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A Computer Graphics Interface Specification for Studying Humans, Vehicles and Their Environment

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ABSTRACT

This paper describes a general purpose computer graphics interface for performing detailed two- and three-dimensional studies involving the dynamic response of humans and vehicles during the pre-crash, crash and post-crash phases of a motor vehicle accident. Specifications are provided for human, vehicle and environment models which can be constructed and analyzed using the interface. The requirements of analysis methods which may be incorporated into the interface are examined, and several examples are provided. Finally, the paper illustrates how the interface is used for creating high-level animations to view the resulting human and/or vehicle motion on various output devices such as computer displays, printers, plotters and video tape recorders.

RESEARCHERS MUST UNDERSTAND the cause of motor vehicle accidents before the number of accident-related deaths and injuries can be reduced. Highway safety researchers have worked hard during the past three decades in an effort to better understand the cause of motor vehicle accidents. Analysis techniques, first consisting of crude hand calculations, have become more sophisticated. Now, the use of computers for accident reconstruction and simulation is common practice.

A motor vehicle accident is a series of complex, inter-related dynamic events. A thorough understanding of those events requires a complete and consistent (i.e., with Newton's laws of motion) analysis of accident site evidence. The inter-relationships between events must also be consistent. Cross-checking of results must be employed to ensure valid conclusions.

A 1989 National Science Foundation study [1]* revealed that 90 percent of the data collected by scientific researchers was ignored because there was no efficient way to analyze it. Scientists have known for years that the human mind grasps complex ideas and relationships from images much more quickly and completely than from the same information presented in the form of text or tables. Computer hardware systems employing 3-D graphics, color and motion are available today which are capable of *showing* how accidents occur, resulting in an increased ability to understand and communicate the causes of accidents.

This paper describes a computer software tool developed for use by accident researchers as well as vehicle and highway designers. The tool has been named HVE, which stands for *Human-Vehicle-Environment*. The purpose of this paper is two-fold: first, to describe the details of the HVE interface so accident researchers may evaluate its applicability to particular reconstructions, and second, to explain the process of using HVE to prepare and view three-dimensional accident simulations.

GENERAL DESCRIPTION

HVE is a software application which reconstructs, simulates, displays and animates motor vehicle crashes. The results of an HVE analysis can be used to determine and

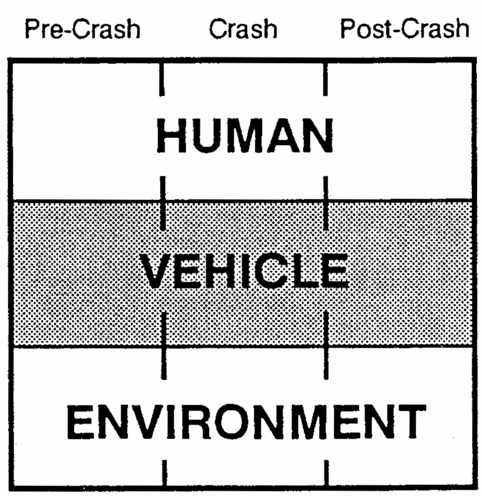

Figure 1 - Nine-cell Matrix For Accident Reconstruction

* Numbers in brackets designate references found at the end of the paper.

show others how an accident occurred by calculating and displaying the sequence of events surrounding the accident. Input is provided by the computer keyboard, mouse and/or scanner. Output can be directed to the computer display, printer, plotter or video tape recorder (VTR).

HVE is a computer abstraction of the nine-cell matrix for accident reconstruction (see figure 1) originally proposed by the late Dr. William Haddon, first Director of the National Highway Traffic Safety Administration [2]. The nine-cell matrix is an illustrative tool which defines the possible interactions between humans, vehicles and their environment during the pre-crash, crash and post-crash phases of an accident. HVE allows the user to create physical and visual 3-D models of humans, vehicles and environments and then analyze and view their interaction using various calculation methods (reconstructions and simulations).

HVE has an open architecture, allowing researchers to develop their own calculation methods for use in HVE. Any calculation method can be used in HVE by following the published HVE input and output specifications.

HVE also provides a set of pre-defined calculation methods. These methods include most of today's popular reconstruction and simulation methods (see Appendix E for a list of these methods).

The remainder of this paper describes HVE.

TECHNICAL DATA

This section of the paper describes the hardware and software systems used for program development as well as system requirements for running HVE.

Development Platform

HVE was developed for use on the Silicon Graphics Iris workstation. This platform was chosen for four reasons.

- Engineering workstations have become cost-competitive with PCs, when viewed in the context of a complete animation system.
- The Silicon Graphics Iris is compatible with the OSF/ACE initiative [3], an important standard for future workstation and PC compatibility.
- The Silicon Graphics Iris has application development tools (described below) not yet available for developing applications on the PC.
- The Silicon Graphics Iris and GL programming language have the *rendering* (drawing, lighting and shading) power required for animating 3-D humans, vehicles and environments.

The importance of computing power can be shown by the following benchmark: A 3-D model of a Porsche (containing 10,000 faces and 6000 vertices) rendered on a 486-based PC (33 mHz) using 3-D Studio Release 2 [4] required 50 seconds (200 faces/sec) to draw. The same file rendered on an entry-level Silicon Graphics Indigo R-3000 required 1.2 seconds (8,333 faces/sec). To put this benchmark into perspective, a typical accident site of photo-realistic quality contains approximately 15,000 polygons (faces) which must be redrawn 30 times per second. Thus, a typical 5 second animation would take the PC approximately 3 hours and 8 minutes. The same animation on the entry-level Indigo would require 4-1/2 minutes. Since it is not practical to spend over 3 hours of computer time per animation, PC animators typically reduce the number of animations as well as their visual quality. Using HVE, it is possible and practical to produce several photo-realistic quality animations including multiple views of an accident sequence in approximately one hour.

Development Tools

The HVE interface was developed using the C++ programming language. Because of its object-oriented design, HVE can be more easily ported to other computer systems. All calculation methods have been programmed in C. When compared to the same calculation methods programmed in other languages, preliminary benchmarks indicate the C language provides a significant increase in calculation speed.

HVE incorporates a graphical user interface (GUI) based on the Open Software Foundation (OSF) Motif interface standard, and follows the design principles defined in the OSF/Motif Style Guide [5]. The HVE interface is visually similar to those found in other windowing applications, such as Windows™ and Macintosh™. A GUI was chosen for HVE because both are graphical and because of the flexibility and future extensibility a GUI affords.

HVE is a three-dimensional (3-D) analysis and presentation environment. 3-D images are displayed using Silicon Graphics GL graphics programming language [6]. All images are rendered using GL and derivative GL programming tools. GL was chosen for HVE because of its robust 3-D graphics function library and its superior rendering speed, described earlier.

System Requirements

The following is an overview of the computer hardware and related equipment required for using HVE:

- Silicon Graphics Iris (Indigo, Personal Iris, Crimson or Power Series) running the IRIX 4.X operating system. The machine must have at least 24 megabytes of random access memory and 400 megabytes of disk storage. To produce VTR output, (see below), the machine must include a video option (either Indigo Video or Video Creator).
- *Externally controlled* Video Tape Recorder (VTR; a "home" VCR is not externally controllable and will not work)
- VTR Animation Controller
- Printed output requires a PostScript™ or PostScript-compatible Printer
- Plotted output requires a Hewlett-Packard or HPGL™-compatible Plotter
- Video input for environments (scanner, digital camera or VCR) requires a TIFF-, RGB- or PCX-compatible device

DESCRIPTION OF USE

While using HVE, the user creates a *case file*. The case file contains any number of humans and vehicles (limited only by available computer memory), and a single environment. These objects are created using the HVE

Human, Vehicle and Environment Editors (described below). The interactions of these objects are then analyzed using a calculation method (reconstruction or simulation).

Each analysis is called an *event*. An HVE case may contain any number of events (again, limited only by available computer memory). Therefore, multiple-car collisions may be analyzed. After the desired events are executed, they are edited and combined into one or more playback windows. The information in these windows may be printed, plotted or routed to a VTR. The case file containing all the objects, events and playback sessions can then be saved for later review and/or modification.

HVE is a windowing application which includes the traditional menu bar (*Files*, *Edit*, *View*, *Options* and *Help*; see figure 2).

While using HVE, the program is always in one of the five following modes:

- Human Mode
- Vehicle Mode
- Environment Mode
- Event Mode
- Playback Mode

The user performs specific operations by first selecting one of these modes. Each mode is described below.

Human Mode

Human Mode is used for creating physical and visual 3-D models of human occupants and pedestrians. Any number of humans may be created for analysis. Using the Human Editor (see figure 2), humans are created and/or modified by defining body segments having user-specified dimensions, inertias and contact surface properties. Segments are connected by joints having user-specified visco-elastic properties. Basic human injury tolerances (HIC, chest SI, femur load, ...) may also be specified.

3-D human drawing files used in HVE were created using Mannequin [7]. These drawing files cannot currently be edited.

An overview of the specification for humans created using the Human Editor is found in Appendix A.

Human Library

HVE contains a library of pre-defined humans which may be selected according to sex (male/female), age (adult/child) and body type (heavy, average or thin). Five percentiles, ranging between 2.5 and 97.5, are available for each human category. These humans are selected from the Human Information dialog (see figure 3). If desired, the physical properties (dimensions, inertias, joint properties, etc.) may then be modified.

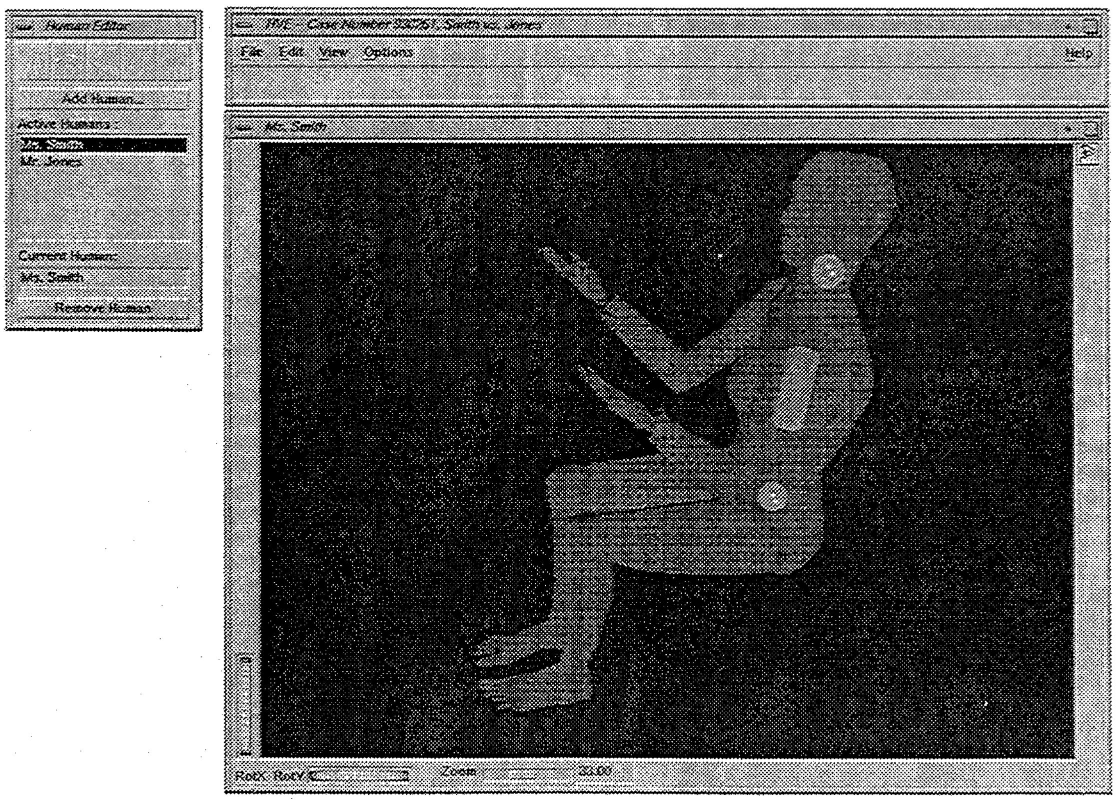

Figure 2 - HVE Human Editor (left) and Current Human Window (right). The Human Editor is used for selecting the human occupants and pedestrians to be analyzed. The Human Editor is also used for editing human properties, including dimensions, inertias, joints and surface ellipsoids. A list of the "active humans" (humans which have been created and may be analyzed), and the name of the "current human" (the human who is currently loaded into the editor) are displayed in the editor panel. The current human is displayed in the Current Human window. The Mode Selector buttons, displayed near the top of the editor panel, allow the user to switch between Human, Vehicle, Environment, Event and Playback modes.

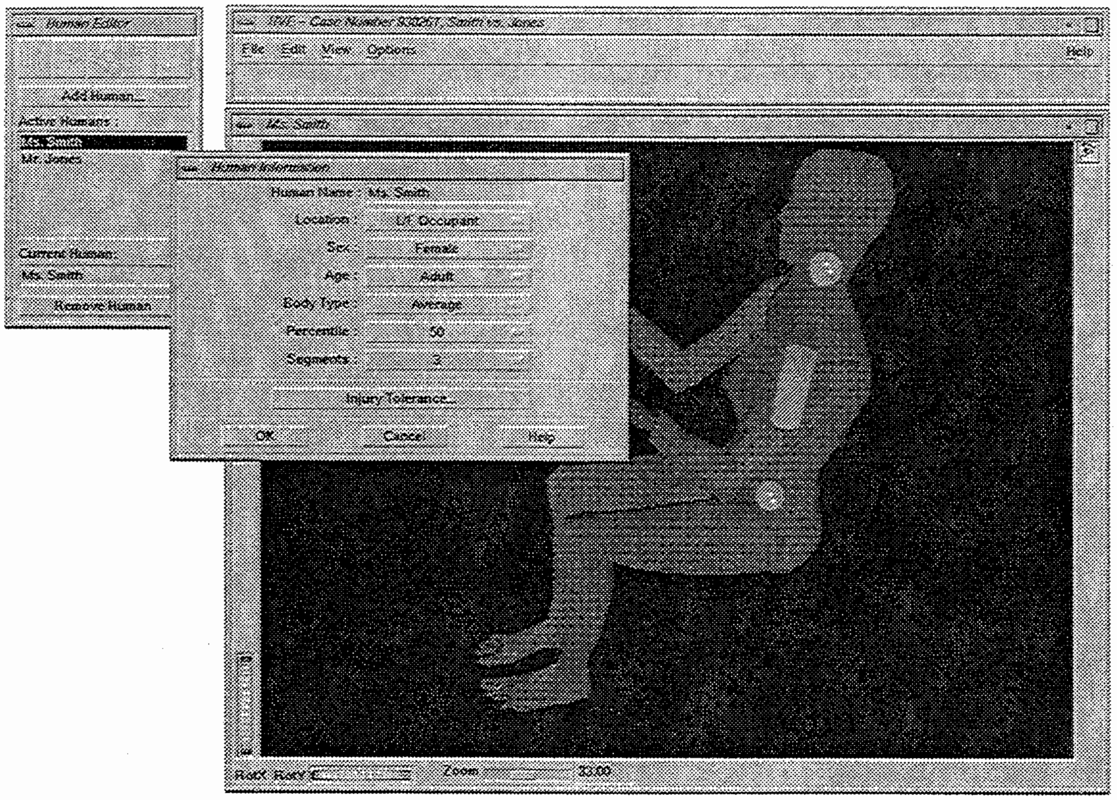

Figure 3 - HVE Human Information Dialog. This dialog is used for adding new humans to the Active Human list. Humans may be selected according to sex, age, body type, and percentile. The number of segments is selected according to the calculation method. Injury tolerances (forces and accelerations above which injury is likely to occur) are user-definable.

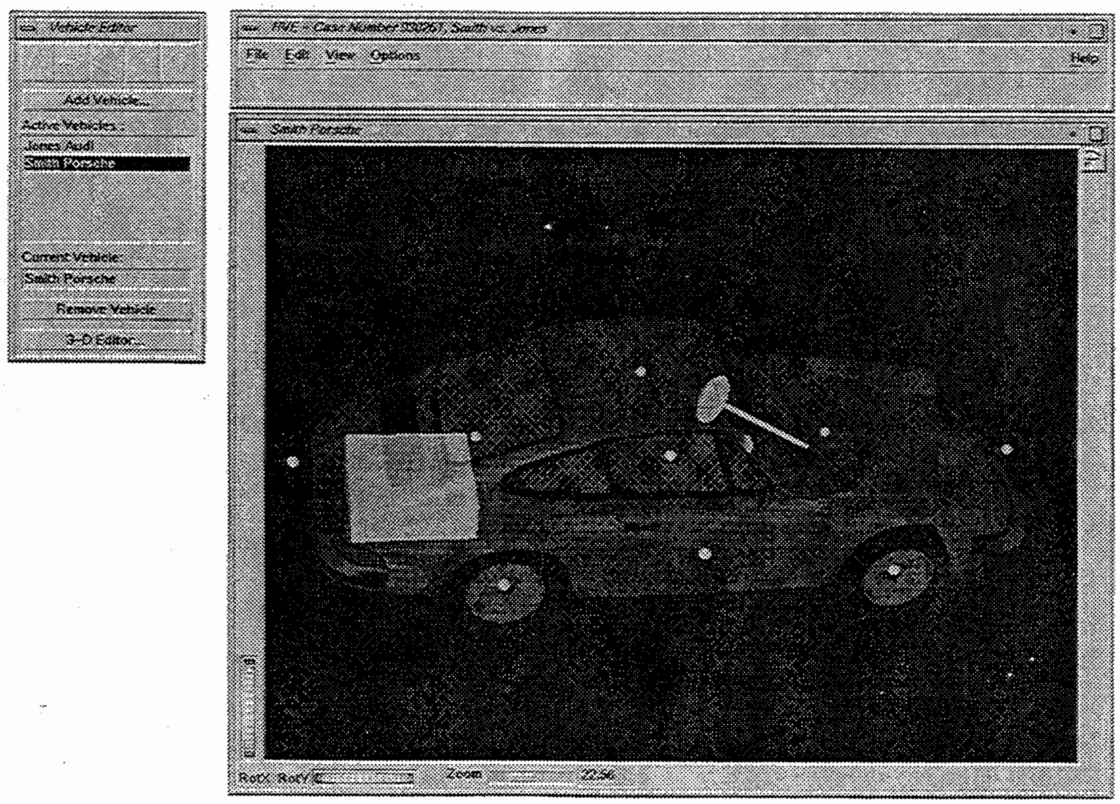

Figure 4 - HVE Vehicle Editor (left) and Current Vehicle Window (right). The Vehicle Editor is used for selecting vehicles (passenger cars, pick-ups, vans, multi-purpose vehicles, trucks, trailers and dollys) for analysis. The Vehicle Editor is also used for editing vehicle properties, including dimensions, inertias, drivetrain, suspensions, tires and brakes.

Vehicle Mode

Vehicle Mode uses the Vehicle Editor to create one or more 3-D vehicle models (see figure 4) for analysis. Basic configurations provided by the Vehicle Editor include body style, engine location, number of axles and drive axle location. Passenger cars, pickups, vans, multi-purpose vehicles, trucks and truck tractors, small and large trailers and trailer dollies may be created using the Vehicle Editor (see fig. 5).

Individual vehicle units are created by defining dimensional and inertial properties, as well as exterior stiffness, the tire, suspension and brake properties at each wheel, the drivetrain (engine, transmission and differential) properties, and steering and brake systems. Restraint systems (lap belts, torso belts and airbags), human contact surfaces, inter-vehicle connections (ball, fifth wheel and pintle hook), drag forces and vehicle lighting systems may also be specified.

The vehicle model is robust enough to allow the analysis of most vehicle in-use maneuvers, including collisions and rollovers. A calculation method may use some or all of the defined parameters. For example, the EDVSM vehicle model is complex; it is able to use nearly all the parameters defined by the vehicle model. On the other hand, the EDSMAC vehicle model is less sophisticated; it uses relatively few model parameters. Those parameters which are used by the calculation are listed in the output.

HVE vehicles can use 3-D drawing files created by Viewpoint Animation Engineering [8]. A typical HVE vehicle is composed of approximately 2000 to 5000 polygons (the number of polygons is a measure of the level of visual realism in the model - the more polygons, the more realistic). HVE includes a 3-D drawing editor which may be used to create new vehicles or modify existing vehicles (see figure 6). In addition, HVE can import vehicles developed using the Wavefront Advanced Visualizer™ (OBJ files) or AutoCad™ (DXF files), although some modification of these files is normally required before using them in HVE.

An overview of the specification for vehicles created using the Vehicle Editor is found in Appendix B.

Vehicle Library

HVE contains a library of generic vehicles which may be selected according to wheelbase. HVE also contains a library of pre-defined vehicles which may be selected according to vehicle type, year, make, model and body style. The pre-defined library of passenger cars was developed from a statistical analysis of the most popular vehicles (determined from Automotive News/Market Data Book sales figures) sold between 1985 and 1990. Some heavy trucks, truck trailers and dollys are also included in the Vehicle Library. The library includes both the physical and visual data files for the above vehicles. Virtually any other

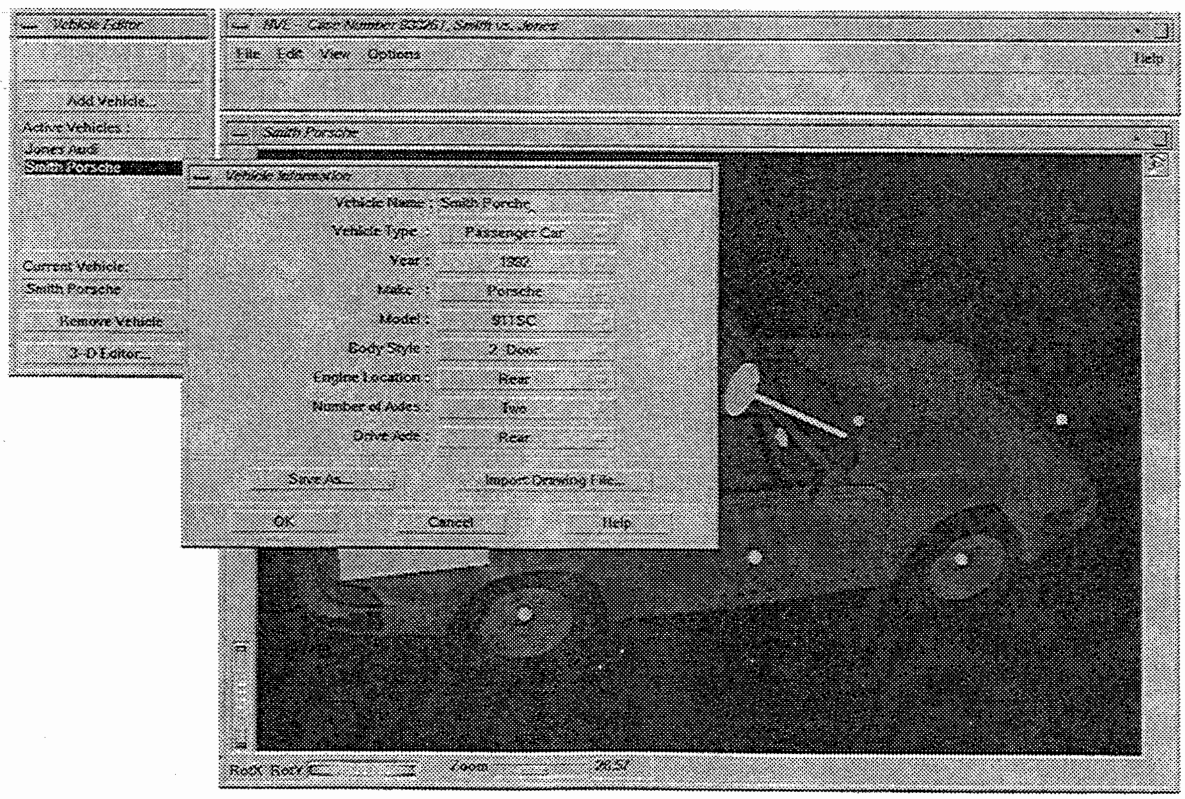

Figure 5 - HVE Vehicle Information Dialog. This dialog is used for adding new vehicles to the Active Vehicles list. Vehicles are selected according to type, year, make, model and body style. Engine location, number of axles and drive axle may also be specified. New vehicles may be added to the Vehicle Library for use in other cases.

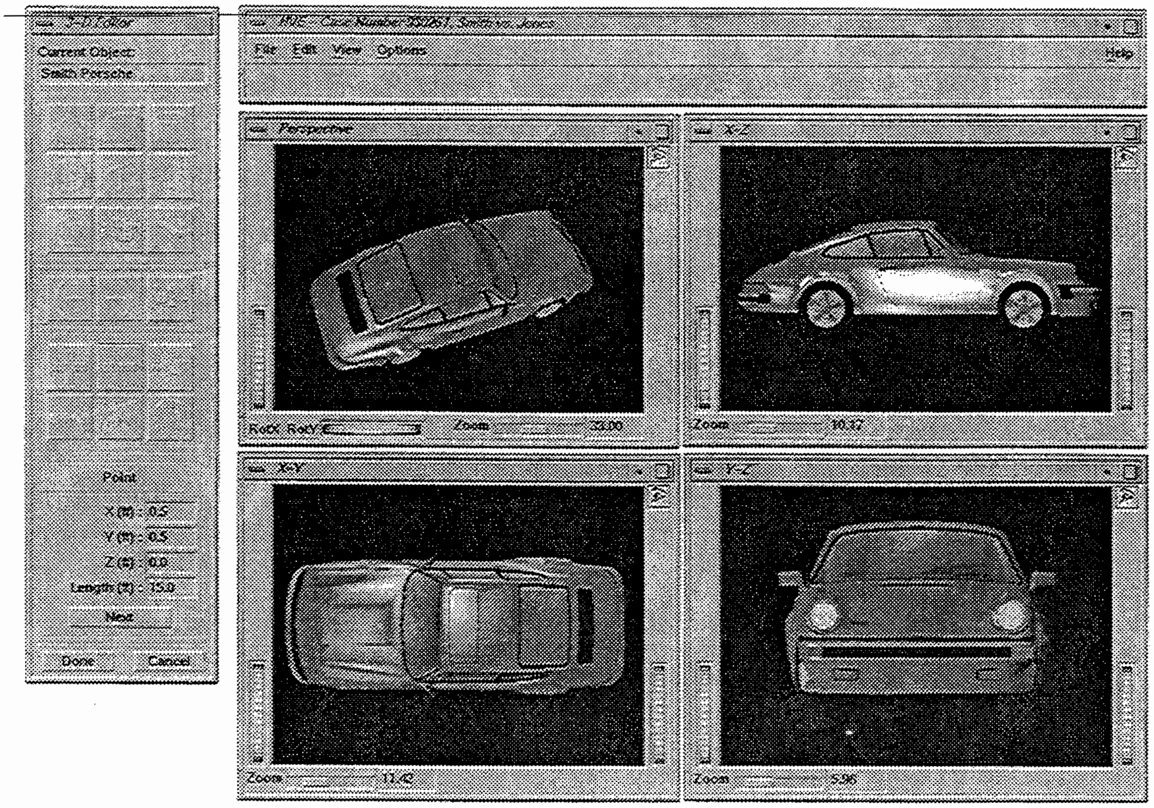

Figure 6 - HVE 3-D Drawing Editor. The 3-D Editor panel has several modeling tools which may be used for creating and/or modifying vehicle drawing files. The 3-D Editor may also be used for creating visual damage on the vehicle surface.

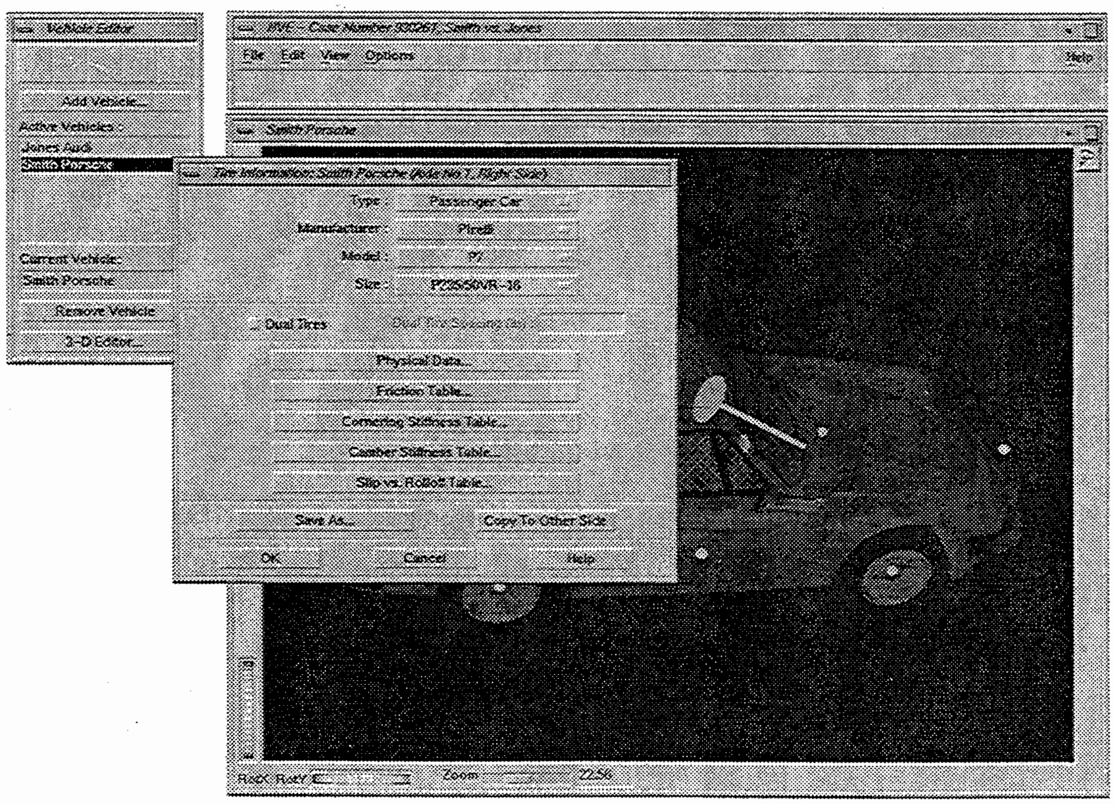

Figure 7 - Tire Information Dialog. This dialog is displayed by clicking on a tire in the Current Vehicle window. It is used for selecting and modifying, if desired, the individual tires for the current vehicle. Tires are selected according to type, manufacturer, model and size. New tires may also be created and added to the Tire Library for use in other cases.

vehicle can be created and added to the library using the HVE Vehicle Editor.

Tire Library

HVE also includes a pre-defined library of passenger car, light and heavy truck tires. Individual tires are defined according to tire type, manufacturer, model and size (see figure 7). HVE allows the user to create new tires to add to the library as data become available. Tire data requirements include physical data (weight, size,...) friction (see figure 8), cornering and camber stiffness, and slip vs rolloff. The user may specify different tires for each wheel position.

Environment Mode

Environment Mode is used for creating 3-D accident site environments (see Figure 9). The environment may be created using 3-D drawing tools (described below) or by importing a scanned photograph of the accident scene taken from a known camera position, as shown in figure 9.

The HVE environment is also a *physical* environment, and includes the time, date and location of the accident (used for positioning the sun, a factor causing glare or reduced visibility in some daytime and nighttime accidents), ambient temperature and pressure, wind speed and direction (used for aerodynamics calculations), overcast and visibility data for visibility calculations and the acceleration of gravity (for lunar collisions). The environment information dialog is shown in figure 10. An overview of the environment model specification is found in Appendix C.

Environment Tools

Historically, 2-D and perspective 3-D accident site diagrams have been used effectively by accident reconstructionists during the presentation process. Their use has increased with the introduction of computer-aided drafting (CAD) systems. Accident site diagrams are an effective way to illustrate spatial relationships which may be a factor during an accident. However, as one of the three accident factors described by the nine-cell matrix, the accident site environment has, in the past, been ignored in the *modeling* process. The reasons are as follows:

- Accident site diagrams are drawings which have only visual properties - no physical properties. The same has been true for 3-D accident site environments used in animations. There is no dynamic feedback between the environment and vehicle to provide the analysis method with all the required physical information (local surface friction, elevation and slope) during an analysis.
- Realistic 3-D accident site environments are extremely time-consuming to produce, requiring up to 200 man-hours. More than any other reason, this time requirement has limited the use of 3-D animation as a routine method of analyzing and visualizing accidents to learn how they happen.

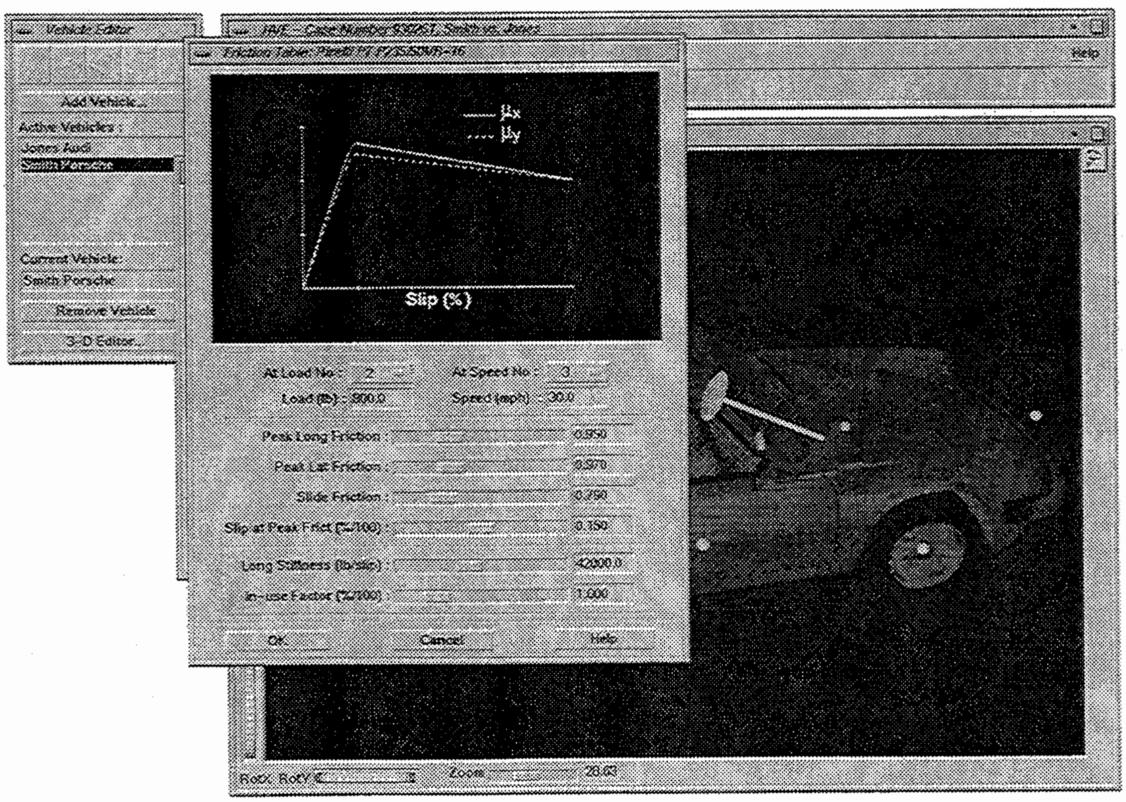

Figure 8 - Tire Friction Table Dialog. This dialog allows the user to enter and modify tire friction data. The dialog also shows the friction data graphically for each load and speed. Like other data in the vehicle model, a sophisticated, 3-D analysis method may use all of this information, while a less sophisticated, 2-D method may use only some of the information.

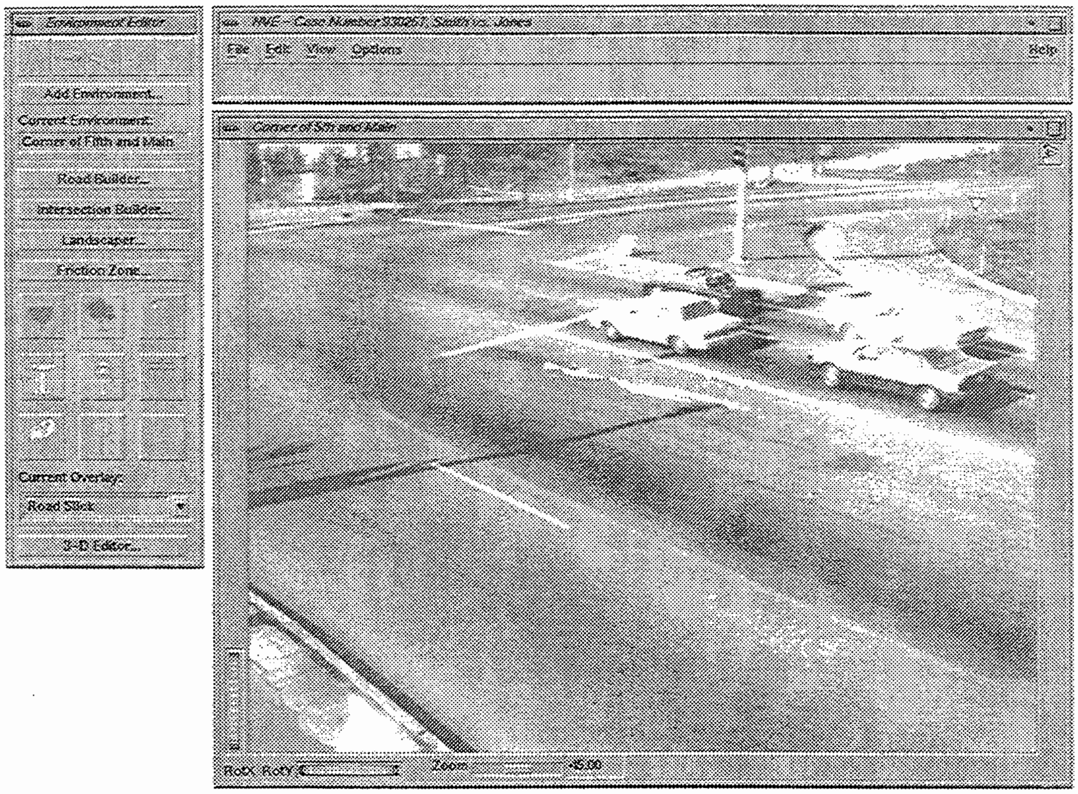

Figure 9 - HVE Environment Editor. The Environment Editor is used for creating 3-D accident site environments and associated physical information and friction zones. In this example, a scanned image was used to create the accident site.

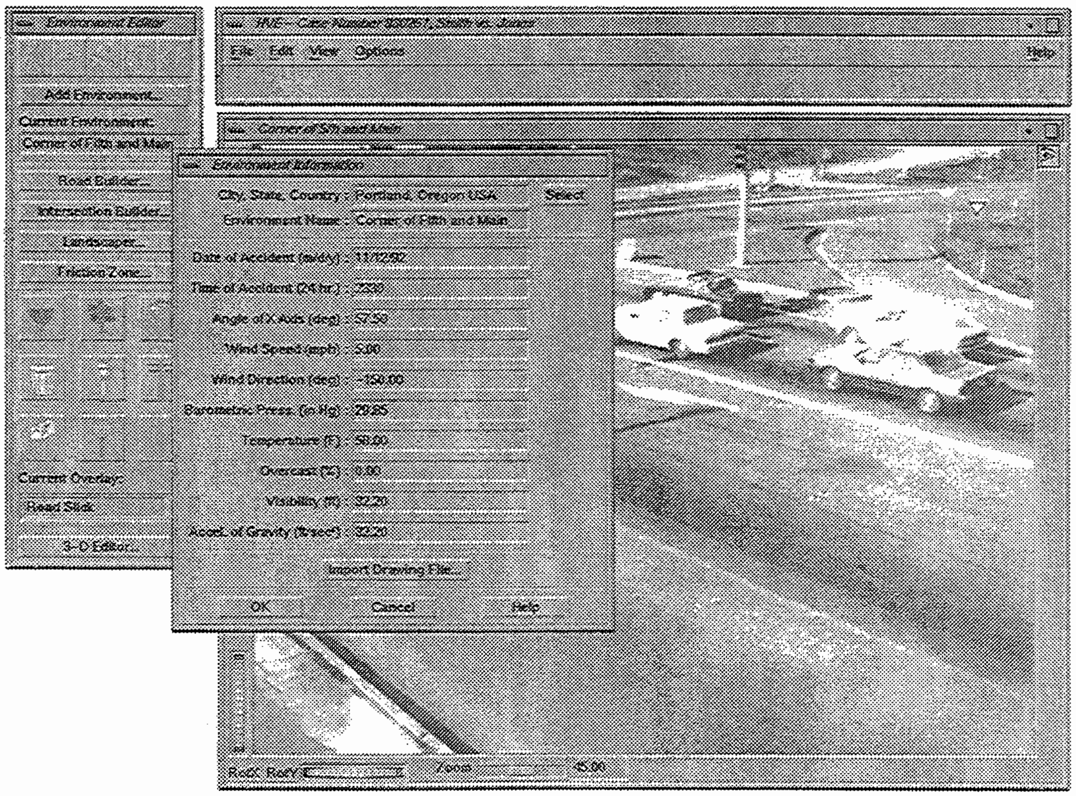

Figure 10 - HVE Environment Information Dialog. This dialog allows the user to enter physical information, including time, date and location of the accident, as well as wind speed and direction, temperature and pressure. This information may be used during calculations.

The HVE interface specification removes both of these previous limitations. First, the HVE environment is a *physical* environment. That is, in addition to the physical properties (time, temperature, pressure, wind velocity) described earlier, all accident site *surfaces* created using HVE have physical properties as well. All environment surfaces are created from polygons, each having a specified earth-fixed X,Y,Z location, friction coefficient and slope. The HVE interface makes this physical information available to any calculation method. From the environment, therefore, the method may extract the elevation, friction and slope at each individual wheel. A sophisticated 3-D vehicle simulator may use this information in the form of virtually unlimited terrain boundaries and surface slopes. In addition, with proper modification of their tire models, this environment information allows all traditional 2-D analyses, such as EDCRASH and EDSMAC, to consider the effects of superelevations and grades. Furthermore, the variation in elevation among wheels may be used to estimate vehicle roll and pitch orientation and CG height, thus extending the useful range of these 2-D programs into a *quasi*-3-D range for slopes up to approximately 15 degrees.

Second, the HVE Environment Editor greatly reduces the time required to create a 3-D accident site. The Editor contains five tools designed specifically for creating 3-D accident site environments. These tools are:

- Road Builder
- Intersection Builder
- Landscaper
- Friction Zones
- Highway Furnishings

Each of these tools is described below.

Road Builder - The Road Builder (see figure 11) creates 3-D highways. The tool has two construction windows. One window allows the user to supply highway centerline geometry (tangents, circular curves and spirals) commonly found in highway design and as-built drawings. The other window allows the user to supply cross-section data (number and width of each lane, lane material, shoulders and medians, cross-slope, delineation, curb, guard rail and barrier details). This information is also found in design and as-built drawings. The Road Builder uses this information to *extrude* the specified highway cross section along the specified centerline. Using this method it is possible to produce very quickly (i.e., in a few minutes) large sections of 3-D highway which include curves and spirals, varying superelevations and grades. Each surface has

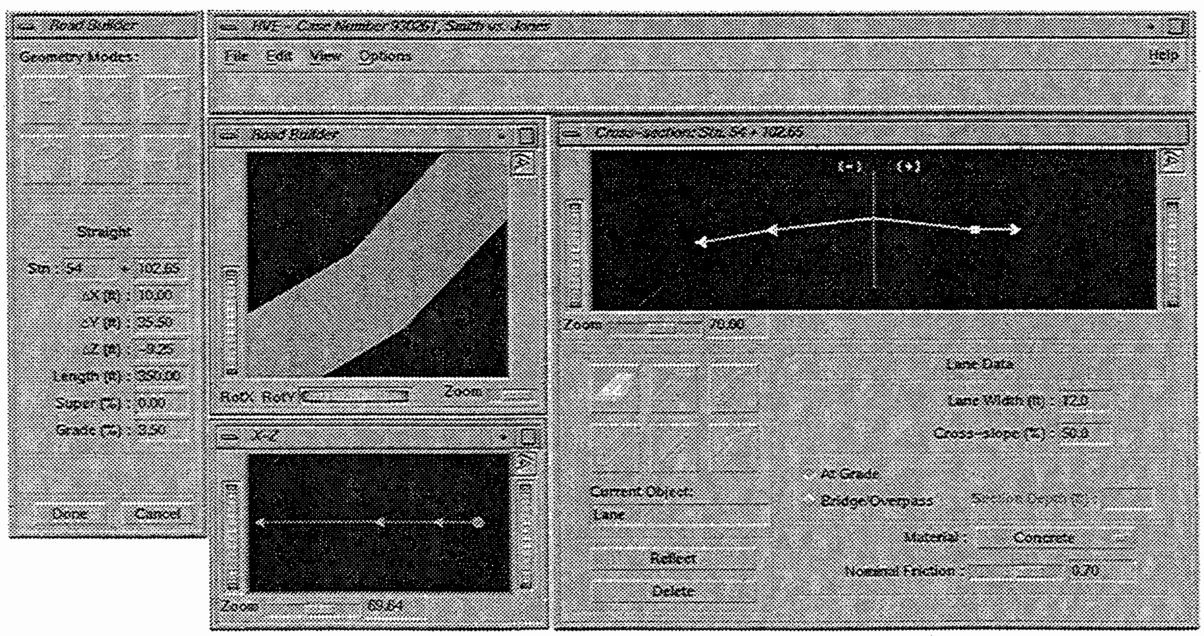

Figure 11 - HVE Road Builder. The Road Builder is one of five tools used for creating 3-D accident site environments. The Road Builder allows the user to create 3-D sections of highway. Building roads is a two-step process. First, a centerline is drawn using a Geometry Mode (Straight, Circular Curve, Spiral Curve or Spline (Bezier) Curve; see dialog on left). Second, a cross-section for that centerline is drawn using the Cross-section tool (Space, Lane, Curb, Rail/Barrier and Delineation are the available tools; see dialog on right). The Road Builder uses this information to "extrude" the supplied cross-section along the centerline. The Road Builder may be used to create complicated, 3-D highway sections, which include super-elevation and grade changes, in a matter of minutes.

friction properties which are available for use by the calculation method. Most roads and highways can be constructed using the Road Builder.

Intersection Builder - The Intersection Builder is similar to the Road Builder, except it is used for creating irregular roads and intersections. It is also used for connecting two sections of dissimilar road created using the Road Builder.

Like the Road Builder, the Intersection Builder allows the user to create road surfaces having specific friction properties. Curbs, rails and barriers, and delineation may also be created. However, unlike the Road Builder, the surfaces created using the Intersection Builder may have an arbitrary shape, and curbs, guardrails and delineation may be placed at arbitrary locations. Using the Intersection Builder, it is possible to quickly create extremely complex roads and intersections.

Landscaper - The Landscaper tool is similar to the Intersection Builder, except it is used for creating the surfaces adjacent to the highway. The landscape is connected to the edges of the roads and/or intersections created using the Road Builder and Intersection Builder. The Landscaper can quickly create flat or hilly surfaces with a specified texture - usually concrete, gravel, dirt or grass. Like the Road Builder and Intersection Builder, all surfaces have user-assigned friction properties which are made available for use by the calculation method.

Friction Zones - The Friction Zones tool is used for creating areas on the road surface having user-assigned material properties and friction coefficients. The area is simply drawn on the road surface, and may have any shape definable by a polygon. It is automatically *mapped* to the road surface. The area is then assigned a nominal friction value.

Any number of friction zones may be created. For example, using the Friction Zones tool it is possible to create a pool of water or spilled oil on the highway, or any other terrain surface having specific visual and friction properties. The friction value is physical information made available to any calculation method.

Highway Furnishings - The Highway Furnishings tool is used to create objects commonly found at accident sites, such as traffic signs and signals, trees and buildings. Virtually any object can be created and saved in the Highway Furnishings library for future use. These objects can then be placed anywhere in the environment. A standard library of highway furnishings is included with the interface.

Using the above tools, it is estimated that the number of man-hours required to create an extremely complex, 3-D accident site environment will be reduced from as many as 200 man-hours to less than 10 man-hours. Moderately complex 3-D accident sites may take less than three hours to create. Simple 3-D accident sites may be created in less than one hour.

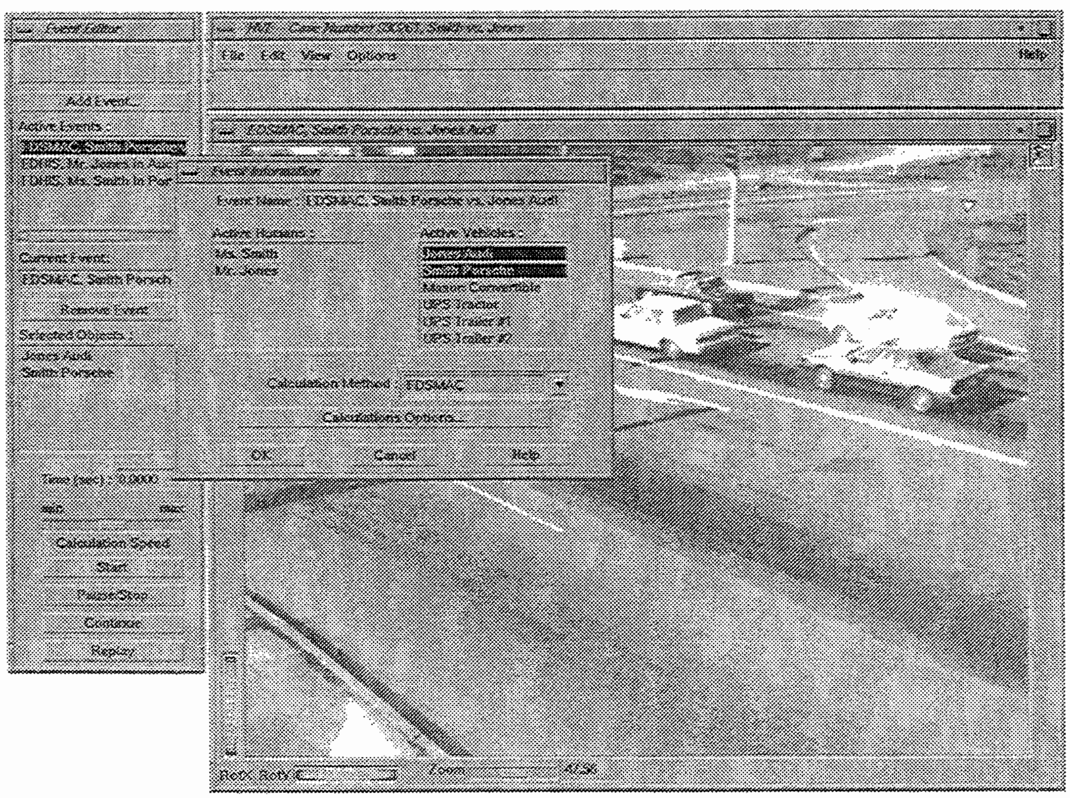

Figure 12 - Event Information Dialog. This dialog is used for adding a new event to the Active Event list. An event is created by selecting one or more objects (humans and vehicles) and a calculation method. In the above example, two vehicles (the Smith Porche and Jones Audi) are selected, and the calculation method is EDSMAC.

Event Mode

An event is defined by a calculation method (i.e., EDCRASH, EDSMAC, etc.) and the objects (human and/or vehicles) used in the calculation. Calculation methods currently implemented include several 2-D and 3-D reconstructions and simulations. A list of the implemented methods is found in Appendix E. The HVE specification also allows researchers to implement their own calculation methods.

The following steps are required to set up and execute an event:

- Select the objects (human and/or vehicle(s))
- Select the calculation method
- Position the objects and, if applicable, assign velocities at each position
- Assign other *in-use* factors for each object (Damage, Driver Controls, Collision Pulse, Payload, Lights and Restraint Systems; see Appendix D)

The event is then executed. Figures 12-14 illustrate the process of creating an event. Figure 15 shows the event ready to execute.

While executing the event, the calculation method produces an *output track* for each human or vehicle object. An HVE output track is a standardized (according to the HVE specification) data stream containing kinematics, forces and other output data for an object as a function of time. An overview of the specification for HVE output tracks is found in Appendix F.

For example, assume the user has created a human object, named Ms. Smith, and two vehicle objects, named Smith Porsche and Jones Audi, respectively. To analyze the car-to-car collision, the user would select the Porsche and Audi as the objects and EDSMAC as the calculation method. The user would then assign initial positions and velocities to each vehicle (additional *target* positions may be entered as well), and assign driver controls (throttle, brakes and steering). Then, the EDSMAC event is executed.

To analyze the occupant collision, the user would select Ms. Smith and the Porsche as the objects, and EDHIS as the calculation method. Ms. Smith is then positioned inside the Porsche and assigned restraints, the Porsche is assigned a collision pulse, and the EDHIS event is executed.

Simulation events may be paused and restarted, making it possible to modify a human, vehicle or environment during the run. For example, a tire blowout while negotiating a curve may be simulated by pausing at the appropriate time and reducing the tire's cornering stiffness, then continuing the calculation. Wind gusts can be simulated by changing the wind speed and/or direction.

Any number of events may be executed and saved for a particular case (limited only by computer memory).

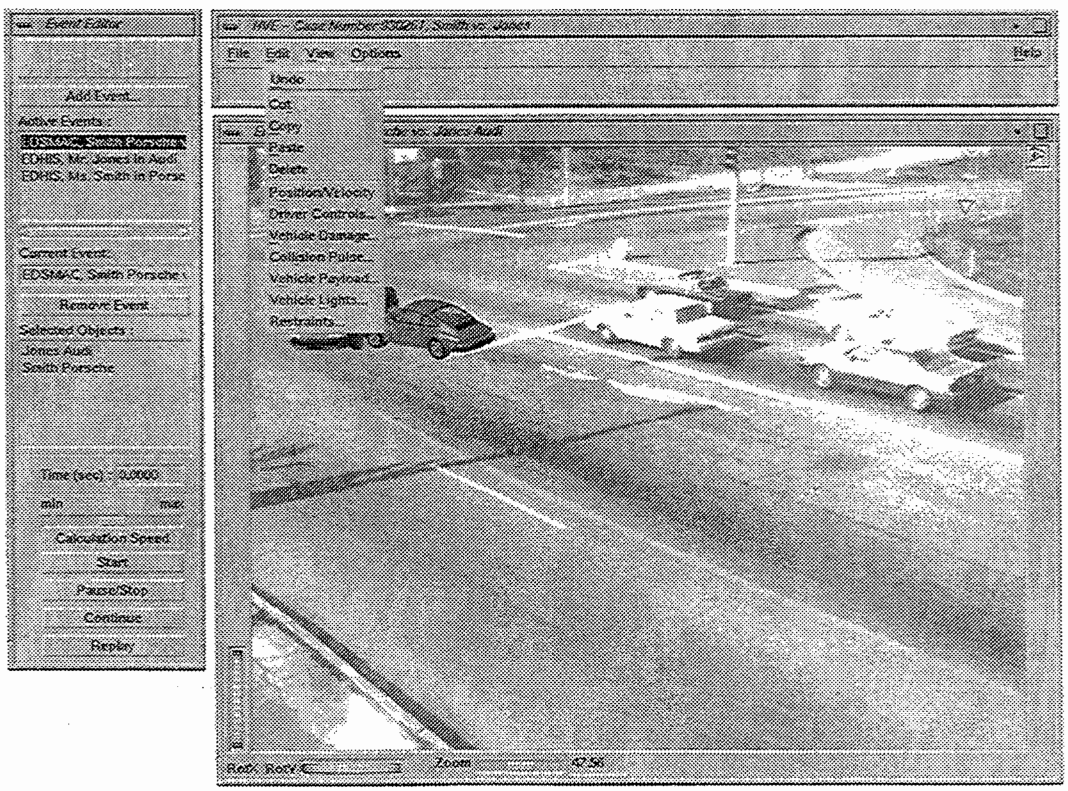

Figure 13 - Event In-use Options (Edit Menu). After selecting the objects and calculation method (see figure 12), the Edit Menu options are used to "set up" the event by assigning in-use factors to each human and/or vehicle. These factors include positions, velocities, driver controls (throttle, brakes and steering) and vehicle damage (see Edit Menu, above).

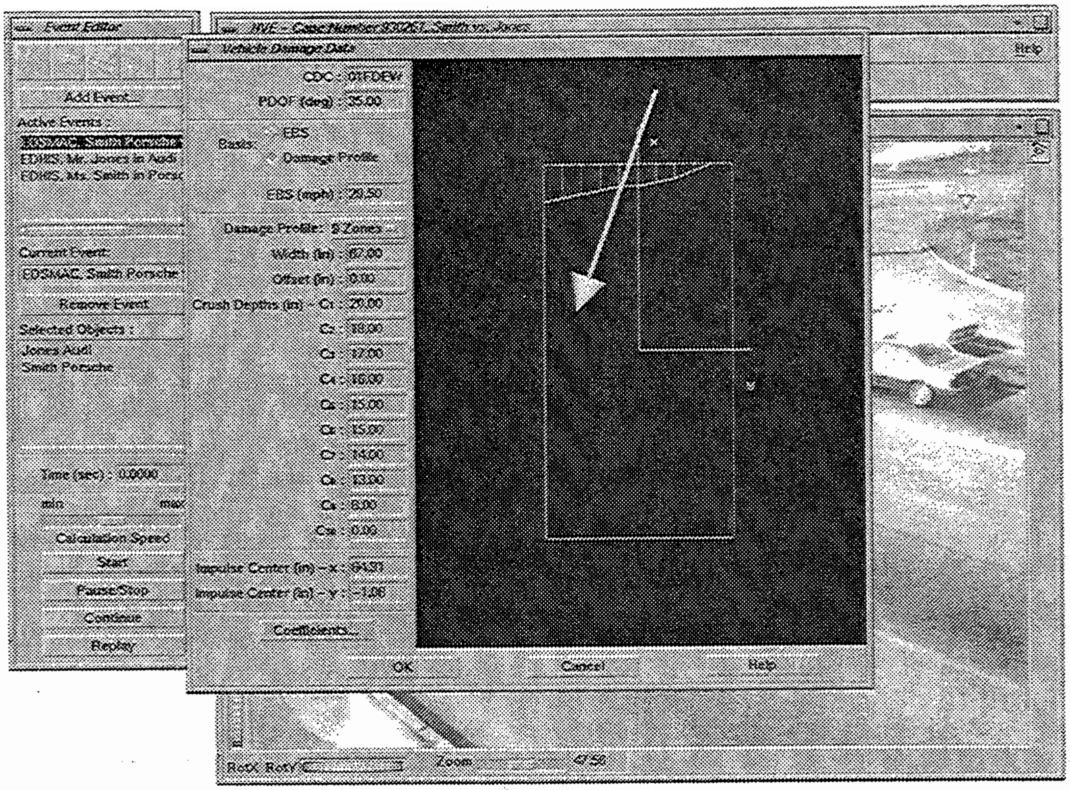

Figure 14 - Vehicle Damage Dialog, used for assigning the CDC, PDOF, EBS and Damage Profile. This in-use data dialog is selected by choosing Vehicle Damage... from the Edit Menu (see figure 13).

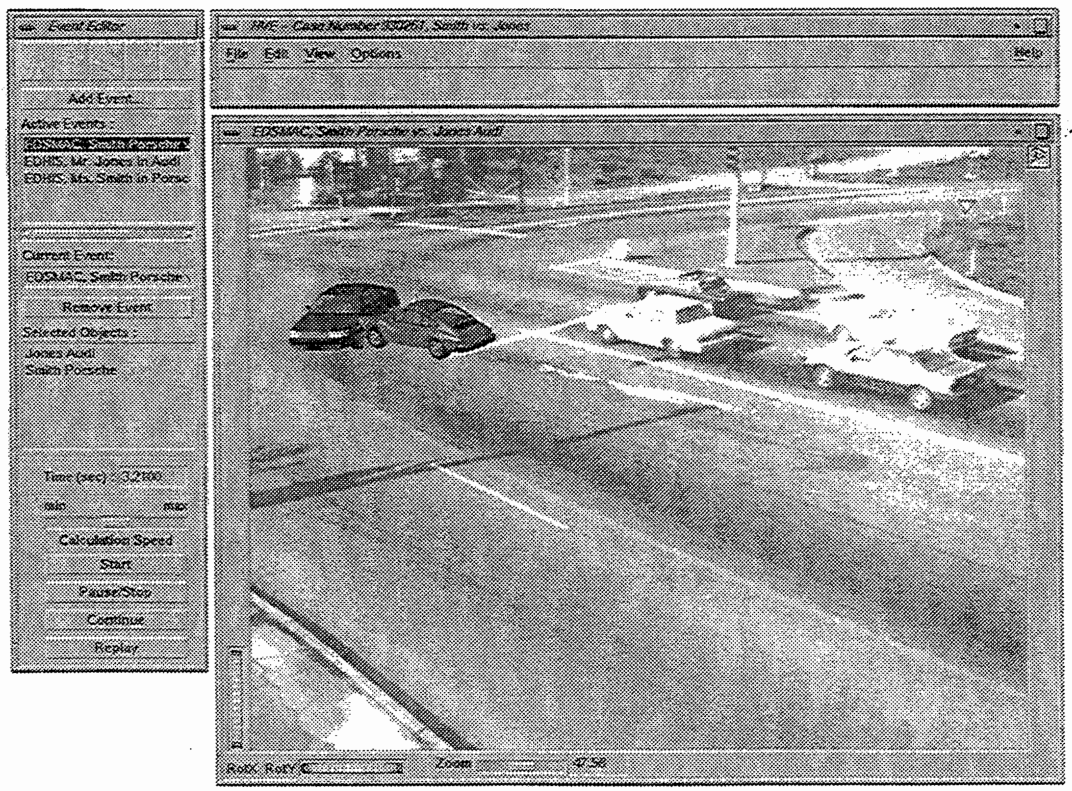

Figure 15 - Event Editor. The event is now ready to execute by pressing Start (see Editor Panel, left). During execution, the event is displayed in the Current Event window (right). A Key Results window, which displays current position and velocity (not shown in this example) may also be shown during the run. Events may be paused and restarted, allowing vehicles to be modified mid-run. Or, in-use factors (position, velocity, driver controls...) may be modified, and the run restarted.

Direct Manipulation

The HVE interface uses *direct manipulation* extensively. Direct maniulation is a process wherein the user selects and moves an object using the mouse. For example, vehicles and humans are positioned by clicking the mouse on their CG's and "dragging" (moving) them to the desired location (a window also displays the exact coordinates and orientation angles for editing). Direct manipulation greatly improves the process of positioning humans and vehicles.

User-created Calculation Methods

Researchers may also implement their own calculation methods by following the specifications provided for the human and vehicle models (see Appendices A, B and F). The process involves the following steps:

- Program the calculation method in C or C^{++}
- In the program, incorporate the input data structures for humans and vehicles provided with the HVE Developer's Toolkit [11]. An overview of the specification parameters may be found in Appendices A, B, C, D and F.
- Incorporate the output data structure for humans and vehicles compatible with the HVE Developer's Toolkit [11]. See Appendices.
- Compile and link the program
- Place the executable in the directory containing the HVE executables

Some limitations are currently placed on user-implemented calculation methods (see Limitations).

Playback Mode

The Playback Editor allows the user to combine any number of events (limited only by computer memory) into a single window for viewing or other output. Thus, a multi-car collision involving several occupants and pedestrians may easily be merged together and viewed in a single simulation.

The Playback Editor works much like a multi-track tape recorder. In the case of HVE, the Playback Editor edits the output tracks produced for each event. The lower part of the Playback Editor (see figure 16) contains a panel which looks like a VCR, containing buttons for *forward*, *reverse*, *pause*, *stop* and *record*. It also allows the user to print key frames *(step-select)* and control the playback speed.

Two types of windows are created during playback mode:

- *Preview Windows* are used to select and edit individual events (see figure 16).
- *Playback Windows* are used to display combined events in a single window (see figure 17).

Each preview and playback window may be viewed from a user-selected position.

For example, earlier, while describing Event Mode, two events were executed. During Playback, the EDSMAC event analyzing the collision between the Porsche and Audi could be displayed in Preview Window 1 (see figure 17). The EDHIS event, a simulation of Ms. Smith inside the Porsche, could be displayed in Preview Window 2. These events could then be combined in Playback Window 1 and display the entire accident sequence as viewed from the driver's (Ms.

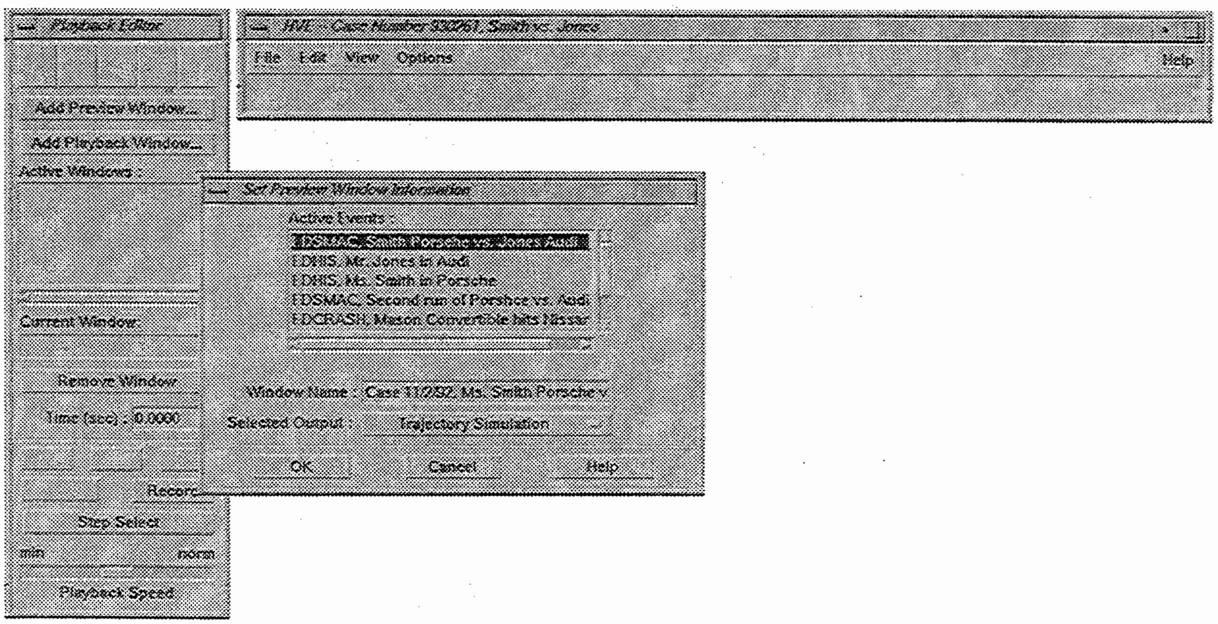

Figure 16 - Playback Mode, Set Preview Window Information Dialog. This dialog is used for selecting an individual event from the Active Event list (the Active Event list contains all the individual events which have been executed; e.g., the EDSMAC event described in figures 12 through 15, named "Smith Porsche vs Jones Audi"). Each of these individual events may be redisplayed in a Preview window. In addition, using a Preview window, the user may edit the starting and ending times so as to synchronize the event with other events. Each Preview window contains an individual event which may be viewed simultaneously with other events and edited in this manner.

Smith) perspective. The same events could also be selected and displayed in Playback Window 2, showing the accident from a different perspective, such as the perspective of a witness standing on the corner or any other vantage point. Thus, the accident sequence may be viewed simultaneously from two (or more) different perspectives.

Trajectory simulations displayed in playback windows may be transferred to a printer, plotter or VTR. A printed or plotted output produces a still "picture" at the current simulation time. VTR output produces a photo-realistic animation on a video cassette which may be played back on a conventional VCR.

To document the events in each playback window, HVE produces an *Audit Trail* containing a chronology of the key information for each event, including the environment information, analysis methods, the objects (human and vehicles) involved, the time at the start and end of each event and any user-entered changes to the humans and/or vehicles which occurred while pausing the event.

Output may be viewed numerically as well as graphically. Numeric output includes a table of selected output track results and any other information assigned to numeric output by the calculation method (typically, human or vehicle properties, program run-time parameters and other input data). Graphic output, in addition to animated trajectory simulations, includes damage profiles, momentum diagrams and data graphs.

LIMITATIONS

Each calculation method contains limitations. For proper use of HVE, it is important that those limitations be thoroughly understood by the user. The reader is referred to the individual method's documentation (reference [10] for those methods included in the interface) for a discussion of those limitations.

The current HVE interface specification also has limitations. These limitations may be inferred by reviewing the human, vehicle and environment model parameters in the appendix. A summary of the limitations follows:

Human Model (see Appendix A) -

- Human has three, six, ten or fifteen segments
- Human Library not user-extendable
- Human drawing files not user-editable

Vehicle Model (see Appendix B) -

- Vehicle or trailer has one, two or three axles with left-side and right-side tires (no motorcycles)
- When dual tires are specified, the inner and outer tires have the same properties
- Vehicle has one damage profile per event

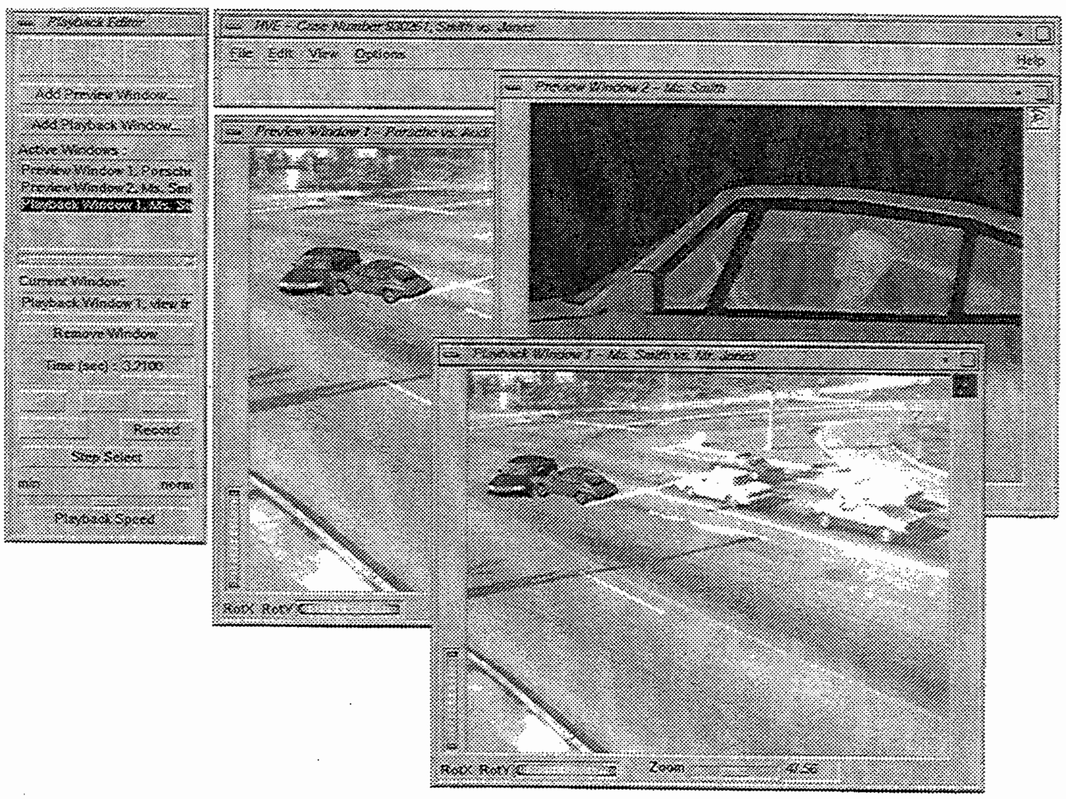

Figure 17 - HVE Playback Editor (left), Preview and Playback Windows (center and right). The Playback Editor is used for creating output windows. In this example, an EDSMAC event is displayed in Preview Window 1 and an EDHIS event is displayed in Preview Window 2. These two events are combined in Playback Window 1 (in Playback Window 1, you may be able to see Ms. Smith inside the Porsche). The information in Playback windows may be routed to a printer, plotter or VTR. The motion in each of these windows is controlled by the Playback Controller (the VCR-like panel located in the Playback Editor).

Environment Model (see Appendix C) -

- Single environment per event
- Input from scanner, VCR or digital camera requires TIFF-, RGB- or PCX-compatible file.

Calculation Methods -

- Object variables limited to those assignable by the Human, Vehicle and Environment Editors
- User-implemented calculation methods do not allow calculation options dialogs.

Playback -

- The number of currently supported output devices (printers, plotters and VTRs) limited.
- Motion blur, fade-in, page-turn and other special effects not currently supported
- Ray-tracing (point-source shadows) not supported

At the time this paper is being written, the HVE interface is still under development. Features may be changed, updated or omitted during this process. It is also assumed that additional limitations will become apparent as the use of the interface increases.

SUMMARY

This paper has described a 3-D computer software interface, called HVE. The paper illustrated the use of HVE for reconstructing, simulating, displaying and animating motor vehicle accidents. The paper provided a technical overview of the program, including system requirements. The paper showed examples of the interface and illustrated its use for creating comprehensive, 3-D models of humans, vehicles and environments. The input and output specifications for the models were reviewed. A list of available calculation methods was provided. Information was also provided to illustrate how researchers can incorporate their own calculation methods into HVE. Finally, the paper described how analyses are performed, and how the results of individual analyses are combined and played back to illustrate an entire accident sequence which may be routed to a printer, plotter or VTR.

TRADEMARKS

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8. Viewpoint Animation Engineering, Orem, UT, 1992.

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10. *HVE Technical Manual, Calculation Methods*, Engineering Dynamics Corporation, Beaverton, OR, 1993 (currently under development).

11. *HVE Developer's Toolkit*, Engineering Dynamics Corporation, Beaverton, OR 1993 (currently under development).

Appendix A - Human Model

Table 1. The Human Model Data Stream Information. The Human Editor creates a 3-D human having the properties shown below. Each variable has a unit name and associated program units for use by the analysis method. The HVE interface displays input and output data according to user-selected units (US, Metric or Custom).

Variable Name	Unit Name	Pgm Units	Comments
SegMass	UnitHumMass	lb-sec^2/in	per segment
SegInertialJK	UnitHumInertia	lb-sec^2-in	per segment
EllipsCoordIJK	UnitHumLength	in	3 per ellipse
EllipsLengthIJK	UnitHumLength	in	3 per ellipse
JointCoordIJK	UnitHumLength	in	3 per joint
JointStopAngMaxIJK	UnitHumAngle	rad	3 per joint
JointStopAngMinIJK	UnitHumAngle	rad	3 per joint
JointStopElastMaxIJK	UnitHumElast	in-lb/rad	3 per joint
JointStopElastMinIJK	UnitHumElast	in-lb/rad	3 per joint
JointElast	UnitHumElast	in-lb/rad	3 per joint
JointDamp	UnitHumDamp	in-lb-sec/rad	3 per joint

Variable Name (cont)	Unit Name	Pgm Units	Comments
ToleranceJointAngleMax	UnitHumAngle	rad	3 per joint
ToleranceJointAngleMin	UnitHumAngle	rad	3 per joint
ToleranceHIC	n/a	(unitless)	head inj crit
ToleranceHeadPitch	UnitHumAngAcc	rad/sec^2	
ToleranceHeadSideAccel	UnitHumAcc	in/sec^2	
ToleranceChestSI	UnitHumChestSI	in/sec^2	severity index
ToleranceChestForce	UnitHumForce	lb	
ToleranceChestFwdAccel	UnitHumAcc	in/sec^2	
ToleranceKneeForce	UnitHumForce	lb	max femur
ToleranceLapBeltRL	UnitHumForce	lb	per belt sect
ToleranceTorsoBeltRL	UnitHumForce	lb	per belt sect

Appendix B - Vehicle Model

Table 2. The Vehicle Model Data Stream Information. The Vehicle Editor creates a 3-D vehicle having the properties shown below.

Variable Name	Unit Name	Pgm Units	Comments
VehicleXf	UnitVehLength	in	CG to front
VehicleXr	UnitVehLength	in	CG to rear
VehicleYr	UnitVehLength	in	CG to right
VehicleYl	UnitVehLength	in	CG to left
VehicleAstf	UnitVehAStiff	lb/in	A stiffness
VehicleBstf	UnitVehBStiff	lb/in^2	B stiffness
VehicleKstf	UnitVehKStiff	lb/in^2	Kv stiffness
VehicleMass	UnitVehMass	lb-sec^2/in	total mass
VehicleInertialJK	UnitVehInertia	lb-sec^2-in	roll, pitch, yaw
VehicleContactCoordXYZ	UnitVehLength	in	surf coords
VehicleContactLinearStf	UnitVehStiffness	lb/in	surf props
VehicleContactQuadStf	UnitVehQuadStif	lb/in^2	surf props
VehicleContactCubicStf	UnitVehCubicStif	lb/in^3	surf props
VehicleContactDampCnst	UnitVehDamp	lb-sec/in	surf props
VehicleContactPentrnMax	UnitVehLength	in	surf props
VehicleContactForceMax	UnitVehForce	lb	surf props
VehicleContactEdgeCnst	n/a	(unitless)	surf props
VehicleContactUnloadStf	UnitVehStiffness	lb/in	surf props
VehicleBeltAnchorRLXYZ	UnitVehLength	in	belt coords
VehicleBeltLinearStfRL	UnitVehStiffness	lb/in	belt props
VehicleBeltQuadStfRL	UnitVehQuadStif	lb/in^2	belt props
VehicleBeltCubicStfRL	UnitVehCubicStif	lb/in^3	belt props
VehicleBeltDampConst	UnitVehDamp	lb-sec/in	belt props
VehicleBeltStrength	UnitVehForce	lb	belt props
VehicleBeltUnloadRate	UnitVehStiffness	lb/in	belt props
VehicleBagXYZ	UnitVehLength	in	airbag coords
VehicleBagRad	UnitVehLength	in	airbag props
VehicleBagLength	UnitVehLength	in	airbag props
VehicleBagPo	UnitVehPressure	lb/in^2	airbag props
VehicleBagThkns	UnitVehLength	in	airbag props
VehicleBagVolume	UnitVehVolume	in^3	airbag props
VehicleBagVentCoef	UnitVehPressure	lb/in^2	airbag props
VehicleBagVentArea	UnitVehArea	in^2	airbag props
VehicleBagPVent	UnitVehPressure	lb/in^2	airbag props
VehicleBagDeflMax	UnitVehLength	in	airbag props
VehicleBagThkns	UnitVehLength	in	airbag props
VehicleBagElast	UnitVehElastic	lb/in^2	airbag props
VehicleBagElastReb	UnitVehElastic	lb/in^2	airbag props
VehicleBagElastBot	UnitVehElastic	lb/in^2	airbag props
VehicleBagGasRho	UnitVehDensity	lb/in^3	airbag props
VehicleBagGasCp	UnitVehAirbagCP	in-lb/lb	airbag props
VehicleColmnColpsDMax	UnitVehLength	in	airbag props
VehicleColmnColpsLoad	UnitVehForce	lb	airbag props
VehicleColmnAngle	UnitVehAngle	rad	airbag props
VehicleBagAlamb	n/a	(unitless)	airbag props
VehicleBagPlane	n/a	(unitless)	airbag props
VehicleConnectXYZ	UnitVehLength	in	frt, rear coords
VehicleConnectRad	UnitVehLength	in	friction radius
VehicleConnectFrict	n/a	(unitless)	friction coef
VehicleConnectArticMax	UnitVehAngle	rad	articulation
VehicleAirDragCoef	UnitVehQuadCd	1/in^2	includes area
VehicleLinearDragCoef	UnitVehLinCd	lb-sec/in	veloc. depend.
VehicleDragConst	UnitVehDragCnst	lb	drag const
VehicleLightMountXYZ	UnitVehLength	in	mount coords
VehicleLightAimedXYZ	UnitVehLength	in	aim coords

Variable Name (cont)	Unit Name	Pgm Units	Comments
VehicleLightBright	UnitVehLightBrght	cd	intensity
VehicleLightAngle	UnitVehAngle	rad	cone angle
VehicleLightTimeOn	UnitVehTime	sec	blinker, on
VehicleLightTimeOff	UnitVehTime	sec	blinker off
EngineRPM	UnitEngineRPM	rad/sec	engine table
EngineWOTPower	UnitEnginePower	in-lb/sec	@ each RPM
EngineClosedThrotPower	UnitEnginePower	in-lb/sec	@ each RPM
TransRatio	n/a	(unitless)	trans table
DiffRatio	n/a	(unitless)	diff table
WheelXYZ	UnitVehLength	in	wheel coords
InterTandemTransfer	n/a	(unitless)	longitudinal
SuspRideRate	UnitSuspLinRate	lb/in	susp prop
SuspRollRate	UnitSuspRollRate	in-lb/rad	susp prop
SuspRollCtrHeight	UnitVehLength	in	susp prop
SuspLatSpringSpace	UnitVehLength	in	susp prop
SuspDampRate	UnitSuspDamp	lb-sec/in	susp prop
SuspCoulombFrict	UnitSuspFrict	lb	susp prop
SuspHysteresis	UnitSuspHystrs	in/sec	susp prop
SuspMass	UnitVehMass	lb-sec^2/in	susp prop
SuspInertialK	UnitVehInertia	lb-sec^2-in	susp prop
SuspMaxDeflection	UnitVehLength	in	susp prop
SuspStopLinearRate	UnitSuspLinRate	lb/in	susp prop
SuspStopCubicRate	UnitSuspCubRate	lb/in^3	susp prop
SuspStopEnergyRatio	n/a	(unitless)	susp prop
WheelCaster	UnitSuspAngle	rad	susp prop
WheelKingPinIncline	UnitSuspAngle	rad	susp prop
WheelOffset	UnitSuspAngle	in	susp prop
SuspDeflection	UnitVehLength	in	susp prop
WheelCamberCurve	UnitSuspAngle	rad	susp prop
WheelHalfTrackChange	UnitVehLength	in	susp prop
WheelCamber	UnitSuspAngle	rad	susp prop
SuspAntiPitch	UnitAntiPitch	lb/in-lb	susp prop
SuspRollSteerConst	UnitSuspAngle	rad	susp prop
SuspRollSteerLinear	n/a	rad/in	susp prop
SuspRollSteerQuad	n/a	rad/in^2	susp prop
SuspRollSteerCubic	n/a	rad/in^3	susp prop
SuspRollSteerCoef	UnitSuspRolStrCf	rad/rad	susp prop
TireFrictionLoad	UnitVehForce	lb	tire prop
TireFrictionSpeed	UnitVehSpeed	in/sec	tire prop
TireFriction	n/a	(unitless)	tire prop
TirePercentSlip	UnitPercent	(unitless)	tire prop
TireLongStiffness	UnitLongStiff	lb/Unit Slip	tire prop
TireFrictionInUseFactor	UnitPercent	(unitless)	tire prop
TireUnloadedRad	UnitVehLength	in	tire prop
TireInitDeflectRate	UnitTireLinearRate	lb/in	tire prop
Tire2ndaryDeflectRate	UnitTireLinearRate	lb/in	tire prop
Tire2ndaryDeflect	UnitVehLength	in	tire prop
TireMaxDeflect	UnitVehLength	in	tire prop
TirePneumaticTrail	UnitVehLength	in	tire prop
TirePolarInertia	UnitTireInertia	lb-sec^2-in	tire prop
TireWeight	UnitVehForce	lb	tire prop
TireCalfaLoad	UnitVehForce	lb	tire prop
TireCalfaSpeed	UnitVehSpeed	in/sec	tire prop
TireCalfa	UnitCalfa	lb/rad	tire prop
TireCalfaInUseFactor	UnitPercent	(unitless)	tire prop

Table 2 (cont). The Vehicle Model Data Stream Information.

Variable Name	Unit Name	Pgm Units	Comments	Variable Name (cont)	Unit Name	Pgm Units	Comments
TireCgammaLoad	UnitVehForce	lb	tire prop	BrakePushoutPress	UnitBrakePress	lb/in^2	brake prop
TireCgammaSpeed	UnitVehSpeed	in/sec	tire prop	BrakeTorquePress	UnitBrakePress	$in\text{-}lb/lb/in^2$	brake prop
TireCgamma	UnitCgamma	lb/rad	tire prop	BrakeProportionPress	UnitBrakePress	lb/in^2	brake prop
TireCgammaInUseFactor	UnitPercent	(unitless)	tire prop	BrakeProportionRatio	n/a	(unitless)	brake prop
TireRolloffLoad	UnitVehForce	lb	tire prop	BrakeAntilockEffect	n/a	(unitless)	brake prop
TireRolloffSpeed	UnitVehSpeed	in/sec	tire prop	BrakePedalRatio	UnitBrakePedRat	$lb/in^2/lb$	brake system
TireRolloff	n/a	(unitless)	tire prop	SteeringGearRatio	n/a	(unitless)	steer system
TireCgammaInUseFactor	UnitPercent	(unitless)	tire prop	SteeringColumnStiff	UnitSteeringStiff	in-lb/rad	steer system
BrakeTimeLag	UnitBrakeTime	sec	brake prop	SteeringLinkageStiff	UnitSteeringStiff	in-lb/rad	steer system
BrakeTimeRise	UnitBrakeTime	sec	brake prop				

Appendix C - Environment Model

Table 3 (cont). The Environment Model Data Stream Information. These are the physical data which describe the environment.

Variable Name	Unit Name	Pgm Units	Comments	Variable Name (cont)	Unit Name	Pgm Units	Comments
EnvironmentXAngle	UnitEarthAngle	rad	rel. to North	EnvironmentGravity	UnitEarthGravity	in/sec^2	calculations
EnvironmentWindSpeed	UnitEarthVelocity	in/sec	aero	EnvironmentLatitude	UnitEarthAngle	rad	sun position
EnvironmentWindDir	UnitEarthAngle	rad	rel. to North	EnvironmentLongitude	UnitEarthAngle	rad	sun position
EnvironmentPress	UnitEarthPress	lb/in^2	aero, airbag	EarthFriction	n/a	(unitless)	environ mult
EnvironmentTemp	UnitEarthTemp	Fahrenheit	aero, airbag	EarthSurfaceXYZ	UnitEarthLength	in	surface coords
EnvironmentOvercast	UnitPercent	(unitless)	rendering	EarthSurfaceIJK	n/a	(unitless)	surface normal
EnvironmentVisibility	UnitEarthLength	in	rendering	EarthFrictionXYZ'	n/a	(unitless)	friction @ XYZ

Appendix D - In-Use Factors

Table 4. The Event-related Data Stream. These data are assigned on an as-required basis for each human or vehicle object involved in the event.

Variable Name	Unit Name	Pgm Units	Comments	Variable Name (cont)	Unit Name	Pgm Units	Comments
SetLinearPosition	UnitEarthLength	in	X,Y,Z coord	SetVehicleBrkPedalForce	UnitVehForce	lb	@ each time
SetAngularPosition	UnitEarthAngle	rad	Φ,Θ,Ψ angle	SetVehicleBrkFrictTime	UnitTime	sec	brakes table
SetLinearVelocity	UnitEarthVelocity	in/sec	u,v,w vel	SetVehicleBrkFriction	UnitPercent	(unitless)	@ each time
SetAngularVelocitye	UnitEarthAngleVel	rad/sec	p,q,r vel	SetVehicleTransGearTime	UnitTime	sec	trans table
SetVehiclePdof	UnitVehAngle	rad	PDOF	SetVehicleTransGear	n/a	(unitless)	@ each time
SetVehicleEbst	UnitVehVelocity	in/sec	EBS	SetVehicleDiffGearTime	UnitTime	sec	diff table
SetVehicleDamageWidth	UnitVehLength	in	profile	SetVehicleDiffGearner	n/a	(unitless)	@ each time
SetVehicleDamageOffset	UnitVehLength	in	profile	SetVehicleStrWheelTime	UnitTime	sec	steer table
SetVehicleDamageDepth	UnitVehLength	in	up to 10	SetVehicleStrWheelAngle	UnitVehAngle	rad	@ each time
SetVehicleImpulseCtrXY	UnitVehLength	in	x,y coord	SetVehicleStrTireTime	UnitTime	sec	steer table
SetVehicleZoneAstf	UnitVehAStiff	lb/in	up to 9	SetVehicleStrTireAngle	UnitVehAngle	rad	@ each time
SetVehicleZoneBstf	UnitVehBStiff	lb/in^2	up to 9	SetVehicleDragFactor	UnitPercent	(unitless)	pre-impact
SetVehiclePayloadXYZt	UnitVehLength	in	x,y,z coords	SetVehicleWheelLockup	UnitPercent	(unitless)	@ each wheel
SetVehiclePayloadMass	UnitVehMass	$lb\text{-}sec^2/in$	payload prop	SetVehicleWheelTireAngle	UnitVehAngle	rad	@ each wheel
SetVehiclePayloadInertia	UnitVehInertia	$lb\text{-}sec^2\text{-}in$	roll,pitch,yaw	SetVehicleCollPulseTime	UnitTime	sec	pulse table
SetVehicleLightOn	n/a	(unitless)	on or off	SetVehicleCollLinPulse	UnitVehAccel	in/sec^2	@ each time
SetVehicleThrotWOTTime	UnitTime	sec	throttle table	SetVehicleCollAngPulse	UnitVehAngAccel	rad/sec^2	@ each time
SetVehicleThrotWOTn	UnitPercent	(unitless)	@ each time	SetVehicleCollPulseFactor	UnitPercent	(unitless)	pulse table
SetVehicleThrotFricTime	UnitTime	sec	throttle table	SetVehicleBeltTorsoXYZ	UnitHumLength	in	attach coord
SetVehicleThrotFriction	UnitPercent	(unitless)	@ each time	SetVehicleBeltSlackLR	UnitVehLength	in	slack
SetVehicleBrkWFTimen	UnitTime	sec	brakes table	SetVehicleBagTo	UnitTime	sec	begin fill
SetVehicleBrkWheelForce	UnitVehForce	lb	@ each time	SetVehicleBagDt	UnitTime	sec	fill duration
SetVehicleBrkPFTime	UnitTime	sec	brakes table				

Appendix E - Calculation Methods

Table 5. Calculation Methods currently implemented in HVE [9,10]

Method Name	Description
General Analysis	
Kinematics Table	A table of results created from user-entered positions and velocities. The General Analysis method interpolates between user-entered values by assuming constant acceleration to calculate and display position, velocity and acceleration as a function of time . Applicable only for single-mass vehicles. Output can be animated. Very useful for credibility testing of suspisious animations by calculating intermediate accelerations.
Momentum	A basic momentum analysis produced from user-entered impact and separation positions which includes both linear and angular momentum. Output can be displayed as numeric results or Momentum Diagram.
Energy	A basic kinetic energy analysis produced from user-entered impact and separation positions. Output is numeric.
EDCRASH	2-D reconstruction of single and two-car collisions. Uses conservation of linear momentum for oblique collisions and damage-based analysis for collinear collisions. Output is numeric (messages, Accident History, Program Data, Vehicle Data) and graphic (Trajectory Simulation*, Site Drawing, Damage Profiles, Momentum Diagram).
EDSMAC	2-D simulation of two-car collisions. Output is numeric (messages, Accident History, Program Data, Vehicle Data, Damage Data, Variable Output) and graphic (Trajectory Simulation, Damage Profiles, Data Graphing).
EDHIS	3-D simulation of occupants and pedestrians. Output is numeric (messages, Accident History, Program Data, Human Data, Vehicle Data, Injury Data, Variable Output) and graphic (Trajectory Simulation, Data Graphing).
EDSVS	2-D simulation of single vehicle loss-of-control. Output is numeric (messages, Accident History, Program Data, Vehicle Data, Variable Output) and graphic (Trajectory Simulation, Data Graphing).
EDVTS	2-D simulation of vehicle-trailer loss-of-control. Output is numeric (messages, Accident History, Program Data, Vehicle Data, Variable Output) and graphic (Trajectory Simulation, Data Graphing).
EDVDS	3-D simulation of loss-of-control for single vehicles and vehicle-trailers (up to 3 trailers). Output is numeric (messages, Accident History, Program Data, Vehicle Data, Variable Output) and graphic (Trajectory Simulation, Data Graphing).
EDVSM	3-D simulation of single vehicle loss-of-control. Output is numeric (messages, Accident History, Program Data, Vehicle Data, Variable Output) and graphic (Trajectory Simulation, Data Graphing).

Appendix F - Output Tracks

Table 6. The Output Track Data Stream Header. These data are created by the calculation method and available for numerical output. They are placed at the start of each output track.

Variable Name	Unit Name	Pgm Units	Comments
VxInit	UnitVehOutVel	in/sec	x initial linear velocity
VyInit	UnitVehOutVel	in/sec	y initial linear velocity
VzInit	UnitVehOutVel	in/sec	z initial linear velocity
VpInit	UnitVehOutAngVel	rad/sec	p initial angular velocity
VqInit	UnitVehOutAngVel	rad/sec	q initial angular velocity
VrInit	UnitVehOutAngVel	rad/sec	r initial angular velocity
VxBrkg	UnitVehOutVel	in/sec	x pre-braking linear velocity
VyBrkg	UnitVehOutVel	in/sec	y pre-braking linear velocity
VzBrkg	UnitVehOutVel	in/sec	z pre-braking linear velocity
VpBrkg	UnitVehOutAngVel	rad/sec	p pre-braking angular velocity
VqBrkg	UnitVehOutAngVel	rad/sec	q pre-braking angular velocity
VrBrkg	UnitVehOutAngVel	rad/sec	r pre-braking angular velocity
VxImpDamage	UnitVehOutVel	in/sec	dam-based x impact lin velocity
VyImpDamage	UnitVehOutVel	in/sec	dam-based y impact lin velocity
VxImpDamage	UnitVehOutVel	in/sec	dam-based z impact lin velocity
VpImpDamage	UnitVehOutAngVel	rad/sec	dam-based p impact ang velocity
VqImpDamage	UnitVehOutAngVel	rad/sec	dam-based q impact ang velocity
VrImpDamage	UnitVehOutAngVel	rad/sec	dam-based r impact ang velocity
VxImpLMomntm	UnitVehOutVel	in/sec	lin mom-based x impact lin velocity
VyImpLMomntm	UnitVehOutVel	in/sec	lin mom-based y impact lin velocity
VxImpLMomntm	UnitVehOutVel	in/sec	lin mom-based z impact lin velocity
VpImpLMomntm	UnitVehOutAngVel	rad/sec	lin mom-based p impact ang velocity
VqImpLMomntm	UnitVehOutAngVel	rad/sec	lin mom-based q impact ang velocity
VrImpLMomntm	UnitVehOutAngVel	rad/sec	lin mom-based r impact ang velocity
VxImpAMomntm	UnitVehOutVel	in/sec	ang mom-based x impact lin velocity
VyImpAMomntm	UnitVehOutVel	in/sec	ang mom-based y impact lin velocity
VzImpAMomntm	UnitVehOutVel	in/sec	ang mom-based z impact lin velocity
VpImpAMomntm	UnitVehOutAngVel	rad/sec	ang mom-based p impact ang velocity
VqImpAMomntm	UnitVehOutAngVel	rad/sec	ang mom-based q impact ang velocity
VrImpAMomntm	UnitVehOutAngVel	rad/sec	ang mom-based r impact ang velocity
DVxImpDamage	UnitVehOutVel	in/sec	dam-based x impact lin delta-V
DVyImpDamage	UnitVehOutVel	in/sec	dam-based y impact lin delta-V
DVxImpDamage	UnitVehOutVel	in/sec	dam-based z impact lin delta-V
DVpImpDamage	UnitVehOutAngVel	rad/sec	dam-based p impact ang delta-V
DVqImpDamage	UnitVehOutAngVel	rad/sec	dam-based q impact ang delta-V
DVrImpDamage	UnitVehOutAngVel	rad/sec	dam-based r impact ang delta-V
DVxImpLMomntm	UnitVehOutVel	in/sec	lin mom-based x impact lin delta-V
DVyImpLMomntm	UnitVehOutVel	in/sec	lin mom-based y impact lin delta-V
DVxImpLMomntm	UnitVehOutVel	in/sec	lin mom-based z impact lin delta-V
DVpImpLMomntm	UnitVehOutAngVel	rad/sec	lin mom-based p impact ang delta-V
DVqImpLMomntm	UnitVehOutAngVel	rad/sec	lin mom-based q impact ang delta-V
DVrImpLMomntm	UnitVehOutAngVel	rad/sec	lin mom-based r impact ang delta-V
DVxImpAMomntm	UnitVehOutVel	in/sec	ang mom-based x impact lin delta-V
DVyImpAMomntm	UnitVehOutVel	in/sec	ang mom-based y impact lin delta-V
DVxImpAMomntm	UnitVehOutVel	in/sec	ang mom-based z impact lin delta-V
DVpImpAMomntm	UnitVehOutAngVel	rad/sec	ang mom-based p impact ang delta-V
DVqImpAMomntm	UnitVehOutAngVel	rad/sec	ang mom-based q impact ang delta-V
DVrImpAMomntm	UnitVehOutAngVel	rad/sec	ang mom-based r impact ang delta-V
VxSep	UnitVehOutVel	in/sec	x separation linear velocity
VySep	UnitVehOutVel	in/sec	y separation linear velocity
VzSep	UnitVehOutVel	in/sec	z separation linear velocity

Variable Name	Unit Name	Pgm Units	Comments
VpSep	UnitVehOutAngVel	rad/sec	p separation angular velocity
VqSep	UnitVehOutAngVel	rad/sec	q separation angular velocity
VrSep	UnitVehOutAngVel	rad/sec	r separation angular velocity
VxPOC	UnitVehOutVel	in/sec	x point-on-curve linear velocity
VyPOC	UnitVehOutVel	in/sec	y point-on-curve linear velocity
VzPOC	UnitVehOutVel	in/sec	z point-on-curve linear velocity
VpPOC	UnitVehOutAngVel	rad/sec	p point-on-curve angular velocity
VqPOC	UnitVehOutAngVel	rad/sec	q point-on-curve angular velocity
VrPOC	UnitVehOutAngVel	rad/sec	r point-on-curve angular velocity
VxEOR	UnitVehOutVel	in/sec	x end-of-rotation linear velocity
VyEOR	UnitVehOutVel	in/sec	y end-of-rotation linear velocity
VzEOR	UnitVehOutVel	in/sec	z end-of-rotation linear velocity
VpEOR	UnitVehOutAngVel	rad/sec	p end-of-rotation angular velocity
VqEOR	UnitVehOutAngVel	rad/sec	q end-of-rotation angular velocity
VrEOR	UnitVehOutAngVel	rad/sec	r end-of-rotation angular velocity
VxEnd	UnitVehOutVel	in/sec	x final/rest linear velocity
VyEnd	UnitVehOutVel	in/sec	y final/rest linear velocity
VzEnd	UnitVehOutVel	in/sec	z final/rest linear velocity
VpEnd	UnitVehOutAngVel	rad/sec	p final/rest angular velocity
VqEnd	UnitVehOutAngVel	rad/sec	q final/rest angular velocity
VrEnd	UnitVehOutAngVel	rad/sec	r final/rest angular velocity
PdofDamage	UnitVehAngle	rad	damage-based PDOF (user-entered)
PdofLMomntm	UnitVehAngle	rad	linear momentum-based PDOF
PdofAMomntm	UnitVehAngle	rad	angular momentum-based PDOF
RstnDamage	n/a	(unitless)	dam-based coefficient of restitution
RstnLMomntm	n/a	(unitless)	lin mom-based coefficient of restitution
RstnAMomntm	n/a	(unitless)	ang mom-based coefficient of restitution
MomntmXImpD	UnitImpulse	lb-sec	dam-based impact x lin mom
MomntmYImpD	UnitImpulse	lb-sec	dam-based impact y lin mom
MomntmZImpD	UnitImpulse	lb-sec	dam-based impact z lin mom
MomntmpImpD	UnitAngImpulse	in-lb-sec	dam-based impact p ang mom
MomntmqImpD	UnitAngImpulse	in-lb-sec	dam-based impact q ang mom
MomntmrImpD	UnitAngImpulse	in-lb-sec	dam-based impact r ang mom
MomntmXImpL	UnitAngImpulse	lb-sec	lin mom-based impact X lin mom
MomntmYImpL	UnitAngImpulse	lb-sec	lin mom-based impact Y lin mom
MomntmZImpL	UnitAngImpulse	lb-sec	lin mom-based impact Z lin mom
MomntmXImpA	UnitAngImpulse	lb-sec	ang mom-based impact X lin mom
MomntmYImpA	UnitAngImpulse	lb-sec	ang mom-based impact Y lin mom
MomntmZImpA	UnitAngImpulse	lb-sec	ang mom-based impact Z lin mom
MomntmpImpA	UnitAngImpulse	in-lb-sec	ang mom-based impact p ang mom
MomntmqImpA	UnitAngImpulse	in-lb-sec	ang mom-based impact q ang mom
MomntmrImpA	UnitAngImpulse	in-lb-sec	ang mom-based impact r ang mom
MomntmXSep	UnitImpulse	lb-sec	separation linear X momentum
MomntmYSep	UnitImpulse	lb-sec	separation linear Y momentum
MomntmZSep	UnitImpulse	lb-sec	separation linear Z momentum
MomntmpSep	UnitAngImpulse	in-lb-sec	separation p angular momentum
MomntmqSep	UnitAngImpulse	in-lb-sec	separation q angular momentum
MomntmrSep	UnitAngImpulse	in-lb-sec	separation r angular momentum
EnergyImpD	UnitEnergy	in-lb	dam-based impact kinetic energy
EnergyImpL	UnitEnergy	in-lb	lin mom-based impact kinetic energy
EnergyImpA	UnitEnergy	in-lb	ang mom-based impact kinetic energy
EnergySep	UnitEnergy	in-lb	separation kinetic energy

Table 7. The Output Track Data Stream for Vehicle Group. This and the remaining data groups are produced at each user-specified output time interval.

Variable Name	Unit Name	Pgm Units	Comments
X	UnitEarthLength	in	earth coord of vehicle CG
Y	UnitEarthLength	in	earth coord of vehicle CG
Z	UnitEarthLength	in	earth coord of vehicle CG
Phi	UnitEarthAngle	rad	angle of rotn about vehicle x axis
Theta	UnitEarthAngle	rad	angle of rotn about vehicle y axis
Psi	UnitEarthAngle	rad	angle of rotn about vehicle z axis
Radius	UnitEarthLength	in	path radius projected on X-Y plane
u	UnitVehOutVel	in/sec	x vehicle velocity component
v	UnitVehOutVel	in/sec	y vehicle velocity component
w	UnitVehOutVel	in/sec	z vehicle velocity compoent
vtotal	UnitVehOutVel	in/sec	total vehicle velocity
beta	UnitVehAngle	rad	projection of total velocity on X-Y plane

Variable Name	Unit Name	Pgm Units	Comments
p	UnitVehOutAngVel	rad/sec	vehicle angular velocity about x axis
q	UnitVehOutAngVel	rad/sec	vehicle angular velocity about y axis
r	UnitVehOutAngVel	rad/sec	vehicle angular velocity about z axis
udot	UnitVehOutAcc	in/sec^2	x vehicle acceleration component
vdot	UnitVehOutAcc	in/sec^2	y vehicle acceleration component
wdot	UnitVehOutAcc	in/sec^2	z vehicle acceleration component
along	UnitVehOutAcc	in/sec^2	longitudinal vehicle acceleration
alat	UnitVehOutAcc	in/sec^2	lateral vehicle acceleration
avert	UnitVehOutAcc	in/sec^2	vertical vehicle acceleration
atotal	UnitVehOutAcc	in/sec^2	total vehicle acceleration
pdot	UnitVehOutAngAcc	rad/sec^2	vehicle angular accel about x axis
qdot	UnitVehOutAngAcc	rad/sec^2	vehicle angular accel about y axis
rdot	UnitVehOutAngAcc	rad/sec^2	vehicle angular accel about z axis

Table 8. The Output Track Data Stream for Wheel Group (one group per wheel).

Variable Name	Unit Name	Pgm Units	Comments
wheelx	UnitVehLength	in	vehicle-fixed x coord of wheel
wheely	UnitVehLength	in	vehicle-fixed y coord of wheel
wheelz	UnitVehLength	in	vehicle-fixed z coord of wheel
wheelR	UnitVehLength	in	wheel radius
alfatire	UnitVehAngle	rad	tire slip angle
gammatire	UnitVehAngle	rad	tire inclination angle
delta	UnitVehAngle	rad	steer angle
fxtire	UnitVehForce	lb	tire force in tire's x direction
fytire	UnitVehForce	lb	tire force in tire's y direction
fztire	UnitVehForce	lb	tire force in tire's z direction
mxtire	UnitVehMoment	in-lb	tire moment about tire's x axis
mytire	UnitVehMoment	in-lb	tire moment about tire's y axis
mztire	UnitVehMoment	in-lb	tire moment about tire's z axis
calfatire	UnitTireStiffness	lb/rad	tire cornering stiffness
cgammatire	UnitTireStiffness	lb/rad	tire camber stiffness
calfafactor	n/a	(unitless)	tire cornering stiffness table multiplier
cgammafactor	n/a	(unitless)	tire camber stiffness table multiplier

Table 10. The Output Track Data Stream for Human Segments Group (one group per human segment).

Variable Name	Unit Name	Pgm Units	Comments
x	UnitHumOutPosn	in	X coord of segment cg
y	UnitHumOutPosn	in	Y coord of segment CG
z	UnitHumOutPosn	in	Z coord of segment CG
roll	UnitHumOutAng	rad	angle of seg. rotn. about seg. x axis
pitch	UnitHumOutAng	rad	angle of seg. rotn. about seg. y axis
yaw	UnitHumOutAng	rad	angle of seg. rotn. about seg. z axis
xdot	UnitHumOutVel	in/sec	segment x velocity component
ydot	UnitHumOutVel	in/sec	segment y velocity component
zdot	UnitHumOutVel	in/sec	segment z velocity compoent
Vtotal	UnitHumOutVel	in/sec	total segment velocity
rollvel	UnitHumOutAngVel	rad/sec	segment angular velocity about x axis
pitchvel	UnitHumOutAngVel	rad/sec	segment angular velocity about y axis
yawvel	UnitHumOutAngVel	rad/sec	segment angular velocity about z axis
xddot	UnitHumOutAcc	in/sec^2	segment x acceleration component
yddot	UnitHumOutAcc	in/sec^2	segment y acceleration component
zddot	UnitHumOutAcc	in/sec^2	segment z acceleration component
along	UnitHumOutAcc	in/sec^2	longitudinal segment accel
alat	UnitHumOutAcc	in/sec^2	lateral segment accel
avert	UnitHumOutAcc	in/sec^2	vertical segment accel
atotal	UnitHumOutAcc	in/sec^2	total segment accel
rollddot	UnitHumOutAngAcc	rad/sec^2	segment angular accel about x axis
pitchddot	UnitHumOutAngAcc	rad/sec^2	segment angular accel about y axis
yawddot	UnitHumOutAngAcc	rad/sec^2	segment angular accel about z axis
ketrans	UnitHumOutEnrg	in-lb	segment translational kinetic energy
kerot	UnitHumOutEnrg	in-lb	segment rotational kinetic energy
ketotal	UnitHumOutEnrg	in-lb	segment total kinetic energy

Table 12. The Output Track Data Stream for Belt Restraints Group (one group per belt segment).

Variable Name	Unit Name	Pgm Units	Comments
fxBelt	UnitHumForce	lb	belt force in x direction
fyBelt	UnitHumForce	lb	belt force in y direction
fzBelt	UnitHumForce	lb	belt force in z direction
totalBelt	UnitHumForce	lb	total belt force
angibelt	UnitHumAngle	rad	angle of belt segment about i vector
angjbelt	UnitHumAngle	rad	angle of belt segment about j vector
angkbelt	UnitHumAngle	rad	angle of belt segment about k vector

NOTE: The interface variables found in the appendices are provided for informational purposes. Detailed specifications for interface variables are available as part of the HVE Developer's Toolkit. See reference 11.

Table 9. The Output Track Data Stream for Inter-vehicle Connections Group (one group per connection).

Variable Name	Unit Name	Pgm Units	Comments
xconn	UnitVehLength	in	vehicle-fixed x-coord of connection
yconn	UnitVehLength	in	vehicle-fixed y-coord of connection
zconn	UnitVehLength	in	vehicle-fixed z-coord of connection
fxconn	UnitVehForce	lb	vehicle-fixed force in x direction
fyconn	UnitVehForce	lb	vehicle-fixed force in y direction
fzconn	UnitVehForce	lb	vehicle-fixed force in z direction
mxconn	UnitVehMoment	in-lb	vehicle-fixed moment about x axis
myconn	UnitVehMoment	in-lb	vehicle-fixed moment about y axis
mzconn	UnitVehMoment	in-lb	vehicle-fixed moment about z axis

Table 11. The Output Track Data Stream for Human Joints Group (one group per joint).

Variable Name	Unit Name	Pgm Units	Comments
iJoint	UnitHumLength	in	segment-fixed i-coord of joint
jJoint	UnitHumLength	in	segment-fixed j-coord of joint
kJoint	UnitHumLength	in	segment-fixed k-coord of joint
rollJoint	UnitHumAngle	rad	joint roll angle between segments
pitchJoint	UnitHumAngle	rad	joint pitch angle between segments
yawJoint	UnitHumAngle	rad	joint yaw angle between segments
fiJoint	UnitHumForce	lb	joint force in i direction
fjJoint	UnitHumForce	lb	joint force in j direction
fkJoint	UnitHumForce	lb	joint force in k direction
miJointElast	UnitHumMoment	in-lb	joint elastic moment about i axis
mjJointElast	UnitHumMoment	in-lb	joint elastic moment about j axis
mkJointElast	UnitHumMoment	in-lb	joint elastic moment about k axis
miJointStop	UnitHumMoment	in-lb	joint stop moment about i axis
mjJointStop	UnitHumMoment	in-lb	joint stop moment about j axis
mkJointStop	UnitHumMoment	in-lb	joint stop moment about k axis

Table 13. The Output Track Data Stream for Human Contacts Group (one group per contact).

Variable Name	Unit Name	Pgm Units	Comments
NameContactSurf	n/a	(char string)	name of contact surface
NameEllipsoid	n/a	(char string)	name of ellipse
fxContact	UnitHumForce	lb	contact force in x direction
fyContact	UnitHumForce	lb	contact force in y direction
fyContact	UnitHumForce	lb	contact force in z direction
fTotalContact	UnitHumForce	lb	total contact force
iContact	UnitHumLengh	in	contact i coordinate on ellipsoid
jContact	UnitHumLengh	in	contact j coordinate on ellipsoid
kContact	UnitHumLengh	in	contact k coordinate on ellipsoid
deflContact	UnitHumLengh	in	contact deflection
rateContact	UnitHumOutVel	in/sec	contact deflection rate

Table 14. The Output Track Data Stream for Airbag Group (one group per airbag).

Variable Name	Unit Name	Pgm Units	Comments
PressAirbag	UnitBagPress	lb/in^2	airbag pressure
RadiusAirbag	UnitVehLength	in	airbag radius
fxAirbag	UnitHumForce	lb	airbag force on body segment in x dir
fyAirbag	UnitHumForce	lb	airbag force on body segment in y dir
fzAirbag	UnitHumForce	lb	airbag force on body segment in z dir
fTotalAirbag	UnitHumForce	lb	total airbag force on body segment