

# A Short History of Nearly Everything! (...about McHenry and Computers in Highway Safety)

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In his 2005 book **A Short History of Nearly Everything**, Bill Bryson takes readers on a spirited journey from the Big Bang to the present day with all things scientific in between. The size of the universe, the creation of the earth, Teutonic plates, tornados, cosmology, astronomy, paleontology, geology, physics, the garden club?, it's all in the book. You will also find some very interesting stories about the many people involved in scientific discovery throughout the ages. I highly recommend the book as you will certainly enjoy the read!

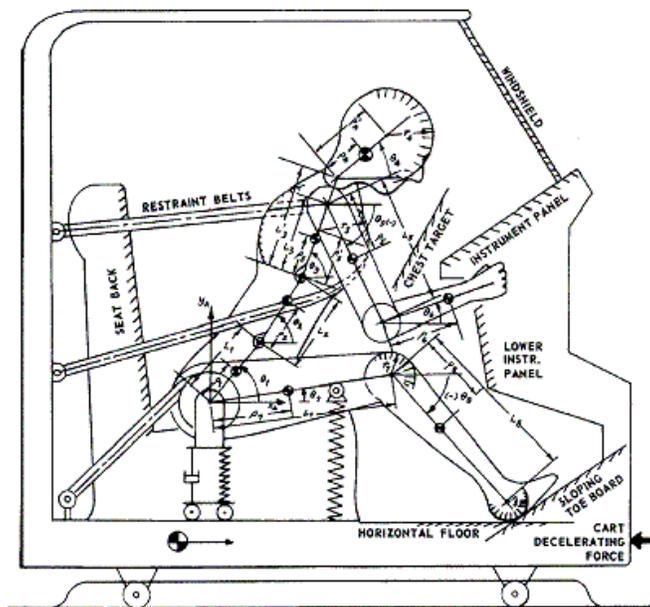
In the same spirit of things, this article will take you from the Big Bang of the 60's digital computer revolution to the present time with all things related to McHenry in highway safety. I will focus in particular on some of the pioneering accomplishments in the field of computer applications to highway safety by my father, Raymond R McHenry in his first 25+ years in the field. I'll also present some of the things he and I have accomplished working together for the past 30+ years as well as what we are planning for the future.

The journey into the field of highway safety for Ray McHenry started in the 1950's. Fresh from WWII Air Force military service and graduating from the University of Maine in Engineering Physics, he took a job in the automobile industry in Detroit, MI. He started with Chrysler (which included attending and graduating from the Chrysler Institute) and then moved to Ford. Around

1960 he decided that he'd had enough of research exercises related to product development. The straw that broke his spirit's back was that after spending an extended and successful effort working on a revolutionary hydro-pneumatic suspension design and implementation, the prototype vehicle was destroyed and the project filed for potential future interest because the 'suits', aka the marketing department, didn't think it would sell in the existing market. It was then that Ray decided that it was time to pursue a different type of engineering work. Around 1960 he took a job in the transportation research department at Calspan (then known as Cornell Aeronautical Lab) in Buffalo New York.

One of the first projects at Calspan which utilized Ray's unique analytical skills was related to occupant kinematics. In 1963 the U.S. Public Health Service and the Automobile Manufacturer's Association, Inc. funded research at Calspan performed by Ray to develop a response to a Consumer Reports issue [1] and related reports [2, 3] that included the assertion that American seat belts failed under the Swedish test conditions and "the major points of failure of the belts tested were the webbing...and the floor brackets themselves".

As part of the research Ray McHenry and his team at Calspan created an occupant simulation model for longitudinal collisions to assist in the investigation and understanding of the differences between US and European belt standards. The resulting computer program was called the CAL-2D [4]. The program represented one of the first computer simulation applications created and utilized in the field of highway safety research.



*Figure 1 CAL-2D Mathematical model of human body and restraint system on test cart (11 degrees of freedom)*

### **CAL-2D – Occupant Simulation**

The CAL-2D model was created "in order to help improve understanding of the complex relationships of force-acceleration-time-position-velocity that occur in the impact and energy-absorbing cycle of automobile passenger restraint systems". The study was performed to provide guidance concerning "(1) fundamental differences in the results obtained by static and dynamic testing and (2) the possible need for dynamic acceptance testing of seat belts.

One of the results of the study was the conclusion that "the use of a very short stopping distance in a dynamic cart test of lap belts can produce a distorted comparison of the strength (when belt loads are not measured) and the performance of webbing materials with different load-elongation characteristics. A short (~3") cart-stopping distance, from 25 mph, used in the European tests, produces increases in the magnitudes of both primary and secondary belt loading cycles over those obtained with a more "realistic" (~17") stopping distance, as encountered in actual automobile crashes".

Subsequent follow-up contracts at Calspan resulted in the creation of a general purpose 3-dimensional crash victim simulation program. The development resulted in the creation of the Crash Victim Simulator (CVS) [5]. In the 1980's, the CVS was adapted for use by the Armstrong Aerospace Medical Research Laboratory at Wright Patterson Air Force Base and was re-named the Articulated Total Body (ATB). The principal investigator of the CVS/ATB development at Calspan was Dr. John Fleck. [6]. The pioneering work by Dr. Fleck included extremely efficient integration routines for economical execution of the program, dynamic memory sharing techniques which permitted the program to run with the limited amount of dynamic memory in computers during the era, and the addition of many extensions and refinements to extend and expand simulation capabilities.

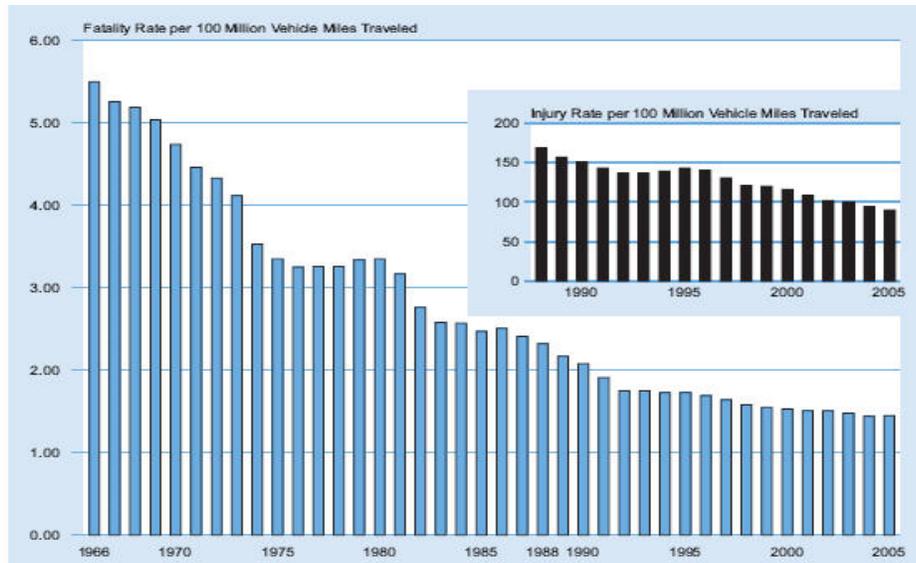
## Highway Safety Research

In 1952, a pioneer program in highway safety research, the Automobile Crash Injury Research Program (ACIR), was created by Cornell University with the objective of determining injury causation among occupants of cars involved in accidents, in order that the injuries might be prevented or mitigated through improved vehicle design. By the mid sixties, 31 states had participated in the program and provided over 50000 cases for study [7]. The main criterion for classifying severity in the ACIR program was through the use of comparison photographs of damaged vehicles.

In 1966 the National Traffic & Motor Vehicle Safety Act (P.L. 89-563, 80 Stat. 718) was passed which established the Federal Motor Vehicle Safety Standards (FMVSS) and the National Traffic Safety Agency (now known as NHTSA). The Motor Safety Act required regulators to establish federal motor vehicle safety standards to protect the public against "unreasonable risk of accidents occurring as a result of the design, construction or performance of motor vehicles" and also against "unreasonable risk of death or injury ... in the event accidents do occur."

At the time of signing the Safety Act into law President Johnson stated "Auto accidents are the biggest cause of death and injury among Americans under the age of 35". In 1965, 50,000 people were killed on our nation's highways. Since 1966, the Department of Transportation (DOT) has taken a comprehensive approach to reducing roadway fatalities by promoting strong traffic safety laws coupled with high-visibility enforcement and through rigorous vehicle safety programs and public awareness campaigns.

*The success of the traffic safety program was demonstrated in year 2010 when NHTSA reported that the number and rate of traffic fatalities in 2010 fell to the lowest levels since 1949, despite a significant increase in the number of miles Americans drove during the year. Since 2005, fatalities have dropped 25 percent, from a total of 43,510 fatalities in 2005 to 32,788 in 2010. The fatality rate will be the lowest recorded since 1949, with 1.09 fatalities per 100 million vehicle miles traveled, down from the 1.13 fatality rate for 2009. The decrease in fatalities for 2010 occurred despite an estimated increase of nearly 21 billion miles in national vehicle miles traveled.*



**Figure 2 Highway Accident Fatality Rate from 1966 to 2005**

Also during the 60's, the digital computer came of age. Mainframe computers, which filled entire floors of buildings, and cost hundreds of thousands to millions of dollars evolved into time-sharing, batch processing machines.

*Before the introduction of the microprocessor in the early 1970s, computers were large multi-million dollar systems (like the IBM/360) which consumed entire floors of buildings, required their own cooling systems, and were owned by institutions like corporations, universities and government agencies. Computer users normally used punched cards to enter tasks into the computer and individual computational 'jobs' on the computer were entered in 'batch mode' and controlled by Job Control Language (JCL). Output from the computers was generally printed output. These were used in conjunction with 9-track tapes (for storage), card punch and reader machines (for creating and reading program input) and terminals to provide to scientists, engineers and others number crunching capabilities unlike any utility ever before imagined.*

*The costs of operating large scientific mainframe computers were dropping significantly in the early sixties. A program which cost \$100 to run in 1962 cost only approximately \$5.65 in 1966 [8]. Other items which we take for granted today are processing speed and disk capacity. A measure of computation power is Floating point Operations Per Seconds (FLOPS). In the mid 1960s FLOPS were at a rate of approximately 1 million, also known as a megaFLOP. In 2010, FLOPS were approaching petaFLOPS ( $10^{16}$ ). Also disk and memory capacities were extremely limited on these computers. We have extraordinary processing capacity and power at our fingertips today with our notebook computers operating at petaFLOPS and containing gigabytes of memory and terabytes of disk capacities. The age of the notebook supercomputer is upon us now!*

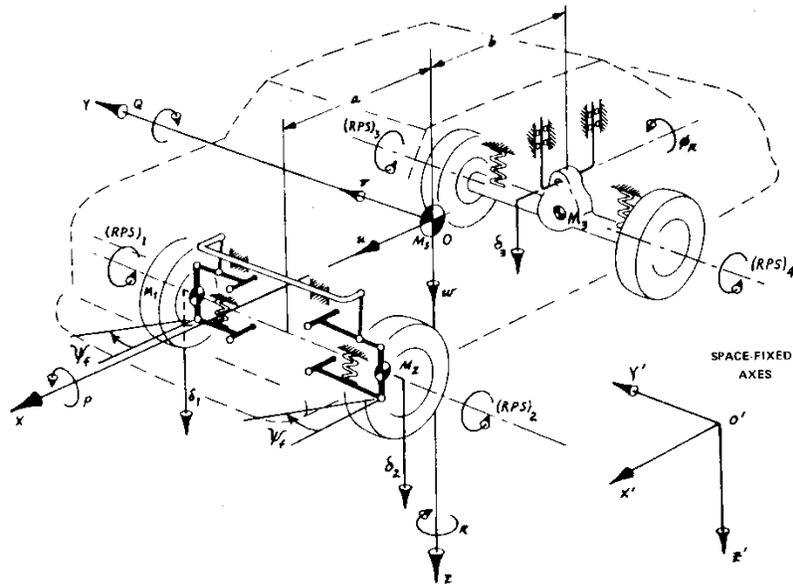


Figure 3 HVOSM analytical representation of vehicle

### HVOSM: The Highway Vehicle Object Simulation Model

Returning to the mid-60's the Calspan Corporation began development of a general mathematical model and computer simulation of the dynamic responses of automobiles under the direction of Ray McHenry [9]. The mathematical model, which was subsequently named the Highway Vehicle Object Simulation Model (HVOSM), included the general three-dimensional motions resulting from vehicle control inputs, traversals of terrain irregularities and collisions with certain types of roadside obstacles.

The development of the HVOSM included an extensive validation effort within which a series of repeated full-scale tests with instrumented vehicles was performed to permit an objective assessment of the degree of validity of the computer model [10].

The need for analytical capabilities in highway safety research becomes apparent when one considers the large number of variables that influence both the occurrence and the consequences of highway accidents. Actual accidents include an infinite variety of combinations of direction, speed, evasive maneuvers, obstacles, vehicle and terrain properties, vehicle occupancy and conditions of occupant restraint. Therefore to perform a rigorous evaluation of the benefits to be achieved by a given change in vehicle or roadside design one must include consideration of a representative sample of vehicles, operating conditions, occupancy and occupant restraints.

In a full-scale experimental evaluation, the generally poor repeatability (i.e., the scatter in results) makes it necessary to include several runs of each test condition. Obviously, a purely experimental evaluation procedure is both time consuming and expensive. Experiments also do not provide a capability of predicting responses of a complex, nonlinear system. Validated analytical procedures can serve to reduce the required number of full scale tests by providing a means of interpolating and extrapolating experimental results for widely spaced test conditions. They can also serve to provide a predictive capability and, thereby, a theoretical framework within which tests can be planned and experimental data interpreted. The highly nonlinear nature of the physical system, both in violent

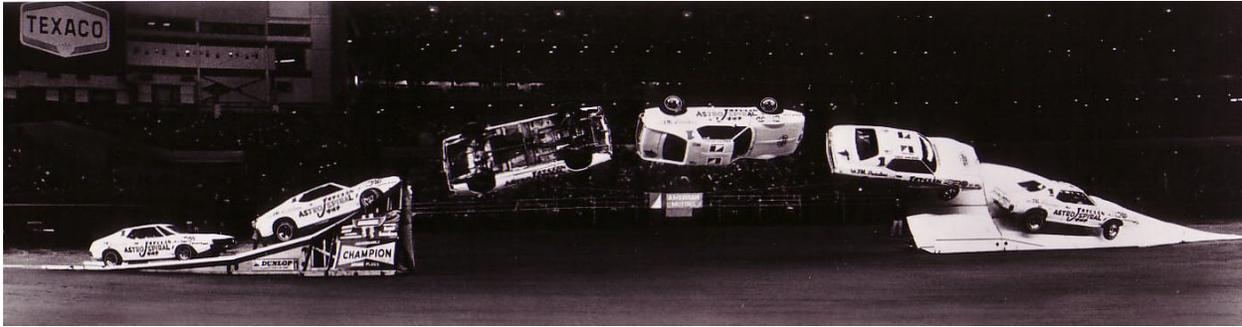
evasive maneuvers and in collisions, demands that realistic analytical procedures be programmed for computer solution.

At the time of the development of the HVOSM, an extensive body of literature existed on analytical studies of automobile dynamics, but the general approach at the time involved separate treatment of motions in the longitudinal plane (ride responses, performance and braking) and motions in the lateral plane (cornering behavior and stability). Furthermore, the equations of motion had generally been linearized. While such practices are acceptable in studies of small disturbance handling qualities, they are not appropriate for violent maneuvers at the upper limits of vehicle control. In view of the extended requirements for a realistic analysis of vehicle dynamics in near-accident and accident situations, where interactions between ride and cornering motions cannot be neglected, the nonlinear HVOSM computer simulation of automobile dynamics was developed to permit the study of simultaneous, large amplitude ride and cornering motions and to include an approximate treatment of collision forces.

The HVOSM vehicle representation has fifteen degrees of freedom: 6 for the sprung-mass, and up to 9 for the unsprung-masses. Tire side forces are generated according to equations allowing for saturation to occur at large slip angles. The "friction circle" and the "friction ellipse" concepts are used to simulate the effects of braking and traction on the side forces. The simulated suspension forces include progressively stiffening, energy dissipating limit stops and a combination of coulomb and viscous damping. The sprung mass is represented as a rigid body with a peripheral layer of homogeneous, isotropic, deformable material. The assumed properties of the peripheral layer, with dynamic pressure directly proportional to depth of penetration, were based on the results of dynamic and static crush tests of automobile structures,

Some researchers in the field of highway safety have a tendency to view experiments, whether part or full scale, as being more real and believable than analyses. At least part of this tendency stems from the fact that physical experiments can be seen and photographed. Computer graphics displays can help in analysis by allowing the direct observation of computer "experiments". In actuality, many physical experiments are poorly defined and controlled. Instrumentation errors sometimes yield individual items of response that are not compatible with each other. For example, in the series of physical experiments that were performed to validate the HVOSM, a number of instrumentation difficulties were revealed by the comparisons with analytically predicted results. It is not intended to suggest that computer simulation can ever eliminate the need for physical experiments; Rather, the intention is merely to point out the fact that computer simulations can serve as valuable aids for interpreting the results of physical experiments with nonlinear systems, as well as for interpolation and extrapolation to other combinations of test conditions.

*In 1969 the paper by Raymond R McHenry on the HVOSM development entitled "An Analysis of the Dynamics of Automobiles During Simultaneous Cornering and Ride Motions", [11] was awarded the Crompton-Lanchester Medal from the Institution of Mechanical Engineers. Awarded by the Board of the Automobile Division for the best paper or for outstanding service considered to have special influence on the advancement of automobile engineering.*



*Figure 4 The first live performance of the astro spiral jump in Houston, TX 1972*

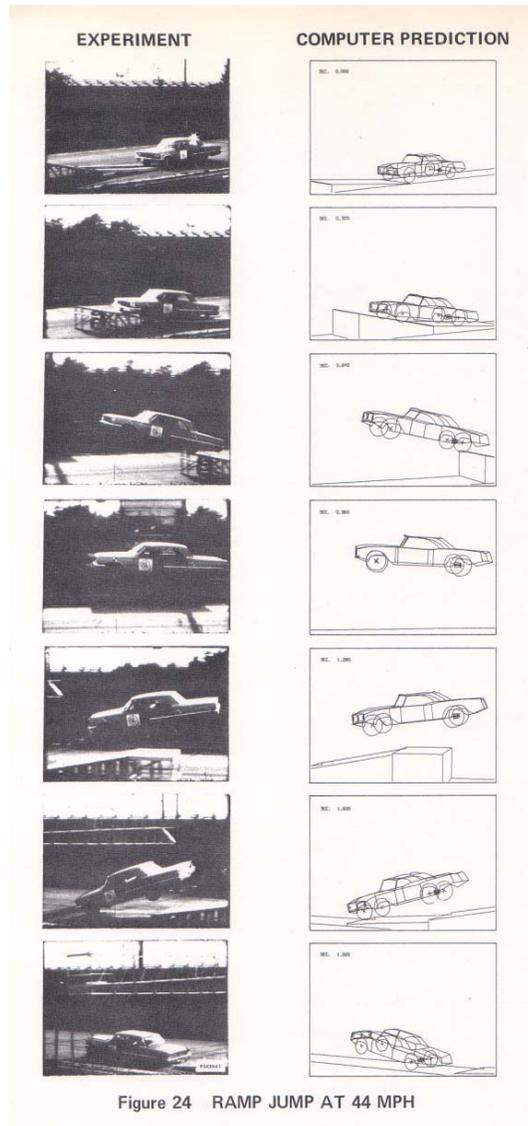
### **The Astro-Spiral Jump**

In addition to the substantial effort in validation of the mathematical model, the HVOSM was also uniquely tested by designing an automobile stunt which was used both in a travelling auto-stunt thrill show and in the 1974 James Bond Movie, “Man with the Golden Gun” produced by United Artists Corporation [12].

As a part of the HVOSM development process, Calspan employed the services of professional stunt drivers in 1968 to perform maneuvers and stunts with an instrumented vehicle and, thereby, to generate vehicle response data in violent maneuvers for use in investigating the validity of the computer simulation. One of the included stunts was a fifty foot jump from a take-off to a receiving ramp. The degree of achieved correlation between analytical predictions and experimental measurements was found to be remarkably good in all of the included maneuvers and stunts. At the time, it was jokingly pointed out that Calspan had unintentionally developed a capability for the design and staging (i.e., via animated perspective displays on motion picture film) of auto thrill shows. A related, "far out" suggestion was the design of ramps to produce a combination of jump and rollover (i.e., a "spiral" jump), such that the stunt car would land on its wheels after passing over an obstacle in an inverted condition.

Subsequent to completion of development and validation of the HVOSM simulation in 1970, the thrill show ideas were given somewhat more serious consideration. Such an application would constitute both a challenging dynamics problem, similar in nature to a particularly violent single-vehicle accident, and an attention-getting demonstration of capabilities. It also had the appeal of a "fun" project to relieve a steady diet of crash protection studies.

In November of 1970 Ray McHenry contacted Jay Milligan, Jr., President, J.M, Productions, Inc., of Hamburg, New York, regarding his possible interest in the design of a new auto thrill show stunt and/or the establishment of speed and dimensional tolerances for existing stunts.



*Figure 5 Comparison of test driver ramp to ramp jump and HVOSM simulation predictions*

The HVOSM simulation does not, of course, provide direct guidance for invention. Its application is equivalent to performing experiments with a fully instrumented-vehicle. Therefore, the analytical study of the spiral jump stunt concept consisted essentially of a trial and error process of exploratory changes in ramp configurations. The initial simulation study indicated that the combined needs to run both ends of the automobile over the same ramp profile in sequence and to generate a large roll acceleration in the 40 MPH speed range would create a serious problem in achieving acceptable pitch and yaw behavior. The limitation to the speed range of 40 MPH, which is based on space restrictions that generally exist for thrill show performances, produced a corresponding limitation on the time in the air that was available for the 360 degree roll-over. Thus, a large roll velocity (approximately 230 degrees per second) had to be generated to achieve a "wheels down" landing on the receiving ramp. The sequential traversal of the take-off ramp by the front and the rear wheels, when combined with the nonlinear suspension characteristics during the traversal (i.e., front

suspension "bottomed out" throughout the roll impulse) was found to create a response sequence in which the rear wheels cleared or only lightly touched the "roll-impulse" end of the ramp.

As a result of this sequence, the initially predicted responses retained a "nose-up" attitude during the entire jump and were found to include excessive yawing. Attempts to achieve a corrective pitch impulse at either of the rear wheels were unsuccessful, The rear wheel that was moving up fastest cleared any ramp configuration that the "bottomed out" front suspension had traversed, An impulse sufficient for the desired pitch response, when applied at the other rear wheel, acted to excessively reduce the roll velocity. Therefore, it became necessary to consider minor vehicle modifications to achieve the desired combination of linear and angular velocities at the end of the take off ramp. The necessary vehicle modification consisted of an auxiliary contact point on the rear axle, for which the primary loading occurred on the last ten feet of the take-off ramp. The additional contact on the rear axle was also found to require a relatively low side-force capability to avoid unwanted yaw accelerations.

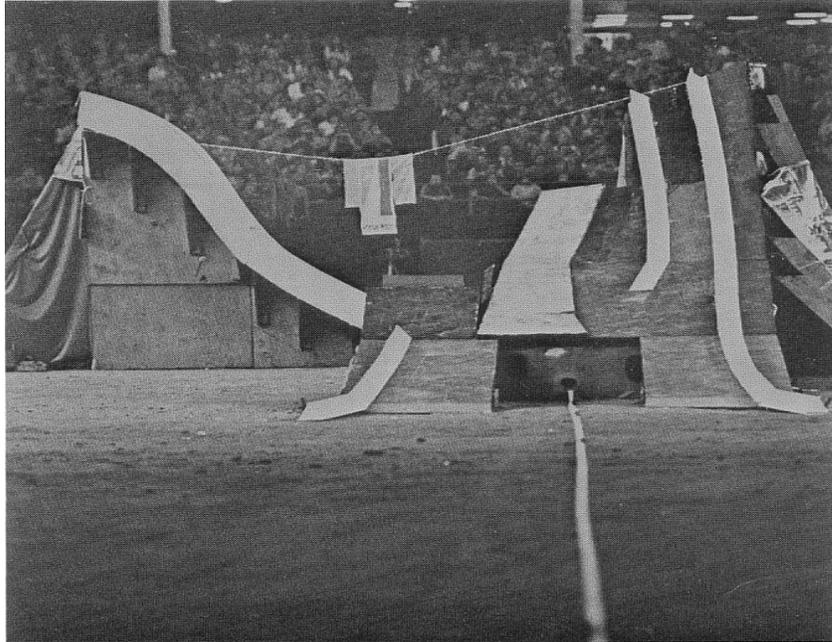
*In the 60's and 70's Ray worked with Bill Milliken[13] at Calspan. Ray has always said that without Bill's perseverance and influence the spiral jump project would have never been completed. Bill fought for the project and fought off the Calspan management who were paranoid about liability. Bill was somehow able to arrange to have the original AMC Javelin vehicle measured at the GM Proving Grounds in Michigan. Yes, that is correct; somehow Bill was able to arrange to have an AMC vehicle measured at the GM facility. Talk about pull! Ray, my brother Stan McHenry and Doug Milliken (Bill's son) all drove from Buffalo to Michigan and on to the GM proving grounds with the AMC Javelin to have the measurements done!*

*The first live performance of the "spiral jump" stunt was performed at the Houston Astrodome in 1972 before a sellout crowd of more than 100,000. For the actual 'traveling stunt' the target speeds, weight and distance were 40 +/- 1MPH and 1461 +/- 3 kg, and 13.85 +/- 0.03 m. A thrill show toured with the stunt both before and after James Bond picked it up for the movie. For many of the tour shows in the US, the drivers came in slow (below the low speed) and damaged the suspension and landing ramp on landing.*

*Bumps Willard, who performed the stunt flawlessly (one take!) for the Bond movie also toured Europe with the thrill show and hit the jump perfectly every time!*

In 1976, after 10 years of development, refinement and applications of the HVOSM by Calspan as well as other research organizations, under FHWA contract Calspan documented all the various developments, refinements and validations of the HVOSM [14].

Since 1976 Ray and I have performed a number research projects which included further refinements and enhancements of the HVOSM under subcontracts with Jack Leisch and Associates [15], Midwest Research Institute [16], Calspan [17] and the Highway Safety Research Center of the University of North Carolina [18] as well as through internal research[19].



*Figure 6 Spiral Jump driver's view to takeoff and landing ramps*

## **SMAC – The Simulation Model of Automobile Collisions**

Around 1970 the SMAC computer program was created by Ray and his team at Calspan on year-end funds. Year-end funds are left over research money which needs to be used before the end of the year (“use it or lose it”). Ray was interested in demonstrating the feasibility of a mathematical model of automobile collisions which could achieve improved uniformity and accuracy in the interpretation of evidence in automobile accidents.

Prior to the creation of SMAC, the general practice in the reconstruction of automobile collisions was to consider the collision and the trajectory phases of the event separately. This division of the analytical task was based on two assumptions: (1) that the effects of tire forces are negligible during the existence of collision forces and (2) that the collision event can be assumed to occur instantaneously.

While these assumptions appear to be reasonable, their application had been found in some impact configurations to produce significant errors during the collision. For example, in moderate-speed intersection collisions multiple contacts frequently occur – front-side followed by side-to-side and/or rear-to-side contact, normally referred to as a “side-slap” secondary contact [20]. If a secondary contact is neglected in a collision reconstruction major errors can be produced in predictions of spin-out trajectories. Also, if tire forces are neglected throughout the time during which the collision contacts occur, significant errors can be introduced during the lateral motions of the vehicle between impacts. Therefore the SMAC program was created with provisions that both the collision and tire forces be considered simultaneously.

SMAC is an "open-form" accident reconstruction program. A requirement of "open-form" programs like SMAC is that the user must initially estimate the impact speeds.

One of the difficulties which arose in setting up SMAC simulations by the NHTSA investigative teams was that the program requirement of an initial estimate of the impact speeds which was not always an easy task. Also, the user had to provide vehicle properties and specifications, many of which were not readily available. Those requirements, combined with the relatively high cost per run for a SMAC simulation run, required that a pre-processor be created which could provide the initial estimate of the impact speeds.

The CRASH computer program [21] was created to assist SMAC users in determining a first estimate of impact speeds. So let us digress for a moment to discuss CRASH:

### **CRASH - Computerized Reconstruction of Accident Speeds on the Highway**

The original CRASH program utilized both piecewise-linear trajectory solution procedures and a damage analysis procedure to provide an initial estimate of impact speeds. The CRASH program was subsequently adopted by NHTSA as an integral part of the NASS investigations.

*The National Accident Sampling System (NASS) was established in 1979 as part of a nationwide effort to reduce motor vehicle crashes, injuries and deaths on the US highways. The NASS General Estimate System (GES) collects data for nonfatal crashes, and combines that data with information on fatal crashes from the Fatal Analysis Reporting System (FARS).*

*Data for GES come from a nationally representative sample of police reported motor vehicle crashes of all types, from minor to fatal. The system was created to identify traffic safety problem areas, provide a basis for regulatory and consumer initiatives, and form the basis for cost and benefit analyses of traffic safety initiatives. The information is used to estimate how many motor vehicle crashes of different kinds take place, and what happens when they occur. GES data are used in traffic safety analyses by NHTSA as well as other DOT agencies. GES data are also used to answer motor vehicle safety questions from Congress, lawyers, doctors, students, researchers, and the general public.*

The rationale for the use of the CRASH program was that for statistical studies, the average error in severity determinations is more important than specific individual errors. The CRASH program, with its question and answer mode, vehicle categorization, single step solution procedure, and most importantly low cost, redirected the NHTSA interest from SMAC towards the CRASH computer program.

The original form of the CRASH computer program, which culminated in the CRASH3 version, was not intended to be a detailed, highly accurate reconstruction program. Rather, it was developed to serve as a simple preprocessor for the SMAC program. While the results of CRASH3 applications can be useful in providing approximate measures of accident severity for use in statistical studies, where the average error is most important, it has been demonstrated in validation tests to produce results which when compared to those of full-scale crash tests can include individual errors as great as  $\pm 45\%$  [22].

Obviously any CRASH results utilized in individual case reconstructions, like for police and/or litigation purposes, need to be further tested and refined with more sophisticated accident reconstruction techniques.

The first project I worked on in the field of Highway safety was in 1979 and was related to a refinement of CRASH3 under contract with NHTSA [23]. My part of the contract was evaluating the results of a large number of SMAC simulations of various accident types to be used to refine SPIN2 of the CRASH3 trajectory solutions procedure.

To improve the accuracy of approximations of separation velocities, provisions for the introduction of a residual linear velocity at the end of the rotational motion and the development of empirical coefficients, in the form of polynomial functions of the ratio of linear to angular velocity at separation, were incorporated in the SPIN2 analytical relationships of the CRASH program. Since the separation velocity ratio is initially unknown, a solution procedure was developed whereby several trial values of the ratio, based on an approximate equation, were used to test multiple solutions.

For the refinement of the SPIN2 coefficients, a representative sample of actual accident cases was selected from the NCSS files for use in the study and then reconstructed with the SMAC computer program. For each of the SMAC reconstructions, separation information was used to formulate a basis for a refinement of the SPIN2 empirical coefficients.

A careful examination of the time-history plots of linear and angular velocities for all of the cases in the sample revealed a significant number of cases in which the SMAC-predicted behavior deviated from the analytical assumptions upon which the SPIN2 routine is based. Attempts were undertaken within the research project to discriminate characteristics of separation conditions. Unfortunately, only partial success was achieved in the attempts to accommodate deviations by means of the use of logic and discriminators. As a result, a realistic appraisal of residual scatter in the empirical fits led to the conclusion:

**"To achieve a general improvement in the reliability and accuracy of approximations of the angular and linear velocities at separation, a step-by-step time history form of trajectory solution should be implemented."**

Since working together on that project, Ray and I have researched and published numerous papers to further refine the CRASH3 solution procedures.. The objective in our refinements of the CRASH3 accident reconstruction procedures has been to simplify the input requirements of the program while providing a significantly improved correlation of the reconstruction results with known test results. A secondary consideration in the form of the refinement has been to limit the total computational time for convergence on a solution to a reasonable amount of time.

With respect to refinement of the CRASH3 trajectory solution procedure, we have investigated the inclusion of provisions for activating the angular momentum solution. These refinements required provisions for approximating changes in positions and orientations during the contact phase of collisions to avoid significant changes in the directions and magnitudes of forces and moments acting on the vehicles if the movement during the collision is ignored[24]. (Note that until the 2000's personal computers were too slow to consider a SMAC collision iteration scheme, however a SMAC trajectory iteration scheme incorporated into the CRASH solution procedure was investigated in the late 1990s [24])

We also worked on refinement of the CRASH damage analysis procedure to incorporate restitution [25]. Crush coefficients for vehicle collision analysis are predominantly based on impact speeds and damage measurements from rigid, fixed barrier crash tests. The residual damage is correlated with

the impact speed by means of fitted linear relationships. In general, there is no consideration given to the effects of restitution in applications of the fitted crush coefficients. However, the ignored effects of restitution on the total impact speed change, corresponding to a given amount of residual crush, are compounded by the fact that restitution acts to reduce the amount of residual deformation, for a given maximum dynamic crush, while also acting to increase the total impact speed change. Thus, substantially different vehicles can share nearly equal slopes and intercepts in CRASH-type plots of the approach period speed-change as a function of residual crush. This can occur even though the actual exposure severity for a given residual crush may be significantly different.

## **Validation of Computer Models**

One of the problems associated with the development and refinement of any accident reconstruction techniques and of research is that of demonstrating correlation with full-scale tests. A test matrix of 18 full-scale crash tests were performed in 1978-1980 which became known as the **Research Input for Computer Simulation of Automobile Collisions (RICSAC)** crash tests [26].

For each of the RICSAC tests, a minimum of 13 accelerometers were mounted on-board each vehicle to record acceleration components at six to seven stations. At three locations triaxial (XYZ) packages were installed ("hard mounted") to provide coverage between the front and rear of the vehicle. The front steer angles were measured on each vehicle by a linear stroke potentiometer attached to the vehicle steering linkage. The time history of the change in vehicle yaw, pitch and roll angles and yaw rate were recorded by two-degree-of-freedom, free gyroscopes and a rate gyro.

The RICSAC tests were specifically designed to serve as standards for such comparisons and were successfully used for comparison validation purposes the CRASH and SMAC computer programs.

Unfortunately, in some studies which included evaluating the correlation of computer codes with RICSAC there have been various levels of interpretation and acceptance of the measured results. Questions have been raised as to the validity of some of the reported RICSAC test results.

Since there had been no consensus on the interpretation of some of the results of the RICSAC tests, Ray and I performed an intensive independent effort toward achieving proper and generally acceptable interpretations of the RICSAC test data [27]. The conclusions of that research were that (1) the RICSAC data are accurate and are suitable for their intended purpose of testing the validity of reconstruction techniques, (2) previously reported findings of gross errors and violations of Newton's laws in the reported RICSAC data are erroneous and (3) the SMAC program once again demonstrated excellent correlation with properly analyzed full-scale test results

## SMAC – The Simulation Model of Automobile Collisions (continued)

The SMAC program was initially developed in the 1970's when all development of computer code was performed on time-share mainframe computer systems which had limitations on the amount of available memory and processing time and for which the costs to perform a single SMAC simulation were relatively high . (e.g., circa 1971, "The range of costs...has been approximately \$25.00 per application run" for the SMAC program). These limitations during the original development of the SMAC program guided the selection of many of the simplifying assumptions of the mathematical model.

Since the early 80's and particularly by the mid to late 1990's, the prevalence of powerful computers creates an availability of virtually unlimited and inexpensive computer resources. This has inspired a detailed re-evaluation and refinement of computer codes, particularly those developed in the 1970's.

In light of the advances in computer technology and our continuing research, development and refinement of the SMAC model, we presented and implemented refinements in the definition of the collision interface, the definition of collision type, the vehicle proximity and collision detection logic, and the form of supplementary impulsive constraints on relative motions [28,29].

Since the initial development of the SMAC program, there has also existed a need to simplify the application process. The ultimate simplification would entail an automatic iteration procedure.

The working hypothesis of the presently described research on the automatic iteration of SMAC, as well as that of other simulation-type analytical approaches to accident reconstruction, is that a unique set of impact conditions is required to achieve an acceptable match of all of the documented evidence (both damage and trajectory). The use of quantitative measures of the overall "fit" to the documented evidence and applications to experimental crash tests provide a means of testing the hypothesis, as well as demonstrating reconstruction accuracy and convergence rates.

As any SMAC user is aware, many iterations of the program may be required to go from an initial approximation to an acceptable match of the measured trajectory and damage targets. Throughout the iterative process, the impact speeds and speed change results may not change significantly. Also, what constitutes an acceptable match can vary widely among users. Sometimes the focus is on a detailed match of the positions of rest; sometimes the focus is on a match of damage locations and extents on the vehicles. There is currently no standardized measure of the correlation of SMAC results with the accident evidence. Since the initial development of the SMAC program, there has existed a need to simplify the application process.

In 2003, we created an automatic iteration procedure for the SMAC computer program [30] which proved the working hypothesis. The use of quantitative measures of the overall "fit" to the documented evidence and applications to experimental crash tests provided a means of testing the hypothesis, as well as demonstrating reconstruction accuracy and convergence rates.

The reported results demonstrate that the SMACITER program successfully converges toward evidence matches in a variety of impact configurations. In initial applications wherein SMAC generated "evidence" was used the errors in impact speeds generally run less than approximately  $\pm 2\%$ . With measured evidence from full-scale tests, wherein the deviations from a perfect evidence match run larger, the errors in impact speeds have been found to run less than approximately  $\pm 10\%$ .



*Figure 7 Still photos from simulation animation of the princess Di Accident reconstruction*

### **SMAC3D: Combining SMAC and HVOSM into one program**

In 1998, I was hired by CBS News to reconstruct the Princess Di accident for the television program “48 Hours”. At that same time we had been working on a 3D collision simulation program which combined the collision capabilities of SMAC with the 3 dimensional vehicle dynamics simulation capabilities of HVOSM. We were provided the survey information for the tunnel, the vehicle information and we used the program, SMAC3D, to simulate the vehicle traveling into the Pont de l'Alma road tunnel in Paris, France, and striking the support post (In that tunnel they do not have guardrails in front of the support posts). The results were presented and I answered questions in interviews broadcast on June 11, 1998 and August 31, 1998. The eighteen-month French judicial investigation which concluded in 1999 correlated closely with the speeds and findings of my investigation and with the simulated reconstruction with the prototype SMAC3D.

Until the early 2000s, the limitations in processing speed of personal computers limited our continued development of the SMAC3D model to simple internal research. Since 2000, we have been testing and refining a 3D simulation and reconstruction tool which merges the strengths of SMAC and HVOSM into a single program.

### **The Future**

The process of reconstructing a motor vehicle collision involves collecting all available information about the interaction of the vehicles including vehicle trajectory information, damage information, vehicle specifications and scene information.

The trajectory information is gathered based upon the police measurements, photographs and scene evidence documentation (skid marks, gouges, etc.). To characterize the interaction of the vehicles the approximate location of the area of impact, the measured positions of rest and any skid and gouge marks should be memorialized. Technological advances in survey and measurement equipment have made equipment available to police and investigators which can quickly, efficiently and accurately memorialize vehicle accident scenes.

The damage information includes measured dimensions of the damage locations and extents. The standard procedure by which damage is characterized is the Collision Deformation Classification (CDC, [31] ) and the Equidistant Crush Measurement (ECM, [32]).



*Figure 8 Preliminary Comparison of a frame from film of ARC-CSI test and a frame from a msmac3D simulation of the collision.*

Collecting vehicle specifications and scene information (roadway layout and topography) completes the required data to permit the performance of an accident reconstruction.

There are many CAD and survey software programs available which can be used to collect and display information on scene and vehicle accident data. Many other program vendors have created commercial versions of accident reconstruction tools and programs, including versions of SMAC and HVOSM . There are also many high end graphics and animation programs available which can be used to create high-end animations of the results of accident simulations and reconstructions.

We are currently looking to work with software partners to use our simulation products to combine with all the other technologies into a single product. No more need for importing or exporting of terrain or animation information to and/or from a reconstruction or simulation programs and tools. It should all be contained in a single software package.

In summary, after working in the field for over a collective 80+ years, and having been a witness and participant in the phenomenal and astounding breakthroughs in computational power and accessibility, particularly with respect to the field of highway safety, we see our work as a consultant to graphical and survey companies implementing our 3-dimensional collision and simulation model as an opportunity for another quantum leap into the future in the highway safety field.

Our hope is that someday in the near future police and investigator applications of our simulation and reconstruction technologies will generate a large volume of high quality accident reconstruction data, including injury/exposure definitions, that can then used by NHTSA/NASS and other governmental agencies or researchers to serve to further guide improvements in highway safety.

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