The Role of Vehicle Dynamics Simulation in Highway Safety Research

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INTRODUCTION

The state-of-the-art of vehicle dynamics analysis and simulation in the early 1950’s was defined by the related Cornell Aeronautical Laboratory (CAL) (now Calspan) papers presented at the Institution of Mechanical Engineers, London, in 1956 (Ref (1)). During the 1950’s and early 1960’s analog computer and some digital mainframe computer simulations of vehicle dynamics were being developed and applied by research organizations and vehicle manufacturers. Such simulations were generally based on linear or mildly non-linear equations of motion and were limited to small amplitude disturbances.

For simulations to be useful in many highway safety applications, it became necessary to include large amplitude disturbances, significant non-linearities, and abrupt discontinuities in the governing three-dimensional (3D) equations. Thus, the resulting simulations had to reliably predict vehicle behavior in response to both small and large amplitude disturbances from equilibrium.

SINGLE VEHICLE ACCIDENTS

One of the first vehicle dynamics simulations specifically developed for highway safety applications was the Highway Vehicle Object Simulation Model (HVOSM) (Ref (2)). It was developed in Bill Milliken’s Full Scale Division of Cornell Aeronautical Laboratory (CAL) under a contract with the Federal Highway Administration (FHWA). It should be noted that the original name for the simulation program, Cornell Aeronautical Laboratory Single Vehicle Accident (CALSVA), was changed to HVOSM by FHWA as a result of objections by competitors to the inclusion of CAL in the program name.

The specific objectives of HVOSM were to develop a means of (1) evaluating highway and roadside geometrics from the viewpoint of vehicle controllability, for a range of highway vehicles, and of (2) analyzing vehicle responses and thereby occupant exposures, in contacts and/or collisions with roadside obstacles and structures. Since the HVOSM (Fig 1) was developed on an early digital mainframe computer, it included many analytical simplifications of the non-linearities (e.g., symmetrical suspension travel stops) aimed at reducing the complexity and the memory requirements. However, the extent of the achieved correlation with 3D test data was found to be very good. In fact, the validity of the predicted vehicle responses was good enough to lead to a small spin-off project, in which the author worked closely with Mr. Milliken. That project was the “spiral jump” stunt of James Bond notoriety (Ref (3)), which is presented herein because of the Milliken connection. It served as an attention-getting means of demonstrating the 3D generality and validity of our vehicle dynamics simulation. It was hoped that it would enhance Calspan’s competitive position for future vehicle dynamics simulation research contracts.

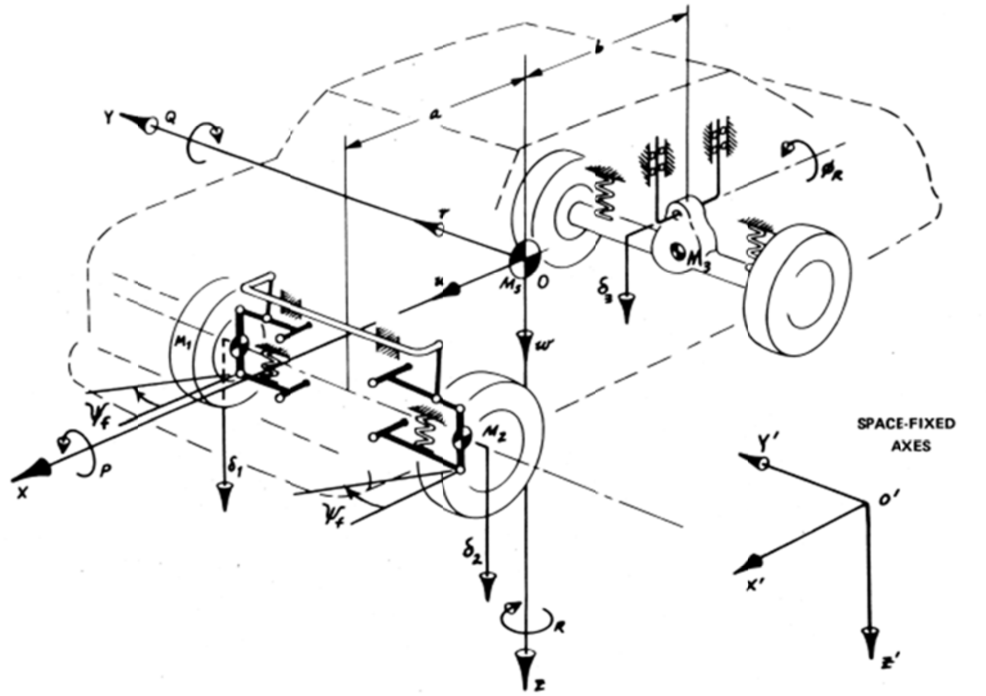


Figure 1 HVOSM Mathematical Model

HVOSM DEVELOPMENT

An early analytical task in the development of the equations of motion for HVOSM was definition of an indexing system for the angular coordinates such that unlimited yaw, pitch and roll angles could be accommodated without trigonometric problems.

Since the predominant non-collision forces would occur at the tires, attention was focused on the force generating properties of tires as a function of loading, terrain surface properties, and angular conditions of operation. Because of limits on the available ranges of measurements of tire properties, it was necessary to estimate behavior beyond the measured ranges. Empirical fits were adopted to match both the measured ranges of behavior and the estimated behavior beyond available measurements. Some corrections of the initially estimated behavior were indicated and adopted in early applications. For example, early predictions of vehicle responses in contacts with a New Jersey type of barrier (Fig 2) included excessive climbing up the barrier. Since that response was clearly produced by excessive camber thrust at very large effective camber angles and loading, the estimated large-angle camber thrust properties were reduced to achieve more realistic climbing.

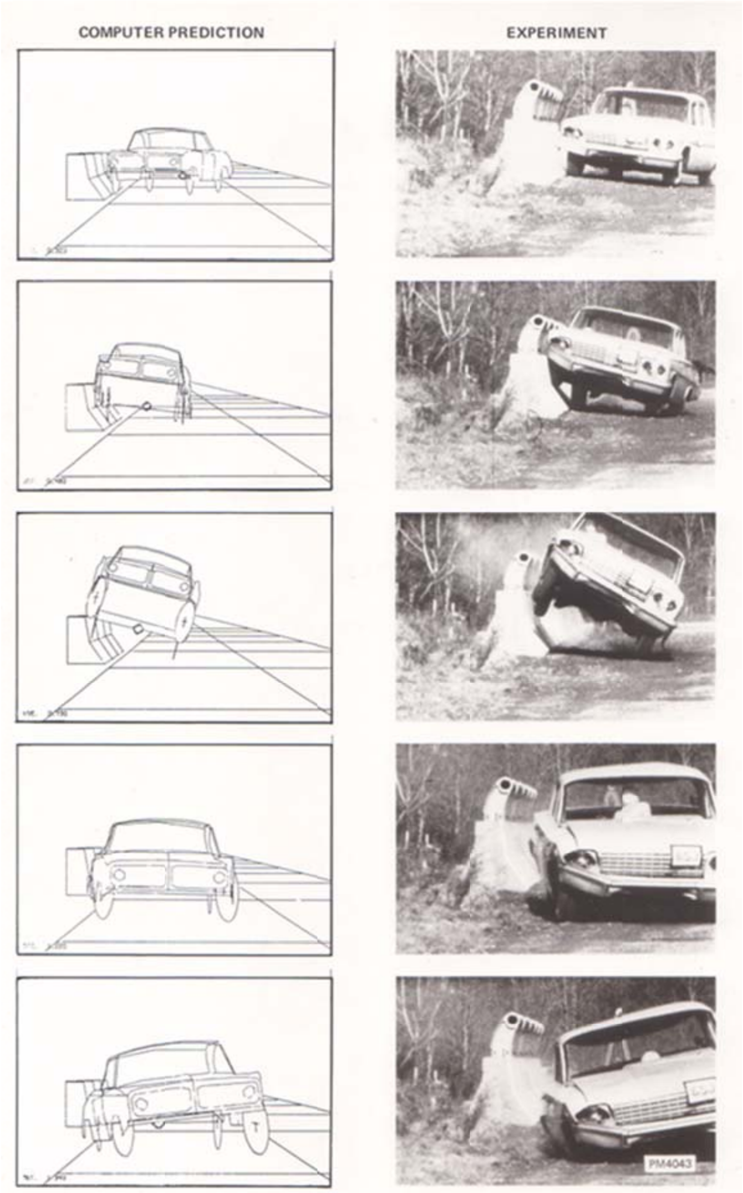


Figure 2 Safety Bridge Parapet Impact at 50 MPH, 12 Degrees

In the initial evaluations of validity, tire test data and the corresponding actual tires were provided by General Motors. The vehicle inertial and suspension properties were measured and provided by the Ford Motor company.

The test vehicles were several used 1963 Ford police vehicles in which an instrumentation package was installed in place of the rear seat (Fig 3 & 4). The tests started out with relatively mild maneuvers (e.g., sinusoidal steer responses) that progressively became more violent (e.g., traversal of small ramps, skidding on wet pavement (Fig 3 & 5). Drivers from a travelling auto thrill show were employed for the large disturbance tests which included a ramp-to-ramp jump (Fig 5 & 6). Detailed comparisons were made of the HVOSM-predicted responses with the measured tests results (e.g. Ref (4))

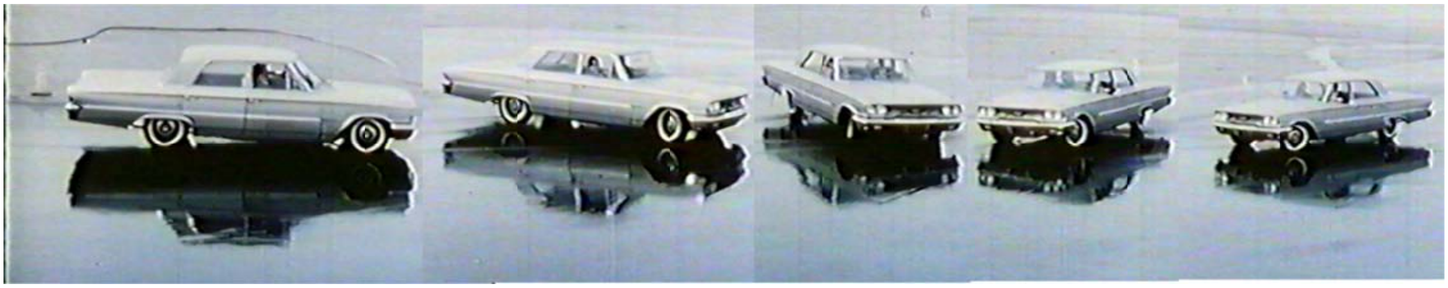


Figure 3 1963 Ford Galaxy Test Vehicle

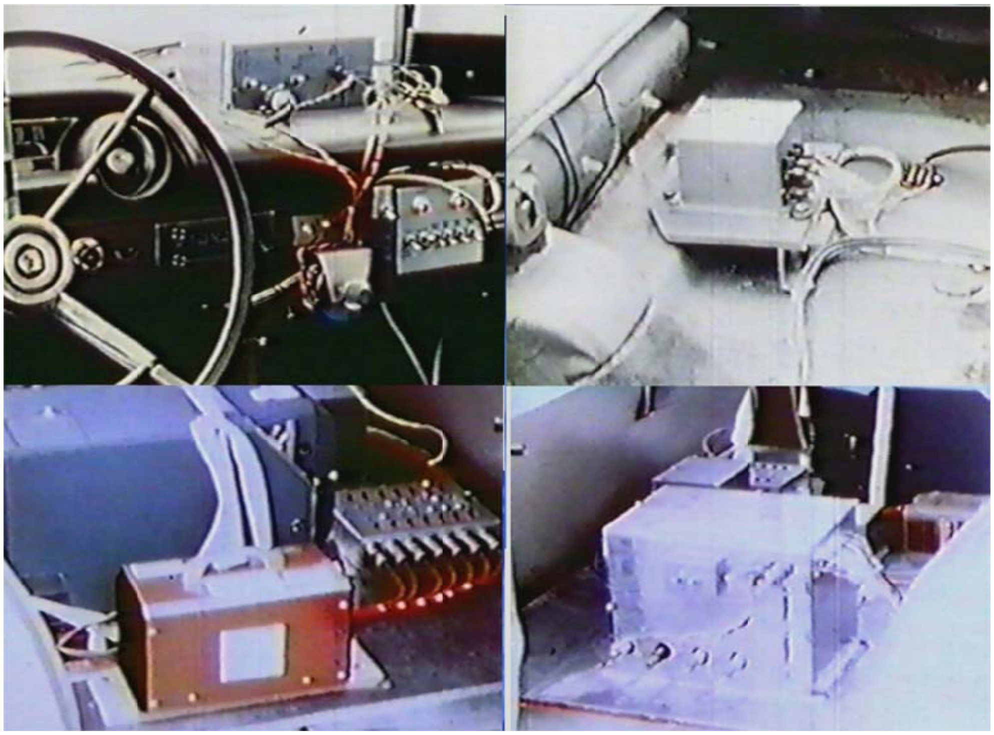


Figure 4 Test vehicle Instrumentation

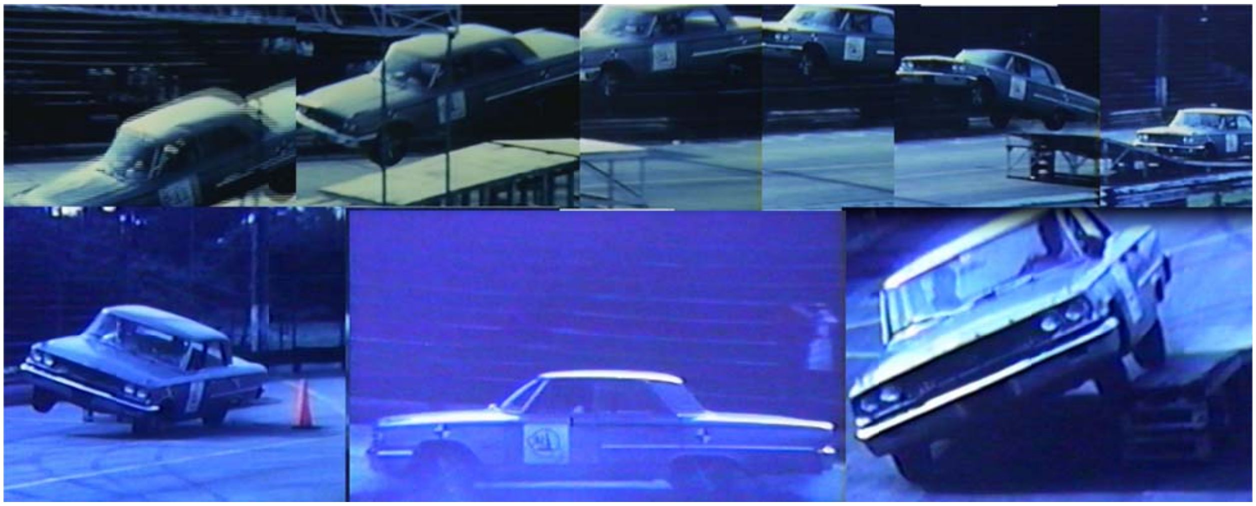


Figure 5 Vehicle Tests for HVOSM Validation

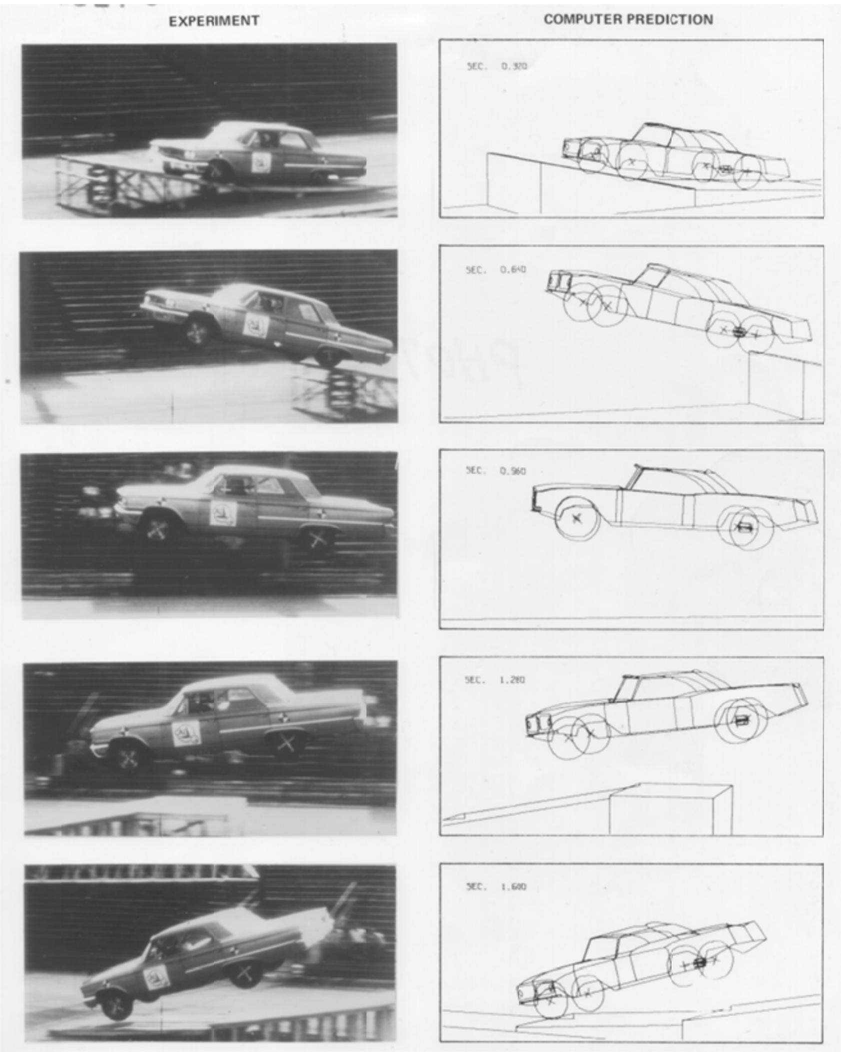


Figure 6 Ramp-to-Ramp Jump at 44 MPH

SPIRAL JUMP

The testing experience with the thrill-show drivers, combined with both the degree of success with HVOSM and the existing competition for related research contracts, led to a lunch time discussion of a small project to further demonstrate Calspan's vehicle dynamics capabilities. A preliminary computer demonstration was prepared for a stunt involving a vehicle rolling over while performing a ramp-to-ramp jump, in the manner of a spiraling football (fig 7). The demonstration wire-form video was shown to a local auto thrill show operator, Mr. Jay Milligan, and he agreed to fund a small feasibility study with actual measured vehicle properties and realistic speed and alignment variations.

Since Mr. Milligan was supported by American Motors, an AMC Javelin was selected for the feasibility study. Through the personal connections of Mr. Bill Milliken, inertial measurements of the AMC vehicle were performed at the General Motors Research Center. After successful spiral jump simulation runs of the HVOSM, actual full-scale physical tests with automatic vehicle control were performed at the Calspan Automotive Test Facility (Fig 8). An anthropomorphic test dummy, representing the driver for ballast, was used in the generally successful tests. The first public showing of the spiral jump stunt with a live driver was at the Houston Astrodome in January 1972 (Fig 9), Bill Milliken and I assisted in ramp placement and alignment, and speed control (Fig 11,12).

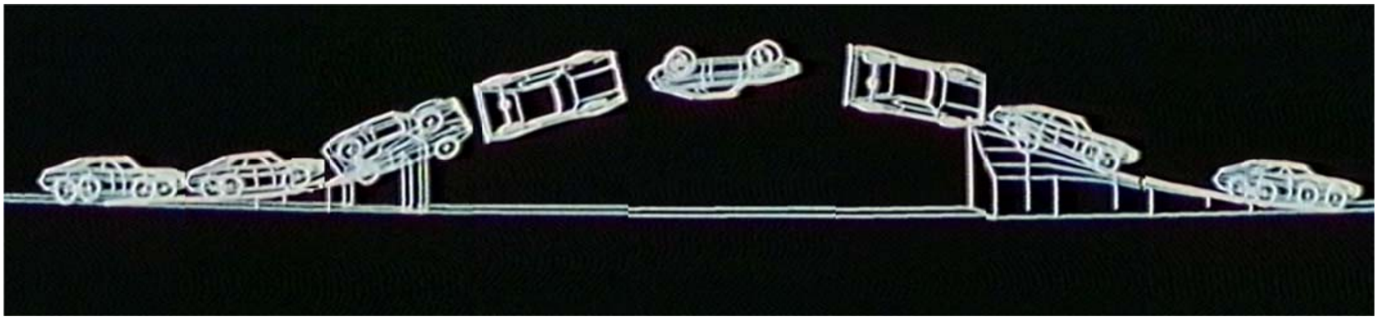


Figure 7 Spiral Jump “wire-form” Computer Graphics

Figure 8 Initial Testing at Calspan Automotive Test Facility

Figure 9 Bill Milliken, Ray McHenry and Jay Milligan circa 1971

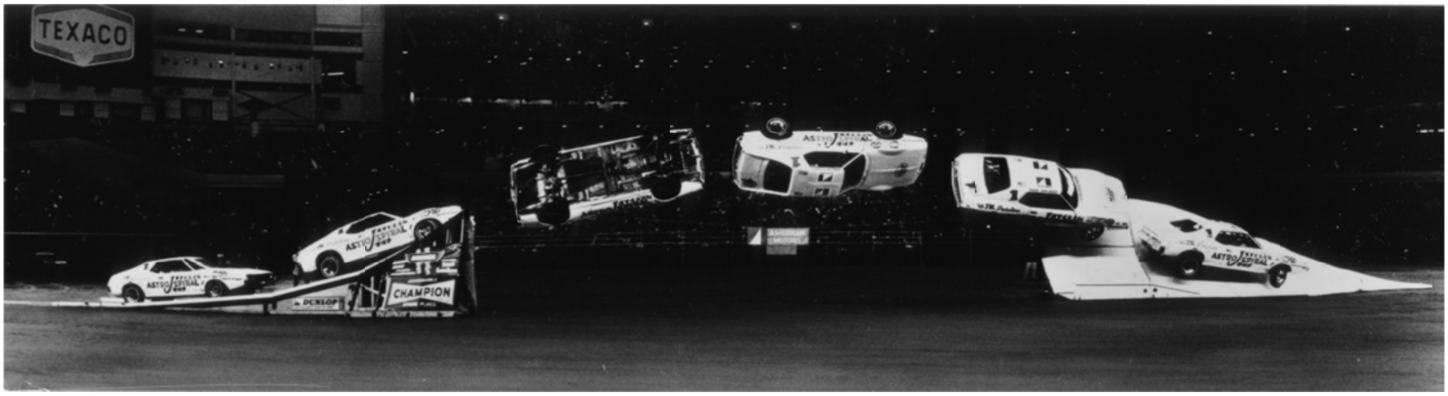


Figure 10 Performance of the Spiral Jump at Houston Astrodome

The successful stunt came to the attention of the producers of the James Bond films who contracted to integrate it into the movie “The Man with the Golden Gun”. For the movie, the stunt was performed “on location” in Thailand over a river (fig 13). The ramp setup is depicted in Fig 14, while many precautions were taken in the form of divers and emergency equipment; the movie performance was a complete success in a single take (Fig 13).

Loren “Bumps” Willert was the stunt driver for the movie and in interviews since the jump he stated that he noted that the ramps were placed out of line to compensate for the sideways travel of the car as it spiraled through the air. (See Fig 12) “I admit it was hard to keep it on the line painted on the launch ramp, when you could see the landing ramp sitting way, way off to the side. But I did it, and the first time I did it was the take you see in the movie." Willert drove the stunt after the movie performance 31 times in auto thrill shows and landed safely 29 times. He was reported to have said "You knew as soon as you left the ramp whether it was going to work or not," and he also added, chuckling. "It was a spectacu1ar stunt when it worked and a spectacular crash when it didn't."

Figure 11 1974 Houston Astrodome setup

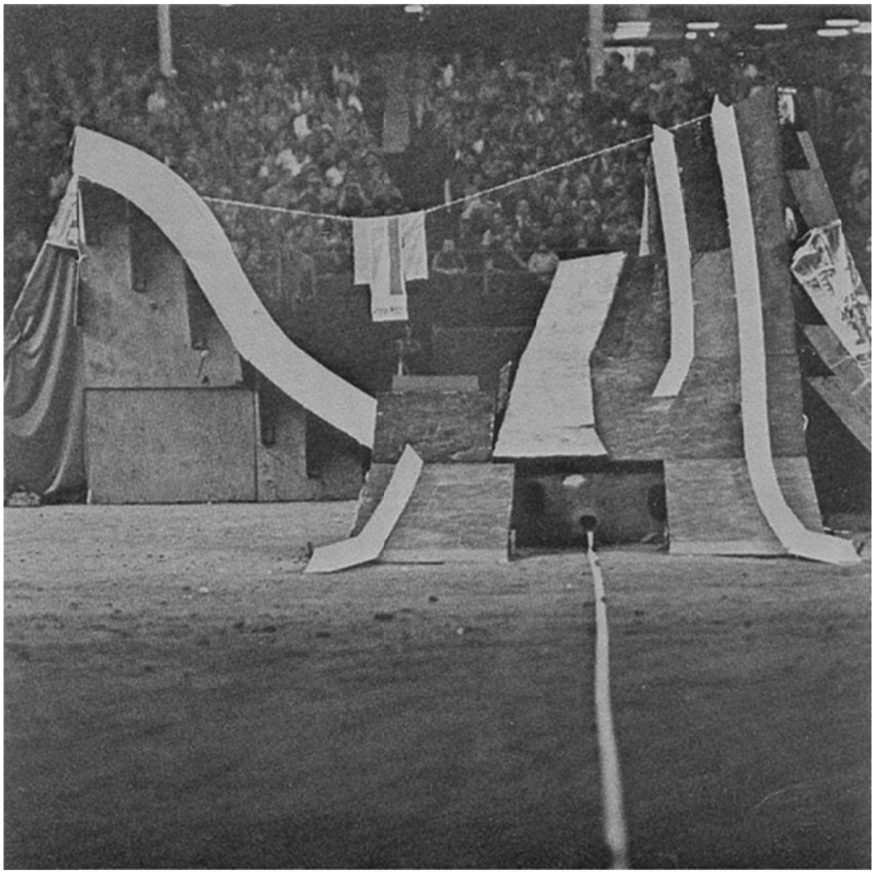


Figure 12 Spiral Jump Driver's View approaching ramps

Figure 13 Stunt over water from the James Bond Movie

Figure 14 Ramps setup in Thailand for James Bond Stunt

Figure 15 Sample of SMAC Collision Reconstruction

RECONSTRUCTION OF COLLISIONS AND RELATED VEHICLE MOTIONS

In the early 1970's, the reconstruction of vehicle-to-vehicle collisions for purposes of law enforcement, statistical research and crash injury investigations was predominantly based on highly simplified damage interpretations and linear momentum calculations. The author proposed to the National Highway Traffic Safety Administration (NHTSA) that improved uniformity and accuracy of evidence interpretations could be achieved by means of a vehicle dynamics simulation approach. The simulation would be used to test approximated impact conditions by generating simulation predicted evidence in the form of corresponding rest positions and headings, and damage extents and profiles for comparison with the actual physical evidence. An acceptable match of the overall evidence would be interpreted as indicating reasonably correct impact conditions (Ref (5)). A small contract was received by Calspan which led to development of the two-dimensional (2D) Simulation of Automobile Collisions (SMAC) program (fig 15)

A series of staged vehicle-to-vehicle collisions were performed by Calspan to provide a basis for evaluating the validity of the SMAC program (Ref (6), (7), Fig 16, 17). The generally impressive validation results have led to a widespread adoption of a digital simulation approach for reconstructing highway collisions.

Figure 16 Example of staged crash tests, CALSPAN RICSAC Test 2

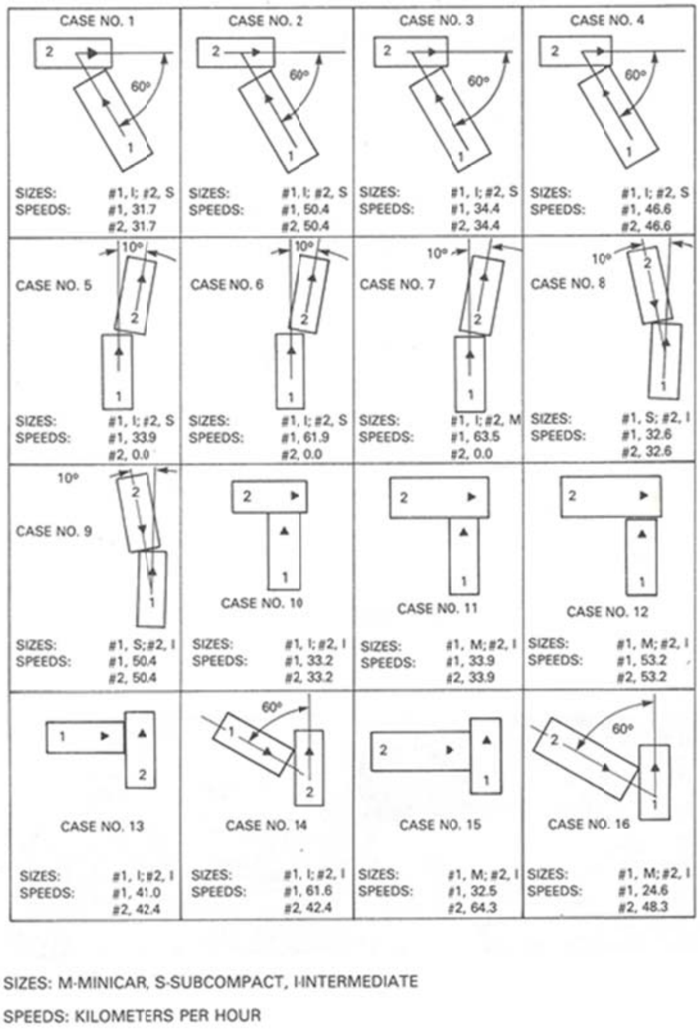


Figure 17 Summary of Full-Scale RICSAC tests (Ref 6, 7)

COMBINING VEHICLE SIMULATION TECHNOLOGY (HVOSM) WITH COLLISION RECONSTRUCTION (SMAC)

In many vehicle-to-vehicle collisions the terrain is not flat and the vehicle responses may include significant pitching and/or rolling, including actual rollovers. Since the HVOSM includes unlimited angular responses in single vehicle accidents, it became attractive to consider the development of a SMAC type of vehicle-to-vehicle collision simulation using 3D vehicles as defined in HVOSM. At McHenry Software our first development and application of such a 3D simulation program for accident reconstruction was in 1998 when my son, Brian, was hired by CBS news to reconstruct the Princess Diana accident in Paris (Fig 18). Subsequent to that time we have continued to develop, generalize and further validate the corresponding mSMAC3D computer program (Fig 19).

Proprietary extensions of the initial mSMAC3D include routines that automatically generate default approximations for the required three-dimensional vehicle inputs (e.g., suspension & tire properties, roll and pitch moments of inertia) corresponding to the plane-motion 2D simulation inputs. This initial input approximation approach combined with the ability to overwrite any inputs for which measured values are available provides a comprehensive and efficient setup to evaluate motor vehicle collisions.

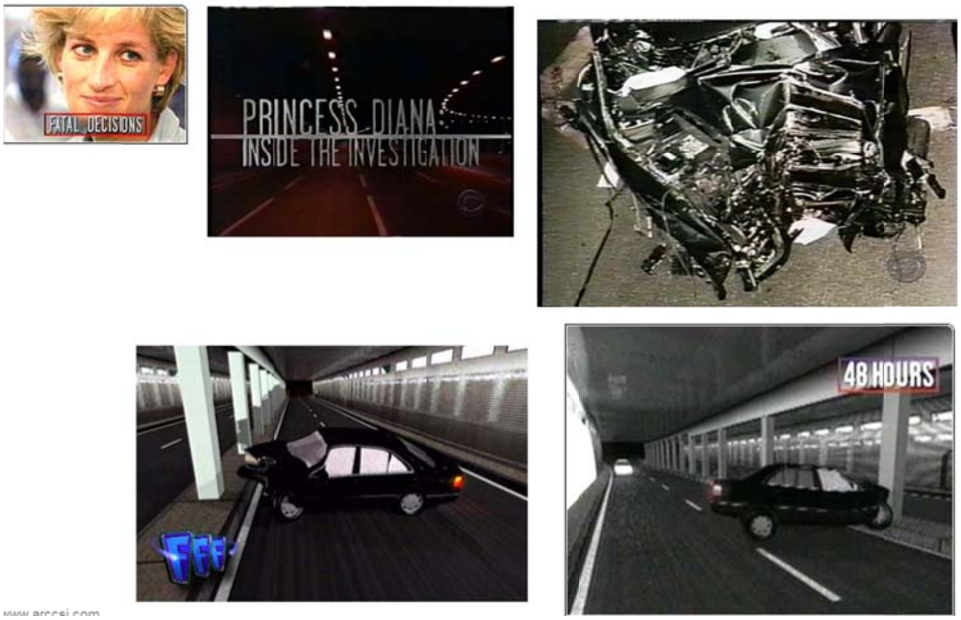


Figure 18 Princess Diana Accident Reconstruction with msmac3D

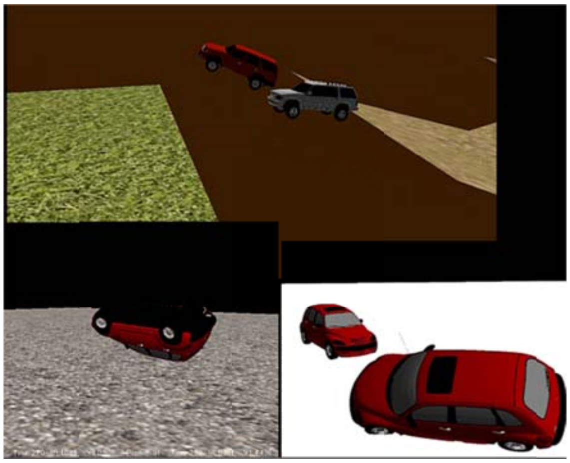


Figure 19 msmac3D

FUTURE PRIORITIES IN HIGHWAY SAFETY RESEARCH

The injury and damage results of actual highway collisions constitute a largely untapped but potentially extremely valuable source of detailed information on human tolerances, injury mechanisms, safety performance of design features and protective devices, and the relative crashworthiness of different makes and models of vehicles. The current state of development of accident reconstruction computer programs makes the following course of action both realistic and attractive.

MEASUREMENT PROTOCOL

A standardized measurement and reporting protocol for accident site topography, vehicle rest positions and orientations, tire tracks, gouge marks, debris locations and vehicle damage should be established. If police organizations can be persuaded to follow the standard protocol, interpretation of the reported evidence in terms of impact speeds and exposure severities can also be standardized.

Trajectory measurements

- The approximate positions and orientations of the vehicles at impact
- The measured positions and orientations of the vehicles at rest
- Distance POI to POR for each vehicle
- Azimuth angle POI to POR for each vehicle
- Direction of the System Momentum

Damage measurements:

- Damage width
- Damage depth
- Damage area
- Centroid of the damage region
- Clock direction of the approximate PDOF

Table 1 Factors considered in the SMAC correlation comparison and score

SCORING OF RECONSTRUCTION RESULTS

With each small adjustment of (1) the approximated individual pre-impact linear and angular velocities, (2) the relative positions and orientations at impact, (3) effects of damage on the wheel rotational resistances, steered angles and tire side forces at individual wheels subsequent to separation and (4) tensile constraints (if any) resisting separation, the overall predicted results obtained with a validated reconstruction program can be compared with the measured evidence (Table 1). A non-dimensional addition of all discrepancies in the comparison match of evidence can serve as a numerical “score” of the evidence match. Note that preliminary efforts toward this goal in a 2D reconstruction are presented in Ref (8), Fig 23. It is anticipated that such a score can ultimately provide a validated measure of the reliability of the reconstruction results. A listing of the largest discrepancies in the evidence match can provide a basis for a detailed review of the reported evidence with a view towards identification of errors and/or overlooked details.

AUTOMATIC ITERATION TO IMPROVE EVIDENCE MATCH

Optimization techniques applied to the evidence match can serve to reduce the required time and effort and, also, can achieve greater uniformity of the evidence interpretation. Note that initial efforts on automatic iteration in the 2D case have been reported in Ref (8) (Fig 20-23).

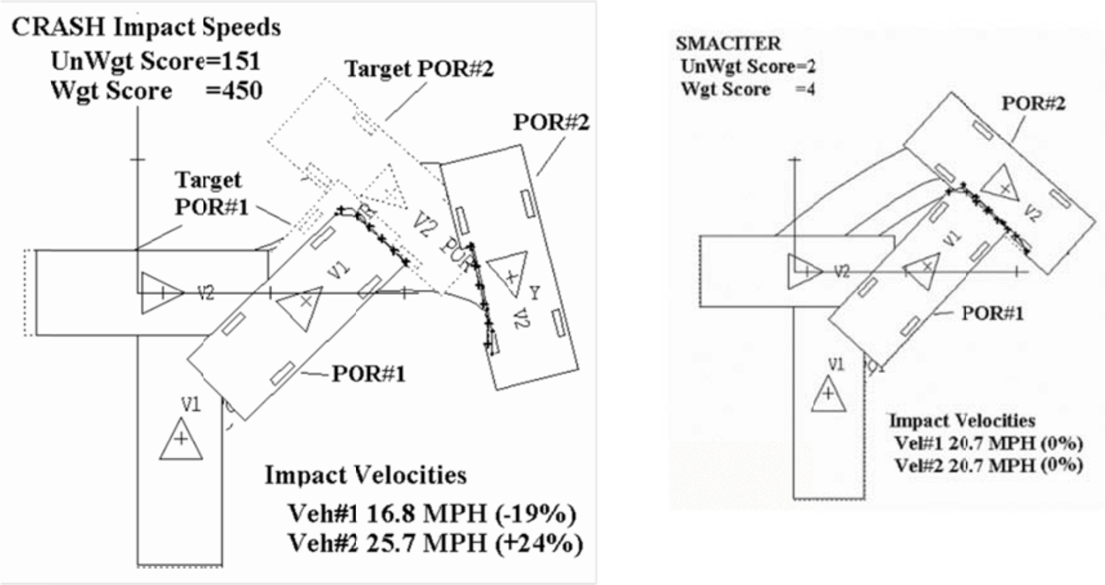


Figure 20 Automatic Iteration solutions of a SMAC Reconstruction of a sample RICSAC Test

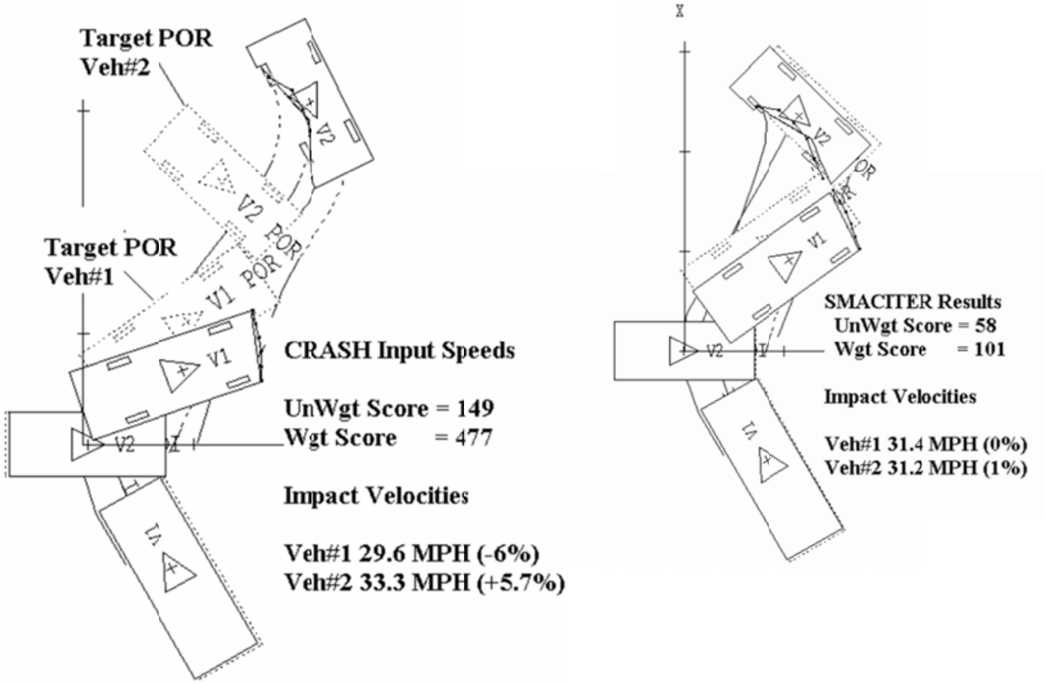


Figure 21 Automatic Iteration solutions of a SMAC Reconstruction of a sample RICSAC Test

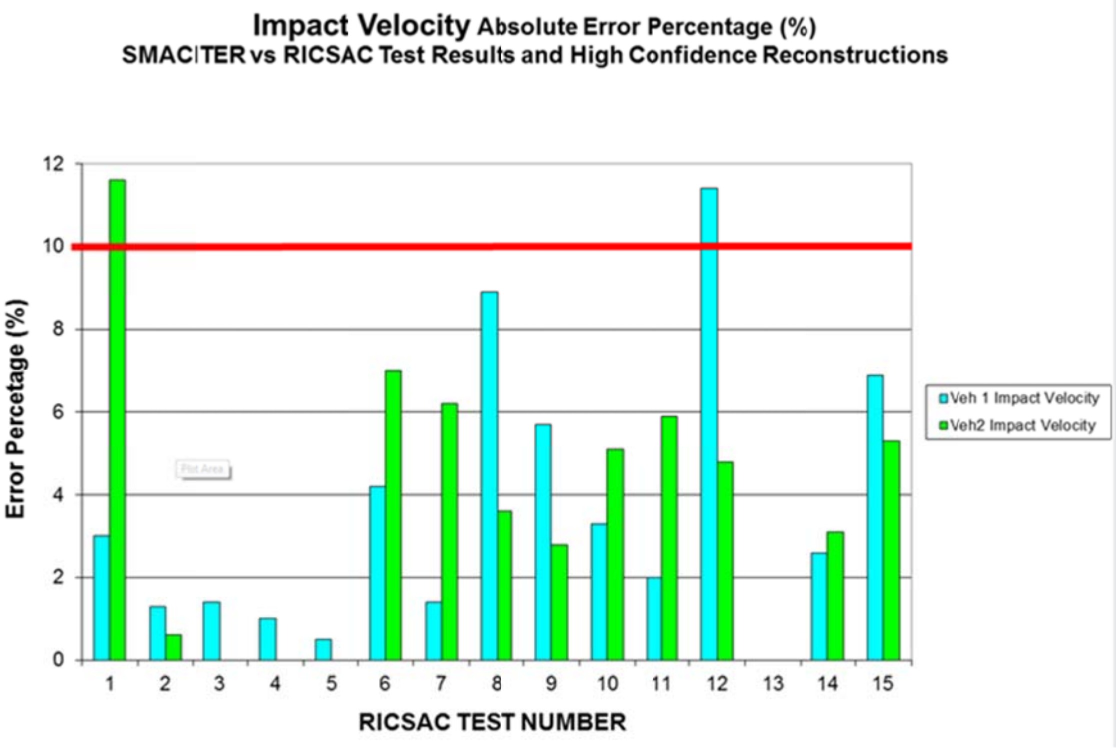


Figure 22 Comparison of msmac Automatic Iteration Rsults with Crash Test results on Impact Velocity

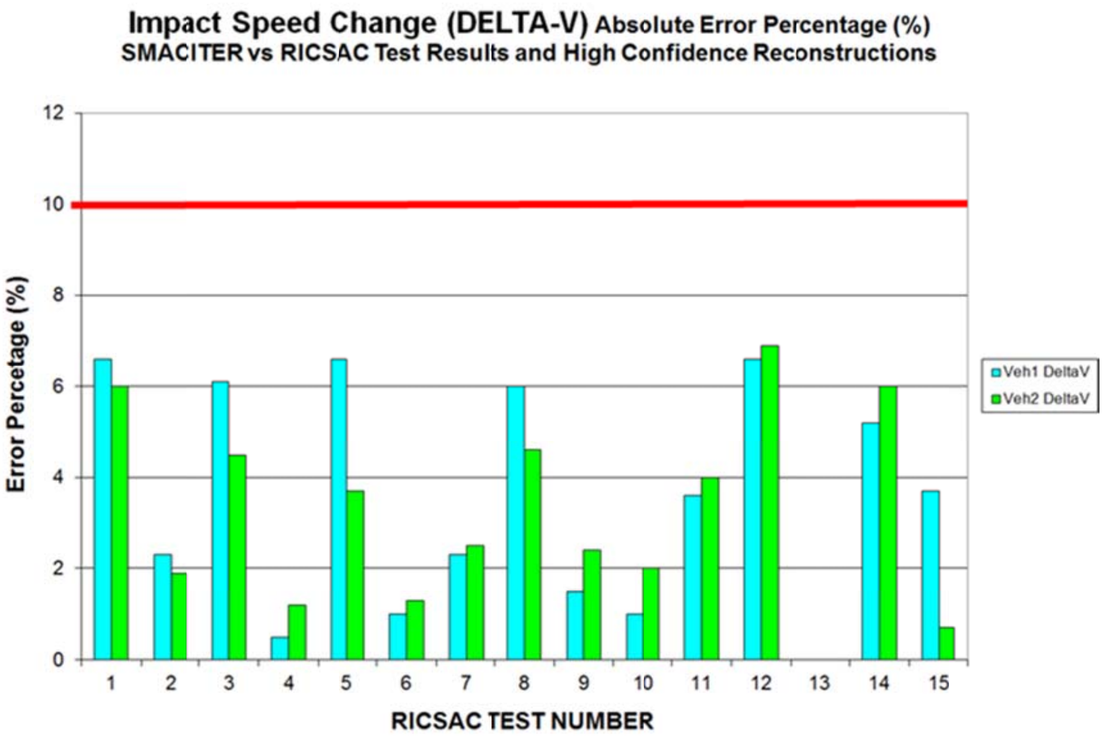


Figure 23 Comparison of msmac Automatic Iteration with Crash Test results on Impact Speed Change

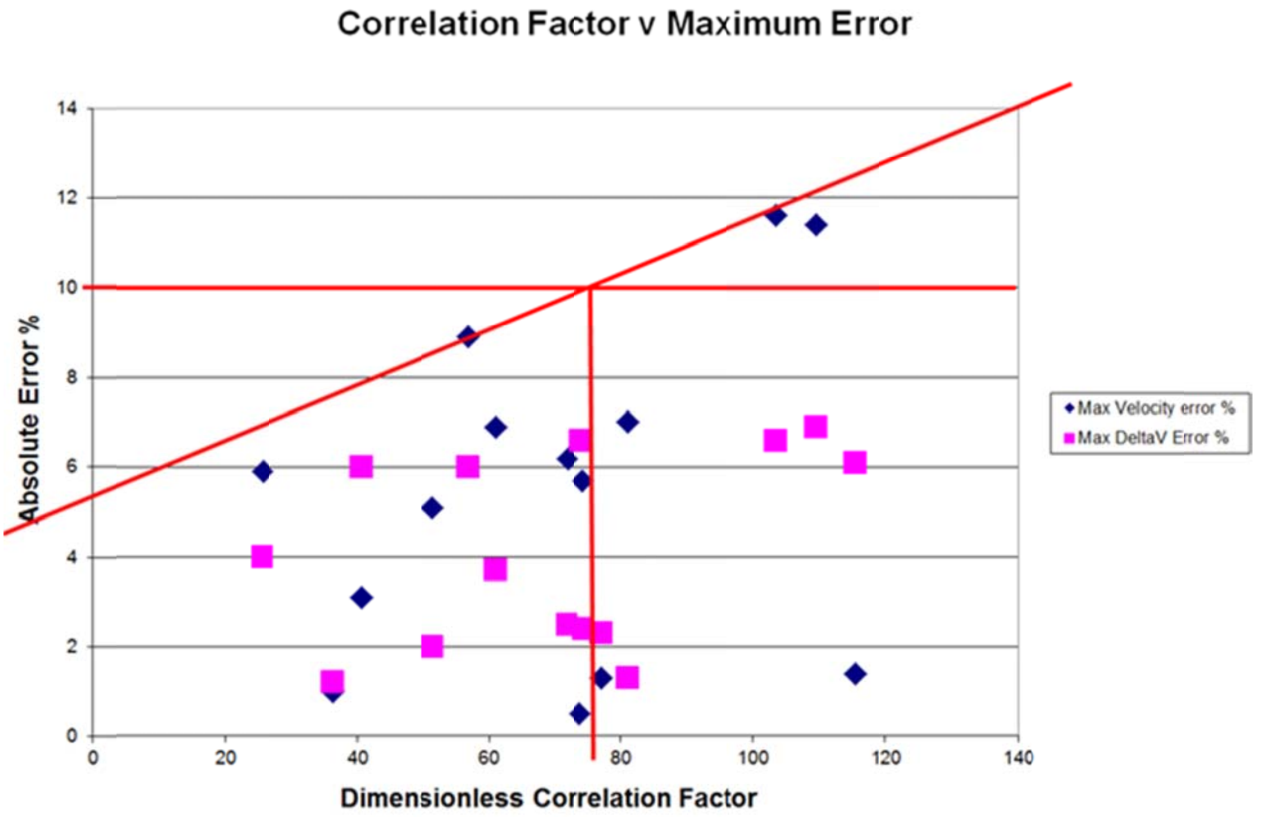
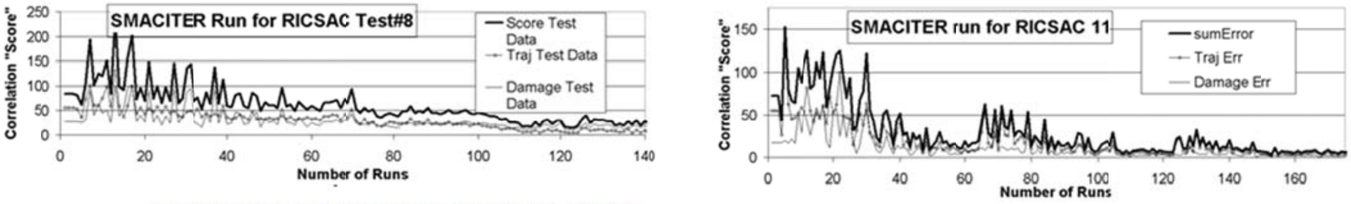


Figure 24 Comparison of msmac automatic iteration correlation factor "score" with maximum error



RICSAC Test#8, SMACITER Correlation "score" during the iterative process

RICSAC Test#11, SMACITER correlation "score" variation during iterative process

Figure 25 msmac automatic iteration change in "score" during the iterative process

CORRELATION OF INJURIES WITH EXPOSURE SEVERITY

When sufficiently developed, reconstruction with automatic iteration can yield high quality interpretations of accident evidence for use in law enforcement and traffic studies. If combined with related medical records from hospitals, the reconstructions can yield detailed information on human tolerances and injury mechanisms. Thus, the described research could provide major refinements in the accuracy and detail of crashworthiness and crash causation studies, such as those being performed as part of the NHTSA Crash Data Collection Programs (Ref (9))

REFERENCES

(1) Milliken, W.F., Jr., et al, Research in Automotive Stability and Control and in Tire Performance, collection of papers, The Institution of Mechanical Engineers, London 1956

(2) McHenry, R,.R, “An Analysis of the Dynamics of Automobiles During Simultaneous Cornering and Ride Motions”, The Automobile Division, The Institution of Mechanical Engineers, London 1969

(3) McHenry, R. R., “The Astro Spiral Jump – An Automobile Stunt Designed via Simulation”, SAE Paper No. 760339, Detroit 1976

(4) McHenry, R.,R.,, Deleys, N.J. “Vehicle Dynamics in Single Vehicle Accidents – Validations and Extensions of a Computer Simulation, Interim Technical Report, CAL No VJ-2251-V-3, Contract No CPR-11-3988, December 1968

(5) McHenry, R,.R., “Approximations of Impact Conditions via Computer Simulation”, NATO Conference on Accident Investigations, Brussels, Belgium, 1973

(6) Smith, R. A., Noga, J. T. "*Examples of Staged Collisions in Accident Reconstruction*", from *Highway Collision Reconstruction*, The American Society of Mechanical Engineers, Nov. 1980

(7) McHenry, B.G, McHenry, R.R., “RICSAC-97, A Reevaluation of the Reference Set of Full Scale Crash Tests”, SAE Paper No 97-061, Detroit 1997

(8) McHenry B.G., McHenry, R.R., “SMAC2003: The Automatic Iteration of SMAC”, SAE Paper 2003-01-0486, Detroit, 2003

(9) Report to Congress NHTSA’s Crash Data Collection Programs, DOT HS 811 337, April 2010, http://www-nrd.nhtsa.dot.gov/Pubs/811337.pdf