## The Effect of Roll Velocity and Roof-to-Ground Impact Angle on Injuries in Lateral Rollovers

## Dagmar Buzeman Jewkes

Jewkes Biomechanics, LLC

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## ABSTRACT

A previously developed two-dimensional model of a vehicle in a lateral roll (Rose, et al. 2008) was used in this study to analytically evaluate the effect of vehicle roll angle and roll velocity on roof-impact  $\Delta V$  and consequent occupant injury mechanism and risk. Both occupants adjacent to (near-side) and remote from (far-side) the rollover's leading side were evaluated. Injury evaluation was limited to head and neck/spinal injuries.

The vehicle's roll angle at the time of roof-impact dramatically affected the local  $\Delta V$  at the point of head-to-roof contact.

Both roof-rail impacts may be injurious to far-side occupants, while near-side occupants are more likely to sustain head or neck injuries in roof impacts with the adjacent roof rail. Far-side occupants have a greater risk of compressive neck injury during impacts with the remote roof rail, while adjacent roof rail impacts subject occupants to primarily lateral head impacts with a higher head injury risk. Contoured roofs may reduce the opportunity and risk of head or neck injury in rollovers.

## INTRODUCTION

Rollover accidents vary considerably from planar collisions in terms of accident duration, the number of rolls and consequent number of ground impacts, and the variety of possible roof-to-ground impact locations. This in turn entails a wide range of possible occupant kinematics and opportunities for injury risk.

ROOF IMPACT ANGLE EFFECT ON ROLLOVER DYNAMICS - Rose et al. (2008) analytically

demonstrated the effect of vehicle-to-ground impact angle on rollover dynamics. The impact angle was defined as the angle between the ground plane and the impact radius, with the impact radius connecting the vehicle's center of gravity with the impact point. The equations of motion for the rolling vehicle established the changes of vertical and horizontal velocity, as well as the change in rotational velocity for the center of gravity. It was shown that low impact angles entail higher vertical changes of velocity. Yamaguchi et al. (2006) measured greater accelerations on far-side roof-rails compared to near-side roof-rail impacts during rollover tests. However, the effect of the vehicle dynamics on near and far-side occupant injuries in rollovers was not addressed in either study.

NON-EJECTED ROLLOVER OCCUPANT STATISTICS - Many papers have been devoted to studying the injury mechanisms of rollover occupants that remained inside of the vehicle. Non-ejected rollover occupants were at a 2 to 4 times lower risk to be severely injured when belted than when not-belted [Digges and Gabler, 2006; Parenteau and Shah; 2000, Viano et al. 2007].

HEAD AND NECK INJURY MECHANISMS IN ROLLOVERS - Belted and non-ejected rollover occupants sustain serious injury primarily to head and neck/spine (Parenteau et al. 2001, Parenteau and Shah, 2000, Viano et al. 2007).

<u>Head Injury</u> - Belted and contained occupants in rollovers most often sustain serious head injuries from impacts with vehicle interior or other occupants (Viano et al. 2007), which may include skull fractures and brain injury. Head injury risk from impacts has been most often described by the Head Injury Criterion (HIC), which

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relates the risk to the resultant translational head acceleration and time duration as follows:

$$HIC = (t_2 - t_1) \left[ \frac{\int_{t_1}^{t_2} a(t)dt}{t_2 - t_1} \right]^{2.5}$$

Padding effectively reduces head injury risk, as it lowers acceleration even though increasing time-duration of an impact; the HIC shows that head injury risk increases more rapidly with acceleration than with time. Nusholtz et al. (1981) and Alem et al. (1984) concluded from cadaver head impact testing that padding is effective in reducing peak impact force and resulting skull injuries.

Other researchers (Ommaya and Gennarelli 1974; Gennarelli and Thibault 1982) have found a correlation of diffuse brain injury with rotational acceleration, especially with non-centroidal loading of the head. Gennarelli et al. (1987) found that lateral or coronal head rotational acceleration was more prone to result in serious brain injury than frontal or sagittal loading. The higher susceptibility of brain injury in the coronal plane was explained by Bradshaw et al. (2001).

<u>Neck Injury</u> - Neck injuries of belted and contained occupants in rollovers are often sustained by head impacts with the roof as the inertia of the torso exposes the neck to a compression load when the head comes to a stop against the roof (Bahling et al. 1990, James et al. 2007, Piziali et al. 1998).

Various cadaver inverted drop-tests (Nusholtz et al. (1983), Yoganandan et al. 1986) and pendulum impact tests to the head-vertex (Culver et al. 1978, Nusholtz et al. 1981 and Alem et al. 1984) have been performed to study neck compression injury mechanisms from head impacts with alignment of the head and spine. In all studies, the majority of the cadavers sustained neck or spinal injuries, while head injury (skull fracture) was relatively rare.

Alem et al. (1984) found vertical head impacts to more likely cause neck injury than head injury, where head injuries consisted mainly of skull fractures in impacts with no or little padding. Nusholtz et al. (1981) and Alem et al. (1984) concluded that padding is effective in reducing skull injuries, but may not reduce neck damage.

Neck injuries from lateral bending or shear are less common in lateral or coronal plane loading than in compression/flexion in the frontal or sagittal plane (Allen et al. 1982). This is in contrast to head injury which was concluded by Gennarelli et al. (1987) to occur more likely in the coronal than in the sagittal plane.

The results of the above-mentioned cadaver studies were recently reanalyzed by Viano and Parenteau

(2008), who found a good correlation between peak head velocity and neck compression injury. They also reported the alignment of head, neck and thoracic spine relative to the impact axis to be the most important parameter for neck compression injury, as did Nusholtz et al. (1981).

NEAR-SIDE VERSUS FAR-SIDE OCCUPANT INJURY RISK - Keifer et al. (2007) found a higher MAIS3+ injury risk for belted far-side occupants than near-side occupants for SUV front occupants in NASS data from 1998-2004. Parenteau et al. (2001) calculated a far-side occupant risk of 2.5 times that of a near-side occupant based on 1992-1998 NASS-CDS rollover data for front seat occupants. On the other hand, Viano et al. (2007) presented no statistical difference in injury risk for far versus near-side occupants.

BODY SEGMENT INJURIES IN FAR-SIDE V. NEAR-SIDE OCCUPANTS - Far and near-side occupant head and neck injuries in belted rollovers were statistically reviewed in a couple of studies (Parenteau et al. 2001; Parenteau and Shah, 2000). Near-side occupants received head injuries more often, while far-side occupants were more susceptible to spinal injuries. However, the difference in head and neck injury risks for near- and far-side occupants was not explained in these studies.

## OBJECTIVE

The objective of this study was to examine and explain the relationship between the vehicle roll angle at roof-toground impact and occupant injury risk and mechanism in lateral rollover accidents, with a focus on head and neck injuries. Injuries were evaluated for near-side and far-side occupants that are belted and contained in the vehicle.

## METHOD

Rose et al. (2008) previously developed a simplified two dimensional model of a vehicle in a lateral barrel-roll. Their model was applied in the current study to analytically evaluate the effect of vehicle roll angle and velocity on roof-impact  $\Delta V$  at the impact location, and consequent occupant injuries. Injury evaluation was limited to head and neck/spinal injuries. The complexity of rollovers in terms of time duration, multiple ground-impacts and variety in ground impact locations may be addressed by applying the model to each of the ground-impacts, and assessing the injury risk for each ground-impact individually.

VEHICLE MODEL - Figure 1 shows the simplified twodimensional model of a vehicle in a lateral roll as previously introduced by Rose et al. (2008), and identifies the location of the center of gravity (CG), impact Point c, Point c's radius (r) from the CG, impact angle  $\phi$ , and horizontal and vertical ground forces (F<sub>y</sub> and F<sub>z</sub> respectively). The vehicle CG is subjected to a gravitational force 'mg', with m the vehicle mass and g the gravitational acceleration. The roll angle  $\beta$  is defined by the angle between the vehicle's vertical axis and the global vertical axis in the direction of the roll velocity. A vehicle inherent angle  $\alpha_n$  indicates the vehicle's relative height and width or aspect ratio. The vehicle has a horizontal ground speed,  $V_{y,i}$ , and a vertical drop-speed,  $V_{z,i}$  while rotating with rotational velocity  $\omega$ .



Figure 1 – Model of a rolling vehicle

MODEL ASSUMPTIONS - The vehicle change of motion at the Point c presented in this paper are based on the following assumptions:

i) The vehicle roll is assumed to be completely lateral, such that all dynamics occur in a two dimensional plane.

ii) The center of rotation coincides with the center of gravity immediately prior to and post roof-to-ground contact. During contact, the center of rotation temporarily moves to the point of contact.

iii) The roof contact is assumed to be a point contact, and the change of roll angle throughout the duration of the ground-impact,  $\Delta t$ , is neglected.

iv) Restitution at roof-to-ground impact location (Point c) is neglected.

v) The effect of roof crush on the radius, r, and on the time duration of contact,  $\Delta t$ , was neglected.

vi) Occupants are belted, contained and seated upright, with the head, neck and upper body (UB) aligned.

vii) The occupant's head is in contact with the roof rail at the time of roof-to-ground impact (Padmanaban et al. 2005, Gloeckner et al. 2007).

viii) No sliding or rebound between head and roof is assumed.

OCCUPANT INJURY ASSUMPTIONS - In this study, head and neck injuries were assessed for belted and contained occupants in lateral rollovers. Head and neck injuries were assumed to result from lateral or vertical head-to-roof impacts. The belted occupants were assumed to be seated upright with head, neck and upper body aligned, such that head or neck injuries were only expected in vehicle-to-ground impacts with the vehicle side or roof. Both near- and far-side occupants were evaluated. Near-side occupants are those seated adjacent to the rollover's leading side, i.e. drivers in a left-side leading roll or right passengers in a right side leading roll. Far-side occupants are seated remote from the rollover leading side, i.e. drivers in a right-side leading roll and right passengers in a left-side leading roll.

In the current study, the injury risk was evaluated indirectly by the local  $\Delta V$  near the head location. The injury risk was assumed to be directly related to local impact severity ( $\Delta V$ ), as the occupant's head is in contact with the roof rail at the time of roof-to-ground impact in high-speed rollovers (Padmanaban et al. 2005, Gloeckner et al. 2007). A relationship between head peak velocity and neck injury risk was previously described by Viano and Parenteau (2008), while the head injury risk is related to head translational or angular acceleration, which in turn increases with local  $\Delta V$ . The effect of roll angle and seating position on the local  $\Delta V$  and related injury risk was evaluated and compared for near-side occupants versus far-side occupants. No attempt was made to calculate actual injury risks.

The injury mechanism for head and/or neck injuries was assumed to best correlate with the angle between the head impact force and the head-neck system. Both head and or neck injury may occur at any alignment angle with sufficiently high  $\Delta Vs$ . However, lateral head impacts were considered more likely to result in head injuries than neck injuries, due to the flexibility of the neck in the coronal plane (Allen et al. 1982) and the higher susceptibility of diffuse brain injury in coronal loading (Gennarelli et al. 1987). Vertical impact forces were assumed to more frequently result in neck injuries from compression loads on the head, as concluded by Alem et al. (1984), Nusholtz et al. (1981) and Viano and Parenteau (2008). Furthermore, vertical head-impacts with the roof often involves some roof-padding which was found more effective in protecting the head than the neck in compression loads (Nusholtz et al. 1981 and Alem et al. 1984), such that vertical impacts are more likely to result in neck than head injury.

LOCAL IMPACT SEVERITY VERSUS ROLL ANGLE -Rose et al (2008) applied Newton's  $2^{nd}$  and  $3^{rd}$  laws to derive the equations of motion for the vehicle center of gravity in lateral rollovers. The velocity changes in vertical, horizontal and rotational direction were presented as a function of the impact angle,  $\phi$ . In the present study, restitution was neglected, and the modified equations are as follows:

$$\Delta V_{z} = -V_{zc,i} \left( \frac{k_{r}^{2}}{k_{r}^{2} + r^{2}(\cos^{2}\phi - \mu\sin\phi\cos\phi)} \right)$$

$$-g\Delta t \left( \frac{r^{2}(\cos^{2}\phi - \mu\sin\phi\cos\phi)}{k_{r}^{2} + r^{2}(\cos^{2}\phi - \mu\sin\phi\cos\phi)} \right)$$
(1)

$$\Delta V_{y} = \mu (\Delta V_{z} + g\Delta t) \tag{2}$$

$$\Delta \omega_r = (\Delta V_z + g\Delta t) \left( \frac{r(\mu \sin \phi - \cos \phi)}{k_r^2} \right)$$
(3)

The parameters  $k_r$  and  $v_{zc,i}$  are the radius of gyration of the car and the pre-impact vertical velocity at impact Point c, respectively. Impulse ratio  $\mu$  represents the vehicle-to-ground friction, including ground contact effects like furrowing, which opposes the vehicle's ground-plane motion. The maximum value of this parameter may be chosen and treated as a friction coefficient, depending on the ground surface and if furrowing or other effects are included. The chosen value is the maximum available ratio of opposing horizontal force and vertical force, and may not be fully reached when the local translational velocity at contact is nonexistent. The effects of this parameter on the vehicle motion were discussed in Rose et al. (2008).

In this study, the equations of motion were focused on the roof-to-ground impact Point c as opposed to the vehicle's center of gravity. Rose et al. (2008) showed that the horizontal and vertical velocities ( $v_{yc,i}$  and  $v_{zc,i}$ ) at Point c were directly related to those at the vehicle CG ( $v_{y,i}$  and  $v_{z,i}$ ) superimposed by the components of the rotational velocity vector,  $\omega x r$ .

$$V_{yc,i} = V_{y,i} - \omega r \sin \phi \tag{4}$$

$$V_{zc,i} = V_{z,i} + \omega r \cos \phi \tag{5}$$

This model was validated by Rose et al. (2008b). Assumption (iv) allows for no rebound at the groundimpact location, such that the post-impact vertical velocity at Point c given by Equation (5) equals zero. Based on this assumption, Equations (1) through (3) can now be rewritten to reflect the vertical, rotational and horizontal velocity components at Point c directly as a function of pre-impact roll conditions:

$$\Delta V_{zc} = \omega_{pre} \ r \cos \phi - V_{z,i}$$

$$\omega_{post} = \frac{k_r^2 \omega_{pre} + r(g\Delta t - V_{z,i})(\mu \sin \phi - \cos \phi)}{k_r^2 + r^2 (\cos^2 \phi - \mu \sin \phi \cos \phi)}$$
(7)  
$$\Delta V_{yc} = -\mu (g\Delta t - V_{z,i} + \omega_{post} r \cos \phi)$$
(8)

Four situations were considered: a near-side occupant in a near-side impact (adjacent roof rail impact), a nearside occupant in a far-side impact (remote roof rail impact), a far-side occupant in a near-side impact (remote roof rail impact) and a far-side occupant in a farside impact (adjacent roof rail impact) as shown in Figure 2.

 $-\Delta\omega r\sin\phi$ 



# Figure 2. Definition of remote and adjacent roof rail impacts

Equations (6) through (8) establish the vehicle dynamics as a function of the impact angle, not the roll angle  $\beta$ . For near-side occupants, the vehicle's roll angle,  $\beta$  is related to the impact angle  $\phi$  and the vehicle inherent angle,  $\alpha_n$ , as follows:

$$\beta = 90 - \alpha_n + \phi \tag{9}$$

Equation (5) indicates that a critical impact angle exists above which no roof-to-ground impact can occur. Figure 3 illustrates the rotational velocity vector at Point c,  $\omega xr$ , pointing upwards.



Figure 3 – Roof-to-ground critical impact angle

At the critical angle,  $\phi_c$ , the positive vertical component of this vector exceeds the drop-speed,  $v_{z,i}$ , after which no impact is possible. The critical angle is given by:

$$\phi_c \ge \arccos(\frac{V_{z,i}}{\omega r}); \text{ with } V_{z,i} \le 0$$
 (10)

It should be noted that the near-side occupant already is in the upward portion of the roll sequence in a remote roof rail landing, such that a head-roof impact is unlikely even though a roof-to-ground impact may still occur.

The minimum roll angle considered for assessment of occupant head or neck injury was at the first roof-impact opportunity involving a lateral or vertical head impact, while the maximum roll angle was related to the critical impact angle (Equation (9)).

LOCAL IMPACT SEVERITY FOR FAR-SIDE OCCUPANTS - It should be clarified that the impact severity experienced by a far-side occupant is below that of Impact Point c during a remote roof-to-ground contact (near-side impact). For these contacts, Equations (6) through (8) are applied to calculate the impact severity at Point c using impact angle  $\phi_c$ , after which the far-side occupant impact severity is calculated using the angle,  $\phi_{FS}$ , between ground and radius from CG to the far-side occupant's head-roof contact, Point FS (Figure 1):

$$\Delta V_{z,FS} = \Delta V_{zc} - \Delta \omega r(\cos \phi_{FS} - \cos \phi_c)$$
(11)

$$\Delta V_{y,FS} = \Delta V_{yc} - \Delta \omega r(\sin \phi_{FS} - \sin \phi_c) \qquad (12)$$

These equations calculate the vehicle's local velocity changes as a function of the impact angle, instead of the roll angle,  $\beta$ . However, impact angle  $\phi_{\chi}$  is related to the vehicle's roll angle,  $\beta$  and the vehicle inherent angle,  $\alpha_n$ , as follows for far-side occupants:

$$\beta = 90 + \alpha_n + \phi_c \tag{13}$$

Equations (11) and (12) show the importance of the distance between Point c and the head-roof contact on the impact severity experienced by the far-side occupant. Different roof-shapes will entail different distances between Point c and the head-roof contact. In this paper, two extreme roof-shapes are discussed to illustrate this effect and evaluate possible benefits of different roof lines: the box-shaped roof and the contoured roof.

<u>Box-shaped roof</u> - The geometry of the box-shaped roof only allows for two locations of Point c: the near-side roof rail for roll angles below 180 degrees and the far-side roof rail for roll angles greater than 180 degrees. Figure 4a demonstrates Point c being located on the leading roof rail (the remote roof rail for the far-side passenger) for roll angles below 180 degrees, and on the trailingside roof rail (the adjacent roof-rail for the far-side occupant) for roll angles past 180 degrees.

<u>Contoured Roof</u> - A contoured roof will have less distance between the remote roof rail ground-impact and the far-side head-roof contact than a box-shaped roof, as shown in Figure 4b.

For convenience in calculating the location of Point c, the contoured roof was assumed to consist of a circular segment, such that Point c was located on the near-side roof rail for roll angles between 120 and 180 degrees, while Point c was placed on the roof on a vertical line from the vehicle's center of gravity for greater roll angles. Consequently, Point c's impact angle was 90 degrees for all injurious roll angles over 180 degrees. It should be noted that this roof shape is an extreme example of a contoured roof and is not realistic.



Figure 4a - Location of impact Point c at remote and adjacent roof rail for box-shaped roofs



Figure 4b – Location of impact Point c at various roll angles for a contoured roof

INJURY MECHANISM - The injury mechanism for head and/or neck injuries was assumed to be directly related to the angle of the impact force with the head. The impact force to head angle was calculated from the alignment between Point c's resultant  $\Delta V$  vector and the occupant's upper body, as it was assumed that upper body, neck and head are in line and upright inside the vehicle.

This alignment angle,  $\zeta$ , is given by:

$$\zeta = \delta - \phi_n \tag{14}$$

where  $\delta$  is the angle of the resultant  $\Delta V$  vector with the vertical global axis, and  $\phi_n$ , is the inverted upper-body orientation with the global vertical axis (Figure 5).



Figure 5 – The impact  $\Delta V$  angle,  $\delta$ , upper-body angle with the global vertical axis,  $\phi_n$ , and alignment angle  $\zeta$ . (Vectors are not drawn to scale.)

### RESULTS

The roll angle at the time of roof-to-ground impact strongly influences the local impact severity at the point of ground contact in terms of horizontal and vertical change of velocity as well as the change in roll speed. Furthermore, the roll angle at ground-impact combined with the location and orientation of the occupant determines the nature of the impact force to the occupant head and the consequent type of injury.

ROLL ANGLE RANGE FOR POTENTIAL INJURY TO A NEAR-SIDE OCCUPANT - Near-side occupants may be subjected to head or neck injuries from a lateral or vertical head impact force during roof-to-ground impacts at roll angles,  $\beta_n$ , of 90 to 180 degrees (plus the number of rolls, n, times 360 degrees):

$$\beta_n \in [90 + n * 360, 180 + n * 360]$$
 (15)

The roll angle range for lateral or vertical head impacts is further limited by the critical angle  $\phi_c$  (Equation (9)), such that the roll angle range for which impacts may be injurious to near-side occupants and can be approximated by (Figures 6a-6f, vectors not drawn to scale):

$$\beta_n \in [90 + n * 360, 180 - \alpha_n + n * 360]$$
 (16)



#### Figure 6a-f – Potentially injurious range of roll angles for near-side occupants during roof-to-ground impacts

(17)

ROLL ANGLE RANGE FOR POTENTIAL INJURY TO A FAR-SIDE OCCUPANT - For far-side occupants, the impact angle  $\phi$  is related to the vehicle's roll angle,  $\beta$ , and the vehicle's inherent angle,  $\alpha_n$ , as given by Equation (13). Far-side occupants may experience a vertical head impact even during near-side roof-to-ground impacts with the remote roof rail (at impact angles of zero degrees). Remote roof rail impacts enable sliding between head and roof, such that lateral head impacts are considerably less injurious; injury may, however, still occur from vertical head impacts. Potentially injurious roof impacts may occur at roll angles,  $\beta_f$ , between 120 and 270 degrees (plus the number of rolls, n, times 360 degrees):

The critical angle further reduces the roll angle range for potential head or neck injury, in accordance with Equation (9), such that far-side occupants have a window of opportunity to sustain head or neck injuries during roof impacts at roll angles of approximately:

$$\beta_f \in [120 + n * 360, 180 + \alpha_n + n * 360]$$
 (18)

Figure 7 shows the vehicle roll angle range that may cause head or neck injury to the far-side occupant (vectors not drawn to scale). The vehicle CG's horizontal and vertical velocity vectors are shown to be constant, while the rotational velocity vector at Point c changes direction affecting the severity of the roof-to-ground impact. Past the critical angle, no impact occurs at all.

$$\beta_f \in [120 + n * 360, 270 + n * 360]$$





Comparison of Equations (16) and (18) reveals that farside rollover occupants have a wider range of roll angles during which head or neck injury may occur than nearside occupants. Most vehicle geometries demonstrate an angle  $\alpha_n$  of approximately 30 to 50 degrees, with higher angles for lower vehicles (e.g. passenger cars). The roll angle range of potential head or neck injuries for far-side occupants is 120 to 210 degrees while the range is 90 to 150 degrees for near-side occupants, assuming an angle  $\alpha_n$  of 30 degrees (minimum). The far-side occupant may sustain head or neck injury during impacts to either roof rail. On the other hand, near-side occupants may only be exposed to head or neck injury in ground impacts with the adjacent roof rail, as near-side occupants are in the upwards moving section of the roll sequence during a remote roof rail impact. The possible severity of the impacts within these roll angle ranges is discussed in the next section.

LOCAL IMPACT SEVERITY - The model was used to evaluate rollovers with drop velocity of 5 mph (drop height = 0.8 ft), translational velocity of 40 mph, a roll rate of 360 % and a time-duration of 65 ms.

Local impact speeds experienced by near or far-side occupants may be more than 2 to 3 times higher than the vehicle CG impact speed depending on the rollover conditions: a far-side occupant was subjected to a maximum velocity change of 11 mph at the head-roof contact during either a remote or an adjacent roof-rail ground impact, which was more than twice as high as the velocity change at the vehicle CG. A near-side occupant experienced a local vertical  $\Delta V$  up to 14 mph during a ground impact with the leading vehicle side, under equal roll conditions. The local impact severity

drastically reduced when roll angles more closely approached the critical angle.

NEAR-SIDE IMPACT SEVERITY - Figure 8a shows the vertical change of velocity at Point c for near-side occupants as a function of the vehicle's roll angle. It should be noted that the maximum local vertical impact speed was calculated at almost 15 mph at Point c while the vehicle's center of gravity vertical speed was only 5 mph. The local impact severity was 3 times as high as that of the vehicle CG under reasonable rollover conditions. The local impact severity showed a sinusoidal decrease with increasing roll angle, until Point c passed the critical angle and no impact was possible.

Under equal rollover conditions, the analysis showed that near-side occupants experience higher vertical velocity changes than far-side occupants in the bottom end of the roll angle range and vice versa in the higher end of the roll angle range.

## FAR-SIDE IMPACT SEVERITY -

<u>Box-Shaped Roof</u> - The geometry of the box-shaped roof was assumed to allow only roof-to-ground impacts at either the near-side roof rail or the far-side roof rail. For this roof, the far-side occupant experiences the highest impact severities during remote roof rail (nearside impact for a far-side occupant) ground impacts at roll angles between 120 and 150°, followed by adjacent roof rail ground impacts immediately past ½ roll (180-210°, Figure 8b). In this roll-angle range, the far-side occupant may move toward the center of the vehicle with the head sliding along the roof. Lateral head impacts in this range are more complex to evaluate and less likely

to occur at injurious levels, whereas vertically oriented head impacts with potential neck injury may still occur. The maximum  $\Delta V$  experienced at the far-side head-roof contact (11 mph) is below that at Point c (15 mph), as the vehicle continues to roll with a downward velocity component at the head location during roof impact, such that the far-side head is exposed to a  $\Delta V$  below that of Point c. The larger the distance between the roof-toground impact Point c and the head-roof contact, the greater the downward component of the vehicle at the head location, and the greater the difference between Point c's  $\Delta V$  and the occupant's head  $\Delta V$ . The impact severity quickly drops with increasing roll angle due to both Point c nearing the critical angle and the distance between Point c and head being at the maximum. Once the roll has progressed past 1/2 roll, the roof may only impact the adjacent roof rail (trailing roof rail with a farside occupant), which exposes the far-side occupant to another injurious roll angle range until the adjacent roof rail passes the critical angle. During this adjacent roof rail impact, the occupant's head is in immediate proximity of impact Point c, such that the occupant is exposed to the same  $\Delta V$  as Point c (maximum of 11 mph).

<u>Contoured Roof</u> - In vehicles with a contoured roof line, far-side occupants impact the roof at the highest impact severity during a remote roof-rail ground impact, which poses the relatively highest injury risk (Figure 8b). Again however, the far-side occupant's head may slide along the roof toward the center of the vehicle, considerable reducing the risk of an injurious lateral head impact.

This roof line causes the injurious roll angle range for far side occupants to be greatly reduced to ground impacts on the remote roof rail, for low drop-speeds. The far-side occupant's head and neck injury risk is considerably lower for roll-angles above  $\frac{1}{2}$  roll, as the rotational velocity vector no longer contributes to the impact severity. Within this range, the maximum  $\Delta V$ experienced at the far-side head-roof contact (11 mph) is below that at Point c (15 mph), as the vehicle continues to roll with a downward velocity component at the head location during roof impact. It should be noted that nearside occupants would also benefit from a contoured roof, due to the lack of rotational velocity contribution to the local impact severity.

For roll angles below 180 degrees, the contoured roof was assumed to have the near-side roof impact with the remote roof-rail, which involves the maximum distance from Point c to occupant head. Furthermore, the impact severity at Point c falls as the impact angle approaches the critical angle, which explains the quick drop in impact severity experienced by the far-side occupant for angles below 180°. Once the roll angle is past 1/2 roll, the contoured roof was assumed to impact the lowest point for all angles, resulting in a constant impact angle of 90 degrees and horizontal rotational velocity at Point c. The horizontal rotational velocity vector causes Point c to experience a vertical velocity change equal to the dropspeed for roll angles over 180°, such that the far-side occupant experiences no higher vertical  $\Delta Vs$  than the drop-speed for these roll angles. It should be emphasized that the roll-angle range in which far-side occupants may receive head or neck injuries is smaller than that of the box-shaped roof, for rolls with a low vertical drop velocity.



8a) Near-side occupant

8b) Far-side occupant Figure 8. Local vertical ∆V

OCCUPANT INJURY MECHANISM - As explained in the 'Method' section, the occupant injury risk was assumed to be directly related to the local impact severity or resultant local  $\Delta V$ , and the injury mechanism to be a function of the angle between the resultant  $\Delta V$  and the inverted upper body. This angle determines the opportunity and thus injury risk for a lateral head impact or a vertical head impact with a compressive neck load.

The resultant local  $\Delta V$  was calculated from the horizontal and vertical local velocity changes (Equations (6) and (8)), and the alignment angle of upper body and resultant  $\Delta V$ ,  $\zeta$ , is given by Equation (12). The resultant velocity change at Point c is displayed in Figure 9a for near-side occupants and at Point FS in Figure 9b for far-side occupants, while the corresponding alignment angles,  $\zeta$ , are shown as a function of roll angle in Figures 9a and 9b. Negative values of the vertical  $\Delta V$  component represented a no-impact condition and were not displayed in Figure 9.

Resultant  $\Delta V$ 's are higher for near-side than far-side occupants in the low end of the roll angle range, and slightly lower in the high end of the roll angle range.

Figure 10a illustrates that the impact force angle to the near-side occupant's upper body is greater than 50 degrees for roll angles of approximately 90° to 110°. At these roll angles, roof-to-ground impacts cause a mostly lateral impact to the near-side occupant which was assumed to entail injury risk primarily to the head. For greater roll angles, the resultant  $\Delta V$  is more aligned with the upper body (smaller angles) and the compression component and relative neck injury risk increase.

Far-side occupants receive mainly vertically oriented impact loads for roof impacts on the remote roof rail, as indicated by the alignment angle under 45 degrees for this roll angle range (120° to 150°, Figure 10b). Vertical impact loads and compressive neck loads are also predicted for adjacent roof impacts on vehicles with a box-shaped roof immediately past the 1/2 roll mark. Vertical impact loads carry a compression component which may pose an injury risk to the neck.

For vehicles with a contoured roof, the analysis showed impacts on the roof top to occur at greater alignment angles, which was assumed to more likely result in head injury than neck injury, although no attempts were made calculate actual injury to criteria.



Figure 10a: Near-side occupant alignment angle,  $\zeta$ . Figure 10b: Far-side occupant alignment angle,  $\zeta$ .

## PARAMETER EFFECTS

Impact severity and alignment angle effects of changes in translational speed, roll rate, impulse ratio, drop-speed and vehicle geometry (represented by angle  $\alpha$ n) were examined. Only vehicles with box-shaped roofs were evaluated in the parameter study, as most current roof lines agree more with this type than the extremely rounded roof that was evaluated for the contoured roof evaluation.

The base parameter values in this parameter study were: rotational velocity  $\omega$ =360°/s, translational velocity V<sub>y,i</sub>=40 mph, vertical drop-velocity V<sub>z,i</sub>=-5 mph, time duration  $\Delta$ t=65 ms, impulse ratio  $\mu$ =0.5, and vehicle geometry parameter  $\alpha_n$ =30°.

EFFECT OF TRANSLATIONAL VELOCITY,  $V_{Y,I}$  - The translational velocity was varied between 20 and 40 mph. Within this range, this parameter did not affect any of the

velocity changes at Point c and therefore no changes were seen in the impact to occupant upper body angle for both near and far-side occupants.

EFFECT OF IMPULSE RATIO,  $\mu$  – A higher impulse ratio did not affect the vertical  $\Delta V$ , but increased the (negative or decelerating) change in translational velocity at Point c (Figure 11), which in turn increased the local impact angle with the vertical global axis. Both near-side and far-side occupants' upper body angles are negative throughout the majority of potentially injurious roll angles, such that greater horizontal  $\Delta Vs$  reduce the alignment angle,  $\zeta$ , (Figure 12). This reduction indicates a relatively higher compression load to the neck. Higher friction would shift rollover occupant injuries to a higher proportion of neck and spinal injuries for far and near side occupants.



Figure 11. Horizontal  $\Delta V$  as a function of impulse ratio  $\mu$ .



12a) Near-side occupant 12b) Far-side occupant Figure 12. Alignment angle, ζ, as a function of impulse ratio μ.

EFFECT OF ROTATIONAL VELOCITY,  $\omega$ -Increased values of the rotational speed raise the severity of the local vertical roof-to-ground impact speed, which would entail higher occupant injury risk (Figure 13). The effect was more apparent for near-side occupants than for far-side occupants at the low end of the roll angle range, as far-side occupants are remote from the impact site and roll rate components at the head are reduced. On the other hand, roll rate effects were greater for far-side occupants at the high end of the roll angle range, as the near-side roof rail impact angle is closer to the critical angle.

Translational velocity changes increase with roll rate, but are small when vertical  $\Delta Vs$  are highest; alignment angles are not significantly influenced by roll rate.(Figure 14).

EFFECT OF VERTICAL DROP VELOCITY,  $V_{Z,I}$  - The local vertical  $\Delta V$  increased proportionally with the vehicle's CG drop velocity,  $V_{z,i}$  depicted in Figure 15. The vehicle's drop velocity only slightly affected the impact alignment with the occupant's upper body (Figure 16) similarly to the influence of the rotational speed.



13a) Near-Side

13b) Far-side Figure 13. Vertical local  $\Delta V$  as a function of rotational velocity.



14a) Near-Side 14b) Far-side Figure 14. Alignment angle, ζ, as a function of rotational velocity



15a) Near-Side 15b) Far-side Figure 15. Vertical local velocity change as a function of the vehicle's drop velocity, V<sub>z,i</sub>





EFFECT OF VEHICLE GEOMETRY,  $\alpha_{N.}$  - An increased angle,  $\alpha_{n,}$  implies a lower and/or wider vehicle. The analysis illustrates that a raised  $\alpha_{n}$  narrows the range of roll angles for which near or far-side occupants might receive head/neck injuries. Furthermore, near-side occupants of wider and/or lower vehicles experience lower  $\Delta Vs$  when subjected to a near-side roof rail impact, as do far-side occupants in remote roof impacts (Figure 17). The opposite is predicted for far-side occupants in a proximate roof impact: a vehicle with higher  $\alpha_{n}$  would expose its occupant to higher local impact speeds.

In lower and wider cars, both far and near-side occupants experience a more aligned impact angle

(Figure 18), shifting injuries to a higher proportion of neck versus head injuries.

The higher local impact speed predicted for far-side occupants in lower and wider cars, as well as the shift to a higher proportion of neck injuries may explain the observation by Padmanaban et al. (2005) that low, wide vehicles have higher odds of fatality or serious injury.



17a) Near-side occupant
 17b) Far-side occupant
 Figure 17. Impact Severity (resultant ΔV) as a function of the vehicle's geometry parameter α<sub>n</sub>.





## DISCUSSION

This study evaluated the role of roll angle at roof-toground impacts on near and far-side occupants that are belted and contained inside the vehicle. An analytical approach was used to calculate impact severity at the point of impact, as well as the alignment angle of the impact force with the occupants' upper bodies. The results were interpreted to predict occupant injury risk and mechanism in lateral rollovers, with a focus on head and neck/spinal injuries.

The analytical approach limited the results to include only perfectly lateral rolls and did not allow for the actual process of roof deformation with accompanying additional rotation and change of impact point. The roof deformation process might be beneficial for the occupant, as the impact angle increases with roll continuation.

Furthermore, rebound from roof impacts was neglected. Rebound would increase the local impact severity and subsequent injury risk.

Finally, results were based on the assumption that occupants were in contact with the roof or roof rail prior to a roof impact, which agreed with findings of Gloeckner et al. (2007) and Padmanaban et al. (2005).

The model may be a helpful tool in explaining injury occurrence and mechanisms for near and far-side occupants in biomechanical evaluation of real world rollover accidents. LOCAL IMPACT SEVERITY - The impact angle and thus roll angle greatly affected the local impact severity and consequent injury mechanism and risk experienced by the occupants, with small impact angles having the highest local impact severity and impact angles greater than 90 degrees approaching a negligible local impact severity for rollovers with a low drop-speed.

Analysis showed that local impact severity ( $\Delta V$ ) may be various times greater than that experienced by the vehicle's center of gravity, due to the contribution of the roll velocity at small impact angles. On the other hand, occupants would be exposed to local  $\Delta V$ s equal to or lower than the vehicle's drop-speed when the roof-ground impact angle approached the critical angle and/or the occupant head was remote from the impact point.

INJURY RISK - The injury risk was evaluated indirectly by calculating the local  $\Delta V$  near the head location. The injury risk was assumed to be directly related to the local  $\Delta V$ , as the occupant's head is in contact with the roof rail at the time of roof-to-ground impact in high-speed rollovers (Padmanaban et al. 2005, Gloeckner et al. 2007). A relationship between head peak velocity and neck injury risk was previously described by Viano and Parenteau (2008), while the head injury risk is related to head translational or angular acceleration, which in turn increases with local  $\Delta V$ . The effect of roll angle and seating position on the local  $\Delta V$  and related injury risk was evaluated and compared for near-side occupants versus far-side occupants. No attempt was made to calculate actual injury risks. Future studies may include calculation of neck and head injury risk using neck and head injury criteria, and applying relationships between local impact severity parameters and injury criteria.

Near-side occupants were predicted to receive more serious injuries in near-side impacts with the risk decreasing rapidly as the impact occurs more towards the roof rail and roof top.

<u>Box-shaped roof</u> - Far-side occupants are expected to receive the more serious injuries during a ground impact on the remote roof rail (near-side impact), and to have a relatively low injury risk during an adjacent roof rail impact (far-side impact) past 5/8 roll, for similar rollover conditions. This demonstrates that roof crush may not be the cause or determining factor in far-side occupant injuries. A stiffened roof may increase far-side occupant injury risk in near-side impacts with the remote roof rail.

For far-side occupants, the actual injurious roll angle range is smaller than indicated by Equation (19), as roof top impacts are virtually impossible due to the boxshaped roof. However, both remote and adjacent roof rail impacts may entail vertical or lateral head impacts to cause head or neck injuries to far-side occupants, while near-side occupants may only sustain injurious head impacts during impacts with the adjacent vehicle side and roof rail (near-side impact for near-side occupants). Far-side occupants have a greater window of opportunity to sustain injuries during roof-to-ground impacts in rollover accidents.

The relatively high injury risk of the far-side compared to the near-side rollover occupant is confirmed by Keifer et al. (2007) and Parenteau et al. (2001). The former researchers found a higher MAIS3+ injury risk for belted far-side occupants than near-side occupants for SUV front occupants in NASS data from 1998-2004; the latter calculated a far-side occupant risk of 2.5 times that of a near-side occupant based on 1992-1998 NASS-CDS rollover data for front seat occupants. On the other hand, Viano et al. (2007) presented no statistical difference in injury risk for far versus near-side occupants.

<u>Contoured roof</u> - Comparison of the contoured roof with the box-shaped roof shows a reduced head or neck injury risk for far-side occupants at roll angles past 180 degrees. A roof-line like the extremely contoured example roof may be designed such that a roof-toground impact is more likely to occur near the critical impact angle, which reduces both far and near-side occupant head and neck injury risk for rollovers with low drop-heights.

INJURY MECHANISM - The injury mechanism for head and/or neck injuries was assumed to best correlate with the angle between the head impact force and the headneck system: Lateral head impacts were considered more likely to result in head injuries than neck injuries, due to the flexibility of the neck in the coronal plane (Allen et al. 1982) and the higher susceptibility of diffuse brain injury in coronal loading (Gennarelli et al. 1987). Vertical impact forces were assumed to more frequently result in neck injuries from compression loads on the head, as concluded by Alem et al. (1984), Nusholtz et al. (1981) and Viano and Parenteau (2008).

Near-side occupants are exposed to the highest velocity changes when the alignment angle is large and impact loads to the head are more laterally oriented with a relatively small neck compression load. However, the lower  $\Delta$ Vs at the higher end of the roll angle range may still be injurious as they involve more vertically oriented loads which are more likely to involve neck compression injury. The analysis predicts more head injuries for near-side than far-side occupants.

Far-side occupants may receive head or neck injuries during both remote and adjacent roof rail impacts. The alignment angle between resultant  $\Delta V$  and upper-body is small for both roof rail impacts with injurious impact severity. The impact loads are more vertically oriented, with relatively higher compression loads to the neck. Farside occupants were predicted to be more susceptible to neck injuries.

The analysis showed injury mechanism differences between far and near-side occupants which agreed with statistical findings of belted and contained occupants: Injured near-side occupants had a higher risk of serious (AIS3+) head injuries versus neck injuries, while far-side occupants were more susceptible to neck/spinal injuries (Parenteau et al. 2001; Parenteau and Shah, 2000).

## CONCLUSION

The simplified model may be a useful tool to evaluate and explain occupant injury risk in real-world rollover accidents, and to predict the local impact severity and consequent relative injury risk, as well as injury mechanism in lateral rollovers of various conditions.

Local impact speed at the point of roof-impact greatly depends on the roll angle at time of ground impact. Roof impacts with low impact angles may experience local impact speeds various times higher than those of the vehicle CG.

Far-side occupants may experience injurious impacts to both remote and adjacent roof rails, and may be more susceptible to neck injuries due to the orientation of the local  $\Delta V$  vector relative to the upper-body. A more contoured roof line may reduce the roll angle range and during which both far-side and near-side occupants may sustain head or neck injuries compared to the box-shaped roof-line.

Near-side occupants may be exposed to injurious impacts on the adjacent vehicle side and roof rail. They would be more prone to head injury in impacts close to <sup>1</sup>/<sub>4</sub> roll while being more susceptible to neck injuries in roof rail impacts at greater roll angles, dependent on the vehicle's drop height.

Rollover conditions and vehicle geometry may influence the impact severity, injury risk and mechanism of the occupants. The analysis indicated that higher dropheights and roll velocities would increase the severity of the roof impacts with consequent injury risk without obvious change of injury mechanism, while wider and/or lower vehicles (higher angle  $\alpha_n$ ) or higher friction coefficients between roof and ground would shift the injury mechanism towards a higher proportion of neck injuries compared to head injuries.

## REFERENCES

- Alem, N. M.; Nusholtz, G.S.; Melvin, J. W. (1984) Head and Neck Response to Axial Impact. 28<sup>th</sup> Stapp Car Crash Conference, SAE 841667. Warrendale, PA, 1984.
- Allen, B.L.; Ferguson, R.L.; Lehmann, T.R.; O'Brien, R.P. (1982) A Mechanistic Classification of Closed Indirect Fractures and Dislocations of the Lower Cervical Spine. Spine 7(1):1-27
- Bahling, G. S.; Bundorf, R. T.; Kaspzyk, G. S.; Moffatt, E. A.; Orlowski, K.F.; Stocke, J. E. (1990) Rollover and drop tests~The influence of roof strength on injury mechanics using belted dummies. Stapp

Car Crash Conference, Orlando, FL. November 1990. SAE No. 902314

- Bradshaw, D.R. S.; Ivarsson, J.; Morfey, C.L.; Viano, D.C. (2001)Simulation of Acute Subdural Hematoma and Diffuse Axonal Injury in Coronal Head Impact. Journal of buiomechanics 34(1), pp. 85-94.
- Culver R. H.; Bender, M.; Melvin, J.W. (1978) Mechanisms, Tolerances and Responses Obtained under Dynamic Superior-Inferior Head Impact. Final report UM-HRSI-78-21
- Digges, K. H.; Gabler, H. (2006). Opportunities for Reducing Casualties in Far-Side Crashes. SAE World Congress & Exhibition, Detroit, MI. April 2006. SAE Paper No. 2006-01-0450
- Gennarelli, T.A.; Thibault, L.E. (1982) Biomechanics of Acute Subdural Hematoma. J Trauma 22:680-686.
- Gennarelli, T.A.; Thibault, L.E.; Tomei, G.; Wiser, R.; Graham, D.; Adams, J. (1987) Directional Dependence of Axonal Brain injury due to Centroidal and Non-Centroidal Acceelration. 31<sup>st</sup> Stapp car Crash Conference, Warrendale, Pa. 1987. SAE Paper No. 872197
- Gloeckner, D. C.; Bove, R. T.;Croteau, J.; Corrigan, C. F.; Moore, T. L. A. (2007) Timing of Head-to-Vehicle Perimeter contacts in Rollovers. SAE World Congress & Exhibition, Detroit, MI. April 2007. SAE Paper No. 2007-01-0370
- James, M. B.; Nordhagen, R. P.; Schneider, D. C.; Koh, S-W. (2007) Occupant Injury in Rollover Crashes: A Reexamination of Malibu II. SAE World Congress & Exhibition, Detroit, MI. April 2007. SAE Paper No. 2007-01-0369.
- Keifer Jr. O.; Keifer Sr. O.; Woodhouse, M. Sport Utility Vehicle (SUV) Rollover Collisions: An Analysis of NASS - CDS Injury Data for 1998 through 2004.
   SAE World Congress & Exhibition, Detroit, MI. April 2007. SAE Paper No. 2007-01-0364
- Nusholtz, G. S.; Huelke, D.; Lux, P.; Alem, N.M.; Montalvo, F. (1983) Cervical Spine Injury Mechanisms. 27<sup>th</sup> Stapp car Crash Conference, Warrendale, PA. SAE Paper No. 831616, 1983
- Nusholtz, G.S.; Melvin, J.W.; Huelke, D.; Alem, N. M.; Blank, J.G. (1981) Response of the Cervical Spine to Superior-Inferior Head impacts. 25<sup>th</sup> Stapp Car Crash Conference, Warrendale PA 1981. SAE Paper No. 811005.
- Ommaya, A.K.; Gennarelli, T.A. (1974) Cerebral Concussion and Traumatic Unconsciousness.

Correlation of Experimental and Clinical Observations on Blunt Head Injuries. Brain 97:633-654

- Padmanaban, J.; Moffatt, E. A.; Marth, D. R. (2005) Factors Influencing the Likelihood of Fatality and Serious/Fatal Injury in Single-Vehicle Rollover Crashes. SAE World Congress & Exhibition, Detroit, MI. April 2005. SAE Paper No. 2005-01-0944
- Parenteau, C. S.; Shah, M. (2000) Driver injuries in US single-event rollovers. SAE World Congress, Detroit, MI. March 2000. SAE Paper No. 2000-01-0633
- Parenteau, C.; Gopal, M.; Viano, D. (2001) Near- and far-side adult front passenger kinematics in a vehicle rollover. SAE World Congress, Detroit, MI. March 2001. SAE Paper No. 2001-01-0176
- Piziali, R.; Hopper, R.; Girvan, D.; Merala, R. (1998) Injury causation in rollover accidents and the biofidelity of Hybrid III data in rollover tests. International Congress & Exposition. Detroit, MI. February 1998. SAE Paper No. 980362
- Rose, N.A.; Beauchamp, G.; Fenton, S. (2008) The Influence of Vehicle-to-Ground Impact Conditions on Rollover Dynamics and Severity. SAE World Congress & Exhibition, Detroit, MI. April 2008. SAE Paper No. 2008-01-0194
- Rose, N.A.; Fenton, S. J.; Beauchamp, G.; McCoy, R.W. (2008b) Analysis of Vehicle-to-Ground Impacts during a Rollover with an Impulse-Momentum Impact Model. SAE World Congress & Exhibition, Detroit, MI. April 2008. SAE Paper No. 2008-01-0178
- Strashny, A. (2007) An Analysis of Motor Vehicle Rollover Crashes and Injury Outcomes. National Highway Traffic Safety Administration, Department of Transportation. DOT HS 810-714. 2007. Springfield Virginia.
- Viano D. C., Parenteau, C. S.; Edwards, M. L. (2007) Rollover Injury: Effects of Near and Far-Seating Position, Belt Use, and Number of Quarter Rolls. Traffic Injury Prevention 8:382-392, 2007. Taylor & Francis.
- Viano, D. C.; Parenteau, C. S.; Gopal, M. M.; James, M. B. (2009) Vehicle and Occupant Responses in a Friction Trip Rollover. Paper Accepted by SAE World Congress and Exhibition 2009. SAE Paper No. 09B-0075
- Viano, D.C.; Parenteau, C. S. (2008) Analysis of Head Impacts Causing Neck Compression Injury. Traffic Injury Prevention, 9(2):144-152. 2008

- Viano, D.C.; Parenteau, C.S. Analysis of Head Impacts Causing Neck Compression Injury. Traffic Injury Prevention, 9:144-152, 2008. Taylor & Francis Group, LLC. ISSN 1538-9588.
- Yamaguchi, G. T.; Ashby, B.; Lai, W.; Carhart, M. R.; Richards, D.; Corrigan, C. F. (2006) Occupant Mechanics in Rollover Simulations of High and Low Aspect Ratio Vehicles. SAE World Congress and Exhibition, Detroit, MI. April 2006. SAE Paper No. 2006-01-0451
- Yoganandan, N.; Sances, A.; Maiman, D.; Myklebust, J.B.; Pech, P.; Larson, S.J. (1986) Experimental Spinal Injuries with Vertical Impact. Spine, Vol. 11, No. 9, pp. 855-860.

## CONTACT

Dagmar Buzeman Jewkes (404) 825 8764 dagmar@wer.com