



An Analytical Review and Extension of Two Decades of Research Related to PC-Crash Simulation Software

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Abstract

PC-Crash is a vehicular accident simulation software that is widely used by the accident reconstruction community. The goal of this article is to review the prior literature that has addressed the capabilities of PC-Crash and its accuracy and reliability for various applications (planar collisions, rollovers, and human motion). In addition, this article aims to add additional analysis of the capabilities of PC-Crash for simulating planar collisions and rollovers. Simulation analysis of five planar collisions originally reported and analyzed by Bailey [2000] are reexamined. For all five of these collisions, simulations were obtained with the actual impact

speeds that exhibited excellent visual agreement with the physical evidence. These simulations demonstrate that, for each case, the PC-Crash software had the ability to generate a simulation that matched the actual impact speeds and the known physical evidence. Simulation of a full-scale rollover test reported by Asay [2010] is also examined. For this test, we obtained a simulation that exhibited an excellent visual match with the pre-roll tire marks and furrows and in which the vehicle rolled 7 times, just as it did in the actual test. The rest position of the vehicle was well matched, though a portion of the simulated roll trajectory did not match the actual roll trajectory. These areas of additional analysis extend the prior literature.

Introduction

PC-Crash is a vehicular accident simulation software that is widely used by the accident reconstruction community. This article reviews the prior literature that has addressed the capabilities of PC-Crash along with its accuracy and reliability for various applications (planar collisions, rollovers, and human motion). In addition to reviewing the literature, this article also adds additional analysis of the capabilities of PC-Crash for simulating planar collisions and rollovers. Simulation analysis of five planar collisions originally reported and analyzed by Bailey [2000] are reexamined. Simulation of a full-scale rollover test reported by Asay [2010] is also examined. These areas of additional analysis extend the prior literature.

The intent of this study is not to promote the use of PC-Crash over and above the use of other simulation software packages available to accident reconstructionists. Other widely used and broadly tested simulation tools are available and in use by accident reconstructionists. A similar study summarizing and expanding the literature for these other simulation tools would also be useful and could be pursued as further research. Many of the terms introduced here and the issues addressed are relevant and applicable to these other simulation tools.

The intent of this study is also not to make the claim that PC-Crash is "fully" validated. Instead, the intent is to help define (or at least summarize through a literature review) the boundaries within which PC-Crash has been validated and

to further advance that validation. All simulations of real systems have their limitations and the boundaries within which they are valid will always be debated. The key is for the user to recognize the limitations of a software, and then, to put in the effort to understand the physical models that software uses.

Before delving into prior studies related to PC-Crash, several terms related to simulation validation will be defined. The definitions and concepts presented here are drawn from articles by Kleijnen [1995], Balci [1997], Robinson [1997], Carson [2002], and Sargeant [2003].

Conceptual Model Validation: Along with all other simulation programs and reconstruction models, PC-Crash uses *conceptual models* that attempt to mimic real world systems. Examples would be the tire and suspension models in PC-Crash. The validity of these conceptual models could be evaluated and demonstrated independent of their implementation in PC-Crash, a process that can be termed *conceptual model validation*. An example would be to compare the PC-Crash tire model to real-world tire data to determine the degree to which the model accurately mimics the behavior of real tires. One important idea to keep in mind here is that the degree to which the model must mimic the real-world system in order to be valid depends on the application to which it is being applied. A tire model intended for accident reconstruction will typically require less sophistication than one intended for predictive vehicle dynamics simulation (predicting the conditions under which a vehicle will roll over, for example).

Calibration: Conceptual model validation could also relate to model *calibration* where the validity of the model is assumed to have been demonstrated and its use is a matter of inputting physically realistic inputs to obtain correct results. An example of this would be to use tire data and curves from Brach's tire modeling publications [2000, 2005, 2008, 2009] to determine reasonable inputs into the PC-Crash TM-Easy tire model. Again, the issue of using reasonable inputs into the model and calibrating the model to generate realistic outputs is not unique to PC-Crash, but applies to any physics model used by accident reconstructionists.

Verification: Each of the conceptual models used by PC-Crash also has its implementation within the software, through the computer code underlying the software. The process of ensuring that these conceptual models are correctly implemented in the code is referred to as *verification*. Verification aims at eliminating any programming errors. Most validation studies of PC-Crash and other simulation software packages assume the software developers have adequately addressed this task.

Operational Validation: Operational validation involves ensuring that the implemented conceptual models, when they are all combined in the software, produce a sufficient level of accuracy when compared to the real-world process or system the model attempts to replicate. Carson [2002] noted that "sufficient accuracy means that the model can be used as a substitute for the real system for the purposes of experimentation and analysis..." Robinson [1997] notes that "a key concept is the idea of sufficient accuracy. No model is ever 100% accurate...the aim is to ensure that the model is sufficiently accurate...this accuracy is with reference to the purpose for which the model is to be used." Again, here, sufficient accuracy would be defined relative to the purpose for which the model will be utilized. Not only that, sufficient accuracy can also be defined in relationship to other available models. If a simulation tool produces accuracy levels comparable to other simulation tools, its accuracy could be considered adequate.

An example of demonstrating the operational validity of PC-Crash would be to compare simulations of crash tests to the measured data from the crash test. One issue that arises when assessing the operational validity of PC-Crash is the validity of the data input into the software. Some parameters needed to run an impact simulation in PC-Crash, such as the coefficient of restitution and the inter-vehicular friction, are not directly measurable from a crash test and calculation of these parameters contain uncertainties [Rose, 2007]. Some studies also ask the analyst to use values for input parameters that they would typically use in their accident reconstruction practice, rather than providing the reported values (a roadway coefficient of friction, for instance). In such instances, it should be recognized that uncertainties in the input values are influencing the error rates. That is, of course, the situation the reconstructionist is in when reconstructing real world crashes. Another way to setup a study would be to provide the analyst with all the known data from the crash test to decrease (though certainly not eliminate) the degree to which the user's knowledge and certainty enter into the results. This would focus the study more on the capabilities of the software.

A related issue is the degree to which user skill affects the simulation results. As the PC-Crash website at one time stated:

"PC-Crash is technical software for serious users. It's powerful and gives you a lot of freedom, so that you can simulate unique events. It therefore necessarily leaves you the option to make a mess. Don't let yourself do this." Clearly, some analysts and users of PC-Crash are more skilled than others. Independent of the validity of the underlying models in PC-Crash, the quality of the simulation produced by an analyst is not guaranteed. This is true not only of analysis conducted within PC-Crash, but of any simulation software or reconstruction technique.

This may seem like a self-evident point, but it is an important issue. A study examining the validity of PC-Crash will not be able to entirely isolate the capabilities of the models from the skill of the user applying the models. The results of validation studies are inevitably reporting an error rate that combines the error rate from the conceptual models of PC-Crash with the additional error rate introduced by the limits the user has. Such studies are still useful, but the underlying models of PC-Crash might be stronger and more robust than what these studies are able to demonstrate.

One could reasonably assume that the authors of validation studies related to PC-Crash are usually skilled users of the software. In the day-to-day practice of accident reconstruction, however, this may not be the case. Day [1989] raised this issue, noting that "misuse [of computer programs for accident reconstruction] is due to the lack of a thorough understanding of how the programs work...Just as the level of skill varies among investigators, the level of understanding how the programs work also varies. When properly used, these computer programs are an invaluable accident investigation tool. When misused, these programs can produce erroneous results - and a misconception of what actually occurred during the accident." Wach [2012] also raised this issue, noting that "it should be emphasized that PC-Crash is only a tool which gives correct results in so far as the data are correct and mathematical models for the investigated physical phenomena are relevant, therefore the final responsibility for the conclusions derived from calculations rests with the user...to use the program correctly knowledge of the dynamics of vehicles and collisions is indispensable..."

The authors of one study related to PC-Crash demonstrated how the results of from a simulation can produce unreasonable results when the user lacks the necessary knowledge and skill related to the software. This was exhibited in their study through countless misstatements about PC-Crash and also in their results [Fay, 2001]. This study was rebutted in a response from MacInnis Engineering Associates (MEA), the North American distributors of PC-Crash. Of note in the MEA response was the fact that Fay and his co-authors did not purchase PC-Crash until 7 weeks after the abstract for their paper was due. This Fay study is mentioned here, not for the purpose of criticizing it, but for the purpose of achieving a reasonably complete literature review. It will not be discussed further.

Credibility: Another issue related to validation is a simulation software's *credibility*. In a validation context, the term credibility refers to the confidence of the community of users in the simulation software. Wide use of a simulation software package like PC-Crash can be an indication that the relevant community accepts it and judges it valid. An indication of this would be the presence of studies in the literature that assume the validity of the simulation software.

Prior Studies - Planar Motion and Collisions

Studies Describing the Conceptual Models: The PC-Crash technical manual describes the theoretical models utilized by the software, and users should consult that manual for information related to the latest versions of the models. Beyond that, Steffan and Moser [1996] described the collision and trajectory models used by PC-Crash. The *trajectory* model utilizes the tire and suspension force models and can also account for trailer coupling forces. The *collision* model utilizes the principle of impulse and momentum, which utilizes a coefficient of restitution and a friction coefficient, or impulse ratio, that influences sliding and relative velocity along the inter-vehicular contact surface. This model assumes the impact force is applied instantaneously to each vehicle and at a single point. The collision model has the capability of incorporating a vertical component. This impact model is similar to the impact model described by Brach and Brach in their accident reconstruction text [2005], though PC-Crash has implemented this model in three dimensions. PC-Crash currently offers two tire models - the linear tire model and the TM-Easy tire model.

At the time of Steffan and Moser's publication, only the linear tire model was available. In relationship to the PC-Crash tire models, it should be noted that the PC-Crash trajectory model can operate in a three-dimensional context, and so, it can account for the transfer of weight between tires that occurs during a vehicle yaw. However, neither tire model accounts for the change in tire model parameters that occur under varying normal loads. Thus, while the PC-Crash trajectory model has been shown to be adequate for speed analysis purposes, it is unlikely to be adequate for modeling the handling properties and responses of a particular vehicle.

In 1998, Moser and Steffan described the implementation and use of automatic optimization (the "collision optimizer") within PC-Crash to achieve a reasonable match between the simulation and the actual post-impact trajectory of the vehicles (as defined by physical evidence) and their rest positions. They defined a quality function that would give an objective measure of how closely the simulation matches the evidence. Moser and Steffan stated that the "quality function defines the target of the optimization process. The assumption has been made, that the lower the difference between simulation results and real accident data...the closer the simulation is to the real case." The quality function is defined with the following equation, in which x_i refers to the difference between the actual and calculated values of a parameter (the center of gravity location at rest, for instance) and w_i refers to the weighting for each optimization parameter. These multipliers enable the analyst to weight one parameter more heavily than another - the distance traveled by a vehicle post-impact over the orientation of the vehicle at rest, for instance.

$$Q = \sqrt{\frac{\sum_i (w_i \cdot x_i)^2}{\sum_i w_i^2}} \cdot 100\%$$

PC-Crash currently offers two optimization routines - a genetic algorithm and a Monte Carlo algorithm. The 1998 study by Moser and Steffan demonstrated the use of linear and genetic algorithms (PC-Crash 11.0 does no longer includes the linear algorithm). Moser demonstrated the use of the Monte Carlo algorithm in a 2003 study.

Steffan and Moser [1998] also published an article describing the trailer simulation model of PC-Crash. This model enabled PC-Crash to consider the additional external forces (coupling forces) that would act on the towing and towed vehicles during driving maneuvers and collisions. Steffan and Moser illustrated the use of this model with several example implementations, including one simulation of a crash test involving a vehicle with a trailer.

In a book published in 2012, Wach described the physical models and assumptions used by PC-Crash, including the coordinate systems, the tire models, the antilock brake model, the electronic stability program (ESP) model, the trailer coupling force model, the impact model, the stiffness-based impact model, the mesh-based impact model, the soft-soil model, and the multi-body model. Wach also reports historical information about PC-Crash, noting that "PC-Crash is a program for road accident simulation. It's first version was created at the Institute of Mechanics of the University of Graz, Austria, in the early 1990's. The author of the original idea and basic physical model is Professor Hermann Steffan, in close cooperation with Wolfgang Neubauer and Dr. Andreas Moser. The program development is supported by Dr. Steffan Datentechnik in Linz. The program, a unique world-wide standard in road accident reconstruction, is available in twenty-two language versions."

Operational Validation Studies: Cliff and Montgomery published a study of the collision and trajectory models of PC-Crash Version 4.1 in 1996. Their stated purpose was "to evaluate PC-Crash in terms of accuracy, based on staged collisions for which speed and trajectory information is known... the staged collisions were reconstructed using PC-Crash and the trajectories were compared to actual measurements of the skid marks and rest positions. Vehicle speeds were compared to the PC-Crash predicted values." Before analyzing the collisions, Cliff and Montgomery also compared PC-Crash results to hand calculations for simple slide-to-stop and roll-out trajectories. They found that "the simulations and hand calculations produced identical acceleration values for vehicles in locked wheel skids, for vehicle decelerating with partially-braked wheels, and for vehicle in various steering maneuvers."

Cliff and Montgomery used seven staged collisions reported by Ishikawa [1985, 1993, 1994], which were run at the Japan Automobile Research Institute (JARI), and the twelve staged collisions often referred to as the RICSAC tests (Research Input for Computer Simulation of Automobile Collisions) [McHenry, 1978; Shoemaker, 1978; Jones, 1978; Brach, 1983]. They also used an additional test reported by McHenry in 1973, bringing the total number of collisions they considered to twenty. Cliff and Montgomery noted some inaccuracies in the original test reports for these collisions, including errors related to the degree to which various wheels were impeded following the collisions. They attempted to correct these inaccuracies by examining photographs and sensor data. They also noted that "the vehicle pre-impact

speeds were measured, while the post-impact speeds were calculated from accelerometer traces or photographs.”

Cliff and Montgomery noted: “Our evaluation of PC-Crash was conducted in two stages. The first stage was to assess the trajectory model by reconstructing only the post-impact phase of the collisions. The second stage was to assess PC-Crash’s ability to model the entire event from initial contact to rest.” The first of these stages would isolate the tire and suspension models in PC-Crash and the second would combine these with the impact model.

In simulating the collisions, Cliff and Montgomery assumed a center of gravity height of 0.5 meters for every vehicle in the study and PC-Crash default suspension values were used on the “medium” setting (now called “normal”). For the first phase (post-impact trajectory only), “Each vehicle was placed in an initial post-impact position on its tire marks...as close to the impact as possible, but where it had likely separated from the other vehicle. Vehicle post-impact velocities and rotational speeds were then varied until the tire traces from the PC-Crash trajectory model matched the tire marks on the [evidence diagram from each test] as closely as possible...Based on the post-impact speeds determined with PC-Crash and the reported pre-impact directions of the vehicles, a linear momentum calculation was done to determine the vehicle pre-impact speeds.” They also ran forward simulations using the PC-Crash collision and trajectory model.

Cliff and Montgomery concluded that “PC-Crash simulation [predicted] speeds were found to be in good agreement with real world results. For the staged collisions, errors larger than about ± 5 km/h could be attributed to inaccuracies in reported wheel brake factors, the inclusion of cases unsuitable for this type of analysis, or tire losses between the initial contact point and where the post-impact simulation was started.”

Other studies agreed with Cliff and Montgomery that there were errors in the RICSAC reports that made up 12 of the collision in their 20-collision dataset. In 1997, McHenry published a reevaluation of the RICSAC collisions, stating that while “the RICSAC tests contain the most comprehensive collection of full-scale test results available to date...some interpretation of the reported results is required, for example, to obtain speed-change (ΔV) and separation velocities from the accelerometer data. Also some evaluations are required for the approximate extent of wheel drag and steer angles.” McHenry reported analysis to correct some of the reported values for impact-speed changes and separation velocities. McHenry developed “generalized analytical techniques to transform the speed-change information from arbitrary accelerometer locations to the center of gravity. A secondary task was to use the calculated CG speed-change information to calculate the separation velocities...” McHenry presented updated velocity changes and separation velocities (post-impact speeds) for the twelve RICSAC collisions.

In 2002, Brach published another reevaluation of the RICSAC collisions, noting that “some of the collisions lead to a loss in total system momentum, as expected. [Based on the reported information,] some show a gain in system momentum which is not physically possible...it can be concluded that the variations in the change of system momentum are random and due to factors that were not under control in the experimental collisions.”

Cliff and Montgomery also observed that “while conducting simulations in PC-Crash it was found that in cases with significant post-impact vehicle rotation, an adequate estimate of the post-impact velocities could be made by matching the vehicle tire marks during the initial portion of the post-impact spinout. It was not necessary to match the entire trajectory exactly in order to get a good estimate for the velocity.” A 1998 study by Cliff and Bowler, titled “The Measured Rolling Resistance of Vehicles for Accident Reconstruction” confirmed this finding. In that study, Cliff and Bowler found that when there was post-impact rotation of a vehicle, that rotation provided enough evidence to reasonably constrain the vehicle speeds in the simulation. It was not critical to know the level of post-impact braking (or longitudinal resistance) at each wheel. In instances where there was not significant post-impact rotation, they noted that the simulation and the calculated speeds would be more sensitive to the brake factors.

In 2000, Bailey used PC-Crash 5.1 to simulate five staged collisions, the results of which were also reported in his paper. In describing the use of PC-Crash to reconstruct a collision, he observed that “if the simulated post-impact path and rest position match the actual ones, then the investigator can have some confidence in the accuracy of the pre-impact vectors used as input. How accurate the estimates are still depends on the validity of the particular collision and trajectory models, and on input parameters for the vehicles and terrain.” In describing his results, Bailey concluded that “there was agreement between measured and simulated collision dynamics...the error in calculated pre-impact speeds of the ten vehicles ranged from -3.3 to +4.1 km/h. Vehicle speeds were determined based on post-impact rotation and paths, without detailed information on the braking from each wheel or the actual collision coefficient of restitution.”

Bailey noted that the “five staged collisions were simulated by an engineer not directly involved in the staging of the collisions. Information on wheel-lockups and brake application time were not given to the analyst.” He also noted that “the optimization was usually based only on intermediate positions for each vehicle, rather than rest positions or rest and intermediate positions. The main reason for this is that the braking level of the vehicles was unknown, due to the fact that the brakes could have been applied by the remote vehicle operator at any time near the end of the vehicles’ trajectories.” Given that there was available data related to the collisions which was not provided to the analyst, the results of Bailey’s study tested the operational validity of PC-Crash along with the user’s skill.

Bailey concluded that “the results of the reconstructions suggest that for most cases, where the scene coefficient of friction and vehicle impact and rest positions are known, and at least photographs of the damaged vehicles are available, pre-impact speeds can be estimated within ± 5 km/h [3.1 mph] using PC-Crash. Steering and braking values do not need to be known initially, as they can be determined from a certain amount of trial and error work. The ability of the reconstructionist to compare predicted and actual tire paths is a valuable tool available in the simulation approach.”

In 2001, Cliff and Moser reexamined the 20 collisions that Cliff and Montgomery had analyzed in 1996. This time,

the collision optimizer was used in PC-Crash Version 5.1. Cliff and Moser stated that “the goal was to let the program determine pre-impact speeds and other impact parameters based on a minimization of the error between the actual and the simulation vehicles’ post-impact trajectories and rest positions. . . The user still has to enter steering angles, wheel brake factors and some other parameters for the simulation since the optimizer does not vary them. If these parameters are not assumed correctly the collision optimizer may not find an acceptable solution, such that there is poor agreement between the simulation results and the actual collision. In this case the weighted total error will be high, which tells the user that some entered values are likely wrong.”

Cliff and Moser reported that “comparison of the PC-Crash optimizer-determined impact speeds with the actual speeds” resulted in calculated errors “in pre-impact speed ranged from -11.8 to +3.4 km/h, with an average of -1.9 km/h.” In examining Cliff and Moser’s results, it becomes evident that the one case that resulted in an 11.8 km/h speed error was an outlier. For 19 of the 20 cases, the error in pre-impact speed was between -6.3 km/h and +3.4 km/h (-3.9 to 2.1 mph). The error in the vehicle velocity changes for these same 19 cases ranged from -6.7 to +3.5 km/h (-4.2 to +2.2 mph). These results were obtained with optimizer errors ranging from about 1.5% to 10.5%.

In 2012, Heinrichs reexamined the same 20 staged collisions that Cliff and Moser had examined in 2001. Whereas Cliff and Moser had not varied any vehicle parameters or the roadway coefficient of friction in their analysis, Heinrichs examined the sensitivity of the simulation results to such factors. Specifically, he varied the coefficient of friction, the vehicle center of gravity positions, the moments of inertia, the suspension stiffness and damping, the tire model parameters, the wheel braking and steering levels, the inter-vehicular friction coefficient for the impact, and the coefficient of secondary impacts. Heinrichs concluded that the simulation results were most sensitive to the roadway coefficient of friction. He also showed that when the coefficient of friction was varied, a range of calculated impact speeds would be associated with a single optimizer error level. In other words, the optimizer error is an indicator of simulation quality (how well the simulation matches the actual vehicle positions), but not necessarily of simulation accuracy. If the analyst used the “correct” coefficient of friction or considered a range of friction coefficients, then the range of speeds obtained with a low optimizer error would be more accurate than those obtained with a high optimizer error.

Heinrichs did not report examining the visual output of a series of simulations that all had the same optimizer error level. This would potentially be a helpful exercise because it is possible that a human analyst would be able to see differences in the simulations that would lead them to reject one of two simulations with the same optimizer error. For instance, one simulation could match tire mark evidence more closely than another and this might not be evident from the calculated optimizer error. At the time of Heinrich’s study, the optimizer error only indicated how well the simulation matched positions input by the user. The most recent version of PC-Crash allows the user to also optimize on tire paths. It would be useful to know the degree to which adding the tire

mark paths as a part of the quality function would make the optimizer error an indication of simulation quality, and also, simulation accuracy. The issue of simulation quality versus accuracy will be taken up later in this study.

A 2004 study by Cliff examined two methods for calculating speed from curved tire marks - the critical speed formula and PC-Crash simulation (Version 6.2). Cliff reported 22 yaw tests run with a 1991 Honda Accord EX-R at speeds between 70 and 120 km/h. He indicated that for half the tests, about 30% braking was applied. In its as-manufactured state, the test vehicle had anti-lock brakes, but the ABS system was bypassed and a non-ABS braking system was installed.

In running PC-Crash simulations of these 22 tests, Cliff used the linear tire model. Cliff concluded that “using the measured sliding coefficient of friction, both the critical speed formula and the computer simulations under-predicted the actual speed of the vehicle. Using the measured peak coefficient of friction, both methods over-estimated the actual speed. There was less variance in the computer simulation results.” With the sliding coefficient of friction, the simulations under-predicted the initial speed by an average of 9.0 km/h. With the peak coefficient of friction, the simulations over-predicted the initial speeds by an average of 2.3 km/h. An important observation made by Cliff is that “since the simulation program also takes the change in vehicle path radius into account over a longer distance, it enables the user to easily determine if braking is taking place.”

Zebala [2010] examined the anti-lock braking (ABS) model used in PC-Crash Version 8.2 and compared it to the results of extreme braking tests run with ABS equipped vehicles on a split- μ surface. Zebala notes that, “The accuracy of simulated vehicle movement in the phase of extreme braking is greatly affected by the ABS model. However, it is not practical to include the actual, individual algorithms used in different cars. This is why in [PC-Crash] universal algorithms are used whose task is to meet general criteria of ABS operation in order to solve the majority of typical problems that appear in road accident analysis.” The PC-Crash ABS model controls the level of braking on a wheel-by-wheel basis to ensure that each individual wheel does not lock-up. For some real-world ABS systems, the braking level for the rear wheels will be adjusted together and will be limited to the braking level appropriate for the tire on the lower coefficient of friction surface. Zebala refers to this as the “select-low principle” and he notes that the PC-Crash ABS model does not contain this logic. He reported good agreement between PC-Crash and the extreme braking tests on the split- μ surface when this logic was taken into account by manually reducing the braking level on the rear wheel that was on the high- μ surface.

Combination Validation/Calibration Studies: Zebala [2014] used PC-Crash Version 9.2 in conjunction with the linear tire model to analyze lane change maneuvers involving vehicles with reduced tire pressure. Zebala stated, “The authors have made an attempt at parameterization of a tire model in PC-Crash program, based on the results of experimental research into vehicle motion. Attention was focused on one program and one, so-called bilinear tire model, which was selected because of its extreme simplicity from the point of view of an average user. The program validation process

enabled first the tuning of the lateral force characteristics of undamaged tires, and next of tires of lowered pressure. Although good compatibility between the simulated and real results was reached, it should be emphasized that the selected maximum slip angles (describing tire lateral force characteristics) have to be treated with the maximum uncertainty of $\pm 33\%$ taken into account. This range also covers the influence of elements neglected in the modeling of the whole vehicle.” Ultimately, Zabala’s study sought reasonable inputs to obtain the best match with his test data, and so while in part a validation study, this study should also be categorized as part calibration study.

Rose [2014] used the “real acceleration” model within PC-Crash 9.0 to model the full-throttle acceleration capabilities of three vehicles with automatic transmissions, as determined from physical testing of those vehicles. This model within PC-Crash yields non-constant vehicle acceleration that depends on speed, weight, engine power, the degree of throttle application, and the roadway slope. Rose reported that “for each vehicle, geometric dimensions, inertial properties, and engine/drivetrain parameters were obtained from a combination of manufacturer specifications, calculations, inspections of exemplar vehicles and full-scale vehicle testing. In each case, the full-throttle acceleration of the vehicles modeled in PC-Crash showed good agreement with the acceleration of the real vehicles in our road tests.”

Dragoş-Sorin [2014] used the genetic optimization algorithm in PC-Crash to reconstruct a crash involving a heavy truck and a passenger car. The crash was also captured on surveillance video from two cameras and tachograph data was available for the heavy truck. Comparison was made between the simulation and the surveillance video and tachograph data and good agreement was achieved. For the optimized simulation, the optimizer error was 2.5%.

Studies that Assume the Validity of PC-Crash: Rose [2016] used PC-Crash to explore the effects of high rates of yaw rotation and steering on the deceleration rates experienced by spinning vehicles. Rose noted that PC-Crash simulation is an efficient and effective manner to deal with these effects that are more difficult to incorporate analytically. He stated: “These software packages [HVE and PC-Crash] account for the actual tire travel distances and the effects of rotational kinetic energy using a vector mechanics approach and numerical integration.”

Prior Studies - Rollovers

Studies Describing the Conceptual Models: Steffan [2004] discussed the models within PC-Crash relevant to modeling rollover crashes (tire and suspension models, ground surface modeling, and the vehicle body-to-ground contact model) and then presented 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 Steffan 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.

Operational Validation Studies: Andrews [2009] published a study at the Enhanced Safety of Vehicles Conference that compared modeling of a staged rollover collision using PC-Crash Version 7.3 to the actual measured and videoed vehicle motion. Andrews concluded that “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.”

Kiefer [2011] used PC-Crash 8.2 to model 26 instrumented handling tests using 1998 and 1999 Ford Explorers. The handling tests involved rapid steering inputs at vehicle speeds between 30 and 60 mph [48.3 and 96.6 km/h]. The vehicle weights, center of gravity positions, suspension stiffness parameters, tire parameters, and steering angle were measured and used as inputs into the simulations. Kiefer utilized the TM-Easy tire model within PC-Crash. The suspension stiffness coefficients were determined by measuring the change in front and rear ride height of the test vehicles under different loading conditions. PC-Crash does not model the tire compliance separate from the suspension compression, and so, the stiffness coefficients included the compliance of the tires. Kiefer noted that “the PC-Crash linear damping rate was increased to approximately twice the default value... The authors did not have shock curves or other suspension information to use as input for the model. As a result, the suspension damping values were increased from the default until the modeled response approached the test data.” Kiefer concluded that “PC-Crash appeared to be a reasonable tool for modeling gross vehicle response. In addition, PC-Crash correctly predicted whether or not the test vehicle would experience rollover instability in a majority of the cases.”

Combination Validation/Calibration Studies: Rose [2009] reported PC-Crash modeling of the dolly rollover crash test. This modeling utilized PC-Crash 7.3. While more recent versions of PC-Crash have incorporated changes relevant to rollover modeling, certain methodological issues addressed by Rose have not changed. Specifically, Rose found that the dominant variables affecting the agreement between the PC-Crash simulation and the test data were the vehicle-to-ground friction coefficients, the vehicle suspension stiffness and damping, and the car body restitution. Perhaps more significantly, Rose found that obtaining a match between the simulated and actual roll velocity histories led naturally to good agreement with the simulated and actual translational velocity histories. This relationship is mediated through the vehicle to ground friction coefficient. This finding indicates that PC-Crash could be used to reasonably 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 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 spatial reconstruction of the gross vehicle motion.

Heinrichs [2013] described a method of measuring suspension properties for use in PC-Crash and he reported suspension stiffness and damping values for 26 vehicles. When vehicle-specific data is not available for a particular vehicle, PC-Crash calculates default suspension stiffness values that are proportional to the static load at each wheel and a damping coefficient that is related to that stiffness. Heinrichs reported that “the deflection of the suspension under the vehicle’s own static weight was lower than PC-Crash defaults. Average pitch deflection was 8 cm and average roll deflection was 6 cm, whereas the PC-Crash ‘normal’ and ‘stiff’ defaults are 15 cm and 10 cm, respectively.” This means that the PC-Crash default suspension stiffness coefficients are generally too low.

In his 2012 study, Heinrichs showed that the reconstructed speeds obtained with PC-Crash for a planar collision were “insensitive to four-fold variations in suspension parameters.” One would expect the suspension parameters to matter more for rollover simulation than for simulating planar impacts and Heinrich’s 2013 study bore this out.

In that study, Heinrichs used PC-Crash Version 9.1 to explore the sensitivity of PC-Crash rollover simulations to variations in the suspension and damping. Specifically, Heinrichs ran simulations for each of the 26 vehicles he tested using both default and measured suspension parameters. He stated that the “simulations consisted of a steering maneuver to the right followed by a hard steering maneuver to the left... the lowest initial vehicle speed was found that resulted in a rollover. After the critical rollover speed was determined, new simulations were run using the measured suspension parameters. The initial speed for these simulations was a randomized value above the critical rollover speed. The results of these simulations were used as trajectory data; it was treated as field data for a reconstruction using the program default suspension values. For each vehicle, an initial vehicle speed was found that gave an operator-assessed best fit to the trajectory data. Vehicle speeds, steering, braking, and friction coefficients could be altered, but geometry, inertial and suspension parameters were fixed.” Heinrichs found that “the critical speed required for a vehicle to roll in a PC-Crash simulation was about proportional to the suspension stiffness.” He further found that the sensitivity of PC-Crash to variations in suspension stiffness for rollover reconstruction was minimized if evidence from all three phases of the rollover (loss of control, trip, and roll) was incorporated in the simulation.

In these findings, Heinrichs inherently distinguishes between two purposes for which PC-Crash could be used. For predicting rollover, Heinrichs found that the results were sensitive to the suspension parameters. For reconstructing a rollover - where the reconstructionist can incorporate evidence from all three phases of the rollover - the sensitivity to suspension parameters was minimized.

Studies that Assume the Validity of PC-Crash: Berg [2003] used PC-Crash to model various rollover test

procedures. He stated that “PC-Crash is a sufficient instrument to simulate these rollover crash tests.”

Viano and Parenteau [2004] reported that “a multi-disciplinary effort was conducted to define the most relevant tests that reflect real-world rollover crashes and injuries. That work prompted a series of rollover tests, including new procedures in which vehicle and occupant kinematics were studied. Also, each test was simulated in mathematical models to study other parameters and scenarios in rollover crashes.” This team utilized and validated PC-Crash software for its mathematical modeling of the vehicle motion for the rollover tests. They used MADYMO to simulate the occupant motion. The article by Viano and Parenteau reports that PC-Crash and MADYMO simulations were 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...Excellent comparability was demonstrated between the tests and the simulation.”

Schubert [2006] reported reconstructions of 3 rollover crashes. He used PC-Crash to simulate the events and to derive crash sensor signals for the events. He stated that “insights derived from these events can aid in development of robust rollover detection algorithms and calibrations.”

Ootani and Pal of Nissan Motor Company published a pair of studies in 2007 in which they used PC-Crash to simulate real-world, soil-tripped rollovers from the NASS-CDS database. In these studies, they noted that “through a process of iteration the overall kinematics of the vehicle movement before and after the crash was captured. The output of this PC-Crash simulation was then used as the initial input conditions (i.e., speed, deceleration, etc.) of a detailed finite element analysis.”

Prior Studies - Human Motion

Steffan [1999] examined the use of PC-Crash to simulate vehicle occupant motion through its coupling with MADYMO. Steffan noted that, “A new interface has been developed between MADYMO and PC-Crash so that, after the reconstruction of an accident, only a few additional parameters regarding restraint system, seat and occupant must be defined. PC-Crash then creates all necessary input files for MADYMO and starts the occupant simulation. The results are then re-imported into PC-Crash for visualization and further analysis.” The interface between PC-Crash and MADYMO allows the user to define characteristics of the occupant and seat. The user can also specify if the occupant is belted, if the seatbelt system has a pretensioner, and if there was a frontal airbag deployment. It should be recognized that the MADYMO plugin for PC-Crash is a limited version with many limitations and is not a complete version of MADYMO.

Steffan used the PC-Crash/MADYMO module to simulate the occupant motion from two crash tests - one a rear impact and one a frontal impact. Steffan’s article presents

a very limited comparison between the test data and the simulation data. His article showed several frames of video for each test with corresponding frames from the simulations. The views were very limited and no quantitative comparisons were made. Even with the limited views, differences between the occupant and restraint system motion from the tests and the simulations were apparent. Nonetheless, Steffan concluded that “the interface...predicts occupant movement quite well.”

He went on to state that “although several limitations exist, many accident situations can now be simulated. The movement of the occupants during the accident can be shown in three-dimensional form and graphically. This tool cannot be used to determine an accurate HIC or certain other injury parameters, as there are too many undefined parameters. However, the software can be used to gain a better understanding of the mechanisms causing certain injuries. When comparing restrained and unrestrained occupants, many questions can be answered, and specific injuries can often be explained.” Despite the limited comparison that was conducted between the tests and simulations, the spirit of this quote is likely correct - the PC-Crash/MADYMO module could be used to make gross comparisons between two different conditions (belted versus not belted, for instance), but quantitative use of the simulation data (excursion distance, for instance) should be avoided.

Steffan published a second study of the PC-Crash/MADYMO module in 2000, in which he reported simulations of three sled tests - a frontal impact, a side impact, and a diagonal impact - and also of a rollover crash test. This time, for the sled tests, Steffan performed numerical comparisons between the tests and the simulations, specifically comparing the head, chest, and pelvis accelerations of the dummies in the tests to the dummies in the simulations. Steffan reported that the occupant motion in the tests and simulations were “quite similar.” Steffan again included comparison frames from the test videos and simulations. The gross occupant motion shown in these frames for the sled tests does appear to be quite similar. For the rollover test, Steffan reported “a much bigger discrepancy between Hybrid III dummy movement and human [stunt driver] than between dummy and simulation.”

In 2006, Maletz and Steffan published another study that utilized the MADYMO module with PC-Crash to analyze occupant motion in frontal impacts. This analysis reported in their study differed from the previous studies in that it utilized the stiffness-based impact model in PC-Crash. This enable them to use PC-Crash to generate a more realistic time-varying crash pulse for the impact, an improvement over the prior studies where constant acceleration had been assumed for the collision pulse.

Moser [1999] examined the use of the PC-Crash pedestrian model to simulate vehicle-pedestrian collisions. The pedestrian model in PC-Crash is a multibody system consisting of 24 rigid bodies representing the various body parts (the head, torso, and pelvis, for example) that are connected with 15 joints. The user can specify the dimensions, inertial properties, stiffness, and frictional properties of each of these body parts, along with the overall weight and height of the pedestrian. The user can also specify the friction and rotational stiffness in each of the joints. The model can sense

and model contact between body parts and contact with vehicles in the simulation.

In his 1999 study, Moser compared this model to a single crash test involving a car and a pedestrian dummy. He indicated that “the dummy was hit partially with the right front part of a VW Polo. The impact speed was approx. 54 km/h and the dummy was only hit on the left leg. Due to the impact forces the dummy was rotated and hit the right A-pillar of the car with the torso.” Moser reported that “a good correlation between the crash tests and the simulation results in general was found. Especially the total post impact travel of the pedestrian as well as contact locations, where the pedestrian hit the car, were predicted in the simulation runs...The pedestrian model showed accurate results for the post impact movement of the pedestrian. Using the impact locations, where the pedestrian had contact with the car, the impact velocity for the vehicle could have been calculated in a range of ± 5 km/h.”

In 2000, Moser published a second study examining the use of the PC-Crash pedestrian model to simulate vehicle-pedestrian collisions. In that study, he compared PC-Crash simulations to 3 crash tests. He also ran additional simulations with 6 different vehicle shapes to determine the pedestrian throw distances predicted by PC-Crash. He compared the simulated throw distances to the predictions of commonly used throw distance formulas (Searle, Stcherbatcheff/Kühnel/Rau, DEKRA). Moser reported that “depending on the shape of the vehicle different throwing distances result in the simulation.” Ultimately, Moser concluded that “the different comparisons show that the PC-Crash pedestrian model gives very good estimates for the total pedestrian trajectory. The influence of the vehicle shape on the pedestrian kinematics and total trajectory can be taken into account easily.”

A 2009 study by Barrios et al. described a methodology to evaluate pedestrian protection systems. Their study utilized analysis of approximately 139 pedestrian accidents which they reconstructed using PC-Crash. These pedestrian accidents occurred in Spain in the cities of Barcelona, Madrid, and Zaragoza.

Chen, Yang, and Otte [2010] used PC-Crash in conjunction with MADYMO to analyze 20 real-world vehicle-pedestrian collisions from two locations - Changsha, China and Hannover, Germany. They noted that “computer simulations provide a powerful tool for studying the kinematics of pedestrians during a crash. Digital models based on rigid bodies connected to one another by joints are time efficient.” For analyzing the real-world crashes, PC-Crash was used to reconstruct the vehicle motion based on physical evidence and then the initial conditions from PC-Crash were input into MADYMO (the full version, in this instance). The authors found good agreement between PC-Crash and MADYMO in their predictions of the pedestrians’ wrap around distances and throw distances.

Wach and Unarski [2014] used PC-Crash to simulate the motion of a person falling from height in a stairwell. They reported that several hundred simulations were run using a detailed computer model of the stairwell and the PC-Crash multibody model. The goal was to determine from where the person had fallen and under what conditions (i.e., an accident fall or being pushed). As is typical with the reconstruction of a vehicular crash, simulations were sought that agreed with

the known physical evidence, including the rest position of the person. Wach and Unarski noted that they were unable to use the simulations to “categorically indicate either the victim’s involuntary falling over or the fall being forced by a third party.” They were able to determine the likely area from which the fall originated. They also observed that “in the case of various hypotheses on an event’s course, it is effective to run a number of virtual experiments after an adopted experiment plan (for various boundary conditions) and select a concrete scenario by way of the likelihood analysis.”

In a 2015 study, Richardson et al. used PC-Crash to examine the influence of vehicle shape and impact location on the throw distance of a pedestrian. He ran 19 simulations for each of 8 different vehicle shapes, varying the impact location across the front end of the vehicle from simulation to simulation. Vehicle impact speeds were ranged between 20 and 80 kph. Richardson observed that “the location where the pedestrian has engaged with the vehicle can and does significantly influence the throw distance (and projection) and subsequent impact speed analysis.”

Reexamining the Bailey Staged Collisions

Bailey [2000] used PC-Crash to model five staged collisions and concluded that “pre-impact speeds can be estimated within ± 5 km/h using PC-Crash” (3.1 mph). Bailey’s article included the [Table 1](#), which summarizes the impact configurations, speeds, and vehicle parameters for the five collisions. Bailey noted that the “five staged collisions were simulated by an engineer not directly involved in the staging of the collisions. Information on wheel-lockups and brake application time were not given to the analyst.” Because known information was withheld from the analyst for the Bailey study, the results of that study reflect, at least in part, the knowledge, certainty, and skill level of the user. Bailey’s results are useful, but it could also be useful to run a set of simulations where the analyst is provided with all the data from the tests. This would further demonstrate the capabilities of PC-Crash in a way that is more independent of the user’s skill, knowledge, and certainty.

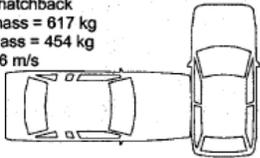
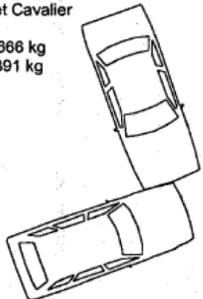
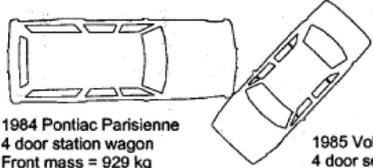
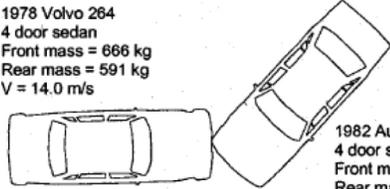
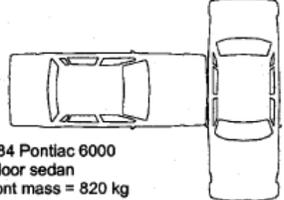
This section reexamines these staged collisions from the Bailey study. In this instance, none of the known data was withheld from the analyst, including the pre-impact speeds. Of course, the analyst was still faced with uncertainty related to inputs such as the coefficient of restitution, the inter-vehicular friction (impulse ratio), and the impact center location. Values for these variables could theoretically be calculated or estimated after the fact based on measured values from the tests. Rose [2007] demonstrated the calculations that would go into determining the coefficient of restitution, for instance. He also quantified the uncertainty that could accrue in these calculations. The situation would be similar for the inter-vehicular friction and the impact center locations. Thus, these parameters are likely better treated as optimization parameters for the simulations.

The five collisions reported by Bailey were run on a flat section of runway at Boundary Bay Airport in British

Columbia, Canada. To document the post-impact trajectories of the vehicles, thin rows of sand were laid down prior to the tests, 2 meters apart over the impact area to create a 20 x 20 meter grid (for all but one test). The coefficient of friction for each test surface was measured with a skid to stop test. In all 5 tests, the vehicle transmissions were in neutral and the vehicles were towed up to the test speed using a cable attached at the front bumper. The tow line was released about a car length from impact and the vehicles were allowed to coast into impact.

For the present study, the simulations utilized the reported coefficient of friction, vehicle speeds, masses, and mass distributions. Vehicle dimensions were obtained from the Canadian Vehicle Specs database. The center of gravity

TABLE 1

Test	Summary
MEA12	<p>1980 Datsun 200SX 2 door hatchback Front mass = 617 kg Rear mass = 454 kg V = 15.6 m/s</p>  <p>1989 Chevrolet Sprint 2 door hatchback Total mass = 660 kg V = 6.7 m/s</p>
MEA22	<p>1986 Chevrolet Cavalier 2 door coupe Front mass = 666 kg Rear mass = 391 kg V = 12.3 m/s</p>  <p>1980 Toyota Corolla 4 door station wagon Front mass = 543 kg Rear mass = 481 kg V = 12.1 m/s</p>
MEA30	 <p>1984 Pontiac Parisienne 4 door station wagon Front mass = 929 kg Rear mass = 894 kg V = 12.1 m/s</p> <p>1985 Volkswagen Jetta 4 door sedan Front mass = 572 kg Rear mass = 457 kg V = 5.3 m/s</p>
MEA31	<p>1978 Volvo 264 4 door sedan Front mass = 666 kg Rear mass = 591 kg V = 14.0 m/s</p>  <p>1982 Audi 5000 4 door sedan Front mass = 802 kg Rear mass = 492 kg V = 7.3 m/s</p>
MEA32	 <p>1984 Pontiac 6000 4 door sedan Front mass = 820 kg Rear mass = 461 kg V = 12.3 m/s</p> <p>1978 Volvo 264 4 door sedan Front mass = 666 kg Rear mass = 591 kg V = 5.2 m/s</p>

height for each vehicle was assumed to be 39% of the vehicle's overall height. Moments of inertia were estimated using data and formulas in MacInnis [1997] and Allen [2003]. The TM-Easy tire model was used for these simulations.

For each simulation, the vehicles were aligned at maximum penetration based on the tire marks and vehicle damage documented in the Bailey study. For each collision, the collision optimizer was used to obtain the best fit with the evidence, including the tire marks and rest positions. Initially, the optimizations focused on intermediate positions that were determined based on the tire mark evidence. As the optimizations progressed, brake factors were used to improve the match with the rest positions.

As the PC-Crash user's manual notes: "The Optimizer does not optimize on parameters such as braking, steering or pre impact rotation. The user must specify these values, and, if necessary, vary them manually." We also examined the resulting simulations for the quality of their match with the tire mark evidence. The collision optimizer was allowed to vary the following parameters: the x, y, and z coordinates of the point of impact, the coefficient of restitution, and the inter-vehicular coefficient of friction. The collision optimizer was run multiple times in each case until the results could no longer be improved. The following recommendation from the PC-Crash user's manual was followed: "It is generally more efficient to optimize only two or three parameters at once. This allows the user to view the results after a short optimization time and then make a decision on what to optimize on in the next optimization process, if it is needed." Thus, we did not optimize with all the parameters at once. The following recommendation from the user's manual was also followed: "During the process, the items checked in the Optimization parameter list are optimized one at a time, such that the program doesn't go back to the first item after optimizing the second, and so on. The optimization process should therefore be performed at least twice if two or more items are checked."

Figures A1 through A5 in Appendix A show the optimization results for the five collisions summarized in Table 1. Each of these figures is a screen capture from PC-Crash. The scale diagram from the Bailey study is shown in the background of each of these figures. The impact and rest positions of the vehicles from the simulation are depicted over these background images so that the reader can discern the degree to which the rest positions were matched in each case. Some intermediate simulated positions are also shown, as are tire marks deposited by the vehicles in the simulations. The impact parameters are also reported in these figures through the inclusion of the Crash Simulation dialogue box. Finally, the final errors percentages reported by the optimizer are shown for each case.

The optimizer errors for the five cases were as follows: 0.4%, 2.0%, 1.4%, 2.0%, and 0.6%. In all five instances, the post-impact trajectories of the vehicles in the simulations exhibited an excellent match with the actual post-impact trajectories based on the physical evidence. Each of these simulations utilized the actual impact speeds reported for these crash tests, thus, they demonstrate that, for each case, PC-Crash had the ability to generate a simulation that matched the actual impact speeds and the known physical evidence.

Quality versus Accuracy

The previous section showed that for each of the Bailey tests, PC-Crash can accurately and reasonably model the collision and the post-impact motion of the vehicles. That, of course, does not ensure that the reconstructionist will discover the real solution and capture the actual impact speeds. More likely, they will capture a reasonable solution, or set of solutions, and a range of speeds that will encompass the actual speeds. There will be uncertainty in any reconstruction, and so, the analyst will be pursuing the best solution (or range of solutions) they can find, while acknowledging the normal uncertainties that are present in any reconstruction. The characterization "best" will typically be assessed through the degree to which the simulation matches the physical evidence.

In his 2012 article, Heinrichs considered the sensitivity of vehicle-to-vehicle collision simulations to variations in various parameters and he showed that the simulation results were most sensitive to the roadway coefficient of friction. He also showed that a single collision optimizer error level could be associated with a range of speeds for each vehicle. In other words, while optimizer error is an indication of the quality of a simulation (how well the simulation matches the optimizer vehicle positions and other physical evidence), low optimizer error does not guarantee simulation accuracy.

A reconstructionist using PC-Crash should still prefer low optimizer error to high optimizer error, and low optimizer error would reasonably be expected to be associated with more accurate simulations than high optimizer error. This simply means that the use of PC-Crash is subject to the same uncertainties to which all methods of reconstruction are subject. Variations inherent in the input values for PC-Crash can be dealt with the same way they are always dealt with in any other method of accident reconstruction - by performing an uncertainty analysis (running simulations with the high and low values for each range, for example) [Brach, 2004] or by simply acknowledging that the results do have uncertainty in them and stating what that level of uncertainty is based on the literature reviewed in this study.

Simulation of Asay's Isuzu Rodeo Test

In 2010, Asay reported a series of steering-induced rollover crash tests that were conducted on a remote, rural highway in the west desert of Utah. These tests utilized six full-size SUVs of differing makes and models. Asay reported 8 total tests, but two of them did not result in rollover. These tests utilized automated steering control. Each vehicle was shifted into neutral and towed to highway speeds, released, and then steered with a sharp left steering input of approximately $\frac{1}{4}$ turn. One second later, the steering controller input a severe steering input back to the right that would turn the wheel as far as it could go. Speed and position data was collected for each test vehicle using a VBOX III GPS sensor that was attached to the roof at the centerline and that collected data at a rate of 100 Hz. A non-contact radar speed sensor was also

attached to the rear bumper and a rotation rate sensor was attached near the center of gravity to measure the roll velocity.

These authors used PC-Crash to simulate one of Asay's tests - specifically the one involving a 1991 Isuzu Rodeo. In this test, the Isuzu was towed up to and released at a speed of 73.5 mph (118.3 km/h). After release, the vehicle was steered with a sharp left steering input of approximately $\frac{1}{4}$ turn, causing the vehicle to travel to the left across the roadway and to yaw counterclockwise, developing a slip angle of sufficient magnitude that tire marks were deposited on the road surface. Then, one second later, the leftward steering input was followed by a severe steering input back to the right. The vehicle continued off the left side of the road into the dirt, but reversed its yaw direction, developing a significant slip angle as it yawed in a clockwise manner. The vehicle deposited furrows in the dirt and then began rolling over. The vehicle rolled 7 times in 181 feet (55.3 meters). Asay surveyed the physical evidence both on and off the roadway from this test and he provided his survey to these authors. In this case, the physical evidence included tire marks, tire furrows, disturbed earth, wheel landings, glass spills, and debris from the vehicle. Based on Asay's survey data, the evidence diagram of Figure A6 was produced.

This physical evidence diagram was used as a background image for the simulation. During the process of producing a simulation of this test, the results were judged based on how closely the calculated vehicle motion followed the evidence depicted on this diagram. A three-dimensional terrain was also produced based on Asay's survey data and was used in the simulation. Manufacturer specifications provided the vehicle dimensions and the vehicle weight reported by Asay was used (4,266 pounds). Moments of inertia were estimated based on formulas in MacInnis [1997] and Allen [2003]. PC-Crash's TM-Easy tire model was used with the default parameters. The suspension parameters were varied and the effects of these variations will be discussed below. Representative shape parameters for the vehicle body of the Isuzu were measured from a computer model and entered for the simulation. A dxf model was used for display purposes, but not for generating the vehicle shape in the calculations.

The initial vehicle speed of 73.5 mph was entered and then steering inputs were input to match the physical evidence. Friction zones were used for the trip phase with the friction values being varied to induce roll of the vehicle at the correct location based on the tire marks.

Figure A7 shows the motion of the vehicle in the final optimized simulation. Figure A8 shows this same motion, but is zoomed in on the loss of control and trip phases. Initial simulation runs made it clear that the PC-Crash suspension parameters had a significant influence on both the roll distance and the number of rolls experienced by the Isuzu in the simulation. The vehicle body stiffness also had a significant influence on the number of rolls. To optimize the simulation, the suspension damping was set at twice the default value and then the suspension stiffness was varied to obtain the correct roll distance. The vehicle body stiffness was then varied to achieve the correct number of rolls in this distance. This proved to be a highly iterative process as the optimization neared completion.

Ultimately, we obtained a simulation that exhibited an excellent visual match with the pre-roll tire marks and furrows.

The vehicle in this simulation rolled 7 times, just as the vehicle did in the actual test. The rest position of the vehicle was also reasonably matched. The first half of the simulated roll trajectory was closer to the paved portion of the roadway than the actual roll trajectory. After that point, there was good agreement between the simulated and actual roll trajectories. Figure A9 is a graph showing the roll velocities of the vehicle during the roll phase in the simulation compared to those during the actual test. As this graph shows, there is a very close match until about $4\frac{1}{4}$ seconds into the simulation, where the roll velocities in the simulation are lower than the actual roll velocities. The peak roll velocity in the simulation was approximately 100 degrees per second lower than the actual peak (650 degrees per second versus 750 degrees per second). In some areas near the peak, the roll velocity in the simulation is as much as 125 degrees per second less than actual. This is compensated for by several later regions in the simulation where the roll velocities are greater than actual. The total roll duration in the simulation is approximately $\frac{1}{2}$ second longer than actual.

Our quantitative analysis of the sensor data from this crash test is an ongoing effort, as is our analysis of it with PC-Crash. One recent article in *Collision* explored the presence of longitudinal forces applied to the vehicle during the trip phase [Rose, 2016b]. This additional analysis of the test took place after the simulation reported here. Another article in *Collision* also continues this exploration of the trip phase of this test and it reports further analysis with PC-Crash that isolated the trip phase [Rose, 2016c].

Discussion

This paper began by defining terms related to the concept of validation. Next, the existing literature related to PC-Crash was reviewed. This literature review identified 34 studies conducted over the last 20+ years that have either described the underlying physical models of PC-Crash, validated those models for use in accident reconstruction, or utilized those models in a research context.

This paper also reexamined a series of staged collisions reported by Bailey in 2000. Bailey had reported simulations of these staged collisions that did not isolate the capabilities of the software from the knowledge and skill level of the user. In our re-examination of simulating these collisions, we attempted, as much as possible, to isolate the capabilities of the software by providing the reported data for these collisions to the analyst. While this study did achieve greater isolation from user skill than what the original Bailey study did, we were, of course, unable to achieve complete isolation from user skill simply because some of the inputs required in PC-Crash cannot be directly measured for a staged collision. We used these parameters (coefficient of restitution, intervehicular friction, and impact center location) as optimizing parameters. Still, the question asked in this study was different than the one Bailey posed. Here, the question was: "If all the measured data were known, to what degree could PC-Crash model these collisions?"

For all five of these collisions, simulations were obtained with the actual impact speeds that exhibited excellent visual

agreement with the physical evidence. These simulations demonstrate that, for each case, the PC-Crash software had the ability to generate a simulation that matched the actual impact speeds and the known physical evidence. Clearly, this does not speak to any analyst's ability to discover this solution in a real-world reconstruction where the actual impact speeds are not known. However, it does illustrate that the physical models within the software can generate a simulation that reasonably models the actual event.

It seems obvious that a reconstructionist using PC-Crash should prefer a simulation that achieves low optimizer error (a measure of the match to the evidence) over a simulation that does not. Low optimizer error should be associated with more accurate simulations than high optimizer error. However, two simulations that both have low optimizer error will not be equally accurate. This simply means that the use of PC-Crash is subject to the same uncertainties to which all methods of reconstruction are subject. Variations inherent in the input values for PC-Crash can be dealt with the same way they are always dealt with in accident reconstruction - by performing some type of uncertainty analysis or by simply acknowledging that the results do have uncertainty in them and stating what that level of uncertainty is based on the literature reviewed in this study.

This paper also reported on a simulation of one of the full-scale, steering-induced rollover crash tests that Asay reported in 2010. For this test, we obtained a simulation that exhibited an excellent visual match with the pre-roll tire marks and furrows and in which the vehicle rolled 7 times, just as it did in the actual test. The rest position of the vehicle was reasonably matched. The first half of the simulated roll trajectory was closer to the paved portion of the roadway than the actual roll trajectory. After that point, there was good agreement between the simulated and actual roll trajectories.

Conclusions

This article has evaluated PC-Crash for use in accident reconstruction by reviewing the prior literature related to the software, by conducting additional analysis of the Bailey staged collisions, and by reporting a simulation of a full-scale rollover crash test. This and prior studies have demonstrated that PC-Crash software can yield accurate simulations of vehicular collisions. This, however, does not guarantee an accurate result if the user lacks the skill or understanding to match the physical evidence and to account for the uncertainties in the analysis.

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Appendix A

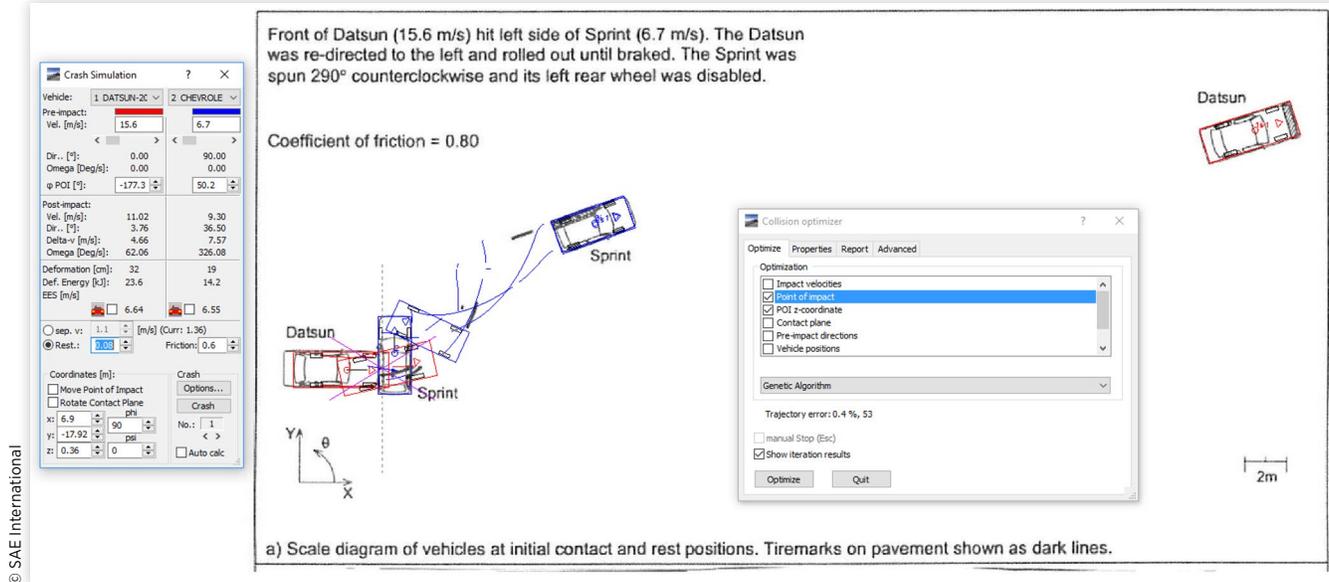
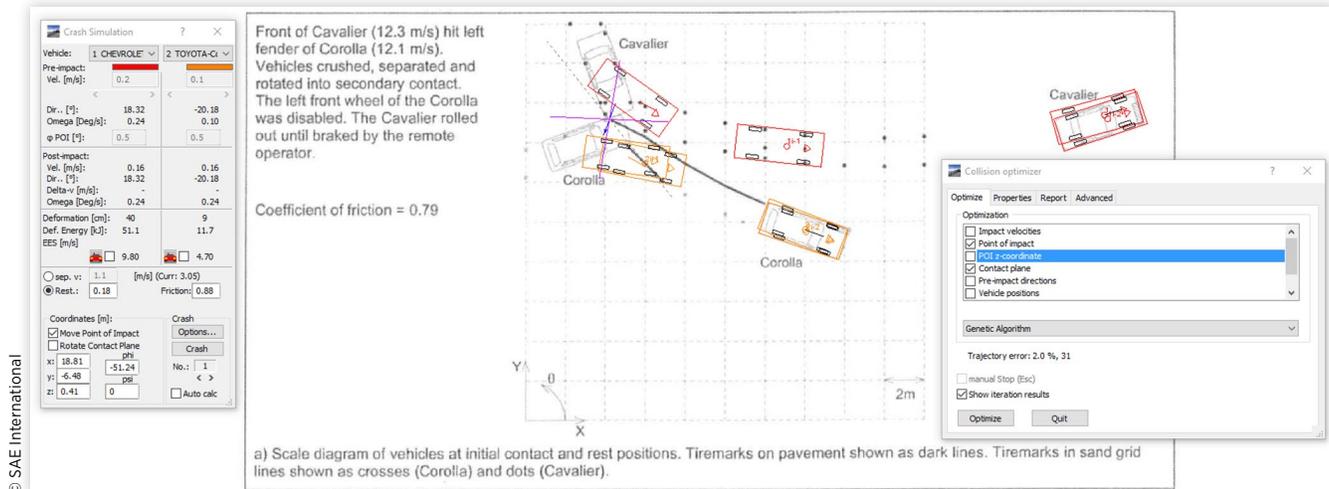
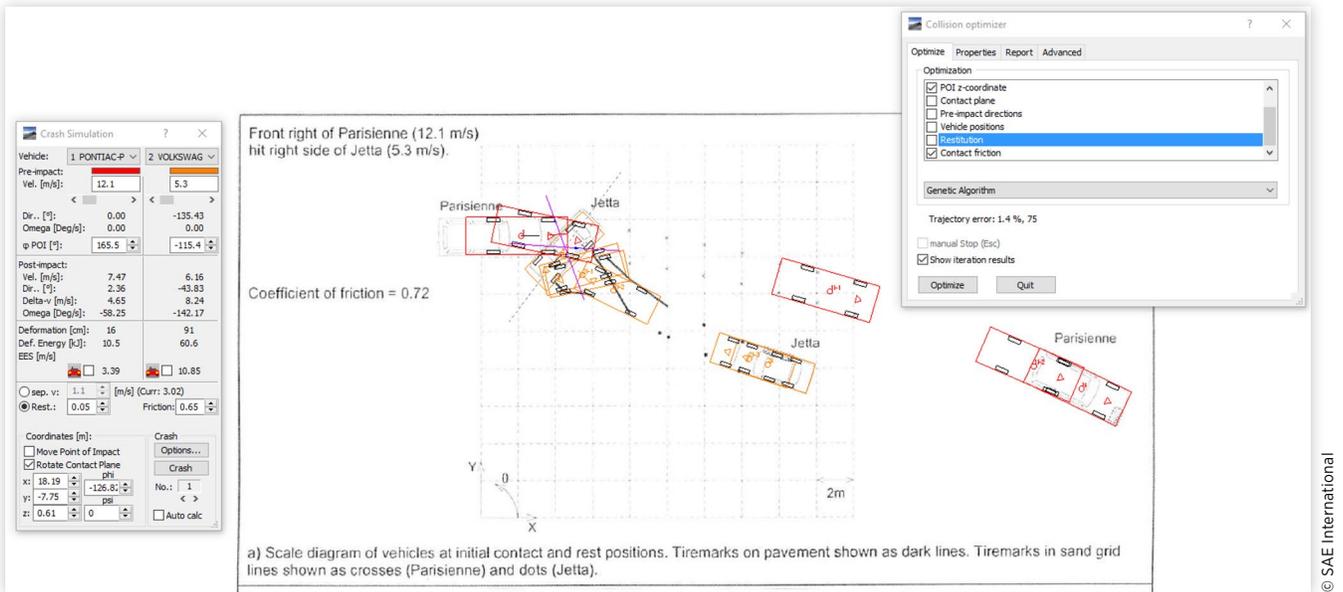
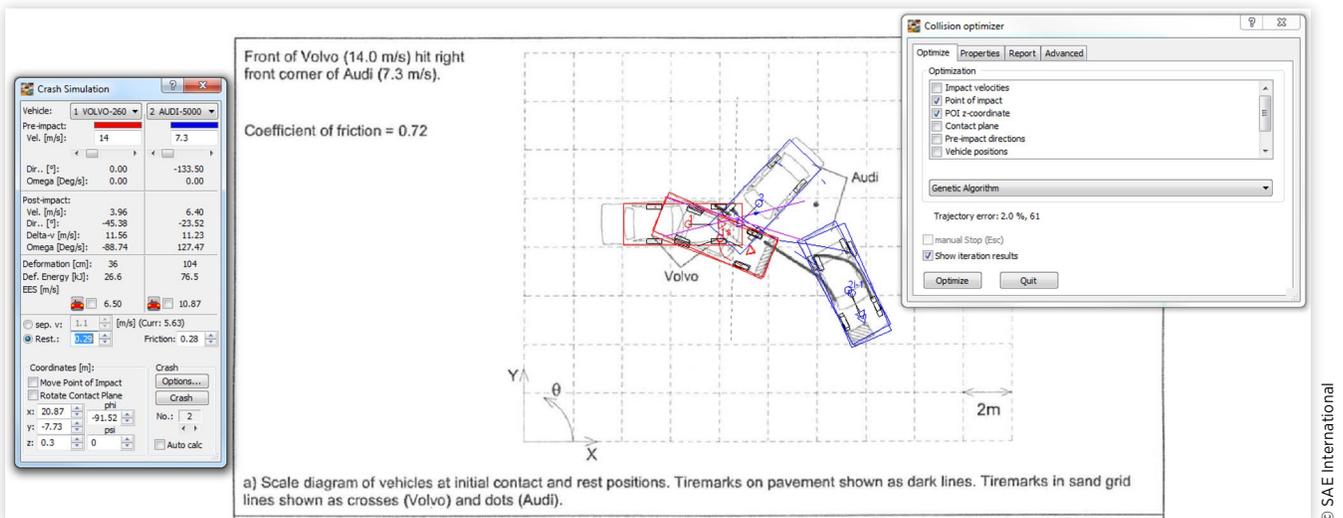
FIGURE A1 Optimization Results for MEA 12

FIGURE A2 Optimization Results for MEA 22


FIGURE A3 Optimization Results for MEA 30

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FIGURE A4 Optimization Results for MEA 31

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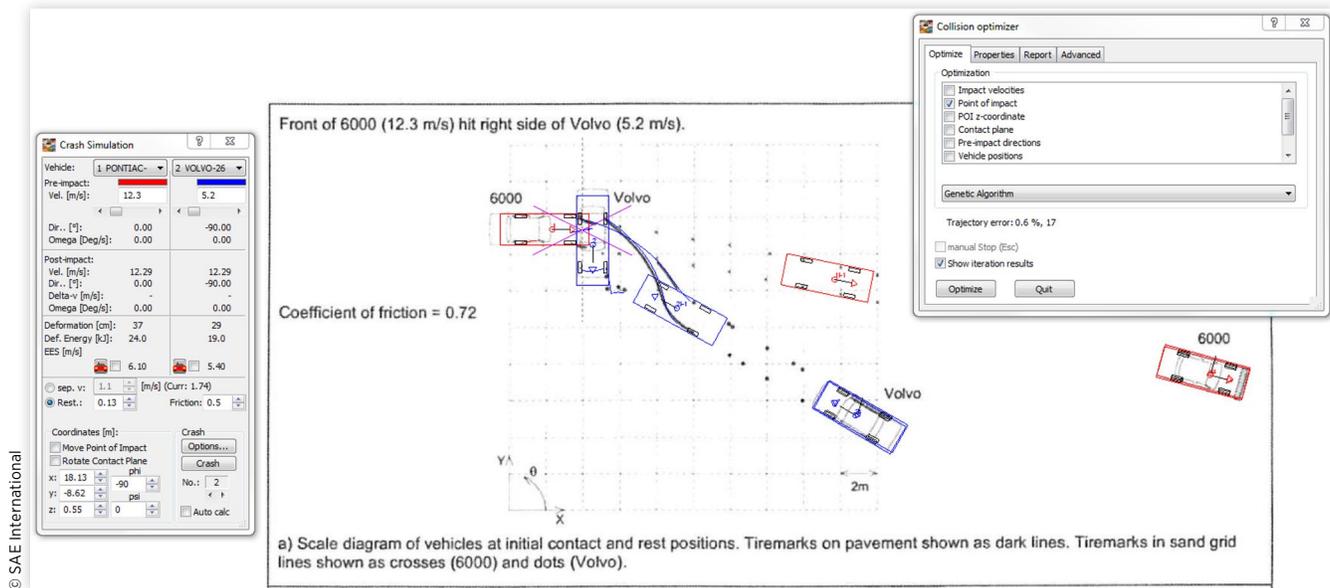
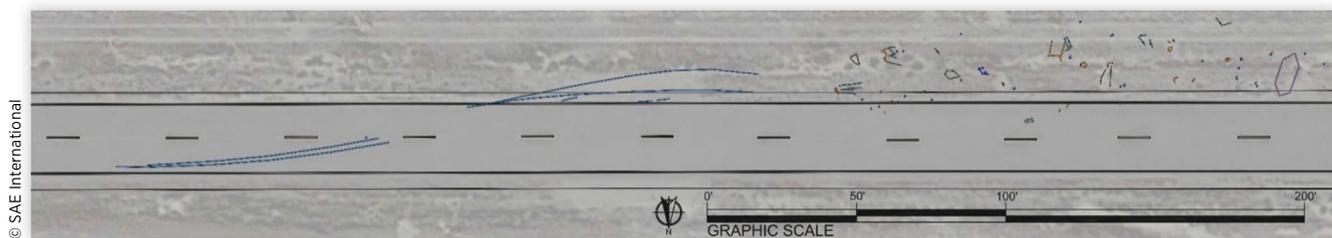
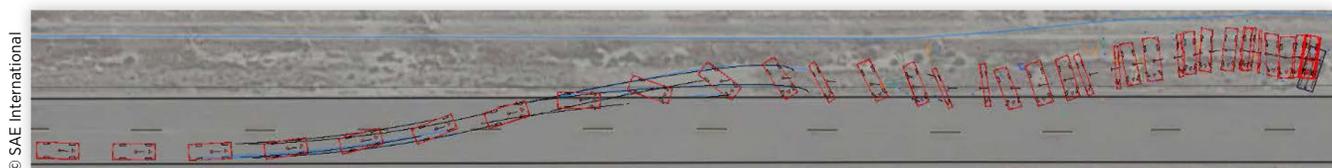
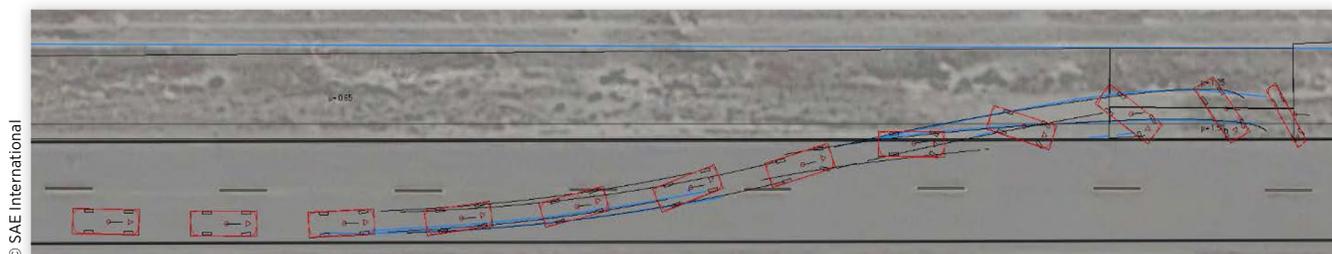
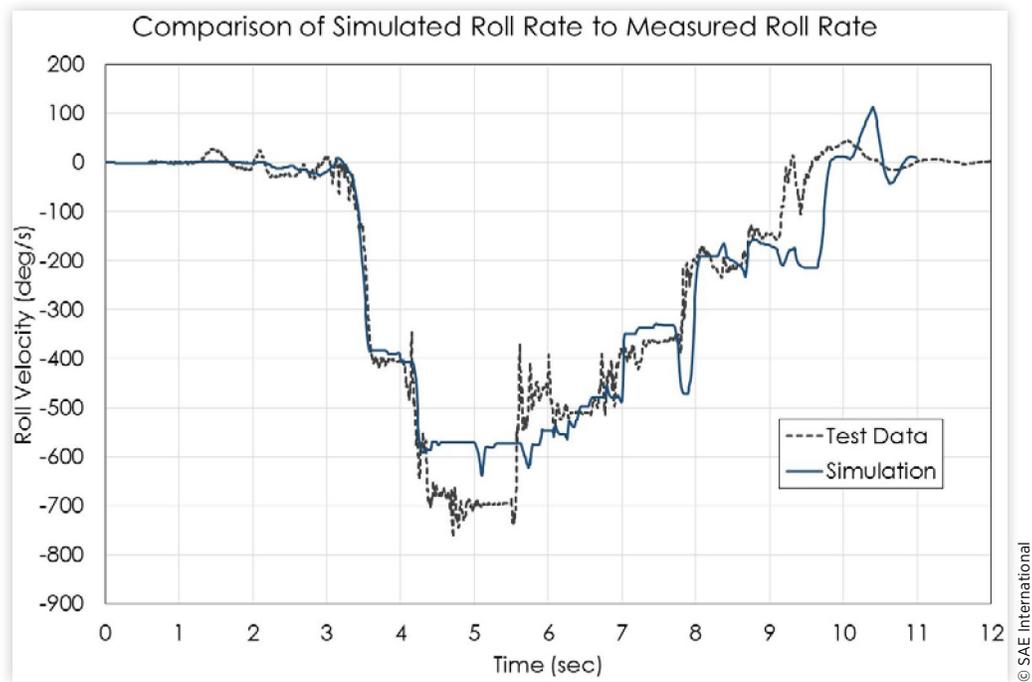
FIGURE A5 Optimization Results for MEA 32**FIGURE A6** Evidence Diagram Created for Asay's Isuzu Rodeo Test**FIGURE A7** Simulated Motion Overlaid on the Evidence Diagram**FIGURE A8** Simulated Motion Overlaid on Evidence Diagram - Loss of Control and Trip

FIGURE A9 Comparison between Roll Velocities in Simulation and Test

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