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# Validation of the EDVSM 3-Dimensional Vehicle Simulator

**Terry D. Day**
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## ABSTRACT

EDVSM is a 3-dimensional vehicle simulator developed for the HVE simulation environment. The EDVSM vehicle model was based on the original HVOSM model, developed at Calspan for the Federal Highway Administration. This paper describes the vehicle and tire models used by EDVSM. The basic model is unchanged from the original HVOSM model, however, tire-road modeling has been substantially improved by the model's integration into the HVE environment. This paper provides the details of the integration procedure. The paper also includes a validation study, comparing results between EDVSM, HVOSM and real-world handling studies. Comparison reveals the results are substantially similar. Finally, applications and limitations of the model are addressed.

THE HVOSM COMPUTER PROGRAM was developed during the late sixties and early seventies as a means to help vehicle safety researchers study the effect of vehicle and highway design on occupant safety [1,2,3][*].

Several versions of the HVOSM model evolved, including HVOSM-SMI1 (Sprung Mass Impact), HVOSM-RD1 (Roadside Design) and HVOSM-VD1 (Vehicle Dynamics) versions. Eventually, the different features of each were combined into two versions: HVOSM-RD2 (Roadside Design) and HVOSM-VD2 (Vehicle Dynamics). The RD2 version included the ability of the vehicle exterior to interact with roadside objects, such as median barriers, while using simplified tire and braking models. The VD2 version did not include vehicle exterior interaction, but included more robust tire and braking models, as well as a drivetrain model. Both models have been experimentally validated [3]. The literature has numerous references documenting its successful use in highway safety research. HVOSM was often used for conducting research into 3-dimensional problems. For example, Sharp and Segel [4] used HVOSM to study vehicle design parameters contributing to rollover propensity. DeLays [5] used HVOSM to study rollover potential related to embankments. Day [6] simulated vehicle rollover during a driver correction maneuver on a highway median.

1995 FARS data [7] show that vehicle rollover was the first harmful event in 3294 fatal crashes (8.8 percent of all fatal crashes), and a subsequent event in an additional 6578 fatal crashes (17.7 percent). These numbers do not include the large number of people who were injured during rollover crashes. Thus, a validated 3-dimensional handling model is an essential tool for highway safety research. In addition, detailed handling studies require consideration of suspension effects. For these reasons, the availability of a sophisticated 3-D tool is important.

Although HVOSM is a very powerful analysis tool, its use has been limited by several factors. Most of these factors fall into one of two categories: First, owing to its complexity, program execution requires substantial time and effort to develop a valid input data set representing the subject vehicle parameters and driver inputs. Second, the program was designed (in the late sixties) for use in batch mode, and had no user interface. The numeric output from HVOSM was voluminous and, thus, difficult and time-consuming to interpret. The potential for user error was high because there was no inherent means available for visualizing the results.

## PURPOSE

This paper describes a new, HVE-compatible version of the HVOSM program, called EDVSM (Engineering Dynamics Vehicle Simulation Model [8]). The purpose of this paper is to describe EDVSM and to compare it to the program

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

upon which it is based. In addition, this paper provides a validation of EDVSM by comparing its results with those obtained using HVOSM, as well as by direct comparison with field measurements. Vehicle dynamics researchers familiar with other models, including HVOSM, may use this information to compare those models with EDVSM. Others may use this as an introduction into the capabilities of 3-dimensional vehicle simulation.

## PROGRAM OVERVIEW

The EDVSM program is an HVE-compatible [9-12], 3-dimensional simulation analysis of a single vehicle. The vehicle model (see Figure 1) includes front and rear suspensions; both solid axle and independent suspension systems are supported. The model includes 14 degrees of freedom: six degrees for the sprung mass (body X,Y,Z, roll, pitch, yaw) and two degrees for each unsprung mass (wheel spin and jounce/rebound). The suspension model accommodates ride and damping rates, anti-sway bars, jounce and rebound stops, camber change, half-track change, anti-pitch and roll steer at each wheel.

Closed-loop driver control parameters include steering, braking, throttle and gear selection. Various user options are available for entering the driver control tables (*At Driver, At Wheel, Percent Available Friction,* and so forth). The terrain is modeled automatically by the HVE environment model; during execution, the current terrain conditions beneath each tire are obtained using the `GetSurfaceInfo()` function in the HVE developer's library. Complex road surface geometry, such as bumps, curbs, ditches or virtually any other surface, is thus handled efficiently and transparently to the user.

Executing the EDVSM model in the HVE user environment involves the following steps:

- The HVE Vehicle Editor is used to select and possibly edit one or more vehicles.
- The HVE Environment Editor is used to create the road surface. A graphical, 3-D editor is available for this purpose. Alternatively, the road surface geometry may be imported from a 3-D survey of a highway and adjacent environment. In either case, the resulting 3-D geometry becomes a drivable surface with any number of polygons. Each polygon has elevation, slope and friction attributes.
- The HVE Event Editor is used to set up the event, assign initial position and velocity, and driver controls. After the event is set up, it is executed. The results are displayed numerically, using Key Results windows, and visually in a 3-D viewer with a user-selectable perspective (see Figure 2). For accident reconstruction, execution of the simulation is normally an iterative process, involving adjustments of the initial conditions and driver control tables, until a satisfactory match is achieved between the

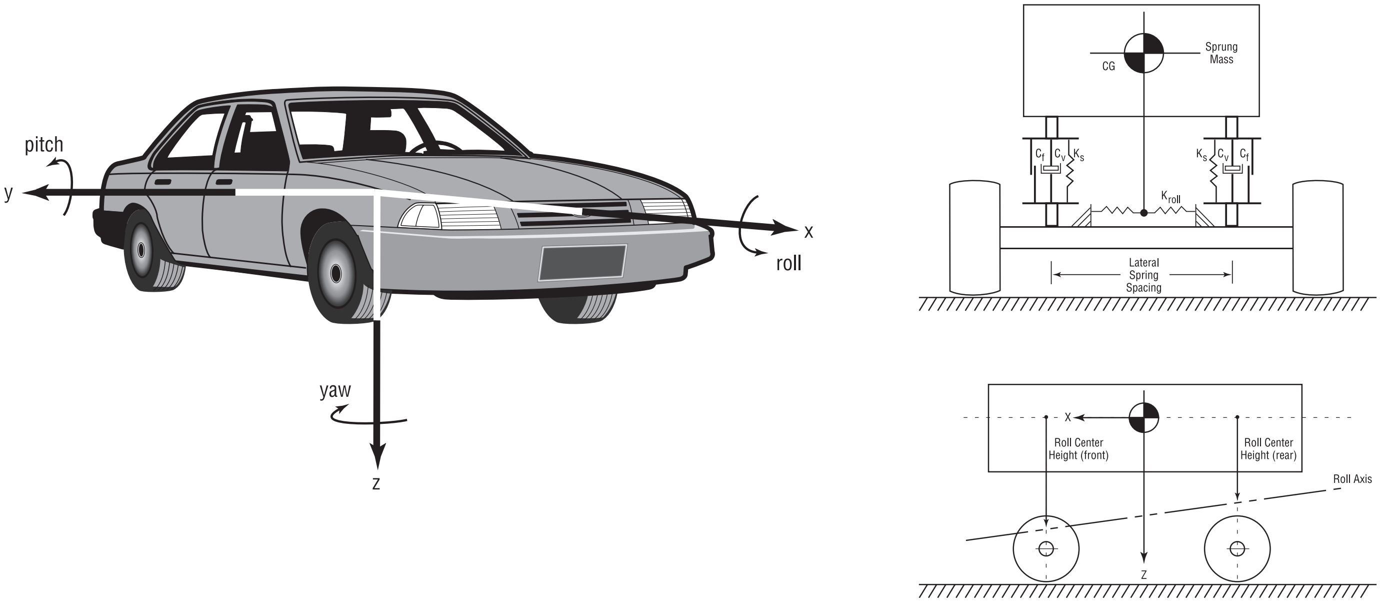

*Figure 1 - EDVSM Vehicle Model. The sprung mass includes six degrees of freedom (body X,Y,Z, roll, pitch, yaw). The unsprung mass includes two degrees of freedom per wheel (solid axle suspensions, right, top, have axle z and roll).*

Active Events :
EDVSM, 0.5 CPS Steer
EDVSM, Cornering Stops
EDVSM, Alternate Ramp Traversal
EDVSM, Wet Pavement Into Soil
EDVSM, Wet Pavement Into Curb

Current Event :
EDVSM, Wet Pavement Into Curb

Event Humans & Vehicles :
Ford Bronco II, Loaded, Test 4

Time (sec): 12.3019

Key Results: EDVSM, Wet Pavement Into Curb

Ford Bronco II, Loaded, Test 4 :

```
                                   Z (ft):      -3,6
                                Roll (deg):    -32,6
                               Pitch (deg):     -4,5
                                 Yaw (deg):    119,1
                               u-vel (mph):     13,9
                               v-vel (mph):     -6,1
                               w-vel (mph):    -10,1
                                Acc-tot (g):      0,7
                                Fwd Acc (g):      0,0
                                Lat Acc (g):     -0,1
                               Vert Acc (g):      0,7
   Axle 1, Right, Outer, Fz' (tire) (lb):      0,0
    Axle 1, Left, Outer, Fz' (tire) (lb):  -2066,9
   Axle 2, Right, Outer, Fz' (tire) (lb):      0,0
    Axle 2, Left, Outer, Fz' (tire) (lb):      0,0
        Axle 1, Right, z disp (whl) (in):      4,6
         Axle 1, Left, z disp (whl) (in):     -2,3
        Axle 2, Right, z disp (whl) (in):      2,6
         Axle 2, Left, z disp (whl) (in):      4,2
Axle 1, Right, Brake Tq (whl) (in-lb):   2973,4
 Axle 1, Left, Brake Tq (whl) (in-lb):      0,0
Axle 2, Right, Brake Tq (whl) (in-lb):   3638,3
 Axle 2, Left, Brake Tq (whl) (in-lb):   3638,3
      Axle 1, Right, Brake Press (psi):    107,5
       Axle 1, Left, Brake Press (psi):    107,5
```

Figure 2 - HVE Event Editor executing an EDVSM Event. The above example was taken from Validation Test No. 4 at t=12.3 seconds, just after the Bronco II struck the curb and began to roll. The Key Results window displays the current conditions.

simulation and actual event. Or, the simulated event may be part of a parametric design study, where vehicle designers wish to establish how various design changes (e.g., suspension rates, anti-sway bars, tire parameters) affect a vehicle's stability.

- The HVE Playback Editor is used to review and print output reports for each event. These reports include numeric tables, graphic displays, a variable output table containing simulation results for user-selectable, time-dependent output parameters, and trajectory simulations that allow additional visualization of the event. The event may be combined with other events into a single coherent sequence involving multiple humans and vehicles. The sequence in this *Playback Window* can also routed to video tape using HVE's built-in video interface.

## VALIDATION PROCEDURE

To provide a direct comparison of program results, the source code for HVOSM-VD2 was obtained from the US Federal Highway Administration. The source code was compiled and and executed in a DOS environment on an IBM-compatible PC. EDVSM, Version 1.0, was ported from the HVOSM-VD2 source code and rewrtten using the C language. The resulting code was compiled and linked with the HVE Developer's Library [11], and executed in the HVE simulation environment, Version 1.0 (see Figure 3). Preliminary validation consisted of running essentially duplicate data sets through each model to confirm the same results were obtained.

After the preliminary validation, a detailed validation study was performed using five well-instrumented handling experiments. EDVSM events were set up and executed for each experiment, and the results were examined and compared with the test data. Similarities and differences between the models were noted, and various program features were exercised to illustrate the EDVSM program capabilities.

The following sections explain the similarities and differences in the two models.

### Similarities

Comparison reveals EDVSM and HVOSM are similar in the following ways:

- Both models share the same basic vehicle model
- Both models require the same input and produce the same output
- Both models share the same basic calculation procedures

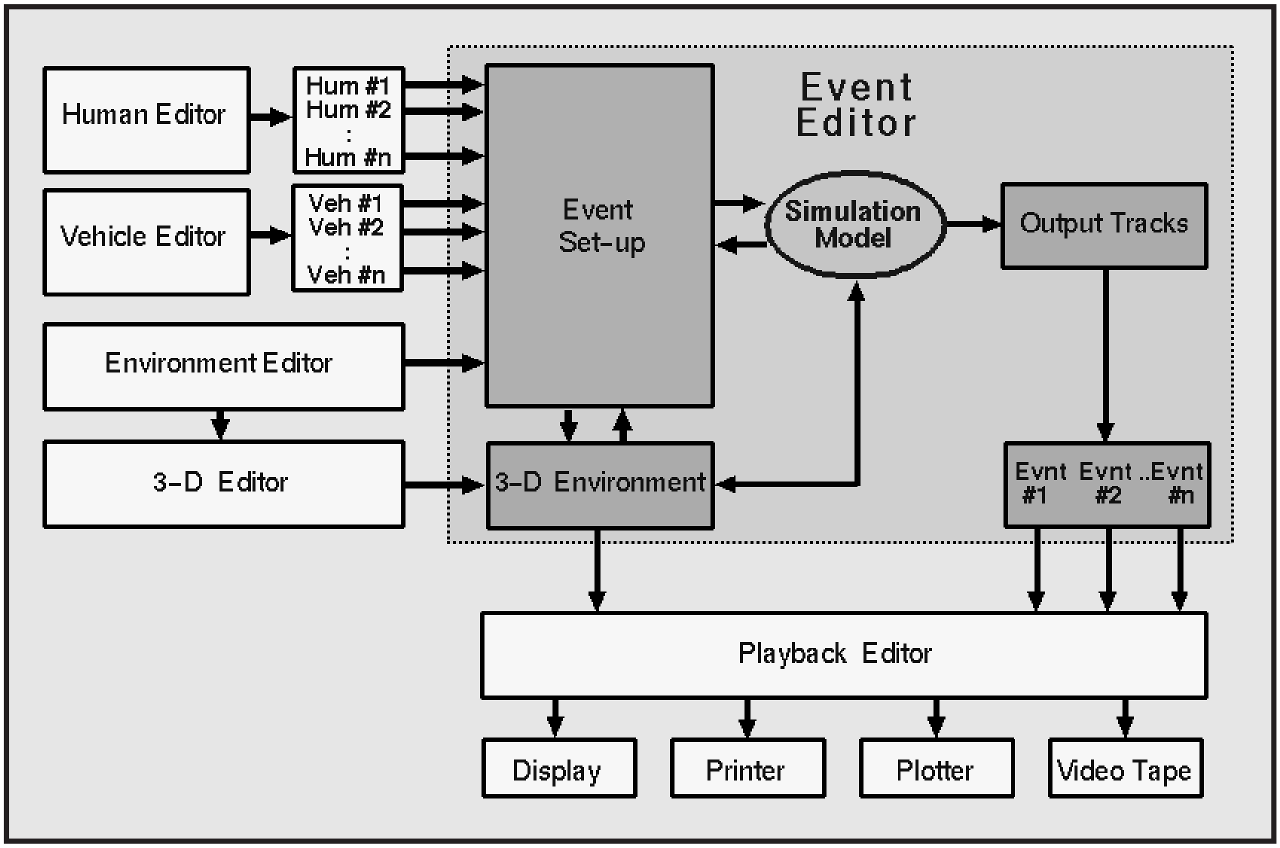

*Figure 3 - HVE Simulation Environment. EDVSM is the simulation model in the above flow chart.*

These similarities are, of course, linked: One would expect substantially similar input and output parameters if the simulations share the same vehicle model. Similar calculation procedures would also be expected, although there are some differences (see *Differences*, below).

The basic calculation procedures for EDVSM (and HVOSM) are shown in Figure 4. This figure shows the basic program design includes the following components:

- *Main Controlling Routine* - The main program logic that controls execution at each timestep
- *Numerical Integration Routine* - The logic used for calculating the velocity and position of each sprung mass at each timestep
- *Vehicle Model Free Body* - The 14 degree-of-freedom engineering analysis of the vehicle that calculates the forces and moments at the vehicle CG for the current timestep
- *Derivative Calculations* - The 14 degree-of-freedom accelerations resulting from the free body analysis

It should be noted the basic components (controlling routine, numerical integrator, force analysis and derivative calculations) are common to all simulations. It is the vehicle model free body analysis that differentiates EDVSM (and HVOSM) from other simulations. A flow chart for the EDVSM Free Body analysis is included in Figure 4 (refer to the box labeled “Vehicle Model”).

The basic calculation steps performed by the vehicle model free body analysis are as follows:

- Determine the current earth-fixed position of each mass (sprung mass and wheels/axles).
- Determine the deflection of each mass from its equilibrium position.
- Determine the current attempted wheel torques (driving and braking) from the driver input tables.
- Determine the current tire forces and moments.
- Determine the suspension forces and moments acting on the sprung mass.

After performing the above steps, a complete free-body analysis is available for the vehicle. The resulting forces and moments are finally supplied, along with an inertial matrix, to a simultaneous solutions routine that calculates the current acceleration for each degree of freedom.

## Differences

Differences between EDVSM and HVOSM were identified in the following areas:

- User Interactivity
- Programming Language
- Road Surface Definition
- Tire Parameter Definition

### User Interactivity

HVOSM is a batch-mode program. To execute an HVOSM run, a card image (80-column format) input file is first prepared according to the required syntax. The cards use a common convention, assigning to each category of data a block number (e.g., the 100 cards contain general runtime descriptors, the 200 cards describe the vehicle parameters, and so on). A typical card image input deck is shown in Appendix A. After the input file is prepared, the HVOSM program is executed from the command line by entering the program name. The program assumes the input file is named `hvosm.in.` Basic results were written to the default output file, `hvosm.out`, and time-based simulation outputs are written to files named `fort.11, fort.12, ..., fort.23`, according to the output report number. The 132-column alpha-numeric output can be viewed by printing the file on a wide-carriage line printer (or regular printer in landscape mode). A partial listing of HVOSM output is shown in Appendix B.

EDVSM is an HVE-compatible program (see Figure 3). Inputs were prepared using HVE Vehicle Editor by clicking on vehicle lists in the HVE Vehicle Database [10]. Vehicle parameters for the selected vehicle are assigned according to vehicle type (e.g., *Passenger Car*, *Pickup*, *Multi-purpose*, *Van*), make, model, year and body style. The parameters can be edited by clicking on the vehicle CG (sprung mass parameters), exterior (outer dimensions and stiffness coefficients), wheels (location, suspension, tire and brake parameters), engine (drivetrain), steering wheel and brake pedal. The HVE Vehicle Editor is shown in Appendix C. The environment (road surface geometry, including elevation, surface normals and friction zones) are created and edited using the HVE Environment Editor (see Appendix D). Vehicle position and velocity are assigned using the HVE Event Editor by visually placing the vehicle in the environment. Driver controls (steering, throttle, brakes, gear selection) are assigned by clicking on the vehicle, choosing the desired driver control table and entering dependent values as a function of time.

The event is executed using the HVE Event Controller, with buttons similar to those on a VCR. The simulated motion of the vehicle in its environment is visualized in fully rendered, 3-D viewers. The motion may be viewed in forward and reverse. Thumbwheels on the viewers quickly change the view, allowing the user to visually inspect details of the vehicle-to-vehicle and vehicle-to-environment interaction. The current value of user-selected results (position, velocity, acceleration, tire force, and so forth) are displayed in *Key Results* windows. An example of the HVE Event Editor is shown earlier (see Figure 2).

Output reports, listing the vehicle data, tire data, simulation controls and other simulation parameters, are available in the HVE Playback Editor. Multiple trajectory simulations may be visualized simultaneously in the Playback Editor. An individual simulation can be combined with any

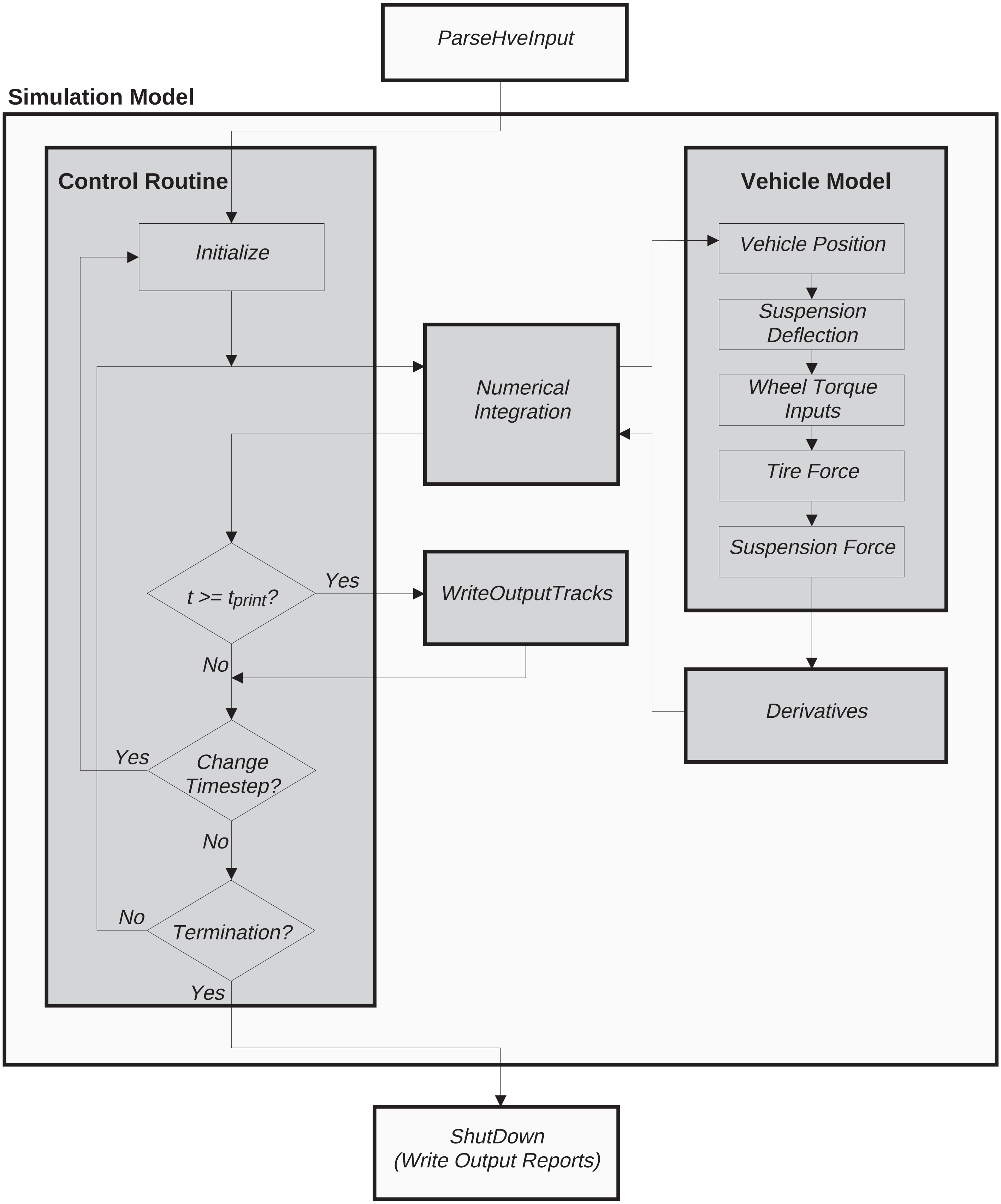

Figure 4 - EDVSM/HVOSM Calculations, Flow Chart, illustrating the four main calculation procedures: the Control Routine, Numerical Integration, Vehicle Model and Derivative (acceleration) Calculations. Te current results for each output interval are written by WriteOutputTracks.

number of additional events in the HVE Playback Window to allow the researcher to visualize a multi-human and/or multi-vehicle collision sequence.

## Programming Language

HVOSM is programmed in FORTRAN. Although FORTRAN is an extremely efficient language for mathematical applications, it is also quite difficult to read and maintain. For example, it is not uncommon to find unresolved conditions related to nested IF statements, although none was found in the HVOSM code. The new generation of structured languages, such as C, provides for much greater readability, extendibility and maintainability. In addition, the software industry is pouring significantly greater resources into these newer languages, resulting in the availability of the latest generation of programming tools, including optimizing compilers and debuggers. Finally, from a mechanical engineering standpoint, porting a program to a different language is the best way to learn about the model's engineering assumptions (programmers do not always implement their code strictly according to specification) and to find coding errors. For these reasons, HVOSM was recoded using the C language. Two code fragments, one from the original FORTRAN code and the other from the same code ported to the C language, are shown in Table 1.

## Road Surface Definition

HVOSM allows the user to supply an X,Y,Z road surface grid using the 500 cards in the input deck. An optional method allows up to six curbs, defined in a similar manner [2]. EDVSM uses the 3-D environment model to directly define the road surface geometry using the HVE `GetSurfaceInfo()` library function [11] (refer to Figure 5). Whatever the user visualizes as the environment also becomes the surface on which the vehicle is driven. This new technique eliminates any ambiguity about how the tire model interacts geometrically and physically with the environment because the user is able to directly visualize the tire-road interaction. In addition, a single call to `GetSurfaceInfo()` placed in the EDVSM code replaces a significant amount of the original FORTRAN code (specifically the INTRPL, INTRP5, GCP and CRBIMP subroutines).

## Tire Parameter Definition

Tire parameters are provided to HVOSM in the form of five coefficients, $A_0$, $A_1$, ..., $A_4$, computed from flat-bed tire test measurements of cornering and camber stiffnesses at various loads [2]. Given these coefficients, the cornering stiffness, $C_\alpha$, is computed for the current load, $F_z$, as follows:

$$C_\alpha = A_0 + A_1 F_z + (A_1/A_2) F_z^2 \qquad \text{(lb/rad)}$$

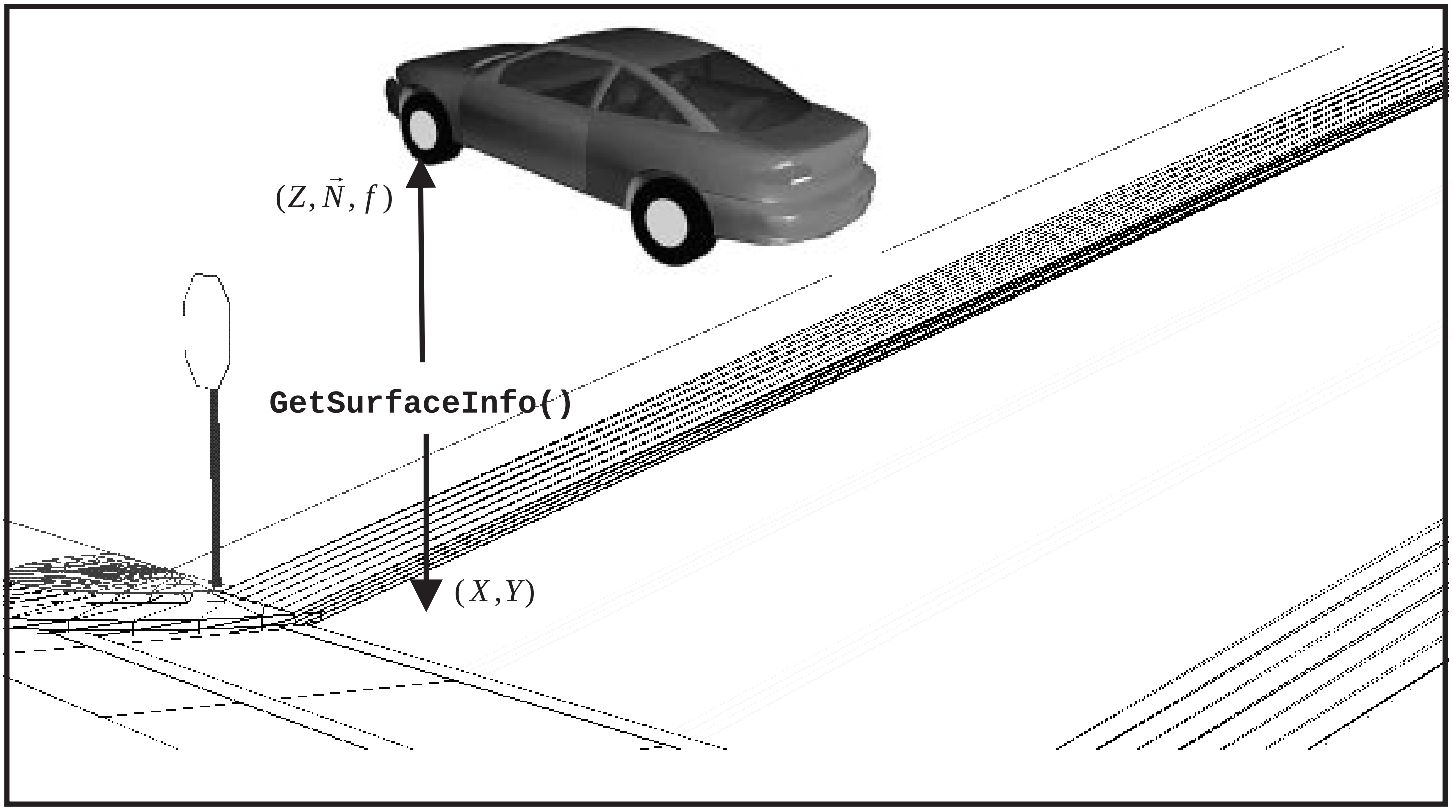

*Figure 5 - The HVE Environment Model allows the EDVSM tire model to directly interrogate the road surface geometry to identify the surface elevation, normal vector and friction beneath each tire at every timestep.*

*TABLE 1. FORTRAN (left) and C (right) Code Fragments*

```fortran
      TQD(1) = 0.
      TQD(2) = 0.
      (IF DRVER.NE.0) GO TO 50
      IF(NTT1+NTT2+NTT3.EQ.0) GO TO 41
      DO 10 I = 2,NTTS
      IA=I -1
      RATIO = 0.0
      PC=TPC(IA)
      TTTS = TTS(IA)
      TTTR = TTR(IA)
      IF((TSEC.GT.TT(I-1)).AND.(TSEC.LT.TT(I))) GO TO 14
      IF(TSEC.GT.TT(NTTS)) GO TO 11
      IF(TSEC.EQ.TT( IA)) GO TO 21
      IF(TSEC.EQ.TT(I)) GO TO 20
   10 CONTINUE
   11 TTTR = TTR(NTTS)
      PRINT 12,TSEC,TTTR
   12 FORMAT(1H0,3X,"TSEC NOT WITHIN RANGE OF TABULAR
     1VALUES TSEC =", 1 E15.8,"SET TRANSMISSION RATIO
     2TTTR=",E15.8)
C     NTTS IS THE LARGEST INTEGER IN  10.*(T1 + DT)
C     + 1.C TO AVOID OUT-OF-RANGE MESSAGES, USE
C     NTTS IS THE LARGEST INTEGER IN  10.*(T1 + DT) +  2.
      GO TO 20
   14 RATIO = (TSEC-TT(IA))/(TT(IA+1)-TT(IA))
      TTTR = TTR(IA)+RATIO*(TTR(IA+1)-TTR(IA))
C  WHEN RATIO IS .GT. 0.5 SET TTR TO NEXT VALUE IN TABLE
      IF(RATIO.GT.0.5) TTTR = TTR(IA+1)
C
C  PARI - FUNCTION SUBROUTINE TO DO LAGRANGIAN INTERPOLATION
C      PC = PARI(NTTS,IA,TSEC,TT,TPC
      IF(PC.LT.0.0) PC = 0.0
      TTTS = PARI(NTTS,IA,TSEC,TT,TTS)
      IF(TTTS.LT.0.0) TTTS = 0.0
      GO TO 21
   20 TTTR = TTR(IA+1)
      TTTS = TTS(IA+1)
      PC = TPC(IA+1)
      GO TO 21
C DRIVER CONTROLS CONVERTED HERE
   50 TTTS = APD/APDMAX
      IF(TTTS.LT.0.0) TTTS = 0.0
      PC = BFP1*FBRK+BFP2*FBRK**2
      IF(PC.LT.0.0) PC = 0.0
      TTTR = GEAR(IGEAR)
      RPME = PIO15R*ARBR(JDEND)*TTTR*(RPSI(L)+RPSI(L+1))
      IF(TQE.LT.0.0) GO TO 55
```

```c
tqd[FRONT] =
tqd[REAR]  =0.0;
TableIntrpol(ThrottleTableLen,MAXWHEELS,t,&ThrottleTable[0][0],fthrot);
if (ThrottleMethod == AT_DRIVER)
{
   /* Linear Interpolation to get current throttle position, engine
      torque and gear number.
   */
   ThrottlePosn = fthrot[0];
   /* Get transmission ratio.
   */
   i=0;
   while (t > TransTable[0][i] && i < TransTableLen) i++;
   if (i > 0) i–;
   TransGearNum = TransTable[1][i];
   TransRatio   = TransRatioTable[TransGearNum];
   DiffGearNum  =(INT)LinIntrpol(DiffTableLen,&DiffTable[0][0],
                 &DiffTable[1][0],t,&temp);
   /* Get differential ratio.        */
   i=0;
   while (t > DiffTable[0][i] && i < DiffTableLen) i++;
   if (i > 0) i–;
   DiffGearNum  = DiffTable[1][i];
   DiffRatio    = DiffRatioTable[DiffGearNum];
   /* Calculate drive torque according to current
      drivetrain conditions.
   */
   EngineSpeed  =
       DiffRatio*TransRatio*(0.5/(DriveAxle[FRONT]+ DriveAxle[REAR]))
           *(DriveAxle[FRONT]*(rpsi[0] + rpsi[1]) + DriveAxle[REAR]
           *(rpsi[2] + rpsi[3]));
   if (EngineSpeed > tct[0][EngineTableLen[1]-1] ||
      EngineSpeed > twot[0][EngineTableLen[0]-1])
   {
      istop = PHYS_MSG_EXCESSIVE_ENGINE_RPM;
      return;
   }
   else
   {
      EngineSpeed = max(EngineSpeed, twot[0][0]);
      LinIntrpol(TransTableLen,&twot[0][0],&twot[1][0],
                 EngineSpeed,&temp);
      TempCT     = LinIntrpol(TransTableLen,&tct[0][0],&tct[1][0],
                 EngineSpeed,&temp);
      EngineTq     = TempCT + ThrottlePosn*(TempWOT -    TempCT);
      Tqd[FRONT]   = EngineTq*TransRatio*DriveAxle[FRONT];
```

Similarly, the camber stiffness, $C_\gamma$, is computed for the current load, $F_z$, as follows:

$$C\gamma = A_3F_z + (A_3/A_4)F_z^2 \qquad \text{(lb/rad)}$$

The above approach is specific to the HVOSM tire model. To provide a general purpose tire parameter interface usable by any vehicle dynamics model, HVE supplies its tire parameters in the form of tables of $F_y$ vs $\alpha$ and $F_y$ vs $\gamma$ at up to three vertical tire loads, $F_z$, and three speeds. HVE also supplies $C_\alpha$ and $C_\gamma$ for each load and speed (note that $C_\alpha$ and $C_\gamma$ are the initial slopes for the $F_y$ vs $\alpha$ and $F_y$ vs $\gamma$ tables, respectively). From the HVE table data, EDVSM calculates the A-coefficients required by the tire model by expressing the above equations in matrix form:

$$[F_z][A] = [C]$$

where $[F_z]$ is a matrix of test loads, [A] is matrix of the required A-coefficients and [C] is the cornering or camber stiffness for each value of $F_z$. The tire model in EDVSM then uses these A-coefficients just like HVOSM.

## VALIDATION RESULTS

For validation purposes, five well-instrumented vehicle handling tests were found in the literature [3, 13]. The tests were then simulated using EDVSM. The simulation results were compared with measured values and with results from other simulation models. The comparison was performed by superimposing the EDVSM results directly against the original test data and previous simulation results. The five handling studies were as follows:

- Sinusoidal Steer
- Braking In A Turn
- Alternate Ramp Traversal
- Turning Maneuver Into Curb (Rollover)
- Wet Pavement Skid Into Soil (Rollover)

*Table 2. Data Acquisition Package for Validation Test Nos. 1, 2 and 3.*

| Measurement | Instrumentation |
|---|---|
| *Pitch/Roll Attitude* | *2-DOF Free Gyro* |
| *Yaw Attitude* | *2-DOF Free Gyro (outer gimbal used)* |
| *Front Wheel Deflection* | *Linear Stroke Potentiometer, 5-inch Stroke* |
| *Rear Wheel Deflection* | *Linear Stroke Potentiometer, 10-inch Stroke* |
| *Steer Angle* | *Linear Stroke Potentiometer, 10-inch Stroke* |
| *Longitudinal Acceleration* | *Accelerometer* |
| *Lateral Acceleration* | *Accelerometer* |
| *Vertical Acceleration* | *Accelerometer* |

*1. All channels recorded on an oscillographic recorder.*
*2. All data filtered with an external 15 Hz filter.*

The results from each of these validation studies are discussed below.

## Sinusoidal Steer

This experiment was performed as part of the original HVOSM validation and is fully described in reference 3. A 1963 Ford Galaxy 4-Dr Sedan was used to perform the maneuver. Detailed measurements of the vehicle parameters required for the simulation were made by Ford Motor Company. Tire parameters for the 8.25-14 tires were provided by General Motors (GM provided the actual tires as well). The data acquisition package used for this and all Calspan validation tests is shown in Table 2.

These tests were conducted by accelerating the vehicle to a nominal 25 mph constant test speed and activating the instrumentation package. The driver then closed a switch activating an external servo that provided a controlled, sinusoidal steering input of +/-5 degrees (measured at the axle) at about 0.5 cycles per second (cps). Three tests were performed. The maneuver was simulated by Calspan using HVOSM-SMI1 (the Sprung Mass Impact model). The same maneuver was simulated for the current validation using EDVSM. In both simulations, the average steering inputs were used. Reference 3 contains experimental results for numerous test results. The input parameters used in the HVOSM-SMI1 simulation are also included in Reference 3. EDVSM simulation results for all input parameters and output results are available in reference 15. Note that, although the parameters are substantially similar, they are not identical because of differences in the way the parameters are supplied to HVOSM and EDVSM (for example, refer to the previous section that describes differences in the way tire parameters are assigned). In addition, because EDVSM was derived from the HVOSM-VD2 (Vehicle Dynamics) model, there are differences in model requirements for tire and suspension parameters.

### Comparison of Results

The experimental and simulation results are shown in Figures 9 and 10. Comparison of results for vehicle roll and yaw responses (Figure 9) reveals very good agreement between the average of the experimental results and the simulation results for HVOSM and EDVSM. Note that the steer angle inputs shown at the top of Figure 9 were used to create the simulated steering inputs, so perfect agreement is expected in this graph.

Some degree of phase shift is observed in the vehicle responses shown in Figures 9 and 10. The simulation used an initial velocity of 24.5 mph, whereas the velocities in the three tests ranged from 22.7 to 27.2 mph. This difference in initial velocity is responsible for much of the phase shift observed in the results (i.e., a faster speed would naturally cause the onset of a particular response sooner). However, trend information shown in the graphs is exceptional. It should be noted that the beginning and ending simulated velocities were nearly the same (initially 24.5 mph, slowing to 24.1 mph). Although total velocity was not recorded, the driver was asked to maintain a constant speed.

The comparisons for wheel displacement and lateral acceleration shown in Figure 10 are also very good, again noting some difference due to the initial conditions. Some asymmetry in the test results is noted for both roll and wheel displacement (the vehicle rolls more during left turns than during right turns), suggesting either a slight difference in driver input (not likely, since the steer angle record is nearly perfect) or a side-to-side difference in either ride rate or shock rate. The simulations did not show this asymmetry.

Direct comparison of the EDVSM and HVOSM-SMI1 simulation results revealed they were substantially similar, even though the tire and suspension models in EDVSM included features, such as load- and speed-dependent tire properties, longitudinal tire stiffness and anti-pitch suspension effects, not found in the HVOSM-SMI1 model. The differences might have been greater had the maneuver been more severe (peak lateral acceleration were only about 0.3 g).

Reference 3 provides additional assessments regarding the test results.

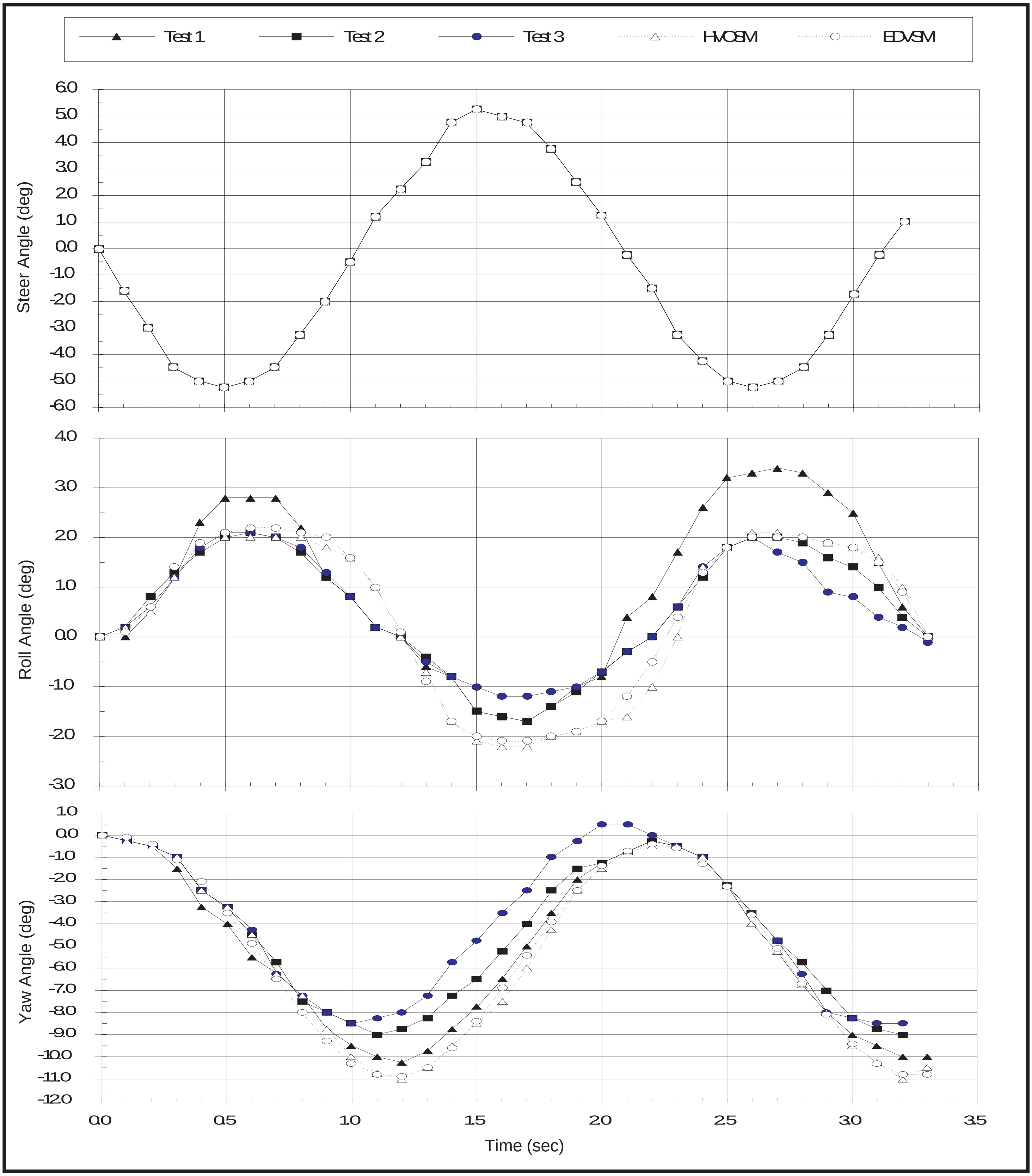

*Figure 9 - Results for Validation Test No.1, Steer Angle Driver Input (top), and Vehicle Roll and Yaw Response (middle and bottom, respectively) vs Time.*

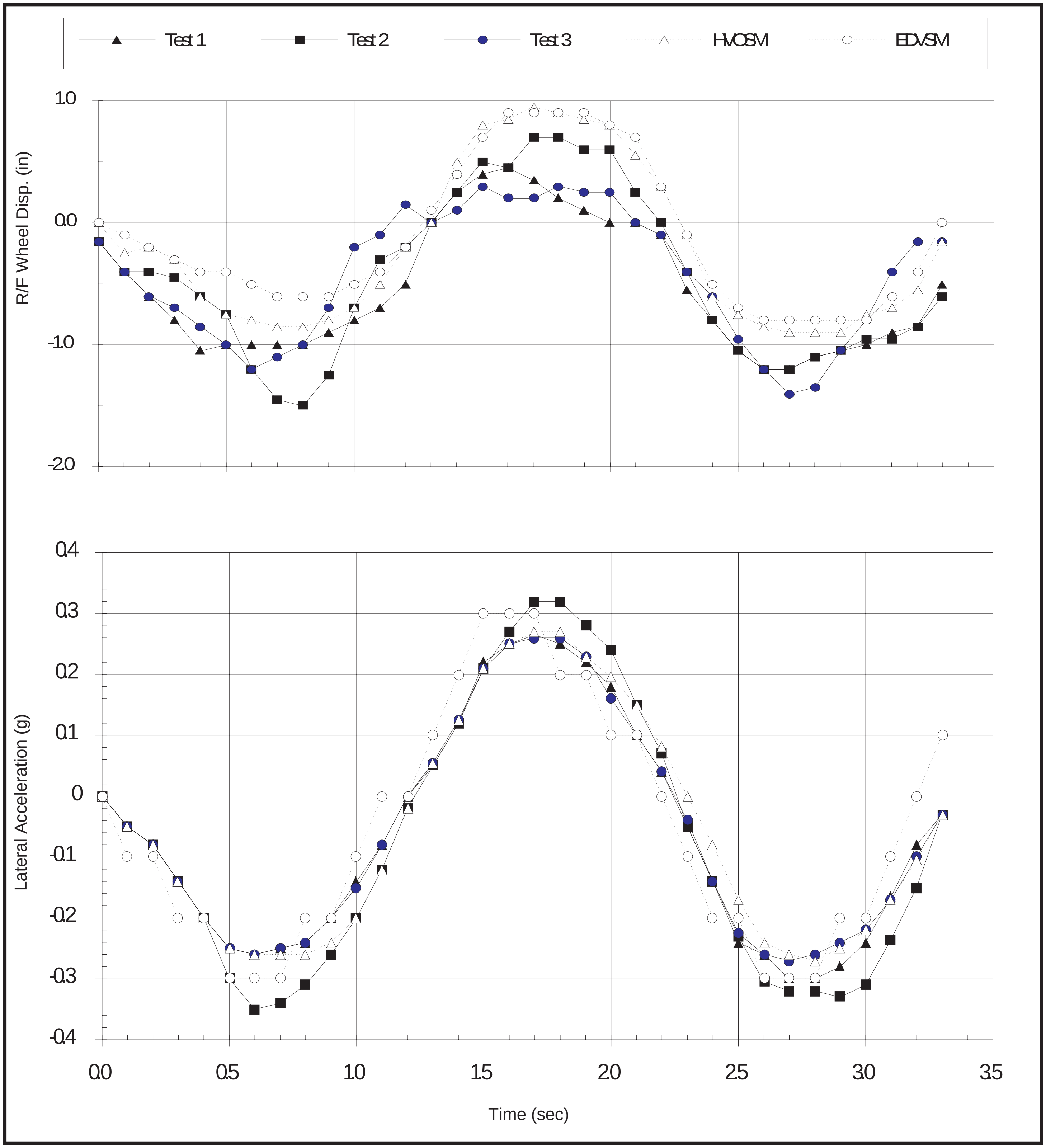

*Figure 10 - Results for Validation Test No. 1, Right Front Wheel Displacement (above) and Lateral Acceleration (below)*

## Braking In A Turn

This experiment was also performed as part of the original HVOSM validation [3]. The same 1963 Ford Galaxy 4-Dr Sedan (see previous run) was used for this study. The instrumentation package was basically the same as used in the previous study. The tests also included thermocouples to measure brake lining temperature, and the brake pedal was fitted with a travel limiting device that resulted in repeatable system pressure at a level just below that required to lock the wheels (i.e., what one might refer to as “hard braking”).

The tests were conducted by accelerating the vehicle to a nominal speed of 40 - 45 mph and activating the instrumentation package. The driver then manually applied the brake pedal hard enough to hold the pedal firmly against the travel stop. Simultaneously, the driver turned the steering wheel one-half turn and held it in that position, resulting in about 7 degrees of steer at the front wheels. Although a servo was not used to control the steering input, the driver practiced the test sequence several times to ensure repeatability.

Three tests were performed. The maneuver was simulated by Calspan using HVOSM-VD1 (the Vehicle Dynamics model). The same maneuver was simulated for the current validation using EDVSM. Both simulations used an initial velocity of 41.25 mph, and the average test values for steering and braking inputs. Again, reference 3 contains numerous test results, including driver steering and braking inputs, vehicle position, velocity and acceleration, wheel angular velocity and suspension deflection. EDVSM simulation results for all parameters are available in reference 15.

Although HVOSM-VD1 and HVOSM-VD2 (and EDVSM) were very similar in most respects, the tire models were different. Whereas the VD1 model used an input table for longitudinal friction vs slip, the VD2 and EDVSM models used a traditional mu vs slip curve with peak and slide friction coefficients. In addition, the VD1 tire model calculated lateral force as a percentage of longitudinal force, whereas the VD2 and EDVSM models used a single peak lateral friction coefficient. However, there were also differences in the VD2 and EDVSM tire models (see Tire Parameter Definition, earlier in this paper). Ultimately, the basic tire parameters used by EDVSM in this validation run were extracted from a later study conducted by Calspan [1], after the HVOSM-VD2 tire model was developed.

### Comparison of Results

Selected experimental and simulation results are shown in Figures 11 - 14. Comparison of results for brake system pressure and steer angle (i.e., driver inputs) are shown in the top two graphs in Figure 11. The results show good repeatability, indicating the manually operated steering and braking systems were satisfactory for purposes of testing. Vehicle longitudinal and lateral acceleration, shown at the bottom of Figure 11, reveal excellent agreement. A “blip” is noted in the HVOSM simulation results at the end of the run because the termination velocity was set too low. The blip was eliminated in the EDVSM run simply by changing the termination velocities to 2 mph and 5 deg/sec. The tire model becomes erratic at speeds lower that these values.

Comparison between simulated and measured wheel spin velocities, shown in Figure 12, reveals near-perfect agreement. The experimental results show an aberration occurring at the left front wheel approximately 0.75 seconds into each test. The reason for the aberration could not be identified, but was not significant to the outcome of the testing. It is interesting to note the spin velocities for the right side (i.e., outside) tires were slightly greater in both the experiments and the simulations. The original authors [3] attributed this to increased circumferential slip at the inside tires. This conclusion is not borne out by the simulation results (the longitudinal slip is virtually identical for inside and outside tires). Instead, the difference is probably due to the smaller rolling radius of the (more heavily loaded) right side tires. (This factor was considered a minor factor by the original authors.) In any case, the important observation is that this subtle experimental result is observed and handled well by the simulation.

Comparison between the measured and simulated vehicle roll, pitch and yaw responses are shown in Figure 13 also reveal good agreement, with some interesting observations. The pitch and yaw angles agree well for two of the three tests; in the first test, the steering input was slightly faster than for the other runs, resulting in a divergent yaw and pitch angles for that run, however, the match is excellent for the the other two runs.

The simulated roll angle, however, does not agree as well with the measured data. Inspection of the test data reveals an interesting observation: According to the experimental results, the vehicle had a negative roll angle from 2.5 seconds until the vehicle came to rest. However, inspection of the measured lateral acceleration (see Figure 11, bottom) reveals the lateral acceleration was negative during this period. These two experimental results are in conflict with each other. Clearly, the left turn should create a negative lateral acceleration (as measured), however, no passenger car would respond to this lateral acceleration with a negative roll angle. Obviously, there is a problem with the measured data. This suspicion is also supported by the observation of a negative initial roll angle (the measured results show an initial angle of about -0.5 degrees), and residual roll angle also equal to about -0.5 degrees (see Figure 13, top). If the experimental results are simply shifted in the positive direction about 0.5 degrees, the roll angle becomes positive, and is consistent with the simulation results.

Wheel deflections for the left front and left rear wheels are shown in Figure 14. The match for the rear wheel is excellent. The results for the front wheel are not as good.

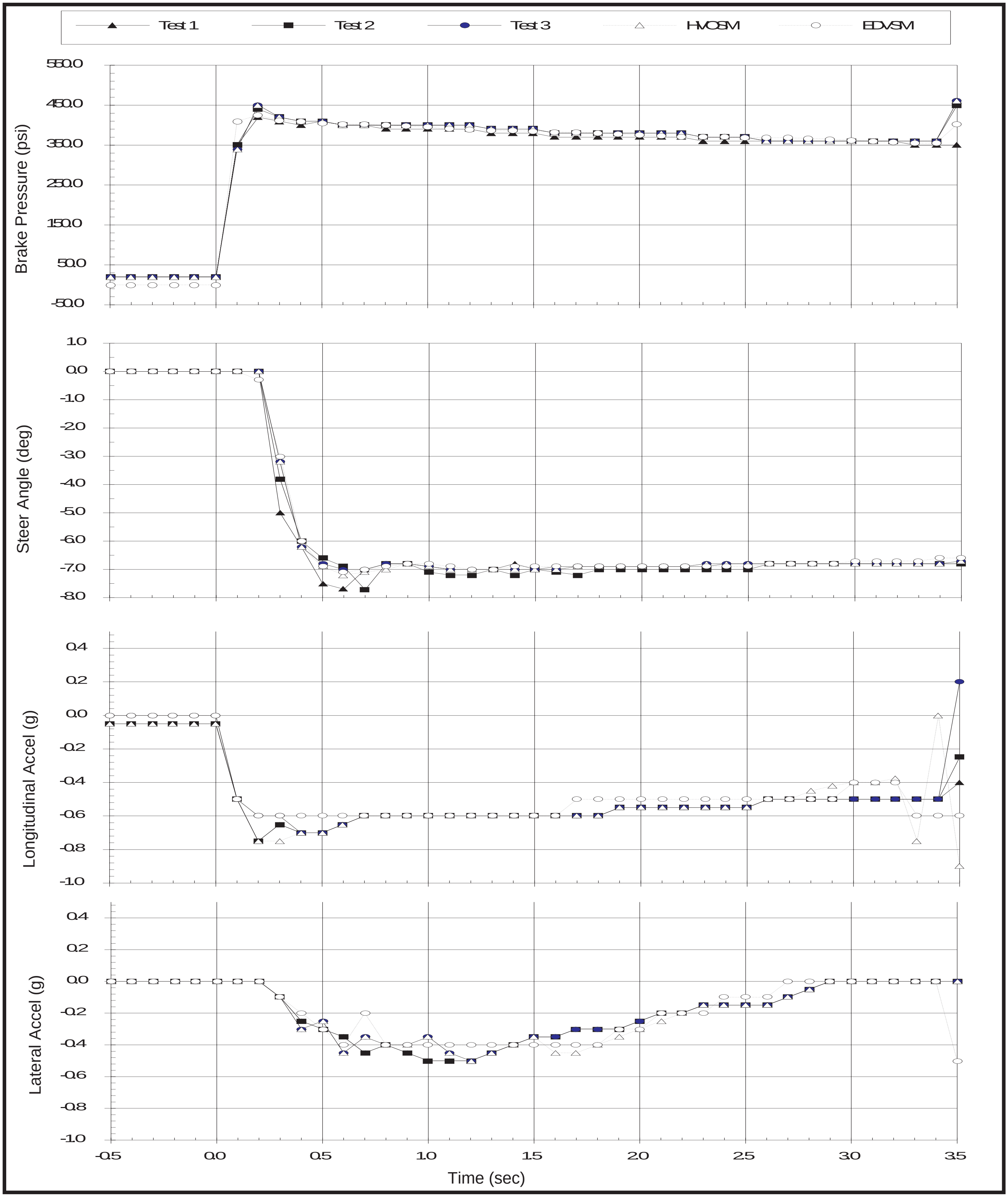

*Figure 11 - Results for Validation Test No.2, Brake Pressure (top) and Steer Angle (second) inputs vs time, followed by Longitudinal Acceleration (third from top) and Lateral Acceleration (bottom) vehicle responses vs time.*

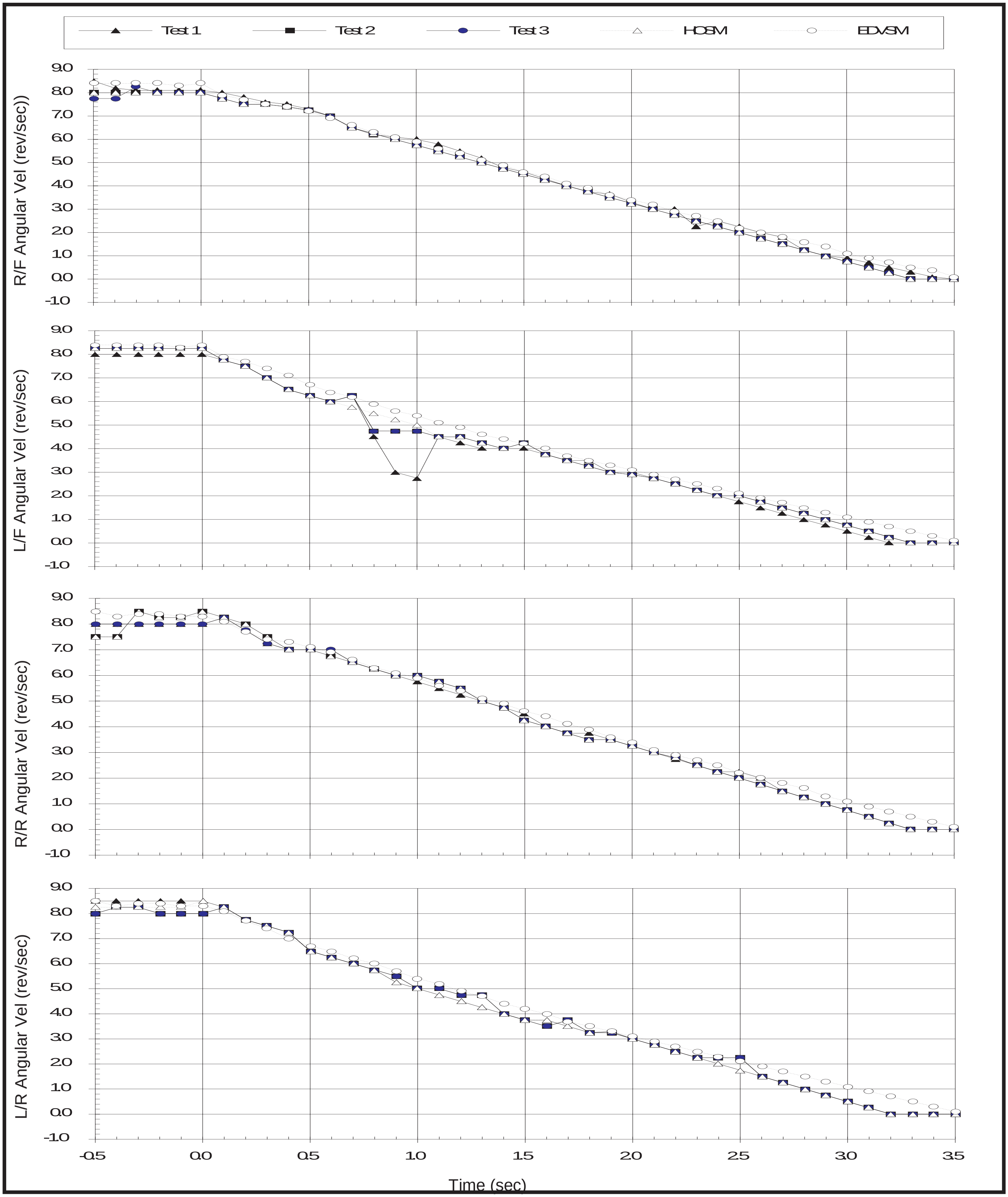

Figure 12 - Results for Validation Test No.2, Wheel Spin Velocities for Each Wheel

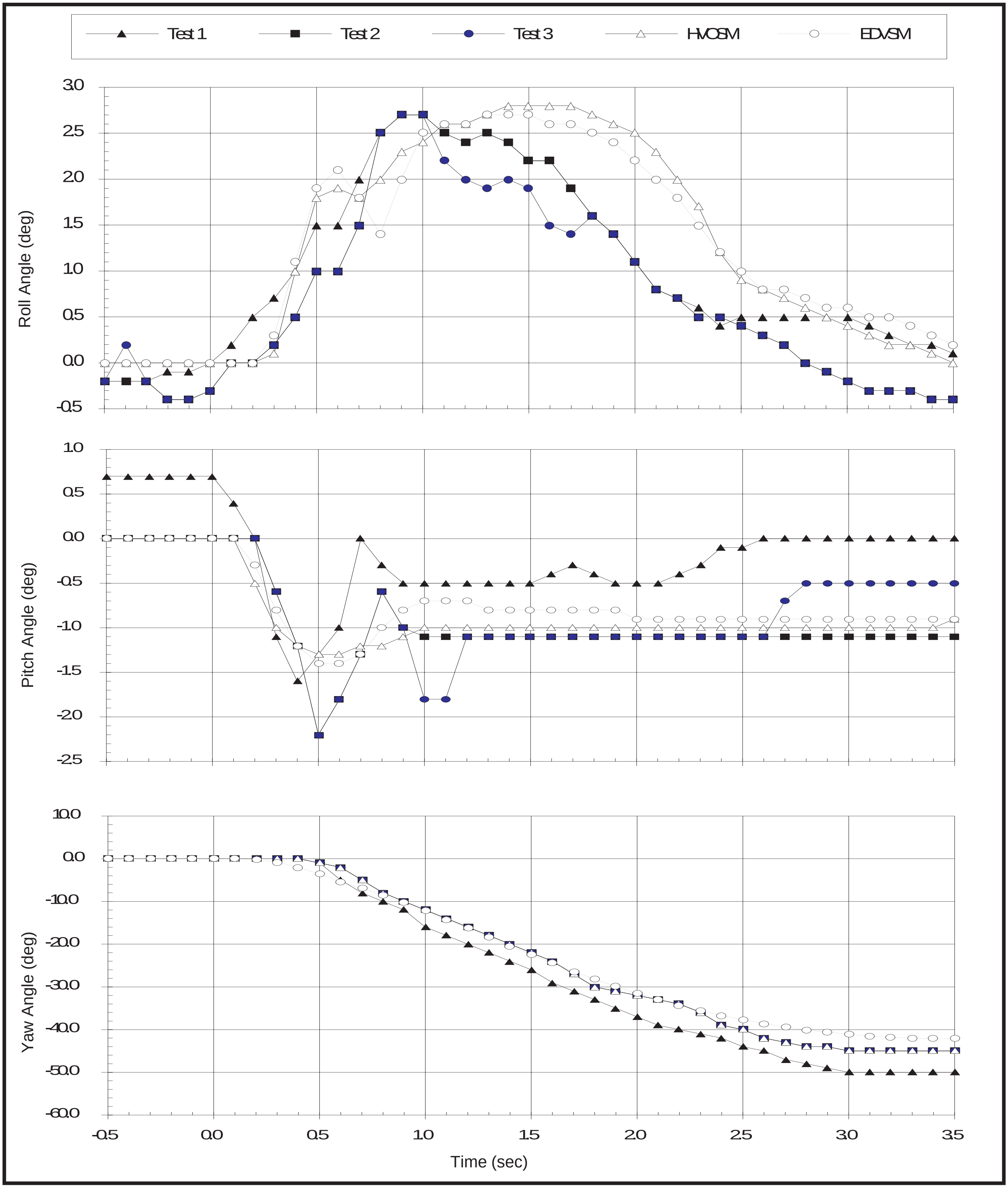

*Figure 13 - Results for Validation Test No. 2, Roll, Pitch and Yaw (top to bottom) vs Time.*

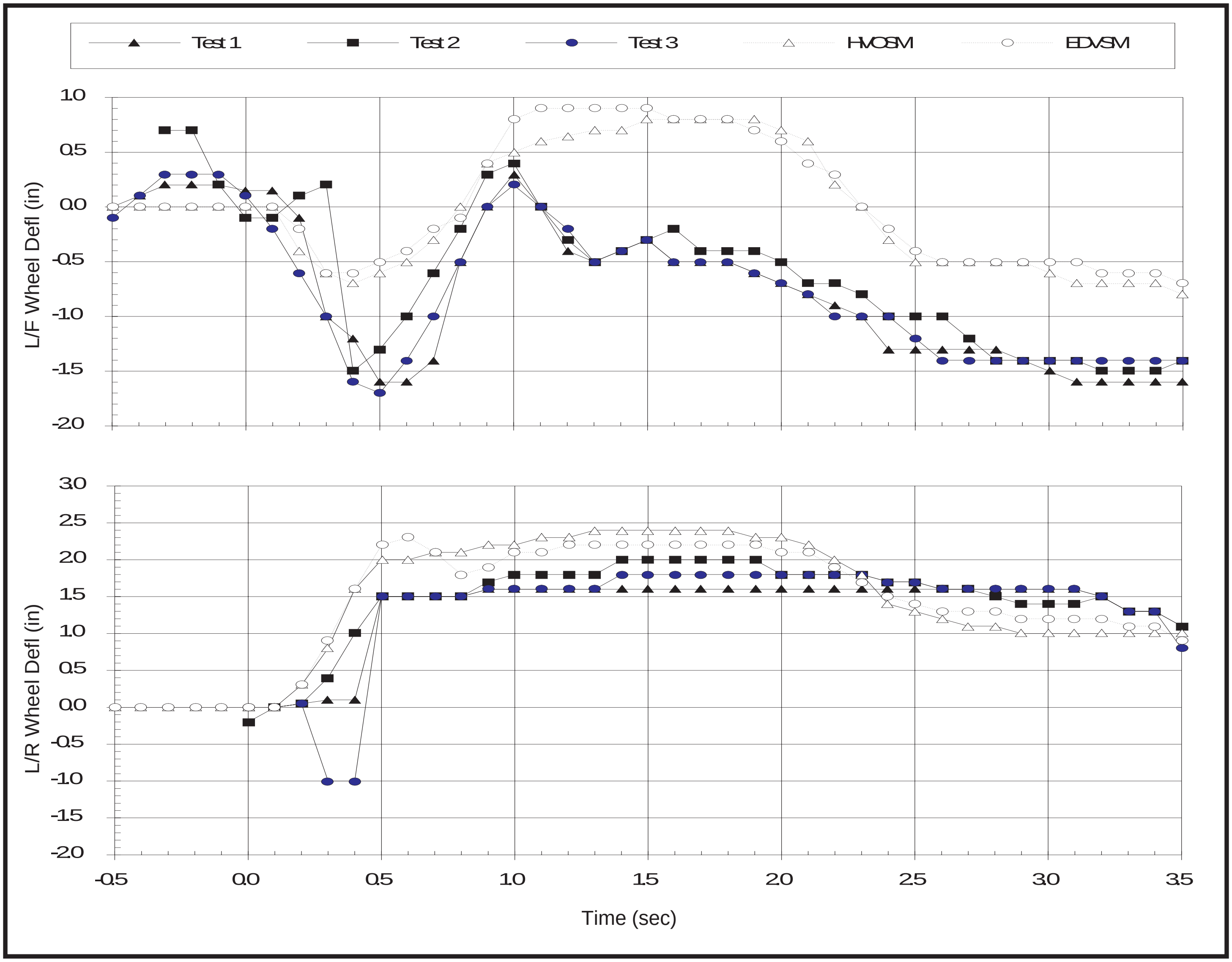

*Figure 14 - Results for Validation Test No. 2, Left Front (top) and Left Rear (bottom) Wheel Deflections vs Time.*

Two counteracting factors are in effect. First, the brakes are applied (hard), resulting in a negative pitch and tendency for jounce at both front wheels. This factor is somewhat offset by steering to the left, resulting in a positive roll angle and a tendency for extension (positive deflection) at the inside (left) front wheel. Because the vehicle pitch angle is simulated with excellent fidelity, while the roll angle is suspicious, the difference between simulated and measured results may be due to measurement errors. However, this finding is not certain, and additional testing would be required to confirm the results. Also, wheel deflections for the right-side wheels were not reported; these results would have been helpful.

The original author [3] suspected the divergence was due to underestimation of suspension ride and damping rates. This hypothesis was tested by rerunning the event after increasing the shock absorber rates by a factor of four. The change in shock rates did not appreciably affect the simulation results.

## Alternate Ramp Traversal

This experiment was also performed as part of the original HVOSM validation [3] using the same 1963 Ford Galaxy 4-Dr Sedan and instrumentation package (see Table 2). Because of the severity of the maneuver (see below), the vehicle's tires were inflated to 65 psig.

The tests involved traversing a series of 21-inch high ramps spaced at 63 foot intervals. In addition, the ramps were

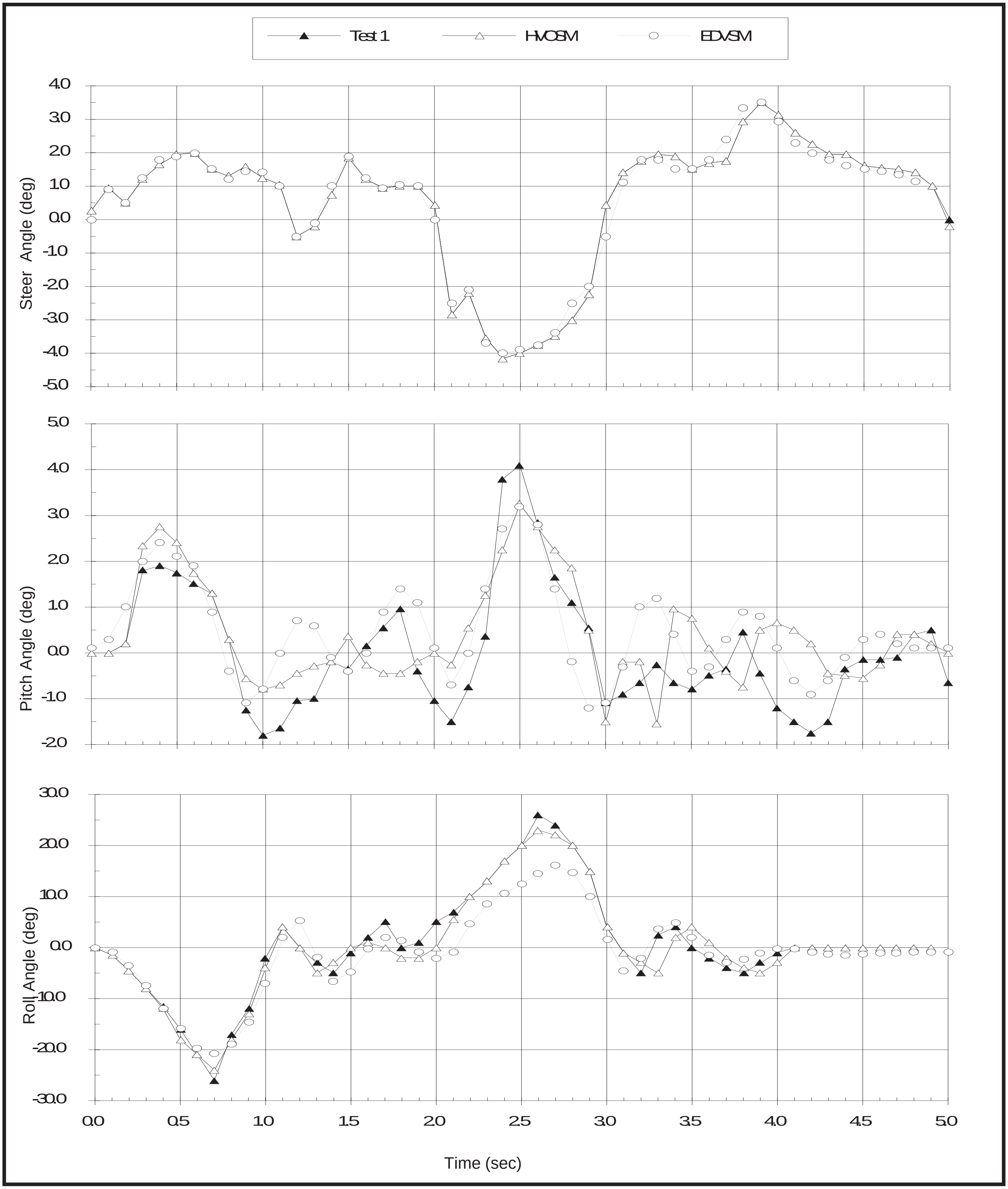

*Figure 15 - Results for Validation Test No. 3, Alternate Ramp Traversal. Driver Steering Input (top) and Vehicle Pitch and Roll Responses (middle, bottom) vs Time*

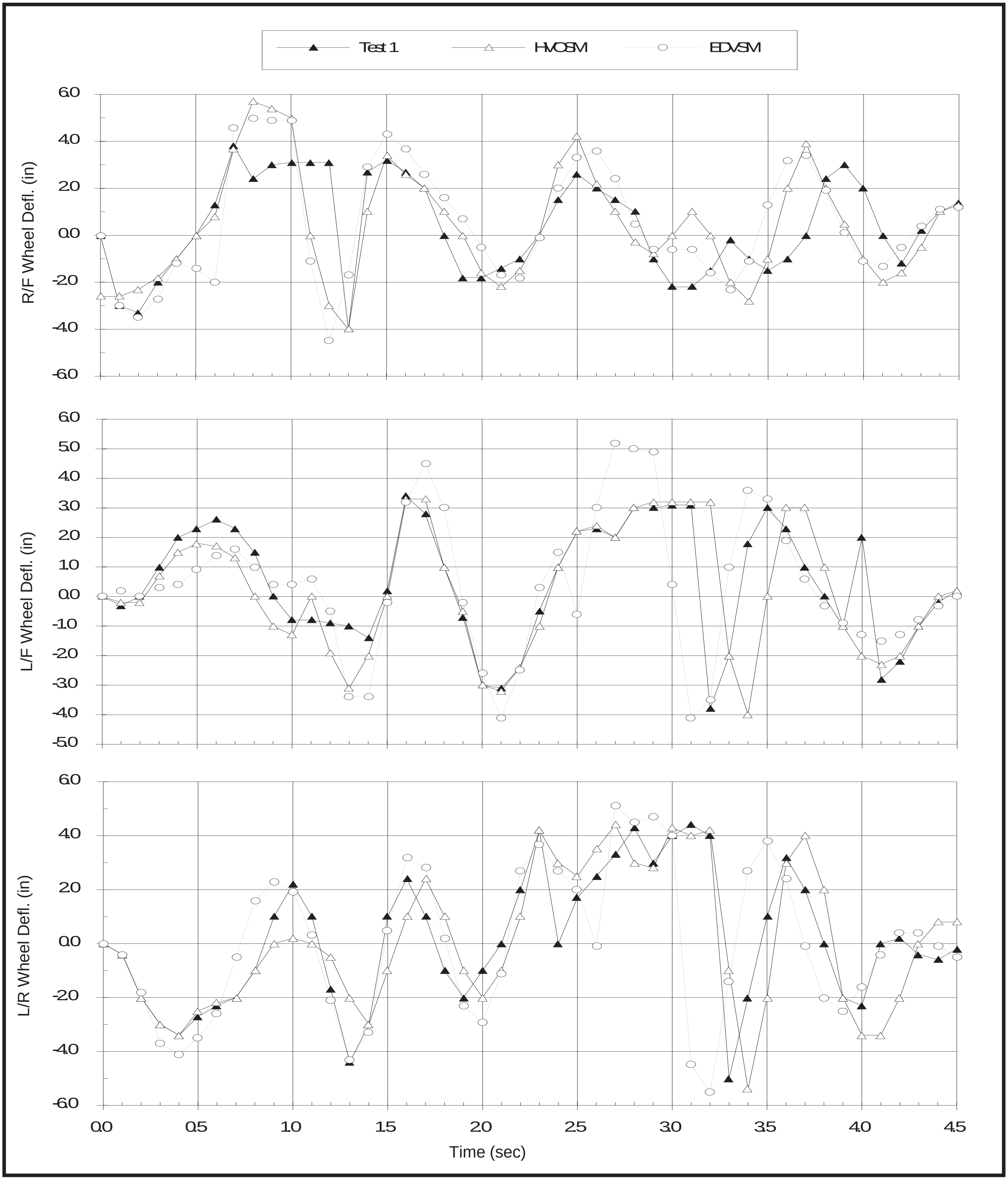

*Figure 16 - Results for Validation Test No. 3, Right Front, Left Front and Left Rear Wheel Deflections (top to bottom) vs Time.*

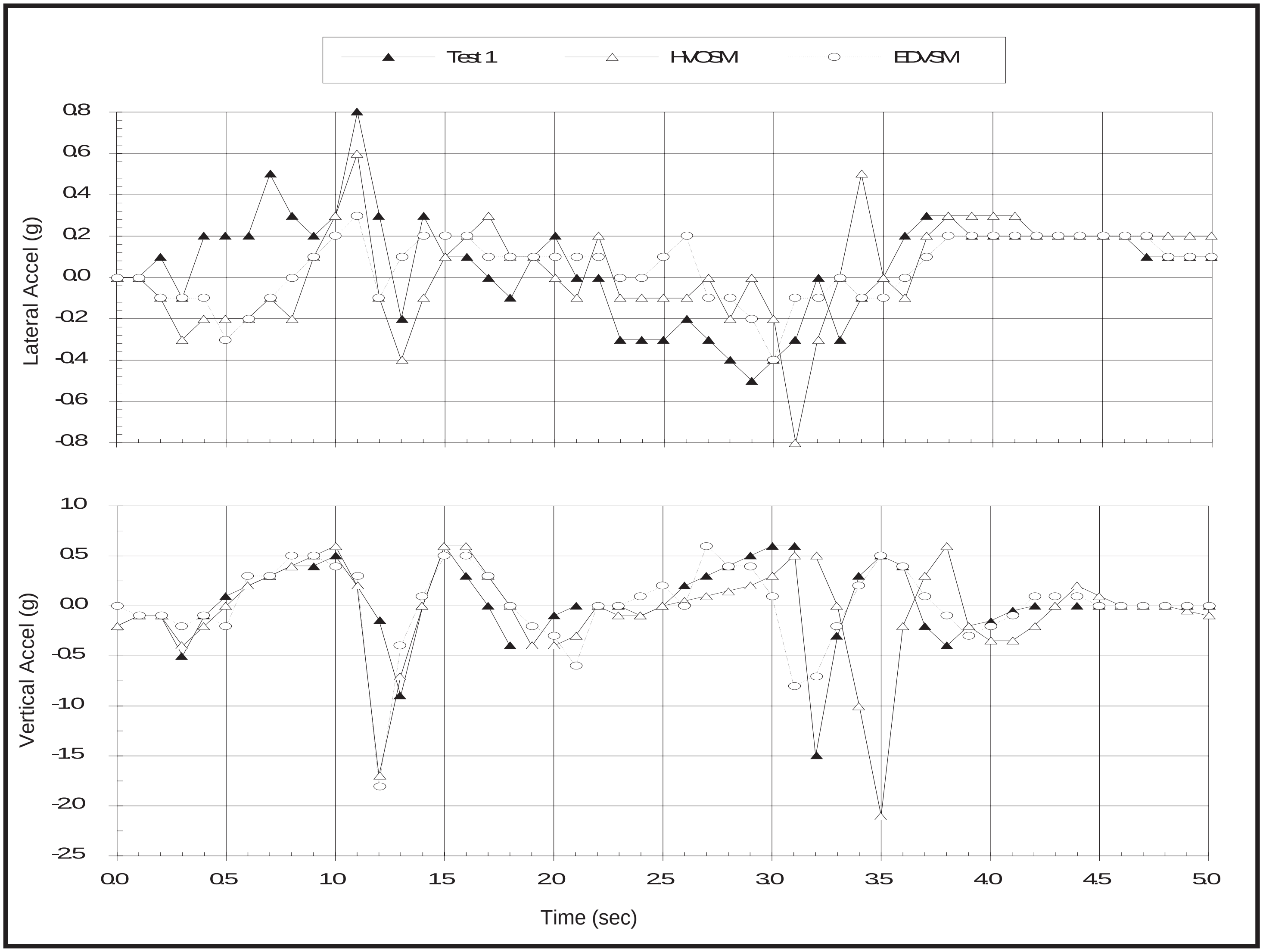

*Figure 17 - Results for Validation Test No. 3, Alternate Ramp Traversal. Lateral (top) and Vertical (bottom) Acceleration vs Time.*

staggered so the right wheels struck the first ramp and the left wheels struck the second ramp.

The tests were conducted by accelerating the vehicle to a nominal speed of 30 mph and activating the instrumentation package. The driver (a professional stunt driver) then manually applied the throttle as required to maintain a constant speed. Because the ramps introduced significant vehicle roll, the driver also steered the vehicle as required to keep the vehicle on path. Two runs were performed. A slight difference in initial speeds, coupled with slight differences in driver inputs, resulted in a significant difference in some results. Therefore, the tests had to be analyzed separately, and the first run was used in this validation.

The maneuver was simulated by Calspan using HVOSM-SMI1 (the Sprung Mass Impact model). The same maneuver was simulated for the current validation using EDVSM.

As in the first test, the EDVSM simulation included several parameters not included in the HVOSM-SMI1 model, including significant differences in the suspension and tire models.

The HVE 3-D Editor was used to construct the terrain according to the parameters listed in the card image input deck listed in reference [3]. It was noted the resulting ramps had sloped surfaces along the inside edges and trailing edges not shown in the visualization shown in reference 3. Never the less, this surface was used for the EDVSM simulations. This finding represents a good example of how important it can be to visualize the physical surface used in the simulation, rather than an idealized post-production pictorial.

## Comparison of Results

Several factors affected this study:

- *Tire Data* **-** No test data were available for the tires inflated to 65 psig. Therefore, estimates were used. Because the vertical stiffness, cornering stiffness and camber stiffness all affect lateral motion (vertical stiffness affects roll, and thus, lateral force, while cornering and camber stiffness affect lateral force directly), some deviation in results was expected.
- *Tractive Effort* **-** Torque was required at the drive wheels to overcome the slowing effect of the ramps. Because these torques were not measured, they had to be estimated. It was noted that the HVOSM simulations, in fact, ignored these torques (drive torques were set to zero), thus, a slowing of the simulated vehicle would be expected due to the motion resistance provided by the 21-inch high ramps.
- *Initial Heading Angle* **-** The driver made a small steering adjustment as he approached the first ramp to ensure correct alignment. Thus, the actual initial heading angle, which was not measured, had to be estimated.

Driver steering inputs and vehicle pitch and roll responses are shown in Figure 15. The comparison of experimental vs simulated roll response was excellent, while pitch response was acceptable. Trend information was very good, especially for vehicle roll angle. Note that simulated peak roll almost exactly duplicated the measured values, even in this extreme maneuver. However, inspection of detailed pitch response reveals it becomes somewhat out of phase near the end of the run. Comparisons of experimental vs simulated wheel deflections (Figure 16) and longitudinal and lateral accelerations (Figure 17) were also very good.

Careful review of the results reveals a phase shift later in the run, suggesting the simulated vehicle was traveling slightly slower than the actual vehicle. This finding would also suggest slightly lower accelerations and wheel deflections, sometimes consistent and sometimes inconsistent with actual results. In general, other factors (in particular, ride rate and damping coefficient estimates) were probably equally responsible for any observed inconsistencies.

An interesting finding discussed by the original authors was that the left rear wheel fell off the inside of the second ramp during the test. This result was duplicated in the current EDVSM simulation. In fact, by zooming in beneath the simulated vehicle, it was observed that the simulated left rear tire actually landed on the sloped surface inside the ramp. In any case, the simulation did an excellent job of duplicating the actual event.

## Turning Maneuver Into Curb

The Advanced Dynamic Vehicle Simulation (ADVS) model, another 3-D vehicle simulator, was developed at the University of Missouri-Columbia [13]. The fourth experiment was performed as part of the ADVS validation, and is described in reference 13. A 1984 Ford Bronco II (2.8L V-6) fitted with Goodyear Polysteel P205/75R15 tires was used to perform the maneuver. Detailed measurements of the vehicle inertial and suspension parameters required for the simulation were developed for the study [13]. Tire parameters were reportedly obtained from Calspan tire studies [14].

Because the experiments were expected to produce vehicle rollover, the vehicle was fitted with outriggers, and a special remote vehicle control system was developed. This system included four basic components:

- *Speed Sensor* **-** driven by the speedometer cable to determine vehicle speed
- *Steering Actuator* **-** connected to the steering wheel to provide and measure steering input
- *Throttle Controller* **-** with input from the speed sensor to determine the need for increased or decreased engine power
- *Brake Controller* **-** with input from the speed sensor to determine time for brake application (braking level is fixed, actuated by an air cylinder)

The complete vehicle control system is described in detail in reference 13. The data acquisition package for both Missouri validation tests is summarized in Table 3.

*Table 3. Data Acquisition Package for Validation Test Nos. 4 and 5.*

| Measurement | Instrumentation |
|---|---|
| *Linear Position* | *Integrated from Accelerometer Data and Video Cameras* |
| *Angular Orientation* | *Integrated from Accelerometer Data and Video Cameras* |
| *Wheel Deflection* | *Rotary Potentiometer* |
| *Wheel Spin Velocity* | *DC Tachometer, 12,000 RPM max* |
| *Steer Angle* | *Stepper Motor at Steering Wheel* |
| *Brake Pressure* | *Strain Gage Pressure Transducer* |
| *Linear and Angular Acceleration* | *Accelerometers (six)* |

1. *All data channels recorded on a Keithley 575 16-channel Data Acquisition System.*
2. *All data acquired on a 1.7 msec read cycle.*

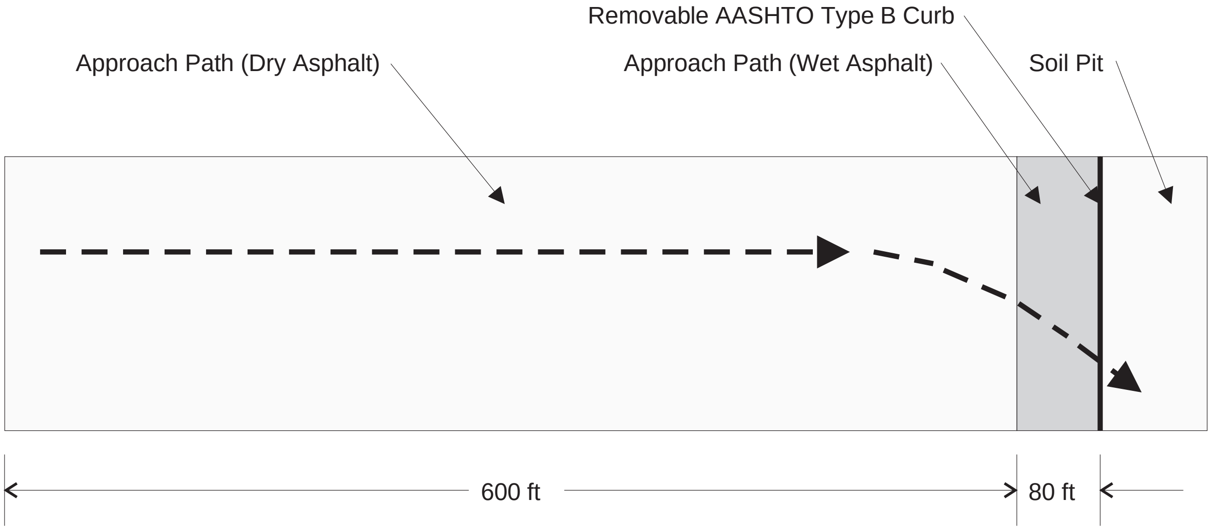

*Figure 18 - Path description for Tests 4 and 5. The vehicle was accelerated up to the nominal test speed. Then, steering and braking were introduced just before reaching the wetted portion, causing the vehicle to reach the soil pit at a nominal angle of approximately 50 degrees.*

In the first test, Turning Maneuver Into Curb, the Ford Bronco II performed a cornering maneuver, then struck an AASHTO type-B curb at a nominal angle of 51.8 degrees, causing the vehicle to roll over.

The test surface for experiments4 and 5 was divided into three sections: a straight path 400 feet in length (long enough to accelerate the vehicle to the highest required test speed, 50 mph), followed by a spiral transition curve 147 feet in length (during which the instrumentation was stabilized), and a 209 foot constant radius curve 114 feet in length (a 208 ft radius was chosen because it produced a nominal lateral acceleration of 0.8 g at the desired maximum test speed, 50 mph). The curb was placed at an angle of 51.82 degrees with respect to the vehicle path. The final 80 feet of test surface prior to the curb was wetted. Averages from several skid tests revealed $FN_{30}$=77.3 for the dry surface and $FN_{30}$=52.6 for the wetted surface. The basic test path is shown in Figure 18.

The first test was conducted by accelerating the Bronco II to the nominal test speed of 35 mph. Steering and braking were introduced as required to follow the prescribed path. The vehicle's brake system was modified by removing the proportioning valve so the rear brakes would lock. The right front brake was also locked. The left front brake was disabled to allow better control. The throttle was released (i.e., closed) when the brakes were applied.

The maneuver was simulated using ADVS. The same maneuver was simulated using EDVSM. The specific vehicle and event parameters used in the original research [13] were not included. In addition, the reference cited for the tire parameters [14] did not include the tire reportedly used in the study (reference 14 does not include any P205/75R15 tires), and no tire data were found in reference 13 or any of the accompanying research. These factors greatly complicated the task of producing validation input sets for EDVSM. As a result, the EDVSM simulation runs used estimated parameters reconstructed from various sources, including direct measurement. Tire friction parameters were estimated from similar tires in reference 14, and cornering stiffness parameters were obtained from unpublished tests on a P205/75R15 conducted by Calspan at the request of Ford Motor Company. The parameters used for each EDVSM simulation test are available in reference 15.

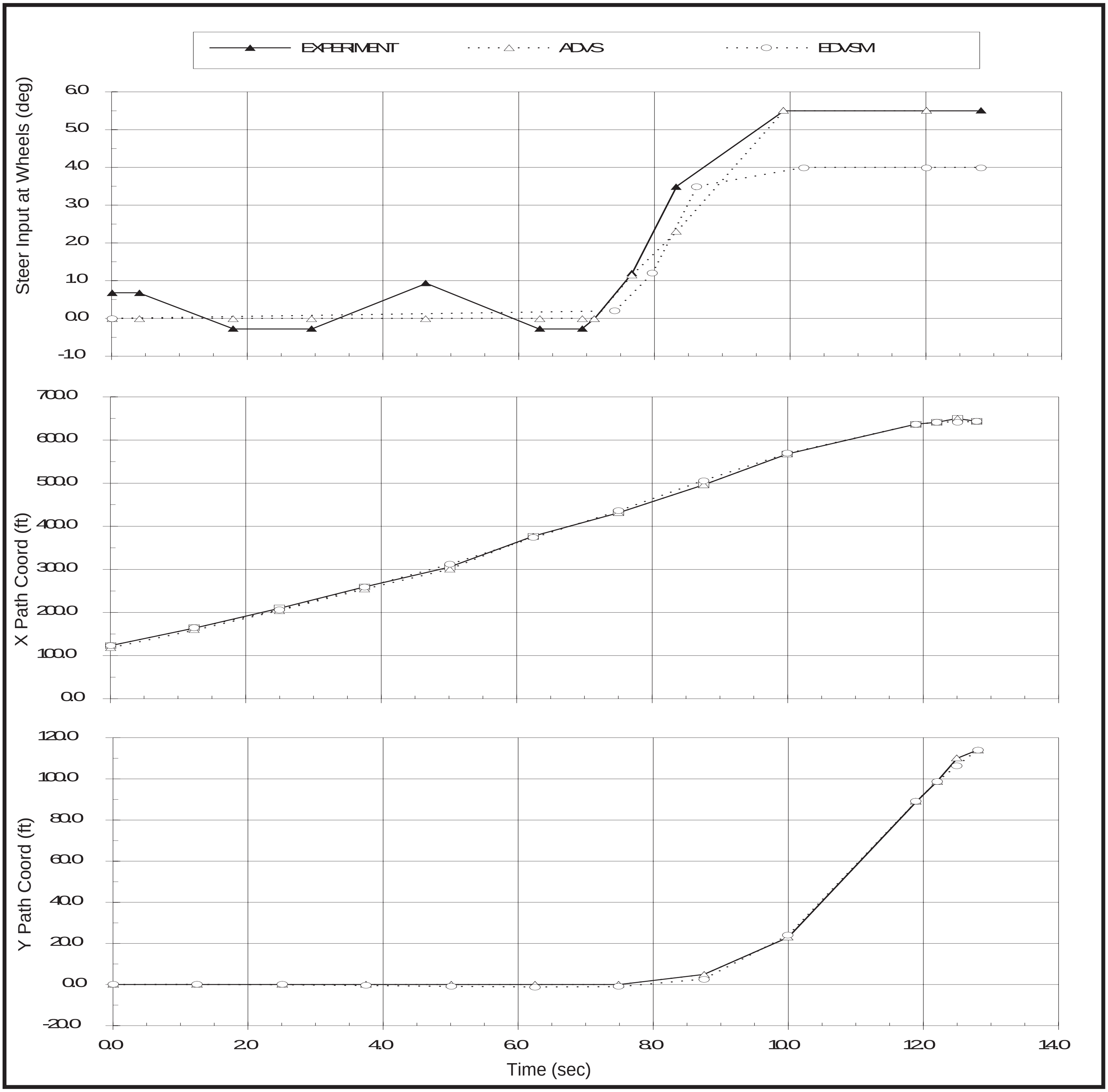

*Figure 19 - Results for Validation Test No. 4, Steering Input (top), X and Y path coordinates (middle and bottom, respectively.*

## Comparison of Results

The experimental and simulation results are shown in Figures 19 through 22. The simulated vehicle behavior was in substantial agreement with the experimental results, including the rollover phase at the end of the run.

Comparison of steer angle inputs in Figure 19 reveals a slight phase shift (the steering for EDVSM started 0.3 sec later than the experiment). Repeated simulation testing revealed the tire cornering stiffness properties used in the EDVSM simulations were probably slightly higher than the actual value. The possibility of using lower values was considered and rejected because we desired to stay with measured vehicle and tire parameters, rather than simply prove that a set of values could be found that produced a match between simulated and actual behavior. The ADVS

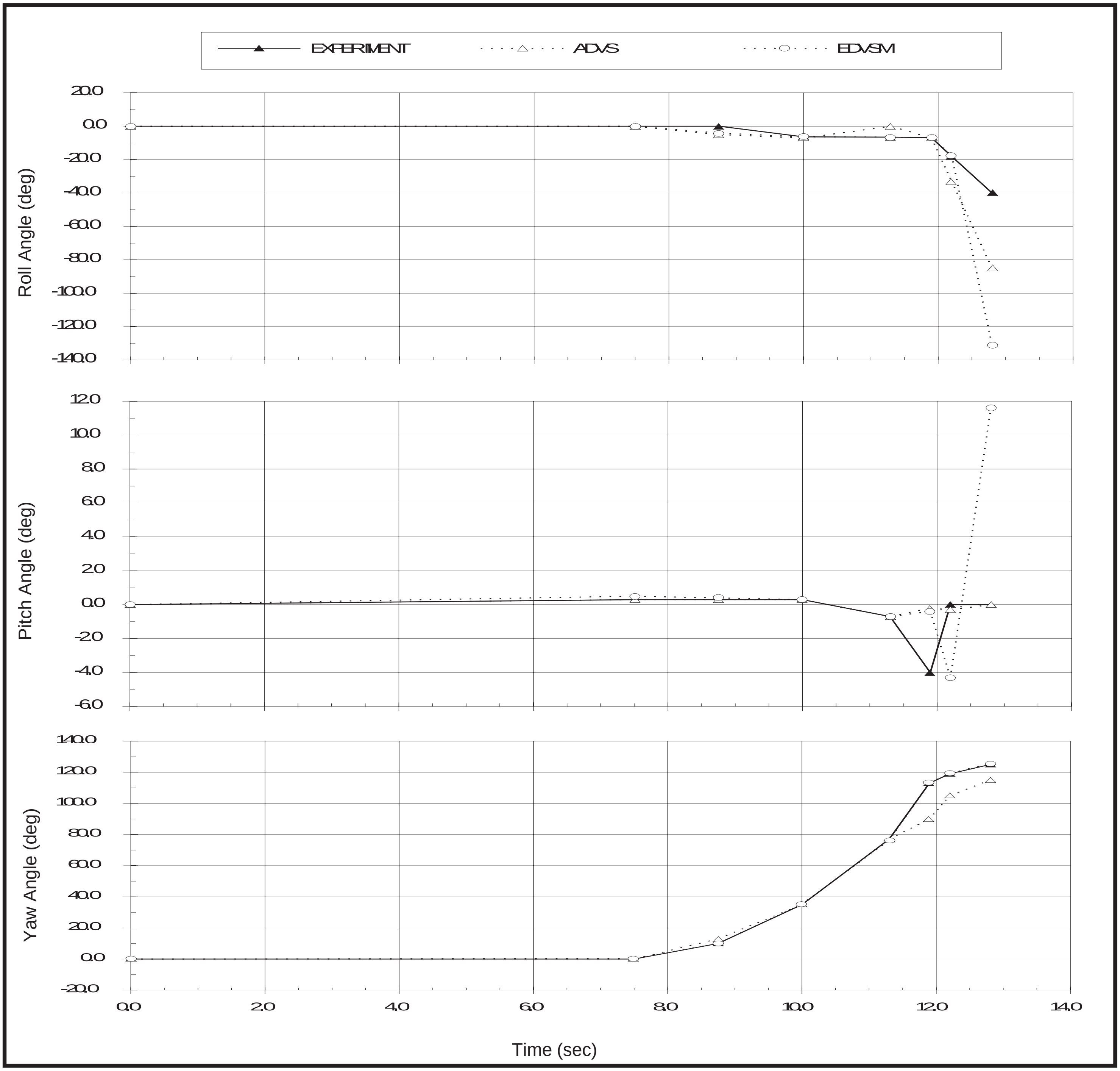

*Figure 20 - Results for Validation Test No. 4, Roll, Pitch and Yaw Orientations (top to bottom).*

simulations used a (measured) steering gear ratio of 22:1, whereas the Ford specifications report a ratio of 18:1. The current researchers measured a ratio of 18:1, thus this ratio was used in the current validation. Figure 19 also reveals excellent agreement in the X and Y path coordinates with the above steering inputs.

Figure 20 also shows excellent agreement between meeasured and simulated roll, pitch and yaw angles. The agreement continues well beyond the initiation of rollover. Note the experimental values stop at a roll angle of about 35 degrees because of the outriggers fitted on the test vehicle

Figure 21 reveals good agreement between measured forward and lateral velocities and those simulated using EDVSM. However, the simulated lateral velocity begins slightly earlier than the test values. A slight difference in test tires vs actual tires could account for the difference. Note also

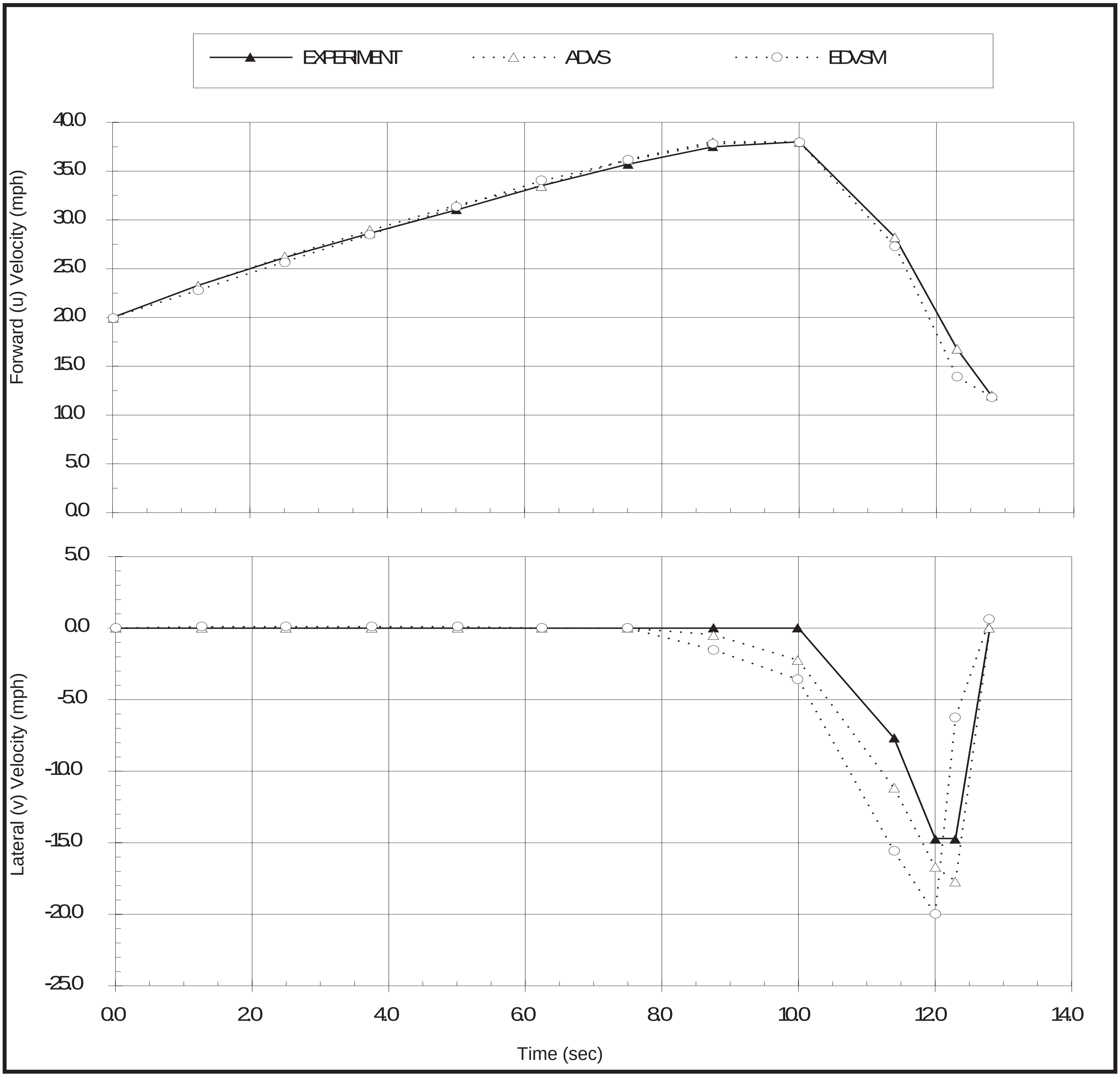

*Figure 21 - Results for Validation Test No. 4, Forward and Lateral Velocities.*

that the actual velocity achieved was about 38 mph, slightly higher than the 35 mph target value.

Figure 22 provides a comparison between simulated and measured wheel displacements. The agreement is extremely good for the entire duration of the run. Near the end of the run, at 12.4 seconds, all four wheels are off the ground. At that point, the wheels are against the rebound stops at 4.7 inches of extension.

## Bronco II Wet Pavement Skid Into Soil

This study was also performed as part of the ADVS validation [13]. The same 1984 Ford Bronco II and test layout were used, except the curb was removed and the vehicle skidded from the wet asphalt into a soil pit. The soil was Missouri River sand with zero cohesion, approximately 1 foot in depth.

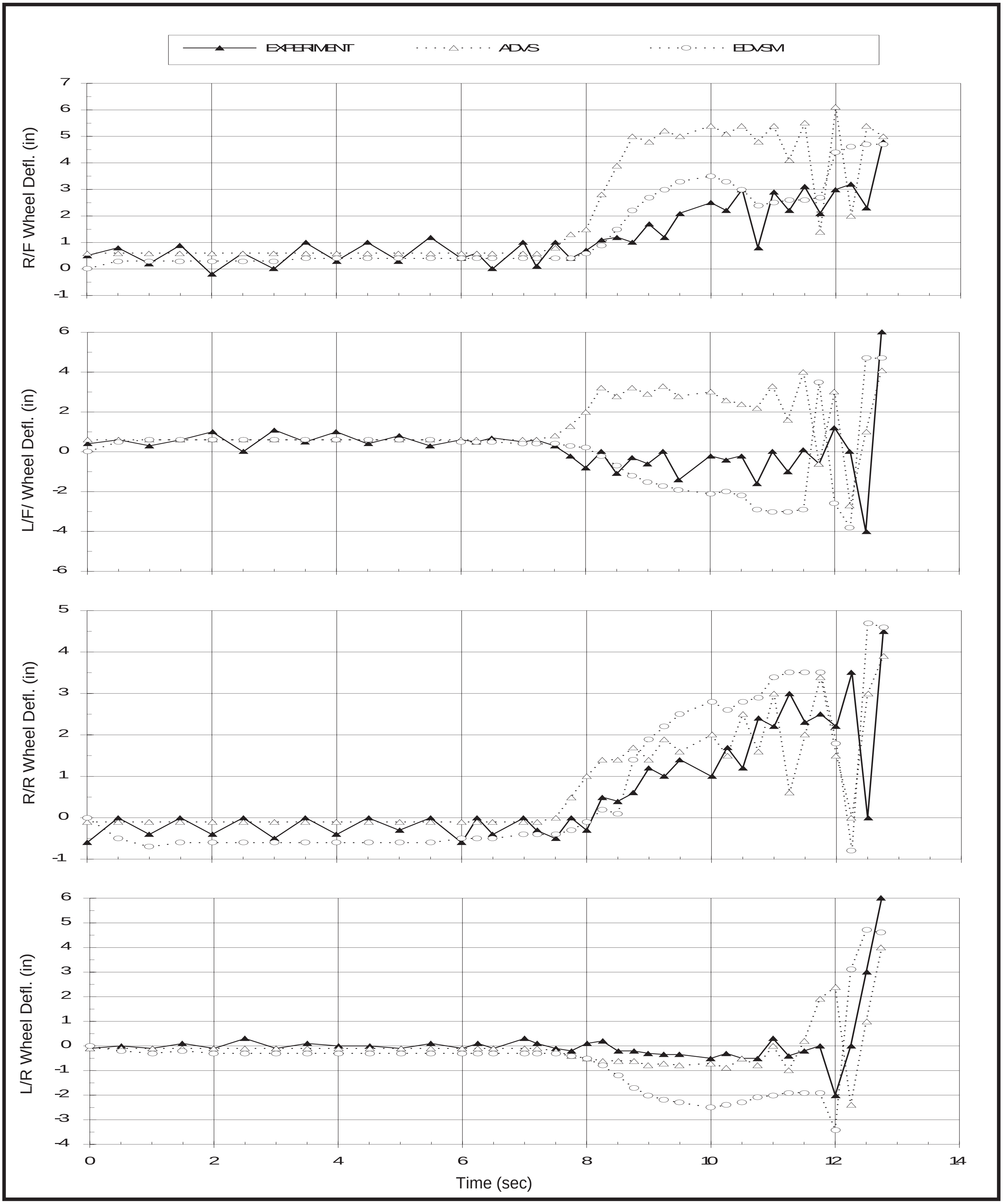

*Figure 22 - Results for Validation Test No. 4, Wheel Displacements for Right Front, Left Front, Right Rear and Left Rear (top to bottom).*

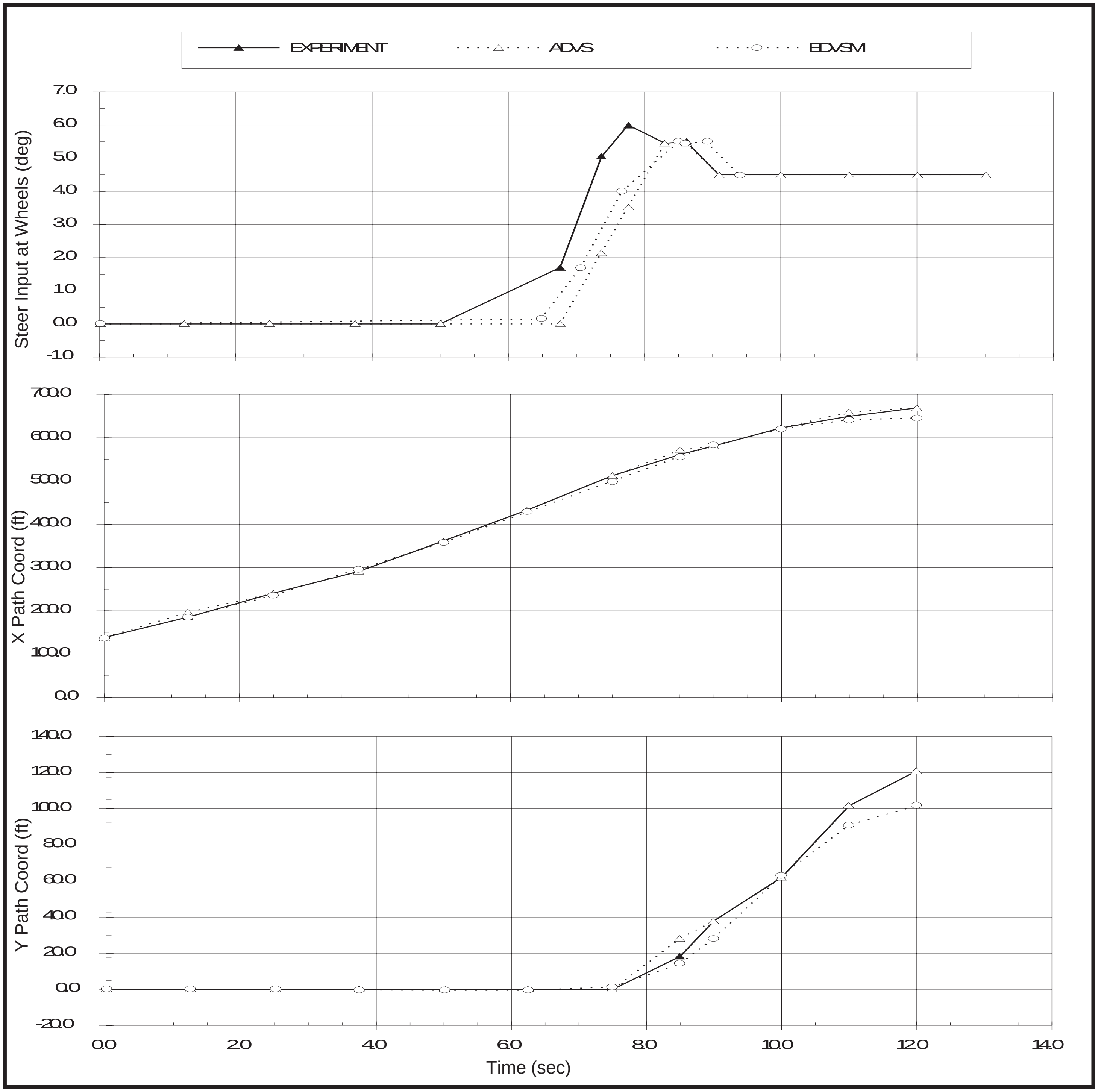

*Figure 23 - Results for Validation Test No. 5, Steering Input (top), X and Y path coordinates (middle and bottom, respectively.*

The test was conducted by accelerating the vehicle to a nominal speed of 40 mph (the actual test speed was 42 mph). Steering and braking inputs were supplied as required to follow the prescribed path. As in the previous study, the brake system had been modified to prevent locking of the left front wheel.

The maneuver was simulated using EDVSM. Several points are noteworthy. As in the previous test, the vehicle and tire parameters were not well documented. The vehicle used in this EDVSM simulation was the same as the one used in the prior simulation. EDVSM does not include the capability to model deformable soil, such as the sand used in this test. To model the soil, the friction factor for the simulated soil surface was increased to 1.5 from 1.0. This issue is addressed later in the paper (see Discussion).

The experimental and simulation results are shown in Figures 23 through 26. Again, the simulated vehicle behavior

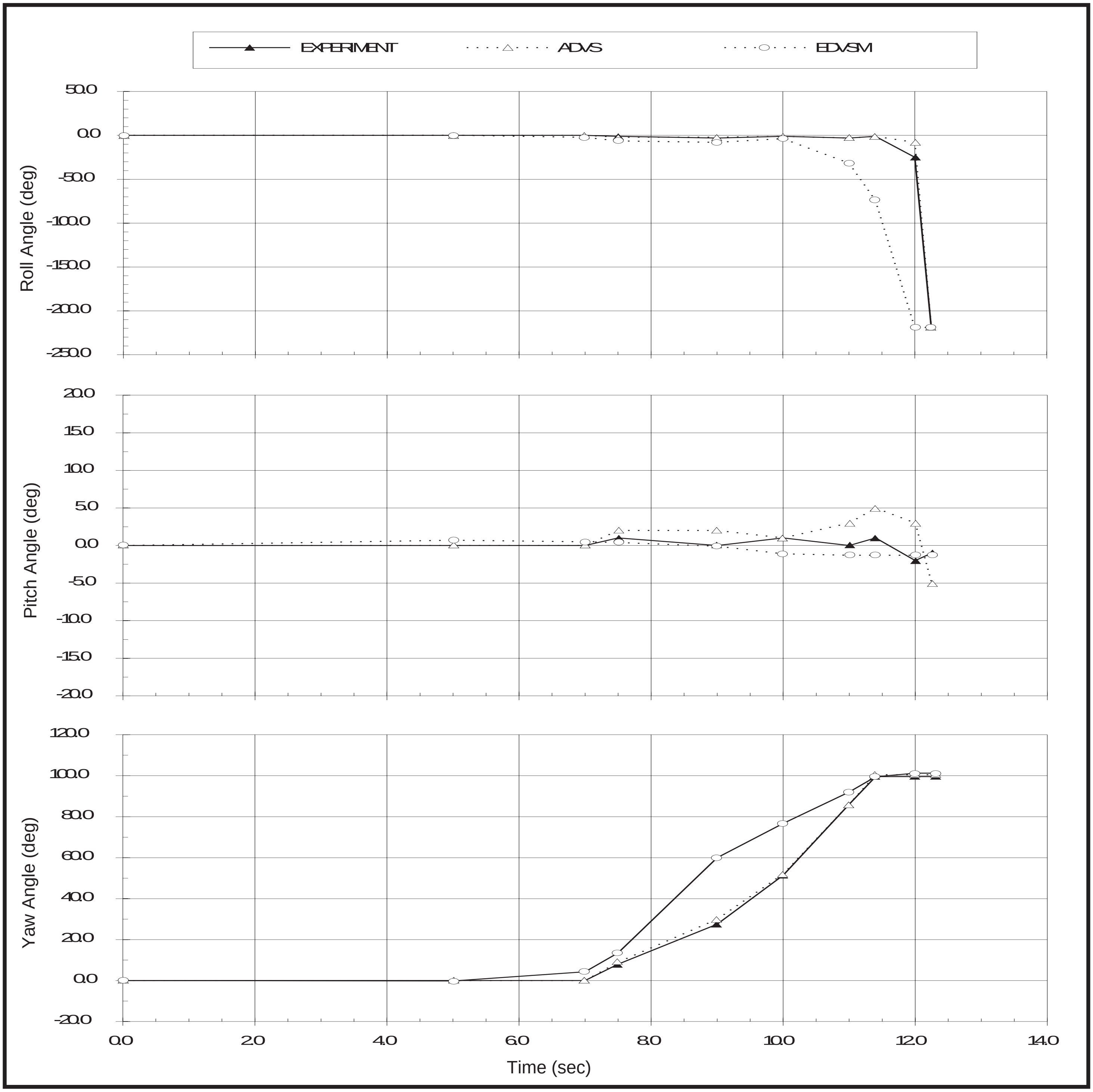

*Figure 24 - Results for Validation Test No. 5, Roll, Pitch and Yaw Orientations (top to bottom).*

was in substantial agreement with the experimental results, however, the problems that plagued the previous test (thought to be related to the tire parameters used for the EDVSM simulation) were more pronounced in this test.

The steer angle inputs are shown in Figure 23. Again, the steering was delayed slightly (0.2 second) in an effort to improve the agreement between simulated and actual path coordinates. Figure 23 shows good agreement in path coordinates, although the Y coordinate diverges for a short period.

Figure 24 reveals good trend information for roll, pitch and yaw angles. However, the EDVSM simulation predicts the rollover occurs about one-half second earlier in the maneuver.

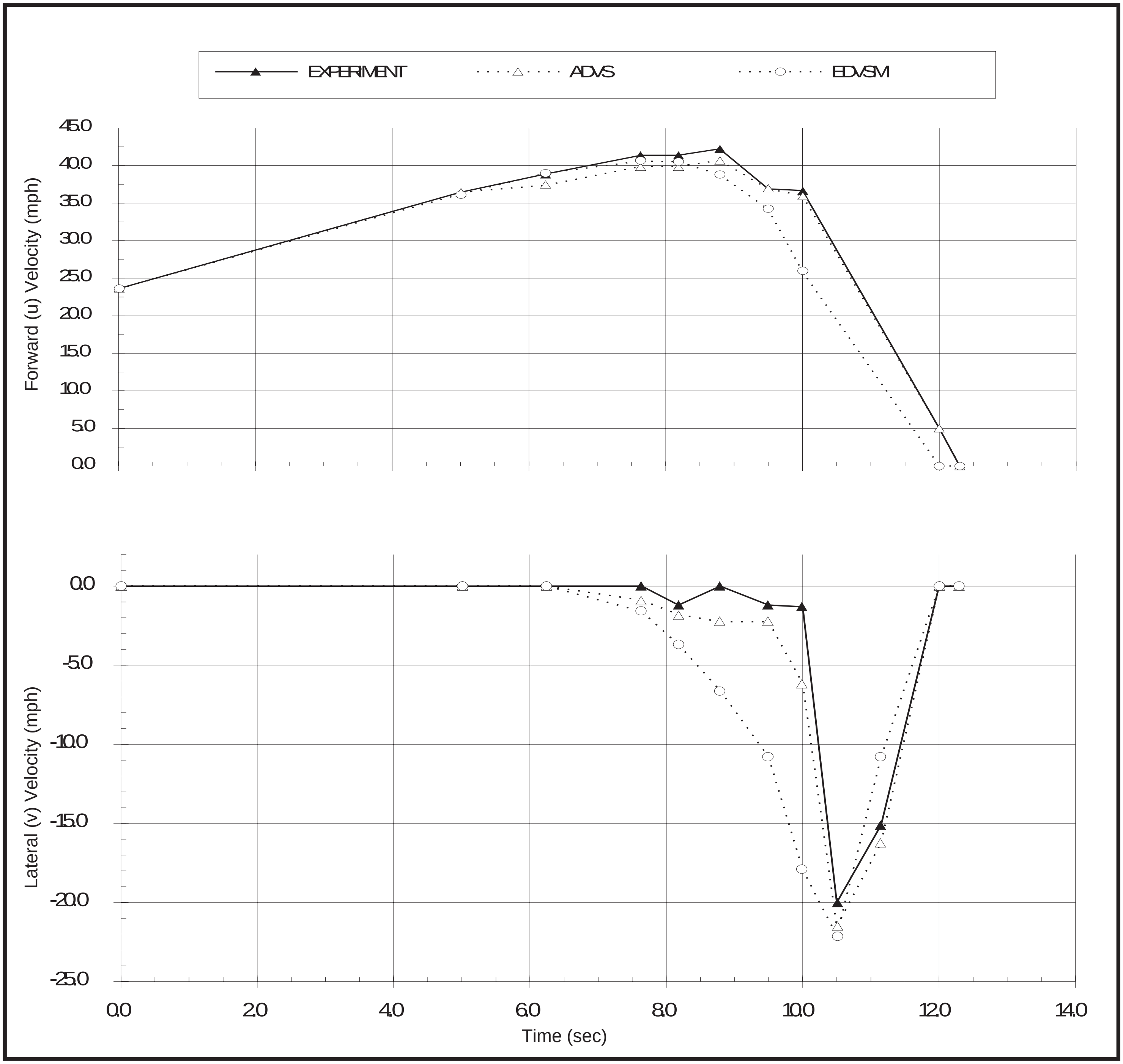

*Figure 25 - Results for Validation Test No. 5, Forward and Lateral Velocities.*

Figure 25 provides a comparison between simulated and actual linear velocities. Careful inspection of these values explains why the EDVSM simulation predicts an earlier rollover: At the time the test vehicle reached the soil pit, its measured sideslip angle was nearly zero (note the measured v-velocity is nil until 9.5 seconds - just before the vehicle reached the sand). However, the simulated vehicle's sideslip angle was about -20 degrees, thus, it slid into the soil sideways resulting in a much more severe roll response.

Increasing the tire-road friction parameters did not improve the match between simulated and measured response. Again, it is felt that a mismatch between simulated and actual tire cornering stiffness parameters is largely responsible for the differences between simulated and actual vehicle behavior.

Comparison between simulated and measured wheel displacements shown in Figure 26 again reveals excellent agreement throughout the entire test.

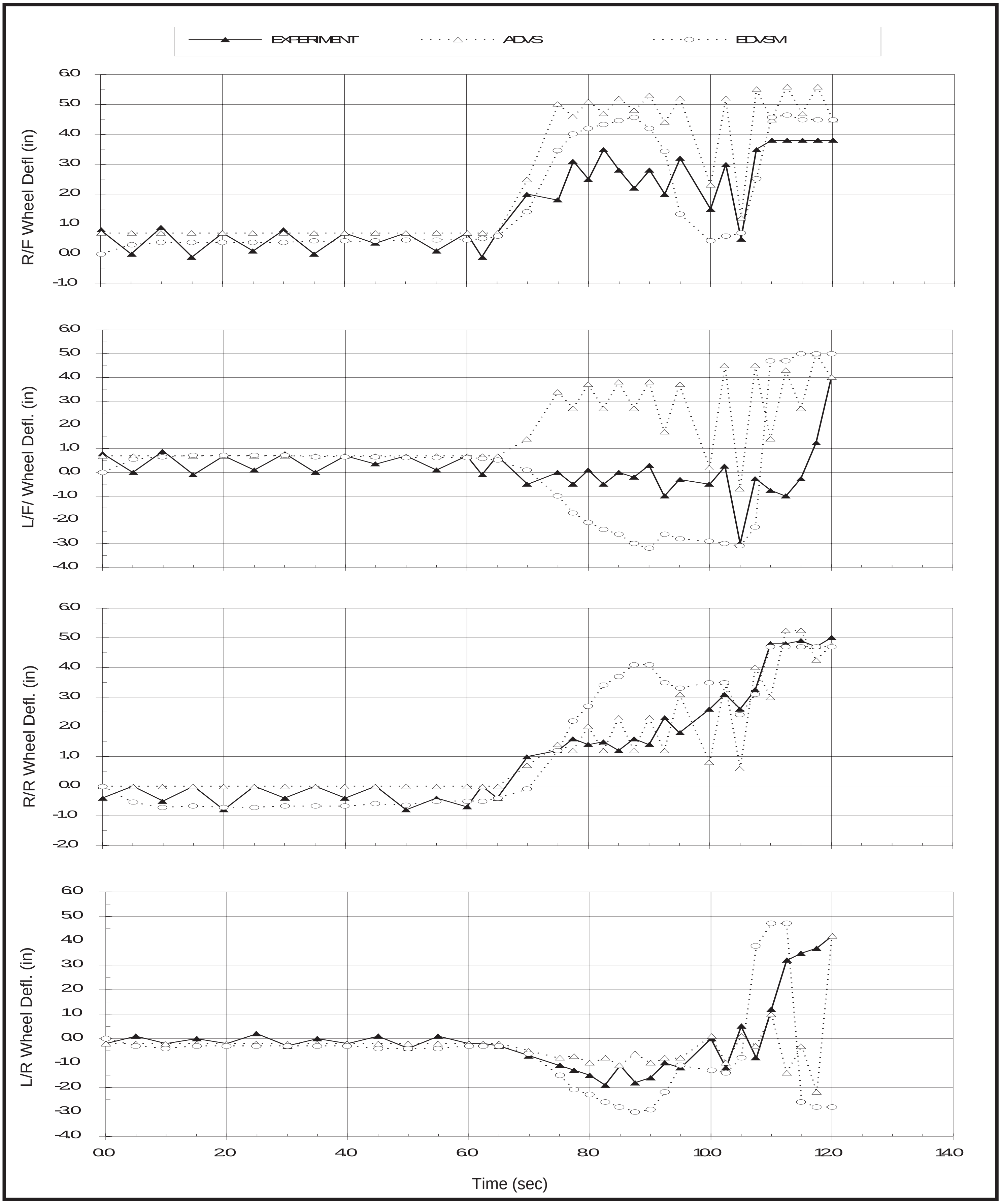

*Figure 26 - Results for Validation Test No. 5, Wheel Displacements for Right Front, Left Front, Right Rear and Left Rear (top to bottom).*

Graphs for lateral acceleration during tests 4 and 5 are not presented. However, inspection reveals lateral accelerations during the approach period of 0.70 to 0.80 g, as expected according to the design criteria mentioned earlier.

## DISCUSSION

The HVOSM-VD1 and HVOSM-SMI1 models used in the original HVOSM validation were replaced by the HVOSM-VD2 and HVOSM-RD2 models. Because of differences in the previous and current models, especially in the tire models, differences are expected between the original results and the results obtained using EDVSM. This validation shows the differences are not significant.

The fact that EDVSM did not include a soil model did not seem to preclude its use for soil-tripped rollover simulation. The elevated friction value used in this simulation was varied greatly (i.e., between 1.5 and 4.0), with little effect on the results. In general, it appears that the elevated friction value simply represents a lumped parameter approach to soil modeling.

An integration timestep of  0.01 to 0.0025 seconds was used for all the EDVSM simulations in this research. This range is adequate for most situations, with the possible exception of a high-speed curb impact. During a single 0.0025 second timestep, a vehicle at 75 mph travels 3.3 inches per timestep, thus, the simulated vehicle could essentially skip over the curb. The user should carefully watch the tire-road interaction and reduce the integration timestep (0.001 seconds is reasonable) if it appears the vehicle is skipping over the curb.

The first three tests in this report were duplicated very easily. These tests, performed by Calspan, illustrate the value in a well documented handling experiment. The final two tests were very difficult to duplicate, and in fact, several assumptions were necessary, as described earlier in this report, in order to provide a useful basis for additional testing. The problems encountered attempting to use these experiments illustrates the need to quantify all parameters. This applies to both the experimental results as well as the parameters used for the simulation study. However, the researchers at Missouri are to be commended for their excellent testing methodology.

The Bronco II experiments deliberately exposed the vehicle to extreme conditions intended to cause rollover. These tests were performed in the interest of helping vehicle safety researchers better understand rollover mechanisms by providing field experiments for use in validation studies.

## FUTURE WORK

A 3-D simulation of rollover is limited by the vehicle body's interaction with the ground. Thus, if a simulated vehicle rolls completely over onto its roof, for example, the interaction between the roof and ground is not modeled. HVE provides two potential methods for simulating this interaction. First, HVE has the capability of supplying the actual vehicle body geometry to EDVSM (the environment geometry is already supplied). Thus, it would be possible for EDVSM to directly model the body vs ground interaction. However, the computational requirements are beyond current computer technologies. The second approach would be to use the contact surfaces available in the HVE Vehicle model. This second approach is well within currently available computer capabilities and could implemented by EDVSM with little effort.

The tire model in HVOSM includes a radial spring model, useful for modeling curb impact. The radial spring model has not been implemented in EDVSM, potentially reducing the fidelity of the EDVSM model for curb impact (although validations of curb impact in this study still showed reasonable results). Although the radial spring model will be implemented for EDVSM, it is expected a more robust model will follow.

Any extension to the tire model should include the capability for modeling tire interaction with deformable soil. Such an extension would require modification to the environment model in addition to the tire model.

HVOSM and several other simulators include an option for closed-loop driver inputs, that is, the driver input tables include a desired path, and the model attempts to calculate the driver inputs required to follow the path. To implement this option in EDVSM first requires a simple extension of the HVE simulation environment.

## CONCLUSIONS

1. An analysis of five well instrumented handling experiments revealed the simulated vehicle response using EDVSM compared vary well with measured vehicle response.

2. EDVSM required essentially the same input and produced the same output as HVOSM-VD2. The basic vehicle models were also very similar. The major difference was in the user environment.

3. The capability of EDVSM to drive directly over any 3-D surface represents a substantial improvement in the ease and accuracy of modeling tire-road interaction. This was the result of a substantial change in the way the EDVSM tire model used the `GetSurfaceInfo()` library function in the HVE simulation environment interacted with the terrain.

4. The ability to visualize the 3-D response of a vehicle in real time (i.e., while the calculations are being performed) represents a substantial improvement compared to previous methods that used a post-processor to visualize the results. The ability to visualize detailed interactions also reduces the potential for error associated with the interpretation of a voluminous numeric output.

5. Improvements to the EDVSM model are necessary to allow its use for rollover crashes that result in the vehicle's upside down body contacting the earth.

6. Enhancements to the EDVSM tire model are suggested in order to provide more robust modeling of curbs and deformable soils.

## ACKNOWLEDGEMENT

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# Appendix A - 80 Column Card Image Input Deck for HVOSM-VD2

The following is an HVOSM card image input deck for Validation Test 2, Braking In A Turn.

```
BRAKING DYNAMICS VALIDATION RUNS 38-40                                     0 100
     0.0     4.5    .005      .1    70.0     1.3    60.0    .001           0 101
     1.0                                                                   0 103
     1.0     0.0     0.0     0.0     1.0     1.0     0.0     1.0           0 104
1963 FORD DATA                                                             0 200
   11.05    .608    .945   6000.  40000.  40000.   -192.   453.6           0 201
    58.5   60.75    61.2    60.5    -2.0   46.52                           0 202
     0.0     0.0    2.52    -97.     0.0     0.0    7.83    9.73           0 203
    131.    300.    600.    300.    600.     0.5    -2.9     4.3           0 204
    194.    300.    600.    300.    600.     0.5    -4.3     4.5           0 205
     1.3     58.     0.1    1.75     97.     0.1                           0 206
 266000.  59244.    .059                                                   0 207
     -5.     5.0     1.0                                                   0 209
    -5.7    -3.9   -2.45    -1.3   -0.4      0.3     0.6     .65     0.3   1 209
    -0.4    -1.3                                                           2 209
    -5.0     5.0     0.5                                                   0 210
   .1079   .1053    .103   .1011  .0994    .0981   .0971   .0964   .0959   1 210
   .0958    .096   .0965   .0973  .0934    .0998   .1015   .1035   .1058   2 210
   .1085   .1114   .1147                                                   3 210
    -5.0     5.0     5.0                                                   0 211
    .092    .092    .092                                                   1 211
     0.0    12.2     6.5    13.6     1.0     3.0                           0 212
     1.0     1.0   1000.   1000.    110.    192.     0.1                   0 213
     3.0     3.0                                                           0 214
    7.62     1.4    0.48    .942     0.0    3.12    6.21    6.43    4.62   1 214
     1.0    9.25    .384     0.0     10.  10.E10  10.E10                   2 214
    7.62     1.4    .476    .691     0.0    3.12    6.21    6.43    4.62   3 214
     1.0    9.25    .381     0.0     10.  10.E10  10.E10                   4 214
    500.   4900.    400.                                                   0 215
    500.    563.    594.    618.    630.    621.    600.    561.    516.   1 215
    480.    438.    420.                                                   2 215
     0.0   -120.   -144.   -165.   -180.   -192.   -204.   -216.   -231.   3 215
   -249.   -267.   -288.                                                   4 215
     0.0   1000.     20.                                                   0 216
     .96    .974    .965    .996     1.0    1.03    1.01     1.0    .995   1 216
    .982    .972    .952    .930    .907    .859    .814     .77    .727   2 216
    .687    .645    .609    .586    .561    .536    .515      .5    .488   3 216
    .475    .465    .454    .444    .441    .438    .435    .432    .429   4 216
    .425    .422    .419    .416    .414    .410    .407    .404    .401   5 216
    .398    .395    .391    .388    .385    .382                           6 216
9.611E-52.853E-2  60.336                                                   0 217
STANDARD TIRES                                                             0 300
     1.0     1.0     1.0     1.0    .987      6.     .25      3.      3.   0 301
    200.   1200.   2200.                                                   1 301
     0.0    704.   1408.                                                   2 301
     1.0                                                                   0 302
   1300.      3.     10.   4000.     8.4   3000.    1.71   4200.           1 302
      1.   14.68    .987  20160.     0.0                                   2 302
   1.123    .987    .918                                                   3 302
    .917    .782    .713                                                   4 302
    .710    .574    .506                                                   5 302
   1.404   1.234   1.148                                                   6 302
   1.146    .978    .891                                                   7 302
    .888    .718    .633                                                   8 302
   1.123    .987    .918                                                   9 302
    .917    .782    .713                                                  10 302
    .710    .574    .506                                                  11 302
     .16     .16     .16                                                  12 302
     .16     .16     .16                                                  13 302
     .16     .16     .16                                                  14 302
CORNERING STOP CONTROLS                                                    0 400
     0.0     4.5     0.1     1.0                                           0 401
      0.      0.      0.      0.      0.      0.      0.     -.3     -3.   1 401
     -6.    -6.9   -7.15     -7.   -6.85    -6.8    -6.8    -6.9   -6.97   2 401
   -6.95   -6.95   -6.95   -6.95   -6.95   -6.95   -6.95   -6.92   -6.91   3 401
    -6.9    -6.9   -6.88   -6.86   -6.82   -6.80   -6.78   -6.77   -6.75   4 401
   -6.72    -6.7    -6.7    -6.7   -6.0    -6.45   -6.32   -6.23    -6.2   5 401
    -6.2                                                                   6 401
     0.0     4.5     0.1     1.0                                           0 402
      0.      0.      0.      0.      0.      0.    410.    425.    412.   1 402
    409.    405.    403.    402.    400.    398.    395.    390.    388.   2 402
    387.    386.    385.    383.    382.    381.    378.    375.    372.   3 402
    371.    370.    370.    369.    369.    368.    367.    365.    362.   4 402
    360.    357.    355.    355.    402.    437.    437.    437.    437.   5 402
    437.                                                                   6 402
41.25 MPH                                                                  0 600
      0.      0.      0.      0.      0.      0.      0.      0.           0 601
      0.      0.  -21.52    726.      0.      0.                           0 602
      0.      0.      0.      0.      0.      0.      0.      0.           0 603
    170.    170.    170.    170.    170.                                   0 604
                                                                           09999
```

# Appendix B - Partial Output from HVOSM-VD2

The following is part of an HVOSM Output Report for Validation Test 2, Braking In A Turn.

```
1963D DA
STAN TIR

                    P R O G R A M   C O N T R O L   D A T A
     START TIME                    T0     =    0.0000  SEC
     END TIME                      T1     =    4.0000  SEC
     INTEGRATION INCREMENT         DTCOMP =    0.0010  SEC
                                                         (0=VARIABLE STEP ADAMS-MOULTON
     INTEGRATION MODE              MODE   =    1        -)1= RUNGA-KUTTA
                                                         (2= FIXED STEP ADAMS-MOULTON
     PRINT INTERVAL                DTPRNT =    0.0100  SEC
                                                         (0= INDEPENDENT FRONT SUSPENSION, SOLID REAR AXLE
     SUSPENSION OPTION             ISUS   =    0        -)1= INDEPENDENT FRONT AND REAR SUSPENSION
                                                         (2= SOLID FRONT AND REAR AXLES
                                                         (0= NO CURB, NO STEER DEGREE OF FREEDOM
     CURB/STEER OPTION             INDCRB =    0        -)1= CURB
                                                         (-1=STEER DEGREE OF FREEDOM, NO CURB
     CURB INTEGRATION INCR.        DELTC  =   0.00000  SEC
     WHEEL SPIN EQUATION FACTOR    COMEN4 =   0.00100


                                               I N I T I A L   C O N D I T I O N S

                                   XC0P   =    0.00   INCHES                                         U0   =  528.00   IN/SEC
     SPRUNG MASS C.G. POSITION     YC0P   =    0.00   INCHES        SPRUNG MASS LINEAR VELOCITY     V0   =    0.00   IN/SEC
                                   ZCOP   =    0.00   INCHES                                         W0   =    0.00   IN/SEC
                                   PHI0   =    0.00   DEGREES                                        P0   =    0.00   DEG/SEC
     SPRUNG MASS ORIENTATION       THETA0 =    0.00   DEGREES       SPRUNG MASS ANGULAR VELOCITY    Q0   =    0.00   DEG/SEC
                                   PSI0   =    0.00   DEGREES                                        R0   =    0.00   DEG/SEC
                                   DEL10  =    0.00   INCHES                                       DEL10D =    0.00   IN/SEC
     UNSPRUNG MASS POSITIONS       DEL20  =    0.00   INCHES        UNSPRUNG MASS VELOCITIES      DEL20D =    0.00   IN/SEC
                                   DEL30  =    0.00   INCHES                                       DEL30D =    0.00   IN/SEC
                                   PHIR0  =    0.04   DEGREES                                      PHIR0D =    0.00   DEG/SEC
     STEER ANGLE                   PSIFI0 =    0.00   DEGREES       STEER VELOCITY                 PSIFD0 =    0.00   DEG/SEC

1963D DA
STAN TIR

     SPRUNG MASS                   XMS   =    11.050 LB-SEC**2/IN     FRONT WHEEL X LOCATION    A    =    58.500 INCHES
     FRONT UNSPRUNG MASS           XMUF  =     0.608 LB-SEC**2/IN     REAR WHEEL X LOCATION     B    =    60.750 INCHES
     REAR UNSPRUNG MASS            XMUR  =     0.945 LB-SEC**2/IN     FRONT WHEEL Z LOCATION    ZF   =     7.830 INCHES
     X MOMENT OF INERTIA           XIX   =  6000.000 LB-SEC**2-IN     REAR WHEEL Z LOCATION     ZR   =     9.730 INCHES
     Y MOMENT OF INERTIA           XIY   = 40000.000 LB-SEC**2-IN     FRONT WHEEL TRACK         TF   =    61.200 INCHES
     Z MOMENT OF INERTIA           XIZ   = 40000.000 LB-SEC**2-IN     REAR WHEEL TRACK          TR   =    60.500 INCHES
     XZ PRODUCT OF INERTIA         XIXZ  =  -192.000 LB-SEC**2-IN     FRONT ROLL AXIS           RHOF =     0.000 NOT USED
     FRONT AXLE MOMENT OF INERTIA  XIF   =     0.000 NOT USED         REAR ROLL AXIS            RHO  =    -2.000 INCHES
     REAR AXLE MOMENT OF INERTIA   XIR   =   453.600 LB-SEC**2-IN     FRONT SPRING TRACK        TSF  =     0.000 NOT USED
     GRAVITY                       G     =   386.400 IN/SEC**2        REAR SPRING TRACK         TS   =    46.520 INCHES
                                   X1    =      0.00 INCHES           FRONT AUX ROLL STIFFNESS  RF   =  59244.00 LB-IN/RAD
     ACCELEROMETER 1 POSITION      Y1    =      0.00 INCHES           REAR AUX ROLL STIFFNESS   RR   = 266000.00 LB-IN/RAD
                                   Z1    =      0.00 INCHES           REAR ROLL-STEER COEF.     AKRS =    0.0590 RAD/RAD
                                   X2    =      0.00 INCHES                                     AKDS =     0.000 NOT USED
     ACCELEROMETER 2 POSITION      Y2    =      0.00 INCHES           REAR DEFL-STEER COEFS.    AKDS1=     0.000 NOT USED
                                   Z2    =      0.00 INCHES                                     AKDS2=     0.000 NOT USED
                                                                                                AKDS3=     0.000 NOT USED
           S T E E R I N G   S Y S T E M
     MOMENT OF INERTIA       XIPS  =     0.000 LB-SEC**2-IN
     COULOMB FRICTION TORQUE CPSP  =     0.000 LB-IN
     FRICTION LAG            EPSP  =     0.000 RAD/SEC
     ANGULAR STOP RATE       AKPS  =     0.000 LB-IN/RAD
     ANGULAR STOP POSITION   OMGPS =     0.000 RADIANS
     PNEUMATIC TRAIL         XPS   =     0.000 INCHES
         D R I V E  L I N E   D A T A
     FRONT WHEEL SPIN INERTIA  FIWJF =  12.200 LB-SEC**2-IN
     REAR WHEEL SPIN INERTIA   FIWJR =  13.600 LB-SEC**2-IN
     FRONT AXLE RATIO          ARBRF =   1.000
     REAR AXLE RATIO           ARBRR =   3.000
     FRONT DRIVELINE INERTIA   FIDJF =   0.000 LB-SEC**2-IN
     READ DRIVELINE INERTIA    FIDJR =   6.500 LB-SEC**2-IN
                                           FRONT SUSPENSION                    REAR SUSPENSION

     SUSPENSION RATE                  AKF    =   131.000 LB/IN            AKR    =   194.000 LB/IN
     COMPRESSION STOP COEFS.          AKFC   =   300.000 LB/IN            AKRC   =   300.000 LB/IN
                                      AKFCP  =   600.000 LB/IN**3         AKRCP  =   600.000 LB/IN**3
     EXTENSION STOP COEFS.            AKFE   =   300.000 LB/IN            AKRE   =   300.000 LB/IN
                                      AKFEP  =   600.000 LB/IN**3         AKREP  =   600.000 LB/IN**3
     COMPRESSION STOP LOCATION        OMEGFC =    -4.200 INCHES           OMEGRC =    -4.000 INCHES
     EXTENSION STOP LOCATION          OMEGFE =     4.000 INCHES           OMEGRE =     4.000 INCHES
     STOP ENERGY DISSIPATION FACTOR   XLAMF  =     0.500                  XLAMR  =     0.500
     VISCOUS DAMPING COEF.            CF     =     1.300 LB-SEC/IN        CR     =     1.750 LB-SEC/IN
     COULOMB FRICTION                 CFP    =    58.000 LB               CRP    =    97.000 LB
     FRICTION LAG                     EPSF   =     0.100 IN/SEC           EPSR   =     0.100 IN/SEC
```

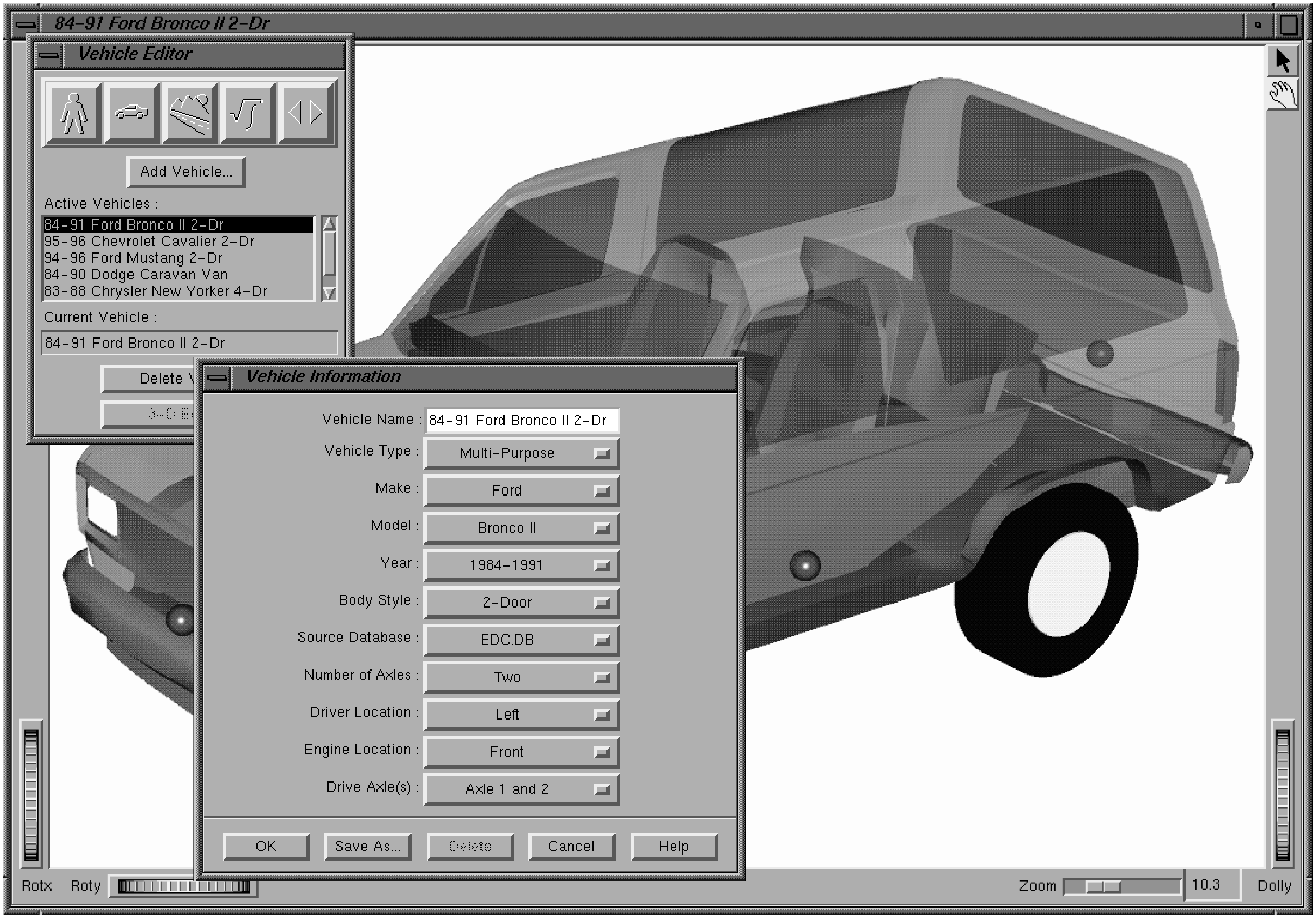
# Appendix B - Partial Output from HVOSM-VD2 (cont.)

The following is part of an HVOSM Simulation  Report for Validation Test 2, Braking In A Turn.

```
                  BRAKING DYNAMICS VALIDATION RUNS 38-40                                                        05-DEC-97
   1963 FORD DATA                          STANDARD TIRES                          CORNERING STOP CONTROLS
   41.25 MPH                                                     PAGE    11.01

                                               S P R U N G    M A S S
TIME   !         POSITION (FEET)           !      VELOCITY (FT/SEC)            !            ACCELERATION (G-UNITS)             !
 SEC   !     XC"   !     YC"   !     ZC"   !  FORWARD  !  LATERAL  !  VERTICAL !    LONG.  !      LAT.  !    VERT.  !  RESULT.  !

0.0000        0.00        0.00       -1.79       60.50        0.00        0.00       -0.03        0.00        0.00        0.03
0.1000        6.05        0.00       -1.79       60.41        0.00        0.06       -0.03        0.00       -0.02        0.03
0.2000       12.08        0.00       -1.79       60.33        0.00        0.08       -0.03        0.00       -0.02        0.03
0.3000       18.11        0.00       -1.79       60.25        0.00        0.05       -0.03        0.00        0.02        0.03
0.4000       24.13        0.00       -1.79       60.16        0.00        0.05       -0.03        0.00        0.07        0.08
0.5000       30.14        0.00       -1.79       60.08        0.00        0.06       -0.03        0.00        0.07        0.08
0.6000       36.13        0.00       -1.79       59.31        0.00       -0.01       -0.56        0.00        0.05        0.56
0.7000       41.97        0.00       -1.80       57.38       -0.01       -0.39       -0.62       -0.02        0.01        0.62
0.8000       47.61       -0.01       -1.80       55.43       -0.13       -0.83       -0.61       -0.13        0.02        0.62
0.9000       53.05       -0.06       -1.80       53.48       -0.19       -1.12       -0.62       -0.23        0.05        0.66
1.0000       58.30       -0.19       -1.79       51.53        0.02       -1.28       -0.61       -0.30        0.00        0.68
1.1000       63.35       -0.40       -1.80       49.58        0.42       -1.28       -0.61       -0.36        0.03        0.70
1.2000       68.21       -0.71       -1.80       47.63        0.89       -1.16       -0.60       -0.39       -0.01        0.72
1.3000       72.86       -1.13       -1.81       45.68        1.35       -1.08       -0.59       -0.41        0.05        0.72
1.4000       77.30       -1.66       -1.82       43.73        1.75       -0.93       -0.59       -0.44        0.05        0.74
1.5000       81.53       -2.29       -1.82       41.78        2.02       -0.82       -0.59       -0.47        0.06        0.76
1.6000       85.55       -3.03       -1.83       39.85        2.15       -0.80       -0.58       -0.48        0.03        0.75
1.7000       89.36       -3.88       -1.83       37.94        2.18       -0.74       -0.57       -0.50        0.06        0.76
1.8000       92.94       -4.83       -1.83       36.03        2.10       -0.69       -0.56       -0.50        0.03        0.76
1.9000       96.30       -5.86       -1.83       34.14        1.92       -0.66       -0.56       -0.50        0.03        0.75
2.0000       99.43       -6.98       -1.83       32.27        1.66       -0.60       -0.56       -0.49        0.02        0.74
2.1000      102.33       -8.17       -1.83       30.42        1.33       -0.52       -0.55       -0.48        0.03        0.73
2.2000      105.01       -9.42       -1.83       28.61        0.93       -0.48       -0.55       -0.46       -0.01        0.71
2.3000      107.46      -10.72       -1.83       26.83        0.51       -0.44       -0.54       -0.41        0.04        0.68
2.4000      109.69      -12.04       -1.83       25.09        0.11       -0.38       -0.53       -0.36        0.04        0.65
2.5000      111.72      -13.37       -1.82       23.39       -0.23       -0.33       -0.52       -0.30        0.04        0.60
2.6000      113.56      -14.68       -1.82       21.74       -0.50       -0.27       -0.51       -0.24        0.04        0.57
2.7000      115.21      -15.97       -1.81       20.12       -0.67       -0.19       -0.51       -0.19        0.03        0.54
2.8000      116.69      -17.20       -1.80       18.51       -0.77       -0.15       -0.50       -0.14        0.01        0.52
2.9000      118.02      -18.38       -1.79       16.91       -0.79       -0.18       -0.50       -0.10        0.00        0.51
3.0000      119.21      -19.47       -1.78       15.32       -0.75       -0.23       -0.49       -0.07       -0.01        0.50
3.1000      120.26      -20.48       -1.79       13.74       -0.68       -0.25       -0.49       -0.05       -0.01        0.49
3.2000      121.18      -21.40       -1.79       12.16       -0.64       -0.19       -0.48       -0.05       -0.01        0.48
3.3000      121.97      -22.21       -1.79       10.58       -0.59       -0.16       -0.47       -0.02        0.00        0.47
3.4000      122.64      -22.93       -1.79        9.01       -0.50       -0.16       -0.45       -0.01        0.00        0.45
3.5000      123.20      -23.53       -1.79        7.44       -0.43       -0.11       -0.43       -0.01        0.00        0.43
3.6000      123.65      -24.03       -1.79        5.86       -0.35       -0.08       -0.39        0.02        0.00        0.39
3.7000      123.99      -24.41       -1.79        4.30       -0.26       -0.08       -0.61        0.03        0.00        0.61
3.8000      124.22      -24.68       -1.79        2.91       -0.18       -0.04       -0.59        0.05       -0.01        0.59
3.9000      124.37      -24.85       -1.79        1.56       -0.11       -0.03       -0.84       -0.02        0.03        0.84
4.0000      124.42      -24.91       -1.79        0.11       -0.13        0.00       -0.32        0.92       -0.04        0.98
4.1000      124.41      -24.93       -1.79       -0.04       -0.12        0.05       -0.03        0.17       -0.03        0.18
4.1050      124.41      -24.93       -1.79       -0.03       -0.07        0.05       -0.03       -0.03        0.01        0.04
```

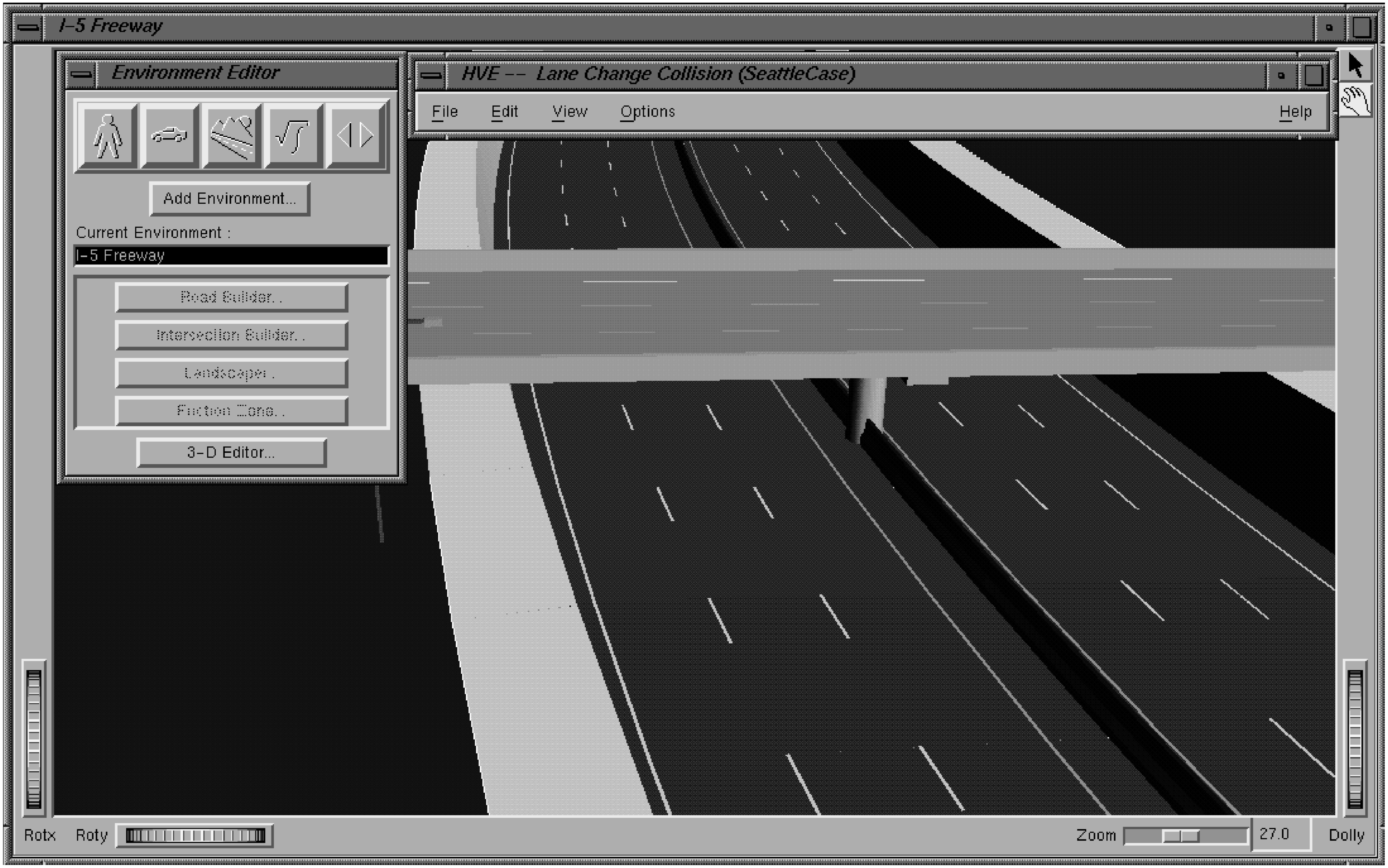


Active Vehicles :
- 84-91 Ford Bronco II 2-Dr
- 95-96 Chevrolet Cavalier 2-Dr
- 94-96 Ford Mustang 2-Dr
- 84-90 Dodge Caravan Van
- 83-88 Chrysler New Yorker 4-Dr

Current Vehicle : 84-91 Ford Bronco II 2-Dr

Vehicle Name : 84-91 Ford Bronco II 2-Dr
Vehicle Type : Multi-Purpose
Make : Ford
Model : Bronco II
Year : 1984-1991
Body Style : 2-Door
Source Database : EDC.DB
Number of Axles : Two
Driver Location : Left
Engine Location : Front
Drive Axle(s) : Axle 1 and 2

*Appendix C - HVE Vehicle Editor, used for creating and editing 3-D vehicles. The Vehicle Editor includes a relational database allowing the user to select vehicles according to Type, Make, Model, Year and Body Style.*



*Appendix D - HVE Environment Editor, used for creating 3-D environments. The geometry being visualized is also used to directly provide the 3-D terrain on which the vehicle is driven using HVE's GetSurfaceInfo() function.*

SAE #970958
Reviewer's Discussion
by Donald F. Rudny, P.E., Rudny & Sallmann Engineering, Ltd.
**Validation of the EDVSM 3-Dimensional Vehicle Simulator**
Terry D. Day, Author

The ability to use a version of the HVOSM program in the HVE environment (called EDVSM) appears to be quite exciting. A vehicle's interaction with road surface disparities such as dips, bumps potholes and edge drops can be evaluated by defining the road surface or discontinuity through survey topography techniques.

The author has done an excellent job in validating the EDVSM program. For those who are not using the HVE simulation environment, the paper is useful in revisiting the validation studies used for HVOSM and ADVS. The author has also demonstrated the extensive work necessary to perform a credible validation of a computer program used in the accident reconstruction community. All too often accident reconstruction or simulation programs surface without adequate documentation or validation.

Although the validation indicated close correlation with experimental data, it appears that highly complex models should only be utilized to predict or evaluate trends in vehicle response to road and driver input. The potential for modeling and predicting a vehicle's rollover dynamics after the tires leave the ground may be limited, because past experimental studies have shown that repeatability is poor.

SAE #970958
Reviewer's Discussion
by Wayne McCracken, Research Engineers, Inc.
**Validation of the EDVSM 3-Dimensional Vehicle Simulator**
Terry D. Day, Author

The EDVSM Simulation Program is a very welcome addition to the HVE environment. The ability to simulate vehicle dynamics using this code and then view the output in fully rendered 3-D animation should not be underestimated. The ability to see what the vehicle is doing, rather than to have to interpret a numeric position time history, can save a substantial amount of time for even the experienced user. The simulation output appears to correlate well with the original HVOSM code. The discussion of future work to include body ground contact so as to simulate multiple rollovers is very desirable.