

Compressive Neck Injury and its Relationship to Head Contact and Torso Motion during Vehicle Rollovers

James Raddin and Joseph Cormier
Biodynamic Research Corporation

Brian Smyth and Jeffrey Croteau
Exponent Failure Analysis Associates, Inc.

Eddie Cooper
B33 Consulting, Inc.

Copyright © 2009 SAE International

ABSTRACT

Previous literature has shown that serious neck injury can occur during rollover events, even for restrained occupants, when the occupant's head contacts the vehicle interior during a roof-to-ground impact or contacts the ground directly through an adjacent window opening. Confusion about the mechanism of these injuries can result when the event is viewed from an accelerated reference frame such as an onboard camera. Researchers generally agree that the neck is stressed as a result of relative motion between head and torso but disagree as to the origin of the neck loading.

This paper reviews the principles underlying the analysis of rollover impacts to establish a physical basis for understanding the source of disagreement and demonstrates the usefulness of physical testing to illustrate occupant impact dynamics. A series of rollover impacts has been performed using the Controlled Rollover Impact System (CRIS) with both production vehicles and vehicles with modified roof structures. Data from these tests were analyzed in both the vehicle reference frame and an inertial reference frame to demonstrate the neck injury mechanisms. The results of these tests show that neck loading was fundamentally a result of torso augmentation rather than roof deformation.

INTRODUCTION

The collection of publications in the literature on the role of roof structure deformation in occupant injury causation is extensive. Much of the early literature either treated the minimization of roof intrusion into the occupant space as implicitly desirable, or presented data which suggested that an association between roof crush and injury implied causation (Strother et al., 1984).

Initial studies of the General Motors testing series known colloquially as "Malibu" found that reinforced roof structures did not afford an increased level of protection for either restrained or unrestrained occupants when compared to production roofs (Bahling et al., 1990, Orłowski et al., 1985). These studies concluded that compressive neck loading at a magnitude associated with cervical spine injury is not caused by roof crush, but by the occupant moving toward the roof panel which is in contact with the ground, and that peak neck loads occur prior to significant roof deformation. A later study of a number of rollover tests in the literature, including the Malibu data, reaffirmed this conclusion (James et al., 1997). Occupant and vehicle motions in the Malibu tests have been further reexamined to quantify occupant and vehicle motions using techniques such as digitized film analysis, in which the occupants' heads were observed

to consistently reach the roof area prior to upper vehicle structure-to-ground impact (Gloeckner et al., 2007). A recent study used a computer simulation to demonstrate that when occupant head excursion is sufficient to contact the interior roof panel, compressive preloading of the neck can occur during the airborne phase of the rollover and prior to roof-to-ground contact, effectively reducing the dynamic loading required for injury on subsequent roof-to-ground impacts (Ashby et al., 2007).

The Controlled Rollover Impact System (CRIS) is a machine that was developed to produce a specific and repeatable rollover impact event, which does not impose any external constraints on the vehicle during or after the initial roof-to-ground impact. (Carter et al., 2002, Cooper et al., 2001). Recently, the CRIS has been used to compare production vehicle roof-to-ground impacts with corresponding impacts of vehicles modified with roll cages (Moffatt et al., 2003). This study reached conclusions similar to those in the Malibu work and found no significant difference in head accelerations and neck loads even when there was deformation of the production vehicle roof structure. These studies have consistently concluded that peak head accelerations and neck loads are the result of the roof striking the ground and stopping and the occupant “diving” into the roof, and are not caused by roof structure deformation.

In 2007, a study was published in light of proposed changes to FMVSS 216 related to rollover crashworthiness (James et al., 2007). In response to the methodologies employed by critics of the original Malibu findings, this study concluded that “observations from an inertial reference frame are necessary to correctly interpret the relationship of vehicle and occupant motions during a rollover crash”. This study also found that neck loading is the result of the torso moving toward the head, and not roof intrusion that would cause the head to move toward the torso.

In 2005, an extensive overview of available literature on the topic of roof strength and occupant head excursion was published, outlining factors influencing overall head excursion and discussing a number of countermeasures and areas for expanded research (Moffatt and James, 2005).

Despite findings that dismiss roof deformation as the basis for compressive neck injury, the topic remains contentious. A study that analyzed high-speed Malibu test video and correlated injury to “roof intrusion rates”, concluded that roof collapse in a rollover “imposes velocities and forces on an occupant’s head that are far greater than an occupant would experience solely from his or her dropping at the vertical velocity of the vehicle’s

center of gravity” (Friedman and Nash, 2001). The same authors also concluded in a later reexamination of Malibu timing data that neck load is caused by roof intrusion “pushing” the head toward the torso (Friedman and Nash, 2005). The long time delays between A-pillar ground contact and peak neck loads, which were the basis of the authors’ conclusion, were shown to be misinterpretations of the original Malibu work (James et al., 2007). Another study which reexamined Malibu data attempted to correlate the timing of peak “roof acceleration” to peak occupant neck loading (Chirwa et al., 2006). This study was shown to have confused vehicle body displacement with roof displacement with respect to the inertial reference frame, and failed to demonstrate a causal relationship between roof crush and neck loading (James et al., 2007). An examination of the timing of peak neck loads and roof crush in a series of Ford Explorer rollover tests concluded “roof crush into the survival space of restrained dummies was the direct cause of neck loads...” (Bidez et al., 2005). This study evaluated data in a vehicle-fixed rather than earth-fixed reference frame. Errors have been identified in this study’s computation of instantaneous roof crush (Yamaguchi et al., 2007). Yamaguchi et al corrected the original derivations and found these methods of computing dynamic roof crush to be “theoretically feasible” but “completely impractical” due to current sensor technology limitations.

The purpose of this paper is to discuss rollover kinematics using fundamental principles and to demonstrate those principles using rollover test data.

ROLLOVER PRINCIPLES

The literature continues to include contradictory papers on the role of roof deformation in rollover neck injury primarily because there remain significant differences in the ways people understand the rollover event. Previous authors tend to portray rollovers either in qualitative terms that are technically deficient or in quantitative terms that are mathematically unapproachable for the average reader. The importance of distinguishing between body-fixed versus inertial reference frames is commonly neglected in the analysis of occupant dynamics in rollovers. This paper will first attempt to characterize the physical rollover event in approachable terms and then define and present data relevant to neck injury causation within that context.

The first requirement is to observe the rollover event from a non-accelerated, non-rotating reference frame, usually called an inertial reference frame. For our purposes, this can be a frame of reference fixed to the earth or moving at constant velocity. If this requirement is not met, motions of objects observed from an accelerated reference frame can be mistakenly ascribed

to what are called “fictitious forces” (Serway, 1996). In other words, the accelerations of the reference frame result in what appear to be accelerations of some object of interest, and, therefore, forces on that object are imputed. In rollovers, this problem commonly arises in interpretation of film or video taken from a vehicle-mounted camera. Ground-based cameras are used to document the vehicle dynamics but vehicle-mounted cameras are more commonly used to study occupant motion. Authors may refer to an observed change in motion of an Anthropometric Test Device (ATD) when, in fact, the observed change in motion may result from a vehicle impact which has changed the motion of the vehicle-mounted camera. This error can cause attribution of injury to forces that are not there with resulting inappropriate protection recommendations.

A second requirement is to adequately describe the motion of the relevant parts of a vehicle involved in a rollover event. Mathematically, the motion of the center of mass as a function of time can be described with respect to an inertial reference frame. The motion is typically described using time functions of displacement, velocity and acceleration. For a rigid body, one can then define the motion of any other point in the body if the angular velocity is also known. For example, the velocity of a Point P in the body is defined by the following equation, where r is the distance from the center of mass to Point P and ω is the angular velocity in radians per second.

$$\vec{V}_P = \vec{V}_{cm} + \vec{\omega} \otimes \vec{r}$$

This general equation involves vector cross products and vector sums, but it is more approachable and illustrative if we reduce it to a simple, specific case.

Consider a symmetrical wheel rolling at constant velocity on a flat, horizontal surface, as shown in **Figure 1**.

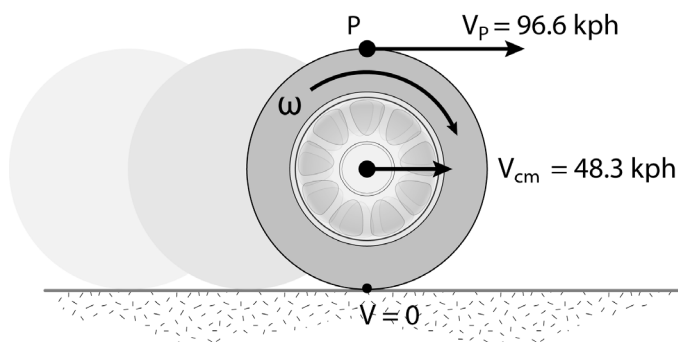


Figure 1: Wheel rolling at constant velocity.

The velocity of the wheel would be described as V_{cm} which would be entirely horizontal, say 48.3 kph or about 13.4 m/s with respect to an inertial or fixed reference frame. If the radius of the wheel is 1.07m and if there is no slipping of the wheel on the surface, we can compute the magnitude of the rotation rate with the following equation.

$$\omega = \frac{v}{r}$$

where ω is the rotation rate in radians per second, v is the velocity in meters per second, and r is the radius in meters. For our example, ω equates to about 12.5 radians per second or nearly 2 revolutions per second. If we were to calculate the velocity of a Point P on the edge of the wheel, again from a fixed reference frame, the observed instantaneous velocity would vary with time depending on where Point P happened to be. Its velocity is in the same direction as the center of mass at the top and in the opposite direction at the bottom. The resultant velocity would never be 48.3 kph in a horizontal direction. In fact, the velocity of Point P when it is right at the bottom would be exactly zero since the wheel is not slipping or moving against the surface. The velocity of P reaches a maximum in the horizontal direction when P is at the top and the vector sum of the velocity is twice the velocity of the wheel's center of mass or about 96.6 kph. In accordance with the vector sum in the first equation, a point on the surface of the rolling wheel has a velocity that is the vector addition of the center of mass velocity and the tangential velocity. The tangential velocity has both magnitude and direction and while its magnitude remains constant (for a constant center of mass speed) the direction of the tangential velocity varies with time. The velocity of P for three distinct wheel orientations is shown in **Figure 2**. The velocity of P, in terms of its horizontal and vertical components, takes the form of trigonometric functions and is shown in **Figure 3**.

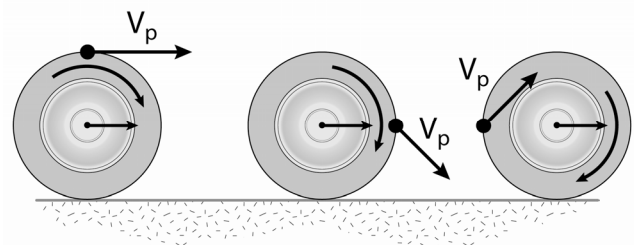


Figure 2: Resultant velocity of point on rolling and translating wheel.

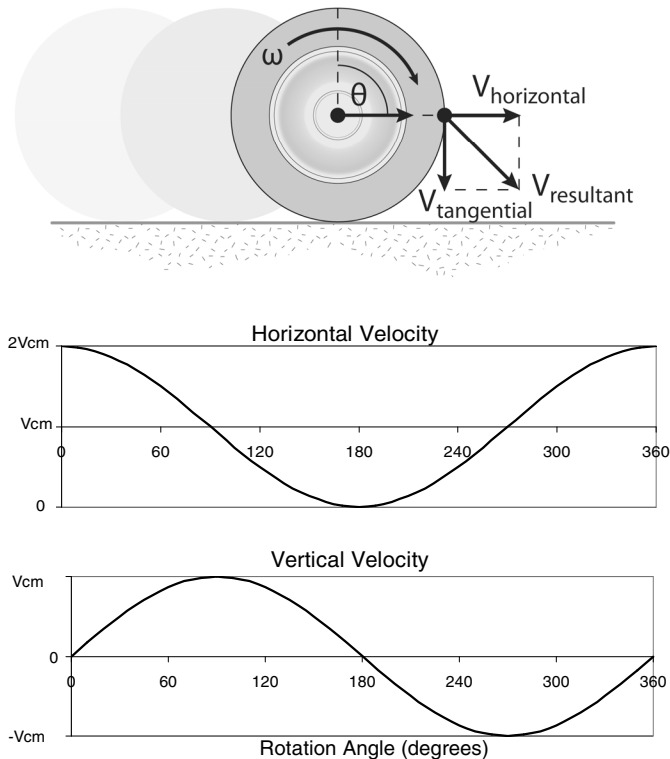


Figure 3: Horizontal and vertical velocity components of point P for one revolution.

The third law of motion states that for every force there is an equal and opposite reaction force. The second law dictates that the sum of the forces gives rise to the rate of change of linear momentum. For our wheel, there is a constant force being applied by the spokes that acts at a 90° angle to the tangential velocity of point P to change its direction but not its magnitude. This is termed a centripetal force and produces a centripetal acceleration in accordance with the second law of motion. A freely movable bead on a spoke of our wheel would move radially outward to the rim until a force constrains it within the wheel's path. This bead motion is analogous to what happens to occupants in rolling vehicles. The inertial force that moves the bead out to the periphery is called a centrifugal force and is equal and opposite to the force of the bead as it loads the wheel rim. In vehicle rollovers, every point in the vehicle and in the occupants generally has a different instantaneous velocity, acceleration, and force taking place. The inertial centrifugal force is directly proportional to both radius and the square of the angular velocity, always directed along a radius from the center of mass. As measured at the head, this force may exceed ten times the force of gravity in a high-speed rollover (for a 550 deg/s roll rate and a 1.07m radius).

A final observation with our wheel analogy relates to angular momentum and angular energy which are angular analogs of the more familiar concepts of

translational momentum and energy. For the translational case, we have

$$\text{Momentum} = \vec{P} = m\vec{v}$$

$$\text{Translational Energy} = E_T = \frac{1}{2}mv^2$$

where momentum is a vector quantity (having both direction and magnitude) and energy is a scalar. The mass of an object is a measure of its resistance to being accelerated by a force. The angular analog is called moment of inertia (I), which is a measure of an object's resistance to being spun around a specific rotation axis by a torque or twisting force. We therefore have

$$\text{Angular Momentum} = \vec{L} = I\vec{\omega}$$

$$\text{Angular Energy} = E_A = \frac{1}{2}I\omega^2$$

Just as momentum is changed by a force acting over time (impulse) and energy is changed by a force applied over distance (work), angular momentum is changed by torque over time and rotational energy is changed by torque acting through an angle. It should be noted that angular momentum and translational momentum have different units (torque-time vs. force-time) while translational and angular energies share the same units (force-distance). The practical application of these concepts includes the understanding of how angular energy and translational energy interchange in a rollover. Specifically, a sliding vehicle prior to rollover has virtually all its energy in a translational form. When it is rolling, some of that energy is converted to angular energy, which implies that it has less translational energy and, therefore, a lower velocity of the center of mass. In other words, when a vehicle starts rolling, its over-the-ground velocity slows down. The proportion of the original translational energy temporarily transformed into rotational energy may be in the range of 10% to 25% or more. The angular momentum of the rolling vehicle also imparts gyroscopic characteristics which result in precession and nutation effects. These are rarely taken into account in rollover analyses but would rationalize what is more commonly assessed to be a chaotic process.

Vehicles typically do not roll like wheels or barrels, but the same mathematics apply. Among the differences is the typical lack of the non-slip situation described above. The external influence that makes vehicles roll is the interactive force between the exterior of the vehicle and the terrain. That force tends to get less effective in increasing the roll rate as the magnitude of the tangential velocity approaches the center of mass velocity. Therefore, the tangential velocity is

lesser in magnitude than the center of mass velocity. This means that the horizontal component of the velocity of a part of a rolling vehicle in contact with the ground is generally less than the center of mass velocity but more than zero as would have been the case with a wheel. The vehicle-ground interaction induces a torque into the vehicle that results in scrapes left on the vehicle. The scrapes can typically be used to assess the roll direction since they are formed in the direction of the angular rotation, or down on the leading side and up on the trailing side, as shown in **Figure 4**.

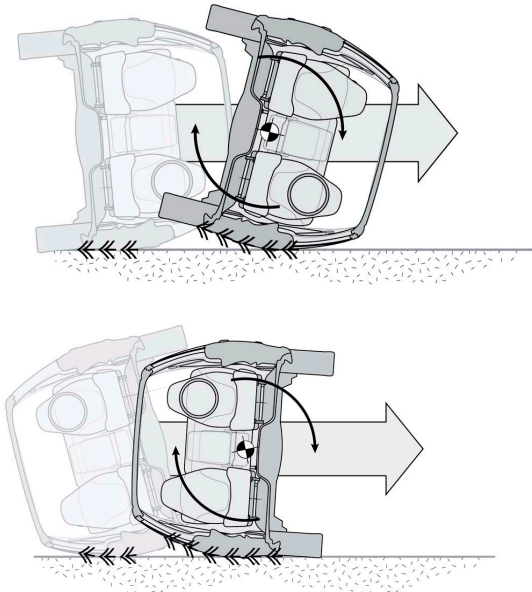


Figure 4: Direction of scrapes created by the vehicle-to-ground interaction.

The velocity of a part of the vehicle away from the ground (and above the center of mass) will be more than that of the center of mass velocity but generally less than twice as much as it would have been in the case of the wheel example presented in **Figure 3**. This explains why occupants ejected from the high side in a rollover leave the vehicle with a higher velocity than those ejected from the low side.

The conceptual underpinnings have now been reviewed sufficiently to allow an examination of the ground impacts of a rolling vehicle. Consider another symmetrical wheel rotating with a constant horizontal velocity but supported barely above a horizontal surface. It is then allowed to touch down on the surface with negligible vertical velocity while rotating at an angular velocity lower than that necessary to roll without slip on

the surface. The touchdown will result in a frictional force between the surface and the wheel that will tend to accelerate the angular velocity of the wheel by acting as a torque, as shown in **Figure 5**. The torque in this case produces an angular acceleration that changes the angular velocity in direct proportion to the torque and in inverse proportion to the moment of inertia.

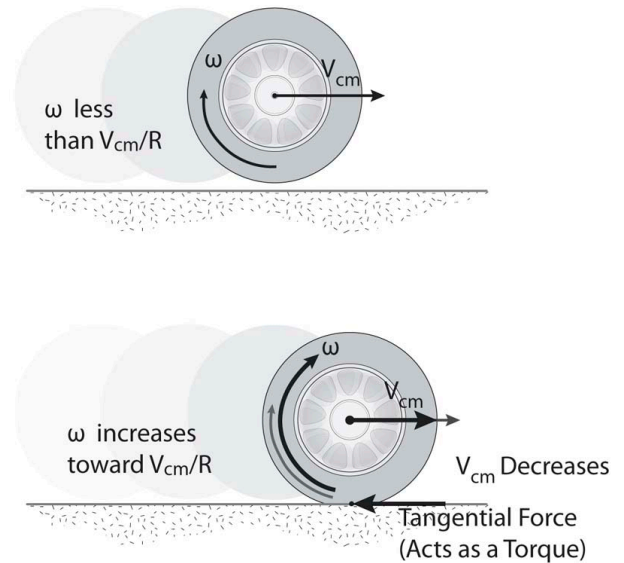


Figure 5: Increase in rotational velocity with touchdown of horizontally translating wheel.

If we were to drop the same wheel from a greater height, it would arrive at the surface with a vertical velocity as well as a horizontal one. Force would be applied by the surface to the wheel (and equally and oppositely by the wheel to the surface) that would be more complex. As shown in **Figure 6**, there would be a vertical (or normal) component of force acting through the center of mass of the wheel to reduce the downward velocity of the wheel.

There would again be a horizontal (or tangential) component acting at a 90° angle to the radius acting as a torque to increase the angular velocity of the wheel similar to the previous example. In general, the coefficient of restitution during the impact will insure some degree of bounce since the normal force not only slows the vertical velocity to zero but also typically continues to act to impart a vertical velocity upward as the elastic compression of the wheel is reversed.

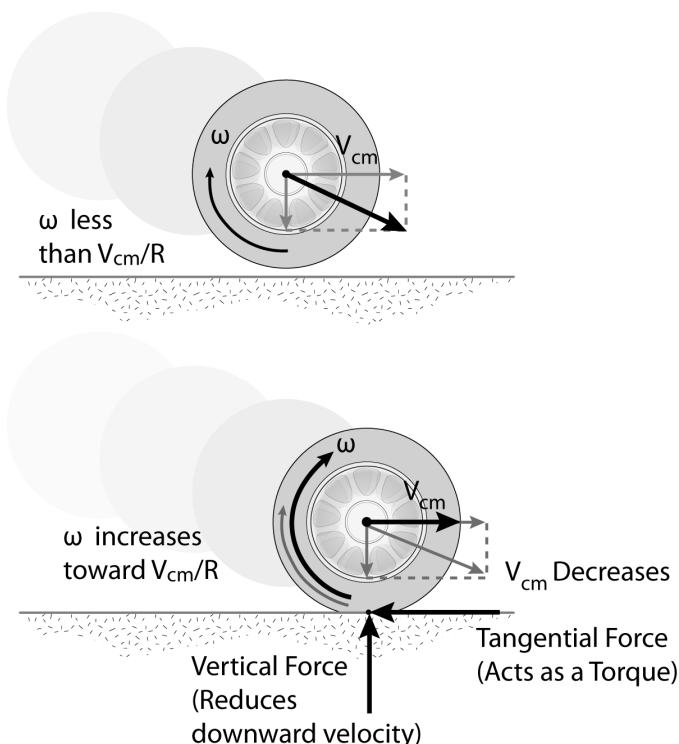


Figure 6: Force generated by touchdown of vertically and horizontally translating wheel.

Vehicle-ground interaction is further complicated by vehicle shape. The roof rail is generally further from the center of rotation, for example, than the center of the roof. The roof rail will generally not contact the ground just as the radius from the center of rotation to the roof rail passes through vertical. When it doesn't, the vertical force from the ground will also tend to act to some extent as a torque, as shown in **Figure 7**, and the horizontal force will also tend to act to a greater extent on the center of mass. Note that **Figure 7** only shows the effect of the vertical component which becomes predominant as ω increases toward V_{CM}/R and as the vertical component of V_{CM} increases.

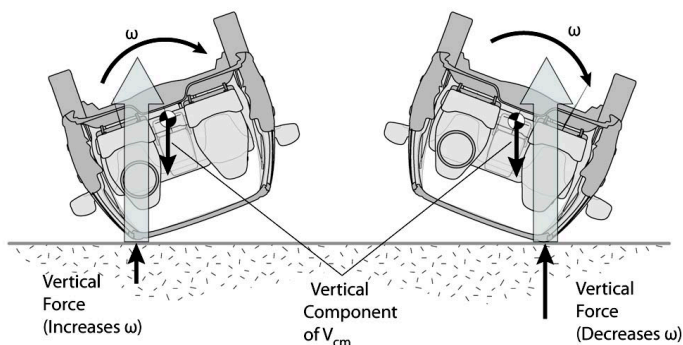


Figure 7: Effect of vertical component of contact force on rotation.

In general, vehicle-to-ground contact may increase or decrease the angular velocity depending on the interaction. Some contacts may first decrease and later increase the angular velocity during a single contact with the net effect depending on the comparative contributions. The graphic in **Figure 7** shows a near-side contact followed by a far-side contact. The continued rolling of the vehicle in this configuration requires some combination of deformation or rapid change of the vertical velocity of the center of mass of the vehicle. There is simply no room for the undeformed far-side roof rail to miss the ground given the downward moving center of mass and the radius to the roof rail being greater than the distance from the center of mass to the ground. This is the reason that designers reject the use of square shapes as wheels and explains why trailing roof rails are often rounded off by rollover deformation. It is fundamentally the same conceptual reason that an occupant whose head is already against a trailing roof rail at a far-side ground contact will be exposed to neck loading prior to roof deformation.

Another effect of irregular vehicle shape is that the tangential velocity of the contact point will in general affect the vertical velocity of the contact, as shown in **Figure 8**. The vertical contact velocity of the roof rail without rotation would simply be the vertical velocity of the center of mass, or 8.05 kph in the example shown in **Figure 8**. With rotation, the roof rail contact velocity will be the vector sum of the center of mass velocity and the tangential velocity at the roof rail. In our example, the vertical velocity of the roof rail contact would increase to 20.45 kph and the horizontal velocity would decrease to 6.28 kph. This increased vertical velocity is certainly within an injurious range, independent of roof deformation. Inverted drop tests conducted with vehicles and instrumented ATDs released from 0.46m that achieved contact velocities of 10.8 kph have been shown to result in injurious neck loads (Nightingale, 1996). Contact of the trailing side roof rail with terrain before it passes under the center of mass is again the most hazardous condition for producing increased vertical velocities.

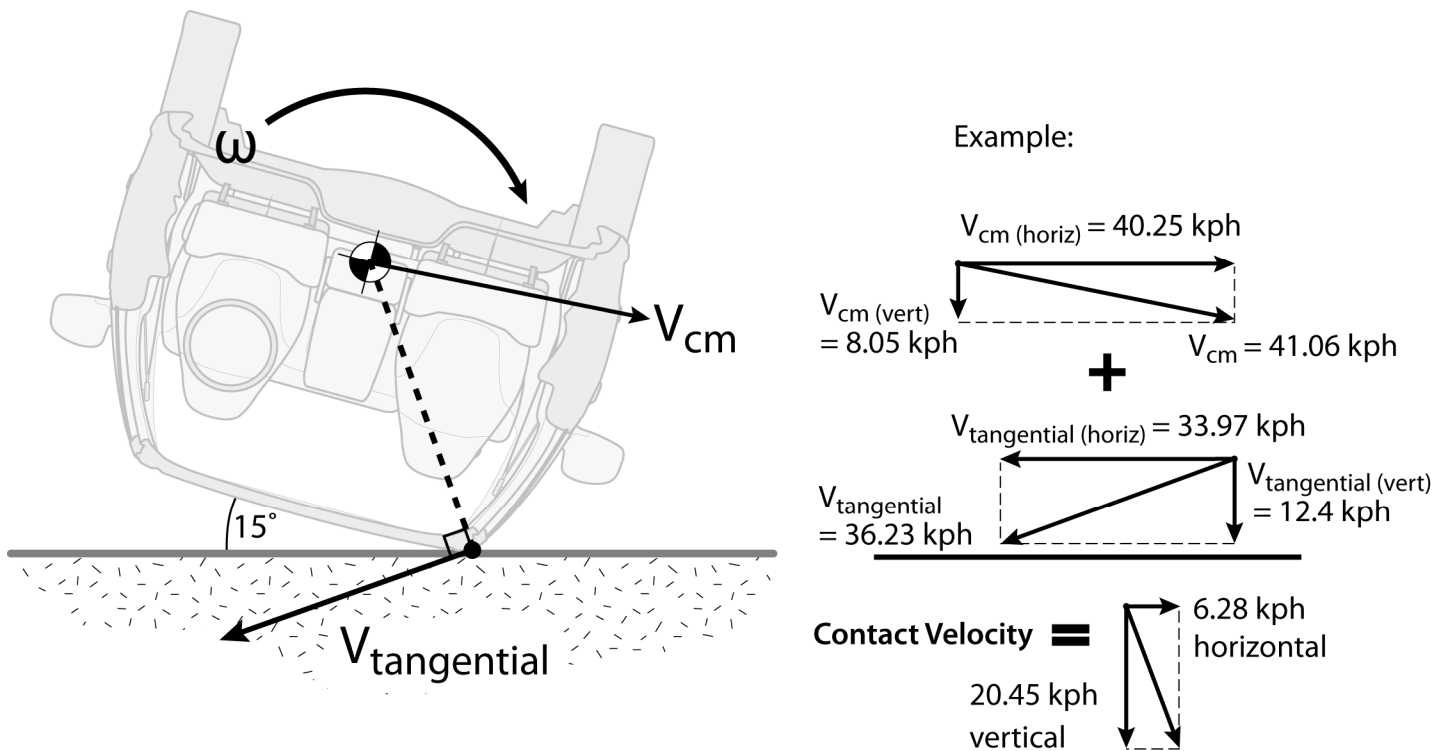


Figure 8: Influence of vehicle rotation rate on contact velocity at roof contact.

Vehicle deformation introduces yet another complexity, as all real materials deform. An idealized non-deforming vehicle bouncing and rolling on a non-deforming surface would experience infinite forces and accelerations. The relatively modest accelerations measured at the center of mass of a rolling vehicle attest to the attenuation (cushioning) effect that the deforming structures make when contacting the ground. The deformation lengthens the distance and duration of the impact, decreasing the peak translational acceleration of the center of mass and of the non-contacted portions of the vehicle. Accelerations of parts of the vehicle nearer the contact point are much higher (Carter et al., 2002). Increased roof stiffness would increase the center of mass acceleration at roof contact and, therefore, increase relative occupant displacements. Further increases in contact severity occur with terrain variations such as an impact into rising terrain, since more of the vehicle horizontal velocity acts like an increased vertical velocity.

The increased time of the contact results in another important effect. Ground contacts in rollovers where the vehicle has high translational and angular velocity may have durations in the range of 100-200 milliseconds. The very late contacts may last even longer. Therefore, the force from the terrain acts at a changing angle during the contact, which often changes over an angular range of more than 40 to 60 degrees as the vehicle continues to rotate and translate and the contact point continues to slide.

Occupant kinematics within the vehicle will vary depending on how the vehicle strikes the ground. For a rolling vehicle, the occupant does not simply move toward the point of ground contact but rather responds in accordance with the laws of motion, generally in a curving path with respect to the rotating vehicle. The centripetal effects at the vehicle periphery ensure the occupant's head is not at a neutral driving position during most of a multi-rollover event. Instead, it is typically at or near the roof rail, which is reachable by most restrained adult occupants since it is generally lower than the roof above a neutral head position. After window breakage, the head may pass beyond the roof rail, becoming susceptible to direct terrain contact. Vehicle-to-ground impacts during a roll sequence can affect occupant kinematics such that head-to-vehicle contact also occurs inboard of the roof rail. The most hazardous impacts typically occur when a trailing side roof rail hits the ground because the tangential velocity is more likely to add to vertical contact severity on the trailing side and decrease vertical contact severity on the leading side. At contact, direct roof rail loading of the head may occur as the roof or roof rail undergoes a significant change in velocity with the head already against it. For typical trailing side roof rail contacts, occupant head motion may carry on out the window since the occupant does not simply move toward the roof rail in contact with the ground.

The complex motions described above dictate the type of test approaches required to investigate them. Simple inverted drop tests are a poor comparison for the following reasons. The lack of vehicle angular velocity mispositions the occupant vertically and laterally since there is no centrifugal or centripetal force. In fact, even the displacing effect of gravity is lost once the vehicle is released. Secondly, the vehicle structure is loaded unrealistically since there is no horizontal component of contact force and no changing angle of force. Thirdly, the occupant kinematic response is not representative since the occupant has only a vertical velocity and it is not subjected to the angular rotation effects. Finally, reference frame confusion is often introduced through the use of vehicle-mounted cameras. Drops onto a roof rail are similarly not representative of the conditions in a roof-to-ground impact during a rollover.

Other test approaches have been devised with rotating vehicles and moving impact surfaces (Friedman et al., 2007) that have more intuitive appeal and may be repeatable but that repeatedly involve fundamental problems. Most critically, the dynamics of these devices lead to the imposition of unrealistic impact forces derived from the constraints imposed by the fixture. They do not have six degrees of freedom like a rolling vehicle, so unrealistic impact forces result from the way the vehicle is prevented from moving along and about the constrained axes. The problems are compounded when partial vehicle segments are used. These are typically weight compensated but the moments of inertia are not representative, resulting in both the rotational and translational impact dynamics being wrong. Finally, reference frame problems are introduced if changes in the velocities of the moving impact surface and the dropping vehicle are unrepresentative of a real impact, no matter where you mount the cameras. To achieve representative impact loading on the vehicle and on the occupant, a true six degree-of-freedom or unconstrained impact must be employed.

It is important to get the mechanism of neck loading right. Otherwise, incorrect notions may lead to well-intentioned interventions with unanticipated adverse effects. For example, attempts to increase the strength of roof supports typically result in more elastic structures that have greater elastic recovery (or bounce more). This results in increased velocity changes for roof-to-ground contacts, increasing the energy change of the event not only for occupants against structure at the contact location but also for remotely located occupants.

ROLLOVER TESTING

To assist in understanding the source of neck loading in rollover impacts, a compilation of test data was reviewed from tests in which impacts were produced, which involve all the rotational, translational, gravitational, and impact conditions of an unconstrained rollover ground impact.

Data were assessed from an inertial frame of reference by utilizing inertial sensors in the head of the ATD. The inertial sensors or accelerometers inherently measure with respect to an inertial reference frame. At the same time, neck load cells measure real forces so that reference frame confusion can be avoided. If, as some authors have claimed, injurious neck force is derived from the head being accelerated into the neck by roof deformation, then the inertial sensors in the head should measure significant acceleration as the roof deforms and the neck is loaded. If, on the other hand, the inertial sensors do not measure significant acceleration of the head during neck loading or during roof deformation, then the neck forces must derive from some other source such as torso loading, or torso augmentation. In particular, contacts of reinforced vehicles with little roof deformation should yield negligible neck loads if neck loads are the result of roof deformation.

CONTROLLED ROLLOVER IMPACT SYSTEM

The Controlled Rollover Impact System (CRIS) is currently the only system that can repeatedly orient a full vehicle for a specific impact while allowing six degrees of freedom (**Figure 9**). The ability to repeatedly configure a specific impact allows direct comparison between production and reinforced roof structures.



Figure 9: Photograph of CRIS system with vehicle attached.

The CRIS consists of a Class-8 tractor and a flatbed trailer that has been modified so that a full-size vehicle can be hung from adjustable supports at the back of the trailer. The vehicle can be spun about its principal roll axis with bearings that are located at the front and rear of the test vehicle. While the test vehicle's principal axis

is fixed relative to the vehicle, this axis can be adjusted relative to the ground. This adjustment allows the test vehicle to be configured to a specific pitch angle, yaw angle, and drop height. Vehicle translation speed is determined by the speed of the tractor-trailer.

An electric motor spins the test vehicle up to the desired roll rate, and the front and back of the vehicle is released simultaneously at both ends. The release is timed so that the vehicle is at the intended roll angle when it impacts the ground. Once the test vehicle is released from the CRIS it is unconstrained, and, therefore, it has six degrees of freedom at impact.

ROLLOVER TEST DATA

Data from ten CRIS tests were analyzed where Hybrid-III ATDs were restrained in the driver seating position of the test vehicles. The tests were conducted to simulate a passenger-side leading rollover with a roof-to-ground impact on the driver side roof. This configuration is also referred to as a far-side occupant impact. A secondary impact was analyzed for the Isuzu Rodeo test where the ATD's head directly contacted the ground through the adjacent window opening (**Figure 10**). By design, except for the second Rodeo impact, all ATD impacts occurred near the 180-degree roll angle. The Volvo XC90 had a pitch angle of 5 degrees at impact, while all other test vehicles had a zero pitch and yaw angle at impact. Refer to **Table 1** for a summary of each impact configuration.



Figure 10: Onboard video showing the head-to-ground contact during the second impact in the Rodeo CRIS test.

Table 1: CRIS test initial conditions at roof contact: translational speed, drop height, and roll rate.

Vehicle	[kph]	[cm]	[deg/s]	ATD	Roof
2005 Volvo XC90	12	27	224	50th	Prod.
1996 Isuzu Rodeo 1	60	48	317	5th	Mod.
1996 Isuzu Rodeo 2	--	--	--	5th	Mod.
1998 Ford Crown Victoria	13	27	227	50th	Mod.
1999 Ford Crown Victoria	13	27	226	50th	Mod.
1999 Ford Crown Victoria	13	28	223	50th	Prod.
1998 Ford Crown Victoria	13	30	227	50th	Prod.
2000 Ford Crown Victoria	32	33	363	50th	Mod.
1999 Ford Crown Victoria	32	32	361	50th	Prod.
1996 Chevrolet Blazer	13	25	226	50th	Prod.
1996 Chevrolet Blazer	13	25	226	50th	Mod.

Instrumentation for the CRIS tests included test vehicle roll rate at release, test vehicle translation speed at release, ATD triaxial head accelerations, and ATD upper-neck triaxial forces and moments. A detailed analysis was conducted on the data collected during these tests. The data referenced to the vehicle coordinate system will be presented in standard SAE J211 sign convention; i.e. the positive longitudinal axis is forward, the positive lateral axis is to the right, and the positive vertical axis is down.

The inertial reference system will be defined with respect to earth with the positive lateral direction oriented by the travel direction of the CRIS test device (**Figure 11**). The longitudinal and vertical directions will be defined from the lateral axis using the right hand rule; i.e. the positive longitudinal axis oriented generally in the vehicle longitudinal direction, and the positive vertical axis into the ground. Note that the positive vertical axis for both the vehicle and earth reference frame are collinear when the vehicle is at a 0-degree roll angle.