

Occupant Ejection Trajectories in Rollover Crashes: Full-Scale Testing and Real World Cases

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ABSTRACT

A simple two-dimensional particle model was previously developed to calculate occupant ejection trajectories in rollover crashes. Model parameters were optimized using data from a dolly rollover test of a 1998 Ford Expedition in which five unbelted anthropomorphic test devices (ATDs) were completely ejected. In the present study, the model was further validated against a dolly rollover test of a 2004 Volvo XC90 in which three unbelted ATDs were completely ejected. The findings from the experimental testing were then compared to two real world rollover crashes with occupant ejections that were captured on video. The crashes were reconstructed by analyzing the video footage and aerial images of the crash sites. In both cases, the model was able to accurately match the observed trajectories of the ejected occupants, and the optimized model parameters were similar to the values obtained from the dolly rollover testing. The model was demonstrated to be a robust method for investigating a wide variety of possible ejection scenarios that can occur in rollover crashes.

INTRODUCTION

Occupant ejection in rollover crashes is a major source of motor vehicle-related casualties. A query of the Fatality Analysis Reporting System (FARS) database reveals that 7,128 completely ejected occupants died in motor vehicle crashes in the U.S. in 2005. 4,606 of these fatal ejections occurred in rollover crashes, which accounts for half of the 9,216 fatalities that occurred in crashes in which rollover was the most harmful event. Unbelted occupants are at a high risk of being ejected from the vehicle in a rollover crash. The risk of ejection for an unbelted occupant is less than 20% for rollovers involving less than one roll, but increases to over 80% for rollovers involving three or more rolls [1-2]. Regardless of the number of rolls, the risk of serious to fatal (AIS 3+)

injury to an occupant ejected in a rollover crash is just over 40% [2].

When analyzing rollover cases, crash investigators are often asked to determine likely occupant ejection scenarios. This task requires determining the ejection portal, the point in the rollover sequence when the ejection occurred, the airborne trajectory, the landing point, and the distance that the occupant slid and tumbled to rest. Physical evidence can establish the portal through which the occupant was ejected. Ejected occupants will frequently leave exit marks, such as a bend in the window frame, scuffs or abrasions (often with a feather edge pointing outboard), fabric marks, polishing, or deposits of hair or clothing fibers. Once the ejection portal is determined, a mathematical model can be used to calculate the airborne trajectory, landing point, and rest position of an occupant ejected at any given point in a rollover crash. Funk and Luepke [3] developed a simple model based on equations of motion for a particle. The model was two-dimensional and neglected the effects of vehicle pitch, yaw, and vertical motion. The occupant's launch velocity vector at the point of ejection was defined as the vector sum of the translational velocity of the center of gravity of the vehicle and the tangential velocity of the occupant at the vehicle perimeter. The airborne path and landing point of the ejected occupant were then calculated using ballistic trajectory equations. The horizontal speed loss upon landing and the subsequent sliding distance to rest were calculated assuming a constant coefficient of friction between the occupant and the ground. Mathematically possible ejection scenarios were determined by calculating ejection trajectories at all roll angles (in 1 ms increments) and matching the predicted rest position to the actual rest position of the occupant. It is then up to the crash investigator to evaluate which of the possible ejection scenarios are most likely based on other considerations such as the timing of glass breakage, occupant injury pattern, etc.

The occupant ejection model described above was validated against a dolly rollover test of a 1998 Ford Expedition in which five unbelted ATDs were completely ejected. Using optimized parameters, the model was able to predict the trajectories of each of the ejected ATDs with great accuracy [3]. However, the model was only validated against a single crash test, and its application to real world rollovers was not demonstrated directly. The purpose of the present study was to compare occupant ejection trajectories in rollover crash tests and real world rollover crashes. To this end, the model was validated against an additional dolly rollover test and two real world rollover crashes.

METHODS

VOLVO XC90 DOLLY ROLLOVER TEST

A dolly rollover test of a 2004 Volvo XC90 was conducted by Exponent Failure Analysis Associates and described by Luepke et al. [4]. The tempered glass in the side door windows was removed and replaced with laminated glass. The roll sensor and canopies were disabled. The vehicle was instrumented with angular rate sensors about the roll and yaw axes. Four (4) Hybrid II 50th percentile male ATDs were seated in the vehicle in the left and right outboard seating positions of the first and second row seats. Their seating positions were designated by row and side (i.e., 1L, 1R, 2L, and 2R). None of the ATDs were restrained. The vehicle was placed in an FMVSS 208 rollover dolly in a driver's side leading configuration. The speed of the dolly was 42.9 mph at contact with the snubber tubes, which decelerated the dolly and initiated the rollover. The vehicle traveled approximately 115 feet over packed soil and completed four and one quarter (4 ¼) rolls, coming to rest on its left side. Three of the ATDs were completely ejected. The crash was captured with high speed digital video (250 Hz frame rate) from several on-board and off-board cameras. Post-crash scene evidence, including the rest positions of the ATDs, was measured and photographed. The portals through which the ATDs were ejected were closely inspected. Exit marks were identified and photographed in both the subject 2004 Volvo XC90 and the 1998 Ford Expedition that was the subject vehicle in a similar dolly rollover test analyzed previously [3-4].

A detailed reconstruction of the Volvo dolly rollover test was performed [4]. The time history of the translational velocity of the center of gravity of the vehicle was calculated based on the location of physical evidence and analysis of the high speed video data. Time histories for roll angle and roll rate were calculated from video analysis and the roll rate sensor data. Times and positions reported in the present study have been shifted from the data presented by Luepke et al. [4] so that the zero point corresponds to the end of the initial tire marks. Luepke et al. [4] used the end of the snubber tubes as their zero reference, rather than the end of the tire marks.

REAL WORLD ROLLOVER CRASHES

Two real world rollover crashes in which the drivers were ejected were reconstructed using video footage of the events. Both crashes were previously studied by Rose et al. [5], who referred to the Lincoln Navigator rollover as Case #2 and the GMC Yukon Denali rollover as Case #3. Rose et al. [5] determined vehicle roll rates using video analysis. To summarize their methodology, each rollover was divided into quarter or half roll increments in which frames with known roll angles could be identified on video. The average roll rate in each increment was calculated by dividing the change in roll angle by the change in time as determined from counting the number of frames on the 30 Hz videos. A cubic spline was fit through the average values in order to define a complete roll rate vs. time curve. In the present study, a similar methodology was used to create translational vehicle velocity vs. time curves. Occupant ejection trajectories were also determined from video analysis.

Lincoln Navigator Rollover

According to news reports, this rollover crash occurred on April 3, 2002 during a police chase [6]. The entire rollover event was captured on video from a helicopter [7]. A red Lincoln Navigator was attempting to enter westbound I-285 from the North Fulton Expressway north of Atlanta, Georgia when it clipped another vehicle, entered a counterclockwise yaw, began rolling over on the roadway, and struck a median barrier. The driver, reportedly the only occupant in the vehicle, was ejected and thrown over the median barrier.

The translational velocity of the vehicle and distances in which the occupant was airborne and sliding were determined through analyzing frames captured from the video. Individual frames were rectified using PC-Rect software [8]. The frames were then overlaid on an aerial image of the crash site [9]. The image was scaled using lane widths and lane line spacing and a scene diagram was created from which distances could be measured.

GMC Yukon Denali Rollover

According to news reports, this rollover crash occurred on February 25, 2005 during a police chase [10]. The entire rollover event was captured on video from a news helicopter [11]. A white GMC Yukon Denali was traveling eastbound on I-270 in St. Louis, Missouri at speeds in excess of 100 mph. The vehicle went off the road, partially jumped an underpass, then entered a grassy area. The vehicle began yawing counterclockwise, then rolled over multiple times, ejecting the driver, who was reportedly the only occupant in the vehicle.

The location of the crash site was determined based on information from news reports [10] as well as audio and visual information from the video [11]. An aerial image of the crash site was obtained [9], and a scene diagram was created and scaled using lane widths and lane line spacing. For some portions of the event, measurable

road markings were not visible in the video, so the position of the vehicle had to be determined at points when the vehicle passed a signpost or other landmarks that were visible in both the video and the aerial image.

MODEL PARAMETER OPTIMIZATION

The methodology for optimizing the parameter values in the occupant ejection model was described in detail in Funk and Luepke [3]. To summarize, there are two parameters in the occupant ejection model that can be optimized based on a detailed rollover crash reconstruction and a trajectory analysis of the ejected occupant: the effective launch radius (r) and the sliding coefficient of friction between the occupant and the ground (μ_{slide}). The launch velocity vector was defined in the model as the vector sum of the translational velocity of the center of gravity of the vehicle and the tangential velocity of the occupant at the perimeter of the vehicle. The tangential velocity of the occupant was defined by the vehicle roll rate (ω) multiplied by the effective launch radius (r). The model then calculated the ballistic trajectory of the ejected occupant assuming a “slingshot release.” The original model neglected the effect of vertical velocity of the vehicle on the trajectory of the ejected occupant. However, the model can easily be refined to calculate the vertical launch velocity (v_{z_launch}), taking into account the vertical vehicle velocity (v_{z_cg}):

$$v_{z_launch} = v_{z_cg} + \omega r \cos(\theta + \phi) \quad (1)$$

where θ is the roll angle of the vehicle and ϕ is the ejection portal angle. Eq. (1) above would replace eq. (12) in the original model [3]. The vertical velocity of the vehicle (v_{z_cg}) was not determined for any of the rollovers studied, but its potential effect on the value of the optimized launch radius (r) was considered theoretically.

The effective launch radius (r) was optimized to match the observed airborne trajectory of the ejected occupant. Because of the interrelationships between various model parameters, the value for the effective launch radius (r) had to be optimized in an iterative fashion until the airborne trajectory predicted by the model matched the actual airborne trajectory with minimal error in terms of the time in the air and the distance thrown. The sliding coefficient of friction between the occupant and the ground (μ_{slide}) was then calculated to match the distance that the occupant slid and tumbled to rest after landing, taking into account the horizontal loss in speed due to friction during landing [3]. Optimized values for the effective launch radius (r) and the sliding coefficient of friction between the occupant and the ground (μ_{slide}) were calculated for the three ejections in the Volvo rollover test and the two ejections in the real world rollover crashes. The optimized launch radius ratio was calculated by dividing the optimized launch radius by the distance between the center of gravity and the vehicle perimeter (beltline or roof rail) measured on an exemplar vehicle.

A more global assessment of occupant ejection kinematics in rollover crashes was made by combining the analyses of the two real world rollovers with the analyses of the Volvo XC90 dolly rollover and the Ford Expedition dolly rollover studied previously [3]. The total data set comprised ten occupant ejections in four different rollover crashes. The distribution of launch radius ratios, sliding friction coefficients, and release angles was analyzed. Occupant ejection kinematics were compared between real world rollovers and dolly rollover tests. Lastly, the dolly rollover test vehicles were carefully inspected for exit marks and other physical evidence indicating that an ATD had been ejected through a known portal.

RESULTS

VOLVO XC90 DOLLY ROLLOVER TEST

The 2004 Volvo XC90 rolled over driver side leading 4 ¼ times over a distance of 103 feet beyond the end of the initial tire marks. Continuous time histories were calculated for the translational velocity, position, roll rate, and roll angle of the vehicle (Figure 1). There was significant pitch and vertical motion of the vehicle in the middle of the third and fourth rolls, and significant yaw during the final roll. A detailed description of the vehicle dynamics and a scene diagram can be found in Luepke et al. [4].

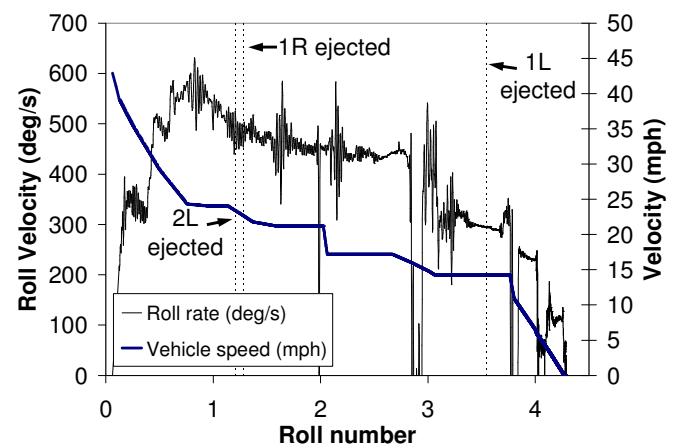


Figure 1. Translational vehicle velocity and roll rate vs. roll number for the Volvo XC90 dolly rollover test. Ejection points for each ATD are shown.

Three out of the four unbelted ATDs were fully ejected from the Volvo during the rollover (Figure 2). One ATD (2R) remained in the vehicle. The three ejections in this test were quite varied. One of the ATDs (1L) was ejected on the “high” side, meaning that it left the vehicle with an initially upward trajectory. This ATD was ejected behind the vehicle near the end of the rollover. Two of the ATDs (1R and 2L) were ejected on the “low” side, meaning that they left the vehicle with an initially downward trajectory. Both of these ATDs were rolled over by the vehicle after being ejected. ATD 1R was thrown downward violently into the ground ahead of the vehicle and bounced approximately 4 feet into the air.

The rolling vehicle struck glancing blows to the dummy's feet, hips, arms, and head when the dummy was airborne after the bounce, which affected the ATD's trajectory only slightly. However, the sliding of ATD 1R appeared to prematurely arrested when the left rocker panel of the vehicle rolled over the dummy. ATD 2L experienced a partial ejection of its legs for approximately half a roll before it appeared to begin the process of complete ejection. The ATD struck the ground before it was completely out of the vehicle and was almost immediately rolled over by the vehicle. The torso of the dummy was compressed between the ground and the left rear door window frame and adjacent roof rail of the vehicle. The interaction left a noticeable upward bow along the top of the window frame. Afterwards, the ATD remained essentially planted on the ground in a sitting position. The ejected ATDs sustained varying degrees of damage: ATD 1L experienced only minor damage, the left hand of ATD 1R was detached, and ATD 2L sustained a bent left lower leg, a broken right femur, and a broken pelvis. Values for the launch radius could be optimized so that the model predictions matched the experimental data almost exactly (most errors < 1 ft, 1 mph, and 1 deg). It was not possible to calculate sliding friction coefficients for any of the ejected ATDs in this test. ATDs 1R and 2R were run over by the vehicle, and therefore were not stopped by friction alone, and ATD 1L landed at a very steep angle (70°) that precluded an accurate calculation of the friction coefficient.

REAL WORLD CASES

Lincoln Navigator Rollover

The Lincoln Navigator rolled over passenger side leading 1 ¼ times before striking the median barrier. The vehicle continued rolling over the median barrier and came to rest on the other side of the barrier in the eastbound oncoming lanes of I-285 after completing a total of 2 ¼ rolls. The driver was ejected from the vehicle through the driver's side window between roll ¾ and roll 1. The driver was thrown approximately 84 feet over the median barrier and landed in eastbound lanes of I-285, where he slid along the pavement for 17 feet and came to rest (Table 1).

It was possible to obtain vehicle and occupant positions by analyzing individual frames from the video (Figure 3). Key video images were rectified, spliced together, and overlaid on an aerial image of the accident scene (Figure 4). This information was used to create a scaled scene diagram (Figure 5). Positions of the vehicle and corresponding times were used to calculate the average translational velocity between positions and create a translational velocity vs. time plot (Figure 6). The roll angle vs. time plot (Figure 6) is the same information that was previously published in Figure 6 of Rose et al. [5]. Using optimized values for the launch radius and friction coefficient, the model was able to match the observed ejection trajectory almost exactly (errors < 1 ft, 1 mph, and 1 deg) (Figure 7).

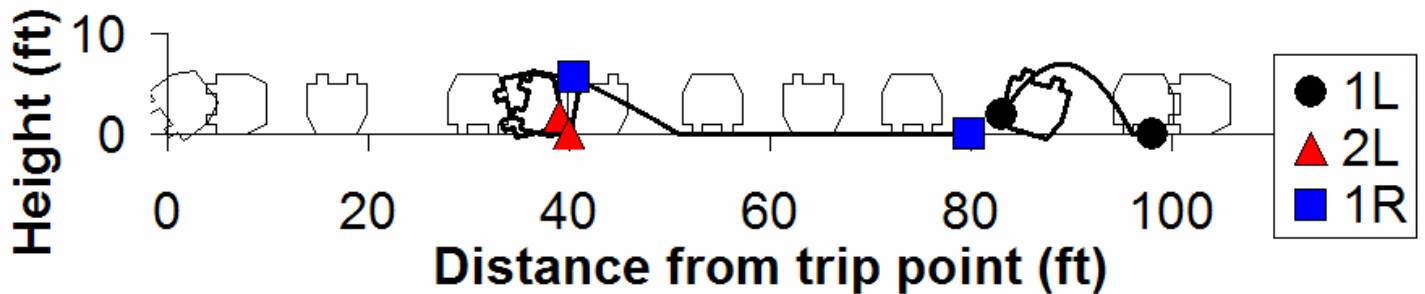


Figure 2. Illustration of the trajectories of the three dummies ejected in the Volvo XC90 dolly rollover test.

Table 1. Summary of results. Positions are relative to the trip point, defined as the end of the initial tire marks.

Crash vehicle	Volvo test	Volvo test	Volvo test	Navigator	Denali
Occupant seating position	1L	2L	1R	1L	1L (1R)
Vehicle speed at ejection	14 mph	23 mph	23 mph	41 mph	24 mph
Vehicle position at ejection	86 ft	36 feet	38 ft	57 ft	97 ft
Throw distance	13 ft	1 ft	11 ft	84 ft	10 ft
Slide distance	4 ft	0 ft	29 ft	17 ft	38 ft
Occupant rest position	98 ft	39 ft	80 ft	154 ft	148 ft
Equivalent maximum height	7 ft	13 ft	14 ft	14 ft	17 ft
Roll number at ejection	3.53	1.20	1.28	0.82	2.03
Roll rate at ejection	295 deg/s	509 deg/s	487 deg/s	365 deg/s	438 deg/s
Launch velocity	13 mph	22 mph	38 mph	37 mph	44 mph
Launch angle	57 deg	-58 deg	-25 deg	30 deg	-25 deg
Landing velocity	16 mph	23 mph	40 mph	38 mph	46 mph
Landing angle	63 deg	60 deg	30 deg	32 deg	30 deg
Time in air	1.18 s	0.06 s	0.21 s	1.78 s	0.17 s
Optimized launch radius	42 in	43 in	42 in	55 in	48 in
Sliding coefficient of friction	--	--	0.59	0.67	0.62



Figure 3. Sequence of video images for the Lincoln Navigator rollover.



Figure 4. Rectified video images from the Lincoln Navigator rollover overlaid on an aerial photograph. Key vehicle and occupant positions have been highlighted.

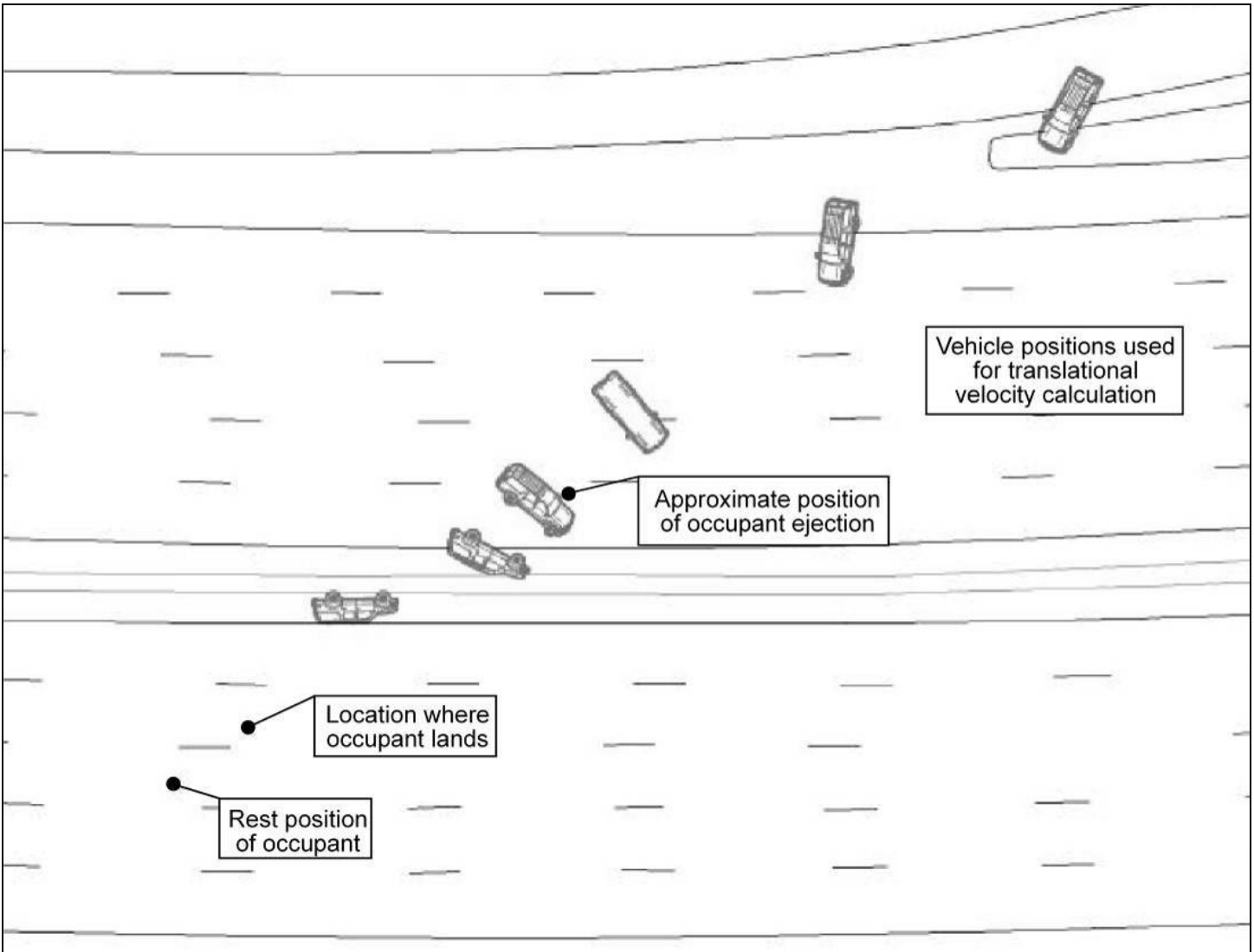


Figure 5. Scene diagram for the Lincoln Navigator rollover.

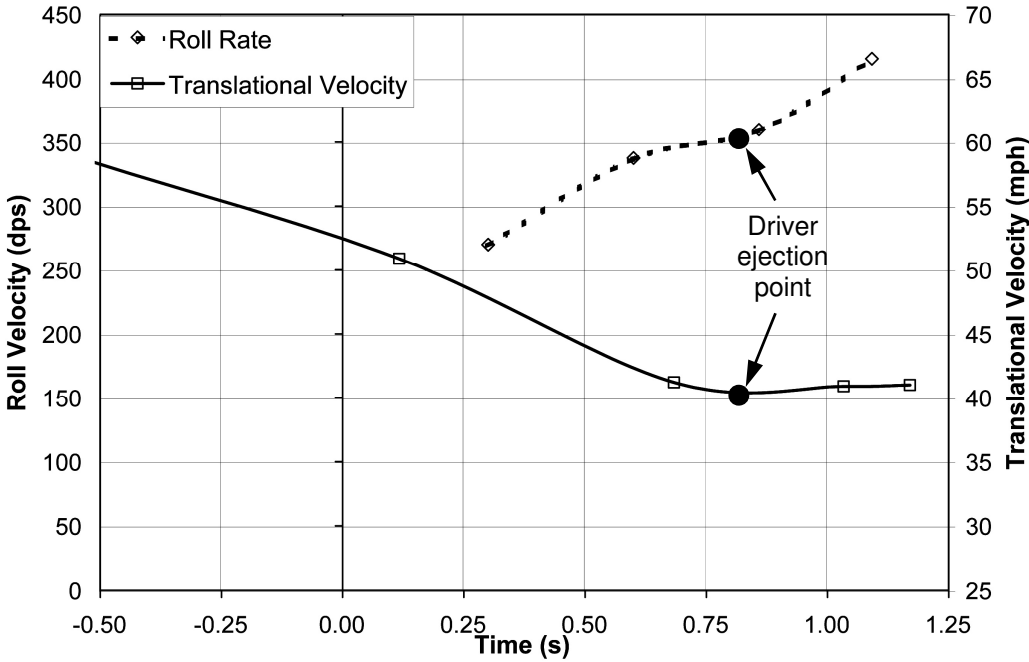


Figure 6. Roll rate and translational velocity for the Lincoln Navigator rollover.

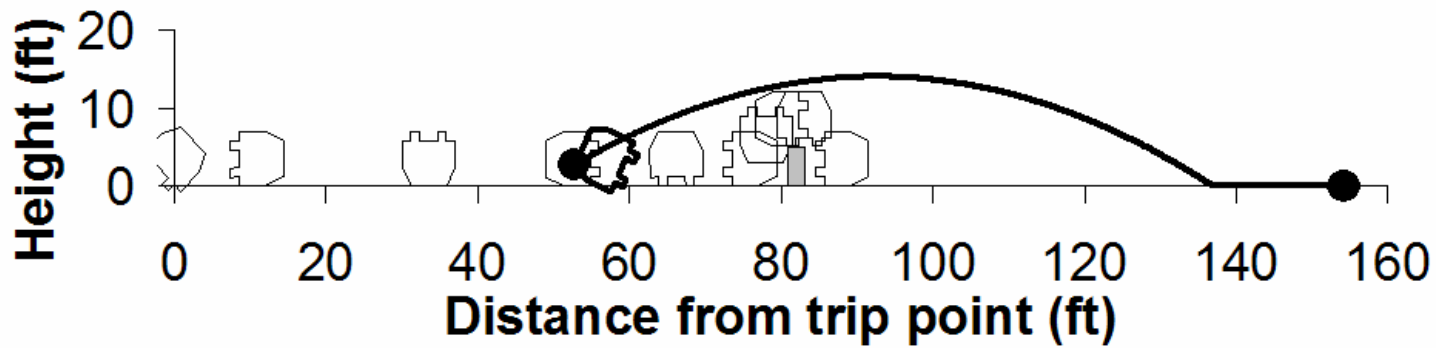


Figure 7. Illustration of the trajectory of the ejected occupant in the Lincoln Navigator rollover.

GMC Yukon Denali Rollover

While traveling at a high rate of speed, the GMC Yukon Denali went off the road to the right and clipped a guardrail, causing the left front tire to detach from the vehicle. The vehicle then traveled through the air over at least two lanes of Lindbergh Boulevard, which was the road that passed under the highway. The vehicle landed near the edge of the pavement on Lindbergh Boulevard and continued onto a grassy area adjacent to the roadway in a counterclockwise yaw. The vehicle then rolled over passenger side leading just over $3 \frac{3}{4}$ times before reversing its roll direction and coming to rest on its left side. During the rollover, the driver was ejected through the right front passenger side window. Because the driver was ejected through the right side window, his position is referred to as “1L (1R).” The ejected

occupant was thrown forward and downward into the ground and slid and tumbled ahead of the vehicle, eventually coming to rest just beyond the vehicle.

Vehicle and occupant positions were obtained with good accuracy by analyzing individual frames that contained landmarks visible in both the video and the aerial image (Figures 8 – 10). By analyzing the speed of the vehicle over a long distance before the crash, it was confirmed that the vehicle was traveling over 100 mph, as stated in the audio from the news helicopter footage (Figure 11). The average deceleration of the rolling vehicle from the end of the tire marks to rest was 0.53 g. Using optimized values for the launch radius and friction coefficient, the model was able to match the observed ejection trajectory almost exactly (errors < 1 ft, 1 mph, and 1 deg) (Figure 12).



Figure 8. Sequence of video images from the GMC Yukon Denali rollover.



Figure 9. Aerial image of the crash site of the GMC Yukon Denali rollover. The six vehicle positions used to calculate the translational velocity of the vehicle are indicated with white circles and numbered.

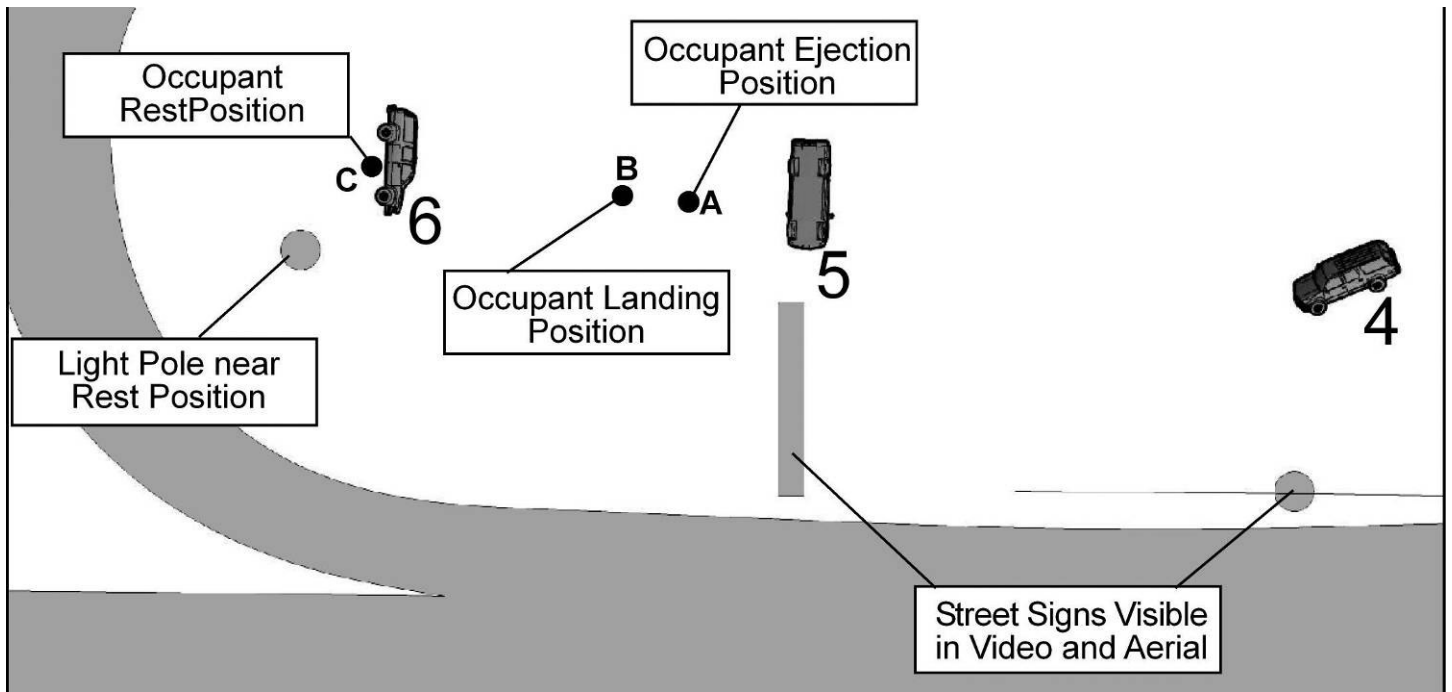


Figure 10. Scene diagram for the GMC Yukon Denali rollover.

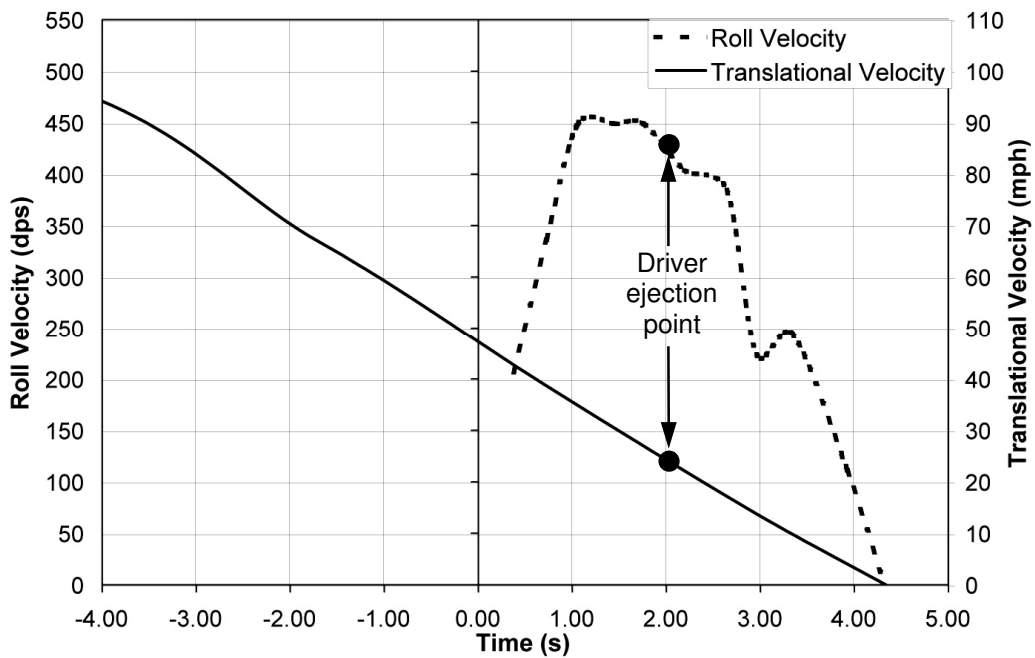


Figure 11. Roll rate and translational velocity for the GMC Yukon Denali rollover.

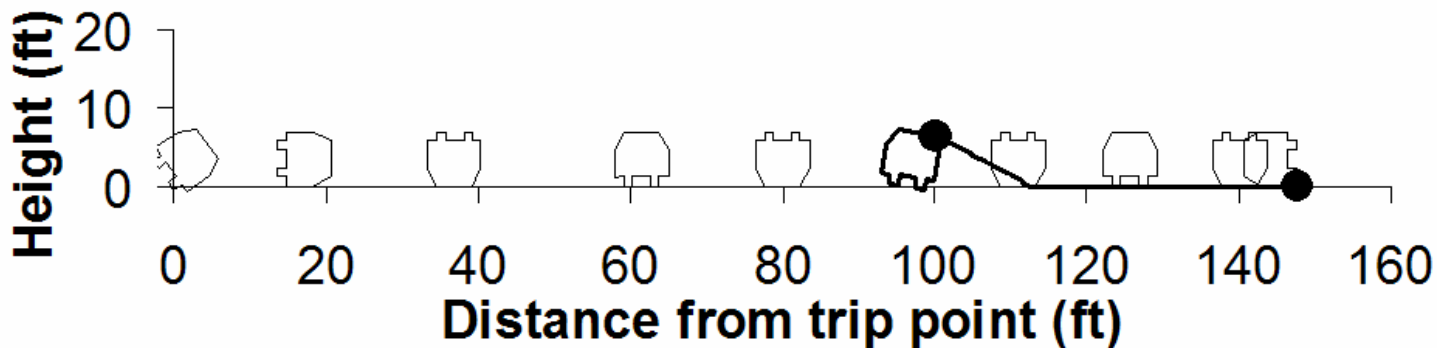


Figure 12. Illustration of the trajectory of the ejected occupant in the GMC Yukon Denali rollover.

Comparison to Dolly Rollover Tests

The occupant ejection kinematics in the two real world rollover crashes did not appear to differ from the ATD ejection kinematics in either the Volvo XC90 dolly rollover test or the Ford Expedition dolly rollover test studied previously [3]. The release angles in the real world rollover ejections were consistent with the range of release angles observed in the dolly rollover tests (Figure 13). The release angle was defined as the roll angle of the vehicle (θ) plus the angle of the occupant's portal of ejection relative to the lateral axis of the vehicle (ϕ), which is nominally 130° for the leading side roof rail and 35° for the trailing side beltline [3].

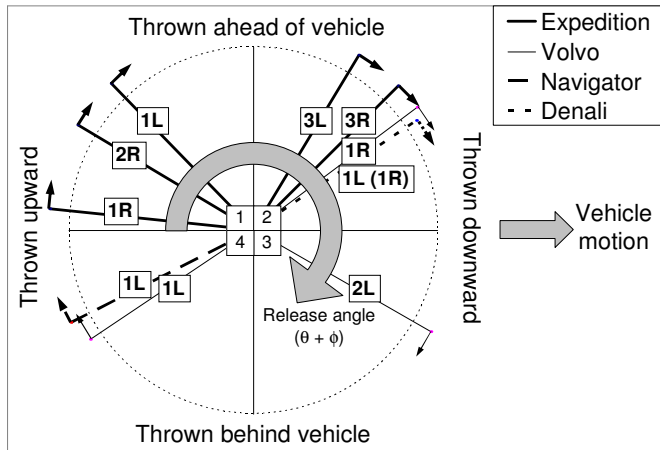


Figure 13. Release angles for each ejected occupant. Release quadrants are labeled 1 – 4.

The average launch radius ratios and sliding friction coefficients were very similar for the real world rollovers and the dolly rollover tests (Table 2). The optimized launch radius ratios in the two real world rollovers were at the low and high ends of the range observed in the dolly rollover tests. The optimized launch radii ranged from about equal to up to 37% greater than the distance between the center of gravity and the perimeter of the vehicle as measured on an exemplar vehicle. The launch radius ratios were higher for occupants ejected from the trailing side of the vehicle compared to the leading side.

There were two ejections in which the optimized launch radius was unusually high (ATD 1R in the Expedition test and the driver in the Lincoln Navigator rollover) (Table 2). Both of these were high side ejections of trailing side occupants that occurred just after the $\frac{3}{4}$ roll point when the vehicle appeared to be bouncing upward after a wheel impact. To evaluate whether the upward velocity of the vehicle may have contributed to the unusually high values in these cases, the optimized launch radii were recalculated assuming an arbitrary but realistic value of 5 mph for the vertical velocity of the vehicle (eq. 1). After the recalculation, the optimized launch radius ratio decreased from 1.35 to 1.14 for ATD 1R in the Expedition test, and from 1.37 to 1.12 for the driver of the Navigator.

EJECTION MARKS

Inspection of the dolly rollover test vehicles revealed pronounced and distinctive marks in most, but not all, of the window openings through which an ATD was ejected. Interestingly, similar marks were sometimes found on window openings through which an ATD was only partially ejected. There was sometimes outward bowing of the door panel or window frame due to loading from an ejected occupant (Figures 14 – 15). Surfaces on the perimeter of the ejection portal were almost always scuffed, polished, or abraded (Figures 16 – 19). In many instances, the abraded material was smeared in an outboard direction (Figures 17 – 18). Fabric marks consisting of closely spaced parallel abrasions were clear evidence of contact from a clothed portion of the ATD (Figures 18 – 19). Exit marks were found in various places around the perimeter of the ejection portals, but the marks tended to be heavier and more numerous on the lower portion of the trailing side ejection portals and on the upper portion of the leading side ejection portals.

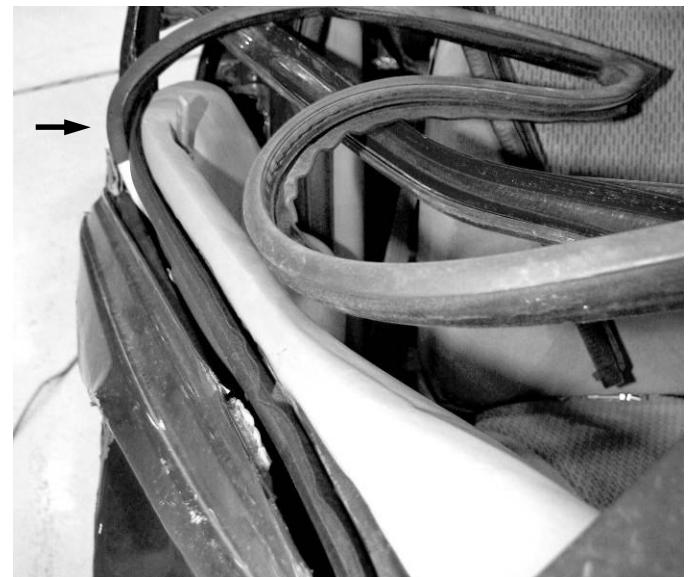


Figure 14. The right front door panel was bowed outward due to loading from ATD 1R in the Expedition rollover test.

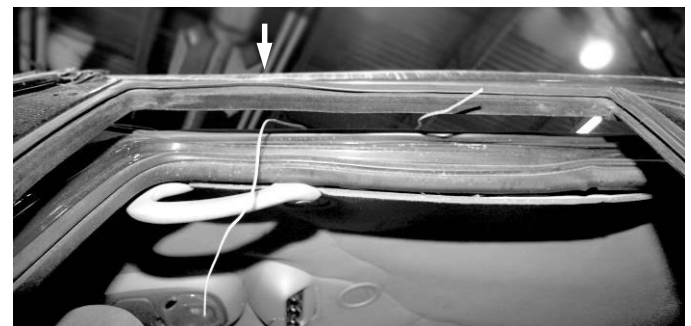


Figure 15. The forward portion of the top of the window frame was bent outward as a result of the partial ejection of the left arm of ATD 2L in the Expedition rollover test.

Table 2. Summary of the kinematics of all ejected occupants studied (including the Ford Expedition rollover [3]).

Crash vehicle	Occupant	Ejection side	Launch radius ratio	Release angle	Tangential launch velocity vector		Release quadrant	Sliding friction	Run over by vehicle?
Expedition	1L	Leading	1.08	46 deg	Up	Ahead	1	0.56	No
Expedition	3L	Leading	0.99	121 deg	Down	Ahead	2	--	Yes
Expedition	1R	Trailing	1.35	6 deg	Up	Ahead	1	0.67	No
Expedition	2R	Trailing	1.14	31 deg	Up	Ahead	1	0.73	No
Expedition	3R	Trailing	1.01	135 deg	Down	Ahead	2	--	Yes
Volvo XC90	1L	Leading	0.98	326 deg	Up	Behind	4	--	No
Volvo XC90	2L	Leading	0.98	210 deg	Down	Behind	3	--	Yes
Volvo XC90	1R	Trailing	1.12	143 deg	Down	Ahead	2	--	Yes
Navigator	1L	Trailing	1.37	333 deg	Up	Behind	4	0.67	No
Denali	1L (1R)	Leading	1.03	146 deg	Down	Forward	2	0.62	No



Figure 16. A scuff mark with upward and outboard smearing of the plastic was left on the beltline as a result of the ejection of ATD 1R in the Volvo rollover test.

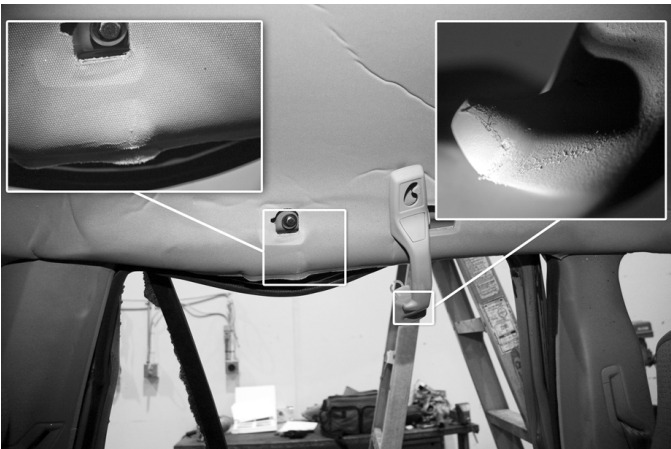


Figure 17. As a result of the ejection of ATD 2L in the Volvo rollover test, the grab handle was knocked outboard, leaving a scuff on the headliner and smearing the plastic on the outboard edge of the grab handle.

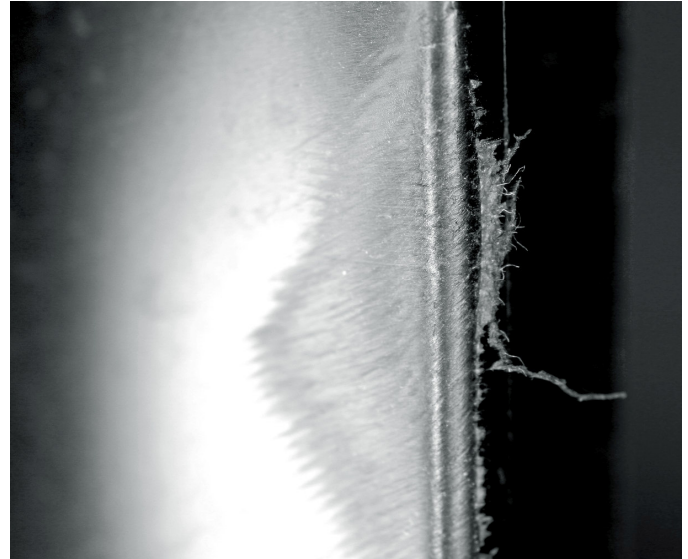


Figure 18. A fabric mark with smearing of the plastic in an outboard direction was left on the divider bar as a result of the partial ejection of ATD 2L in the Expedition rollover test.



Figure 19. A fabric mark consisting of light diagonal abrasions was left on the rear fixed window lower plastic trim as a result of the ejection of ATD 3L in the Expedition rollover test.

DISCUSSION

The ten occupant ejections from four rollover crashes that have been studied in detail represent a wide variety of possible ejection scenarios that can occur in rollover

crashes. Ejections in this group occurred as early as the end of the first roll and as late as the beginning of the last roll, though most of the occupants were ejected during the first half of the rollover. Ejection scenarios can also be classed based on the direction the ejected occupant is thrown relative to the vehicle (upward or “high side”, downward or “low side”, ahead, or behind). Four combinations are possible, corresponding to the quadrant of the release angle at the point of ejection (Figure 13). The ejected occupant may be thrown upward and ahead of the vehicle (quadrant 1), downward and ahead of the vehicle (quadrant 2), downward and behind the vehicle (quadrant 3), or upward and behind the vehicle (quadrant 4). All four of these general scenarios were represented in the group of ejections studied. It should be noted that even when ejected occupants are thrown behind the vehicle (quadrants 3 and 4), they typically still have a forward velocity (in the same direction as the vehicle) relative to the ground. No ejections with release angles near 270° were observed in this study, possibly because the ground tends to block the ejection portal at that point. Otherwise, the release angles in the ten ejections appeared to be distributed more or less randomly.

The release angle at which an occupant is ejected from the vehicle is important because it relates to the severity of the landing. A release angle of 270° would represent a pure deposit, the least violent ejection possible. A release angle near 0° will generate the greatest ejection height and longest throw distance for a given translational and rotational velocity (e.g., ATD 1R in the Expedition dolly rollover). A release angle near 180° will produce an equally severe landing with a very short throw distance. Low side ejections in which the ejected occupant is thrown downward are associated with release angles of $90^\circ - 270^\circ$ (quadrants 2 and 3). In low side ejections, there is a substantial risk that the vehicle will roll over the occupant after the ejection occurs. At release angles of $180^\circ - 270^\circ$ (quadrant 3), the occupant is thrown downward and behind the vehicle while still in front of the vehicle, making subsequent contact with the vehicle very likely (e.g., ATD 2L in the Volvo dolly rollover). Even in low side ejections where the occupant is thrown ahead of the vehicle at release angles of $90^\circ - 180^\circ$ (quadrant 3), there is a significant risk that the vehicle will catch up to and roll over the occupant. The ejected occupant can lose a significant amount of speed upon landing, and will then tend to decelerate at a faster rate than the vehicle. In four out of the five low side ejections studied, the vehicle rolled over the occupant after the occupant was ejected (Table 2). The exception was the Denali rollover, and in that case the vehicle came very close to rolling over the occupant (Figure 8).

Although occupant ejections were modeled as occurring at a single point, ejection of the occupant from the vehicle is really a process. For occupants who were ejected cleanly, the process of ejection from the time any part of their bodies extended beyond the perimeter of the vehicle to the time no part of their bodies remained inside the vehicle typically occurred within a quarter roll. Sometimes the process of ejection was arrested before

the ejection was complete, and a part of the occupant's body remained partially ejected for nearly an entire roll. However, once the ejection process resumed, it was typically complete within a quarter roll. The “point” of ejection as defined in the model was the time the ejected occupant was first in free flight. This point typically corresponded to the time when the occupant's body was approximately halfway out of the vehicle.

The occupant's launch velocity vector at the point of ejection was defined as the vector sum of the translational velocity of the center of gravity of the vehicle and the tangential velocity of the occupant at the vehicle perimeter. In other words, the tangent to the release angle determines which direction the ejected occupant will be thrown relative to the vehicle (Figure 13). There is no need to consider the normal speed at which the occupant passes through the ejection portal when calculating the launch velocity vector, because this speed does not contribute to the launch velocity vector as calculated in a fixed, ground-based reference frame. It must be remembered that occupants are not pushed away from the center of gravity of the vehicle by centrifugal force. Rather, a radially-directed containing force is required to keep them within the vehicle on a curved path through space. Ejection does not occur when this force gets too high, but rather when it gets too low. When this containing force goes away completely, the occupant is in free flight. Once ejected, an occupant's airborne trajectory, landing, and subsequent sliding and tumbling to rest can be accurately quantified using the simple mathematical model presented in Funk and Luepke [3].

Using the crash reconstruction and occupant kinematic data, optimized values for the launch radius (r) and sliding coefficient of friction (μ_{slide}) were calculated for each case of occupant ejection. The optimized values for the effective launch radius were most accurate for the high side ejections in which the occupant was airborne for a relatively long period of time. Low side ejections with very short airborne trajectories could sometimes be accurately modeled by a fairly wide range of launch radii, which made it difficult to determine a precise optimum value. The optimized launch radius was typically greater than the distance between the center of gravity and the perimeter of the vehicle as measured in an exemplar vehicle, and the ratio between the two varied from 0.98 – 1.37 (mean 1.11 ± 0.14) (Table 2).

There are several possible explanations for this wide range. First, the doors and roofs of vehicles tend to deform in a rollover in such a way as to make the distance between the center of gravity of the vehicle and the perimeter of the vehicle physically larger than in an intact vehicle, but only slightly. Second, the interaction between the occupant and the vehicle perimeter may have some intrinsic variability that affects the effective launch radius (possibly related to interaction with flailing body parts or rebound between the occupant and the vehicle during ejection). Third, and perhaps most importantly, errors in the crash reconstruction must be

offset by a counterbalancing error in the optimized launch radius in order to calculate a launch velocity vector that correctly predicts the observed trajectory of the ejected occupant. For all of the ejections modeled in Funk and Luepke [3] and in the present study, detailed crash reconstruction data were generated from photographic and video data. Accurate time histories were obtained for the translational and rotational velocity of the vehicle, as well as its position and roll angle. The vertical velocity of the vehicle was not calculated, although it can be incorporated into the model by using eq. (1) in this paper as a substitute for eq. (12) in Funk and Luepke [3]. We expect that if the vertical vehicle velocity could have been determined precisely in this study, the optimized launch radii would have fallen within a much narrower range.

The optimized values for the sliding coefficient of friction (μ_{slide}) were most accurate in cases where the occupant slid for a relatively long distance after landing. This parameter could be extremely sensitive to small changes in the estimated sliding distance of the ejected occupant if the sliding distance was very short (< 5 ft) (i.e., ATD 1R in the Expedition test). In cases where the vehicle rolled over the occupant and arrested the sliding prematurely, the optimized value of the friction coefficient was artificially raised. When the above cases are excluded, only four cases remain in which the optimized friction value was felt to have good accuracy. In these four cases, the average sliding coefficient of friction between the occupant and the ground was 0.65 ± 0.07 , which is in good agreement with the findings of Wood and Simms [12] for pedestrian throw.

CONCLUSIONS

The trajectories of people ejected in real world rollover crashes can be modeled in the same way as the trajectories of ATDs ejected in dolly rollover tests using the occupant ejection model of Funk and Luepke [3]. Appropriate ranges for the launch radius and sliding coefficient of friction can be chosen based on the optimized values reported in the present study of ten occupant ejections in four rollover crashes. Findings of exit marks similar to those documented in the present study can aid in the determination of the occupant's portal of ejection. The results of the occupant ejection model should be interpreted in light of the limitations of the model and the quality of the crash reconstruction. Most importantly, although the model is useful for determining mathematically possible occupant ejection scenarios, the results must be analyzed in conjunction with other physical evidence in order to determine which of the scenarios most likely occurred in a given crash.

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