A COMPARISON OF COMPUTER MODELING TO ACTUAL DATA AND VIDEO OF A STAGED ROLLOVER COLLISION

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ABSTRACT

Vehicle accidents in which the automobile "rolls over" or overturns are among the most difficult accidents to reconstruct. Vehicles typically overturn about their longitudinal axis and in highway speed rollovers can overturn multiple complete revolutions. The accident reconstruction specialist is left to piece together the incident from physical evidence produced both on the vehicle and at the accident site. A number of works have been published by various authors detailing the methods for calculating many aspects of the accident. Using these methods the reconstruction professional is obliged to illustrate and present the accident using two-dimensional or three-dimensional drawings to illustrate the accident. One can also use such a diagram to produce an animation of the accident. These animations are based on one's own conceptualization of the accident as physical evidence reveals, but they are not the result of the extensive time step calculations of vehicle dynamics that can be done with computer reconstruction software.

As the computer has become more powerful and faster, physics based modeling programs have been developed to aid the reconstruction professional with the analysis of automobile accidents. For the most part, accident reconstruction software packages do not contain detailed component/suspension modeling capability. However, for the purposes of accident reconstruction, the models in these software packages are more than sufficient to model an accident scenario such as a vehicle tumbling or rolling over.

In this paper, a reconstruction of a staged rollover accident involving an SUV type vehicle will be presented. The subject rollover is a staged un-tripped rollover. The test vehicle overturns because of frictional forces at the tires imparted by steering inputs. This rollover is modeled using PC Crash™. The test site was well documented after the event and pertinent physical data was recorded. Damage produced on the vehicle as a result of the rollover is also well documented. Numerous video cameras were used to record the rollover from a variety of vantage points. All of this information is used in conjunction with the software to demonstrate how properly used software can effectively model a rollover accident. If rollover accidents can be accurately modeled, then the data may be used in developing vehicle safety and occupant protection systems.

INTRODUCTION

In recent years rollover accidents have become more significant in number. Computer modeling is becoming more widely used for the reconstruction of rollover accidents. PC-Crash is a modeling program which is able to simulate the vehicle motion during rollover events. The accuracy of any accident reconstruction depends heavily on the available evidence used in analyzing the event. The accident reconstruction professional is obliged to ascertain whether sufficient information is available to draw whatever level of conclusions are desired.

Over the past years modeling programs have become powerful tools to aid in determining vehicle and occupant motions. PC-Crash is just one of the programs which have gained popularity over the past few years. PC-Crash has been validated in many studies and has proven its accuracy and capability (1-3). Studies have even shown that occupant motion can be determined by coupling PC-Crash and MADYMO (4). The majority of these studies have not necessarily included rollovers.

Although rollover accidents are among some of the most difficult to accurately reconstruct, PC-Crash has been found capable of determining vehicle paths, timing, number of rolls and most relevant rollover parameters (5). In this study, the vehicle motion prior

to and during the rollover event is determined using PC-Crash, version 7.3.

Rollover simulations to model occupant kinematics have been published in peer reviewed publications as early as 1984 (6). Shortly thereafter three-dimensional rollover modeling of occupant kinematics using ATB and MADYMO begin to appear in publication (7-9). Next, complete vehicle and occupant kinematics were modeled within MADYMO and demonstrated a good match to FMVSS 208 test data.(10,11). The combined use of MADYMO and a separate vehicle dynamics prediction program approach appeared in publication in 1999 (12) Direct simulation by extracting vehicle motion and accelerations from NTSHA crash data has been limited due to the unreliable data rendered by the rollover crash sensing for these tests (13). This difficulty in rollover crash sensing was acknowledged and addressed by Viano, et. al. in a research program aimed at defining rollover sensing requirements to activate belt pretensioners, roof-rail airbags and convertible pop-up rollbars. (14) Here is an interesting excerpt:

Throughout the [research] program, mathematical simulation was used to assure robust testing, sensing and algorithms. The mathematical models were applied to each specific test condition, validated and used for evaluation of parameters influencing rollover sensing requirements. The simulations were found to be robust representations of a vehicle rollover. Two simulations tools were used: PC-Crash, which simulates vehicle dynamics and the rollovers, and Madymo, which simulates occupant kinematics in the vehicle. Madymo allows the quick study of various safety systems to prevent ejection and interior impact injury. **Excellent comparability was demonstrated between the tests and simulation.** [Bold Emphasis Added]

In this study, a staged rollover collision is reconstructed using a computer simulation program known as PC-Crash. The results of the PC-Crash reconstruction were compared to results from a conventional hand reconstruction and data collected from the staged rollover collision. The hand reconstruction has been published in Collision magazine. (15)

PC-CRASH MODEL

PC-Crash utilizes physical vehicle data that can be obtained through several databases or data that can be actual measurements. Once the vehicle data has been entered, *sequences* are used to define braking/acceleration, steering, friction parameters, or vehicle geometry changes. These sequences are used to model the vehicle as it moves over the intended path.

The test vehicle for this event is a 1991 Ford Explorer XLT, 4-door, 4X2. The VIN is 1FMDU32X5MUD76298. The vehicle is equipped with a 4.0 L V-6 and an automatic transmission. The vehicle is loaded with sandbag ballast of 150 lbs for each seating position for a total of 750 lbs. The tires are Goodyear Wrangler RT/S P235/75R15. The vehicle data used in the PC-Crash model are shown in table 1 found in Appendix A.

The model has been overlaid onto a very detailed survey of the rollover site. This survey was performed with a Total Station type laser device and documents tire marks, scrapes, gouges, location of broken glass, and other pertinent information. The survey data was imported directly into PC-Crash.

SEQUENCES

PC-Crash uses sequences in order to provide inputs to the model and re-create the accident scenario. These sequences specify the vehicle steering, drag factors, timing, and other parameters, such as geometry changes to be input for the simulation.

- Sequence 1: Starts the model at 50 mph and last for 0.6 seconds. No braking or steering is applied during the first sequence. This sequence allows the vehicle to approach the first set of yaw marks.
- Sequence 2: Applies left steer to match the first set of documented yaw marks. No braking is applied during the yaw marks. The sequence last for 0.38 secs.
- Sequence 3: This sequence last for 4.5 secs and applies right steer to match the final yaw marks leading up to the point of roll. Steering was applied at the same rate and magnitude as the steering input in the staged rollover. (note: steering remains constant throughout the rest of the rollover sequences.)
- Sequence 4: At the end of sequence 3, sequences 4 and 5 are activated. The left rear tire breaks off of the vehicle and the friction is increased to 1 at the left rear tire location in order to account for any axle gouging.
- Sequence 5: Is a geometry change at the left rear tire position that is used to simulate the left rear wheel breaking from the axle.

- Sequence 6: Is a time sequence used to separate sequence 5 and sequence 7. At the left rear tire position the brake force is set to 500% to simulate the broken off wheel. Steering remains unchanged.
- Sequence 7: Is a second friction change used to simulate the right front wheel breaking from the vehicle and at the same time, sequence 8 is activated.
- Sequence 8: Is a second geometry change used to simulate the right front wheel breaking off.
- Sequence 9: Is used to finish out the simulation. The time is set for 15 sec, the steering is constant and the same as sequence 3, and the braking force for the two broken wheel are set at 500% to prevent any possibility of rolling.

The data for the sequences are presented in table 2 in Appendix B.

The results of the simulation show the vehicle approaching the first set of yaw marks at approximately 50 mph. The vehicle is traveling approximately 43 mph at the point of roll. The vehicle then rolls 4 complete revolutions and comes to rest in an upright position. Figure 1 shows the motion of the vehicle as indicated by the PC-Crash simulation.

COMPARISON OF SIMULATION TO ACTUAL DATA

The results of the simulation were compared to the prior reconstruction and the actual data collected at the time of staged rollover. The data from each of the four rolls are compared in table 3 located in Appendix C. As can be seen in the table, the results of the PC-Crash simulation very closely correlate to the data and manual reconstruction results.

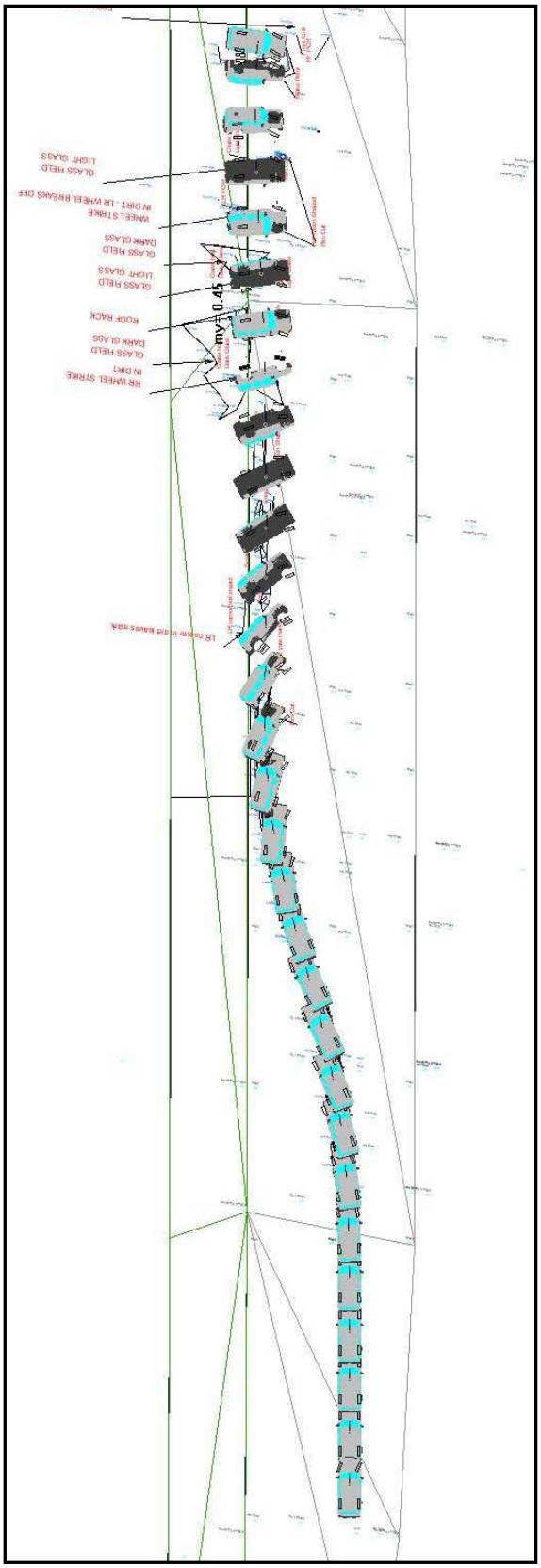

Figure 1: PC-Crash vehicle motion diagram.

PC-Crash was able to model the vehicle passing over the surveyed yaw marks. In figure 2 the heavy yaw marks are surveyed marks and the thin/light marks are yaw marks from the PC-Crash model. As can be seen in figure 2, the PC-Crash yaw marks very closely correlate to the surveyed yaw marks.

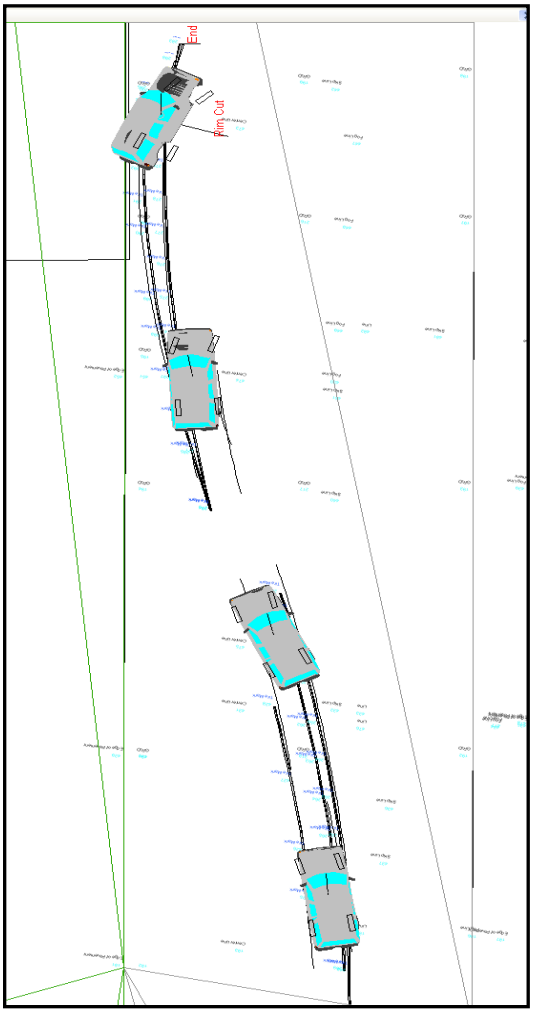

Figure 2: Vehicle positions during pre-roll yaw from PC-Crash. The heavy yaw

The following figures (*figures 3 through 6)* compare the position of each roll from the simulation to that of the hand reconstruction diagrams. The image on the top of each figure is the layout according to the hand reconstruction and the image on the bottom of each figure is from the PC-Crash output. In general, the positions during the rollover sequences are consistent. However, as can be seen, the angle of the vehicle varies in agreement between the two.

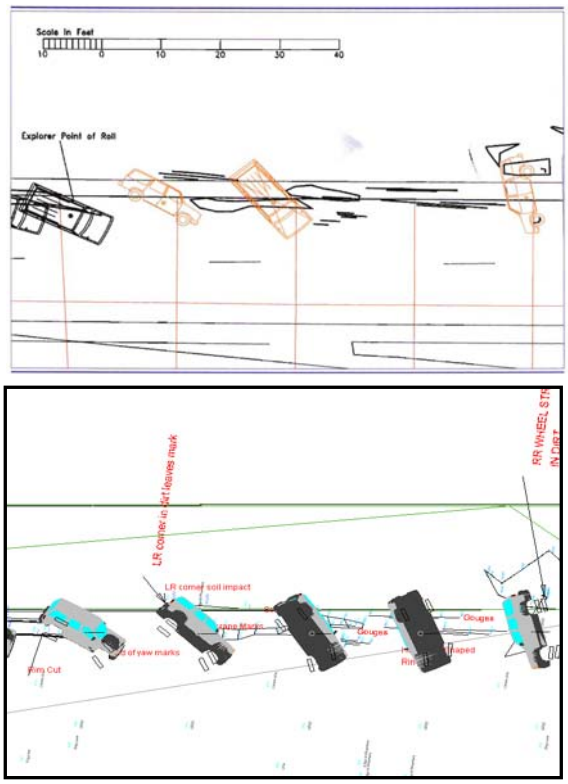

Figure 3: Roll 1 of the rollover sequence. Hand reconstruction results above and PC-Crash output below.

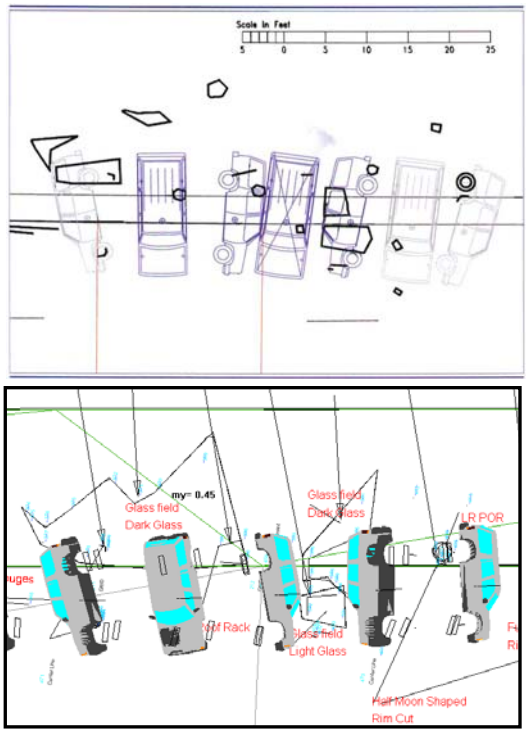

Figure 4: Roll 2 of the rollover sequence. Hand reconstruction results above and PC-Crash output below.

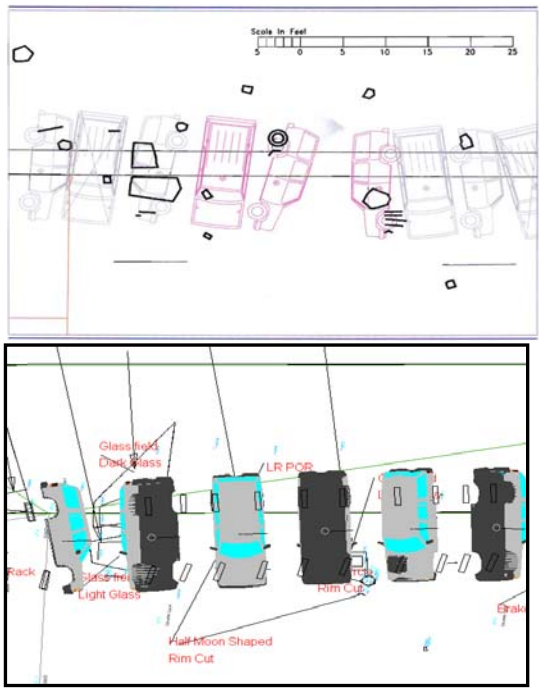

Figure 5: Roll 3 of the rollover sequence. Hand reconstruction results above and PC-Crash output below.

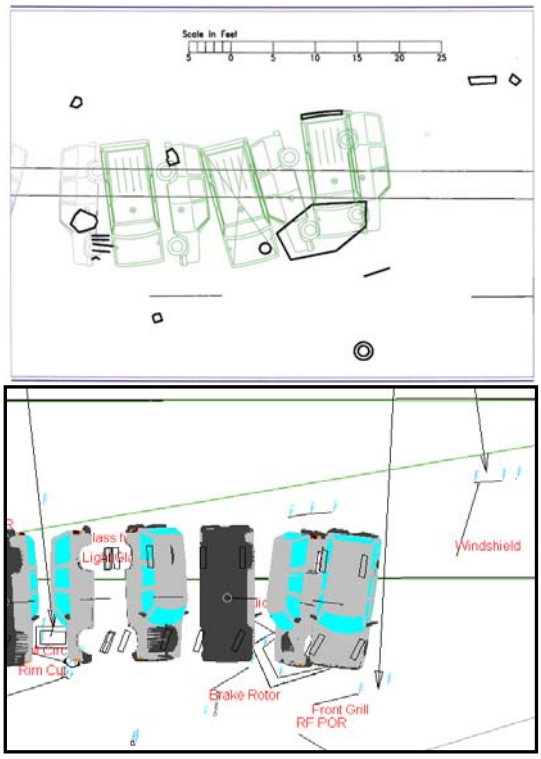

Figure 6: Roll 4 and the final rest position of the rollover sequence. Hand reconstruction results above and PC-Crash output below.

PC-Crash generates data and graphs of pertinent reconstruction results such as yaw rate, roll rate, acceleration, and other information. Yaw rate and roll rate were compared to actual data collected during the staged rollover. The figures below show the comparison of the data presented in the form of graphs.

As can be seen in figure 7 the yaw rate during the first yaw (left hand yaw) from PC-Crash very closely matches the data collected during the staged rollover. The data comparison of the second yaw (right hand yaw) shows that PC-Crash produced a slightly higher yaw rate than the actual data suggested. This is also shown in figure 2 with the left rear wheel of the model tracking just outside the surveyed yaw marks.

Figure 8 compares the roll rate from recorded data and PC-Crash. It should be noted that the roll rate exceeded the capability of the instrumentation at 350 deg/sec. PC-Crash indicates that the peak roll rate was approximately 520 deg/sec., and occurred during the time when the instrumentation clipped data at the maximum. The graph shows that PC-Crash data

closely matched the actual data before and after the truncation at 350 deg/sec.

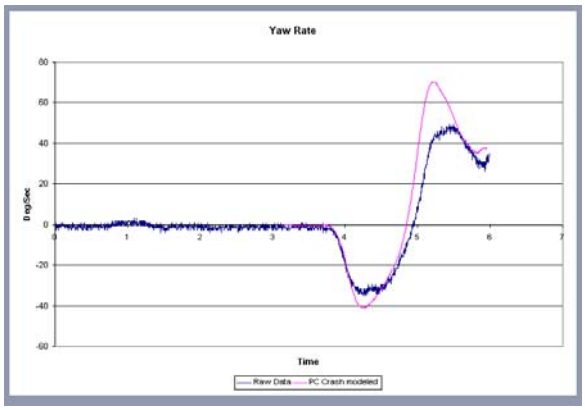

Figure 7: Yaw rate comparison of data from staged rollover and PC-Crash model.

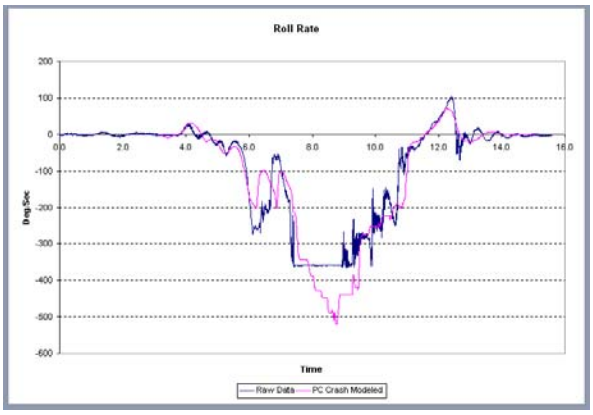

Figure 8: Roll rate comparison of data from staged rollover and PC-Crash model.

An additional feature of PC-Crash is the ability to produce real time videos of the simulation. Figures 9 and 10 compare the video frames of the PC-Crash simulation to videos of the actual staged rollover.

Figures 9 and 10 illustrate the comparison of the vehicle positions at the Point of Roll and the Point of Rest, respectively. In the PC-Crash model, the vehicle comes to rest at the documented Point of Rest. However, the final rest position in PC-Crash is approximately 15 deg clockwise of the documented Point of Rest for the staged rollover.

Figure 9: Compares the Point of Roll form PC-Crash (upper image) to an actual video frame of the rollover (lower image).

Figure 10: Compares the Point of Rest form PC-Crash (upper image) to an actual video frame of the rollover (lower image).

CONCLUSIONS

PC-Crash was successfully utilized to reconstruct the staged rollover collision. The PC-Crash reconstruction showed the speed of the vehicle at the point of roll to be within 2.1 mph of the actual data. The number of rolls and the vehicle path during the yaw phase and the rollover phase were consistent between PC-Crash and the collected data.

There were slight deviations in the vehicle position angles throughout the rollover sequences. However the vehicle locations were consistent with the hand reconstruction and evidence documented in the survey.

The yaw rate recorded in PC-Crash was slightly higher than data suggested but followed similar trends. Roll rates calculated by PC-Crash also followed similar trends as the actual data collected during the rollover.

Although the final point of rest in the PC-Crash model was consistent with the surveyed data, PC-Crash showed the vehicle point of rest rotated approximately 15 deg clockwise of the documented point of rest.

In general, PC-Crash was able to accurately reconstruct the staged rollover collision based on the surveyed data. When compared to actual data, PC-Crash data followed similar trends and was consistent with data collected during the staged rollover collision.

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References

1. Cliff, William, and Andreas Moser. *Reconstruction of Twenty Staged Collisions with PC-Crash's Optimizer.* Maclnnis Engineering Associates. SAE 2001-01-0507. 2001.

2. Cliff, William, Darcy Montgomery. *Validation of PCCrash-A Momentum- Based Accident Reconstruction Program*. Maclnnis Engineering Associates. SAE 960885. 1996

3. Moser, Andreas, et al. *Validation of the PC-Crash Pedestrian Model*. DSD Linz. 2000.

4. Steffan, Hermann, Andreas Moser and B. C.Geigl, *A New Approach to Occupant Simulation Through the Coupling of PC-Crash and MADYMO," Graz University of Technology*. SAE 1999-01-0444. 1999.

5. Steffan, Hermann, Andreas Moser, *How to Use PCCrash to Simulate Rollover Crashes.* SAE 2004-01-0341. 2004.

6. Robbins, D.H. and D.C. Viano. *MVMA 2-D Modeling of Occupant Kinematics in Rollovers.* SAE 840860, 1984.

7. Obergefell, L.A., I. Kaleps, and A.K. Johnson. *Prediction of Occupants Motion During Rollover.* SAE 861876, 1986.

8. Ma, D., A.L. Rizer, and L.A. Obergefell. *Dynamic Modeling and Rollover Simulations for Evaluation of Vehicle Glazing Materials.* SAE 950050. 1995.

9. Cheng, H., A.L. Rizer, and L.A. Obergefell. *ATB Model Simulations of a Rollover Accident With Occupant Ejection.* SAE 950134. 1995.

10. Renfroe, D.A., J.F. Partain, J.F. and J. Lafferty. *Modeling of Vehicle Rollover and Evaluation of Occupant Injury Potential Using MADYMO. S*AE 980021. 1998.

11. Renfroe, D.A. and J.F. Partain. *Modeling of Occupant Impacts During Rollover Conditions.* SAE 2000-01-0854. 2000.

12. Bardini, R. and M. Hiller. *The Contribution of Occupant and Vehicle Dynamics Simulation to Testing Occupant Safety in Passenger Cars During Rollover.* SAE 1999-01-0431. 1999.

13. Martin, Mark R. and Kerry Allen. *A Comprehensive Evaluation of NHTSA Rollover Test Data For Use In Computational Model Validation.* ASME IMECE 2004-60809. 2004.

14. Viano, David C. and Chantal S. Parenteau. *Rollover Crash Sensing and Safety Overview.* SAE 2004-01- 0342. 2004

15. Wilson, Lawrence A., Gilbert, Michael, Godrick, Daniel A. *Reconstruction and Analysis of Steering-Induced, On-road, untripped SUV Rollover Test*, Collision, Vol 2, Issue 1, 2007

APPENDIX A

Table 1:
PC-Crash input data

Length [in] :	184
Width [in] :	70
Height [in] :	67
Number of axles :	2
Wheelbase [in] :	112
Front overhang [in] :	30
Front track width [in] :	59
Rear track width [in] :	59
Mass (empty) [lb] :	4142
Mass of front occupants [lb] :	303
Mass of rear occupants [lb] :	457
Mass of cargo in trunk [lb] :	0
Mass of roof cargo [lb] :	0
Distance C.G. - front axle [in] :	55.91
C.G. height above ground [in] :	28.75
Roll moment of inertia [lbfts^2] :	513.2
Pitch moment of inertia [lbfts^2] :	2875.5
Yaw moment of inertia [lbfts^2] :	2732.5
Stiffness, axle 1, left [lb/in] :	175.7
Stiffness, axle 1, right [lb/in] :	175.7
Stiffness, axle 2, left [lb/in] :	175.11
Stiffness, axle 2, right [lb/in] :	175.11
Damping, axle 1, left [lb-s/ft] :	237.19
Damping, axle 1, right [lb-s/ft] :	237.19
Damping, axle 2, left [lb-s/ft] :	236.4
Damping, axle 2, right [lb-s/ft] :	236.4
Max. slip angle,axle 1, left [deg]:	10
Max. slip angle,axle 1, right [deg]:	10
Max. slip angle,axle 2, left [deg]:	10
Max. slip angle,axle 2, right [deg]:	10

APPENDIX B

Table 2:
PC-Crash sequences

Sequence 1	
Velocity [mph] :	50.5
Time [s]	0.6
Brake force [%]	0
Sequence 2	
Time	0.38
Brake force [%]	0
STEERING	
Steering time [s] :	0.4
New steering angle [deg]	
Axle 1 :	13.34
Axle 2 :	0
Sequence 3	
Time [s]	4.5
Brake force [%]	0
STEERING	
Steering time [s] :	0.99
New steering angle [deg]	
Axle 1 :	-19
Axle 2 :	0
Sequence 4	
Friction change	
Friction coefficient (mu)	
Axle 1, left :	0.8
Axle 1, right :	0.8
Axle 2, left :	1
Axle 2, right :	0.45
Sequence 5	
GEOMETRY CHANGE	
Sequence 6	
Time [s]	0.95
Brake force [%]	
Axle 1, left :	0
Axle 1, right :	0
Axle 2, left :	500
Axle 2, right :	0
mean brake acceleration [g] :	-0.1
STEERING	
Steering time [s] :	0.99
New steering angle [deg]	
Axle 1 :	-19
Axle 2 :	0
Sequence 7	
Friction change	
Friction coefficient (mu)	
Axle 1, left :	0.8
Axle 1, right :	1
Axle 2, left :	1
Axle 2, right :	0.45
Sequence 8	
GEOMETRY CHANGE	
Sequence 9	
Time [s]	15
Brake force [%]	
Axle 1, left :	0
Axle 1, right :	500
Axle 2, left :	500
Axle 2, right :	0
mean brake acceleration [g] :	-0.2
STEERING	
Steering time [s] :	0.99
New steering angle [deg]	
Axle 1 :	-19
Axle 2 :	0

APPENDIX C

Table 3:
Comparison of manual accident reconstruction to PC-Crash

		Manual Reconstruction Results	PC-Crash Results
Roll 1	Speed at Point of Roll [mph]	44.8	42.7
	Distance [ft]	84	91
	Ave Speed [mph]	41	36
	Time [sec]	1.4	1.8
	Ave Roll Rate [deg/sec]	250	173
Roll 2	Distance [ft]	34	31
	Ave Speed [mph]	29	24
	Time [sec]	0.8	0.9
	Ave Roll Rate [deg/sec]	450	417
Roll 3	Distance [ft]	23	22
	Ave Speed [mph]	18	18
	Time [sec]	0.9	0.8
	Ave Roll Rate [deg/sec]	400	451
Roll 4	Distance [ft]	23	22
	Ave Speed [mph]	11	11
	Time [sec]	1.5	1.5
	Ave Roll Rate [deg/sec]	250	248