)
Upper interior head protection	62 % AIS 4+ 30 % head injury as cause of death (NHTSA, 2011a)	Unknown	Likely unaffected (Bambach, Grzebieta, & McIntosh, 2013; Bambach et al., 2014)
Ejection mitigation	25% for ejected occupants (NHTSA, 2011b)		

[1] Based on implementation in current vehicle fleet

Rollover restraints

The seat belt is the most important passive safety technology available in vehicles today; it is credited with saving the lives of over 15,000 passenger vehicle occupants in 2012 in the US alone (Kahane, 2015). Historically, the main function of restraints has been to reduce forward motion during frontal crashes. The primary benefit that restraints provide to rollover occupants is preventing ejection (L. Evans, 1990).

Occupants in a rollover crash undergo a series of discrete inertial and direct loading scenarios due to a combination of free-flight rotation and vehicle-to-ground contact events. With standard restraints occupants can readily contact the upper interior structure of the vehicle (Gloeckner, Bove, Croteau, Corrigan, & Moore, 2007; Moffatt & James, 2005), a common source of head and spine injuries (Bambach, Grzebieta, Mcintosh, et al., 2013; Bedewi, Godrick, Digges, & Bahouth, 2003; Mattos et al., 2013a). Occupants are also subject to lateral loading directions and suffer thoracic injury due to contact with the door, seatbelt or centre console (Bambach, Grzebieta, & McIntosh, 2013; Digges et al., 2013). Advanced restraints are likely to mitigate injury in rollover crashes by reducing occupant excursion and limiting their interaction with the vehicle interior as well as by providing a higher level of support for oblique and lateral loading conditions.

The two main design considerations that can be optimised to prevent unwanted motion include passive features such as seat and restraint geometry, which help to maintain optimal seat position, and active features such as pre-tensioning devices, which reduce the amount of slack available in the system (Hu, Chou, & Yang, 2009). A well-designed belt geometry can reduce occupant excursion significantly by limiting pelvis vertical motion, torso rotation, and maintaining the position of the sash belt over the shoulder (Arndt, Mowry, Dickerson, & Arndt, 1995; Bostrom & Haland, 2005; Meyer, Oliver, Hock, & Herbst, 2010; Moffatt, Cooper, Croteau, Parenteau, & Toglia, 1997; Rains, Elias, & Mowry, 1998; Sword &

Sullivan, 2007; Ward, Der Avanessian, Ward, & Paver, 2001; White et al., 2011). Active restraints currently require the use of pyrotechnic, motorised, or mechanical devices to limit slack in the belt system. The use of such systems has proven to be effective in reducing excursion in experimental tests (Hu et al., 2009; Meyer, Davis, Chng, Herbst, & Forrest, 2000; Rains et al., 1998; Sword & Louden, 2009; Sword & Sullivan, 2007); however they rely on very early activation times to be optimally beneficial (Hare et al., 2002; McCoy & Chou, 2007; Moffatt et al., 1997; Newberry et al., 2006). Motorised retractors are likely the current best option for removing belt slack early in an event as they can deploy prior to significant occupant loading and can be reversed in the case of a non-event (Schoneburg, Paurevic, Fehring, Richert, & Bogenrieder, 2015).

Testing and evaluation: rollover restraints

A method to evaluate the performance of restraint systems in the rollover crash mode must assess multiple criteria. This is highlighted by the difference in the experimental and field performance of some promising restraint systems. For example, seat integrated restraints (SIR) have shown promising results in the laboratory (Bostrom, Haland, & Soderstrom, 2005), yet these results have not been supported by real world data (Haaland, 2013; Padmanaban & Burnett, 2008). A general outline for a systematic evaluation method is given in Table 2 where recommended evaluation methods and criteria for each attribute of a restraint system are proposed. The table describes general response requirements without quantifying them, as the requirements would have to be determined in conjunction with the specific test procedures used to evaluate them. Three subsystem tests may be required to evaluate the entire system; one to evaluate sensor activation, one to evaluate restraint performance under rollover conditions, and one to evaluate thorax injury due to primarily lateral motion.

Activation times are already assessed by the Australasian New Car Assessment Program (ANCAP) using the manufacturers test data (ANCAP, 2014). Additional tests as required could be implemented using physical tests or numerical models to determine the activation times in critical pre-rollover events (Berg, Rucker, & Kroninger, 2007; Gugler & Steffan, 2006; Ridella, Altamore, & Nayef, 2001). It is important to note that rollover sensors are expected to deploy with sufficient time to be effective for 84 % of rollover crashes (Lange, Iyer, Pearce, Jacuzzi, & Croteau, 2011). It is not currently possible to predict the remaining 16 % of rollover crashes early enough for the deployment of interior safety features to have a significant effect. This is due to their being caused by vehicle-to-vehicle or fixed-object collisions that have much shorter rollover initiation times. A rating scheme could possibly give higher rating for features that are reversible and allow for earlier deployment or deployment in cases that are not covered by go/no-go sensors.

Table 2. General recommendations for restraint assessment criteria

Characteristic	Evaluation method	Proposed criteria for better performance	Example technology
Active restraint deployment time	• On-road manoeuvres of critical pre-crash scenarios (Eigen & Najm, 2009; Ridella et al., 2001) • Numerical simulation (Berg et al., 2007; Gugler & Steffan, 2006) • Manufacturers data (ANCAP, 2014)	• Prior to significant belt loads • Earlier activation time • Non-hazardous result for false-positive	• Motorised retractors (Schoneburg et al., 2015) • Rollover sensors (Cassatta et al., 2011)
Belt slack removal and occupant excursion	• Repeatable impact test (Chirwa, Stephenson, Batzer, & Grzebieta, 2010; Chou, McCoy, & Le, 2005) • Inverted drop (D. Friedman & Chng, 1998) • Component tests (Sword & Sullivan, 2007)	• More slack removed • Non-injurious belt loads • Reduced vertical/lateral motion • Lower head contact force • Critical contact locations	• Pre-tensioner (White et al., 2011) • Motorised retractors (Schoneburg et al., 2015) • SIRS (Meyer et al., 2010) • 3+2 pt belt (Bostrom & Haland, 2005)
Lateral/oblique loading	• Sled tests (Humm et al., 2015) • Side impact with far-side ATD/Criteria (Fildes & Digges, 2009)	• Meet thoracic injury criteria	• Front centre airbag (Thomas, Wiik, & Brown, 2013) • Torso airbag (Bostrom et al., 2005)

Many different methods have been used to assess the effectiveness of restraints under simulated rollover conditions including spit tests (i.e. pure rotation of a vehicle without impact) (Meyer et al., 2010; Moffatt et al., 2003), component tests with rotation and inverted impact (Sword & Sullivan, 2007), full scale rollover tests (White et al., 2011), or inverted drop tests (D. Friedman & Chng, 1998). The use of a dynamic component test method has many advantages, including the ability to replicate actual rollover conditions and allow for simultaneous evaluation of other interior countermeasures (Cassatta et al., 2010). However, the complexity and cost of performing such tests may hinder the repeatability of such methods.

Finally, the performance under lateral and oblique loading scenarios could readily be evaluated in a sled test or in conjunction with side impact tests using an appropriate far-side anthropomorphic test device (ATD) (Fildes & Digges, 2009). More work is necessary to develop performance metrics and a more biofidelic ATD as current ATDs do not replicate human-to-restraint motion for non-frontal loading directions, especially with regard to thorax injury (Fildes et al., 2002; Kent, Patrie, & Benson, 2003; Ward et al., 2001).

Benefit to rollover occupants: rollover restraints

It is hard to calculate the direct benefit that advanced restraints would provide to occupants involved in rollover crashes. They are expected to have a large benefit to multiple body regions. This is because over 75 % of serious injuries sustained due to a rollover occur to the head, spine or thorax, which are the body regions that would be advantaged the most by an advanced restraint system (Bambach, Grzebieta, & McIntosh, 2013; Bambach, Grzebieta, Mcintosh, et al., 2013; Mattos et al., 2013a).

Structural Performance

The severity of roof intrusion in a rollover crash is a function of a vehicle’s roof strength (NHTSA, 2010; Young & Grzebieta, 2010). Roof strength is also independently associated with the rate of injury in rollover crashes; a 20 per cent reduction in the injury rate is predicted for each 1 unit increase in vehicle roof strength-to-weight ratio (SWR) (Brumbelow & Teoh, 2009; Brumbelow, Teoh, Zuby, & McCartt, 2009). Roof intrusion has been shown to be associated with non-ejected occupant injury in general (Conroy et al., 2006; Mackay & Tampen, 1970), and head and spine injury specifically (Austin, Hicks, & Summers, 2005; Bedewi et al., 2003; Dobbertin, Freeman, Lambert, Lasarev, & Kohles, 2013; Freeman, Dobbertin, Kohles, Uhrenholt, & Eriksson, 2012; D. Friedman & Friedman, 1998; Hu, Cho, Yang, & King, 2007; Huelke, Lawson, & Marsh Iv, 1977; Mandell, Kaufman, Mack, & Bulger, 2010; Rains & Kanianthra, 1995; Strashny, 2007; Terhune, 1991). While correlation between the two does not imply causation, as highlighted by the serious head and spine injuries observed to occur in rollovers with minimal roof intrusion (Bambach, Grzebieta, Mcintosh, et al., 2013; Mattos et al., 2013a), limiting the amount of structural deformation during a crash is fundamental to providing a safe environment for the occupant (De Haven, 1952). This is partly due to ensuring that interior restraint systems are able to perform as effectively as possible without being obstructed by intruding components. Further, roof intrusion has been reported by emergency services to hinder the extrication of occupants which reduces the effectiveness of post-crash care (Mattos, Grzebieta, Bambach, & McIntosh, 2013b).

Testing and evaluation: structural performance

In reviewing the feasibility of implementing an Australian Design Rule (ADR) with regard to roof strength Henderson and Paine concluded that an improvement in roof strength, along with other countermeasures, would increase the safety of vehicles in a rollover (Henderson & Paine, 1998). They could not, however, recommend the use of the original US roof strength standard, i.e. Federal Motor Vehicle Safety Standard (FMVSS) number 216, as it was seen as inadequate at the time. Since then the FMVSS 216 has been updated to require a SWR of 3, instead of 1.5, in a two-sided, rather than one-sided, test (NHTSA, 2009). Additionally the Insurance Institute of Highway Safety (IIHS) has implemented a rating system that requires a

SWR of 4.0 or greater for a vehicle to receive a good rating (IIHS, 2009). The IIHS model was scheduled for implementation by ANCAP, but was withdrawn in 2013 (ANCAP, 2015).

Many test methods have been proposed to evaluate roof strength for passenger vehicles. The most appropriate, based on repeatability and replication of real-world deformation patterns, include the quasi-static roof strength test, the inverted drop test, and the Jordan Rollover System (JRS) or equivalent Dynamic Rollover Test System (DRoTS) (Chirwa et al., 2010; Gugler & Steffan, 2006; Kerrigan et al., 2011). Two categories of test methods, along with proposed criteria, are summarised in Table 3. While JRS and DRoTS tests are more complicated to run they have the additional advantage of providing a dynamic environment in which the entire vehicle, inclusive of all its features and countermeasures, can be assessed in conjunction with the structural performance. These features and countermeasures include those discussed in this paper as well as other design choices that may indirectly affect occupant safety such as interior roof shape and door panel stiffness.

Benefit to rollover occupants: structural performance

The head and spine, specifically the cervical and upper thoracic regions, are affected the most by structural deformation of the roof. It is estimated that up to 66 % of AIS 3+ head injuries and up to 39 % of AIS 3+ spine injuries are associated with roof intrusion (Bambach, Grzebieta, Mcintosh, et al., 2013; Bambach et al., 2014; Mattos et al., 2013a). Thoracic injuries, however, do not appear to be related to the amount of intrusion that occurs to the adjacent roof or door during a rollover crash (Bambach, Grzebieta, & McIntosh, 2013). The overall injury rate due to rollover crashes may further be reduced in vehicles that have better structural performance if it allows for easier extrication by emergency services (Mattos et al., 2013b).

Table 3. General recommendations for structural performance criteria

Method	**Recommended criteria**
Quasi-static (i.e. FMVSS 216)	• Strength-to-weight ratio • Door performance (i.e. ease of opening)
Dynamic (i.e. inverted drop, JRS, DRoTS)	• Roof intrusion • Roof intrusion speed • Ejection portal creation • Door performance • Effect of deformation on other countermeasures

Upper interior head protection

The greatest risk of head injury in rollover crashes is due to direct contact between the head and the upper interior roof of the vehicle (Mattos et al., 2013a, 2013b). The most straightforward technique used to reduce the risk of head injury from these contacts is to increase the compliance of the upper interior structure via use of energy absorbing components such as honeycomb-type structures or even roof-mounted airbags (Heudorfer, 2005; Seong, Park, & Woo, 2002). These techniques are most effective in combination with greater roof strength. Vehicles in the US and Australia have been required to meet general interior protection standards since 1968 and 1989, respectively (Department of Infrastructure and Transport, 2006). In 1999 the US extended the FMVSS no. 201 to include upper interior head protection (NHTSA, 2013). The extension of the rule is now referred to as FMVSS 201U. The added cost of implementing the head protection countermeasures, including additional lifetime fuel costs due to the added weight of the system, to each vehicle has been estimated to be approximately 25 USD (NHTSA, 2011a).

Testing and evaluation: head protection

Compliance testing consists of firing a free motion headform at predetermined locations on the upper interior vehicle roof structure (NHTSA, 1998). The US standard, FMVSS 201U, requires that the Head Injury Criterion (HIC) value resulting from the impact not exceed 1000 (NHTSA, 2013). HIC values have decreased from an average of 909.0 in pre-FMVSS 201U standard US vehicles to 667.5 in post-standard vehicles (NHTSA, 2006). A rating system could easily be developed based on the US model in which either a pass/fail criterion was set or more points were awarded for lower injury measures.

Benefit to rollover occupants: head protection

The countermeasures are estimated to reduce AIS 4+ head injuries due to upper interior contact in rollover crashes by up to 62 % in the US and are expected to have a similar benefit in Australia (Mclean et al., 1997). There is, however, the potential for increased padding to merely shift injuries from the head to the spine as it would increase the ability of the head to ‘pocket’ resulting in a head-neck constraint that increases the risk of spinal fractures (Nightingale, Richardson, & Myers, 1997), though this could be minimised by reducing the friction of the surface (Hu, Yang, Chou, & King, 2008).

Ejection mitigation

Occupants that are ejected during a rollover crash are more than 3 times as likely to be fatally injured than those that remain inside the vehicle (El-Hennawy et al., 2014). Full ejection is almost entirely prevented with the use of a standard restraint system, even in older vehicles without modern restraints (Huelke, Marsh Iv, Dimento, Sherman, & Ballard, 1973). However, partial ejection can still occur to restrained occupants (Parenteau & Shah, 2000). Thus, additional safety systems such as rollover-activated side curtain airbags with long-duration inflators (Cuerden, Cookson, & Richards, 2009; Eigen, 2003; N. C. Evans & Leigh, 2013; Rechnitzer & Lane, 1994), and laminated side window glazing (Batzer et al., 2007; Malliaris, DeBlois, & Digges, 1996; Sances, Carlin, & Kumaresan, 2002; Willke et al., 1999) combined with a reduction in roof intrusion (K. Friedman, Hutchinson, Mihora, & Cummings, 2015; Moffatt & Padmanaban, 1995) are required to prevent partial ejection of the head, torso, and upper extremities by eliminating ejection portals.

Testing and evaluation: ejection mitigation

Methods currently used to evaluate the ability of a system to prevent ejection, such as those employed by the FMVSS No 226 in the US, include deploying a headform into the countermeasure, which is typically a rollover-activated side air curtain, and measuring its excursion beyond the window frame (NHTSA, 2011b). The performance could be rated based on pass fail criterion such as a set excursion distance or in conjunction with select impact energy levels (e.g. a higher rating for preventing excursion at a higher impact energy level) (Dix et al., 2010). The algorithms used to deploy the ejection mitigation countermeasures, which are also responsible for firing the active restraints, could be assessed as described in Table 2.

Benefit to rollover occupants: ejection mitigation

The primary portals through which rollover occupants are ejected include the front side windows (Malliaris et al., 1996). By preventing partial or full ejection through these portals up to 18 % of injuries sustained by belted occupants and 49 % of injuries sustained by unbelted occupants can potentially be prevented (Bedewi et al., 2003). A preliminary analysis of the benefit of rollover-activated side airbags indicates a 41 % reduction in fatalities due to rollover crashes (Kahane, 2014).

Conclusions

Four approaches to reducing injury in rollover crashes through the use of passive and active safety features have been reviewed in light of recent findings regarding head, spine, and thorax injury. All of the approaches and estimated benefits are supported by real world evidence and are expected to provide similar benefit to Australia.

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