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**Richard P. Howard, Charles P. Hatsell and James H. Raddin**
Biodynamics Research Corp.

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## ABSTRACT

Predictions of occupant motion in passenger vehicles undergoing rollovers have been hampered by the uncertainties of the vehicular motion. These uncertainties arise due to a host of factors which may be difficult to quantify, such as trip conditions, vehicle/terrain interaction dynamics and mass eccentricities. In this paper the initial segment of a roll sequence of high angular velocity (greater than 4 radians per second) about a longitudinal axis is examined. The resultant unrestrained motions of the near and far side occupants are studied. To facilitate this analysis a mathematical model has been developed which incorporates dynamic characteristics of the occupant, the vehicle and the terrain surface. The analysis is carried through the first significant vehicle/ground impact following roll initiation. Occupant kinematics are described.

## INTRODUCTION

Dynamics of vehicle rollovers have been described in the scientific literature by numerous authors over the past three decades. Occupant motion in passenger vehicles has been sparsely described. In a seminal paper on rollovers, Moffat, 1975 (1) described elements of kinematics of unrestrained occupants. Orlowski, et al, 1985 (2) described the motions of automotive test dummies in the 1983 Chevrolet Malibu automobile test series. The "Malibu" tests were conducted using test vehicles carried laterally on a dolly with a cant of 23E to facilitate the initiation of the lateral roll. The dolly carriage also incorporated a drop height of several inches which added kinetic energy to the roll initiation. Cooperrider, et al, 1990 (3) reported on a series of rollover tests which included vehicles tripped on prepared soil which was considered to be more characteristic of "real world" rollover initiation than the more abrupt rigid "curb" trip and certainly the canted pre-roll position utilizing a dolly. It was observed by Orlowski (2) that once the roll was initiated and a roll rate was established the ATD would move outward away from the roll center and tend to remain in that position against the interior of the occupant compartment at the farthest distance from the roll center permitted by the vehicle envelope. The ATD buttocks made no further contact with the seat once this position was attained. Only major vehicle impacts with the terrain or other objects would disturb this perimeter position of the dummy. Much of the thrust of the kinematic discourses in the foregoing cited publications dealt with roof crush and the propensity of some authors to confuse the association of roof crush to injury with assumptions regarding causation. Pizialli, et al 1998 (4) have written a comprehensive paper summarizing this issue. It will not be revisited here. It has been adequately demonstrated by Huelke, 1972 (5) and others that occupants ejected in rollovers expose themselves to an environment of greater injury potential than those left behind in the rolling vehicle. A significant portion of this difference may be attributable to the difference in restraint utilization for ejected versus non-ejected occupants. This issue will not be further discussed here except to indicate the conditions for ejection and to acknowledge that it is incrementally bad compared to other kinematic possibilities.

## ANIMATION OF A SIMPLE ROLLOVER MODEL

To facilitate the analysis of occupant kinematics in rollover phenomena a mathematical model has been constructed. In order to describe with some accuracy the occupant motions in a roll it is necessary to limit the rollover segment to be analyzed. In a multiple rollover sequence the possible outcomes multiply with the number of rolls. The interplay of variables cause specific events later in the sequence to be increasingly unpredictable. Hence the segment to be considered in this analysis will be from roll initiation through the first terrain strike. The initial rate of roll will be at an angular velocity which would typically be expected to produce additional rolls (4+ radians/sec).

In high speed rollovers on reasonably flat terrain, it has been found that the first significant vehicle/terrain impact occurs in the region of the trailing roof rail. (Orlowski, 1989)(6) The rollover initiation model approximates the soil tripped initiation and the first ground hit was at the trailing roof rail for the velocity, vehicle restitution, friction factors, and other parameters selected.

In order to illustrate in a simple manner some of the basic features of occupant motion in a rollover accident and to emphasize the ballistic nature of occupants not coupled to the rotating vehicle, a very simple two-occupant rollover model was programmed using a finite element dynamic mechanical model. The particular software package used was Working Model 2D. The vehicle boundaries were modeled by joined rectangles and the occupants were modeled by spheres. The center of gravity of the vehicle was approximately one-third of the total vertical dimension from the datum. A furrowing trip was modeled by a series of masses interconnected by dashpots of increasing viscoelastic constant. The damper constants are 500 lb-sec/ft, 1200 lb-sec/ft and 3000 lb-sec/ft; the masses are 500 lb, 2000 lb, and 5000 lb. Trip velocity is 47 miles per hour. These parameters cause the vehicle to begin rolling in less than 10 feet of furrowBa hard trip. Figure 1 shows a series of stations in the animation provided by this model. The essential feature of occupant capture by the periphery of the vehicle due to centrifugal force is demonstrated as is the ballistic nature of objects which become uncoupled from the vehicle. Because of the simple spherical models used for the occupants, this ballistic feature is undoubtedly overemphasized in this method of animation. For example, interaction of vehicle surfaces with a non-spherical occupant would inhibit the tendency for occupant inversion shown in the less constrained spherical model. Also, vehicle deformation and associated changing inertial parameters are not accounted for in this model; however, vehicle-ground interactions are maintained "soft" by specifying a low coefficient of restitution (E=0.2) between the vehicle and ground. The model is correct as all calculations carry an audit trail to Newtonian laws. This trip is a fairly hard one and results in the trailing side occupant moving across and interacting with the leading side occupant with recapture of the trailing side occupant as the first roll develops. Figures 2, 3 and 4 shows some of the dynamic parameters of the modeled vehicle and its occupants. It can be seen in this type of trip that the vehicle has gone through substantial rotation by the time the leading tires depart the trip point.

## VEHICLE ROLL DYNAMICS

The following observations relate only inferentially to the foregoing model analysis and are based on general dynamic principles.

If the transverse cross section of the vehicle were circular and the terrain over which it rolled were planar the vehicle would be expected to undergo perimeter rolls with no loss of ground contact. However, passenger vehicles are not circular in cross section. In the absence of outside forces they rotate about a longitudinal axis which passes through the center of mass. The center of mass rather than being at the geometric center of the vehicle is located at the approximate junction of the lower third and upper two thirds of the vehicle's height. (See Fig. 5) Because of this geometry it is not possible for a sustained roll to occur with the center of mass maintaining a constant distance from the ground. The initiation of the roll therefore requires energy, not only to overcome angular inertia, but also to do the work required to lift the center of mass to its maximum height. This energy is obtained through the transformation of kinetic energy of the vehicle's translational velocity. As vertical velocity of the center of mass is developed early in the first phase of a high speed roll sequence the vehicle loses contact with the ground and commences to roll about a longitudinal axis which passes through the center of mass (rotation about any other axis would require greater angular energy). (See Fig. 6) The path through space followed by the center of mass is dictated by the vector sum of its vertical and translational velocities and the acceleration of gravity (a ballistic trajectory). Renewed ground contact occurs with a cross sectional prominence, i.e., left wheels, right wheels, right side, right roof/roof rail, left roof/roof rail and left side.(2) The force vector imposed on the vehicle by this ground impact will, decrease the roll rate if the vector passes above the center of mass and will increase the roll rate if it passes below the center of mass. In fact, a single contact will have a time-varying force vector which may not stay above or below the center of mass during a contact.

## AXIS OF ROTATION

Predictions regarding occupant motion in a rolling vehicle are based by some analysts on an assumption that the vehicle rotates at the time of ground contact about the point of contact. This is a misconception. (See Fig. 7) A seemingly straightforward analysis based on this assumption will lead to error. The non-translating point about which vehicular motion is occurring is correctly used as a reference source only if the equations account for rotational, orbital and translational motion. Additional difficulties arise if this comprehensive approach is taken. The likelihood that no slide would exist at the contact point, i.e. the tangential and translational velocities at the point of contact are equal and opposite, is extremely low. Even if that condition were met, (pavement rim gouges and curb contacts) vehicle suspension dynamics also allow translational and rotational motion of the occupant compartment while the wheel rim is briefly stationary. It is far better to compute centripetal acceleration imposed on an occupant in a rotating vehicle by separately calculating the $r\omega^2$ value about the longitudinal axis of rotation which passes through the vehicle center of mass. Vertical and horizontal translational motions of the center of mass are then obtained from the formulas for ballistic motion. (See Fig. 8)

The effect on occupant motion imposed by a ground impact can be estimated early in the roll sequence when the roll rate is high, the occupant's position in the occupant compartment prior to the impact is fairly well known and the magnitude and direction of the impact force vector has been established with acceptable accuracy. Should occupant contact with the perimeter of the occupant compartment be lost due to vehicle ground impact the occupant's trajectory is purely ballistic. When a rapidly rotating vehicle makes its first significant impact with relatively flat terrain, the contact is typically near the roof/ roof rail on the side opposite the side leading at roll commencement.(See Fig. 9) The dynamics of the impact are influenced by irregularities in the terrain and its surface composition, the vehicle translational and rotational velocities, the vertical fall, friction factors, the vehicle moment of inertia, and the vehicle compliance. A principal factor affecting hazard to the occupant is the orientation of the vehicle at impact. The impact may increase or decrease the roll rate depending on the impact force vector relationship to the CG. The vertical velocity will obviously decrease in response to the terrain impact. The translational velocity will decrease as well (except in the unlikely case where the magnitude of the tangential velocity of the vehicle contact point exceeds that of the translational velocity of the CG). The occupant response to this impact is typically described with respect to the vehicle reference frame wherein the occupant's collision with some part of the vehicle interior is characterized by the magnitude and direction of the impact force.

## OCCUPANT KINEMATICS

The initiation of the roll sequence typically follows a progressive yaw and tire to ground furrowing. The vehicle in this trip scenario will furrow for some distance (3) with peak lateral acceleration occurring just prior to the roll. The trailing side occupant response (unrestrained) during this phase is a tendency toward the leading side. The upper body leads the response as the lower body lags behind due to seat friction and lower extremity drag. (Habberstad, et al, 1986)(7) The trailing side occupant, if unimpeded by bracing or restraint usage, will move toward the leading side during this phase. The model demonstrates for initial roll rates resulting in at least one complete roll that although the trailing side occupant migrates toward the leading side in the trip phase, "recapture" of the occupant against the trailing side and roof occurs later in the first roll. (See Fig. 1) However, once the occupant has been "recaptured" by the trailing side, little movement of the occupant with respect to that recapture location on the vehicle interior will occur as long as the roll rate is sufficient to produce significant centripetal forces.

## CENTRIPETAL ACCELERATION

The concept that an occupant is pulled outward by centrifugal force in a rollover sequence is convenient but fundamentally misleading.(See Fig. 10) The unrestrained occupant travels along a ballistic path determined by the horizontal and vertical launch velocities existent at occupant disengagement from the internal structures in the occupant compartment. The occupant continues on this trajectory until renewed contact with the compartment interior occurs. Constrained by the internal surface of the compartment, centripetal forces imposed by the curvilinear motion of that surface accelerate the occupant toward the vehicle's axis of rotation. The occupant will remain lodged at this last interior contact point until the roll rate diminishes to a level permitting gravity or acceleration produced by external ground contact forces to overcome the centripetal acceleration ($r\omega^2$).

## IMPACT FORCE TRANSIENTS

Vehicle-to-ground impact durations in high speed rollovers are typically very transient, generally in the 80 ms duration range (2). Although wheel impacts may be significantly longer in duration (and hence result in greater impulses), Orlowski, et al found that resultant vehicle CG velocity changes produced by roof structure-ground impacts were normally in the 3 to 4 meters per second range. Average CG acceleration associated with these impacts is approximately 3.9 to 5.2 g. However, the occupant lodged on the opposite perimeter from the impact will develop a significant separation velocity from that perimeter only when the $r\omega^2$ acceleration at the occupant site on the perimeter is exceeded by an opposing ground impact-produced translational acceleration at the CG. Moreover, the impact-related acceleration pulse must exceed the $r\omega^2$ acceleration for sufficient time to produce occupant motion across the center of rotation or the occupant will again move away from the CG toward the perimeter area. The occupant's trajectory then will again result in a rendezvous with the perimeter some distance from the area on the perimeter which received the vehicle-to-ground impact. It may be readily seen that with roof structure impact durations of 80 ms or less the ground impact must be very significant to dislodge occupants on the opposite side of the perimeter who are undergoing centripetal acceleration of 3 to 4g. As an example, let the occupant be lodged in a position against the vehicle's inner periphery across the occupant compartment from the point of ground impact. (See Fig. 11) In order to demonstrate, with a calculation based on physical laws the relationship between centrifugal and translational acceleration during a ground strike, a mathematical model was constructed which provides a graphical display of this relationship.

The event modeled is a ground strike at 330E as shown in Fig. 12. The acceleration pulse affecting an occupant is shown in its components and in combination in Fig. 13. Motion is with positive angular velocity and translation from left to right as viewed. The viewpoint is that of a camera riding with and anchored to the vehicle.

Note in Fig. 12 that the occupant's displacement in response to the acceleration pulse causes separation from the circular periphery, and becomes ballistic for a short time until recaptured by the centripetal reactive force between the occupant and the periphery. Separation is less than one foot. At greater roll rates under these same conditions there would be no separation at all.

Seen from the Earth reference frame, an impact producing a force vector toward the center of rotation from the leading side will flatten the arc being traveled by the area on the periphery opposite the impact. If the impact is of sufficient magnitude the arc becomes less curved than the occupant's ballistic trajectory and contact with the inner periphery is lost. The occupant then follows a ballistic trajectory until contact with the periphery again occurs.

The concept that the dominant acceleration factor in high angular velocity rollovers is $r\omega^2$ has other implications. Huelke (5) wrote that a "variety of force vectors are applied to car occupants with these vectors changing a number of times during very brief periods." Examination of the force vectors imposed on occupants of high speed rollovers indicates, contrary to this statement, that as long as high roll rates are maintained, predominant force vectors exist which maintain the occupant's position within the vehicle despite the imposition of lesser transient forces from ground contact. Opinions are often expressed that flail motions of the occupant's extremities cause unintentional latch release or that slackening of lap belt tension produces webbing retractor unlocking. Clearly, in the phase of the roll sequence that the predominant forces imposed maintain the occupant's position firmly against the internal perimeter of the occupant compartment there is no flail toward the lap belt latch or slackening of the webbing tension. Later in the roll sequence as the roll rate typically diminishes, centripetal forces imposed on occupants correspondingly diminish decreasing the likelihood of late ejection. Ejection of unrestrained occupants in high speed ejections is more likely to be relatively early while centripetal forces are higher. Very late ejections, should they occur, will be at lower speed with respect to terrain and imply some impediment to earlier ejection. Large excursions of occupants within the occupant compartment typically do not occur until late in a high-speed roll sequence.

## REFERENCE FRAME SELECTION

A common error in predicting occupant kinematics occurs due to reference frame selection. If the motion of an ATD in a rolling vehicle is recorded by on board cinematography the ATD motion is being viewed with respect to the vehicle reference frame. It must be recognized that such a selection will produce a perspective which requires the invention of fictitious forces to explain changes in motion of the ATD. Whenever the reference frame chosen is accelerating or rotating (or both) the apparent motions viewed will differ from motions viewed from a fixed reference frame (Earth). Viewed from a rotating reference frame, the linear path of an object will appear curvilinear. The perspective from an accelerating reference frame will cause an object to appear to be sustaining an acceleration in the opposite direction. The commonly cited beliefs that roof crush in rollovers is causally linked to head and neck injuries and that an occupant's head moves rearward when the vehicle is rear-ended are recurring examples of reference frame errors.

## EJECTION

A consequence of an occupant's migration to a location on the inner perimeter of the occupant compartment (typically the area above the belt line and the roof structure), is ejection. (See Fig. 11) As the roll sequence progresses, ground impacts to the upper structures of the vehicle deform the window and sun roof frames and fracture the glazing. The persistent force imposed by the occupant on these areas promotes extrusion of the occupant's body through a portal which, when closed, would have provided a centripetal force against the occupant. Indeed the relative outward force imposed by the occupant's mass may create such a portal. Ejection early in the roll sequence may produce high energy impacts between the ejectee and the ground. Partial ejection at any point in the roll sequence potentially allows the ejectee to sustain significant mechanical injuries. It must be remembered that at the point of separation the occupant's trajectory is tangential to the rotating vehicle, not radial. The force imposed on the ejectee in the partially ejected state comes from the trailing edge of the ejection portal.(See Fig. 14) Thus, the abrasion marks left by the occupant's passage are typically found on the sill of the ejection portal on the trailing side and on the upper frame of the portal on the leading side. Occupants ejected through a relatively small portal such as a door window may have that passage retarded at a partial ejection stage by entanglement with other occupants, steering wheel or portal irregularities. At that point, with the upper body outside of the vehicle, the ejectee's spine will tend to align with the rotational radius of the vehicle at constant rotation rate. The ejectee's head (assuming a head first exit) will acquire a radius of rotation that may be nearly twice that which it had while in the vehicle. The tangential velocity of the head at that point would also be proportionately greater. If a head strike with the ground were to occur at that stage (more likely in view of the partial ejectee's projection) the enhanced head impact velocity would add to the family of unpleasantries already associated with ejection.

## FORCE-GRADIENT CONSIDERATIONS

The forces imposed on the unrestrained occupant by the inner surface of the rotating occupant compartment vary linearly with the distance of body parts from the axis of rotation. If the occupant's head is located, say, three feet from the rotational axis, the pelvis may be only a foot from the axis. Thus, the centripetal force necessary to maintain the occupant's body along its arcing path is greater per unit mass for the parts of the occupant's body farthest from the rotational axis. Indeed, it is possible that the occupant's legs may be "below" the CG and are being "pulled" with an oppositely directed vertical component (with respect to the vehicle) from that of the torso and head. The occupant whose pelvis is coupled to the seat by a lap belt will tend to extend during the roll with straightening of the spine in response to this force gradient. The alignment of the spine will tend to be along a radial except for variation imposed by other structural contact forces. This may predispose to axial compression spinal injuries in certain impact instances. (Bahling, et al 1990)(8) For the unrestrained occupant the centripetal force imposed by the occupant compartment interior will tend to impinge firstly on the head and shoulders. As those parts of the occupant's body which are not in contact with the compartment interior migrate toward the compartment envelope, the occupant takes a position against that envelope which tends to align the torso and extremities parallel with the perimeter interior surface. Of course these motions will be disrupted and retarded to some extent by occupant interaction with other elements, i.e. seats, steering wheel, and other occupants.

## CERVICAL INJURY POTENTIAL

The trailing side occupant has been described as the person at greatest risk of injury.(1) As the roll commences the trailing side occupant travels the greater distance (longer arc) than the leading side occupant for the first half of the roll. At the completion of the first half roll, the trailing side occupant is traveling at a greater velocity toward the ground than the leading side occupant and is approaching the ground inverted. (See Fig. 15) The opportunity for upper spinal injury is apparent. The leading side occupant has opportunity for a higher velocity approach to the ground in a more upright position. The force of impact at this stage of the roll will be borne by the leading side occupant more through the buttocks, which is a better tolerated impact direction.

It should be appreciated that various parts of the occupant's body are subjected to different centripetal acceleration magnitudes (force-gradient phenomena) but also experience resultant velocities which act in different directions (see Fig. 16). Thus, although the whole body center of mass may be traveling in a relatively vertical direction at the time of vehicle/ground impact, the head and neck will have progressed in the arc of travel such that the cervical spine has rotated into a more horizontal direction. In this scenario the cervical spine is less likely to be subjected to injurious axial loading. The distributed load event is clearly not analogous to a vertical drop scenario.

## COMMENTS

The simple model employed in this analysis of high-speed rollover dynamics is useful to the understanding of occupant kinematics in early segments of the roll sequence where entry conditions can be ascertained with acceptable accuracy. Further refinement of this model incorporating more precise mass properties of the vehicle and occupant morphology remains to be done. It is expected that such improvements will produce a model which will aid in the prediction of gross occupant motion including ejections.

As any analyst who has attempted to duplicate the high-speed rollover event by staged tests knows, seemingly trivial variations in terrain, vehicle stiffness, and trip condition characteristics can produce surprisingly different vehicle roll dynamics as the roll sequence progresses. The possibilities of additive, subtractive or nullifying effects multiply with the number of vehicle/ground interactions making precise predictions regarding the roll sequence and the resultant motion of the occupants difficult. Several principles are helpful to the analysis, however. Kinetic energy from the translational velocity of the vehicle is variously transformed into angular kinetic energy and vehicle deformation during the roll sequence. Accident site evidence of pavement rim gouges and off-pavement wheel furrowing provides additional data. Ground contact marks, vehicle abrasions and excoriation patterns, vehicle rest position and ejectee rest positions provide additional clues which may be useful. Tentative conclusions regarding occupant kinematics may then be achievable. Refinement of the understanding of occupant motion may be obtained from witness marks within the vehicle, around portals of ejection and on the vehicle exterior. Lastly, examination of medical findings, i.e. road rash, foreign bodies in tissues, and the characteristics of the mechanical injuries of occupants may provide sufficient evidence to establish specific injury mechanisms imposed by the rollover events.

## CONCLUSIONS

- The subject model is a useful aid to demonstrate fundamentals of occupant kinematics in rollover accidents.
- Proper selection of reference frame facilitates the analysis of occupant motion.
- Occupant motion tendencies in high speed rollovers can at least be generally described, particularly early in the rollover sequence with known entry conditions.
- The variety of forces imposed on occupants is, for most high roll rates, dominated by centripetal dynamics.

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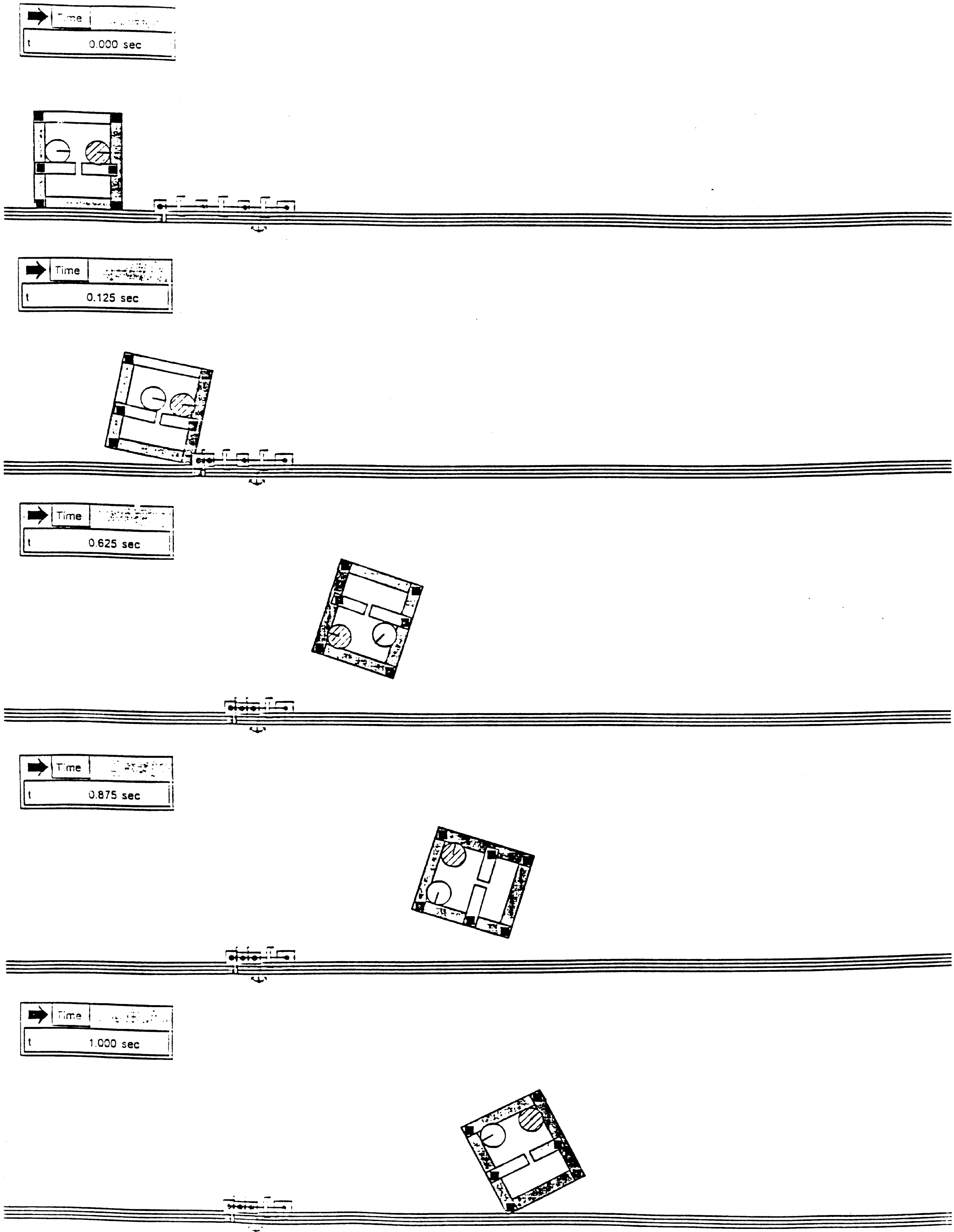

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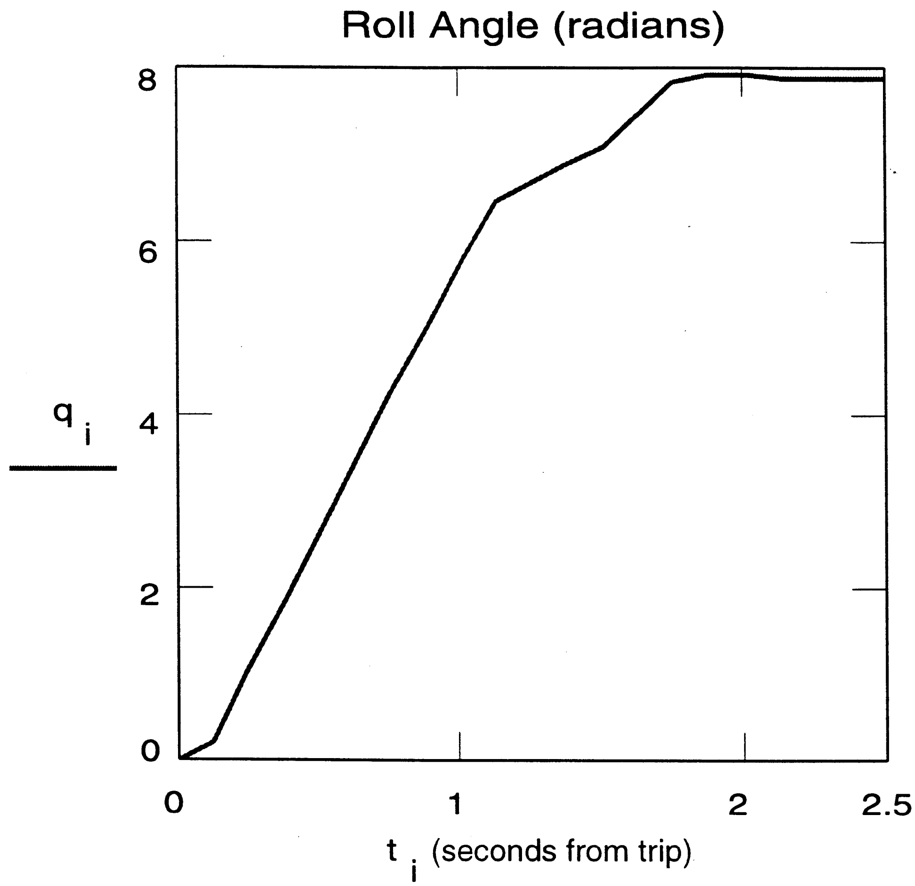
Time
t 0.125 sec
Time
t 0.625 sec
Time
t 0.875 sec
Time
t 1.000 sec


Figure 1.



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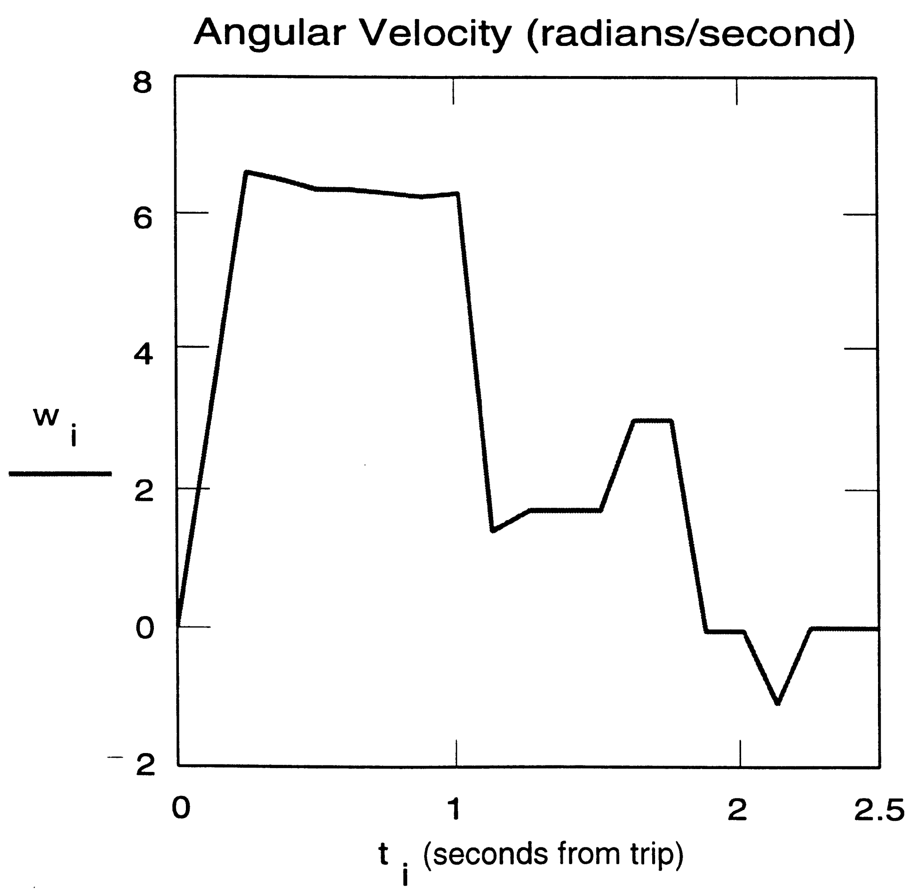
6
4
2
0
$q_i$
0
1
2
2.5
$t_i$ (seconds from trip)

Angular Velocity (radians/second)
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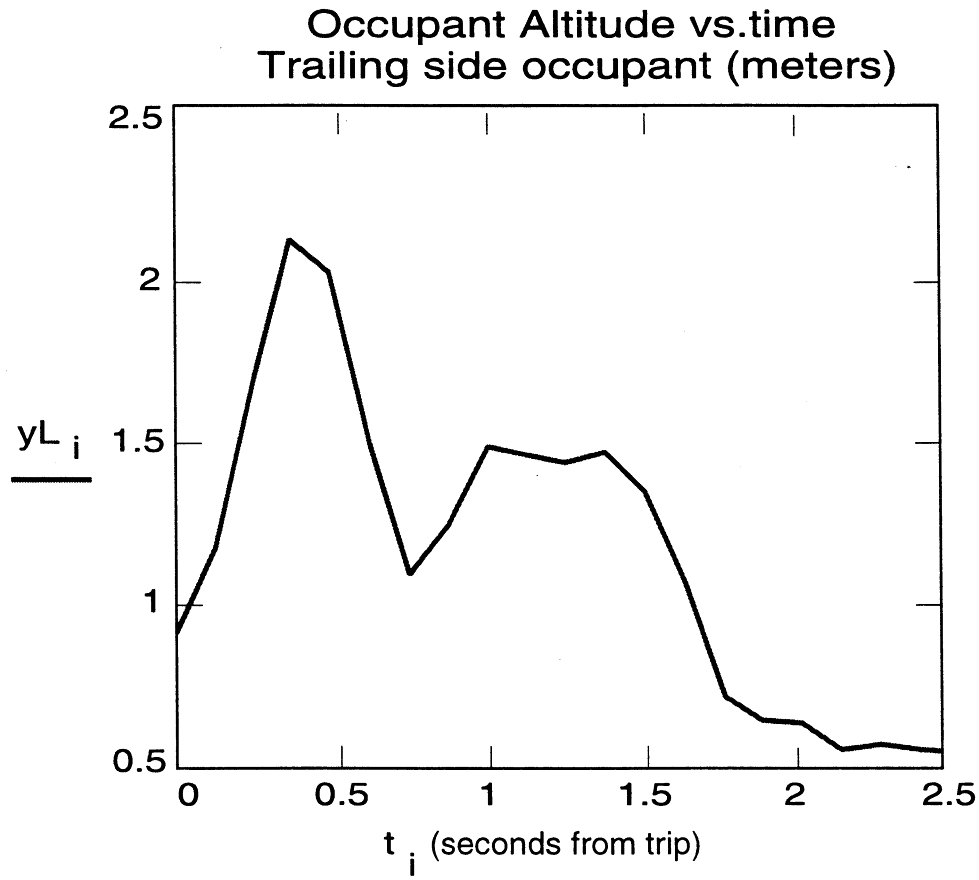
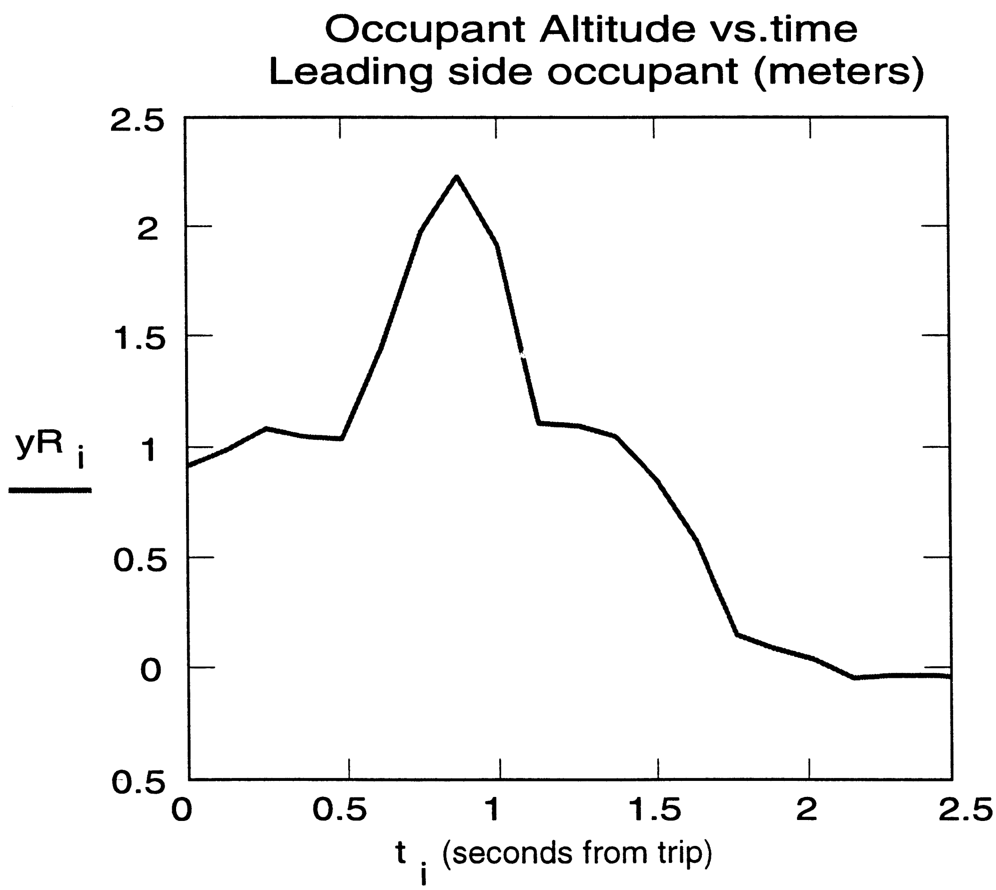
6
4
2
0
− 2
$w_i$
0
1
2
2.5
$t_i$ (seconds from trip)


Figure 2.

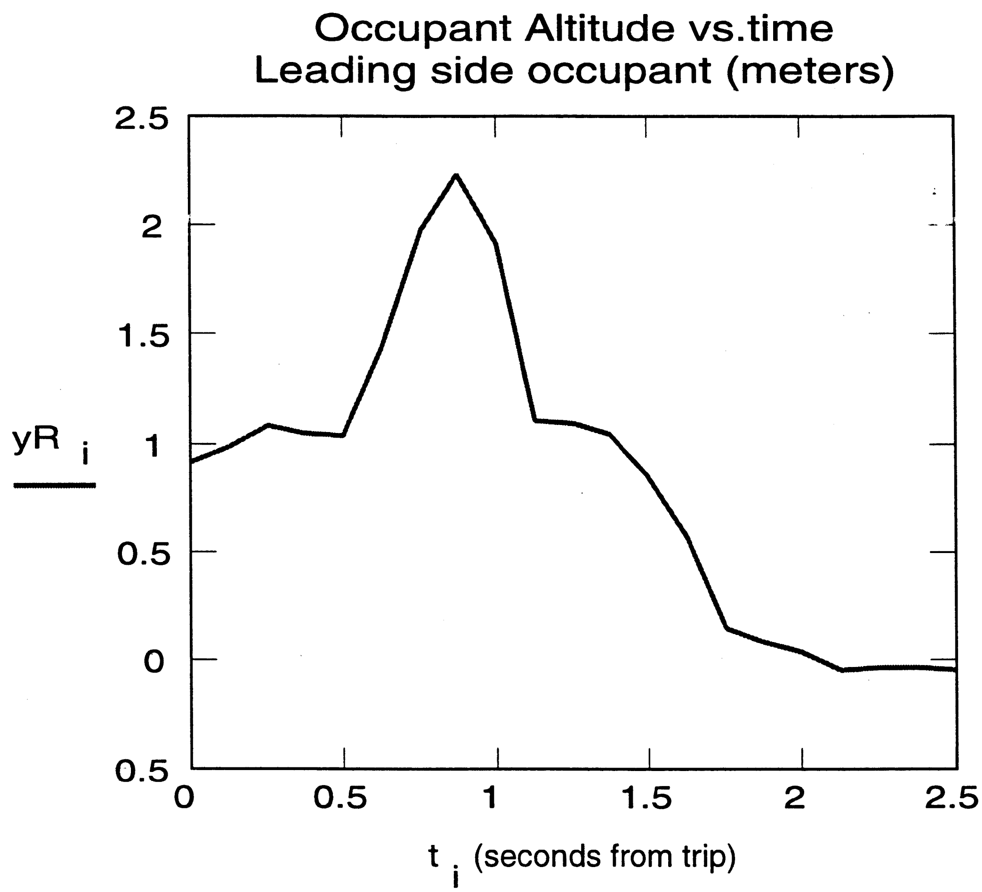


Occupant Altitude vs.time
Trailing side occupant (meters)
2.5
2
1.5
1
0.5
yL i
0
0.5
1
1.5
2
2.5
t i (seconds from trip)

Occupant Altitude vs.time
Leading side occupant (meters)
2.5
2
1.5
1
0.5
0
0.5
yR i
0
0.5
1
1.5
2
2.5
t i (seconds from trip)


Figure 3.


Occupant Altitude vs.time
Leading side occupant (meters)
2.5
2
1.5
1
0.5
0
0.5
yR i
0
0.5
1
1.5
2
2.5
t i (seconds from trip)

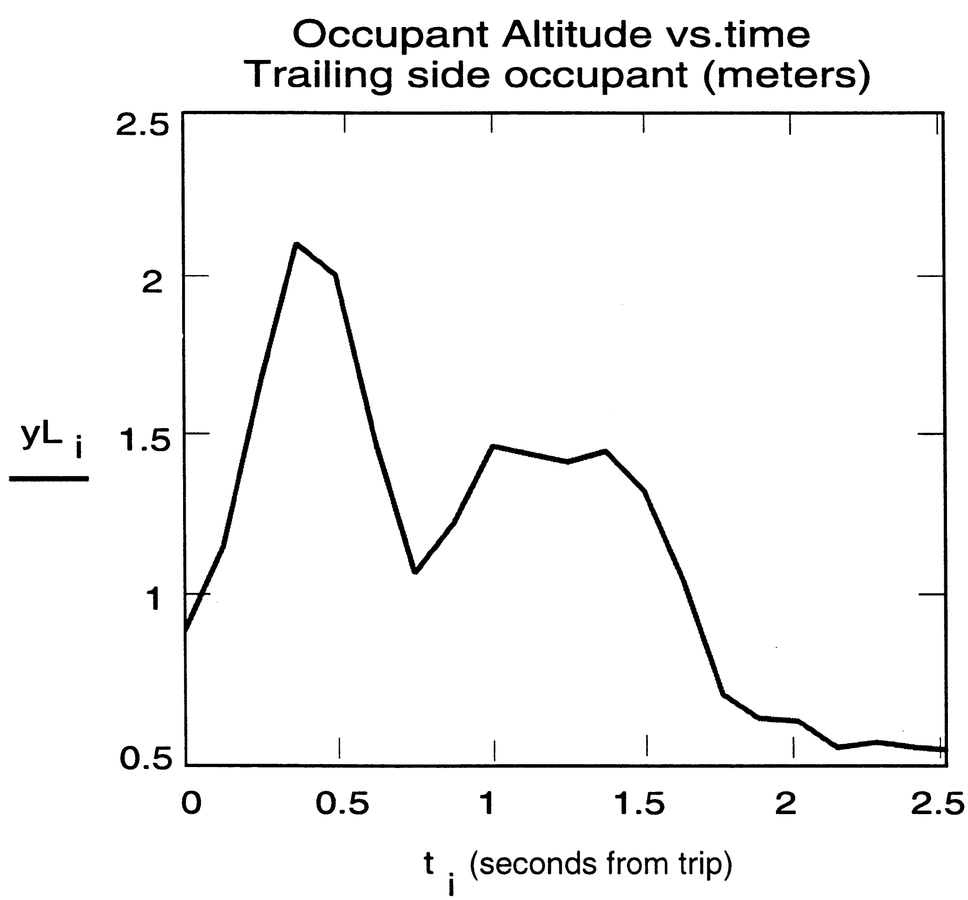

Occupant Altitude vs.time
Trailing side occupant (meters)
2.5
2
1.5
1
0.5
yL i
0
0.5
1
1.5
2
2.5
t i (seconds from trip)

Figure 4.

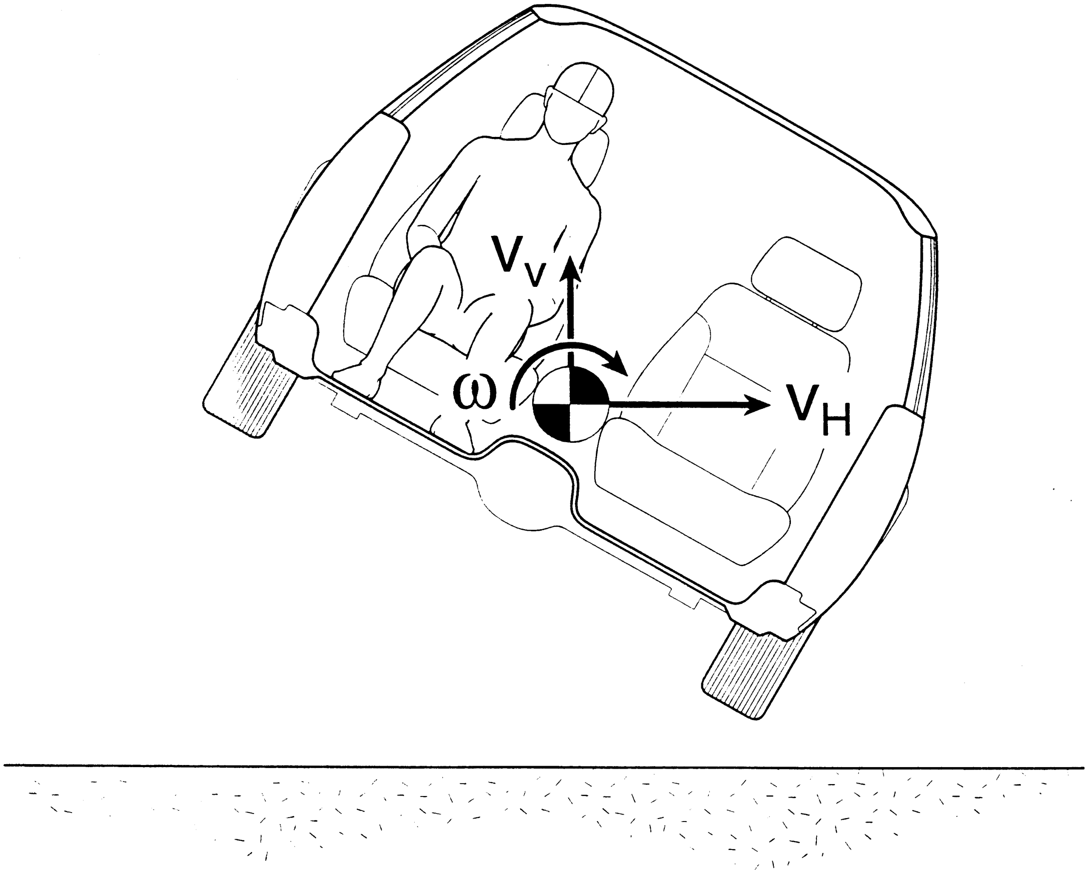



Figure 5.

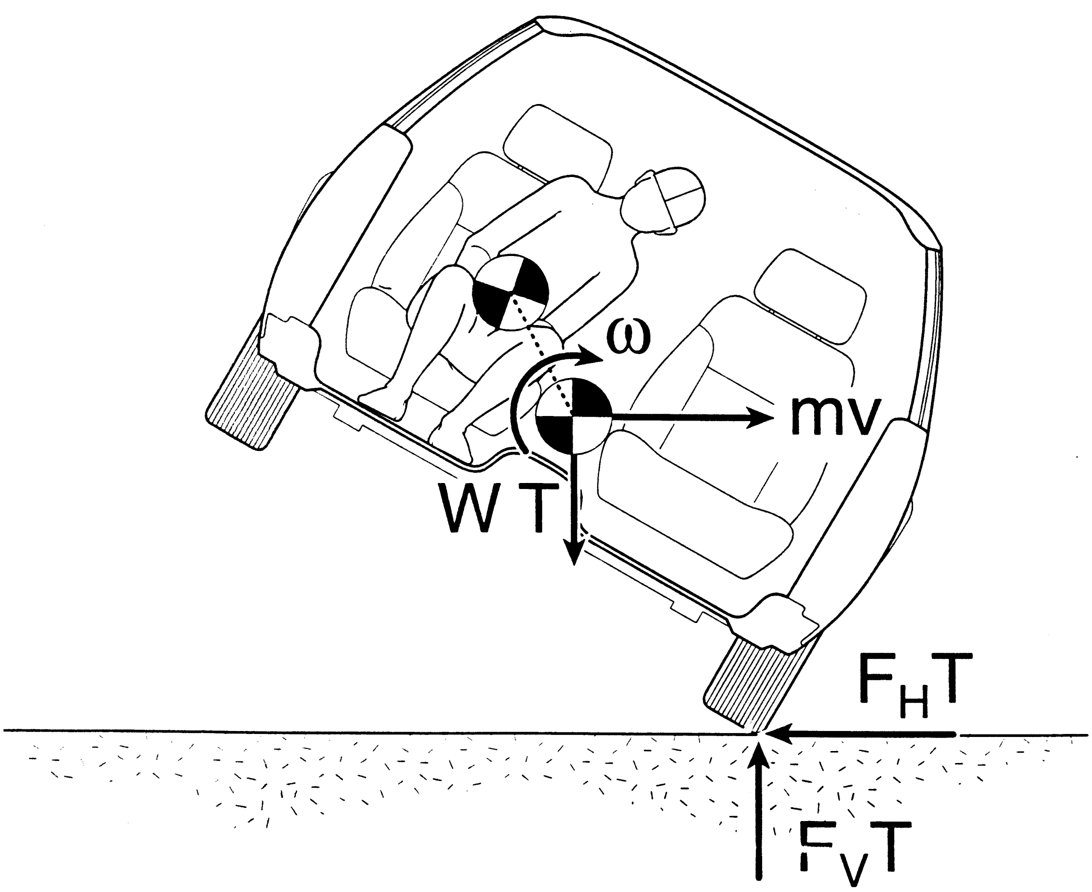



Figure 6.

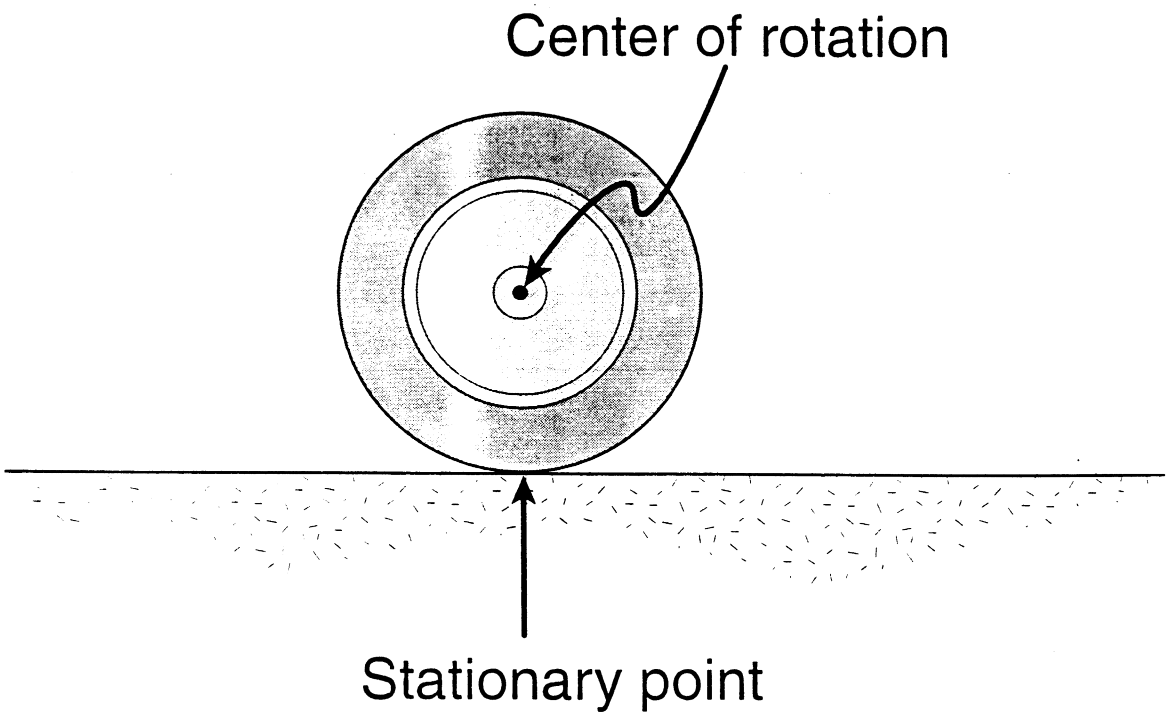



Figure 7.

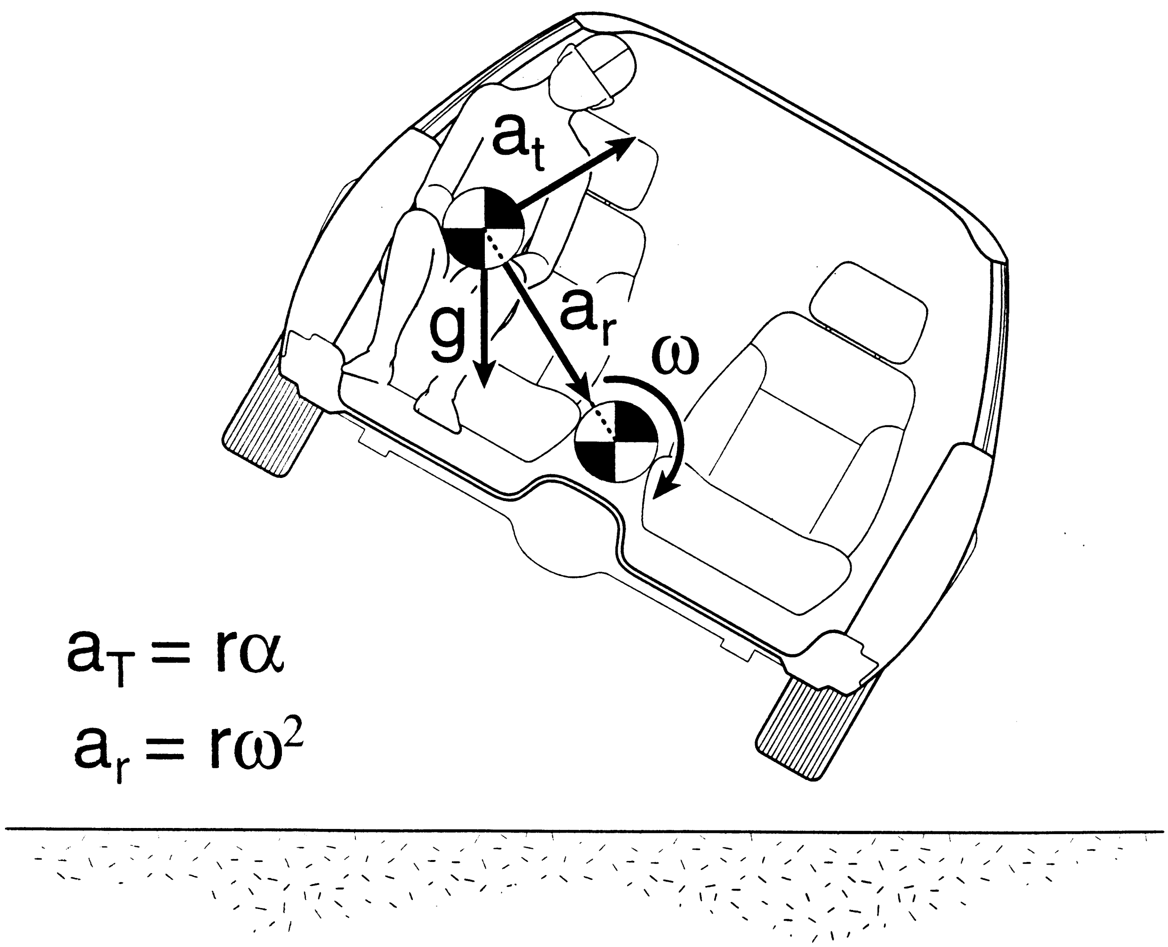



Figure 8.

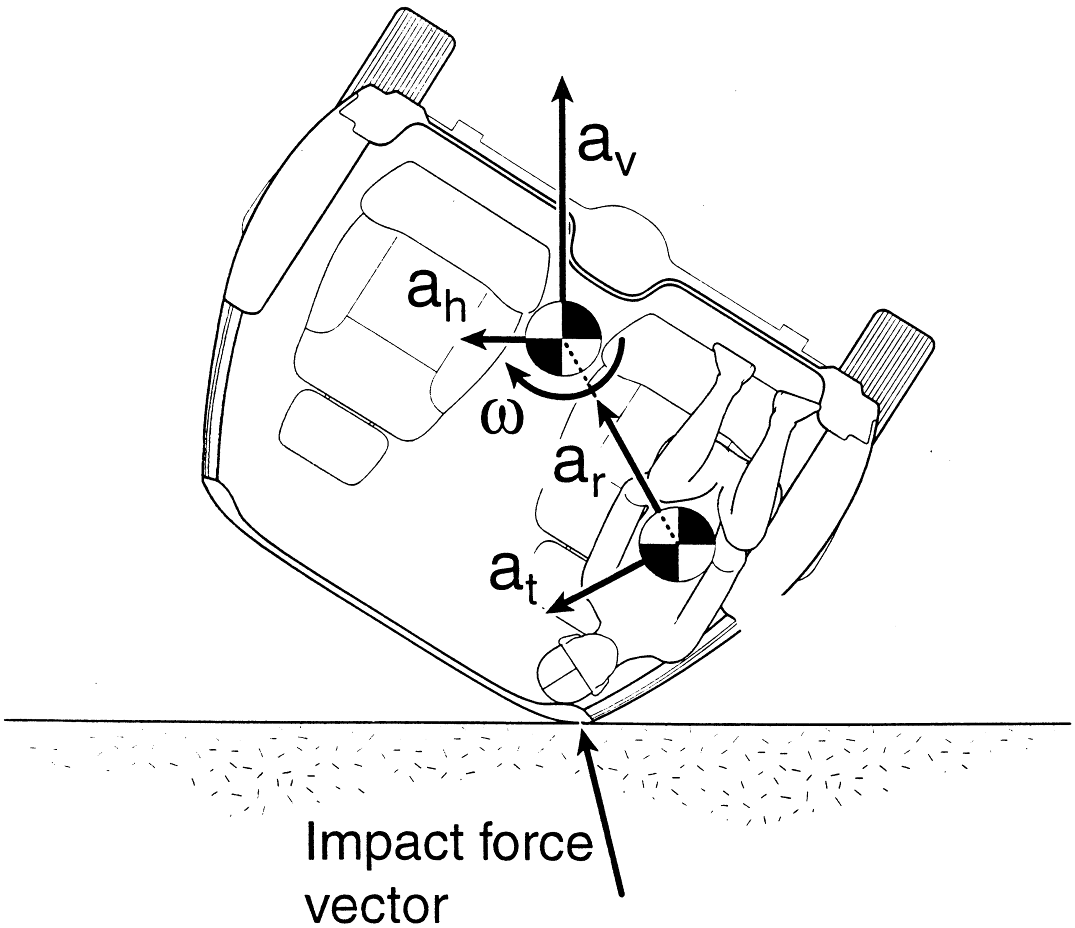



Figure 9.

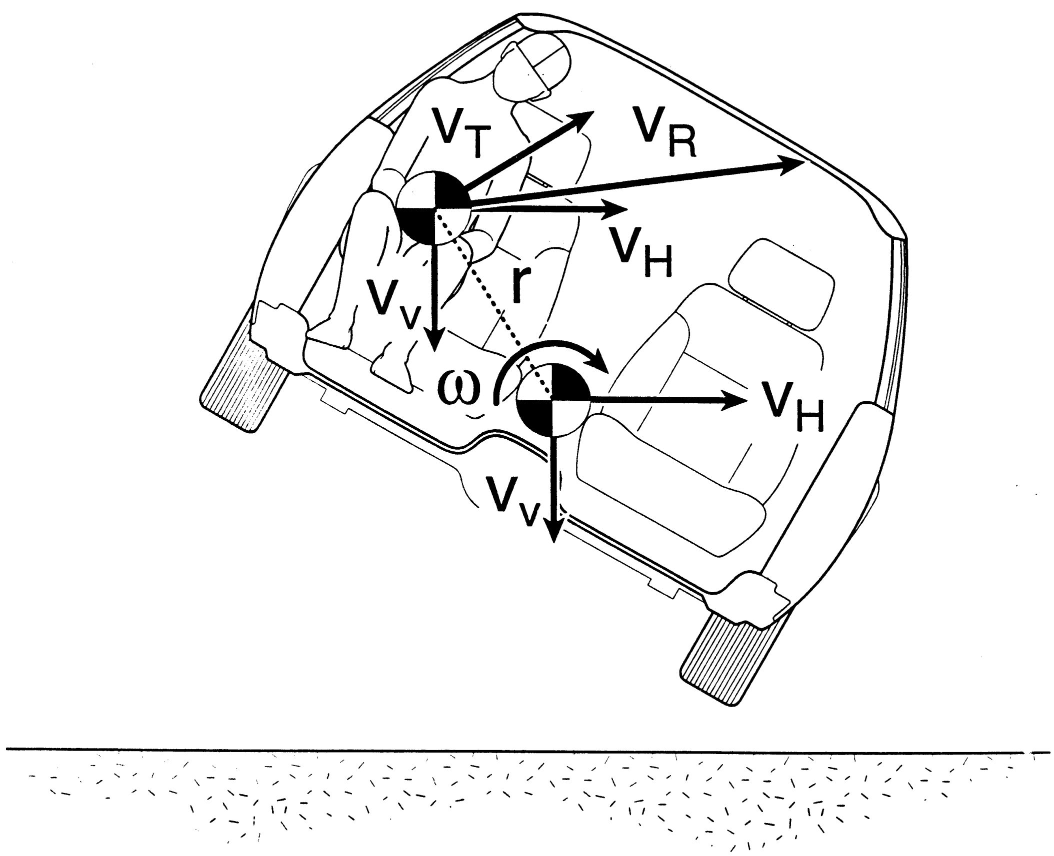



Figure 10.

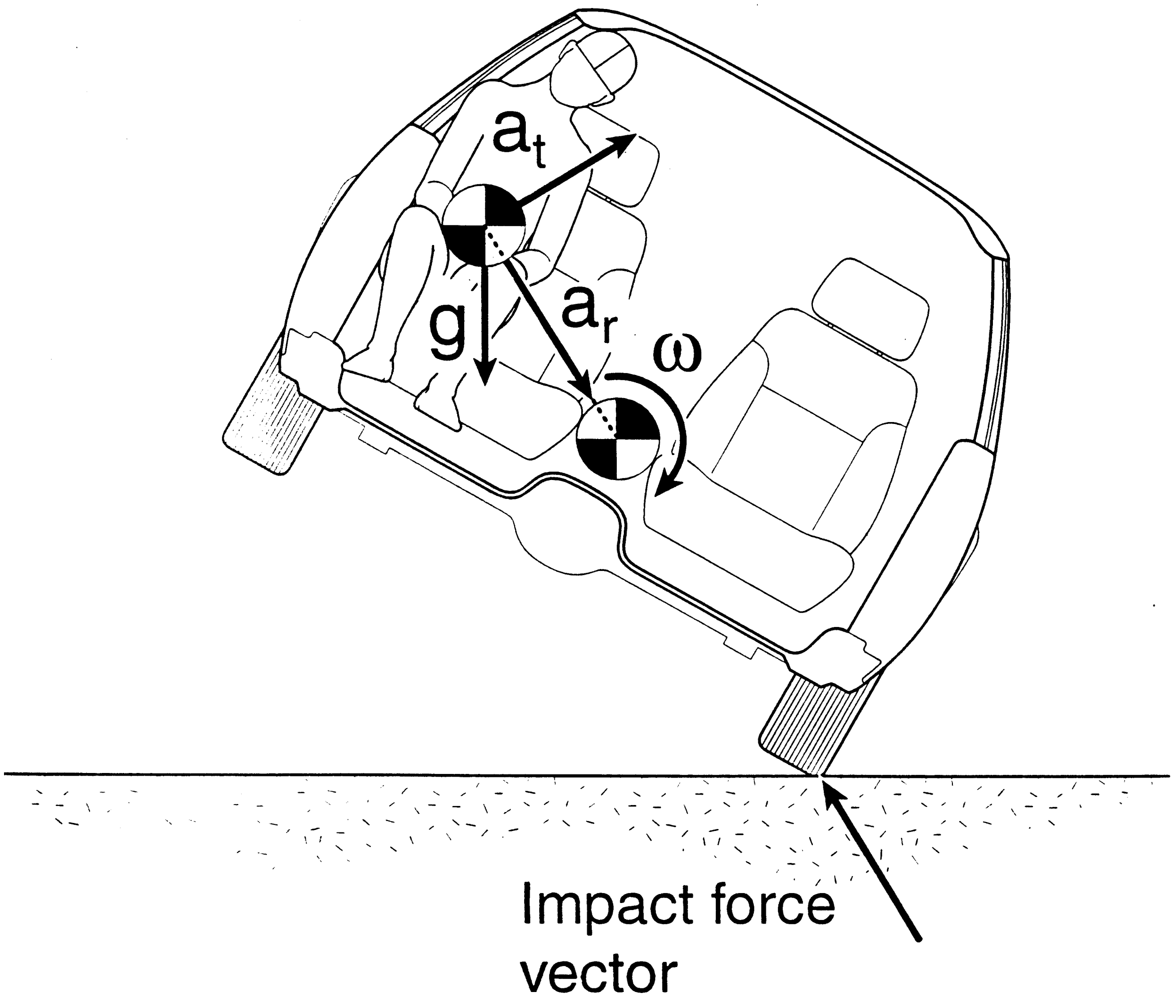



Figure 11.

Occupant displacement with a 3g ground impact at 330 degrees. Impact duration is 80 ms and is sinusoidal in shape. Viewpoint is vehicle frame, not inertial frame.

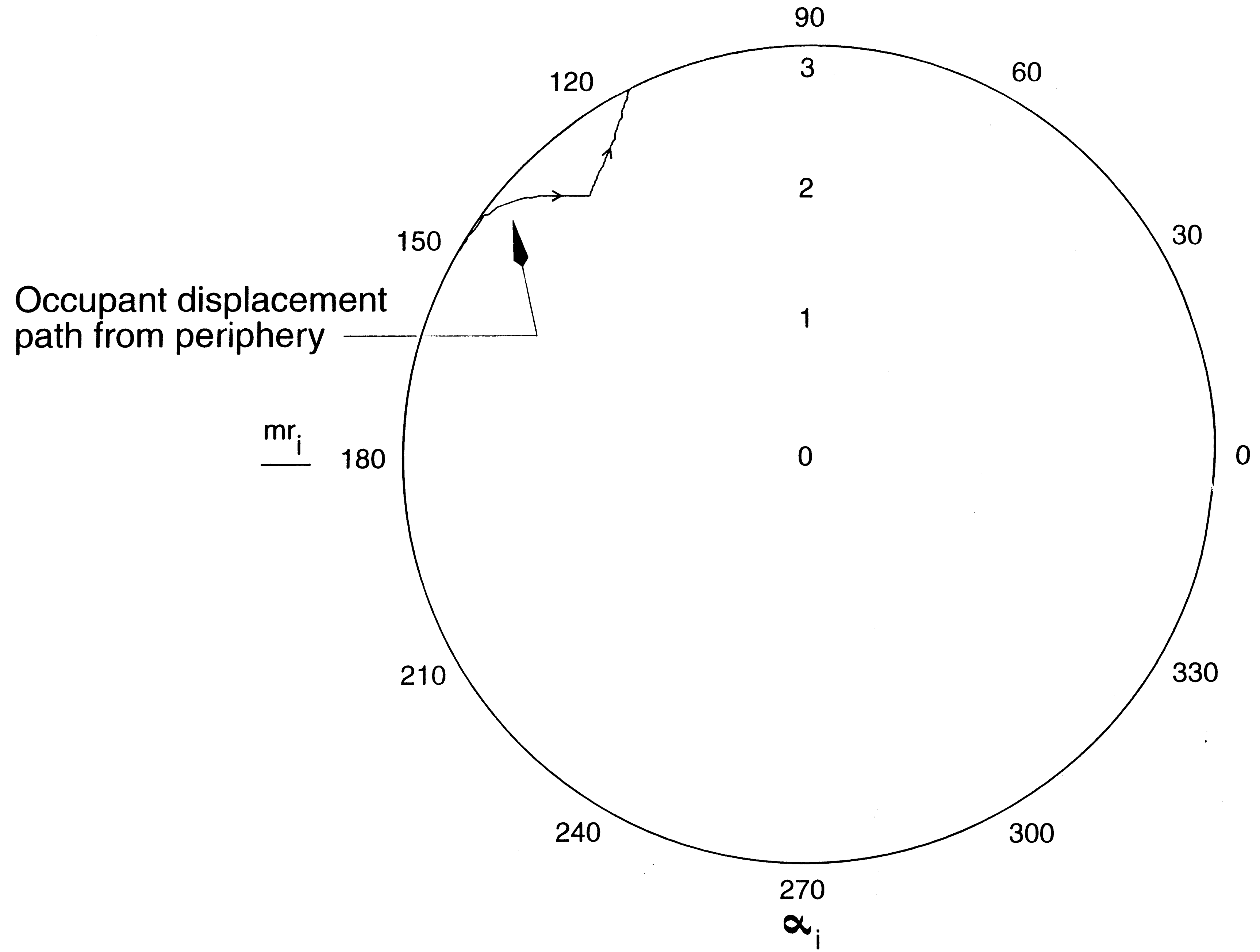
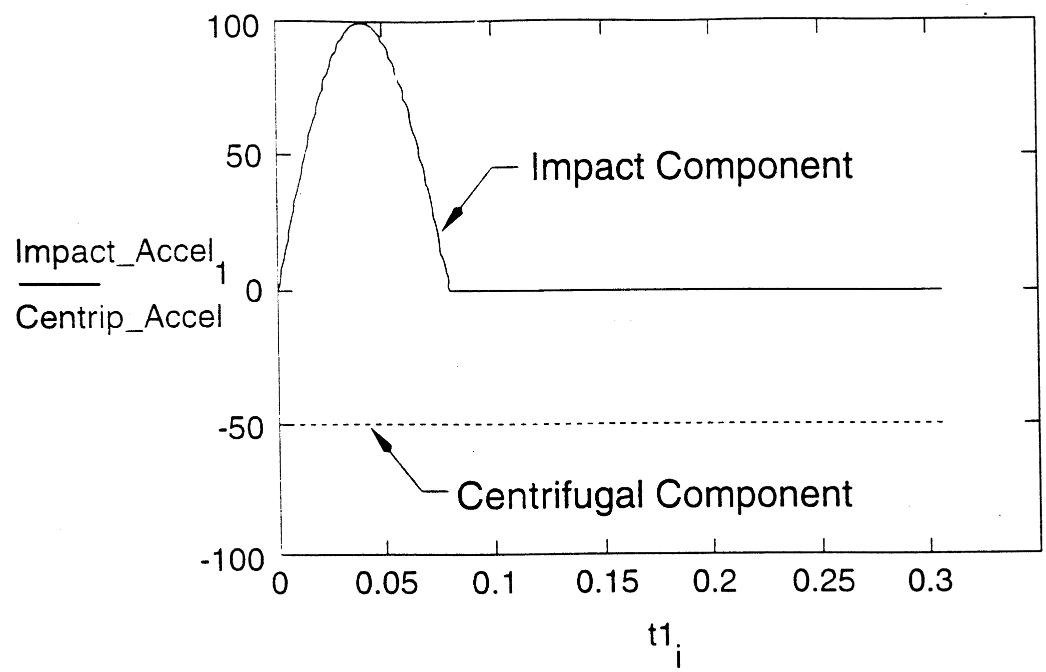



Figure 12.

Impact and centrifugal acceleration components in f/s^2




Combined Impact and centrifugal acceleration components in f/s^2

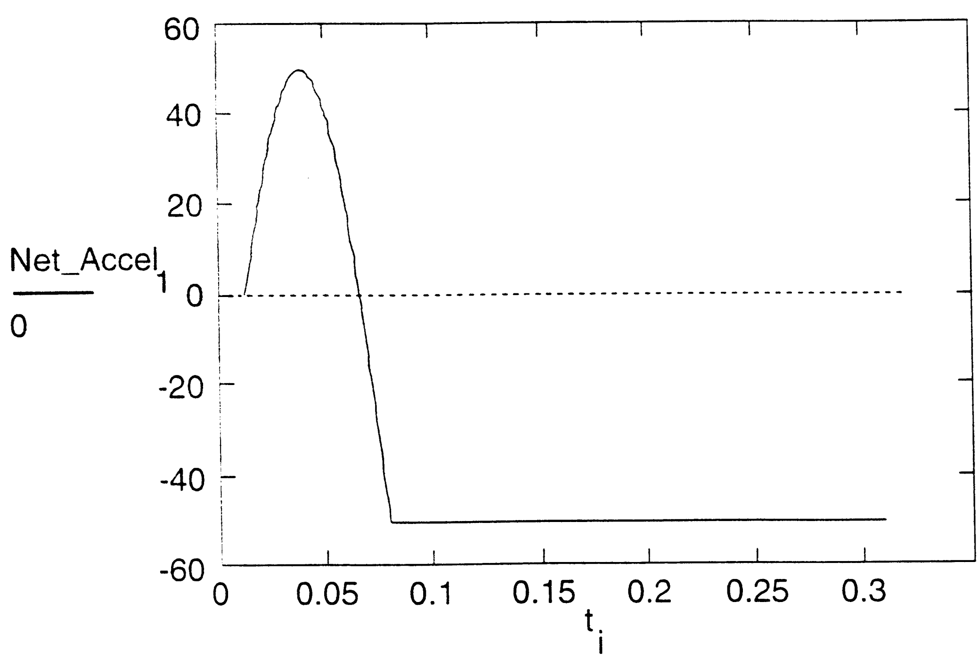



Figure 13.

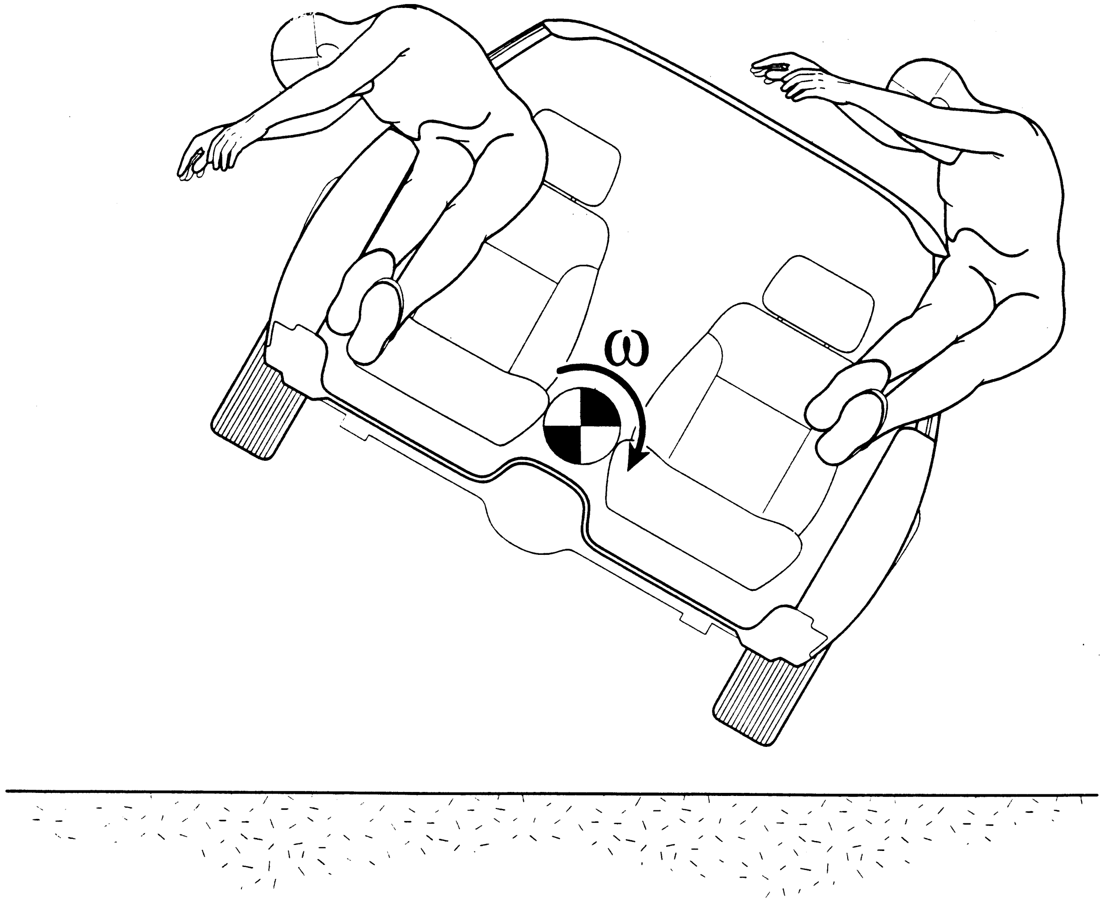



Figure 14.

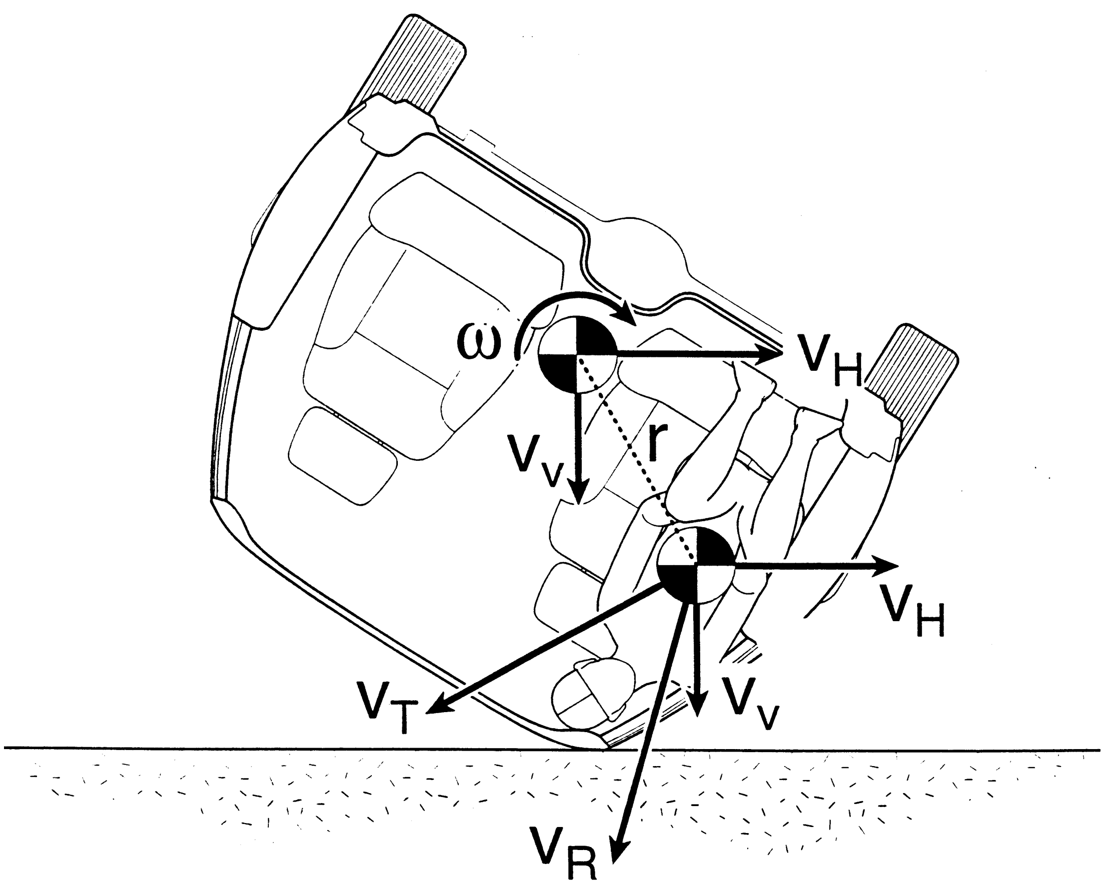



Figure 15.

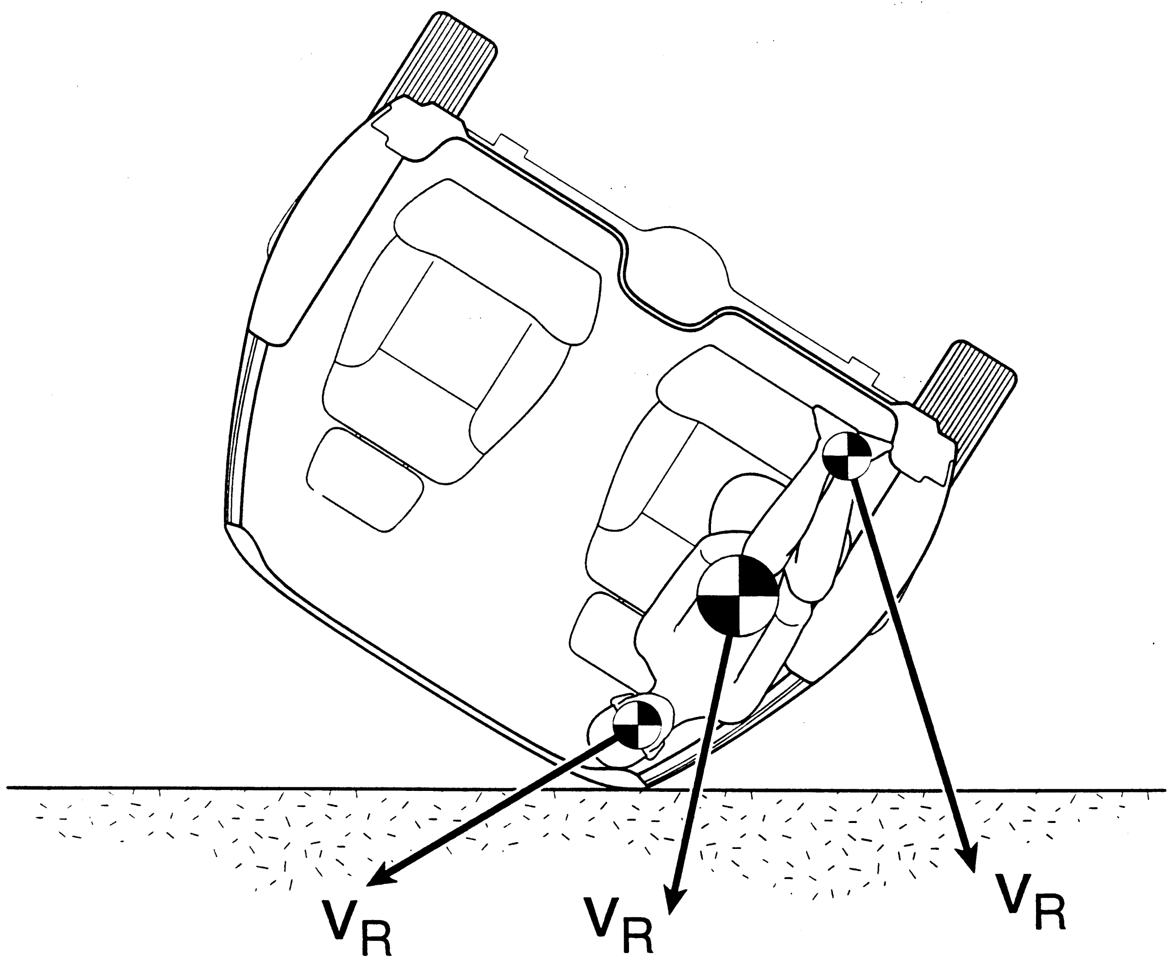



Figure 16.