

CALSPAN 3-D CRASH VICTIM SIMULATION PROGRAM

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For several years, research has been performed to develop mathematical models for the computer simulation of motor vehicle crash victims. A recent paper by King and Chou (1) outlined this development of these computer simulators and summarized the capabilities and limitations of several of the existing models. The advent of larger scale computers and the corresponding trend toward decreasing computer costs (per operation) has made it feasible for these models to become more sophisticated.

Calspan has been continuously involved in the development of crash victim simulators (CVS). Initial efforts by McHenry (2) in 1963 consisted of a two-dimensional, eight degree-of-freedom system, confined to planar motion to simulate frontal collisions with a fixed configuration for the body segment structure and of the crash environment. Further developments by McHenry and Segal (3, 4, 5) increased the capabilities of the model and Segal (6) adapted it to pedestrian studies.

The development of a three-dimensional model was initiated by Bartz (7, 8) cosponsored by the Motor Vehicles Manufacturers Association and the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation. Further mathematical developments by Fleck (9, 10), sponsored by the NHTSA, has resulted in the current Calspan 3-D Crash Victim Simulation Program.

The latest version of the model, known as CVS-III is a cumulation of a sequence of model developments designed to complement experimental research in motor vehicle crash environments and to provide a functional instrument for parametric investigations. A wide variety of user supplied input options and parameters are available to provide the required flexibility to adapt this tool to simulate many physical situations.

Usage of the Calspan model has become widespread by many governmental agencies, universities, research organizations and motor vehicle manufacturers in several countries. The model has been used to study pedestrian accidents by Chrysler Corporation, Peter R. Niederer of General Motors and the University of Zurich, and A. J. Padgaonkar of Wayne State University. R. E. Knight of the Denver Research Institute has adapted the model to study the behavior of the crash victim in motorcycle accidents. The model has been modified for the Aerospace Medical Research Laboratory of Wright-Patterson Air Force Base to study the ejection of a pilot from an aircraft. These and many other applications have been made possible by the generalization, versatility and capabilities that have been built into the model.

The program itself has been written completely in FORTRAN IV, originally for IBM 360 and 370 computer systems, but it has been successfully implemented on large scale CDC, Burroughs and Univac computers. The program is quite large, it has eighty subroutines consisting of ten thousand source cards and requires about 500K bytes of core storage on IBM 360 and 370 computer systems. Double precision arithmetic is required on these 32 bit word IBM computers but single precision is sufficient on the 60 bit word CDC computers. Typical execution times are 2000 seconds on the IBM 360/65 and 360/67 computer for pedestrian runs of 500-600 msec. real time duration and 100-200 seconds on the IBM 370/168 computer for occupant simulations of 150-200 msec. real time duration. These times may vary considerably depending on the complexity of the user options and the integration accuracy control parameters specified.

Dynamics of the Specified Crash Victim

Earlier versions of the Calspan CVS used a 15 segment, 40 degree-of-freedom linked structure configuration for the crash victim. However, in the current version, the number of segments and joints and the corresponding number of degrees-of-freedom are specified by the user with the maximum determined by the storage limits specified by the program. The vehicle and ground (inertial reference) are treated as additional segments with prescribed motions. These segments are rigid bodies which are connected by different types of joints.

One of the primary features of the program is the utilization of a "tree structure" for defining the segments. The user specifies a base or reference as the first segment, and each succeeding segment must be connected to a previously defined segment. Originally, Calspan used the head for the reference segment, but experience with the model showed that it was better to use a heavier, more central segment, such as the lower torso as the reference segment.

These segments are then connected by joints. Each joint, j , connects segment number $j + 1$ with a previously defined segment specified by JNT_j . Several different types of joints are available. They include:

1. Ball and Socket Joint: this has complete freedom of motion with torques computed as a function of the flexure and twist angles.
2. Pinned or Hinged Joint: this is a joint with only one degree of freedom about a specified pin axis.
3. Euler Joint: this is a three axis joint with spin, nutation and precession axes.
4. Null Joint: as the name implies, this joint is no joint at all and gives the program the capability of describing sets of disjoint segments thus allowing for multiple bodies.

All joints (except for the null joint) may be specified as locked or unlocked initially. They will subsequently unlock or lock on the basis of prescribed torque levels. The Euler joint may lock or unlock on any combination of its axes. The typical joint used in many dummies is an Euler joint with

either the spin or the precession axis permanently locked. The spring and viscous characteristics are supplied by the user along with the parameters to control the locking and unlocking feature of the joint and to control the use of an impulse option when a joint passes through a joint stop.

The orientation of the axis system and the location of each joint is specified by the user with respect to the local reference system of the two segments that it connects. By specifying joint j as a null joint, segment $j + 1$ becomes the base or reference segment of another body. The program integrator computes the new position and velocity of the c.g. of each reference segment and the direction cosine matrix for all segments, the initial values for these must be supplied by the user. The use of this data along with each joint location allows the chain routine in the program to compute the position and velocity of the c.g. of all the other segments.

The System Equations

The system equations were derived considering each segment as a free body subject to the forces and the torques of constraint and of external contracts generated by the program. In block matrix form, the system equations are:

$$\begin{bmatrix}
 M & 0 & A_{11} & 0 & A_{13} & 0 \\
 0 & \Phi & A_{21} & A_{22} & A_{23} & A_{24} \\
 B_{11} & B_{12} & B_{13} & 0 & 0 & 0 \\
 0 & B_{22} & 0 & B_{24} & 0 & 0 \\
 B_{31} & B_{32} & 0 & 0 & B_{35} & 0 \\
 0 & B_{42} & 0 & 0 & 0 & 0
 \end{bmatrix}
 \begin{bmatrix}
 \ddot{X} \\
 \ddot{\omega} \\
 f \\
 t \\
 q \\
 \tau
 \end{bmatrix}
 =
 \begin{bmatrix}
 U_1 \\
 U_2 \\
 V_1 \\
 V_2 \\
 V_3 \\
 V_4
 \end{bmatrix}
 \begin{matrix}
 \text{Forces} \\
 \text{Torques} \\
 \text{Linear Joint} \\
 \text{Angular Joint} \\
 \text{Constraints} \\
 \text{Flexible Elements}
 \end{matrix}$$

Each of the elements in the matrix form of the system equations are subdivided into 3×3 matrices or 3 element vectors, the number of which is either NS (the number of segments), NJ (number of joints), NQ (number of constraints) or NF (number of flexible elements). The nomenclature for the variables used in the system equations is as follows:

<u>Variable</u>	<u>Type</u>	<u>Size</u>	<u>Definition</u>
Aij, Bij	Matrices	-	Coefficients of system equations
M	Matrices	(3*NS)x(3*NS)	Mass matrix (diagonal)
Φ	Matrices	(3*NS)x(3*NJ)	Inertia matrix (diagonal)
\ddot{X}	Vectors	3*NS	Translational accelerations
$\ddot{\omega}$	Vectors	3*NJ	Angular accelerations
f	Vectors	3*NJ	Joint constraint forces
t	Vectors	3*NJ	Joint constraint torques
q	Vectors	3*NQ	Special constraint forces
τ	Vectors	3*NF	Flexible element constraint torques
U_1	Vectors	3*NS	Sum of external forces
U_2	Vectors	3*NJ	Sum of external torques
V_j	Vectors	3*NS	Sum of constraint generalized forces

These systems equations are first reduced by eliminating the accelerations, thus yielding a set of equations for the forces and torques of constraints. The system of equations is not symmetrical when sliding constraints or tension elements are specified. The reduced set of equations is then solved using sparse matrix and symmetry techniques where possible. The current program is dimensioned to handle 306 system equations or 186 reduced equations.

The accelerations are then computed from the system equations. These are then integrated by a newly developed vector exponential integrator with variable step size that was especially designed for this problem. The direction cosine matrices, which are used for the angular orientation of the segments, are updated using quaternions. The use of direction cosines had the advantage of allowing unrestricted angular motion with no singular points in the system of equations.

Allowed Contacts and Special Constraints

The external forces and torques of the system equations are computed by many contact and special constraint routines within the model. The contact surfaces of the body segments are represented by ellipsoids, and the surfaces of the motor vehicle can be defined as either planes or ellipsoids. Force and torque generating routines within the model include the following:

1. Plane-ellipsoid contacts.
2. Ellipsoid-ellipsoid contact.
3. Airbag routine.
4. Belt routine.

5. Joint torque generating routines.
6. Fixed point and fixed distance constraints.
7. Rolling and sliding constraints.
8. Tension and deformable elements.
9. Spring-damper connections between segments.
10. Singular segments suitably constrained.

Special Features of the Program

A wide variety of user supplied input options and parameters are available to provide the required flexibility to adapt this program to a wide variety of physical situations. Some of the other features of the program include:

1. Complete flexibility in describing the model.
2. Program is written in modular form allowing for easily adding additional constraint and contact force generating routines.
3. The input to the program is in modular form permitting the replacement of data sets for parametric studies.
4. User defined units of length, mass and time and generalized coordinate systems.
5. A completely built-in restart capability useful for continuing a simulation or making minor changes to the input without re-running the entire program.
6. Two dimensional and mirror symmetry options are available.
7. An elaborate force deflection algorithm that allows for energy loss, permanent deflection and friction.
8. Optional use of impulsive forces at first contact of segments and contact surfaces or joints and joint stops.
9. An elaborate scheme for defining and evaluating functions of three forms: constant value tabular data and a fifth degree polynomial.
10. User has complete control of all output of the program:
 - a. Program tape useful for plotting or further post-processing.
 - b. Restart tape.

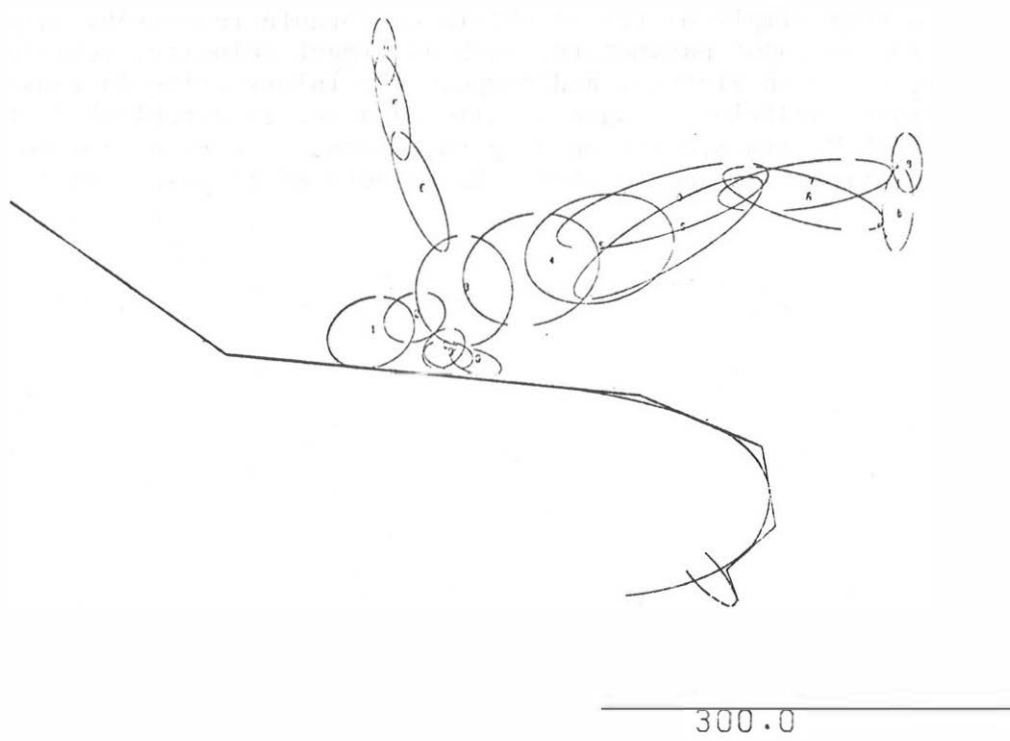
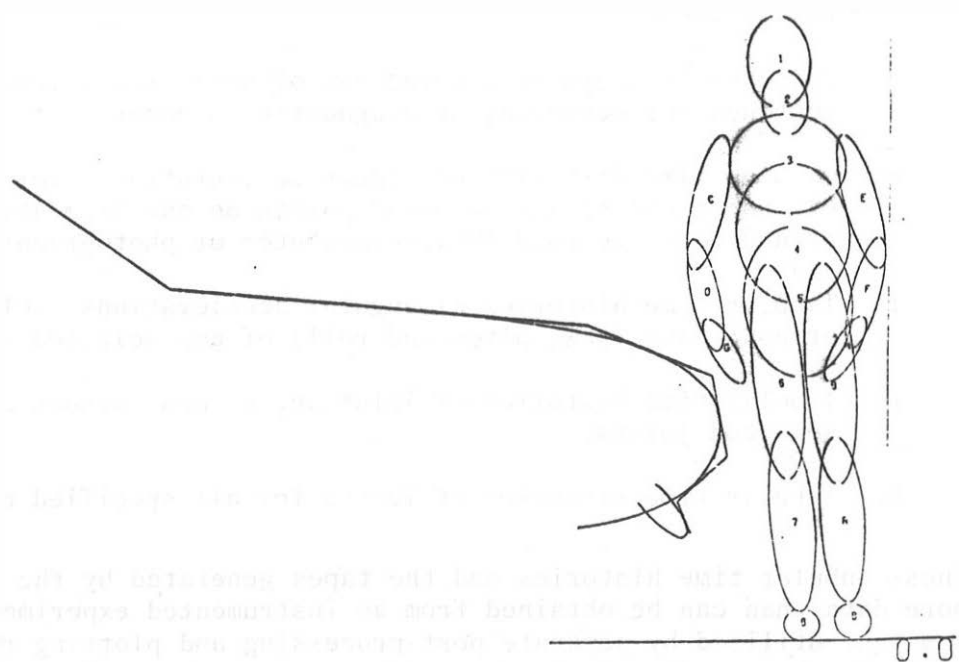


Figure 1 Computer Plot of Pedestrian Impact

- c. Complete variable print out of system variables at fixed time points.
- d. 23 types of diagnostic print out of data from selected routines for debugging or diagnostic purposes.
- e. Tabular time histories of linear accelerations, velocities or positions of any selected points on any segments designed to correspond to accelerometer or photographic data.
- f. Tabular time histories of angular accelerations, velocities or positions (yaw, pitch and roll) of any selected segments.
- g. Tabular time histories of joint angles and torques of selected joints.
- h. Tabular time histories of forces for all specified contacts.

These tabular time histories and the tapes generated by the program give much more data than can be obtained from an instrumented experimental test. They may be utilized by separate post-processing and plotting routines to further analyze the results of the run. For example, Figure 1, generated by Chrysler Corporation, presents a plot of a 17 segment pedestrian at initial time zero and at the point of initial head contact with the vehicle. It thus becomes a very simple matter to obtain comparable results by varying some of the program input parameters, such as impact velocity, vehicle configuration, or crash victims, and compute the injury criteria caused by the various crash conditions. Once a valid data set is established, the Calspan 3-D Crash Victim Simulation Program, becomes a very useful tool for parametric investigations and to study the effects of proposed safety features.

References

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