Effect of Vehicle Roof Shape on Rollover Safety

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Abstract

Most rollover safety research considers the vehicle in an inverted (upside-down) position as the major cause of serious injuries. For example, neck injuries mostly occur when the vehicle roof strikes the ground. However, recent studies have identified that significant injuries can occur to restrained and contained occupants during other phases of the rollover event, including when the vehicle is on its side and upright. Some injurious impacts between the occupant and vehicle interior such as torso injuries are likely related to changes in their relative velocities ($\Delta v$). Such velocity changes are believed to be associated with a higher number of quarter turns during a rollover event.

This study seeks to identify the role of roof shape for Sports Utility Vehicles (SUVs) in the potential for exacerbating vehicle-occupant $\Delta v$ and thus the potential risk for associated occupant injuries. Detailed computer finite element model (FEM) rollover crash analysis, determining the kinetic energy, translational velocity and roll rate changes of a simplified proxy SUV FEM vehicle that occur during a two roll event for two vehicle roof shapes (square and rounded), is presented. The vehicle’s kinetic energy, translational velocity and roll rate for each considered roof shape during the rollover are compared. It is hypothesised that the rounder roof design results in a less severe change for each of these variables particularly towards the end of the rollover event, thereby reducing occupant-vehicle impact severity. This work is part of an ongoing study needing further work to confirm these findings in real-world SUV rollovers.

Introduction

Rollover fatalities and associated serious injuries continue to be a source of major concern for road safety practitioners with regard to development of effective countermeasures. Rollover crashes cause disproportionate death and serious injury when compared to other crash types on Australian roads. Almost one in five road deaths (19\%) occur as a result of a crash involving vehicle rollover and almost one in four deaths among occupants of a light vehicle result from a rollover crash, yet this crash type represents only 2.4\% of all vehicle crashes (Grzebieta et al. 2007, Richardson 2003). In the US the disproportionate contribution of rollover to fatal crashes is even higher, with one in three fatalities resulting from a light-vehicle rollover crash and rollover crashes representing only 2\% of the total vehicular crashes (NHTSA, 2013).

There has been much vehicle rollover safety research that has considered the vehicle rolling through the inverted position as the major cause of serious injuries during a rollover event. Head and neck injuries are often associated with roof crush (Rechnitzer and Lane 1994, Mattos et al., 2014). In more recent years, this research has focused on the benefits of increasing the roof Strength-to-Weight Ratio (SWR) in order to reduce serious injury risk in rollover crashes (Brumbelow et al., 2009). More recently, researchers have shown that increasing SWR alone will not result in reductions of all rollover injuries (Bambach et al., 2013; Digges and Eigen, 2003, 2007, Digges et al., 2005). Further, some of the injury distribution to body regions appears to be associated with different phases of the rollover, e.g., Bambach et al (2013) identified that torso injuries mostly occur independent of roof intrusion.
Some injuries occurring during vehicle rollover crashes are likely related to changes in the relative velocity, Δv, between the occupant’s body and the vehicle interior. Such Δv could be associated with one or multiple specific quarter turns during the rollover event, and may not be limited to the vehicle’s inverted position (i.e., end of the second quarter turn). Digges and Eigen (2007) found that the contact region for serious injuries was around 36% with upper interiors and 44% were with mid vehicle interiors. Bambach et al (2013) found the greatest source of thoracic injury was caused by contact with the door (nearly 60%, with no other source of contacts greater than 15%). These findings suggest that the collisions between occupant and vehicle interior are occurring at various times during the rollover event and are not limited to the inverted phases of the rollover.

Both Bambach et al (2013) and Digges et al (2013) demonstrated that increasing the amount of roll beyond four quarter turns (i.e., the vehicle passes through the upright condition as it continued to roll) has a significant increase in odds ratio for injury risk. Bambach found that “An increase of one full vehicle roll (four quarter turns) was 8.40 times more likely to result in serious thoracic injury.” This finding has not been disaggregated, to determine if the increasing injury risk per number of quarter turns is a function of initial crash or roll severity, or the shape of the vehicle in allowing more quarter turns to occur for the same initial crash energy.

The contribution of roof shape to head and neck injury risk associated with reduced roof crush has also been subject of research (Friedman et al., 2013, Mongiardini et al., 2015), although this relationship has not been proven conclusively. This current study is concerned more with what may cause increasing numbers or severity of thoracic injuries. It is surmised that a rounder roof shape would result in smoother roll and, hence, a reduced injury risk for occupants (at least during the inverted phase of a rollover crash), when compared to a more square shaped roof structure. The rounded roof geometry will have a continuous point of contact at roughly a uniform distance from the body CG compared to the square roof geometry, for which not all contact points will be the same distance from the body CG. This effectively causes the square roofed body to rise and fall as it passes over each corner, compared to barrel type rolling of the rounded roof geometry. In particular, the shape of the vehicle roof may play a relevant role in determining the vehicle-occupant Δv during each phase of a rollover event.

This study seeks to identify the role of roof shape in determining the potential conditions for injuries to occur for vehicle occupants in a rollover. It is hypothesised that the rounder the roof design, the less severe will be the vehicle velocity changes for each of the analysed quarter turn phases of rollover, thereby reducing the potential severity of impacts between occupants and the vehicle interior. An analysis of the vehicle kinematics and the corresponding kinetic energy was carried out of a rollover event that was simulated using simplified Finite Element method (FE) vehicle models characterised by different roof shapes. Injury risk is not estimated from these simulations, but it is intended to do so in future using more detailed models.

**Method**

Initially, a series of simple rigid block FE proxy vehicles were created and simulations of rollovers were carried out using the LS-DYNA non-linear Finite Element Method (FEM) solver (LS-DYNA, 2012), which is suitable to simulate such crash events. The block models shown in Figure 1 generally represent the dimensions of a 2002 Ford Explorer. Two variations of the model were analysed, differing in the shape of the roof. These two versions of the FE proxy vehicle were characterised by a square and a round roof, respectively. A model without wheels was initially

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1 The 2002 Ford Explorer dimensions were available from rollover crash testing conducted by TARS for another research project. Analysis by Tahan (et al., 2013) has shown the physical properties and crash performance to be comparable for 1997 through 2003 model Ford Explorer.
created for each roof geometry and a subsequent evolution that included wheels was further developed, as shown in Figure 1.

It should be noted that the authors have carried out FEM analyses of both full-scale and reduced models of the Ford Explorer vehicle with and without an occupant (Mongiardini et al., 2013, 2014, 2015). However, modelling the detailed vehicle and occupants was not carried out in this study as this would have complicated the analysis with too many confounding factors, thus potentially masking the effect of roof shape on the rollover crash outcomes that were studied. Hence, proxy vehicles were simulated for the FE analysis.

The round-roof and square-roof simplified block vehicle models were assigned a mass of 1,960 kg and 1,967 kg, respectively. Also, each model had principal moments of inertia close to those of a 1998 Ford Explorer vehicle taken from the National Highway Transportation Safety Administration (NHTSA) Vehicle Inertial Parameter Measurement Database (Heydinger et al., 1998). A summary of the inertial properties of the FE models and the actual Ford Explorer is provided in Table 1.

![Figure 1. Round-Roof and Square-Roof block proxy vehicle models (versions with and without wheels).](image)

**Table 1. Inertial Properties of FE Vehicle Models and Ford Explorer**

<table>
<thead>
<tr>
<th></th>
<th>FE (Square Roof)</th>
<th>FE (Round Roof)</th>
<th>1998 Ford Explorer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Mass (kg)</strong></td>
<td>1.967</td>
<td>1.960</td>
<td>2017</td>
</tr>
<tr>
<td><strong>Moments of Inertia</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(I_{Roll}) (kg*mm(^2))</td>
<td>6.45E+08</td>
<td>6.35E+08</td>
<td>7.40E+8</td>
</tr>
<tr>
<td>(I_{Pitch}) (kg*mm(^2))</td>
<td>3.51E+09</td>
<td>3.34E+09</td>
<td>3.56E+9</td>
</tr>
<tr>
<td>(I_{Yaw}) (kg*mm(^2))</td>
<td>3.63E+09</td>
<td>3.39E+09</td>
<td>3.68E+9</td>
</tr>
</tbody>
</table>

The reference diagram provided in Figure 2 indicates the roll angle, which part of the rollover event the proxy vehicle is experiencing in terms of quarter turn, and the definition of the rollover terminology used for this study.

There is a large range of initial conditions that could be considered for modelling a real-world rollover event. For the purpose of this investigation, the initial conditions imposed at the beginning of the impact with the ground were taken from a previous research conducted by the US National Crash Analysis Centre (NCAC) (Tahan et al., 2013) and the authors (Grzebieta et al., 2013a, 2013b). These conditions were from a computer simulation that has been validated against a real
world crash, known to generate more than four quarter turns in a Ford Explorer rollover crash. The vehicle initial conditions were: initial roll velocity of 190 degrees/second and initial lateral velocity of 24.14 km/h (15mph); an initial downward vertical velocity of 1.4 m/s, which is equivalent to a vertical drop of 10 cm; and the first contact point with the ground was at 125 degrees of roll toward the left side of the vehicle. Initial pitch and yaw were set at zero.

Gravitational load of 9.81 m/s$^2$ was assigned to the model and a ground plane surface created just below the lowest point of the vehicle, which was at a roll angle of 125 degrees. The ground surface was initially assigned a coefficient of friction of 0.45, which is assumed to replicate body metal on asphalt ground surfaces (Tahan et al, 2013).

During preliminary simulations, the block models were defined as stiff structures characterised by a Young’s Modulus of 10 GPa. The models were first considered as rigid blocks, not hollow structures that are deformable, and a Young’s Modulus of 10 GPa was assigned as a starting point for iterative testing to develop a model that is representative of a vehicle rollover. The model progressed through rigid, elastic and elastic-plastic iterations. The rigid block preliminary models were found to be excessively stiff could not be considered as representative of a real-world vehicle rollover crash (Digges et al, 2013). To be able to compare the effects of vehicle geometry in rollover, at least one full revolution of the models were required. This was in keeping with the rollovers studied by Tahan (2013) that modelled four and eight quarter turns. These preliminary model blocks were unable to complete a full roll rotation (i.e., four quarter turns), despite the initial conditions and the model inertia properties which should have definitively provided for enough kinetic energy for the vehicle to complete at least a full roll.

![Figure 2. Angle, quarter turn and orientation viewed looking at front of vehicle.](image-url)
One reason the preliminary model was unable to complete a full revolution was that when an impact occurred with the ground, the model bounced violently reacting in an elastic manner. Consequently, its roll motion reversed several times as it started rocking from front to rear about its centre of gravity.

It was found that part of the inability of this preliminary model to roll was also due to the fact that the FE proxy vehicle block would simply bounce off or skate along the road surface rather than interact with the road so that a trip initiated. In reality when a vehicle impacts and deforms a relatively soft road surface, debris can sometimes accumulate in front of the contact point that momentarily increases the coefficient of friction at that point. To address this effect of the ground deformation, the coefficient of friction of the rigid plane surface modelled to simulate the ground was increased to 0.85, to better reflect the engagement of a rolling vehicle with the roadway (not just metal sliding on asphalt). Also, to ensure a more realistic response of the model during the transition to the upright position, wheels simulating rubber tyres were added to the block models as shown in Figure 1. These changes provided some improvement to the behaviour of the FE Proxy vehicle model in terms of better replicating the kinematic behaviour of real-world and dolly launched rollover crashes observed in the literature as well as other studies and crash testing conducted by the authors and others (Digges et al., 2013, Grzebieta et al., 2013a & 2013b, Mongiardini et al., 2015). However, the model responses were still found to be unrealistic in terms of real-world vehicle rollover kinematics.

To reduce the ‘tin can’ bouncing effect, the model stiffness was reduced to better represent that of a real vehicle body structure. A first attempt to reduce the Young’s Modulus of the modelled body block to 1 GPa and even 0.1 GPa still produced chaotic and unrepresentative kinematics. The model still bounced erratically and the square roof variant could not complete a full rotation, although with the latter value of the Young’s Modulus, the simulated kinematics started to resemble more closely what is often observed in a real-world rollover crash event.

To further adjust the FE proxy vehicle to better simulate real-world vehicle deformation and produce more realistic kinematics, akin to a vehicle rolling over the roadway, plasticity was introduced into the model. This allowed the block proxy vehicle model to simulate material plastic yielding during the impacts with the ground throughout the simulated rollover event. The elastic-plastic mechanical properties behaviour assigned were:

- $E = 0.1 \text{ GPa}$
- Yield Stress = 200 MPa
- $E_{\text{tan}} = 0.01 \text{ GPa}$
  (Slope of a linear behaviour used to model the plastic region of the stress-strain relationship)

The vehicle’s kinetic energy, translational velocity and roll rate for each considered roof shape during the rollover are compared. Each roof design is considered in terms of the severity of changes for each of these variables to gain some basic insight into what would be sudden changes in vehicle movement and thus the potential for likely occupant-vehicle impacts. The results obtained using the elastic-plastic FE proxy model are discussed in more detail in the following section.

**Results**

The simulated total kinetic energy (i.e., the sum of rotational and translational kinetic energies), the translational velocity and the roll rate, are shown in Figures 3 through 5, respectively. Note that the vehicle images overlapped onto the graphs show the simulated position of the proxy vehicle as viewed from the front and rolling from left to right (i.e., clockwise).
Total Kinetic Energy

For the square-roof proxy vehicle, the first significant change of energy from the initial setup condition (at 1½ quarter turns) occurs after 320 ms, when the model completed 2½ quarter turns and impacted the front left section of the bonnet with the ground. The model continued to roll clockwise, while bouncing from front to rear, such that the rear left hand-side corner impacted the ground after 560 ms. The model bounced front to rear again, while continuing its clockwise roll, impacting the lower left hand-side front corner area, after around 900 ms. The model rolled across the location of the front bumper (with its rear end raised) until the right front corner impacts the ground after about 1,280 ms, causing the vehicle to become airborne again. The vehicle continued its roll motion in free flight for nearly 500 ms until it impacted the ground across the locations of the windscreen header and the bonnet leading edge after around 1,780 ms. This impact caused a significant loss of translational velocity, as evidenced by the energy decrease from 45 kJ to 6.6 kJ, and the vehicle reversed its roll direction and then rolled counter-clockwise with much lower residual energy. In other words, using Figure 2 for orientation, the proxy vehicle rolled to an angle within the 7th quarter (between 540° and 630°) after which it then rolled back anticlockwise to an angle within the 5th quarter (360° to 450°). Thus, the total accumulated number of quarter turns the vehicle had undergone after 2.5 seconds are 8 quarter turns.

Also for the round-roof proxy vehicle the images overlapped to the graph also show the vehicle model rolling clockwise. From the initial setup condition at one and a half quarter turns, the first significant change of energy occurred after 310 ms, when the model completed two and a half quarter turns and impacted the ground at the location of the front left hand-side bonnet. The proxy vehicle continued to roll clockwise, while bouncing from front to rear, such that the rear left hand-side corner impacted the ground after 620 ms. The proxy vehicle bounced front to rear again, while continuing its clockwise roll, raising the rear end and impacting the ground with its lower left hand front corner area, after around 920 ms. The proxy vehicle became airborne as it rolled through the upright position, until its right front corner and the location equivalent to the right side of the windscreen header / A pillar impacted the ground after about 1,570 ms, with a loss of energy from 47.3 kJ to 22.4 kJ. The proxy vehicle bounced front to rear along the right side of its roof (at 5½ quarter turns), then became airborne again and continued to roll over without ground contact. The proxy vehicle impacted the ground on its left side of the roof having completed 6½ quarter turns, after about 2,500 ms. The model continued to roll and bounce, although with lower residual energy.

Translational Velocity

The translational velocity of the proxy vehicle at its centre of gravity is shown in Figure 4. The graphs show that the round-roof proxy vehicle experienced similar changes in velocity as the square-roof proxy vehicle model up until 1,700 ms. At this time, the round-roof proxy vehicle becomes airborne and rolls over its roof, without ground contact, whereas the square roof proxy vehicle impacts the ground on its bonnet and location equivalent to the roof header, causing a sudden loss of lateral velocity in the direction toward which it was rolling.

Roll Rate

Figure 5 shows the roll rate about the vehicle’s longitudinal axis for each of the two simplified proxy vehicle models analysed. Comparison of the square roof versus round rates is discussed in the next section.
Figure 3. Total Kinetic Energy of Square Roof (top) and Round Roof (bottom) elastic-plastic Simplified proxy vehicle.
Figure 4. Translational velocity of the Square Roof (top) and Round Roof (bottom) elastic-plastic simplified proxy vehicle.
Figure 5. Roll velocity of the Square Roof (top) and Round Roof (bottom) elastic-plastic simplified proxy vehicle.
Discussion

For ease of comparison, Figure 6 shows the respective overlay of the graphs in Figures 3 to 5.

The portion of the simulation that was analysed in detail was the first 2500ms (2.5 seconds). Beyond this time, the round roof model continues to roll onto its wheels (eighth quarter turn) and then travels along on its long axis until it eventually rolls onto its side in a low energy “fall over” at about 4.5 seconds. The square roof vehicle rolls back onto its left side and rocks between the front and rear on that side until it comes to rest after nearly 6 seconds. The final stages for both models are not considered representative of real world kinematics and so were not included in the analysis.

In regards to the total kinetic energy (sum of rotational and translational kinetic energies), the round-roof proxy vehicle compared to the square-roof one appears similar up until around 1,600 ms (1.6 seconds). After that moment, the round-roof proxy vehicle had only minor impacts with the ground as it continued to roll, whereas the square-roof proxy vehicle landed inverted on its bonnet and at the location of the windscreen header rail, thus experiencing a significant phase shift and change in total energy dissipated.

When considering the translational velocity the behaviour of the two proxy vehicle models are quite similar up until around 1,720 ms (1.7 secs), with minimal differences between their velocities (and thus kinetic energy decay). The round-roof proxy vehicle model becomes airborne and rolls over its roof, without ground contact, whereas the square roof proxy vehicle model impacts the ground on its bonnet and location equivalent to the roof header, causing a sudden loss of velocity in the direction it is travelling (and rolling). Such a sudden and significant velocity change is likely to cause occupants to experience injurious impacts with vehicle internal components such as the door, seat back, centre console, roof header rail and their seat belt as well as any other item not cushioned by an airbag or padding.

In regards to the roll rate, the two proxy vehicle models are again similar for the first 1,500 ms of simulation, with minor differences associated with the slightly different points of impact around generally the same parts of the model. After about 1,760 ms, the square-roof proxy vehicle model impacts the ground in an inverted orientation, with the leading edge of the bonnet and the location equivalent to the windscreen header rail striking together. The stiffness of the model causes it to bounce off the ground, reversing its roll direction. The model rapidly goes through a change of about 428 deg/s (from around -250 deg/s to around 170 deg/s), likely resulting in significant Δv between the occupant and the vehicle body. After 1,500 ms the round roof proxy vehicle model impacts the ground surface with the front left side of the bonnet and bounces nose to tail slightly, as it continues its roll (over its roof) in the original roll direction. The round roof proxy vehicle model goes through several roll rate changes, the largest being at 1,640 ms with a roll rate change of 114 deg/s (from around -210 deg/s to around -95 deg/s) The changes to roll rate experienced by the round-roof proxy vehicle model is significantly less than that of the square-roof model.

This initial study has carried out a series of simplified FEA models to consider the effects of rounded vs square shape roofs on severe injury risk for contained occupants in rollovers involving SUVs. It has been hypothesised that more rounded roof designs for SUVs may reduce the injury risk in rollovers.

Simplistic models of a block proxy vehicle were used, which while they do not accurately reflect the array of physical properties exhibited by a real vehicle in a rollover crash, nonetheless, these simulations provided an insight into the total energy and individual translational velocity and roll rates involved and the effect that different roof shapes can have on these towards the end of the roll event.
Figure 6. Overlayed graphs of total kinetic energy, translational velocity and roll rate from Figures 3 through 5 for Square Roof (blue) and Round Roof (red) elastic-plastic simplified proxy vehicles.
In these simulations, it was found that the greater changes in both translational velocity and roll rate occurred with the square-roof vehicle, and it is surmised that this would cause a greater Δv between the vehicle body and its occupants. Consequently, more internal collisions are likely to occur with the occupants, which are likely to be injurious, for an occupant within a square-roof vehicle than in a round-roof vehicle. This is consistent with the findings by Bambach et al. (2013) where the injury risk increases with larger number of accumulated quarter turns.

Simulations infer that, at least for SUVs, a round roof compared to a square-roof design may likely reduce the violence of the impacts with the ground and the magnitude of changes in both translational velocities and roll rate associated with rolling more than one full roll, i.e. through the inverted position after at least 4 quarter turns. However, more significant deformation of the vehicle glasshouse (upper) structure during the second full roll (more than 4 quarter turns) may occur, thus potentially varying this result, as also would a more realistic modelling of the stiffness for parts of the structure, including its corners.

Simulations conducted in this study considered only one set of initial conditions, which involved lateral rollover, which is the more common rollover event. Clearly there are a large range of other possible rollover crash scenarios. Simulations showed that the block proxy vehicle model impacted its front corners and was rolling over the bonnet, being biased toward a nose down pitch attitude according to the distribution of mass of the engine and transmission. The effect of ground contact with the wheels during the fourth and fifth quarter turns has not been of any note in these simulations. Further studies of alternate initial conditions are required in order to confirm whether there indeed are any differences between a vehicle with a square roof and a round roof.

**Conclusions**

This results of this study suggests, that for an SUV at least, roof shape does contribute to the potential conditions for injuries to occur for vehicle occupants in a rollover. For this proxy vehicle model under these initial conditions, the round roof design experienced less severe changes to translational and rotational velocity, thereby reducing the potential for severe impacts between occupants and the vehicle interior compared to the square roof geometry. It is important to note that the proxy vehicle model has not been validated against any particular vehicle or crash event and simply suggests a relationship may exist, that requires further research to confirm.

The round roof proxy vehicle model completed more quarter turns than the square roof model over the 2.5 second period analysed and for the whole event. Further work is required to determine the significance of this in terms of injury risk. The literature identifies that increasing the number of quarter turns increases injury risk significantly, but it is yet to be demonstrated if this is a consequence of increasing initial crash energy and hence the severity of those quarter turns experienced, or simply a consequence of the number of quarter turns achieved and the relationship roof shape has in regards to this outcome.

Further research is also required that would compare vehicle roof shape to injury outcomes in real-world rollover crashes. Support for this theory could be provided by a future investigation aimed at comparing injury type, severity and frequency to contained and restrained occupants during pure-rollover crashes of vehicles characterised by a more round roof compared with a square roof vehicle (assuming that both types of vehicles have similar roof strength).

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