

Analysis of Vehicle-to-Ground Impacts During a Rollover with an Impulse-Momentum Impact Model

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ABSTRACT

This paper explores the accuracy of a planar, impulse-momentum impact model in representing the dynamics of three vehicle-to-ground impacts that occurred during a SAE J2114 dolly rollover test. The impacts were analyzed, first, using video analysis techniques to obtain the actual velocity conditions, accelerations, impact force components and the energy loss for each of the impacts. Next, these same impacts were analyzed using the known initial velocity conditions and the subject impact model. The equations of this impact model yielded calculated values for the velocity changes and energy loss for each impact. These calculated results were then compared to the actual dynamics data from the video analysis of the impacts to determine the accuracy of the impact model results. For all three vehicle-to-ground impacts considered in this study, the impact model results for the velocity changes and energy loss showed excellent agreement with the video analysis results for these parameters. These results suggest that it is reasonable to use this impact model to examine the influence of various factors on rollover dynamics.

INTRODUCTION

This paper explores the accuracy of a planar, impulse-momentum impact model in representing the dynamics of three vehicle-to-ground impacts that occurred during a SAE J2114 dolly rollover test [6, 8]. The paper begins by introducing the equations of that impact model and then discusses video analysis of the three vehicle-to-ground impacts that will be considered in the paper. This video analysis yielded the actual initial velocity conditions, velocity changes and the energy loss for each of the impacts. After discussing these video analysis results, the equations of the impact model are used, in

conjunction with the known initial velocity conditions, to obtain calculated velocity changes and energy loss for each of the three vehicle-to-ground impacts. These calculated values are then compared to the known values of these parameters from the video analysis. The accuracy of the impact model is explored and guidance is given for selecting impact model parameters that maximize that accuracy.

The equations of the impact model used in this paper were introduced in Reference 17 and they are given a fuller treatment in Reference 19. For convenience, these equations are repeated in this paper and their derivation is given in Appendix A. This impact model represents a relatively straightforward application of the principle of impulse and momentum with the exception that the effects of the gravity impulse are included in the equations. Our main purpose in using this simple, planar impact model was to determine whether such a model could be used to explore the influence certain factors will have on rollover dynamics. For instance, could such a model illuminate the factors that influence a vehicle's deceleration rate during a rollover or those factors that determine the number of rolls a vehicle will experience during a rollover? These parameter influences are likely to be more visible in a simple, planar impact model than they would be in a fully three-dimensional impact model such as those used in certain accident simulation software packages. In using the impact model of this paper to illuminate such factor influences, it would, of course, be beneficial to know the degree to which the results from that model will have actual relevance to real-world rollover dynamics, which are, in general, highly three-dimensional. That is the issue that this paper aims at addressing.

There are, of course, computer software packages with the capability of analyzing vehicle-to-ground impacts in three-dimensions and there will clearly be vehicle-to-ground impacts that occur during rollovers for which such three-dimensional analysis will be essential [5, 7, 21]. Nonetheless, the research reported in this paper does show that, at least for the three vehicle-to-ground impacts reported here, a simple, planar impulse-momentum impact model can yield reasonably accurate velocity changes and energy loss for a vehicle-to-ground impact.

VEHICLE-TO-GROUND IMPACT MODEL

Figure 1 depicts an idealized impact between a vehicle and the ground. The impact shown here is a trailing side roof impact for a passenger's side leading roll. This image shows the coordinate system orientation and the parameters with which the impact model equations were developed. The impact radius, which is the distance from the vehicle center-of-mass to the contact point C, is designated with the symbol r . The impact angle, which is the angle between the ground plane and the impact radius, is designated with the symbol ϕ . The vehicle's velocity vector is designated with the letter v and the vehicle's roll velocity is designated ω_r .

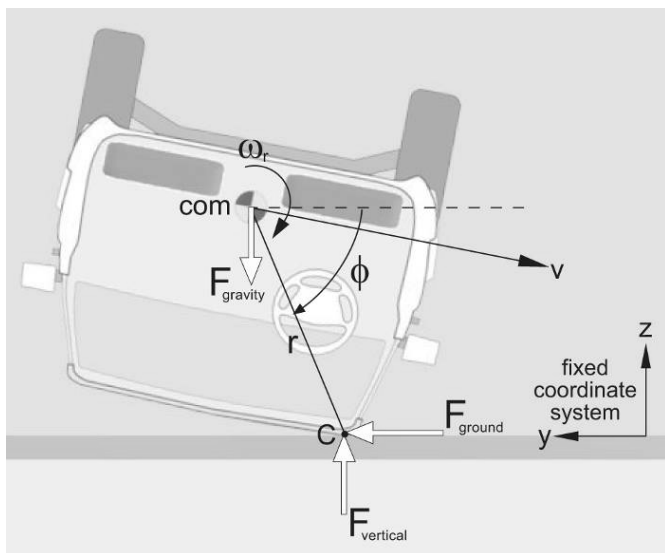


Figure 1 – Free-Body Diagram for a Vehicle-to-Ground Impact

During the depicted impact, the vehicle is subjected to both upward and ground surface impact force components, F_{vertical} and F_{ground} , and the gravity force, which is the vehicle's weight. In general, F_{ground} can act in either the positive (left) or negative (right) direction. On the other hand, F_{vertical} will always act in the positive-z direction and the gravity force will always act in the negative-z direction.

IMPACT MODEL ASSUMPTIONS

Before discussing the equations that will yield the velocity changes and energy loss for the impact of Figure 1, consider the assumptions that the mathematics of those equations will invoke. These assumptions include the following:

1. The impact will be assumed to occur entirely in a single plane, and thus, velocity changes along the vehicle's longitudinal axis are neglected, as are changes in pitch and yaw velocity.
2. The impact model equations will recognize no change in the position of the vehicle through the impact.
3. The impact force will be assumed to be concentrated at a single point.
4. It has been assumed that no moment arises at the contact point.
5. Any effects of ground plane restitution have been neglected. In other words, the ground surface impact force has been assumed to be a retarding force that depends on relative velocity at the contact point for its development. It is assumed that there is no structural restitution that could potentially cause a velocity reversal in the contact region.

The meaning of the first three of these assumptions should be relatively clear. We suspect that the meaning of the last two will be less clear, and thus, we refer the reader to the extensive discussion of these concepts in the text by Brach, titled *Mechanical Impact Dynamics* [2]. Relaxing these last two assumptions is possible. However, in our judgment, this would make the modeling reported in this paper needlessly complex.

All five of these assumptions have the potential to be violated during any particular vehicle-to-ground impact. The degree to which any one of them is an appropriate assumption will depend on the specifics of the particular vehicle-to-ground impact under consideration and on the degree to which violating any of these assumptions will actually degrade the accuracy of the results the impact model yields. That issue will be addressed in the "Discussion" section of this paper.

IMPACT MODEL EQUATIONS

Once these assumptions are invoked, application of the principle of impulse and momentum results in Equations (1) through (3), which yield the vehicle's upward and ground plane center-of-mass (CoM) velocity changes

and the vehicle's change in roll velocity.¹ Appendix A contains a full derivation of these equations. In these equations, $v_{zc,i}$ is the vertical velocity of the vehicle at Point C immediately preceding the ground contact, k_r is the vehicle's radius of gyration for the roll axis, g is the gravitational constant, Δt_i is the duration of the impact, and the letters s and c designate the sine and cosine. Note that although it is assumed that the vehicle position does not change during the impact, accounting for the effect of the gravity impulse has required inclusion of the impact duration [9].

$$\Delta V_z = -(1+e) \cdot v_{zc,i} \cdot \left\{ \frac{k_r^2}{k_r^2 + r^2(c^2\phi - \mu \cdot s\phi \cdot c\phi)} \right\} - g \cdot \Delta t_i \cdot \left\{ \frac{r^2(c^2\phi - \mu \cdot s\phi \cdot c\phi)}{k_r^2 + r^2(c^2\phi - \mu \cdot s\phi \cdot c\phi)} \right\} \quad (1)$$

$$\Delta V_y = \mu \cdot (\Delta V_z + g \cdot \Delta t_i) \quad (2)$$

$$\Delta \omega_r = (\Delta V_z + g \cdot \Delta t_i) \cdot \frac{r \cdot (\mu \cdot s\phi - c\phi)}{k_r^2} \quad (3)$$

Examination of Equations (1) through (3) reveals that the initial downward velocity at the Point C ($v_{zc,i}$) directly influences the velocity changes that occur during the impact, with the velocity changes increasing as this velocity increases. This initial vertical velocity at Point C, which is given by the following equation, is related to the vehicle's CoM vertical velocity, its roll velocity and the impact angle and radius:

$$v_{zc,i} = v_{z,i} - r \cdot c\phi \cdot \omega_{r,i} \quad (4)$$

In this equation, $v_{z,i}$ is the vehicle's vertical velocity at its CoM immediately preceding the impact.

Equations (1) through (3) also include the coefficient of restitution, e , and the impulse ratio, μ . The coefficient of restitution is the negative ratio of the post-impact to the pre-impact vertical velocity at Point C. The impulse ratio is the ratio of the ground surface collision impulse to the vertical direction collision impulse. In some instances, the impulse ratio can be thought of as a coulomb friction value, though its application is not limited to this interpretation [2, 3, 4, 14, 19]. In addition to the effects of friction between the ground and the vehicle body, the ground plane impulse may also include the effects of forces generated by snagging between the vehicle and the ground. When such snagging occurs, the impulse

ratio should be set at a value that incorporates that snagging.

Within this impact model, the sign of the impulse ratio governs the direction in which the ground plane collision force acts. A positive impulse ratio produces a ground plane force that acts in the positive direction and a negative impulse ratio results in a ground plane force that acts in the negative direction. The direction of the ground surface impact force, in turn, determines whether the vehicle will experience a positive or negative ground plane velocity change and whether the ground surface impact force will tend to increase or decrease the roll velocity. Also, note that for a passenger's side leading roll, as depicted in the image above, the ground speed will be negative, the roll velocity positive, and the impact angle will always be less than 90 degrees. For a driver's side leading roll, like the crash test analyzed in this paper, the same impact model equations apply, but the ground speed will be positive, the roll velocity negative and the impact angle will always be greater than 90 degrees.

The energy loss that occurs during the vehicle-to-ground impact of Figure 1 can be written as follows:

$$\Delta E = \frac{m}{2} \cdot (v_{zi}^2 - v_{zf}^2 + v_{yi}^2 - v_{yf}^2 + k_r^2 \omega_{r,i}^2 - k_r^2 \omega_{r,f}^2) \quad (5)$$

The energy loss of Equation (5) includes the energy loss due to vehicle deformation, ground deformation, and sliding, snagging or furrowing between the vehicle structure and the ground.

ROLLOVER CRASH TEST SETUP

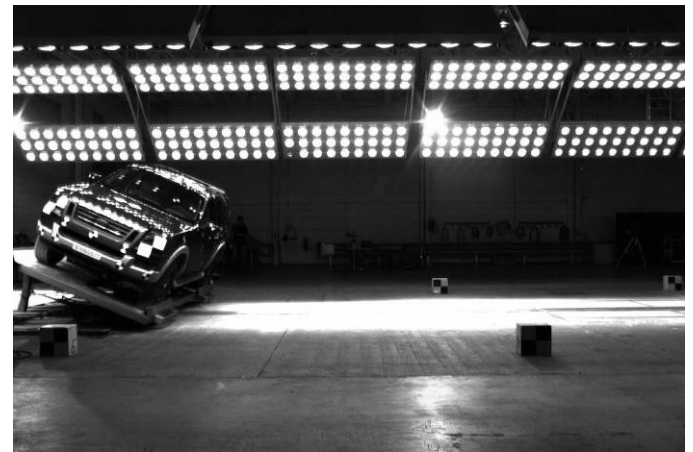


Figure 1 – Rollover Crash Test Configuration

The rollover crash test used in this paper was run with a Ford sport utility vehicle in accordance with the SAE Recommended Practice J2114 (Dolly Rollover). This test procedure involves generating a lateral roll of the test vehicle by accelerating a cart, on which the vehicle sits, up to the test speed, then decelerating that cart at a

¹ The authors presented these equations in Reference 17. However, in that reference, Equation (2) failed to include the gravity term.

sufficient rate to initiate the rollover. The vehicle is situated on the cart perpendicular to the initial velocity direction with an initial roll angle of 23 degrees. In the test under consideration in this paper, the vehicle was situated on the cart with its driver's side leading and the cart and test vehicle were accelerated up to a speed of approximately 31 mph before the cart deceleration was initiated. Figure 1 shows the test vehicle just before it began exiting the cart.

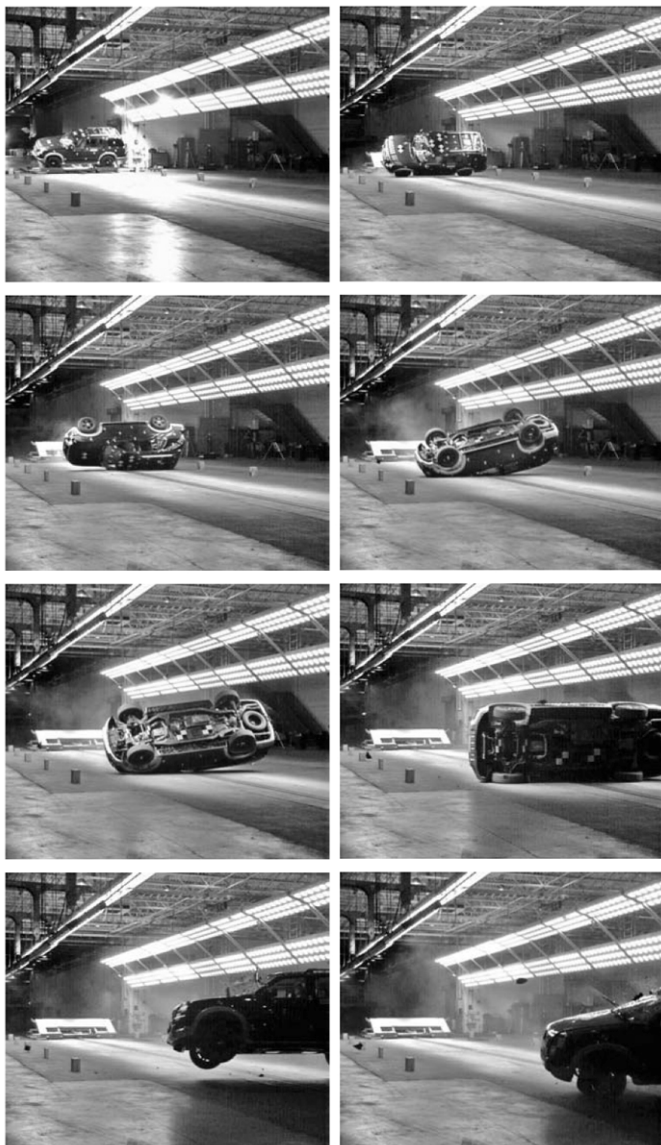


Figure 2 – Rollover Crash Test Dynamics

The roll dynamics that occurred during this test are depicted in Figure 2. The images in this figure were captured by a high-speed camera located downstream of the roll. As these images show, the vehicle rolled just past 360 degrees and then came down to rest on its wheels. During this test, the vehicle was instrumented with sensors to measure the vehicle-fixed longitudinal, lateral and vertical accelerations at the center tunnel between the seats and the lateral and vertical

accelerations at the lower A-pillar and B-pillar on both sides of the vehicle. The vehicle was also instrumented with two rotation rate sensors for each principal axis. These were mounted on the center tunnel just rearward of the seats. Nine high-speed fixed cameras and one real-time panning camera recorded the test. The high-speed video was taken at 500 frames per second and the real-time video was taken at the NTSC standard frame rate of 29.97 frames per second.

Three-dimensional dynamics data for this crash test was obtained using video analysis that is described in detail in a companion paper [20]. That analysis will also be covered briefly in the next two sections.

CAMERA-MATCHING VIDEO ANALYSIS

This section describes the methodology utilized to track the vehicle motion in the crash test video. This methodology consisted of the following steps: 1) preparing the test vehicle with targets that would be tracked; 2) surveying the test facility and vehicle geometries; 3) creating a computer environment that included the geometries of the test facility and the test vehicle; 4) analyzing the actual cameras and the video images to determine characteristics, distortion and resolution so that these could be replicated with computer-modeled cameras; 5) accurately placing computer-modeled cameras in a three-dimensional computer environment and matching them to the test video; and 6) tracking the movement of the test vehicle by matching the location of the computer generated vehicle targets to the targets on the test vehicle for each frame of the video sequence. These steps are more fully described in the following paragraphs.

- 1) Prior to running the crash test, the test vehicle was marked with high-contrast yellow and black fiducial targets. It was the motion of these targets that was ultimately tracked in the video. In placing these targets, the primary goal was to generate a wide range of points on the vehicle that would be visible and identifiable in the crash test video.
- 2) Once these stickers were placed, their locations were surveyed so that they could be replicated on a computer-generated model of the test vehicle. Also prior to running the crash test, a survey of the test facility was completed. This survey provided the three-dimensional geometry of the rollover test facility, including the ground surface, the control joints in the concrete of the test surface, the walls surrounding the test surface, and the light fixtures located above the test surface.
- 3) Based on survey data and photographs, computer-generated models of the test facility and test vehicle were constructed. The entire computer environment was then oriented relative to the general roll

direction. With the survey of the test vehicle aligned to the computer model, the target stickers that were placed on the test vehicle, and subsequently surveyed, could be transferred to identical locations on the computer model of the vehicle. These target locations were used to track the motion of the test vehicle.

- 4) The optical and geometric characteristics of all the cameras were documented and analyzed in order to create computer-generated cameras that mimicked each individual camera that captured video of the rollover test. The data for these cameras came from the survey of these cameras, analysis of the sensors, and analysis of the technical and specification drawings. Each camera was created according to its specific characteristics, since these characteristics differed between cameras. These computer-modeled cameras were also located and oriented to be identical to the cameras surveyed at the facility at the time the dolly rollover test was conducted.
- 5) Having created a computer-modeled environment that contained the geometry of the test facility, the test vehicle and a series of computer-modeled cameras that replicate the actual cameras, test video from each camera was then designated as a background image for its corresponding computer-modeled camera. Each computer-modeled camera could then be used to simultaneously view the computer model of the test facility and the crash test

video. If the location and characteristics of each camera were set properly, then this step would yield an overlay between the video background and the computer-modeled environment. Crash test facility features visible in computer model should overlay those same features visible in the crash test video. Figure 3 depicts this process of camera-matching the computer-modeled cameras to the video of the rollover test. This step was repeated for each camera position and video sequence, such that all cameras and computer geometry were visually determined to be matched to their background video sequence.

- 6) With this determination, the computer model of the test vehicle could then be placed in the computer-modeled environment and positioned at each frame to mimic the movements of the vehicle visible in each frame of the video sequence. The images in Figure 4 depict a properly matched computer model of the vehicle and facility for several frames of the video. The mesh model of the vehicle contains yellow dots as seen in the video image overlay. These yellow dots are the surveyed points of the test vehicle before it was damaged from the rollover. It can be seen in Figure 4 that these images match with all the corresponding targets that were placed on the test vehicle. In addition to the vehicle matching the video, the computer model of the environment and background can also be seen in this image properly oriented and positioned relative to the same background and environment of the facility seen in the video.

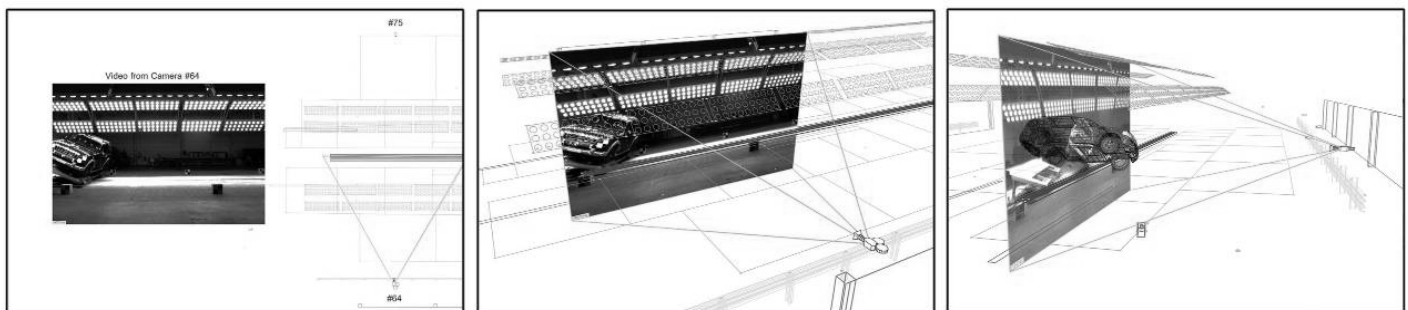


Figure 3 – Camera-Matching Process



Figure 4 – Images from Camera-Matching Video Analysis

MOTION ANALYSIS

The video analysis described in the previous section yielded the earth-fixed x , y , and z coordinates of the vehicle CoM and the yaw, pitch and roll angles of the vehicle at 10 millisecond intervals throughout the first 2 seconds of the test. For the analysis presented here, the earth-fixed coordinate system was setup with the x -direction running along the initial travel direction of the rollover dolly and the test vehicle. The y -direction was oriented along the initial heading direction of the vehicle and the z -axis was oriented upward.

Once the vehicle's positions and orientations were obtained, they were used to calculate the velocities for the vehicle during the test. For instance, the following centered difference equation was used to obtain the vehicle's ground plane velocity throughout the test [11]:

$$v_{x-y} = \frac{\sqrt{(x_{t+\Delta t} - x_{t-\Delta t})^2 + (y_{t+\Delta t} - y_{t-\Delta t})^2}}{2\Delta t} \quad (6)$$

In this equation, x and y refer to the x and y coordinates of the vehicle's CoM, the subscripts $t+\Delta t$ and $t-\Delta t$ reference these coordinate values from time steps surrounding the time step of interest, and Δt is the duration of each time step.

Overall, it was found that the motion of the vehicle in the y -direction was negligible, such that the velocity of the vehicle in the x -direction (along the rollover track) was nearly identical in magnitude to the overall translational speed of the vehicle given by Equation (6). This x -

direction velocity was obtained with the following equation:

$$v_x = \frac{x_{t+\Delta t} - x_{t-\Delta t}}{2\Delta t} \quad (7)$$

Similarly, the following centered difference equation was used to obtain the vehicle's vertical velocity throughout the test:

$$v_z = \frac{z_{t+\Delta t} - z_{t-\Delta t}}{2\Delta t} \quad (8)$$

In this equation, z refers to the z -coordinate of the vehicle's CoM.

In general, the accuracy and precision of the velocities calculated with Equations (6), (7) and (8) will depend on the magnitude of the measurement uncertainties in the positional coordinates and on the time step used for the calculation. On the one hand, if too small a time step is used, the velocity calculations will be excessively sensitive to any measurement errors and will exhibit excessive uncertainty. On the other hand, if too large a time step is used, the velocity curves will suffer from over-smoothing error and the velocity peaks could be truncated.

To explore the degree to which measurement errors might affect the accuracy and the precision of the velocities calculated with Equations (7) and (8), the authors had a second analyst use the previously described camera-matching video analysis technique to obtain a second set of motion for the vehicle in the first