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Analysis of a Dolly Rollover with PC-Crash

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ABSTRACT

This paper evaluates the use of PC-Crash simulation software for modeling the dynamics of a dolly rollover crash test. The specific test used for this research utilized a Ford sport utility vehicle and was run in accordance with SAE J2114. Scratches, gouges, tire marks and paint deposited on the test surface by the test vehicle were documented photographically and by digital survey and a diagram containing the layout of these items was created. The authors reviewed the test video to determine which part of the vehicle deposited each of these pieces of evidence. Position and orientation data for the vehicle in the test were then obtained using video analysis techniques. This data was then analyzed to determine the vehicle's translational and rotational velocities throughout the test.

Next, the test was modeled using PC-Crash. The simulation was optimized to yield a reasonable fit with the actual test dynamics by changing the following parameters in PC-Crash: (1) the friction coefficient associated with each vehicle-to-ground impact; (2) the coefficient of restitution for vehicle-to-ground impacts; (3) the vehicle body stiffness; and (4) the vehicle suspension and damping. PC-Crash results were then compared to the actual dynamics data to determine how well the simulation matched the actual translational, vertical and roll velocities throughout the test. Comparisons were also carried out in terms of the vehicle's kinetic energy and the forces applied to the vehicle during each vehicle-to-ground impact. The input parameters to the final simulation are discussed, as are issues that came up in the modeling process. The current capabilities of PC-Crash for rollover modeling are discussed and suggestions are made for how PC-Crash might be improved for modeling rollovers.

INTRODUCTION

This paper explores the use of PC-Crash, a vehicular crash simulation software package, for modeling the dynamics of a dolly rollover test run in accordance with SAE J2114. The dolly rollover test was analyzed, first, using video analysis techniques to obtain the actual dynamics for the test. Next, the test was modeled using PC-Crash. These PC-Crash results were then compared to the actual dynamics data from the video analysis to determine the accuracy of the simulation. The degree to which PC-Crash is useful for rollover modeling within the contexts of accident reconstruction and safety system development is then discussed.

There is a fair amount of technical literature related to the use of PC-Crash for simulating vehicle and occupant motion during planar collisions [4, 12, 13, 14, 15, 21, 23, 24, 33, 34, 35]. However, the literature related to the use of PC-Crash for modeling rollovers is much more limited. While previous literature has included cursory discussion of the use of PC-Crash for modeling rollover dynamics [36], none of this literature has offered a rigorous evaluation of PC-Crash's ability to replicate the dynamics of an actual rollover, nor has it offered recommendations for improving rollover modeling within PC-Crash.

Reference 36, for instance, discusses the models within PC-Crash that are relevant to modeling rollover crashes (tire and suspension models, ground surface modeling, and the vehicle body-to-ground contact model) and then presents a basic validation of PC-Crash for modeling rollovers. This validation consisted of using PC-Crash to model two rollover crash tests and then visually comparing the overall vehicle motion between the tests and the simulations. While the authors of Reference 36

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obtained favorable visual agreement between the overall vehicle motion in the tests and the simulations, no comparisons were made between the translational and angular velocities and accelerations experienced by the test vehicles and those experienced by the vehicles in the simulations.

The present study attempts to improve on the prior work reported in Reference 36 by not only modeling the dynamics of a rollover crash test in PC-Crash, but by also offering a detailed comparison between the translational and rotational velocities exhibited by the vehicle during the crash test and those exhibited by the vehicle during the simulation. Accelerations and ground contact forces are also compared between the test and the simulation. A detailed comparison like this allows for greater insight into the strengths and weaknesses of PC-Crash as a tool for modeling rollovers within the contexts of accident reconstruction and vehicle safety system developmental work [3, 19, 20, 25, 26].

Second, this study attempts to improve on previous ones by identifying and discussing specific ways in which the models of PC-Crash could be modified to improve its suitability for rollover modeling. Along these lines, it should be stated that our experience with PC-Crash has led us to the conclusion that it is not, in its current form, a *predictive* tool for rollover modeling.[1] In other words, a user of PC-Crash cannot simply put in a vehicle's initial conditions, hit "Go", and expect that the software will generate the same vehicle motion that would be realized in the real-world for those same initial conditions. This statement will not come as much of a surprise to experienced users of PC-Crash or to those with a sense for the chaotic nature of real-world rollover dynamics.[2]

Given that, we hope it is clear that the research reported here does not constitute an attempt at validating PC-Crash for rollover modeling. Instead, it represents an exploration of the strengths and weaknesses of PC-Crash for rollover modeling. PC-Crash is a physics-based software package. Its validity for any particular application relates to the quality of the models it uses to calculate the magnitude and temporal variation of the forces applied to the vehicle. Its capabilities do have the potential to be improved through detailed examination and improvement of these models, and so, blanket dismissals of PC-Crash as a tool for rollover modeling are ill-considered. As the statistician George E.P. Box has said, "Essentially, all models are wrong, some are useful" [7].[3] The relevant question in this study is, therefore, this: To what degree and in what contexts is PC-Crash useful for rollover modeling?

Thus, this study has asked the following set of questions: Was it possible for PC-Crash to generate reasonable vehicle motion of a rollover crash test, assuming that motion is already known? If so, what parameter inputs were necessary? Were those parameter inputs physically realistic? What problems were encountered in the modeling? Were those problems due to deficiencies in the models of PC-Crash, or instead, were they due to deficiencies in our understanding of rollover dynamics? Answers to these questions lead naturally to a discussion of ways in which PC-Crash can be improved for rollover modeling.

In closing this introduction, two additional points should be made. First, it should be stated that the authors of this study have sufficient knowledge of PC-Crash and of real-world rollover dynamics to prevent our skill level from jading our evaluation of the capabilities of PC-Crash. Our experience with both rollover dynamics and PC-Crash simulation has occurred primarily within the realm of accident reconstruction. User skill level and expertise is an important issue for studying the capabilities of any modeling program and far too little attention has been paid to this issue within the literature related to PC-Crash, particularly in its application as a reconstruction tool. In at least one instance, a clear lack of skill and expertise led researchers to reach unwarranted conclusions about PC-Crash [17].

Second, the applicability of this study is confined to rollover modeling. A particular model within PC-Crash could be inadequate for one application, but entirely adequate for another [5, 7, 22, 32]. Thus, the results and discussion contained within this paper are only applicable to rollover modeling with PC-Crash. Along these same lines, it should also be stated that even within rollover modeling, PC-Crash could be adequate for one application and not for another. For instance, as we discuss later, PC-Crash may be a helpful tool for reconstructing the deceleration-time history for a rolling vehicle within the context of accident reconstruction. As rollover reconstruction techniques begin to move beyond a constant rollover deceleration rate approach, such simulation may become necessary in certain cases [8, 31]. That PC-Crash is useful for such a purpose, though, does not mean that PC-Crash is currently acceptable for use as a fully predictive rollover dynamics model.

THE DOLLY ROLLOVER CRASH TEST

The dolly rollover test considered here utilized a Ford sport utility vehicle. The test was run in accordance with the Society of Automotive Engineers Recommended Practice J2114, which 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 sufficient rate to initiate the rollover [9, 16]. The

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[1] In our experience, there is no basis for the statement found in Reference 2 that PC-Crash is "capable of determining vehicle paths, timing, number of rolls and most relevant rollover parameters" (emphasis added).

[2] Here, it should perhaps be stated that when we refer to rollover dynamics in this paper, we are referring to the phase of a rollover crash after which the roll has been generated. In other words, this exploration of rollover modeling within PC-Crash does not include the trip phase.

[3] *See also…*Wikipedia, *George E. P. Box*, http://en.wikipedia.org/wiki/George_E._P._Box (as of Dec. 9, 2008, 20:12 GMT).

vehicle is situated on the cart perpendicular to the initial velocity direction with an initial roll angle of 23 degrees. In the test considered here, 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. After exiting the dolly, the vehicle's driver's side wheels were the first to contact the ground and at the time this occurred the vehicle was traveling approximately 29.5 mph.

The images of Figure 1, which were captured by a high-speed camera located downstream of the roll, show the roll dynamics that occurred during this test. As these images show, the vehicle rolled one complete revolution.

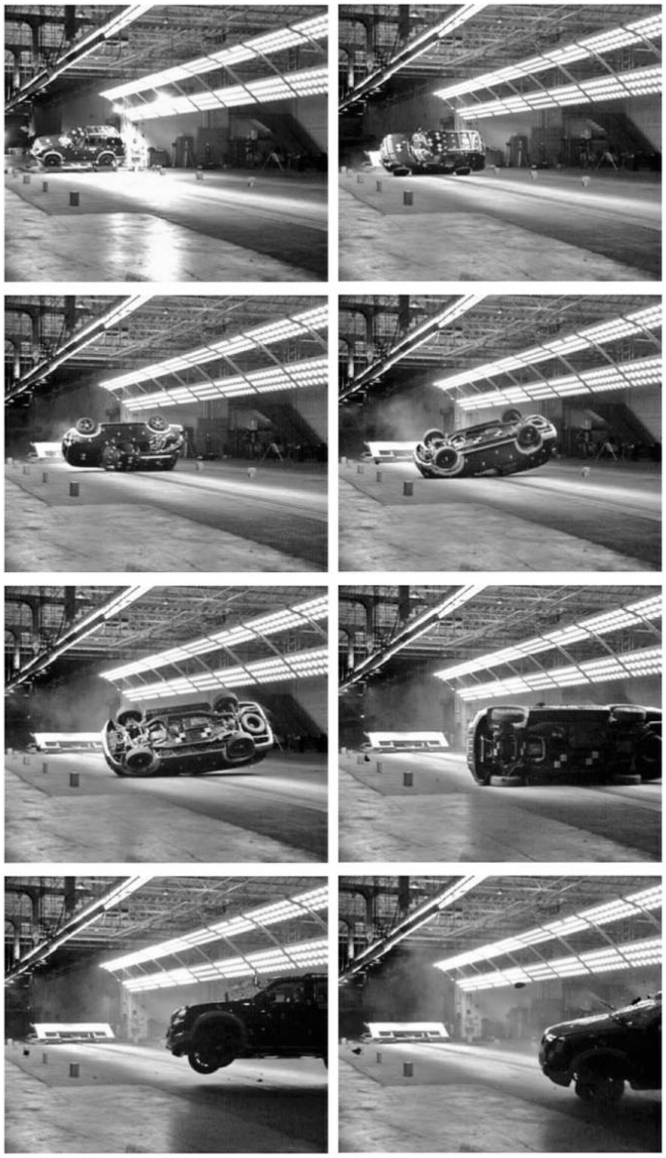


Figure 1 – Rollover Crash Test Dynamics

The vehicle was instrumented with sensors to measure the vehicle-fixed longitudinal, lateral and vertical accelerations at the center tunnel between the front 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 a frame rate of 29.97 frames per second.

Prior to the test, the overall geometry of the vehicle was surveyed as was the geometry of the crash test facility. These surveys were used in our video analysis of the test, as described in Reference 30. After the test, additional surveys of the vehicle and the test facility were conducted with the purpose of documenting the post-test condition of the vehicle and the test surface. The post-test facility survey included the locations of tire marks, scrapes, paint and material transfer, and rim imprints deposited by the vehicle on the test surface.

Figure 2 is a diagram that depicts certain features of the crash test facility along with the specific locations of evidence that the vehicle deposited on the test surface during the test. When optimizing the PC-Crash simulation of this crash test, the authors used Figure 2 as a background image for the simulation and sought to achieve motion of the vehicle that agreed with this physical evidence.

As Figure 2 shows, there were two locations at which the vehicle deposited paint. It should be noted here that this was grease paint that was placed along the upper parts of the vehicle's front door window frames prior to running the test, not the vehicle's body paint. This grease paint was placed on the vehicle with the intent that such transfer to the test surface would occur so that the locations of the roof rail-to-ground impacts could be more easily identified on the test surface.

Figure 2 depicts a number of other features of the crash test facility that were either used in our analysis of the test or that will be relevant to our discussion of the test. Specifically, Figure 2 depicts the location of the snubber rails that contained the pneumatic brakes which decelerated the rollover dolly, the metal cover of the tow cables, the location of film pit covers, and the location of expansion joints in the concrete surface (light gray lines in the figure).

The actual position and orientation of the vehicle for the first 2 seconds of the test was obtained at 10 millisecond intervals using camera-matching video analysis. Chou, et al., reported this technique in Reference 10 and then the results for the specific test under consideration here were reported in Reference 30 [Reference 11 reports additional analysis of this test, using finite element analysis.]. Once the vehicle's position and orientation at each 10 ms time step was obtained, this data was used to calculate the velocities, accelerations, impact forces and energy loss for the vehicle throughout the first two seconds of the test.

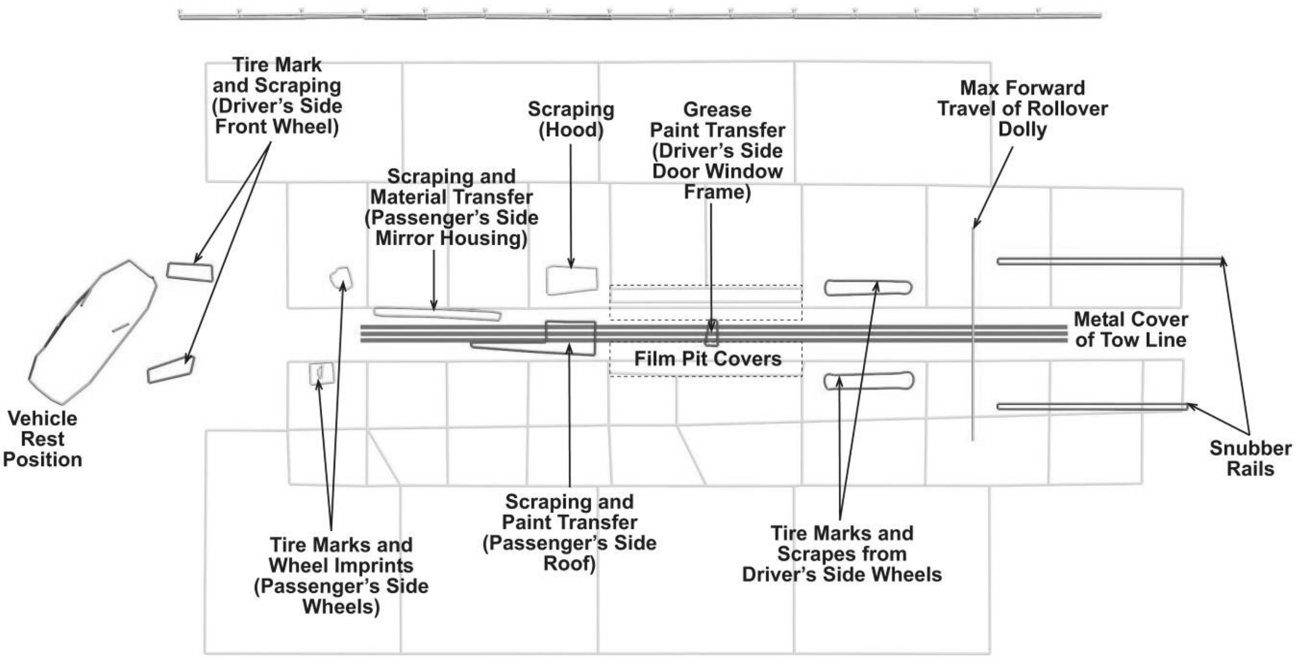


Figure 2 – Physical Evidence Diagram

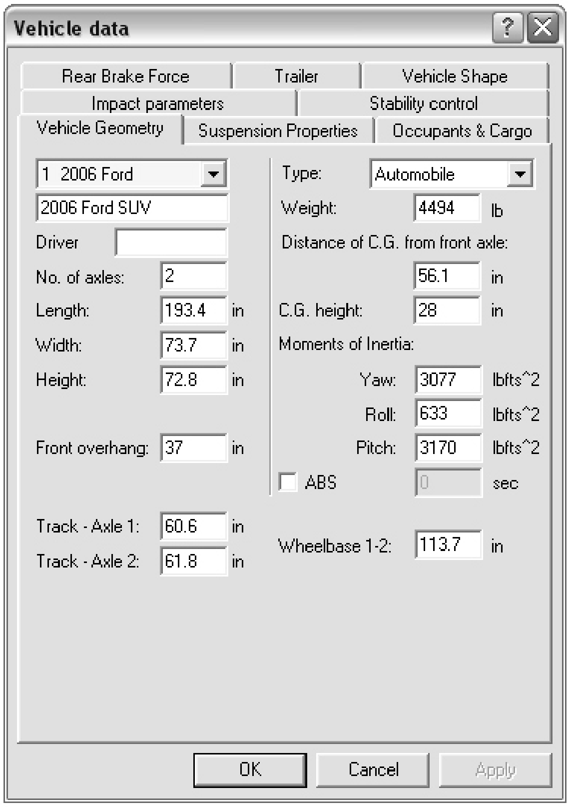
PC-CRASH INPUT PARAMETERS

This section describes the input parameters for the PC-Crash simulation reported in this paper. References 15 and 36 describe the PC-Crash tire and suspension models, the vehicle body-to-ground contact model, and methods for ground surface modeling within PC-Crash. The reader is referred to these references for the specifics about how each of these parameter inputs are used within PC-Crash.

Figure 3 shows the "Vehicle Geometry" inputs for the PC-Crash simulation reported in this paper. The dimensions of the test vehicle were obtained from our pre-test survey of the vehicle and from published vehicle specifications. The test vehicle weight was measured prior to the test and the moments of inertia were estimated using the formulas in References 1 and 21.

Figure 4 shows the vehicle suspension and body-to-ground impact parameter inputs. The maximum suspension travel was set at PC-Crash's default value of 3.94 inches (10.0 cm). The suspension and damping values shown in Figure 4 represent the values used in the final simulation reported later. Initially, these values were set at the default values calculated by PC-Crash. However, in the course of optimizing the simulation, the authors found it necessary to move away from the default values. These stiffness and damping values were set to achieve the best match with the known gross vehicle motion from the crash test.

As will be discussed later in this paper, the PC-Crash suspension model is not ideal for rollover modeling and the suspension and damping values in Figure 4 represent values that produced the best match with the overall gross motion of the vehicle, not values that produced the most accurate or realistic suspension response. This may be an acceptable approach as long as the analyst's primary interest is overall motion of the vehicle during the rollover and not any analysis of the loading on the suspension components. Still, the PC-Crash suspension model could be improved to provide a more realistic modeling for rollovers.



1 2006 Ford

2006 Ford SUV

Driver:

No. of axles: 2

Length: 193.4 in

Width: 73.7 in

Height: 72.8 in

Front overhang: 37 in

Track - Axle 1: 60.6 in

Track - Axle 2: 61.8 in

Type: Automobile

Weight: 4494 lb

Distance of C.G. from front axle: 56.1 in

C.G. height: 28 in

Moments of Inertia:

Yaw: 3077 lbfts^2

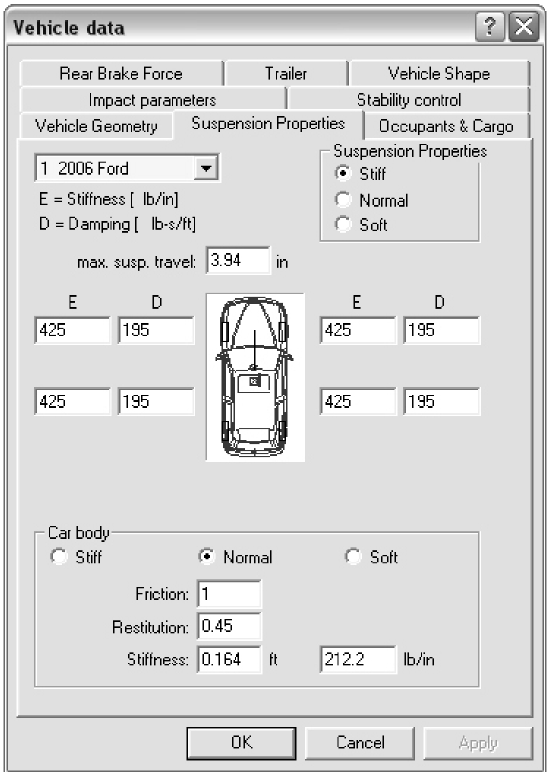
Roll: 633 lbfts^2

Pitch: 3170 lbfts^2

☐ ABS 0 sec

Wheelbase 1-2: 113.7 in

Figure 3 – Input Parameters
(Vehicle Geometric and Inertial Parameters)



1 2006 Ford

E = Stiffness [lb/in]
D = Damping [lb-s/ft]

Suspension Properties: ● Stiff ○ Normal ○ Soft

max. susp. travel: 3.94 in

E	D	E	D
425	195	425	195
425	195	425	195

Car body: ○ Stiff ● Normal ○ Soft

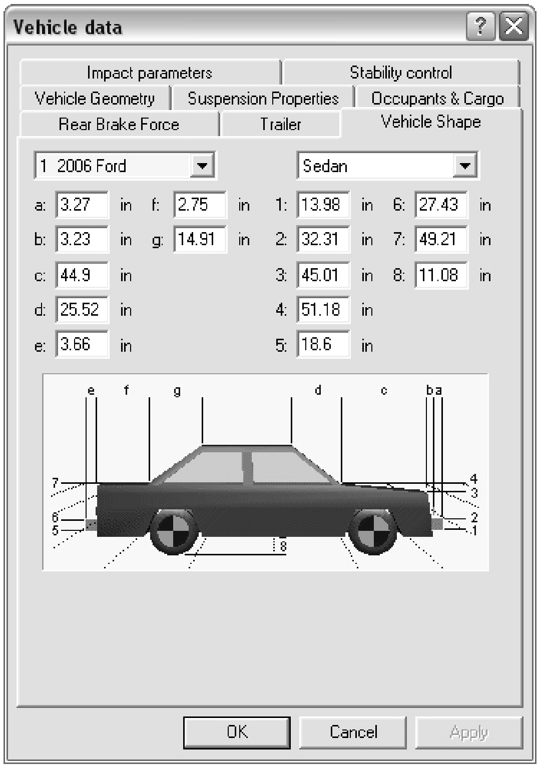
Friction: 1
Restitution: 0.45
Stiffness: 0.164 ft 212.2 lb/in

Figure 4 – Input Parameters
(Vehicle Suspension and Body Parameters)

The overall scene coefficient of friction in the PC-Crash file was set at a value of 1.0 as was the car body friction coefficient shown in Figure 4. The actual coefficients of friction for the specific vehicle-to-ground impacts during the simulation were controlled with friction polygons, as described below.

Figure 5 shows the “Vehicle Shape” parameter inputs used for the simulation. The authors selected the “Sedan” designation for the Ford because, within PC-Crash, this is the only vehicle type for which the user can change the vehicle shape parameters. The image of the sedan in Figure 5 is simply an image that accompanies this “Vehicle Shape” dialogue box in PC-Crash and it does not represent the vehicle shape used in our simulations. The specific shape parameters given in Figure 5 were estimated from our pre-test vehicle survey and vehicle specifications. The actual vehicle shape that these inputs produced can be viewed below in Figure 8.

In modeling this crash test, the authors utilized PC-Crash’s TM-Easy tire model. Figure 6 shows the longitudinal tire model parameters used in the final simulation. These same input values were also used for the lateral tire model parameters. Similar to the way in which the body-to-ground friction was handled, the actual tire-to-ground friction was handled using friction polygons. To obtain a good match with the actual roll velocity history for the subject crash test, the authors found it necessary to control the vehicle-to-ground (body or tire) friction coefficient on an impact-by-impact basis during our optimization of our simulations.

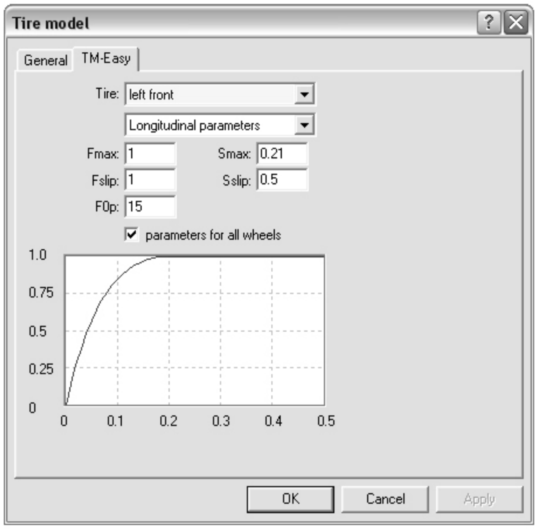


1 2006 Ford

Sedan

a: 3.27 in
b: 3.23 in
c: 44.9 in
d: 25.52 in
e: 3.66 in
f: 2.75 in
g: 14.91 in
1: 13.98 in
2: 32.31 in
3: 45.01 in
4: 51.18 in
5: 18.6 in
6: 27.43 in
7: 49.21 in
8: 11.08 in

Figure 5 – Input Parameters
(Vehicle Shape Parameters)



Tire: left front
Longitudinal parameters
Fmax: 1
Smax: 0.21
Fslip: 1
Sslip: 0.5
F0p: 15
☑ parameters for all wheels

Figure 6 – Input Parameters
(Longitudinal and Lateral Tire Model Parameters)

To achieve this, we set the tire and body friction multipliers to 1.0 and then used friction patches to set the friction for various phases of the simulation. Ultimately, we used six separate friction zones – one for each of four vehicle-to-ground impacts that occurred during the crash test and two for the final motion of the vehicle coming to rest. These friction patches are visible in Figure 7, which is a screen capture from PC-Crash. These friction coefficients were varied to obtain the best match with the actual crash test dynamics, particularly the actual roll velocity history.

In the simulation discussed below, we ended up with the following friction zones: (1) $\mu = 0.42$ for the first wheel-to-ground impact that occurred after the vehicle exited the dolly; (2) μ = 0.23 for the leading side roof-to-ground impact; (3) μ = 0.25 for the trailing side roof-to-ground impact; (4) μ = 0.10 for the trailing side wheel impact; and (5) friction zones of μ = 0.5 and 0.65 to bring the vehicle to rest at the correct location.

Figure 8 shows the setup of the initial conditions for the vehicle's position, orientation and velocity. These conditions were determined from our video analysis of the subject crash test, though small changes in these parameters were made to optimize the simulations. In short, these parameters were as follows: the initial position of the vehicle's center of mass above the ground, 3.95 feet; the vehicle's initial over-the-ground speed, 29.6 mph, the vehicle's initial roll angle, -23.0 degrees; the vehicle's initial roll velocity, -55.5 degrees per second. These inputs represent the vehicle conditions shortly after it exited the dolly.

RESULTS

The authors were able to obtain several simulations that exhibited acceptable agreement with the actual motion of the crash test. One of those simulations was chosen for the discussion here. In using the phrase *acceptable agreement*, we mean that, to a degree that would be considered acceptable in an accident reconstruction context, a simulation exhibited a reasonable match with the overall gross motion of the vehicle in the test. In this context, one would be determining the vehicle's translational and rotational velocities throughout the rollover, but the level of accuracy required would be driven primarily by a comparison with the accuracy that other reconstruction methods would be able to produce.

For instance, traditionally, rollover reconstruction has assumed a constant deceleration rate for the vehicle during the roll phase. Reference 8 demonstrated that this constant deceleration rate approach produces errors in the calculated translational and angular velocities. Reference 31 demonstrates that implementing a variable deceleration rate approach can accomplish significant improvement to the accuracy of the reconstructed translational and angular velocity histories. As Figure 11 below shows, our simulation of this crash test yielded good agreement with the actual translational velocity history, and therefore with the actual deceleration rate history, of the vehicle in the test. If one were able to obtain this level of accuracy for a reconstructed case, then one would have essentially implemented a variable deceleration rate approach and would have achieved a level of accuracy exceeding that achieved with traditional reconstruction techniques. Thus, this simulation can be given the designation "acceptable agreement". We leave it to those working in contexts other than accident reconstruction to judge from the data we present, whether this level of accuracy is sufficient for their purposes.

Figure 9 presents a side-by-side comparison of images from the crash test video and from the simulation. These images demonstrate that there was reasonable agreement between the gross vehicle motion in the crash test and the simulation. During the leading side roof-to-ground impact, though, the roll angle of the vehicle in the simulation does lag behind the roll angle of the vehicle in the crash test. Later, during the trailing side roof impact, the roll angle of the vehicle in the simulation gets out slightly ahead of the roll angle of the vehicle in the crash test. The vehicle in the simulation also appears to penetrate into the ground more than what is warranted by the actual vehicle deformation during the crash test. While the amount of penetration of the vehicle into the ground in PC-Crash can be affected by changing the body stiffness, such changes did not produce any clear improvement in the degree to which the simulated motion matched the actual motion.

Figures 10 and 11 are graphs that compare the test vehicle's actual and simulated ground plane and vertical speeds. For the ground plane speed, the simulation data exhibited good overall agreement with the trend of the actual dynamics data throughout the simulation. For the vertical velocities, the simulated vertical velocities follow the trends of the actual data through the first 1200ms. After this, the match between the simulation and the crash test degraded significantly.

Figure 12 is a graph that compares the test vehicle's actual and simulated roll angles. Between 700 and 1200 ms, the actual roll angle outpaced the simulated roll angle slightly. Later in the simulation, the simulated roll angle caught up and passed the actual roll angle. These differences relate to corresponding differences in the actual and simulated roll velocity histories. Figure 13 is a graph that compares the test vehicle's actual and simulated roll velocities. The overall trends of the curves are similar, though the simulated vehicle spent too little time at the peak roll rate and then, later in the simulation, had a roll rate that exceeded that of the actual.

Figure 14 is a graph that compares the test vehicle's actual and simulated kinetic energy and Figure 15 is a graph that compares the actual and simulated vertical impact forces applied to the test vehicle. For the kinetic energy, the simulation data exhibited good overall agreement with the trend of the actual dynamics data. The trends in, and magnitude of, the simulated impact forces showed reasonable agreement with the actual impact forces, through the first 1200 ms of the simulation. The impact forces associated with the roof-to-ground impacts in the simulation were slightly out of phase with the timing of these impacts in the test. The magnitude of the simulated forces associated with the first two impacts underestimated the actual and that associate with the third overestimated the actual.

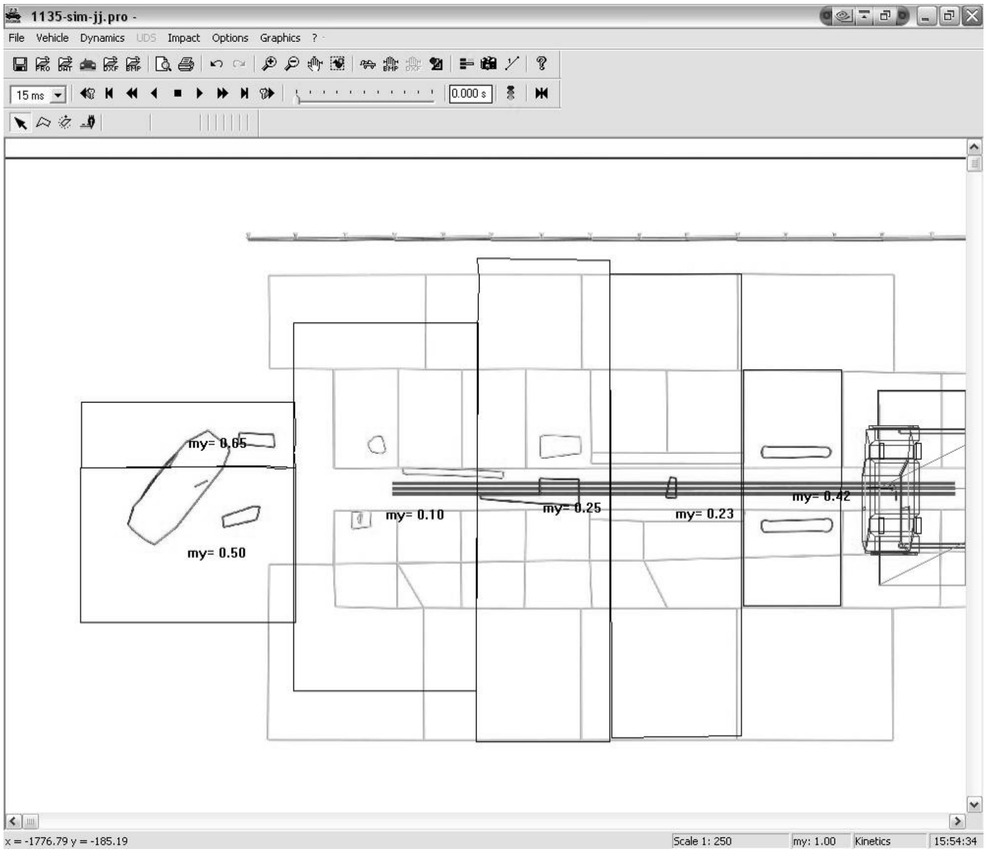
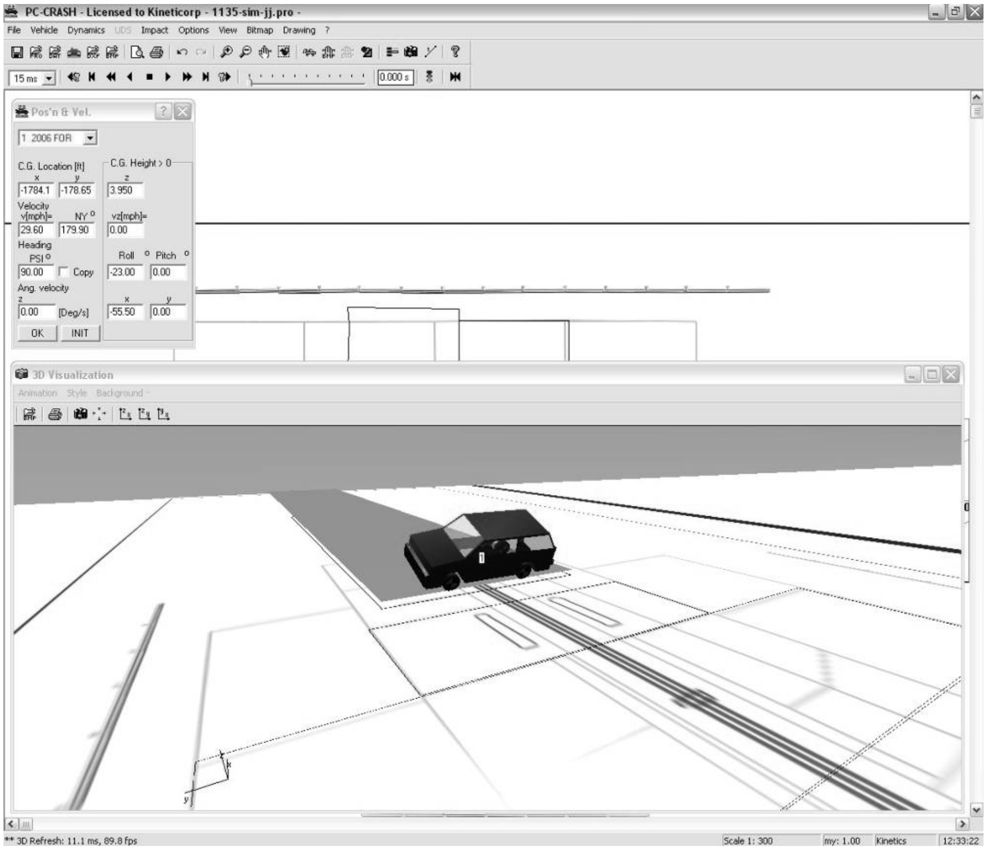


Figure 7 – Input Parameters
(Background Diagram and Friction Polygons)



1 2006 FOR

C.G. Location [ft] x: -1784.1 y: -178.65

C.G. Height > 0 z: 3.950

Velocity v[mph]= 29.60 NY °: 179.90

vz[mph]= 0.00

Heading PSI °: 90.00 ☐ Copy

Roll °: -23.00 Pitch °: 0.00

Ang. velocity z: 0.00 [Deg/s] x: -55.50 y: 0.00

Figure 8 – Input Parameters
(Initial Position and Velocity Conditions)

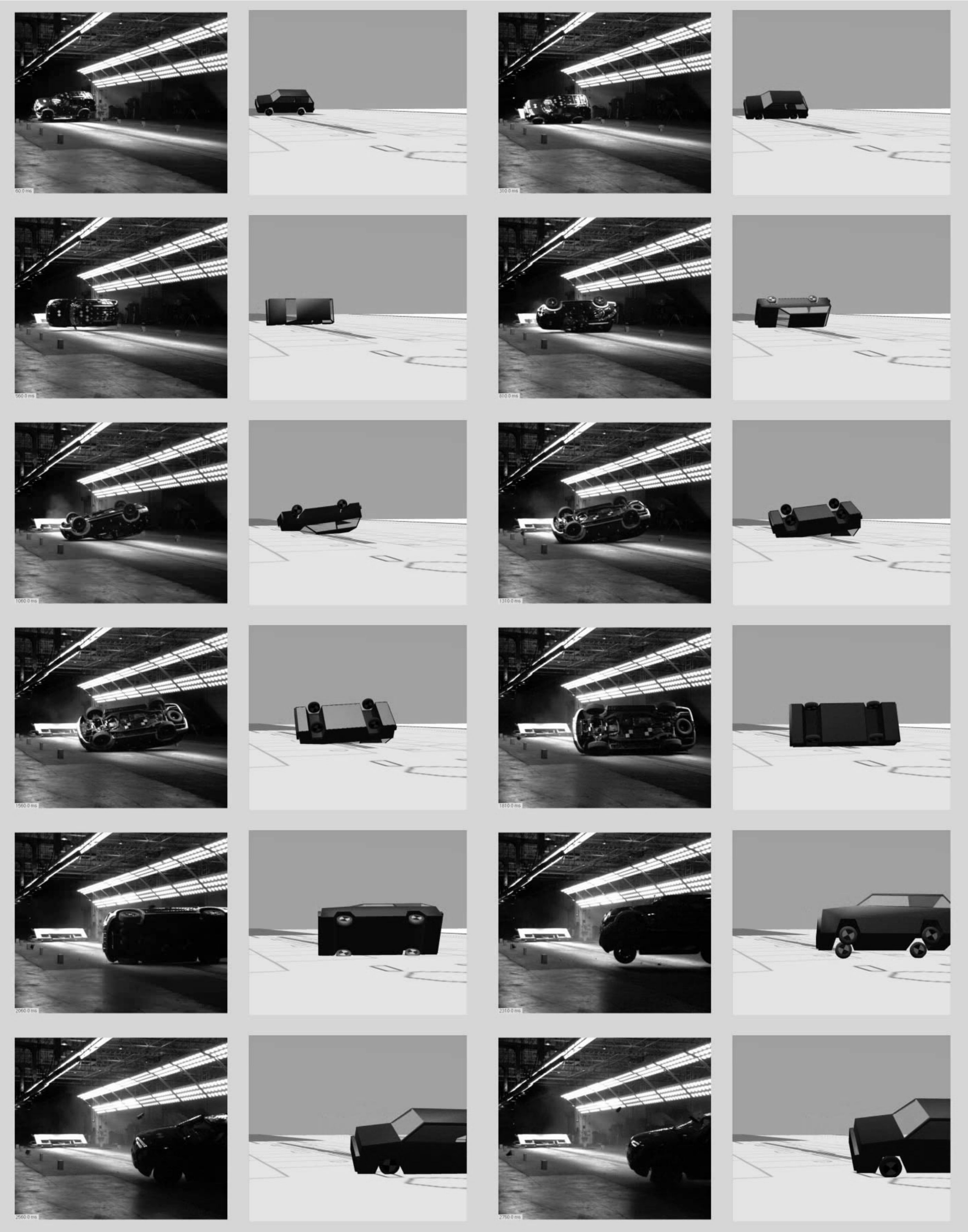


Figure 9 – Comparison of Simulation with Test Video

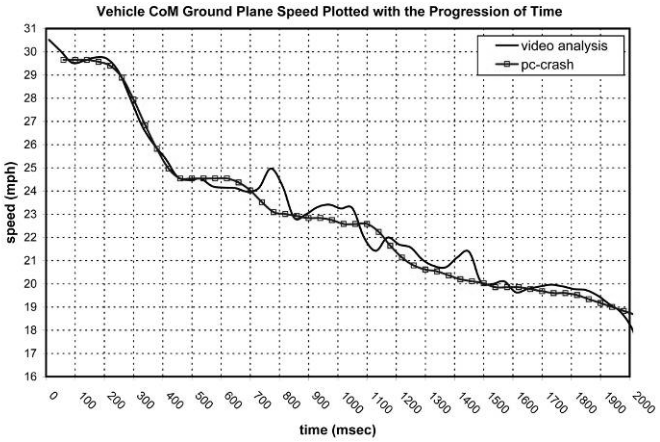


Figure 10 – Comparison of Test and Simulation
(Over-the-Ground Speed)

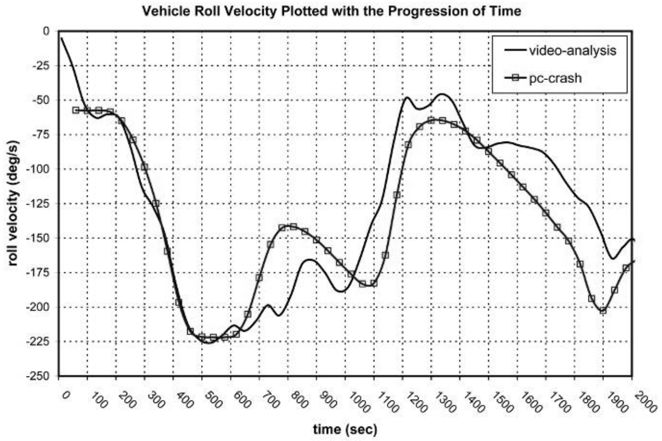


Figure 13 – Comparison of Test and Simulation
(Roll Velocity)

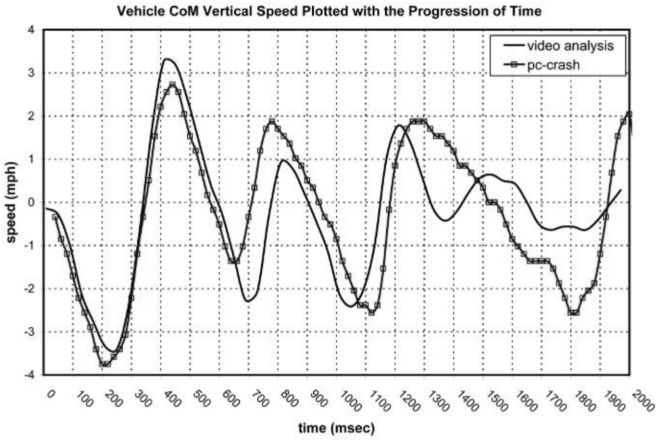


Figure 11 – Comparison of Test and Simulation
(Vertical Speed)

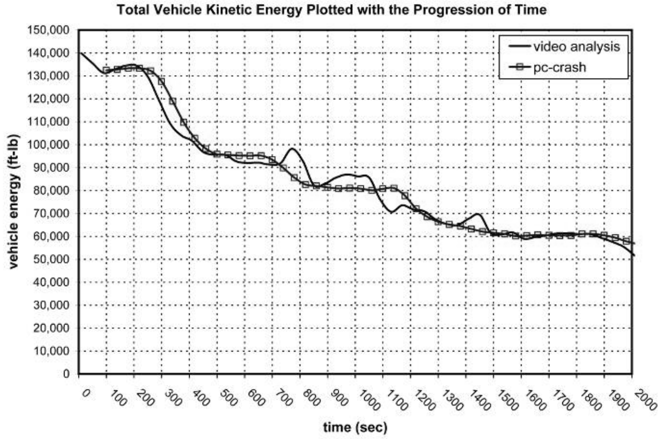


Figure 14 – Comparison of Test and Simulation
(Vehicle Kinetic Energy)

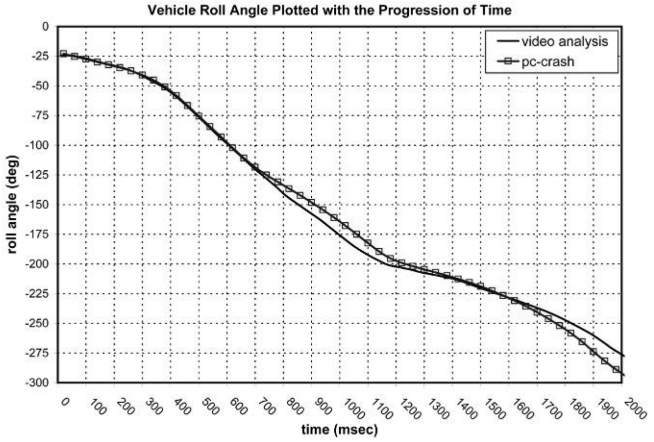


Figure 12 – Comparison of Test and Simulation
(Roll Angle)

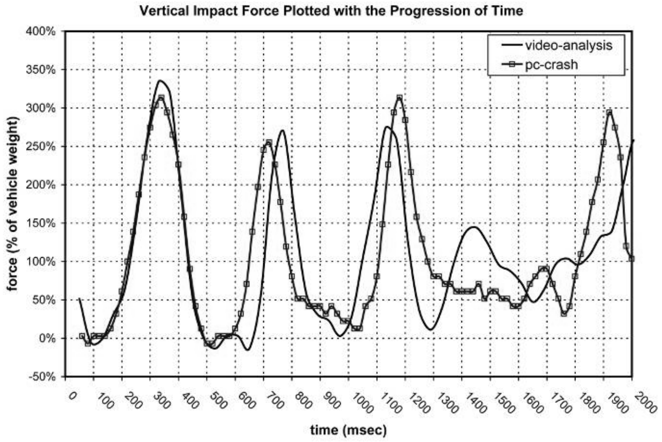


Figure 15 – Comparison of Test and Simulation
(Vertical Impact Force)

DISCUSSION AND CONCLUSIONS

The dominant variables affecting the accuracy of our PC-Crash simulations were the vehicle-to-ground friction coefficients, the vehicle suspension stiffness and damping, and the car body restitution. As we have previously stated, to obtain good agreement between the actual and simulated vehicle motion, we found it necessary to control the vehicle-to-ground friction on an impact-by-impact basis. This was accomplished in PC-Crash with the use of friction polygons, with the friction coefficient of each polygon being set at a value that yielded the best fit with the actual roll velocity history for the vehicle.

Matching the roll velocity history led naturally to good agreement with the translational velocity history. This is consistent with the conclusions of Reference 31, which used a planar, impulse-momentum impact model to demonstrate a relationship between the roll velocity history experienced by a vehicle and the vehicle's deceleration rate history. That model is depicted below in Figure 16.

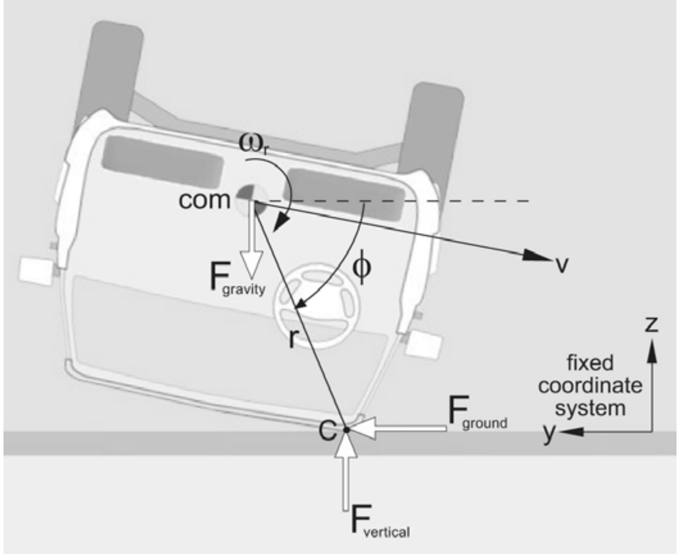


Figure 16 – Planar, Vehicle-to-Ground Impact Model

The vehicle in this figure is depicted in an inverted orientation with the driver's side roof impacting the ground. The vehicle has velocity both along and into the ground and a roll velocity that contributes to the speed with which the roof impacts the ground. As a result of this impact, the vehicle is subjected to an impact force that consists of both vertical and ground surface components. The geometry of the impact is defined by the impact radius, which is the distance from the vehicle center-of-mass (CoM) to the point at which the impact force is applied, and the impact angle, which is the angle between the ground plane and the impact radius.

The impact angle and impact radius are designated with the symbols ϕ and r. The velocity vector is designated with the letter v and the vehicle's roll velocity is designated ω_r. 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. A full treatment of this model, using the principle of impulse and momentum, is contained in References 28 and 29. Suffice it to say, here, that in Reference 31 this model was utilized to obtain the following equation:

$$f_{impact} = \left[\frac{k_r^2}{r}\right] \cdot \left[\frac{\mu}{\mu \cdot s\phi - c\phi}\right] \cdot \left[\frac{\Delta\omega_r}{g\Delta t}\right]$$

In this equation, f_{impact} is the average ground plane deceleration rate for a vehicle during a vehicle-to-ground impact, μ is the impulse ratio or vehicle-to-ground friction coefficient, Δt is the impact duration, and $\Delta\omega_r$ is the change in roll velocity that occurs during the impact. The significance of this equation is that it demonstrates a relationship between the average deceleration rate experienced by a vehicle during a ground impact and the change in roll velocity experienced by the vehicle during that impact. Further, it demonstrates that this relationship is mediated through the vehicle-to-ground friction coefficient. This equation, therefore, embodies our findings during this study that, first, controlling the friction coefficient on an impact-by-impact basis was essential to obtaining a good match with the vehicle's roll velocity history, and second, that once such a match was obtained, a match with the vehicle's translational velocity history follows naturally.

This finding is significant for accident reconstruction and indicates that PC-Crash could potentially be used to reconstruct the deceleration history for a vehicle during a rollover. To do this, the reconstructionist would first reconstruct the vehicle's roll motion spatially based on physical evidence. Then, the vehicle's speed at the beginning of the rollover could be calculated using a constant deceleration rate. The vehicle's initial roll rate could be estimated based on models available in the literature [6] or based on simulation. Starting with these initial conditions, the motion of the vehicle could be simulated to match the spatial reconstruction. In generating a simulation that matched the reconstructed roll motion, one would inherently reconstruct the deceleration rate history. The accuracy of such an approach would clearly depend on the accuracy of the underlying reconstruction.

References 8 and 31 have demonstrated the importance of the deceleration rate history for certain aspects of rollover reconstruction and this topic is likely to receive additional attention in the future literature of accident reconstruction. In fact, it is possible that a parameter sensitivity study could be carried out with PC-Crash that would further illuminate the degree to which various factors influence a rolling vehicle's deceleration rate. Ultimately, it is the need to obtain accurate translational and angular velocity histories that might lead a reconstructionist to invest the extensive time necessary to obtain an accurate simulation of a rollover crash. The accuracy of the reconstructed instantaneous velocity histories becomes relevant and significant when one begins to consider a rollover on an event-by-event basis [28, 29] and when one uses mathematical models to analyze occupant dynamics [Reference 18, for instance].

In conducting our simulation work for this study, we also found that it would have been beneficial to be able to control the coefficient of restitution on an impact-by-impact basis. Since PC-Crash does not give the user this ability, we chose a value for the coefficient of restitution that yielded the best overall match between the simulated and actual motion. The value of the coefficient of restitution used in the simulation discussed here (0.45) fell within the range of values reported in Reference 28 for this specific crash test. However, when compared on an impact-by-impact basis, this value agrees relatively well with the coefficient of restitution for the first wheel-to-ground impact, but is significantly higher than that for either of the wheel-to-ground impacts.

The approach of selecting a single coefficient of restitution to obtain the best match with the actual vehicle motion would be less feasible for cases where the vehicle rolled more than one time. In such a case, controlling the coefficient on an impact-by-impact basis would be essential because the user would be unlikely to find a single value for this parameter that would give a reasonable match with the known vehicle motion over multiple rolls. Of course, controlling this parameter on an impact by impact basis would be cumbersome if it had to be done manually. Perhaps a more promising approach would be to implement an equation within PC-Crash that would vary the coefficient of restitution automatically based on the impact conditions. Such relationships have been developed for other facets of crash simulation [27]. Of course, different restitution relationships would likely be necessary for impacts with different vehicle structures. As it stands now, a user attempting to simulate a crash of multiple rolls would likely have to split the rollover up into segments, say from airborne phase to airborne phase, and simulate each of these segments independently.

This would also be the case with the suspension parameters, since for a multiple roll crash, the analyst would be unlikely to find a single combination of suspension stiffness and damping that produced an acceptable match with the entire roll phase. The authors do not have sufficient data to determine if the suspension properties we employed in the simulation discussed here are realistic. We presume they are not since the specific values used result as much from a quirk in the way that PC-Crash handles wheel-to-ground impacts, as anything else. Based on our experience with PC-Crash, it seems likely that the need to vary the suspension properties over the course of a rollover and the need to input potentially unrealistic values could be eliminated by making a conceptually simple improvement in the PC-Crash suspension model.

Currently, within PC-Crash, the user inputs a value for the maximum suspension travel. However, this is not actually the maximum suspension travel since PC-Crash simply doubles the suspension stiffness when this maximum suspension travel is reached. For rollovers, this doubling of the suspension stiffness doesn't appear to be sufficient. When using PC-Crash to model rollovers, we have encountered cases where a wheel-to-ground impact produced a force that caused the vehicle wheel to displace up into and even above the vehicle body. This is obviously not physically realistic. This could, perhaps, be resolved by having the software switch over to a rigid body impact model to calculate the impact force and energy loss associated with a wheel-to-ground impact in cases when the user-defined maximum suspension travel is exceeded. In this case, the energy loss for the wheel-to-ground impacts would be handled within PC-Crash in a manner similar to the way the body-to-ground impacts are handled. This would be more physically realistic, since as it stands, PC-Crash asks its suspension model to account not only for actual suspension compression, but also for tire and frame/body deformation.

This research does not represent a validation of the PC-Crash rollover model. Instead, what we have attempted to do in this research is to explore the following questions: Given PC-Crash, as it stands today, what parameters most affect the rollover motion that it yields? What values must be used for those parameters to yield a good match with the known motion from a crash test? Does the way that PC-Crash models rollovers need to change, given the answers to these previous question?

In response to these questions, we offer the following thoughts:

- Through the use of friction zones, PC-Crash currently gives the user the ability to control the vehicle-to-ground friction on an impact-by-impact basis. We found this capability essential to achieving a reasonable agreement with the actual vehicle motion in this case. Beyond that, it is physically realistic to expect the vehicle-to-ground friction to vary from impact-to-impact during a rollover. The "friction" associated with any particular vehicle-to-ground impact will, at least, depend on what parts of the vehicle are engaging the ground and on the structural properties of the ground surface.

- The PC-Crash suspension model could, perhaps, be improved for rollover modeling by switching to a rigid body impact model to calculate the impact force and energy loss associated with a wheel-to-ground impact in cases when the user-defined maximum suspension travel is exceeded.

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