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# Validation of the SIMON Model for Vehicle Handling and Collision Simulation – Comparison of Results with Experiments and Other Models

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## ABSTRACT

SIMON is a new 3-dimensional vehicle dynamic simulation model. The capabilities of the model include non-linear handling maneuvers and collision simulation for one or more vehicles. As a new model, SIMON must be validated by comparison against actual handling and collision experiments. This paper provided that comparison. Included in the validation were lane-change maneuvers, alternate ramp traversals, limit maneuvers with combined braking and steering, vehicle-to-vehicle crash tests and articulated vehicle handling tests. Comparison against other models were included. No metric was provided for handling test comparisons. However, statistical analysis of the collision test results revealed the average path range error was 6.2 to 14.8 percent. The average heading error was -4.7 to 0.7 percent. Delta-V error was -1.6 to 7.5 percent.

VEHICLE SIMULATION has many uses in the vehicle design and safety industries. Applications include suspension modeling, vehicle-tire system modeling, brake system modeling, virtual prototyping and compliance testing (ISO braking and lane change maneuvers) and safety analysis (collision simulation and post-crash reconstruction of actual on-road events).

Advances in vehicle modeling and computer hardware and software technologies have made possible significant improvements in vehicle simulation, resulting in newer and more powerful modeling capability. For example, simulations in the 1980's and early 1990's typically used 2-dimensional models employing three degrees of freedom. More sophisticated models existed, but were seldom used because of their crude user interfaces.

In 1996, the HVE simulation environment was introduced [1-6][*]. HVE (Human-Vehicle-Environment) was developed as a sophisticated, 3-dimensional user environment for setting up and executing simulations involving humans and vehicles interacting with their environment. HVE was designed to be a general purpose tool, making few assumptions about the details of the actual simulation. Those details were left up to the designer/programmer of the simulation model.

In 2001, a new HVE-compatible simulation model, called SIMON (*SI*mulation *MO*del *N*onlinear), was introduced. SIMON provided the capability to simulate maneuvers involving 3-dimensional vehicle dynamics, such as driving on irregular terrain and vehicle rollover. With the addition of DyMESH [7], SIMON provided the capability to simulate collisions involving over-ride and other 3-dimensional collision issues. A report was published [8], providing the technical details and capabilities of the SIMON model. This is the second technical report on SIMON. This report presents the results of a detailed validation study of the SIMON model.

## PROCEDURE

The SIMON model is applicable to unit vehicles (i.e., a vehicle having a single sprung mass), articulated vehicles (i.e., multiple unit vehicles connected together) as well as unit and articulated vehicle collisions (vehicle-to-vehicle and vehicle-to-barrier).

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

To exercise each of these capabilities, the following tests were included in the validation study:

- Unit Vehicle – Four unit vehicle handling maneuvers were simulated
- Articulated Vehicle – Two articulated vehicle handling maneuvers were simulated
- Unit Vehicle Collisions – Five vehicle-to-vehicle collision experiments were simulated

Tables 1 through 3 provide a description of these tests. The tests were selected according to the following criteria:

- Availability of quality experimental data
- Range of test conditions reflecting real-world driving conditions
- Exercising the features of the model

The detailed results from these tests are contained in three volumes comprising several hundred pages. This report contains a synopsis of those detailed test results [9].

This report presents results for 3-dimensional sprung mass kinematics (position, velocity and acceleration) for all tests for all available data (none of the experiments recorded results for all variables). SIMON results are compared directly against experimental results, where available, and in some cases, results from other simulation models.

In addition to sprung mass kinematics, the collision simulations also include comparisons for rest position error, delta-V, peak acceleration and vehicle damage.

The experimental data used in this validation were obtained from several sources (see Tables 1-3).

## Vehicle Parameters

Vehicle parameters for tests UV-1 and UV-2 were developed by Ford Motor Company. All other simulations were performed using vehicle models in the EDC Vehicle Database [10]. The actual vehicles from which the models were built have been physically inspected. Vehicle exteriors were measured and digitized using a FARO 3-D mechanical arm [11]. Vertical loads at each wheel were measured using platform scales [12]. Suspension rates and other parameters were measured or estimated. Shock rates were calculated assuming critical damping. Rotational inertias were obtained from VRTC [13] or from similar vehicles [14]. Exterior stiffnesses were obtained from the NHTSA Crash Test Database [15] or from similar vehicles [14]. Brake properties were calculated using the HVE Brake Designer [6]. Steering gear ratios were measured. All tires were from the Generic Tire Database [10], derived from Calspan test data.

*Table 1. Unit Vehicle Handling Experiments*

| Test | Description |
|---|---|
| UV-1 | Passenger Car Combined Steering and Braking [16] |
| UV-2 | Passenger Car Alternate Ramp Traversal [16] |
| UV-3 | Light Truck Rollover [17] |
| UV-4 | Straight 3-Axle Truck (30 mph), Combined Braking and Steering [19] |

*Table 2. Articulated Vehicle Handling Experiments*

| Test | Description |
|---|---|
| AV-1 | Chevrolet Pickup (55 mph) towing Open-wheel Utility Trailer, ISO Lane-change with braking |
| AV-2 | Tractor-trailer (27 mph), Combined Braking and Steering (U of M) [19] |

## Environment Parameters

All simulations were performed using environments created in the HVE 3-D Editor. Friction zones (regions having different, user-definable tire-ground friction characteristics) were assigned where appropriate to model different terrains. All experiments were performed on a nominally flat, horizontal surface.

## Event Set-up Parameters

The vehicle CGs were located longitudinally and laterally to approximate the experimental static vertical tire loads for each test vehicle (within 25 lb at each tire). These tire loads also reflected the inertial changes due to on-board instrumentation and test dummies.

Initial positions were obtained directly from the test reports, and modified as required to reflect the inertial position of the *sprung mass* center of gravity (test reports presented *total vehicle* CG location). Initial velocities were obtained directly from test data.

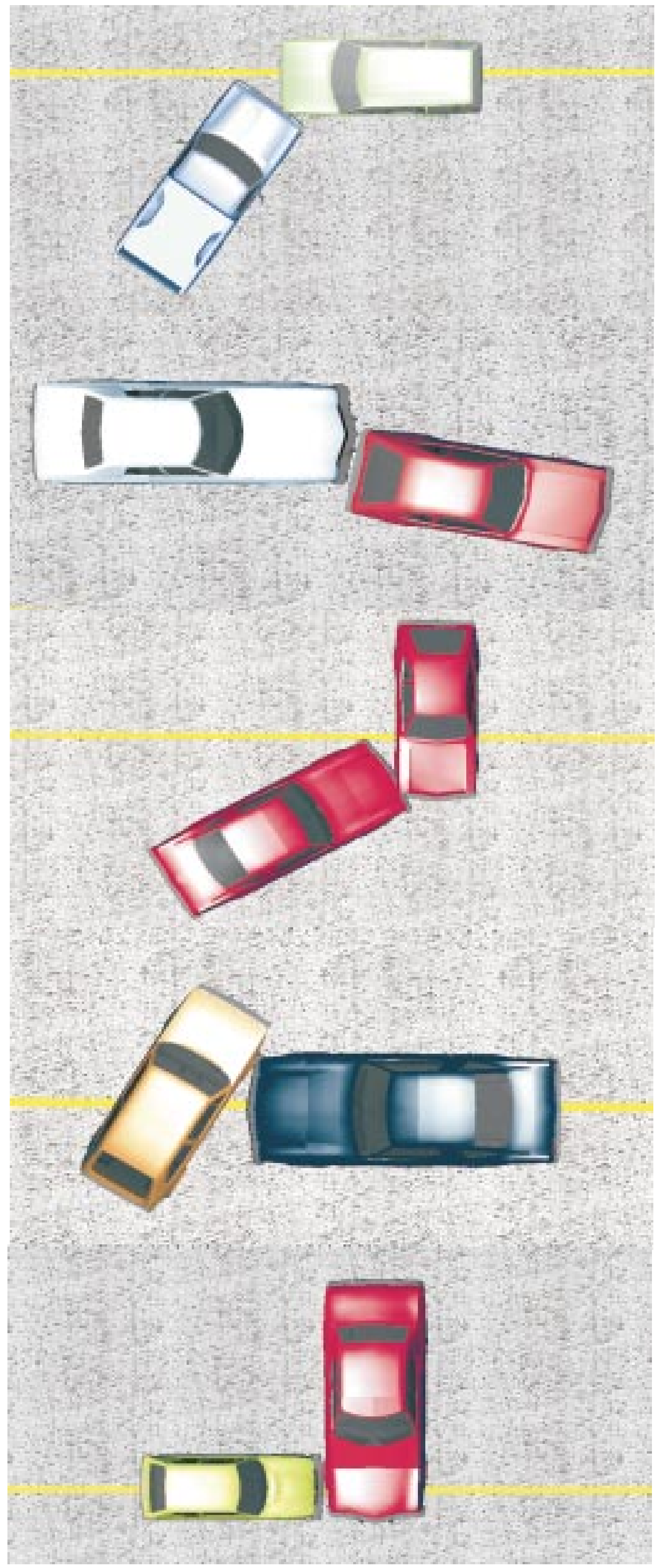
Vehicle transmissions were assigned the gear specified in the experimental reports. Tire rolling resistances used default values. Where applicable for collision tests, post-impact wheel lock-ups were estimated from the available experimental data.

Driver inputs (steering, braking, throttle and gear position) were obtained directly from the test reports.

Virtual accelerometers were fitted to the vehicles according to the locations specified in the test reports. The

*Table 3 - Vehicle Collision Experiments*

| Test | Description | Collision Type | Configuration at Impact |
|---|---|---|---|
| VC-1 | 1992 Ford Explorer (45.9 mph) vs. 1984 Ford F-150 Pickup (46.1 mph), 55 Degree Angled Impact [25] | Oblique | |
| VC-3 | 1974 Ford Torino (21.23 mph) vs. 1974 Ford Pinto (0 mph), 10 Degree Offset Rear-end Impact (Calspan, RICSAC 3) [20] | Collinear | |
| VC-7 | 1974 Chev Chevelle (31.53 mph) vs. 1974 Ford Pinto (31.53 mph), 60 Angled (Calspan, RICSAC 2) [20] | Oblique | |
| VC-8 | 1974 Chevrolet Chevelle Malibu (21.47 mph) vs. 1975 Volkswagen Rabbit (21.47 mph), 60 Degree Angled Impact (Calspan, RICSAC 6) [20] | Oblique | |
| VC-11 | 1974 Honda Civic CVCC (31.35 mph) vs. 1974 Ford Torino (31.35 mph), 90 Degree Angled Impact (Calspan, RICSAC 10) [20] | Oblique | |



coordinate locations were corrected to reflect locations relative to the sprung mass center of gravity. Many vehicles were fitted with multiple accelerometers.

## Event Execution

Events were executed to completion. Simulation results were then compared against the experimental data.

## Calculation of Error

Program *error*, when applied to simulation programs, describes how well the simulation predicts the outcome of the experimental event. The outcomes for the collision experiments simulated in this study were rest position and delta-V. These results are shown in Tables 7 and an analysis of error is shown in Table 8. The errors were analyzed differently, depending on the nature of the experimental data.

### Path Position

Path position errors were computed according to the distance from the predicted position to the actual (experimental) position; see Figure 1. (This same procedure was also used in the calculation of the error score in previous validations [24].) For the difference in X,Y path coordinates (*range error*), the error was

$$ERROR = \frac{\Delta(X,Y)}{L_{Act}} \times 100$$

where

$\Delta(X,Y)$ = difference between predicted and measured rest position

$$= \sqrt{(X_{Pred} - X_{Act})^2 + (Y_{Pred} - Y_{Act})^2}$$

$L_{act}$ = actual path length

$$= \sqrt{(X_{Rest} + X_{Imp})^2 + (Y_{Rest} - Y_{Imp})^2}$$

*Pred* = predicted value
*Act* = actual (measured) value
*Rest* = rest coordinate
*Imp* = impact coordinate

For the difference in heading angle, the error was

$$ERROR = \frac{\Delta\psi_{Pred} - \Delta\psi_{Act}}{360} \times 100$$

where

$\Delta\psi_{Pred} = (\psi_{Rest} - \psi_{Imp})_{Pred}$
$\Delta\psi_{Act} = (\psi_{Rest} - \psi_{Imp})_{Act}$

### Delta-V

Velocity change (Delta-V) errors were computed using the difference between predicted and actual (measured) values:

$$ERROR = \frac{\Delta V_{Pred} - \Delta V_{Act}}{\Delta V_{Act}} \times 100$$

It is important to recognize that the delta-Vs originally reported for the RICSAC [20] tests were incorrect. This has been attributed to fact that the accelerometers were not located at the vehicle CG, but were instead located on the firewall (actually, the vehicles were fitted with several accelerometers; the firewall accelerometers were used for purposes of delta-V calculation in the original RICSAC reports). Later reports [21, 22, 23] used high-speed films and further data analysis to refine the delta-V estimates. This report uses the best available data for each experiment.

### Damage Profile

For collision experiments, the simulated damage and actual damage were compared qualitatively using photographs from the post-crash vehicle inspections and the damage profile visualization output from the simulation. No attempt was made to perform any quantitative assessment of the damage profile error.

# TEST RESULTS

The tests included in this paper are a subset of a large number of test comparisons included in reference 9. In addition, reference 9 also includes detailed simulation tests results, such as wheel spin velocity and suspension deflection, not found in this paper. The interested reader is referred to reference 9 for more information.

Specific results for each unit vehicle handling test, articulated vehicle handling test and vehicle collision test are discussed in this section.

## Unit Vehicle Tests

The four unit vehicle handling tests are described in Table 1. The results are presented graphically in Figures 2 - 5. A brief description of the results for each test is presented below.

### Test UV-1, Combined Steering and Braking

This experiment was conducted as part of the original HVOSM validation [16]. A 1963 Ford Galaxy 4-Dr Sedan was used to perform the maneuver (see Discussion for comments regarding the age of the vehicle). Detailed measurements of the vehicle parameters required for the simulation were made by Ford Motor Company. Tire parameters were provided by General Motors (GM provided the actual tires as well). The data acquisition package for this test is shown in Table 4.

The test was conducted by accelerating the vehicle to a nominal speed of 40 - 45 mph and activating the instrument package. The driver then 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. A brake pedal stop was used to limit pedal travel and ensure repeatability of the applied brake pressure. Although a servo was not used to control the steering input, the driver practiced the test sequence several times to ensure repeatability of the steering input.

**Discussion of Results -** Figure 2 provides a comparison of the results obtained using SIMON and EDVSM. Some experimental results are also included. Comparison of X-Y path coordinates revealed SIMON and EDVSM yielded very similar results. Sprung mass roll and yaw angles also agreed closely, although both simulations predicted that roll and yaw would begin later when compared to experimental values (experimental results for roll and yaw actually began *before* the steering input, suggesting the time trace may have been out of phase in the strip charts). SIMON and EDVSM results also agreed closely for linear and angular velocities. SIMON, EDVSM and experimental results also agreed quite nicely for forward and lateral accelerations. Instability may be observed in EDVSM and, to a lesser extent, SIMON as the velocities approach zero (this is not uncommon in simulations when the termination velocities are set to zero; see Discussion).

*Table 4. Instrumentation for unit vehicle experiments*

| Test | Measurement | Instrumentation |
|---|---|---|
| UV-1 UV-2 | Pitch/Roll Attitude | 2-DOF Free Gyro |
| | Yaw Attitude | 2-DOF Free Gyro (outer gimbal used) |
| | Steer Angle | Linear stroke potentiometer |
| | Linear Accel | Accelerometer |
| UV-3 | Linear Position | Integrated from accelerometer data and video |
| | Angular Orientation | Integrated from accelerometer data and video |
| | Steer Angle | Stepper motor at Steering Wheel |
| | Brake Pressure | Strain gage pressure transducer |
| | Linear and Angular Accel | Accelerometers (six) |
| UV-4 | Linear Vel | 5th Wheel |
| | Linear Accel | Humphrey Platform |
| | Angular Orientation | Humphrey Platform |
| | Steer Angle | Linear Stroke Potentiometer |
| | Brake Pressure | Strain gage pressure transducer |
| | Wheel Spin Vel | Bicycle Generators |

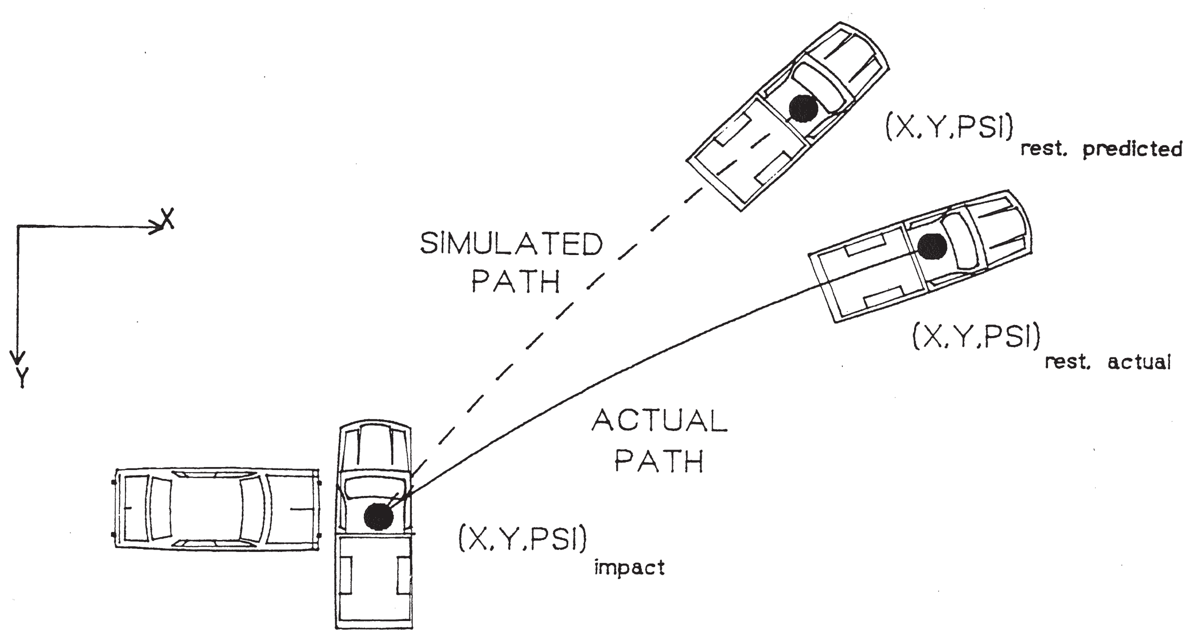



*Figure 1 - Path error analysis*

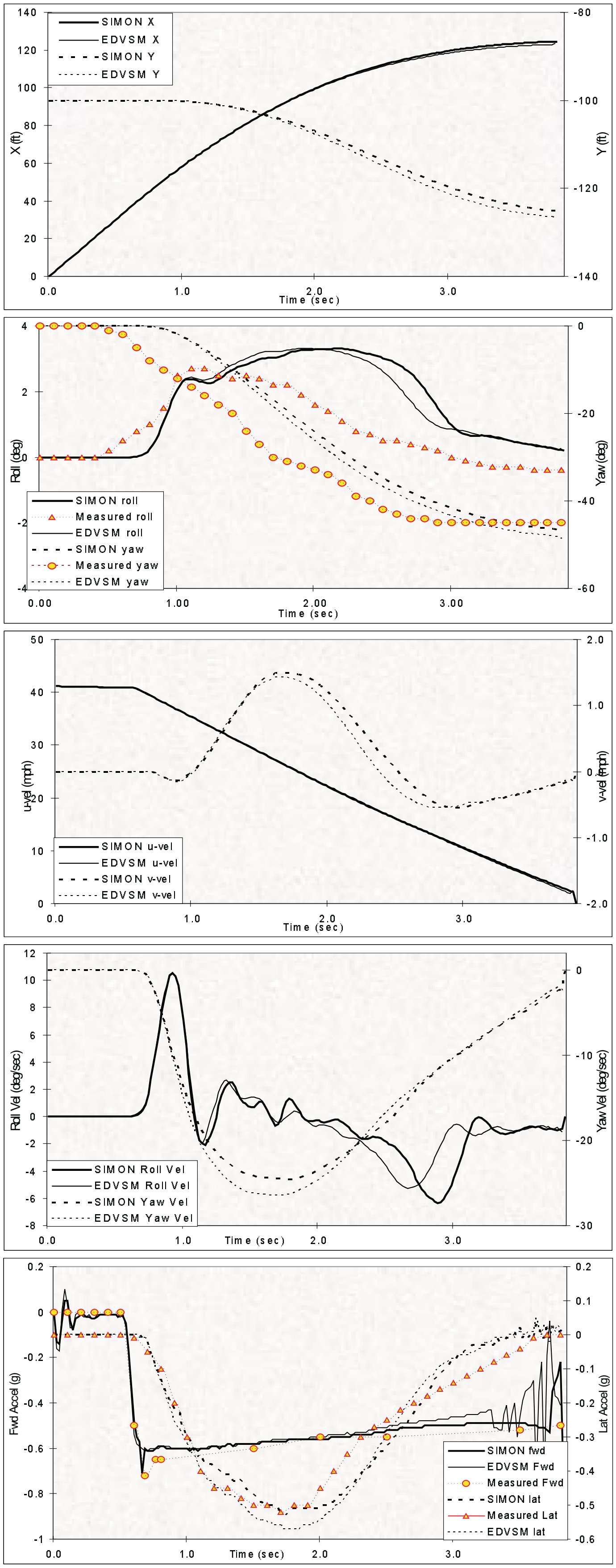



*Figure 2 – Comparison between simulation results and measured data for Test UV-1, Combined Braking and Steering*

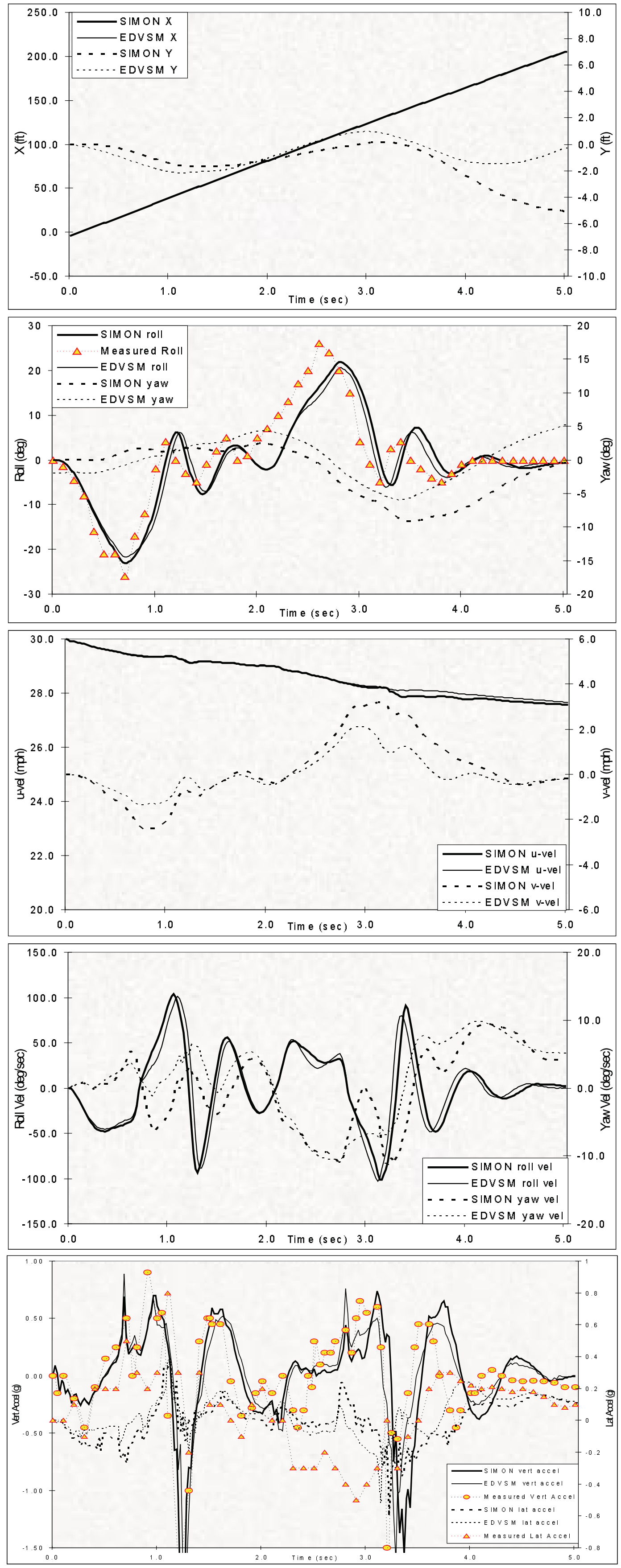



*Figure 3 – Comparison between simulation results and measured data for Test UV-2, Alternate Ramp Traversal*

### Test UV-2, Alternate Ramp Traversal

This experiment was also performed as part of the original HVOSM validation [16] using the same 1963 Ford Galaxy 500 4-Dr Sedan and instrument package as were used for Test UV-1 (see Table 4).

The test involved traversing a series of 21-inch high ramps spaced at 63-foot intervals. In addition, the ramps were staggered so that the right wheels struck the first ramp and the left wheels struck the second ramp. Because of the severity of the maneuver, the vehicle's tires were inflated to 65 psi. To reflect this change, tire radial stiffness was increased to 2200 lb/in from 1098 lb/in. Also, cornering stiffness was reduced (normally, increasing tire pressure results in an increase in cornering stiffness; however, the tires were grossly over-inflated).

The test was conducted by accelerating the vehicle to a nominal speed of 30 mph and activating the instrument 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 the path.

**Discussion of Results -** Identical steering inputs were used for SIMON and EDVSM. Using these steering inputs, SIMON's tires just barely contacted the last ramp, but EDVSM's tires missed it completely. Therefore, the EDVSM simulation was begun with minus 2 degrees of yaw to ensure that the tire hit the ramp.

Figure 3 shows the results for this test. SIMON and EDVSM path predictions showed close agreement for both X and Y coordinates, although the Y coordinate diverged approximately 5 feet after traveling 200 feet. This divergence was caused by a slight difference in the way the tires contacted the last ramp. Roll and yaw angles were in close agreement between SIMON and EDVSM (notwithstanding the above comment regarding initial yaw angle), as well as with experimental results. The roll response occurred earlier in the actual test than in simulations. This was attributed to the lack of throttle input in the simulations (as stated above, the driver attempted to maintain constant speed during the test; throttle was not used in the simulations). SIMON and EDVSM linear and angular velocity predictions were also in close agreement, and showed the slowing described above. Lateral accelerations compared reasonably well between both simulations and experimental results, although the experiments showed some spikes not seen in the simulations. Vertical acceleration compared extremely well for both simulations and experimental results. The general agreement between simulation and experiment was remarkable, especially considering the (violent) dynamic nature of the test.

### Test UV-3, Curb-Tripped Vehicle Rollover

This test was performed at the University of Missouri as part of the of the ADVS validation [17]. A 1984 Ford

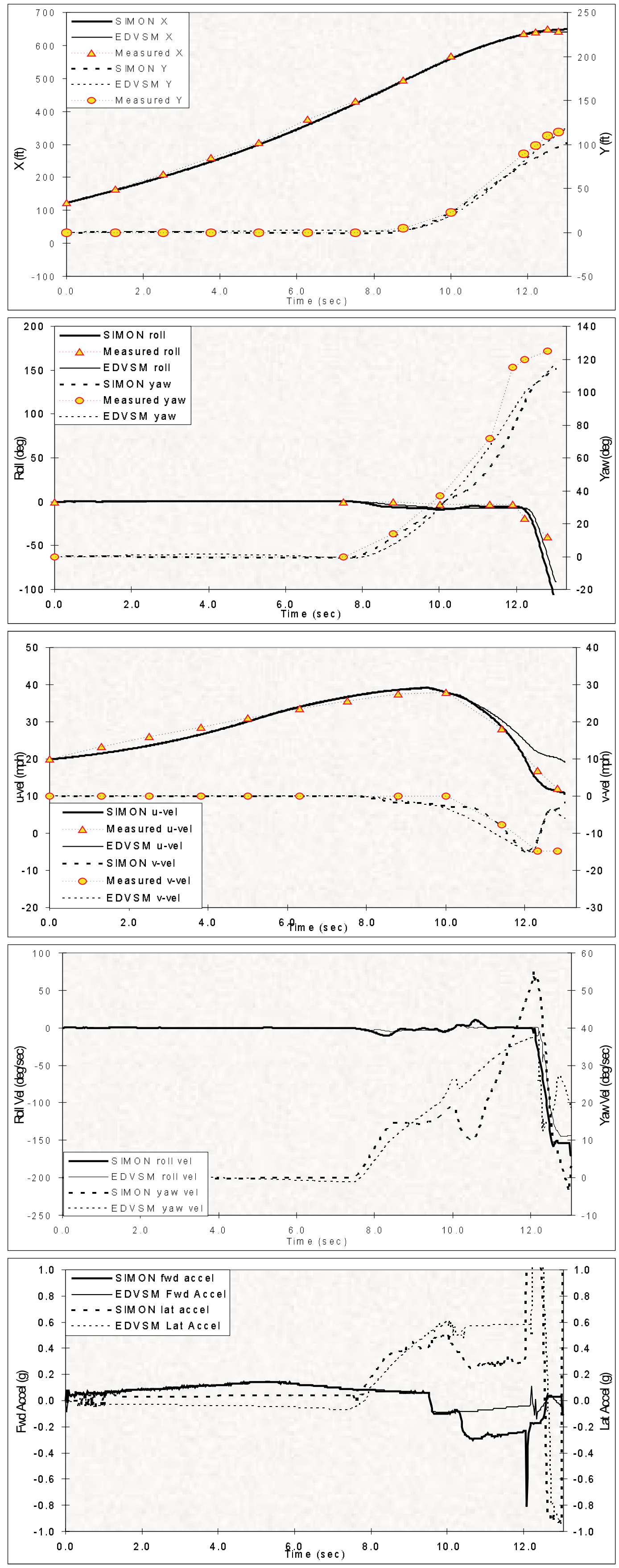



*Figure 4 – Comparison between simulation results and measured data for Test UV-3, Curb-Tripped Rollover*

Bronco II (2.8-L V-6) fitted with Goodyear Polysteer P205/75R15 tires was used to perform the maneuver. Detailed measurements of the vehicle inertial and suspension parameters were developed by the University of Missouri. Tire parameters were reportedly obtained from Calspan tire studies [18].

Because the experiment was expected to produce vehicle rollover, the vehicle was fitted with outriggers, and a special remote vehicle control system was developed. The complete control system is described in reference 17. The data acquisition package used for the test is summarized in Table 4.

The test was conducted by accelerating the vehicle to a nominal test speed of 35 mph. Steering and braking were applied using externally controlled servos as required to follow the prescribed path. The vehicle's brake system was modified by removing the proportioning valve so the rear wheels could lock. The right front brake was also locked. The left front brake was disabled to allow better directional control. (The measured time history for steering was provided in the test report; the time-history of the brake and throttle application were not.) The throttle was reportedly released when the brakes were applied.

The specific vehicle and event parameters used in the original study were not published with the results. In addition, the reference cited for the tire parameters [18] did not include any P205/75R15 tires, and no tire data were found in reference 17 or any of the accompanying research. These factors greatly complicated the task of producing the validation input sets for SIMON and EDVSM. As a result, input data sets were developed using a variety of sources, including direct measurement. Tire data were developed from unpublished tests on a P205/75R15 test conducted by Calspan at the request of Ford Motor Company.

It should also be noted that neither the SIMON nor EDVSM tire models has a sidewall impact model. Therefore, the friction multiplier was increased to 2.0 from 1.0 to provide an additional impulsive force as the tires mounted the curb.

**Discussion of Results -** Figure 4 provides a comparison of the results. Simulated vehicle behavior was in substantial agreement with experimental results, including rollover. SIMON and EDVSM simulations used slightly different steering and braking inputs in order to ensure that the vehicle reached the curb at precisely the same position (missing the curb would result in a meaningless comparison of the results for rollover).

SIMON and EDVSM results showed substantial agreement with experiment for all recorded values (path X-Y position and linear and angular velocity). Forward and lateral acceleration accelerations were in agreement until braking began. In the EDVSM simulation, the brakes were not applied, whereas in SIMON (and experiment) the brakes were applied; the onset of braking may be observed in the SIMON velocity and acceleration results.

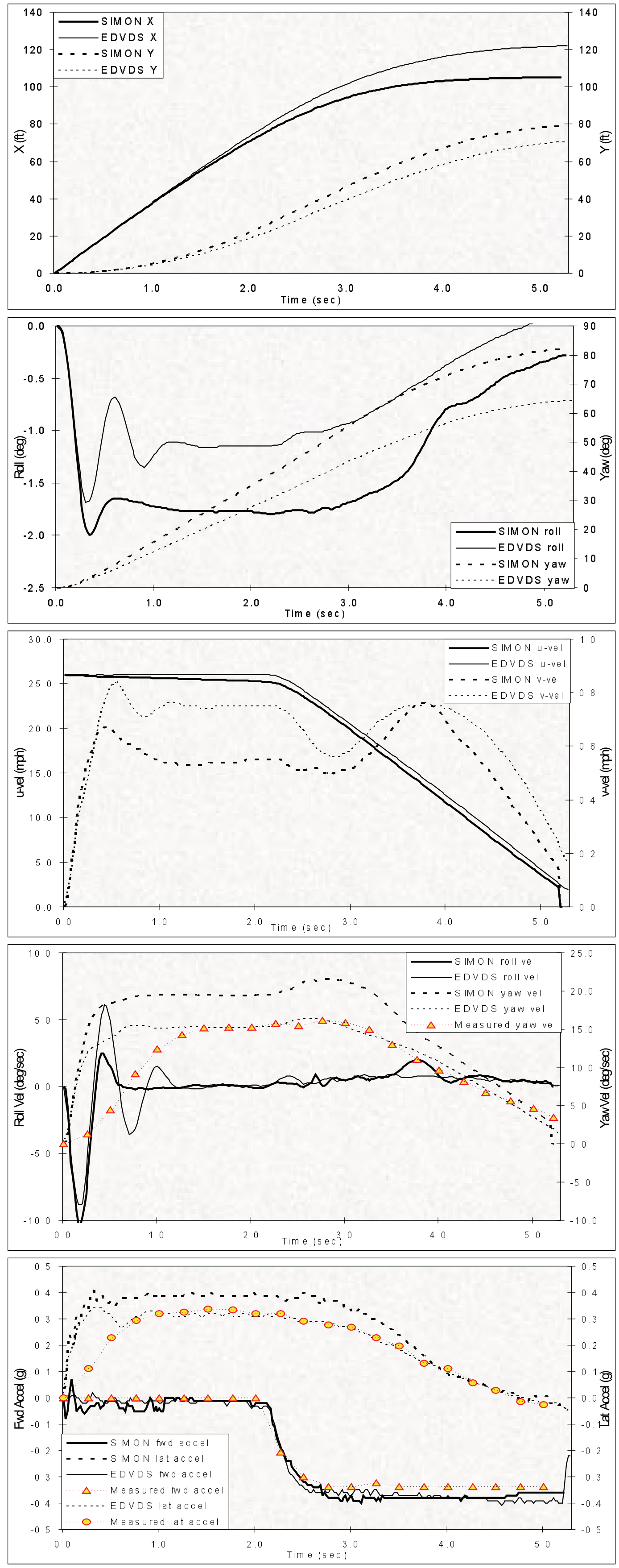



*Figure 5 – Comparison between simulation results and measured data for Test UV-4, Straight Truck Braking and Steering*

*Table 5. Instrumentation for articulated vehicle experiments*

| Test | Measurement | Instrumentation |
|---|---|---|
| AV-1 | N/A | N/A |
| AV-2 | Position, Velocity, Acceleration | Humphrey, Inc. Stabilized Platform Unit, CF 18-0109-1; Tracktest 5th Wheel |
| | Wheel Steer Angle | Markite Type 3595 Potentiometers |
| | Wheel Spin Velocity | Enwell Bicycle Generators (Go/No-Go indication only) |
| | Path Position and Orientation | N/A |
| | Path Trajectory | N/A |
| | Rest Position and Orientation | N/A |

### Test UV-4, Straight Truck Braking and Steering

This test was performed at the University of Michigan as part of the original Phase II research [19]. The test vehicle was a Diamond Reo 3-axle truck. Vehicle and tire parameters were developed by University of Michigan researchers and are presented in reference 19.

The test was conducted by accelerating the vehicle to a nominal test speed of 26 mph and applying a step-steer input from 0 to 7.7 degrees. The steering wheel was blocked to ensure the desired steer angle. Two seconds after the onset of steering, the brake pedal was depressed. The pedal travel was stop-limited to ensure the desired brake system pressure, 21.8 PSI. Test results were recorded using the instrumentation package shown in Table 4. The experiment was simulated using SIMON and EDVDS.

**Discussion of Results -** Figure 5 provides a comparison of the results from the SIMON, EDVDS and experiment.

The results immediately revealed one difference between the SIMON and EDVDS models: The EDVDS model does not include aerodynamic drag, while SIMON does. Given that there was no throttle input, the SIMON vehicle decelerated and, thus, did not travel as far over the 5-second time interval. The divergence in the path Y-coordinate was attributable to differences between the tire models. SIMON's tire model includes load and speed-dependent cornering stiffnesses whereas EDVDS's does not. The resulting additional lateral tire force also produced greater roll, roll velocity and lateral acceleration. Some yaw divergence was expected and was consistent with the divergence in path Y-coordinate. Forward velocity and acceleration initially showed the effects of aerodynamic drag and rolling resistance, although this effect was overshadowed by brake force application later in the run.

## Articulated Vehicle Tests

The two articulated vehicle handling tests are described in Table 2. The results are presented graphically in Figures 5 and 6. A brief description of the results for each test is presented below.

### Test AV-1, Articulated Light Vehicle Lane Change

The author searched the published literature for a well instrumented test involving a light vehicle/trailer performing a lane-change maneuver. However, a test with sufficiently detailed experimental results was not found. In the absence of such an experiment, the author chose to set up and compare the results from SIMON and EDSMAC4 (a validation of EDSMAC4 for articulated vehicles was published earlier [26]). The simulation for the current research was a 1999 Chevrolet C-10 Fleetside Pickup towing a 2-axle, 6x12 U-Haul utility trailer. The simulated vehicle performed a single lane-change maneuver under moderate braking. The initial speed was 50 mph.

**Discussion of Results -** The SIMON model includes rolling resistance and aerodynamic drag. EDSMAC4 does not. Therefore, for EDSMAC4 these motion-resisting forces were simulated through the appropriate selection of wheel lock-up values (the *percent available friction* method was used) in order to achieve the same final velocities.

Figure 6 provides a comparison of the results. Path X-coordinates matched perfectly (this was expected as it was dictated by the selection of wheel lock-ups for EDSMAC4). The change in path Y-coordinate during the maneuver was approximately 2 ft more for EDSMAC4 than for SIMON (-14 ft vs. -12 ft.). The difference was probably due to the tire models. Considering the 280 ft. path length, a Y-divergence of 2 ft. was considered quite small. Yaw angles and yaw rates matched quite well. Roll angle is not computed by the (2-dimensional) EDSMAC4 model; thus, no comparisons were made for roll angle or roll rate. Forward and lateral velocity components also matched quite well, as did forward and lateral accelerations. In general, the two models' predictions matched extremely well for this handling test on flat, level terrain.

### Test AV-2, Tractor-Trailer Braking and Steering

This test was performed at the University of Michigan as part of the original Phase II research [19]. The test vehicle was a White COE 3-axle tractor towing a 40 ft Freuhauf 2-axle semi-trailer. Vehicle and tire parameters were developed by University of Michigan researchers and are presented in reference 19.

The test was conducted by accelerating the vehicle to a nominal test speed of 27 mph and applying a step-steer input from 0 to 4.62 degrees. The steering wheel was blocked to ensure the desired steer angle. Two seconds after the onset of steering, the brake pedal was depressed. The pedal travel was stop-limited to ensure the desired brake system pressure of 19 psi. Test results were recorded using the

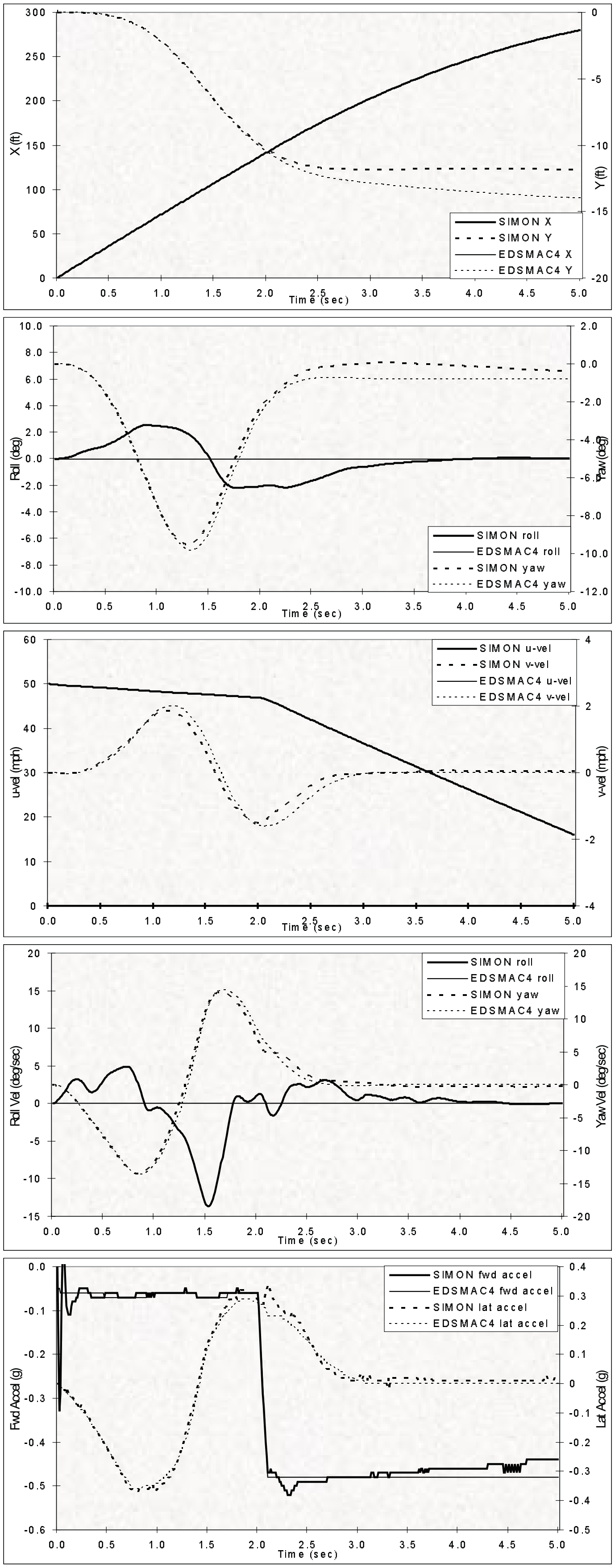



*Figure 6 – Comparison between SIMON and EDSMAC4 simulation results for Test AV-1, Articulated Light Vehicle Lane Change*

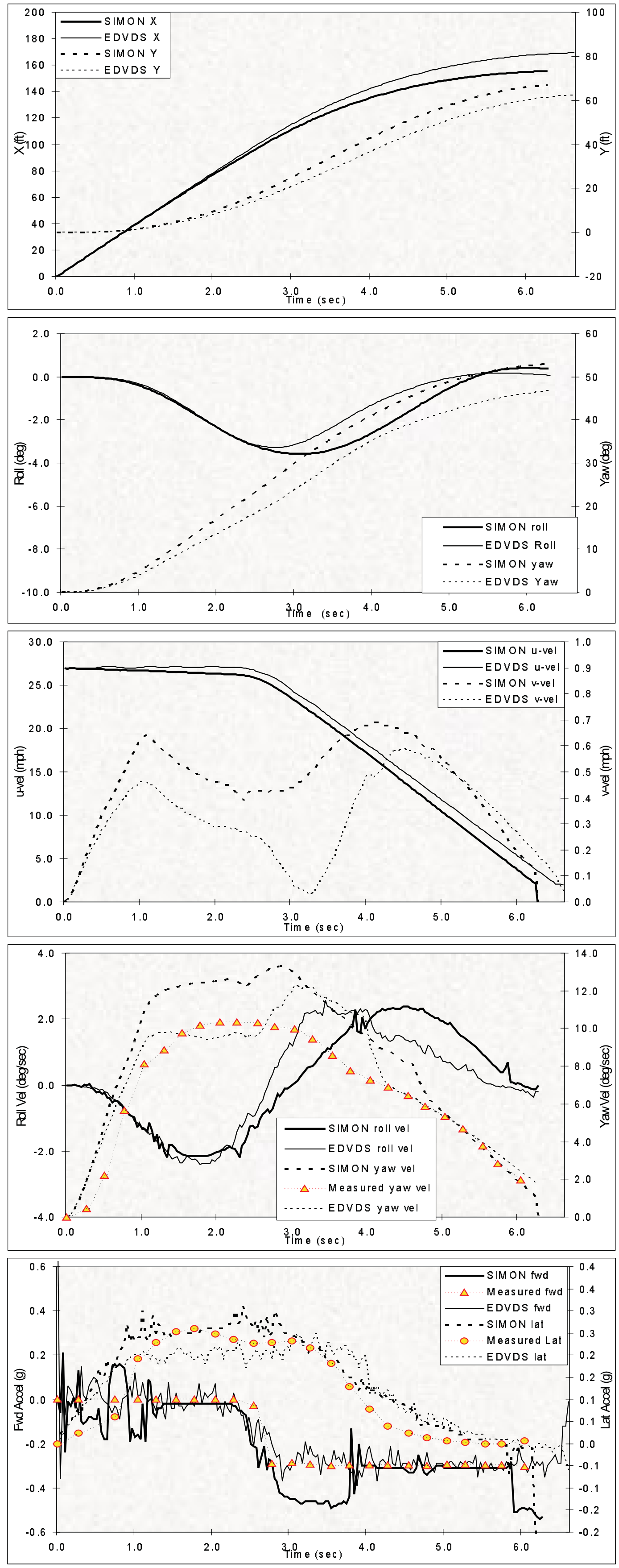



*Figure 7 – Comparison between simulation results and measured data for Test AV-2, Tractor-Trailer Braking and Steering*

instrumentation package shown in Table 5. The experiment was simulated using SIMON and EDVDS.

**Discussion of Results -** Figure 7 provides a comparison of the results. As discussed in the UV-4 test, EDVDS does not include rolling resistance or aerodynamic drag. Therefore, the SIMON simulation slowed more quickly. This was evidenced in the path X- and Y-coordinate comparisons. Again, the load-dependent tire model in SIMON probably accounted for some of the difference. Roll and yaw angles compared favorably. Forward velocity was also in quite good agreement. Again, the initial slowing due to rolling resistance and aerodynamic drag was apparent. Lateral velocities were very similar in appearance. However, the magnitude of the SIMON lateral velocity was generally greater. Considering the scale, however, the actual values were very small (both were less than 1 mph throughout the run). Roll and yaw velocity predictions were very similar; the EDVDS prediction for yaw velocity provided a slightly better match to experimental results than did SIMON. Forward and lateral accelerations were also quite similar (the initial drag was too small to show up in the forward acceleration results), with the SIMON lateral acceleration results providing a slightly better match to experimental data than EDVDS.

## Collision Tests

The five collision tests are described in Table 3. The results are presented graphically in Figures 8 through 12 and summarized in Tables 7 and 8. A brief description of the results for each test is presented below.

### Test VC-1, 2-Vehicle Angled Collision

This collision experiment was an angled collision (55 degrees) between a 1992 Ford Explorer (45.9 mph) and a 1984 Ford F-150 Fleetside pickup (46.1 mph). Both vehicles were brought up to speed using tow cables, which were released before impact. Both vehicles moved freely after impact. The test was performed on a dry surface, one portion of which was concrete (ASTM Skid Number 75, approx) and the remainder was hard-packed gravel (ASTM Skid Number 50, approx). Test results were recorded using the instrumentation package described in Table 6. Steering and wheel lock-ups were not recorded, and were estimated from crash films and photographs. Wheel displacements were also estimated from films and photographs. Default settings were used by DyMESH for the SIMON simulation. Tessellation for the F-150 was set to 20 inches to capture the secondary impact along the side of the bed. The test was conducted by Exponent Failure Analysis at the Phoenix Test and Engineering Center [25].

**Discussion of Results -** Figure 8 and Tables 7 - 9 provide a comparison of the results. The post-impact path of the Explorer was easily simulated by both SIMON and EDSMAC4; SIMON's match was slightly better. Both models had difficulty modeling the post-impact trajectory of the F-150, possibly because of the short path length and significant rotation. SIMON over-predicted the path length and slightly over-predicted the rotation; EDSMAC4 properly predicted the path length but under-estimated the rotation.

*Table 6. Instrumentation for vehicle collision experiments*

| Test | Measurement | Instrumentation |
|---|---|---|
| VC-1 | Velocity, Acceleration, Delta-V | Triaxial accelerometers (2) |
| | Damage Profile | Post-crash inspection |
| | Path Position and Orientation | High-speed cameras (6) |
| VC-3 VC-7 VC-8 VC-11 | Position, Velocity, Acceleration | Triaxial accelerometers (up to six per vehicle) Velocity and position integrated from acceleration data |
| | Impact Velocity | Speed trap |
| | Damage Profile | Post-crash Inspection |
| | Wheel Steer Angle | Linear stroke potentiometers |
| | Wheel Spin Velocity | Electronic tachometers located on at least 3 wheels |
| | Path Position and Orientation | 10 (or more) high-speed cameras |
| | Path Trajectory | Marker paint sprayed from nozzles at vehicle front and rear |
| | Rest Position and Orientation | Post-crash inspection |

Both SIMON and EDSMAC4 over-estimated delta-Vs (see Tables 7 and 8). The peak acceleration estimates for both vehicles were estimated better by SIMON than EDSMAC4. Measured accelerations were estimated by averaging test values for the left and right B-pillars. Thus, these were only estimates of the CG acceleration. In addition, accelerations predicted by both models were strongly influenced by the selection of stiffness coefficients; see Discussion. Comparison of the actual and predicted damage profiles (Table 9) revealed a good match by SIMON (EDSMAC4 damage profiles are not included in this report). The runtime for the SIMON DyMESH simulation was 15 minutes.

### Test VC-3 - 2-Vehicle Rear-end Collision (RICSAC 3)

This collision experiment was a 10 degree offset rear-end collision between a 1974 Ford Torino (21.2 mph) and a 1974 Ford Pinto (0 mph). The test surface was dry with an ASTM Skid Number of 87. Both vehicles were brought up to speed with tow cables and released approximately one car length before impact. Subsequently, both vehicles moved freely throughout the entire test, their

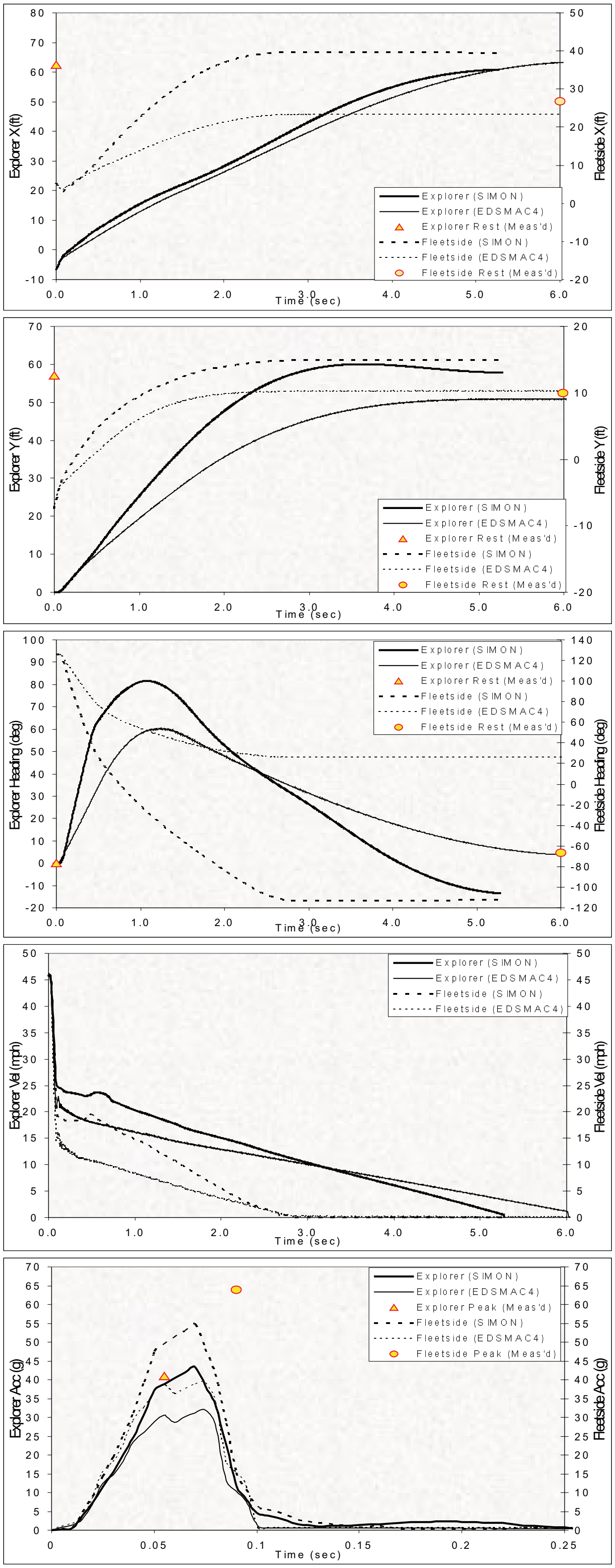



*Figure 8 – Comparison between simulation results and measured data for Test VC-1, 2-Vehicle Angled Collision (SUV vs. Pickup)*

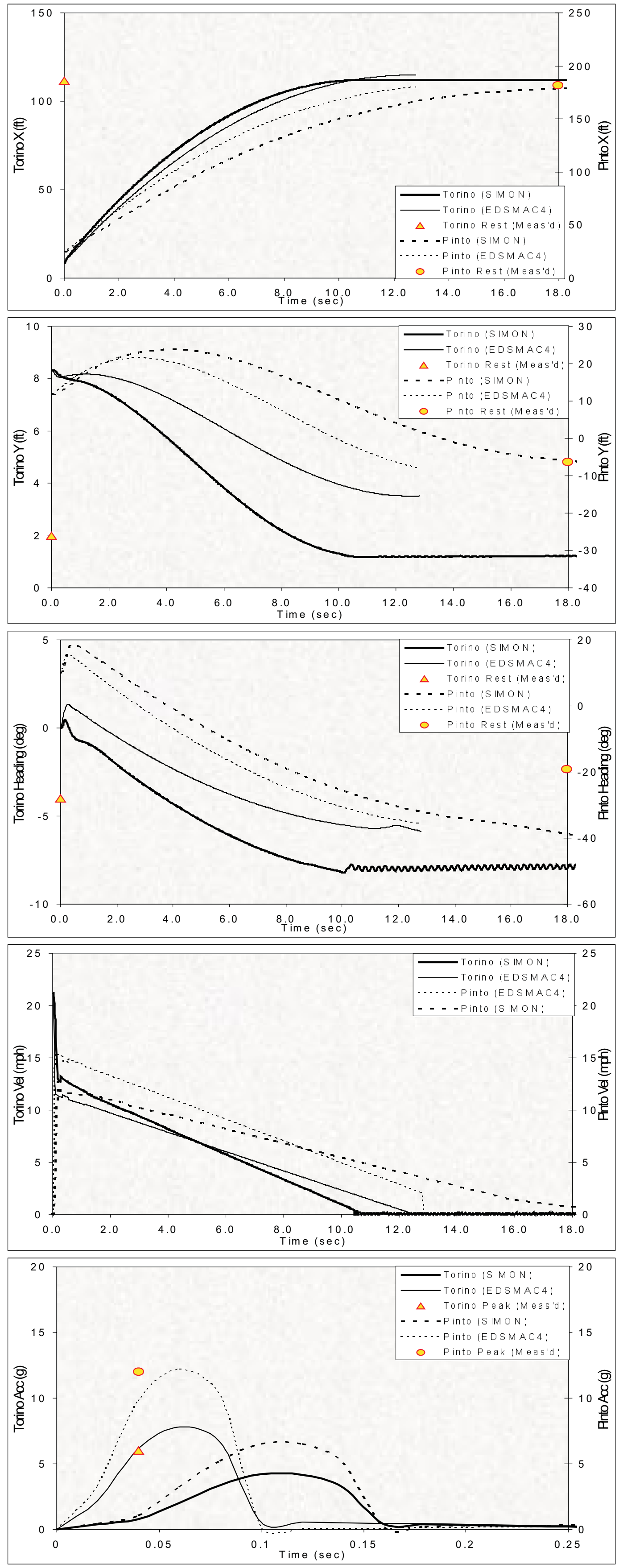



*Figure 9 – Comparison between simulation results and measured data for Test VC-3, 2-Vehicle Rear-End Collision (RICSAC 3)*

motion being affected by only collision, aerodynamic and tire forces. Both vehicles were in high gear; there were no driver steering, braking or throttle inputs. Test results were recorded using the instrumentation package described in Table 6.

The test was conducted by Calspan as part of the RICSAC Staged Collision Study; this is RICSAC Test No. 3. Detailed documentation of test set-up and measured results may be found in reference 20.

**Discussion of Results -** Figure 9 and Tables 7 - 9 provide a comparison of the results. Both models provided very good predictions of the post-impact trajectories, with SIMON's being slightly better. A slight yaw oscillation (-7.9 to -8.2 deg) was seen in the SIMON heading angle results for the Torino after reaching its rest position. This instability is occasionally observed in many models when attempting to simulate a vehicle at zero velocity (see Discussion). The delta-V prediction for EDSMAC4 were excellent; SIMON underestimated delta-V for both vehicles. EDSMAC4 acceleration predictions also more closely matched measured (firewall) results. SIMON damage profiles provided a good general characteristic of the damage, but crush depth was over-estimated for both vehicles, especially the Torino (in the actual crash test, the Torino's residual damage was limited to its extremely stiff bumper, which was simply pushed back about 2 inches). Selection of stiffness coefficients is a key factor in simulated crush depth and acceleration results (see Discussion). Default settings were used by the SIMON DyMESH simulation; the runtime was 3 minutes.

### Test VC-7, 2-Vehicle Angled Collision (RICSAC 2)

This collision experiment was a 120 degree angled collision between a 1974 Chevrolet Malibu (31.53 mph) and a 1974 Ford Pinto (31.53 mph). The test surface was dry with an ASTM Skid Number of 87. Both vehicles were brought up to speed with tow cables, which were released approximately one car length before impact. Subsequently, both vehicles moved freely throughout the entire test, their motion being affected by only collision, aerodynamic and tire forces. Both vehicles were in high gear; there were no driver steering, braking or throttle inputs. Test results were recorded using the instrumentation package described in Table 6.

The test was conducted by Calspan as part of the RICSAC Staged Collision Study; this is RICSAC Test No. 2. Detailed documentation of test set-up and measured results may be found in reference 20.

**Discussion of Results -** See Figure 10 and Tables 7 - 9. Both models provided very good predictions of the post-impact trajectories; the SIMON results provided a slightly better match with measured rest positions and headings. SIMON delta-V's were good, especially for Torino. EDSMAC4 over-predicted delta-V for both vehicles. EDSMAC4 acceleration predictions were higher than SIMON's; no valid experimental results were available

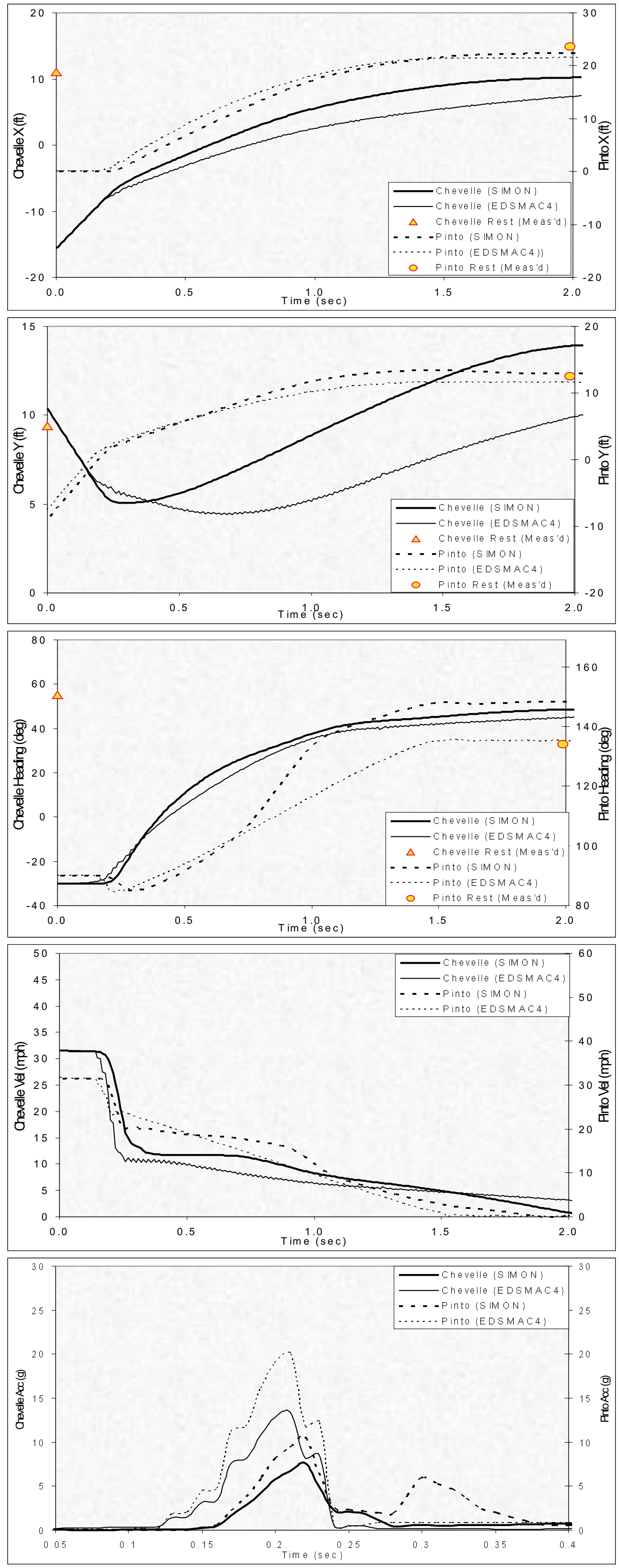



*Figure 10 – Comparison between simulation results and measured data for Test VC-7, 2-Vehicle Angled Collision (RICSAC 2)*

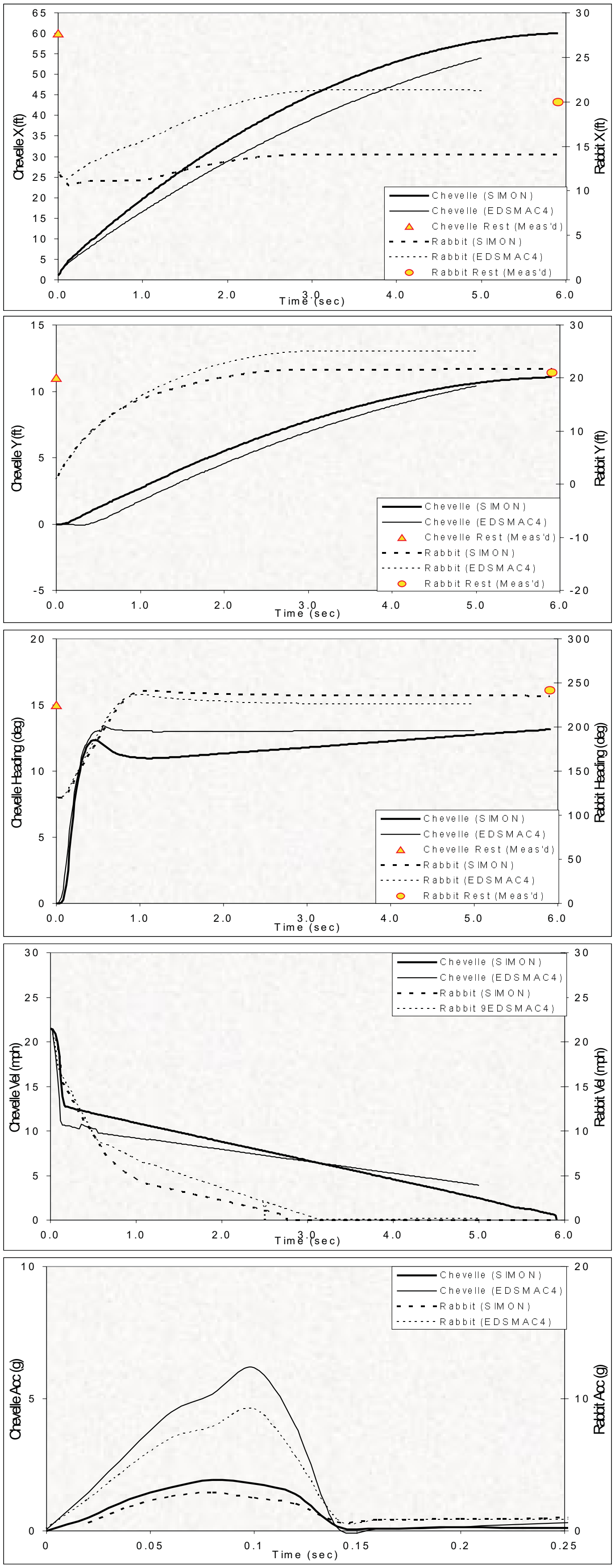



*Figure 11 – Comparison between simulation results and measured data for Test VC-8, 2-Vehicle Angled Collision (RICSAC 6)*

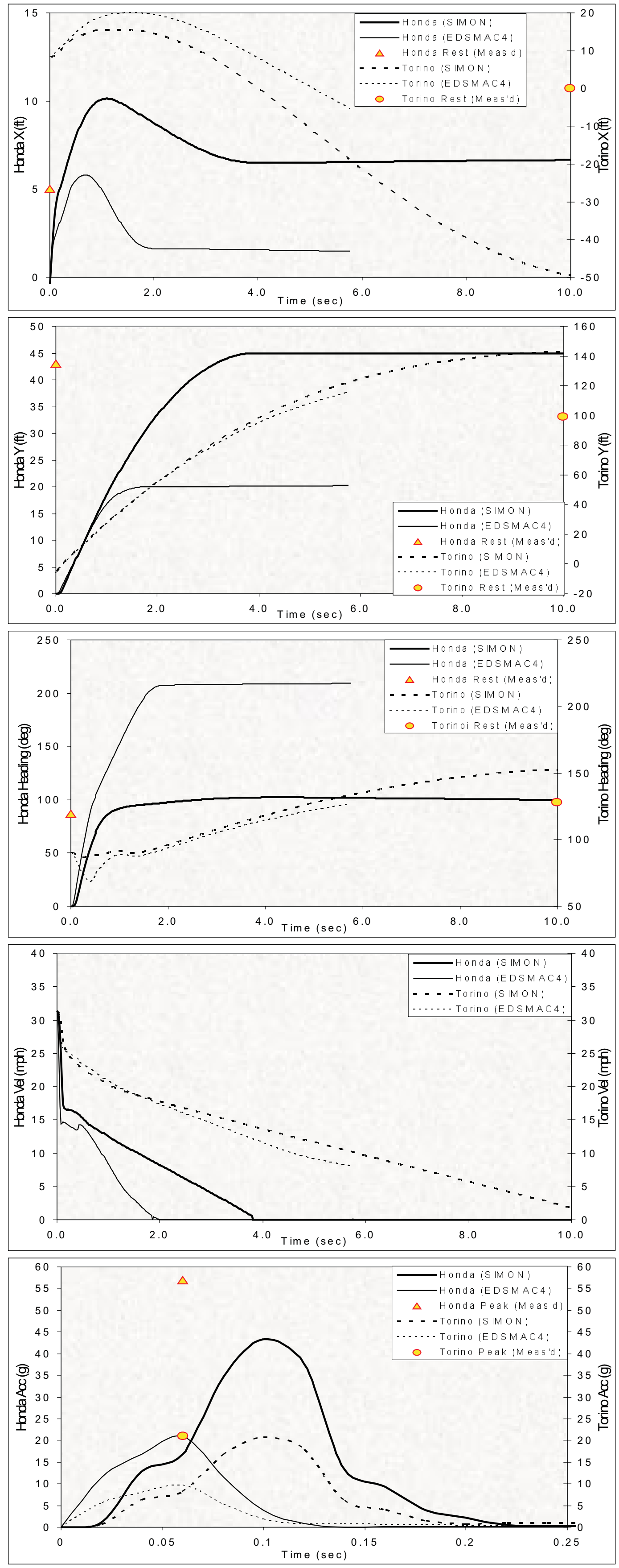



*Figure 12 – Comparison between simulation results and measured data for Test VC-11, 2-Vehicle Angled Collision (RICSAC 10)*

*Table 7. Path and Collision Results*

| Test | Method | REST POSITION | | | | | | DELTA-V* | |
|---|---|---|---|---|---|---|---|---|---|
| | | Veh #1 | | | Veh #2 | | | Veh #1 | Veh #2 |
| | | X (ft) | Y (ft) | Ψ (deg) | X (ft) | Y (ft) | Ψ (deg) | (mph) | (mph) |
| VC-1 | Experiment | 62.6 | 57.0 | 0.0 | 26.7 | 10.0 | -66.3 | 30.0 | 42.0 |
| | SIMON | 60.9 | 57.8 | -13.5 | 39.5 | 14.9 | -112.4 | 39.6 | 52.6 |
| | EDSMAC4 | 63.4 | 50.9 | 3.7 | 23.4 | 10.3 | 25.7 | 38.1 | 48.5 |
| VC-3 | Experiment | 111.4 | 2.0 | -4.0 | 181.5 | -6.3 | -19.0 | 9.4 | 15.4 |
| | SIMON | 111.9 | 1.2 | -7.9 | 179.5 | -6.5 | -40.0 | 7.7 | 11.8 |
| | EDSMAC4 | 114.8 | 3.5 | -5.9 | 180.2 | -8.1 | -35.7 | 9.9 | 15.5 |
| VC-7 | Experiment | 11.0 | 9.4 | 55.0 | 23.6 | 12.5 | 134.0 | 19.5 | 25.8 |
| | SIMON | 10.3 | 13.9 | 48.4 | 22.3 | 13.0 | 148.8 | 23.0 | 26.7 |
| | EDSMAC4 | 8.3 | 11.0 | 46.4 | 21.5 | 11.7 | 135.0 | 31.3 | 31.3 |
| VC-8 | Experiment | 60.0 | 11.0 | 15.0 | 20.0 | 21.0 | 242.0 | 9.2 | 14.6 |
| | SIMON | 60.0 | 11.1 | 13.2 | 14.1 | 21.7 | 235.3 | 9.5 | 13.1 |
| | EDSMAC4 | 54.1 | 10.4 | 13.1 | 21.3 | 25.1 | 225.7 | 10.8 | 16.6 |
| VC-11 | Experiment | 5.0 | 43.0 | 87.0 | 0.0 | 99.5** | 128.5 | 28.7 | 13.1 |
| | SIMON | 6.7 | 44.9 | 99.8 | -0.8 | 99.5 | 102.3 | 28.4 | 12.7 |
| | EDSMAC4 | 4.6 | 41.9 | 98.1 | 22.2 | 99.5 | 113.4 | 28.9 | 13.5 |

**Sources: VC-1 from [25]; VC-3, VC-8, VC-11 from [23], VC-7 from [22].*
***NOTE: VC-11 terminated at Veh 2 impact w/ transformer box at Y=99.5 ft.*

for comparison (measured peak accelerations occurred at decidedly different times in the acceleration output traces, suggesting a problem with the data acquisition). Simulated SIMON damage profiles are shown in Table 9. No photographic results of sufficient quality were found for the actual vehicles. However, the simulated damage profiles compared favorably with crush diagrams in reference 20. Default settings were used by the SIMON DyMESH simulation; the runtime was 4 minutes.

### Test VC-8, 2-Vehicle Angled Collision (RICSAC 6)

This collision experiment was a 60 degree angled collision between a 1974 Chevrolet Malibu (21.47 mph) and a 1975 Volkswagen Rabbit (21.47 mph). The test surface was dry with an ASTM Skid Number of 87. Both vehicles were brought up to speed with tow cables, and were released approximately one car length before impact. Subsequently, both vehicles moved freely throughout the entire test, their motion being affected by only collision, aerodynamic and tire forces. Both vehicles were in high gear; there were no driver steering, braking or throttle inputs. Test results were recorded using the instrumentation package described in Table 6.

The test was conducted by Calspan as part of the RICSAC Staged Collision Study; this is RICSAC Test No. 6. Detailed documentation of test set-up and measured results may be found in reference 20.

**Discussion of Results -** See Figure 11 and Tables 7 - 9. Path predictions for both SIMON and EDSMAC4 matched the measured paths quite well. This was impressive considering the rapid post-impact rotation of the Rabbit. SIMON delta-Vs are in close agreement with experimental values. EDSMAC4 slightly over-predicted both delta-Vs. EDSMAC4's predictions for accelerations were significantly higher than those predicted by SIMON. Again, no credible experimental data exist. Damage profiles predicted by SIMON were good. Crush depth was slightly over-predicted on the Chevelle and under-predicted on the Rabbit. Default settings were used by the SIMON DyMESH simulation; the runtime was 2 minutes.

### Test VC-11, 2-Vehicle Angled Collision (RICSAC 10)

This collision experiment was a 90 degree angled collision between a 1975 Honda Civic (31.35 mph) and a 1974 Ford Torino (31.35 mph). The test surface was dry with an ASTM Skid Number of 87. Both vehicles were brought up to speed with tow cables, which were released approximately one car length before impact. Subsequently, both vehicles initially moved freely. However, after the Torino traveled approximately 100 ft., it struck a power

*Table 8. Path and Collision Errors*

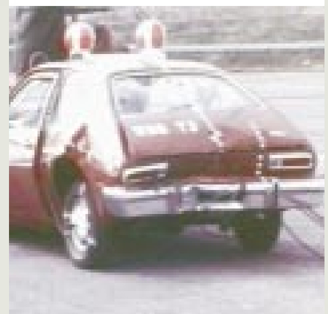
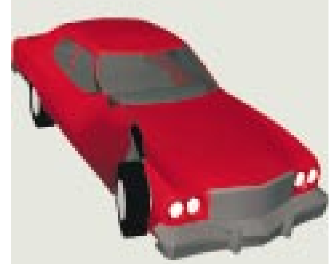
| Test | Method | PATH ERROR | | | | COLLISION ERROR | |
|---|---|---|---|---|---|---|---|
| | | Veh #1 | | Veh #2 | | Veh #2 | Veh #2 |
| | | Range, ft (%) | Heading, deg (%) | Range, ft (%) | Heading, deg (%) | ΔV, mph (%) | ΔV, mph (%) |
| VC-1 | SIMON | 1.9 (2.1) | -13.5 (-3.8) | 13.7 (49.8) | -46.1 (-12.8) | 9.6 (32.0) | 10.6 (25.2) |
| | EDSMAC4 | 6.2 (6.9) | 3.7 (1.0) | 3.3 (12.0) | 92.0 (25.6) | 8.1 (27.0) | 6.5 (15.5) |
| VC-3 | SIMON | 0.9 (0.9) | -3.9 (-1.1) | 2.0 (1.3) | -21.0 (-5.8) | -1.4 (-14.9) | -3.6 (-23.4) |
| | EDSMAC4 | 3.7 (3.6) | -1.9 (-0.5) | 2.2 (1.4) | -16.7 (-4.6) | 0.3 (3.2) | 0.1 (0.6) |
| VC-7 | SIMON | 4.6 (21.9) | -6.6 (-1.8) | 1.4 (5.0) | 14.8 (4.1) | 3.5 (17.9) | 0.9 (3.5) |
| | EDSMAC4 | 3.1 (14.8) | -8.6 (-2.4) | 2.3 (8.2) | 1.0 (0.3) | 11.8 (60.5) | 5.5 (21.3) |
| VC-8 | SIMON | 0.1 (0.2) | -1.8 (-0.5) | 5.9 (27.4) | -6.7 (-1.9) | 0.3 (3.3) | -1.5 (-10.3) |
| | EDSMAC4 | 5.9 (9.8) | -1.9 (-0.5) | 4.3 (20.0) | -16.3 (-4.5) | 1.6 (17.4) | 2.0 (13.7) |
| VC-11 | SIMON | 2.6 (6.0) | 12.8 (3.6) | -0.8 (-9.5) | -26.2 (-7.3) | -0.3 (-1.0) | -0.4 (-3.1) |
| | EDSMAC4 | 1.2 (2.8) | 11.1 (3.1) | 22.2 (264.2) | -15.1 (-4.2) | 0.2 (0.7) | 0.4 (3.1) |
| Avg Error % (Std. Dev) | SIMON | 6.2 (9.0) | 0.7 (2.7) | 14.8 (23.7) | -4.7 (6.3) | 7.5 (18.0) | -1.6 (18.0) |
| | EDSMAC4 | 7.6 (4.9) | 0.1 (2.0) | 61.2 (113.7) | 2.5 (13.1) | 21.8 (24.2) | 10.8 (8.7) |

transformer box, bringing it to rest. The Honda moved freely to its rest position. Both vehicles were in high gear; there were no driver steering, braking or throttle inputs. Test results were recorded using the instrumentation package described in Table 6.

The test was conducted by Calspan as part of the RICSAC Staged Collision Study; this is RICSAC Test No. 10. Detailed documentation of test set-up and measured results may be found in reference 20.

**Discussion of Results -** See Figure 12 and Tables 7 - 9. Because the Torino struck an object before coming to rest, the simulations were terminated early and path comparisons were based on that point (the Honda had already come to rest). The SIMON path prediction was excellent for both vehicles. The EDSMAC4 prediction was excellent for the Honda, while the Torino's X-coordinate at termination was in error by approximately 22 ft. Delta-V predictions were exceptional for both SIMON and EDSMAC4. SIMON's peak acceleration estimate for the Torino matched the measured (firewall) value extremely well; the Honda prediction was not as good. EDSMAC4 underestimated accelerations for both vehicles. Again, these issues were related to the selection of stiffness coefficients. Actual photographs of the damaged vehicles were not available. However, the simulated damage patterns were consistent with the crush diagrams in reference 20, including secondary impact damage caused by rapid rotation during impact. Default settings were used by the SIMON DyMESH simulation; the runtime was 2 minutes.

*Table 9. Visual Damage Comparison*

| Test | DAMAGE VIEW | | | |
|---|---|---|---|---|
| | Veh #1 | | Veh #2 | |
| | Experiment | SIMON | Experiment | SIMON |
| VC-1 |  |  |  |  |
| VC-3 |  |  |  |  |
| VC-7 | Photo Not Available |  | Photo Not Available |  |
| VC-8 |  |  |  |  |
| VC-11 | Photo Not Available |  | Photo Not Available |  |

## DISCUSSION

One of the challenges in producing this validation study was the lack of available experimental data of sufficient detail. For collision studies, the RICSAC data provided high quality data sets. However, these data sets were not without problems. They were rather dated (1978), and although the laws of motion have not changed, vehicle design has. Questions regarding the placement of accelerometers and the resulting effect on measured accelerations and delta-Vs have been addressed. This research also raised questions regarding the peak accelerations; it was noted in several experiments that the peak accelerations for a colliding pair of vehicles occurred at different times, according to the strip-chart data. The data were also heavily filtered. Well-instrumented collision experiments involving articulated vehicles were also lacking.

Reference 16 provided good data for handling experiments for a unit vehicle. However, this data, too, was quite dated. Again, the laws of motion have not changed, thus the tests were very useful. However, well-instrumented handling experiments on newer vehicles would be welcome. The same is true for handling tests for articulated light vehicles. Because experimental data were lacking, this research relied on a simple comparison between SIMON and a previously validated model for an articulated light vehicle handling study.

The ideal data sets for any type of experiment (handling or collision) would include 3-D accelerations at the CG, linear and angular positions and velocities, driver control inputs (steering, braking, and throttle) and wheel spin velocities. High-speed film is also extremely valuable, as is measured damage for collision experiments. No single data set used in this research (or found elsewhere) included all these results.

The term accuracy is felt to be somewhat misleading when applied to simulation programs used for crash reconstruction. This is true for several reasons. The investigator is normally interested in the accuracy of velocity estimates. However, simulations require initial velocity as an input. The true purpose of simulation is to predict the outcome of an event - in the case of crash reconstruction, these are vehicle paths and damage profiles. Given sufficient time, an investigator can probably adjust the program parameters until the simulated paths and damage profiles match the measured results nearly perfectly. One must then address the accuracy of the individual parameters used to achieve such a match. The most logical and useful inference is that, by using a physical simulation model which duplicates (or nearly so) all the known evidence, any unknown parameters (e.g., vehicle initial velocities) must be nearly duplicated by the simulation as well. Stated another way, if one is able to match the evidence using the simulation, and if one agrees with all the data used to achieve the match, then one should also agree a priori with the speeds used to achieve the match. However, uniqueness is not guaranteed. Slightly different sets of steering and braking inputs may result in the same (or nearly the same) path.

Previous collision validations have involved models that used a wheel lock-up parameter to provide post-impact deceleration. The SIMON model includes complete vehicle brake and drivetrain systems with inertial and friction characteristics (motion-resisting forces), as well as the ability to lock individual wheels resulting from collision damage. This model did not work well in these tests (VC-1, VC-3, VC-7, VC-8 and VC-11). Therefore, the *percent wheel lock-up* method was used in the SIMON collision validations.

This is the first validation of the DyMESH collision model. Much was learned. All the collision simulations included in this report used default DyMESH parameters; *tweeking* was not required. HVE's Tessellation option was used in VC-1 because the secondary impact occurred along the side of the bed of the F-150 pickup in an area where the original mesh contained no vertices (DyMESH requires vertices to calculate the deformation and resulting force). The Tessellation option worked well.

Like EDSMAC4, the inter-vehicle friction value played a key role in establishing the post-impact (departure) path angle for DyMESH collision simulations. Stiffness coefficients also played a key role in the acceleration vs. time profile (*collision pulse*). These validations all used a *Height Factor* of 30 inches to calculate $\overline{A}$ and $\overline{B}$ (3-D versions of A and B; see reference 7). More remains to be learned in this area, and improvements in the calculated collision pulse are possible. Because the area under the collision pulse changed very little when stiffness coefficients were modified, the delta-Vs produced using the current technique were valid. SIMON damage profiles also tended to over-predict the actual crush depth. This, too, needs further research.

The meshes used by DyMESH were the standard 3-D meshes shipped with HVE vehicles. There were no special requirements (other than outward-facing polygons) or modifications made to these meshes. Additional DyMESH simulations revealed that if a mesh was not available, the Generic Vehicle mesh also worked well by using the Tessellation option (typically 20 inch tessellation was used).

The average EDSMAC4 Range Error for Veh #2 (61 %) was unusually large. This error was due to a single run, VC-11, in which the Torino Y-path coordinate was 22.2 ft. from the measured position. That position represented a 264.2 percent error that overwhelmed the statistical analysis. No attempt was made to determine the cause of this error. However, it was known that the vehicle struck a transformer prior to coming to rest.

Run times for DyMESH collision simulations using a 3 GHz Pentium 4 varied from 2 to 15 minutes. Run time was strongly correlated to the number of vertices in the vehicle mesh (the vehicles in this research had between 2000 and 5000 vertices) and the duration of the collision phase.

Because EDSMAC4 runtimes were typically less than 5 seconds, that model may be preferable (simply because of time savings) to DyMESH for simulating collisions on flat terrains not resulting in 3-dimensional vehicle behavior. However, the DyMESH model would offer a significant advantage for collisions involving over-ride, rollover and large amounts of pitch and/or roll because EDSMAC4 does not model those behaviors.

Two of the simulations (UV-1 and VC-3) produced oscillations in vehicles after they had come to rest . This is a known problem: Simulating a vehicle with zero velocity is problematic because tire forces still exist for a motionless vehicle, leading to small accelerations (both linear and angular). This problem needs to be addressed because it causes the vehicle to move slightly instead of remaining firmly fixed at its rest position.

## RECOMMENDATIONS

Publication of reports that include well-instrumented handling and collision experiments is needed and is recommended.

The collision studies included in this paper were performed on flat, level terrain. Validations of crashes that include 3-dimensional effects (e.g., roll, pitch, over-ride, rollover) were not included because of a lack of data for collision experiments performed on irregular terrain. Collision experiments performed on irregular terrain are recommended.

The DyMESH model inherently includes the capability to simulate vehicle vs. environment collisions (e.g., complete rollover with the vehicle body contacting the terrain). It is recommended that this capability be implemented.

Time constraints precluded investigation using the *Append* steer table option (i.e., *steer DOF*). This method allows a vehicle to be steered by forces produced at the tire-road interface, rather than relying on a user-entered steer table. For collision simulations, the benefit is obvious. Research using the *Append* option is recommended.

More research is recommended in the area of post-impact deceleration using SIMON's brake and drivetrain system models.

More research is recommended in the area of 3-D stiffness coefficients (a function of choosing the correct *Height Factor*) for use by DyMESH collision simulations.

## CONCLUSIONS

1. The SIMON simulation model has been validated against experimental data for handling and collision tests. Comparison revealed good to excellent agreement for path, velocity, acceleration and delta-V.

2. SIMON tended to under-predict peak accelerations and over-predict crush depth for collision experiments. These differences were attributed to the selection of stiffness coefficients.

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