Accident Analysis and Prevention 85 (2015) 111–117

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Occupant injury in rollover crashes – Contribution of planar impacts with objects and other vehicles

Johan Ivarsson*, Gerald Poplin, Tim McMurry, Jeff Crandall, Jason Kerrigan

University of Virginia Center for Applied Biomechanics, 4040 Lewis and Clark Drive, Charlottesville, VA 22911, USA

ARTICLE INFO

Article history:
Received 4 June 2015
Received in revised form
11 September 2015
Accepted 12 September 2015
Available online 27 September 2015

Keywords:
Rollover crash
Occupant
Injury
Planar impact

ABSTRACT

Planar impacts with objects and other vehicles may increase the risk and severity of injury in rollover crashes. The current study compares the frequency of injury measures (MAIS 2+, 3+, and 4+; fatal; AIS 2+ head and cervical spine; and AIS 3+ head and thorax) as well as vehicle type distribution (passenger car, SUV, van, and light truck), crash kinematics, and occupant demographics between single vehicle single event rollovers (SV Pure) and multiple event rollovers to determine which types of multiple event rollovers can be pooled with SV Pure to study rollover induced occupant injury. Four different types of multiple event rollovers were defined: single and multi-vehicle crashes for which the rollover is the most severe event (SV Prim and MV Prim) and single and multi-vehicle crashes for which the rollover is *not* the most severe event (SV Non-Prim and MV Non-Prim). Information from real world crashes was obtained from the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) for the period from 1995 through 2011. Belted, contained or partially ejected, adult occupants in vehicles that completed 1–16 lateral quarter turns were assigned to one of the five rollover categories. The results showed that the frequency of injury in non-primary rollovers (SV Non-Prim and MV Non-Prim) involving no more than one roof inversion is substantially greater than in SV Pure, but that this disparity diminishes for crashes involving multiple inversions. It can further be concluded that for a given number of roof inversions, the distribution of injuries and crash characteristics in SV Pure and SV Prim crashes are sufficiently similar for these categories to be considered collectively for purposes of understanding etiologies and developing strategies for prevention.

1. Introduction

In the United States, rollover crashes only constitute about 2% of all crashes but account for approximately 20% of all fatal crashes (National Highway Traffic Safety Administration (NHTSA), 2012a). Field data studies on rollover crashes have utilized the number of quarter turns completed by the vehicle as the sole measure of crash severity and showed that the frequency of occupant injury increases with increasing number of quarter turns (Moore et al., 2005; Gloeckner et al., 2006; Parker et al., 2007). Other studies have emphasized the importance of also accounting for planar impacts preceding or succeeding the roll sequence as such impacts add to the overall crash severity and may contribute to occupant injury (Hight et al., 1972; Digges and Eigen, 2003, 2005, 2006a,b, 2007; Fay et al., 2003; Viano et al., 2007). A planar impact is defined as an impact that does not involve any lateral or end-over-end rotation of the vehicle.

Digges and Eigen (2006a) identified two types of rollover crashes for which the frequency of injury is higher than if predicted by the number of quarter turns (aggregated into the number of roof inversions) alone; crashes for which the roll sequence is preceded by planar impact causing severe (as opposed to minor or moderate) vehicle damage, and one-quarter roll crashes for which the roll sequence is the first event and the vehicle planar impact damage is classified as severe.

Excluding rollover crashes with severe planar impact damage, Digges and Eigen (2007) showed that the frequency of MAIS 3 + F injury (occupants with at least one injury of serious or greater severity, i.e. AIS 3+ injury, or fatal injury regardless of maximum coded injury severity) to belted front outboard occupants increased monotonically with increasing number of roof inversions for both pure rollovers, i.e. single vehicle single event rollovers, as well as for rollover crashes involving planar impact causing minor or moderate damage. The frequency of MAIS 3 + F injury for these types of

* Corresponding author.
E-mail addresses: johan@biomechscientific.com (J. Ivarsson), gsp3j@virginia.edu (G. Poplin), tlm6w@virginia.edu (T. McMurry), jrc2h@virginia.edu (J. Crandall), jrk3z@virginia.edu (J. Kerrigan).

http://dx.doi.org/10.1016/j.aap.2015.09.008
0001-4575/

crashes was found to be similar for crashes involving two or more roof inversions but higher for the latter type in crashes involving zero and one roof inversion. This suggests that planar impacts do not have to cause severe vehicle damage for such impacts to contribute to injury in rollover crashes involving no more than one roof inversion.

Given the influence of planar impact on occupant injury in rollover crashes, recent field data studies have utilized various approaches to exclude potential contribution from planar impacts when studying rollover induced occupant injury. The most conservative approach is to limit the case selection to pure rollovers. While conservative, the fact that it involves exclusion of all multiple event cases regardless of whether planar impacts contribute to occupant injury leads to relatively small population samples. Bose et al. (2011a) introduced the concept of *primary* rollover crashes which, in addition to pure rollovers, also included single vehicle multiple event rollover crashes for which the rollover portion of the crash is classified as the most severe crash event. The pure and primary single vehicle multiple event rollovers had similar distributions of crash kinematics and damage location, whereas the corresponding distributions for the non-primary rollover crashes were characterized by a substantially higher proportion of cases involving zero roof inversions and the front as opposed to the top of the vehicle being the most common vehicle damage location. According to the authors, these similarities and differences between the aforementioned distributions justified combining pure rollovers and single vehicle multiple event rollovers for which the rollover portion is classified as the most severe event into one *primary* category.

More recently, Funk et al. (2012a), in a field data study on occupant injury risk factors in rollover crashes, pooled not only pure rollover crashes and single vehicle multiple event crashes for which the rollover portion is coded as the most severe event but also multiple vehicle rollover crashes for which the rollover portion is coded as the most severe event. This approach reportedly doubled the number of cases compared to if only pure rollovers had been included. The frequency of various injury measures were compared between the multiple event and pure rollover crashes and were not significantly different ($p > 0.10$), which, according to the authors, justified combining the three types of rollover crashes into one population for which occupant injury was assumed to be from the rollover portion of the crash.

The current study aims to further evaluate similarities and differences in vehicle type distribution, crash kinematics, injury, and occupant demographics between single vehicle single event rollovers (pure rollovers) and multiple event rollovers with or without multiple vehicle involvement to determine which of the four types of multiple event rollovers can be used in combination with pure rollovers to study rollover induced occupant injury.

2. Methods

Data for the current study were obtained from the NASS-CDS database for the 17-year period from 1995 through 2011. NASS-CDS is a database of police reported tow-away crashes strategically sampled and weighted to represent all such motor vehicle crashes occurring in the United States (NHTSA, 2013). It provides extensive information about the vehicles and occupants involved as well as characteristics of the crash. Occupant injuries are coded by type and severity according to the Abbreviated Injury Scale (AIS), which ranks injuries on a scale of 1–6 based on their threat to life (Association for the Advancement of Automotive Medicine (AAAM), 2005). For each crash, NASS-CDS identifies the highest severity event for each involved vehicle based on energy management and the amount of reduction of occupant space for non-collision events such as rollover events (NHTSA, 2012b).

Occupants for the current study were limited to lap and shoulder belted, contained or partially ejected, adults (16+ years) in vehicles that completed at least one but no more than 16 lateral quarter turns. A lateral quarter turn is defined as 90° degrees of vehicle rotation about the vehicle longitudinal axis. A vehicle that completes one quarter turn from its upright orientation would consequently end up on its driver side or passenger side, whereas two quarter turns would involve the vehicle coming to rest on its roof. End-over-end rollovers (rotation about the vehicle pitch axis) were excluded due to their low frequency (<1% of all rollover crashes) and substantially different kinematics compared to lateral rollovers (Bose et al., 2011a). Included occupants were further limited to those in vehicles that were less than 10 years old at the time of the crash, in order to maintain consistency with a change in a 2009 and onward NASS-CDS sampling strategy to only include injury details in crashes of those vehicle ages. All occupants who fulfilled the inclusion criteria were assigned to one of the following five categories based on the type of rollover crash:

- *Single-vehicle, pure (SV Pure)*: single vehicle rollover crash with only one event.
- *Single-vehicle, primary (SV Prim)*: single vehicle, multi-event crash for which the rollover event was coded as the most severe event.
- *Multi-vehicle, primary (MV Prim)*: multi-vehicle, multi-event crash for which the rollover event was coded as the most severe event.
- *Single-vehicle, non-primary (SV Non-Prim)*: single vehicle, multi-event crash for which the rollover event was *not* coded as the most severe event.
- *Multi-vehicle, non-primary (MV Non-Prim)*: multi-vehicle, multi-event crash for which the rollover event was *not* coded as the most severe event.

Distributions, means, and proportions of vehicle type (passenger car, SUV, van, and light truck), crash related parameters, occupant demographics, and occupant injury measures were determined for the five different rollover categories. Head, thorax, and cervical spine injuries were selected as occupant injury measures since they represent the most common serious injuries sustained by belted occupants in rollover crashes (Bedewi et al., 2003; Digges et al., 2005; Hu et al., 2005; Ridella et al., 2009; Bose et al., 2011a; Foster et al., 2012). Maximum overall injury severity of moderate or greater (MAIS 2+), serious or greater (MAIS 3+), and severe or greater (MAIS 4+) severity as well as fatal injury were also included as occupant injury measures to account for overall injury severity and injuries to other body regions than the head, thorax, and cervical spine. Injury frequencies were calculated as the weighted number of occupants in a population who sustained the specific type and/or severity of injury divided by the total weighted occupant count for the same population.

One of the crash related parameters in the current study is rollover initiation for which NASS-CDS assigns each case to one of the following eight types: Trip-over (rollover induced when the lateral motion of the vehicle is suddenly slowed or stopped), Flip-over (the vehicle is rotated about its longitudinal axis by a ramp-like object), Turn-over (rollover induced by centrifugal forces from a sharply turning or rotating vehicle), Climb-over (the vehicle climbs up and over a fixed object and rolls to the opposite side from which it approached the object), Fall-over (rollover results from the vehicle traversing a surface that slopes in the lateral direction of the vehicle, causing the vehicle center of gravity to fall outboard of its wheels), Bounce-over (the vehicle deflects off of a fixed object such that the vehicle's rotation causes it to overturn), Collision with another vehicle (impact with another vehicle causes the rollover), and Other type (none of the seven previously defined types can be used to describe the initiation).