2000-01-0852

Applications and Limitations of 3-Dimensional Vehicle Rollover Simulation

Terry D. Day
J. Travis Garvey
Engineering Dynamics Corporation

ABSTRACT

Vehicle crashes often involve rollover. A vehicle rollover is a complex, 3-dimensional event that is quite difficult to model successfully. As a result, crash investigators often make simplifying assumptions that compromise the quality of the information learned from the analysis. Advances in vehicle simulation modeling have greatly reduced the amount of work required to perform rollover simulations. Rollover simulation holds promise as a tool to learn more about crashes involving rollover. This paper describes how the EDVSM simulation model calculates 3-dimensional forces and moments on the sprung mass (i.e., body exterior) and how these forces and moments are integrated into the equations of motion. The paper also provides some examples of the use of rollover simulation. Finally, the paper addresses the practical and theoretical limitations of rollover simulation as a tool for routine reconstruction of on-road and off-road crashes.

VEHICLE ROLLOVER is a significant safety problem. According to the NHTSA, an average of 227,000 rollover crashes (i.e., crashes in which rollover was the first harmful event) occurred annually between the years 1992 and 1996. These crashes resulted in an average of 9063 fatalities and over 200,000 non-fatal injuries each year. Rollover is second only to frontal crashes in terms of severity [1]. However, it cannot be concluded from previous research that speed alone is the major factor causing rollover crashes. Because of the frequency of this crash mode, and because of the typical severity of the resulting crash injuries, understanding the cause of rollover crashes is a critical aspect of motor vehicle safety research. Better understanding can ultimately lead to the development of safer vehicles and highways, as well as lead to a more knowledgeable driver.

This paper describes procedures for investigating rollover crashes. A literature review is included to assess the current state of the art and findings of other researchers. The main component of the paper is an in-depth evaluation of the use of the EDVSM [2] vehicle simulation model for studying rollover crashes. The vehicle model assumptions are presented and evaluated. Several examples of the use of EDVSM are provided. Finally, limitations of the model for use in rollover simulation are explored.

SURVEY OF CURRENT PROCEDURES

A survey of the existing literature reveals the current methods for analysis of rollover crashes fall into the following general categories:

- Evidence Analysis
- Static Analysis
- Simulation
- Testing

Several of these procedures and methods are reviewed below. Additional references are found at the end of the paper.

Evidence Analysis

Numerous researchers have presented papers describing how to interpret the crash site and vehicle-related artifacts from rollover crashes. Orlowski [3], Martinez [4] and Marine [5] provide examples of such research. A discussion of maneuvers leading to rollover and procedures for testing rollover propensity are also presented.

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

Static Analysis

The most traditional analysis of rollover propensity is a simple static analysis of the forces and moments acting in the vehicle roll plane. Such an analysis yields the simple formula,

$$A_{Lat} = \frac{t}{2h}$$

where A_{lat} is the lateral acceleration required to cause rollover, t is the track width and h is the elevation of the center of gravity. The key observation for this traditional approach is that the maximum lateral acceleration is limited by the available tire-ground friction force. Thus, if A_{lat} is greater than the tire-ground friction, μ, the vehicle cannot roll. The difference between A_{lat} and μ is sometimes referred to as the *static margin*. If $A_{lat} - \mu$ is negative, rollover can occur. The static approach is discussed in numerous references [e.g., 6,7]. The major advantage of this approach is its simplicity. The key limitation is that it ignores the inertial roll moment caused by dynamic steering inputs. This issue is discussed in reference 8. It is further explored in the current research (see example 1 later in this paper). Other factors not normally considered in the static analysis are the lateral displacement of the sprung mass due to suspension travel (reference 7 shows how this effect may be included in the static analysis) and vertical tire deflection. Even with these limitations, the static analysis is considered to provide a valuable metric.

The *tumble number* approach was proposed by Bratten [9]. The tumble number is essentially a statistically derived value based on observation and experience. Bratten compares the tumble number with numerous other published deceleration rates for pedestrians and vehicle rollovers [10-12] and concludes that the deceleration rate tends to be very close to 0.5 g both for pedestrians struck by vehicles and for vehicles following rollover. He suggests exercising caution in the use of the tumble number, but as a first order approximation, Bratten concludes it seems to provide a reasonable first estimate for speed calculations.

Simulation

Allen [8] developed a vehicle dynamic simulation model. He has used that model to illustrate various vehicle and driver rollover mechanisms.

Nalecz et al [13-15] also developed a vehicle simulation model for the purpose of studying rollover propensity of passenger cars, light trucks and vans. As part of the work by Nalecz, a significant number of vehicle rollover tests were performed. Vehicles were fitted with outriggers to limit the roll angle to 50-60 degrees. The model did not include the capability of body vs ground interaction and no attempt was made to study this aspect. An interesting outcome of this research was the development of a factor, called the *Rollover Prevention Energy Reserve* (RPER). The RPER is a quantitative measure that the authors say predicts a vehicle's rollover propensity.

Garrott et al [16] used simulation to study on-road, untripped rollover with a focus towards developing new and updated federal safety standards.

Day [2] developed a vehicle dynamic simulation model. Two rollover experiments were simulated as part of that model's validation. At the time of its initial validation, contact between the vehicle body and terrain was not modeled.

Chace and Wielenga [17-19] published on the use of the ADAMS [20] program for simulating rollover. Their research also discussed tire parameters that affect rollover. An interesting braking schema is also proposed for reducing on-road rollover by changing the side-to-side balance of the vehicle's front brakes.

Renfroe [21] used the MADYMO program to simulate vehicle rollover, comparing their results with video footage and data from an actual FMVSS 208 rollover test conducted by the NHTSA. The exterior was modeled as a series of approximately 40 strategically located surface nodes. According to the authors, the match between simulated and actual vehicle paths was very good. The amount of time required to produce the match was not provided.

Cheng used the ATB model to first simulate the rollover dynamics of a pickup truck [22], and then to use the resulting acceleration history as input to an occupant simulation [23].

Testing

Cooperrider developed a testing program to study rollover. The first test results were published in 1990 [24], and involved five curb-tripped rollover tests, one FMVSS 208 dolly test and two soil-trip tests. That work was followed by six additional soil-trip tests in 1998 [25].

Cooperrider's initial study developed the mechanics of various trip modes (e.g., curb impact, soft soils) and resulted in the development of a simple analytical model to represent trip mode behavior. The subsequent study extended the earlier work, focusing on a single vehicle and trip mechanism (soft soil) over a range of speeds. These tests provided information about minimum trip speeds as well as the characteristics of rollover at various speeds.

Numerous other researchers have published on rollover test procedures (e.g., [26,27]) and the information that can be gathered from such testing (e.g., [28]).

REQUIREMENTS FOR MODELING ROLLOVER

The preceding section suggests that the detailed simulation of rollover requires a sophisticated simulation model. At a minimum, the vehicle model must include six degrees of freedom for the sprung mass ($X,Y,Z,roll,pitch,yaw$)

and one degree of freedom (wheel vertical travel) for each wheel of an independent suspension or two degrees of freedom (axle vertical travel and roll angle) for a solid axle suspension. Suspension parameters affecting roll moment generation (roll center, lateral spring spacing and auxiliary roll stiffness from an anti-sway bar device) are also required. Because suspension excursions are often large during a rollover, suspension jounce and rebound stops must be included as well.

Vehicle rollover is, by definition, a limit maneuver. Thus, the tire model must operate well into the non-linear range for sideforce calculations resulting from both tire slip angle and inclination angle. When combined steering and braking are present, the model must be able to handle simultaneous steering and braking forces. Because the vertical tire load changes dramatically during a rollover event, tire model braking and cornering force characteristics should be load-dependent. Tire radial stiffness is an important parameter because tire deflection contributes to vehicle roll angle.

Many rollover events are initiated by a high lateral force applied to the sidewall (as from a curb trip or plowing in soft soil). For these types of events, the model must incorporate interaction between an arbitrary 3-dimensional terrain and the tire sidewall. Similarly, rim gouging can produce momentary high forces that should be accounted for in the tire model.

A rollover event ultimately results in contact between the vehicle body and the terrain. Simulation of this phase of the event requires that forces and moments produced by such contact be modeled. Thus, 3-dimensional geometric descriptions of the vehicle exterior and terrain must be supplied and a method of calculating localized vehicle body forces and deformations must be included.

EDVSM MODEL

The basic characteristics of the EDVSM model were published and validated in reference 2. The validation included limit maneuvers and rollovers. The rollover validations were terminated at about 35-50 degrees of roll because the vehicles were fitted with outriggers. In addition, the EDVSM version used in the validation did not include the capability to model vehicle body contact with the environment terrain.

The EDVSM model has recently been extended to include force and moments created by interaction between the vehicle body and environment terrain. The model is described below.

General Description

The general modeling approach used by the EDVSM body vs terrain model is similar to the “hard point” method used by HVOSM-RD2 [29]. The vehicle body is comprised of nodes that may interact with the environment terrain. The nodes have material attributes and, thus, generate forces as a result of their interaction with the terrain. The forces are resolved into vehicle-fixed components, which are then summed to calculate forces and moments acting at the center of gravity of the sprung mass. These forces and moments are included in the equations of motion, along with suspension forces and aerodynamic forces, to calculate the current sprung mass linear and angular acceleration vectors.

Node Definition

The nodes required by the model are the vertices supplied by the vehicle 3-D geometry file. Since every HVE vehicle has a geometry file, every vehicle has the nodes required to perform the simulation. A vehicle may have an

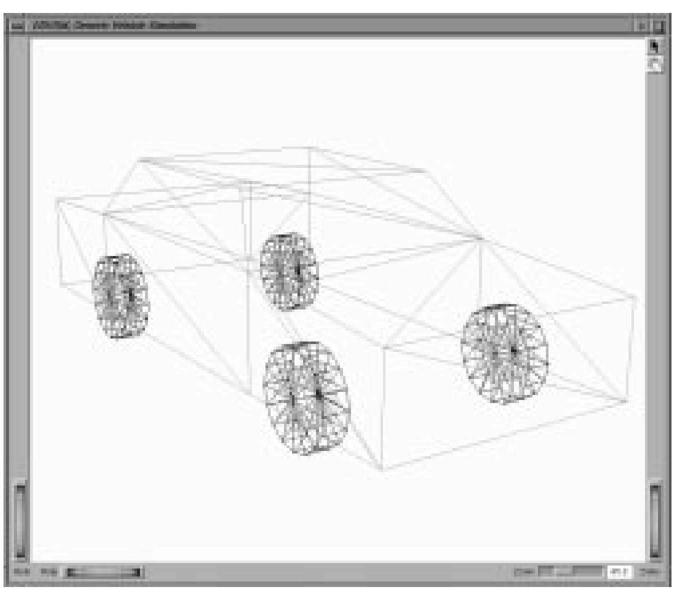


Figure 1 - Generic Vehicle (Passenger Car) in Wireframe [30]. Vehicle has 20 nodes (vertices).

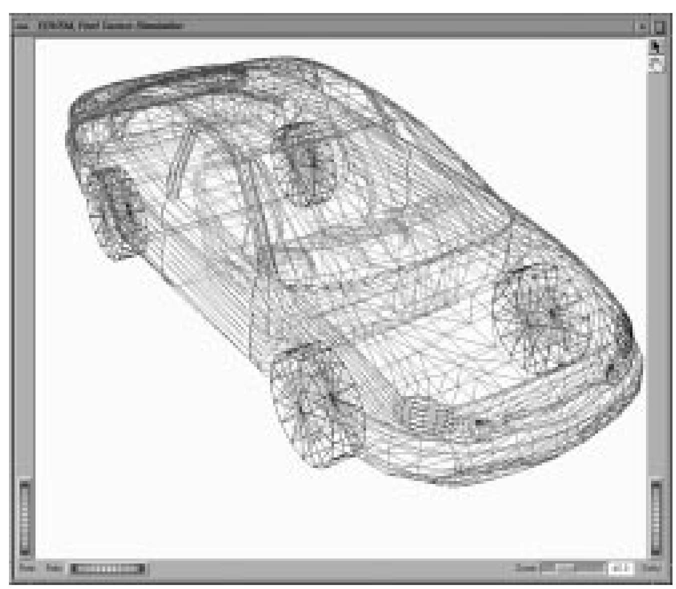


Figure 2 - 1998 Ford Taurus in Wireframe [31]. Vehicle has 2792 nodes (vertices).

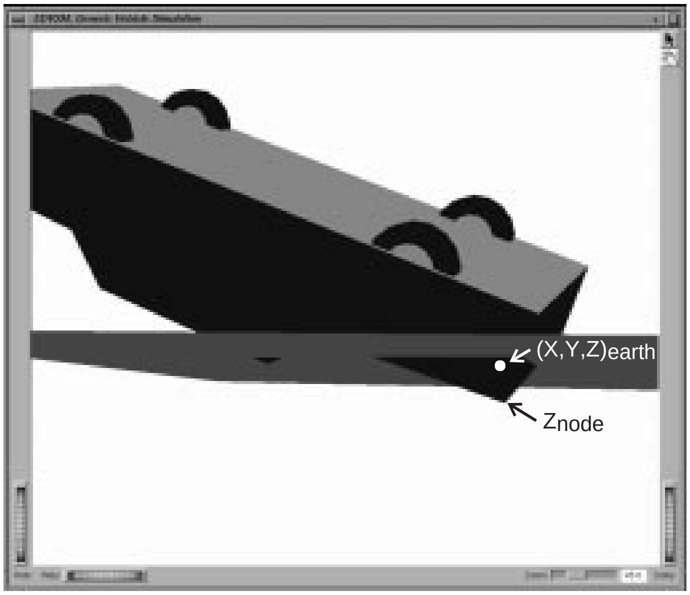


Figure 3 - Body vs ground interaction using GetSurfaceInfo()

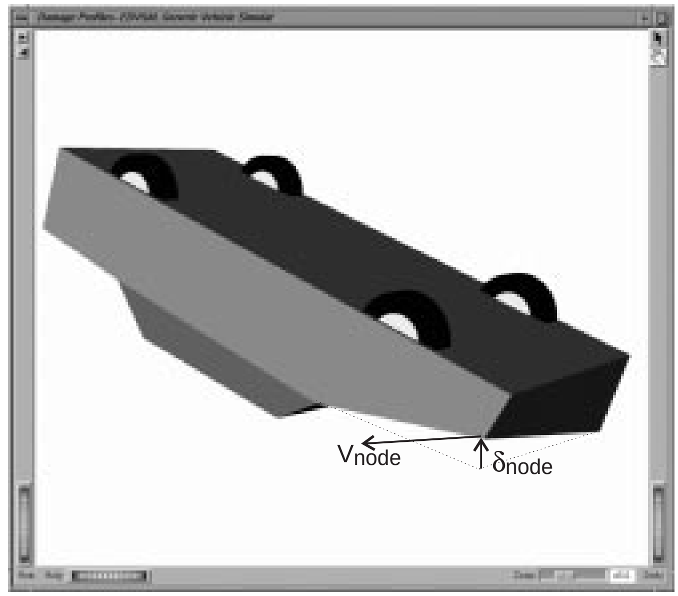


Figure 4 - Node deformation (displacement) and velocity

unlimited number of nodes. The vehicle-fixed coordinates for each node are inherently included in the geometry file, as is the number of nodes.

Force and deformation can occur only at node coordinate locations, thus, the number of nodes determines the resolution of the model. For example, a Generic Class 1 Passenger Car [30] is comprised of 20 vertices. Thus, forces can be produced only at 20 locations on the vehicle (see Figure 1). On the other hand, a 1998 Ford Taurus 4-Dr Sedan [31] is comprised of 2792 vertices (not including tires and wheels). Thus, forces can be produced at 2792 locations on the Ford Taurus. The resulting analysis can include significantly more detail (see Figure 2).

Node Material Attributes

The HVE simulation environment [32] supplies each node with a complete set of material attributes; the attributes are user-editable. However, the EDVSM body model uses only the exterior stiffness, K_v, and vertex friction, μ_v. The material attributes are omni-directional (i.e., force-displacement characteristics of the node are independent of the direction of deformation).

The material attributes are not assigned according to the area surrounding each vertex. Routines of significantly greater complexity are required for such an approach [33,34]. Thus, closely spaced vertices will create a harder region than widely spaced vertices. To some degree, this correlates with one's intuition because complex regions comprised of many vertices, such as door pillars, tend to he harder than flat areas comprised of fewer vertices, such as door panels. However, the user should be aware of this characteristic when assigning stiffness values.

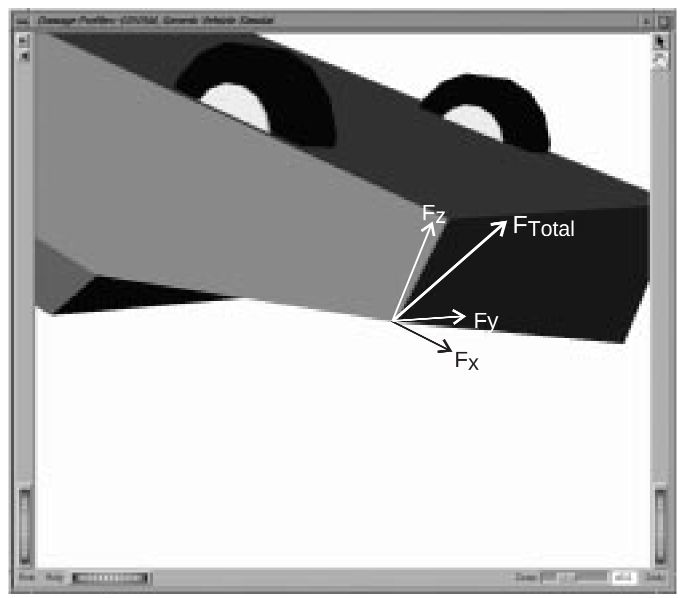


Figure 5 - Vehicle-fixed node force components

Because node force is not assigned according to the area surrounding the vertex, the proper selection of K_v depends on the number of vertices included in the vehicle geometry. Experience has shown that a value of 15-25 lb/in^2 (actually lb/vertex) is reasonable for vehicles having 1000 to 3000 vertices. Because the forces are impulsive, the effect of selecting a lower value of K_v is to decrease the peak force and increase the deformation and duration of impact. Selecting a higher stiffness generally increases the peak force and decreases the deformation and duration of impact. In any case, the impulse (area under the force vs time curve) is approximately the same over a rather wide range of stiffness values. The basic approach is to select a K_v value that results in a crush depth that approximates the actual crush.

K_V is assigned using the HVE Vehicle Editor by clicking on the desired surface icon (*front, right, back, left, top* or *bottom*), choosing the Stiffness dialog and entering the desired K_V stiffness value (*A* and *B* stiffnesses are also available in the dialog, but are not used by the EDVSM body model).

The default body-terrain friction coefficient is 0.50. The body-terrain friction may be modified using friction zones.

Node Force

The force at each node (or vertex) is calculated from the penetration of the node into the surface terrain. An HVE function, called `GetSurfaceInfo()`[35], is used to perform this calculation (see Figure 3), the same as for calculating tire radial force. These calculations require that each vertex be transformed from the vehicle-fixed coordinate system to the earth-fixed coordinate system. The node deformation is then calculated in the earth-fixed coordinate system (see Figure 4). The earth-fixed node velocity is then calculated to determine the direction of the friction force. The earth-fixed normal component of the node deformation is calculated and applied to the friction coefficient to determine the frictional force component. Ten percent restitution is applied during unloading. Finally, the total force is calculated in the earth-fixed coordinate system and resolved in the vehicle-fixed coordinate system to be applied to the vehicle sprung mass (Figure 5). This procedure is performed for each vertex in the vehicle geometry file.

Forces and Moments on Sprung Mass

Once the 3-dimensional force components are known for each vertex location, it is a simple matter to calculate the total forces and moments on the sprung mass:

$$F_{x_{Vehicle}} = \sum_{i=1}^{NumNodes} F_{x_{Node}}$$

$$F_{y_{Vehicle}} = \sum_{i=1}^{NumNodes} F_{y_{Node}}$$

$$F_{z_{Vehicle}} = \sum_{i=1}^{NumNodes} F_{z_{Node}}$$

$$M_{x_{Vehicle}} = \sum_{i=1}^{NumNodes} \left(F_{z_{Node}} y_{Node} - F_{y_{Node}} z_{Node} \right)$$

$$M_{y_{Vehicle}} = \sum_{i=1}^{NumNodes} \left(F_{x_{Node}} z_{Node} - F_{z_{Node}} x_{Node} \right)$$

$$M_{z_{Vehicle}} = \sum_{i=1}^{NumNodes} \left(F_{y_{Node}} x_{Node} - F_{x_{Node}} y_{Node} \right)$$

Note that the vertex *x,y,z* coordinates used in the above calculations are based on the current node deformation. This is important for two reasons: First, current node coordinates define the moment arm for a node's moment calculations, thus, current deformation must be considered, and second, if the vehicle rolls twice (or more) on the same portion of the vehicle, the calculation procedure must remember the deformation associated with previous contact.

APPLICATIONS

The EDVSM model may be used for simulating and evaluating proposed vehicle designs. Within the context of issues related to rollover, proposals such as alternative suspension systems or tire selections may be evaluated. For a given proposal, a suite of simulated maneuvers may be executed to show, for example, the rollover propensity for various steering rates. Although such tests must ultimately be run at the proving ground, the design engineer can use simulation to perform a test matrix of vehicle configurations and maneuvers much larger than would be practical at the proving ground. The result is an evaluation of many more designs than would otherwise be possible, as well as a significant reduction in testing cost.

Another application of the EDVSM model is the simulation of an FMVSS 208 [36] rollover test. The results may be used to approximate the test conditions before actual testing is performed. Such a simulation may prevent an unanticipated outcome that would require an additional test.

The EDVSM model may also be used to study real-world crashes involving on-road and off-road rollover. The vehicle may roll any number of times and the terrain may be flat or 3-dimensional (see **Limitations**, below). Such a simulation is helpful to confirm the conditions leading up to the loss of control and/or rollover. The results can also be used as an input to an occupant simulation to study the motion of occupants during the rollover process [22,23].

EXAMPLES

Three examples are included in this paper to illustrate various uses of rollover simulation:

- Effect of Steer Phasing on Vehicle Rollover
- Simulated FMVSS Rollover Test
- Real-world Crash Involving an Off-road Rollover

These examples were selected to show a variety of different applications for rollover simulation applied to important vehicle safety issues.

Effect of Steer Phasing on Vehicle Rollover

The static analysis metric, *t/2h* (described earlier), can be misleading. It can predict that a vehicle should not rollover

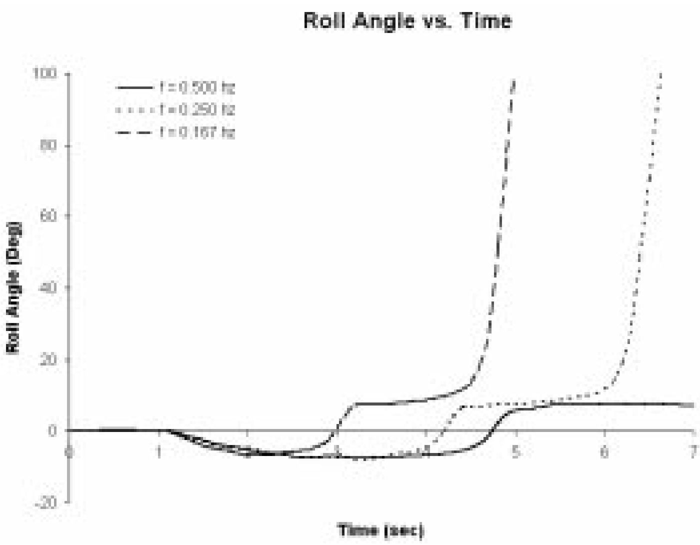


Figure 6 - Vehicle roll angle vs time for three different steering input rates

when, in fact, it will. The rollover occurs because two important factors are missing from the static analysis: the effect of roll inertia and the effect of body roll displacement on the CG lateral location.

The example used to illustrate these effects goes one step further: A Generic Class 1 SUV from the EDC Generic Vehicle Database [31] * has a sprung mass CG height of 26.66 inches and a track width of 56.78 inches, so

$$\frac{t}{2h} = \frac{56.78}{2 \times 26.66} = 1.064$$

Thus, this vehicle requires tires with a friction coefficient of 1.064 to reduce its static margin to zero (i.e., rollover). The vehicle is fitted with generic LT235/75R15 tires from the HVE Generic Tire Database. These tires have a peak lateral friction coefficient of 0.80 to 0.95 (depending on vertical tire load) and a slide friction coefficient of 0.50 to 0.75 (again, load-dependent). Therefore, the available friction is less than *t/2h* for all tire load conditions and rollover should not occur on a level surface (according to the static analysis metric).

Three simulations are performed with an initial velocity of 55 mph and maximum steer amplitude of 180 degrees. The vehicle is in 3^{rd} gear at 50% wide-open throttle. The steer frequency is varied: 0.167 hz in run 1, 0.25 hz in run 2 and 0.50 hz in run 3. The results are shown in Figure 6. In run 1, the vehicle remains upright, achieving a maximum roll angle of 7.6 degrees. The linear velocity at this time is 38.6 mph. In run 2, the vehicle rolls over. Interestingly, the velocity at the time of rollover is less than 35 mph, slower than in the (stable) preceding run. Finally, the results for run 3 are similar to run 2; the vehicle rolls over. The velocity at the time of rollover is approximately 40 mph.

These runs show the influence of steer frequency on vehicle stability. It is an interesting exercise to apply the brakes at various points during the maneuver. Braking can either amplify or diminish the tendency for rollover, depending on when the brakes are applied. (Reference 17 discusses how controlled braking can be used to reduce rollover propensity; it does not make the corollary point that (untimely) braking can increase the propensity for rollover.)

This example also illustrates that the use of the static rollover metric is not always a good indicator of rollover propensity. A rollover is a complex dynamic event, the analysis of which is further complicated by driver inputs and the frequency response of the vehicle's suspension.

Simulated FMVSS 208 Rollover Test

FMVSS 208 includes a rollover test procedure [36]. The purpose of the test is to establish the occupant protection capacity of a vehicle during a rollover event.

In this example, we use EDVSM to simulate an FMVSS 208 test conducted in [24]. The actual test involved a 1981 Dodge Challenger. The vehicle was placed on a dolly at an initial roll angle of 28 degrees, as shown in Figure 7. The dolly was towed at a nominal speed of 30 mph and stopped suddenly, causing the vehicle to separate and imparting an initial lateral velocity (in the ground plane) of 30 mph. A minor roll moment was imparted to the vehicle as the dolly stops, however, the major roll moment occurs when the vehicle's right-side tires contact the pavement with a tire slip angle of 90 degrees, thus inducing the rollover. The results are shown in Figure 8.

As a computer model of the Dodge Challenger was unavailable, a substitute vehicle (Chrysler New Yorker 4-Dr sedan) was used for the simulation. The initial conditions for the simulation (test speed, initial roll angle) were the same as the test conditions. The initial condition is shown in Figure 7. The simulation results are shown in Figure 8, superimposed over the actual test results. The results for the first run are used in this example. We have intentionally shown the results for the first run because, while practically any simulation can be adjusted to achieve a match with an actual test (given that the

* A Generic vehicle is defined as a vehicle with representative properties assigned according to its wheelbase. It is not intended to represent any specific vehicle.

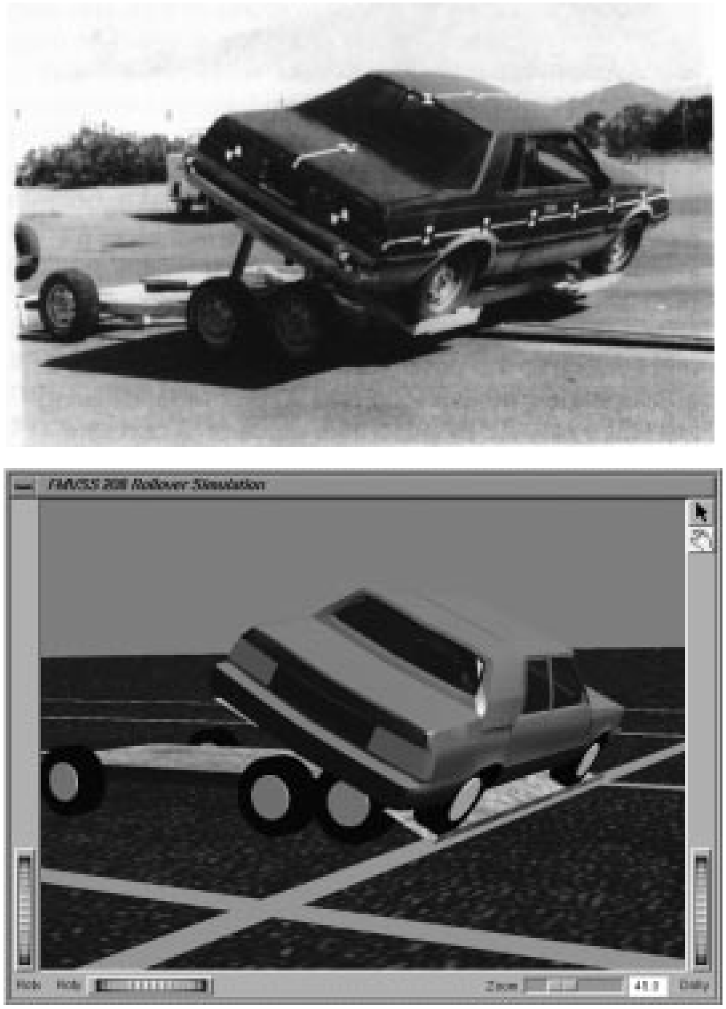
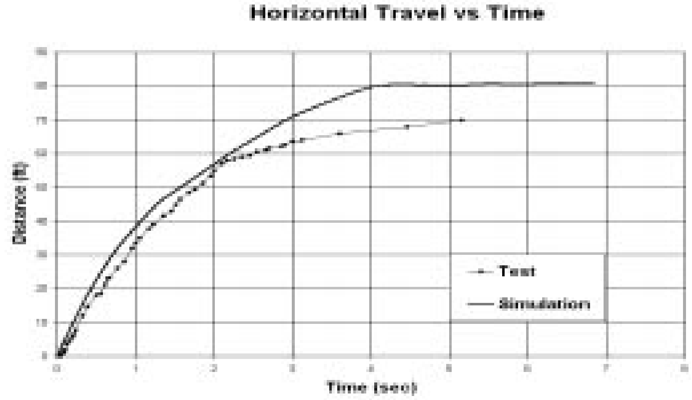
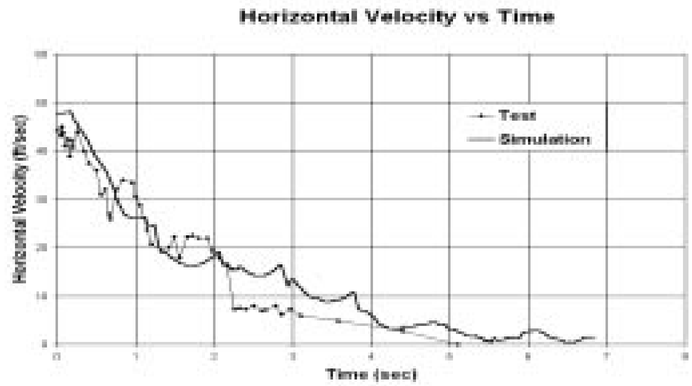
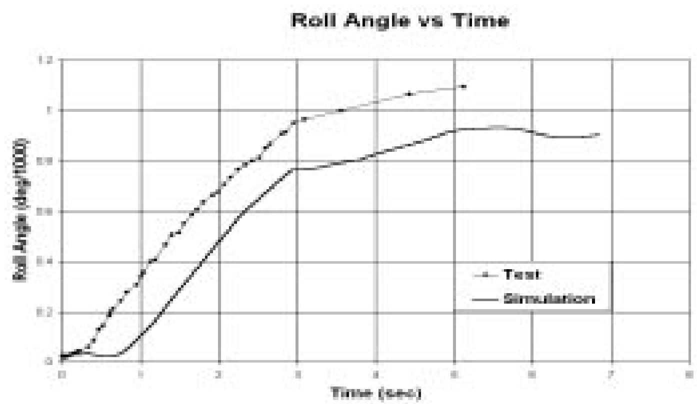
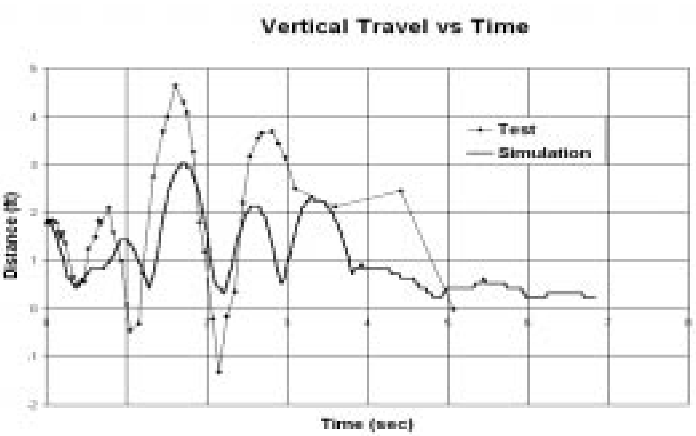


Figure 7 - FMVSS rollover test setup. The actual test setup is shown at the top [24], and the simulation setup is below.









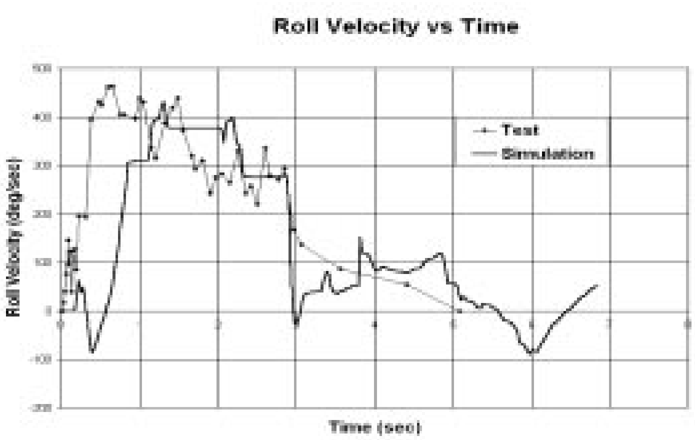


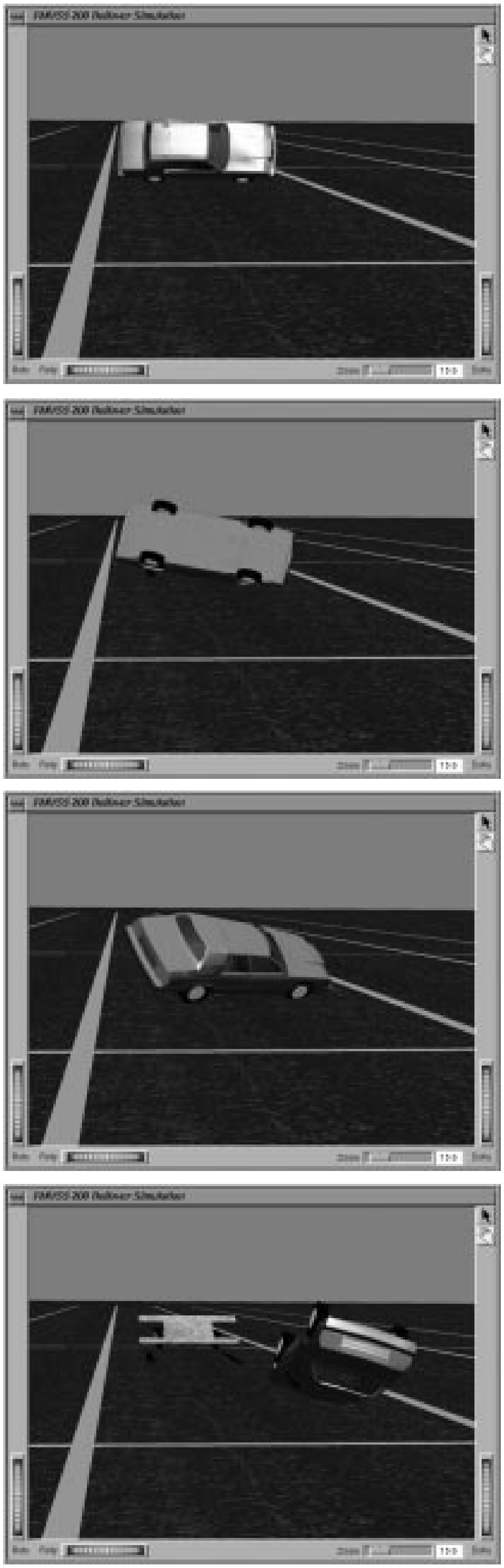
Figure 8 - FMVSS 208 rollover test showing actual test results along with the results from the EDVSM simulation.

user has enough time), the first run is a better measure of the model's capability to show convergence. The results compare quite favorably. For example, the total distance traveled for the test was 71 feet, compared with 80 feet in the simulation; total number of rolls was 3 in the test, compared to 2-1/2 for the simulation (the test vehicle comes to rest on its tires, while the simulated vehicle came to rest on its roof). It is apparent from Figure 8 that the initial total velocity in the simulation was slightly higher than in the test. Perhaps this is partially responsible for the additional distance traveled. However, the simulated vehicle rolled *less* than the test vehicle, thus, there must be some other factor at work; perhaps higher suspension shock absorber rates in the simulation model. Experience has shown that vehicles with like-new shocks, such as those on vehicles in the EDC Vehicle Database, do not roll as many times - nor as violently - as vehicles with worn shocks. This behavior appears to be the result of damping in both the vertical and roll degrees of freedom; both of these modes are very active during multiple rollover events.

Sequences from the simulated rollover test are shown in Figure 9. The simulated vehicle damage is visualized in Figure 10.

Real-world Crash Involving an Off-road Rollover

The final example illustrates the use of a robust 3-dimensional simulation for studying a real-world, off-road crash involving rollover. The crash site is a suburban, 4-lane, undivided highway with an uphill curve to the right. Sidewalks line each side of the highway. A small embankment exists between the sidewalk and a parking lot (see Figure 11). In the actual crash, the vehicle speed was not known (in fact, the vehicle make and model are not known). Tire marks were clearly present showing the path. A 1998 Volkswagen Jetta



t = 0.9 sec Following Launch

t = 1.4 sec

t = 3.0 sec

t = 5.1 sec (~rest)

Figure 9 - Frames from simulation of FMVSS 208 Rollover Test.

Figure 10 - Simulated vehicle damage resulting from FMVSS 208 Rollover Test.

Figure 11 - Real-world rollover crash site

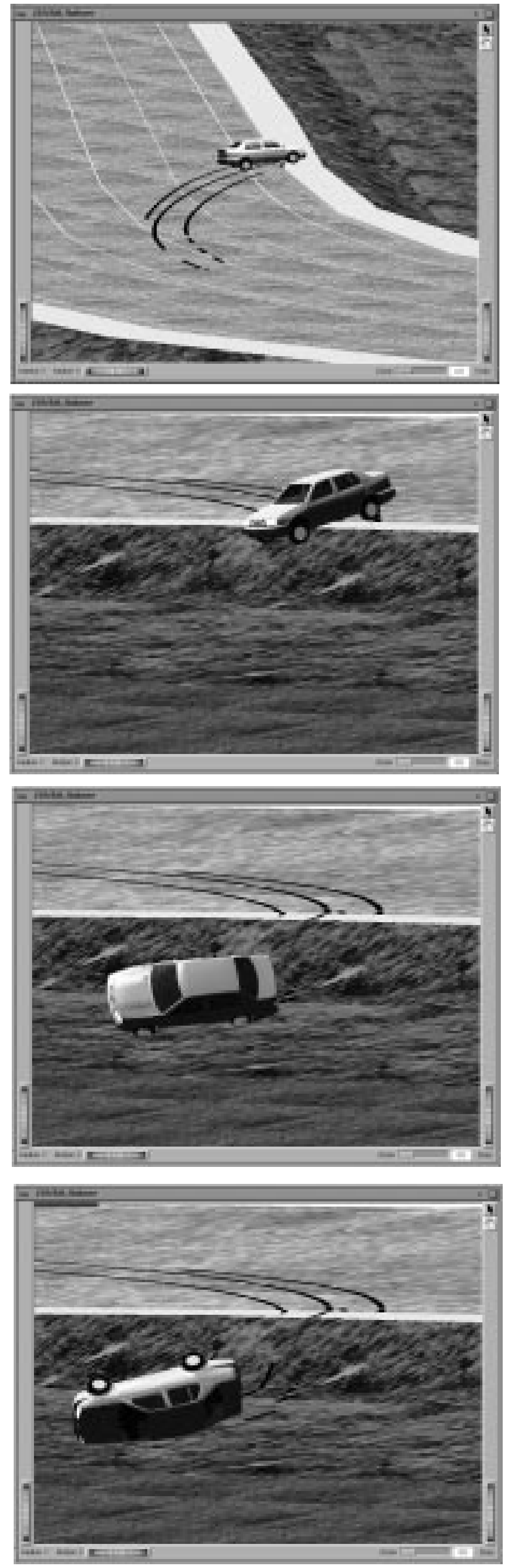


Figure 12 - Frames from simulation of real-world rollover crash

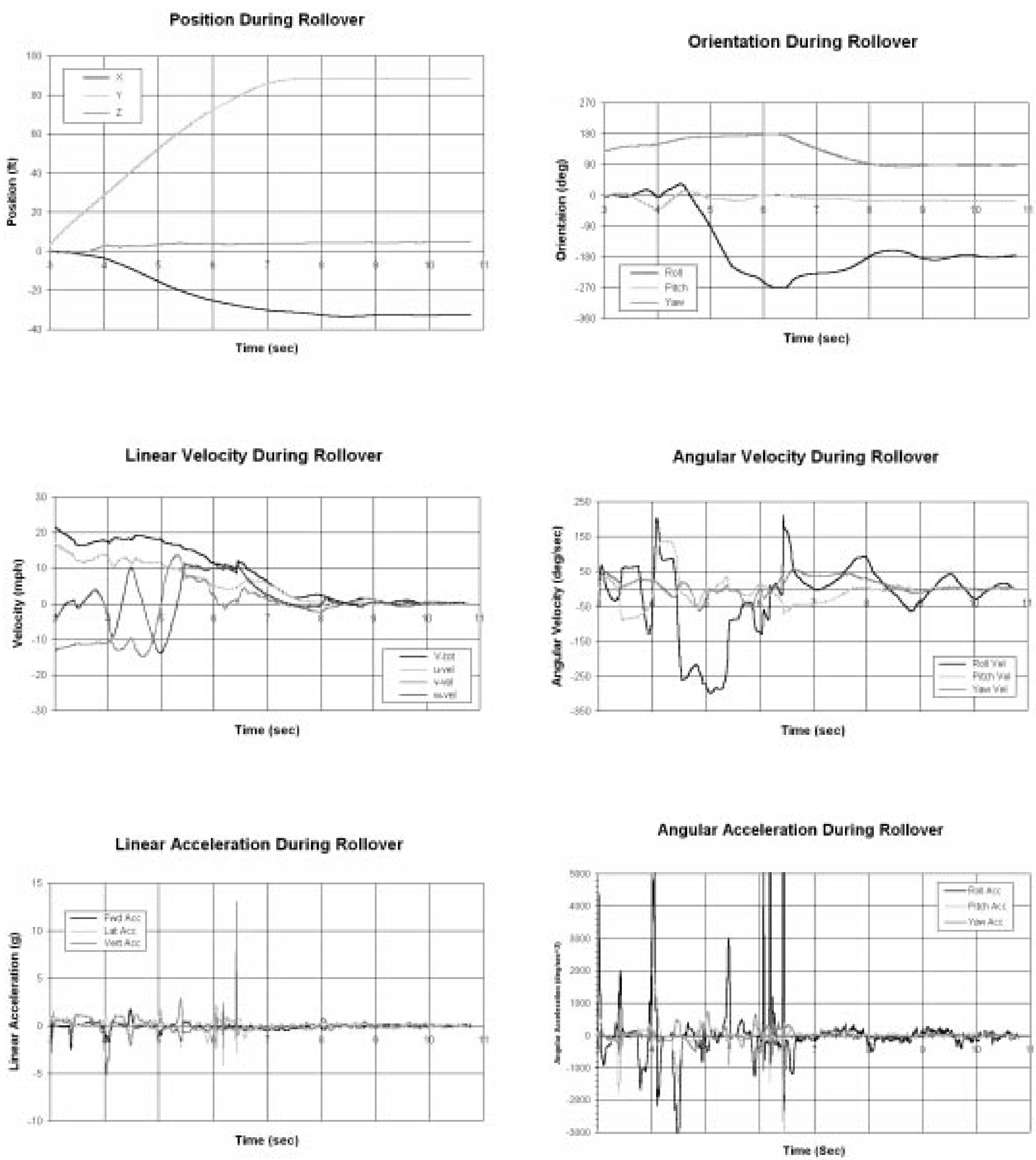


Figure 13 - Simulation results for sprung mass position (top) velocity (middle) and acceleration (bottom) during off-road rollover crash.

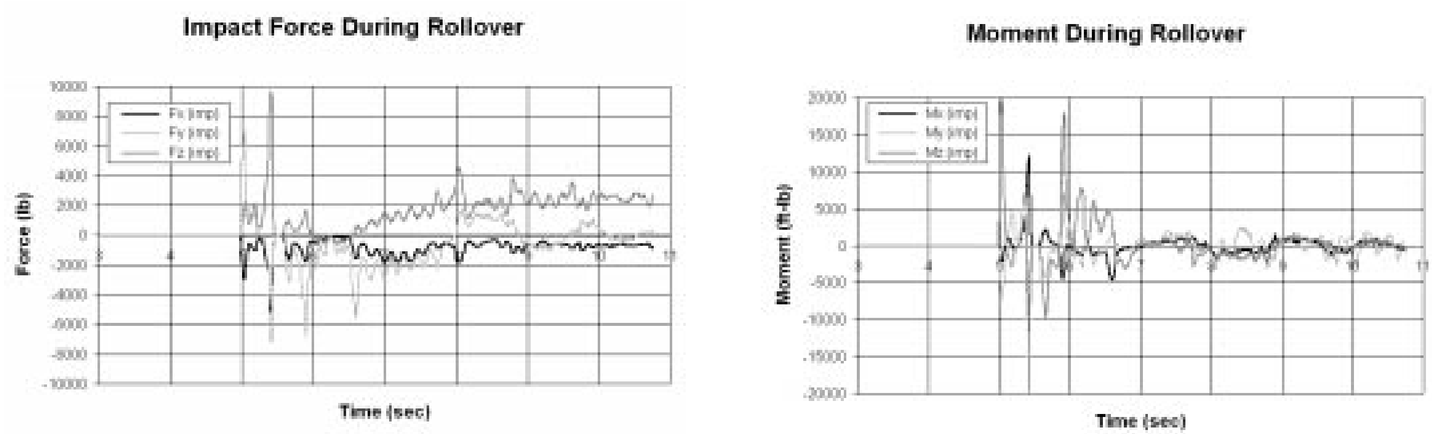


Figure 14 - Forces (left) and moments (right) acting on sprung mass during rollover. The body first contacts the terrain 5 seconds into the simulation.

was selected for the analysis. Initial speed and driver steering and braking inputs were supplied and adjusted until a satisfactory match was achieved between the simulated and actual vehicle path (47.5 mph was used). The simulation is performed simply for purposes of illustrating the EDVSM body model for studying a real-world, off-road rollover. Frames from the simulated rollover sequence are shown in Figure 12. Graphical results for sprung mass kinematics are shown in Figure 13; sprung mass kinetics (forces and moments) are shown in Figure 14. The simulated vehicle damage resulting from the rollover is shown in Figure 15.

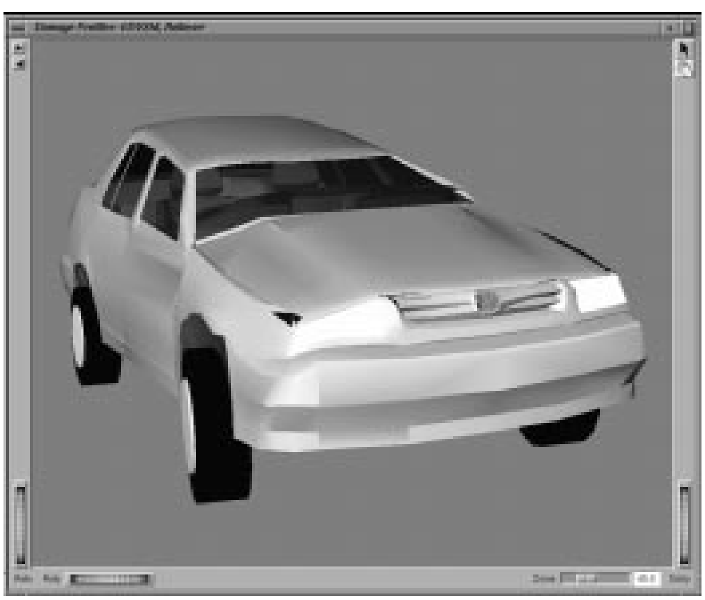


Figure 15 - Simulated vehicle damage resulting from the off-road rollover crash.

As a result of simulating the rollover sequence, an interesting observation was made: The rollover did not occur on the sloped embankment. In fact, the wheels unloaded during this portion of the sequence so that there was insufficient tire force (plowing or otherwise) to develop a large roll moment. The rollover actually occurred as a result of the orientation at the instant the vehicle reached the lower parking lot. Significant vertical tire force existed at the left front tire at the same time the vehicle sideslip angle was approximately -45 degrees. Occurring simultaneously, these factors produced the roll moment that caused the rollover.

LIMITATIONS

The EDVSM body model includes material attributes for each vertex, or node. This suggests that hard spots and soft spots could be easily modeled. This is not the case because there is currently no interface in HVE to supply the data on a per-vertex basis. Rather, material attributes are assigned on a per-surface basis (i.e., *front, right, back, left, top* and *bottom*). The material attributes are constant for each surface.

The EDVSM body model does not model contact with a vertical surface. Thus, barrier collisions are not allowed. This limitation arises from the use of `GetSurfaceInfo()` to determine contact between the body and terrain. Vertical faces are ignored by `GetSurfaceInfo()`.

Curb-tripped rollover is not handled by the current EDVSM tire model. To model this condition requires tire sidewall forces to be included in the tire model. Options for including these forces are currently being evaluated. It has been suggested that curb-tripped rollover may be modeled through the use of an increased local friction coefficient (i.e., a *friction zone*). This approach would allow tire shear forces to be increased in the region of the high-friction surface.

However, forces associated with curb tripping are not shear forces, they are impulsive forces of very high magnitude lasting a very short duration. For this reason, it is not generally recommended that friction zones be used for modeling curb-tripped rollover.

Although HVE includes sophisticated terrain material attributes that allow for tire penetration into soft soils (called *plowing*), tire plowing in the EDVSM tire model is not yet implemented. To do so requires tire-soil sidewall forces to be included in EDVSM's tire model. Such a model is under development. However, unlike forces associated with curb tripping (described in the preceding paragraph), plowing forces are not impulsive and are modeled quite well using a friction zone. Thus, soil-tripped rollover may be simulated, although care must be exercised.

Rim gouging into hard pavement is not modeled. To do so rigorously is quite a complex modeling problem, primarily because the mechanics of interaction between a pneumatic tire and terrain assumed by the tire model are very different from the mechanics of scraping (with possible deformation and fracture) between two rigid bodies. (See **Discussion**, below.) However, the forces from rim gouging are (like plowing) more shear-like than impulsive, so using friction zones probably provides a reasonable approximation in many cases. Such an approach should be validated, and until such a validation exists, the user should exercise caution when using this approach.

DISCUSSION

Matching the detailed results from a simulation with real-world crash site evidence and vehicle damage is a time-consuming process. This is especially true if the goal is to match the vehicle damage patterns. As with any reconstruction involving vehicle rollover, significant skill is required in the proper interpretation of the evidence. These issues are addressed in numerous references, including those cited earlier in this paper. Once the evidence is properly interpreted numerous simulations must be performed, adjusting key parameters until a satisfactory match is achieved. The most important parameter is the velocity at the start of the rollover. However, matching the vehicle damage patterns also requires careful selection of vehicle stiffness on various portions of the vehicle. The problem can become even more challenging for crashes involving multiple rolls that caused superimposed damage on the same portion of the vehicle.

The model described in this paper has a significant advantage over finite element methods because it does not require a detailed mesh with inertias and connectivity defined for each node. In addition, a run using this model requires seconds, rather than hours (or days) of execution time. Therefore, numerous runs are possible in a relatively short period of time. A large number of runs encourages greater exploration of possible scenarios. However, finite element methods have a significant advantage over the method described in this paper when extreme fidelity is required for a specific vehicle component (e.g., the design of an A-pillar).

MADYMO and ATB have been used successfully to simulate vehicle body vs terrain interaction. The approach used by the EDVSM body model is essentially the same as that used by these other methods. The primary advantage is that the HVE user environment automates the process of setting up and executing a complex simulation by coupling the mesh directly into the physical model, thus reducing the time required to set up the simulation and view the results.

During a rollover simulation where the roll angle exceeds 90 degrees, unrealistic behavior has been observed in some EDVSM simulations. This behavior manifests itself as a high linear acceleration resulting in a large velocity change and vehicle displacement during a single timestep. This behavior was traced to the tire model, which begins by calculating radial tire deformation. Because of the geometrical interaction between the tire and terrain as the tire plane becomes nearly parallel to the road plane, the calculated radial deflection may be quite large (the deformation may even extend beyond the maximum tire deflection, i.e., into the rim), the resulting radial tire force may become excessive in magnitude and (seemingly) arbitrary in direction. Testing has shown this problem can often be solved successfully by reducing the tire secondary stiffness and increasing the deflection at secondary stiffness and maximum deflection. This approach works because it prevents the calculation of an excessive force during a single timestep. It should be noted that the force calculated during this timestep for the tire in question is probably incorrect, however, the force is too short in duration to significantly affect the vehicle motion.

CONCLUSIONS

1. The use of simulation has the capability of extending the current knowledge and understanding of complex dynamic events, such as vehicle rollover.

2. Applications for rollover simulation studies include vehicle design and testing, as well as the study of real-world crashes.

3. While it is possible, the exact matching of simulation results with crash site evidence is time-consuming and is probably not justified in most crash reconstruction cases where estimating the pre-loss-of-control speed is the researcher's primary objective. For these cases, the gross vehicle kinematics (e.g., distance traveled, number of complete rolls) can sometimes be simulated in a minimal number of runs, possibly as few as one or two.

4. Rollover simulation for use in occupant injury simulation studies is possible, but time-consuming. In these cases, a close matching of the simulation results with crash site and vehicle damage evidence is required because the vehicle acceleration vs time history is used to drive the occupant simulation.

ACKNOWLEDGMENT

The authors wish to thank Dr. Stephen Werner, of Exponent Failure Analysis, for providing the original test data and film footage of the FMVSS 208 rollover test used in this paper, and to Ms. Elsebeth Stampke, of Engineering Dynamics Corporation, for performing the time-consuming task of digitizing the graphical data from the test plots to obtain the numerical results used in the comparisons.

REFERENCES

1. US Department of Transportation, NHTSA Website, URL *http://www-nrd.nhtsa.gov/vtrc/ca/rollover.htm*, Background for Phase II of NHTSA's 1997-1998 Vehicle Rollover Research Program (see reference 16).

2. Day, T.D., "Validation of the EDVSM 3-Dimensional Vehicle Simulator," SAE Paper No. 970958, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1997.

3. Orlowski, K.R., Moffatt, E.A., Bundorf, R.T., Holcomb, M.P., "Reconstruction of Rollover Collisions," SAE Paper No. 890857, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1989.

4. Martinez, J.E., Schlueter, R.J., "A Primer on the Reconstruction and Presentation of Rollover Accidents," SAE Paper No. 960647, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1996.

5. Marine, M.C., Wirth, J.L., Thomas, T.M., "Characteristics of On-Road Rollovers," SAE Paper No. 1999-01-0122, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, March, 1999.

6. Jones, I.S., Penny, M.B., "Engineering Parameters Related to Rollover Frequency," SAE Paper No. 900104, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1990.

7. *Mechanics of Heavy Vehicles*, Conference Proceedings, University of Michigan Transportation Research Institute, Ann Arbor, 1981.

8. Allen, R.W., Rosenthal, T.J., "A Computer Simulation Analysis of Safety Critical Maneuvers for Assessing Ground Vehicle Dynamic Stability," SAE Paper No. 930760, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1993.

9. Bratten, T.A., "The Development of a Tumble Number for Use in Accident Reconstruction," SAE Paper No. 890859, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1989.

10. Hight, P.V., Siegel, A.W., Nahum, A.M., "Injury Mechanisms in Rollover Collisions," SAE Paper No. 720966, Society of Automotive Engineers, Warrendale PA, 1972.

11. Baker, J.S., *Traffic Accident Investigation Manual*, The Traffic Institute, Northwestern University, Evanston IL.

12. Searle, J.A., Searle, A., "The Trajectories of Pedestrians, Motorcycles, Motorcyclists, etc., Following a Road Accident," SAE Paper No. 831622, Society of Automotive Engineers, Warrendale, PA, 1983.

13. Nalecz, A.G., Lu, Z., d'Entremont, K.L., "An Investigation into Dynamic Measures of Vehicle Rollover Propensity," SAE Paper No. 930831, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1993.

14. Nalecz, A.G., Lu, Z., d'Entremont, K.L., "Advanced Dynamic Vehicle Simulation (ADVS) To Investigate Rollover Behavior," NHTSA -U.S. DOT Contract No. DTNH22-87-D-27174, April, 1991.

15. Nalecz, A.G., et al, "Sensitivity Analysis of Vehicle Tripped Rollover Model," NHTSA - U.S. DOT Final Report No. DOT-HS 807 300, Washington, D.C., July, 1988.

16. Garrott, W.R., Howe, J.G, Forkenbrock, G., "An Experimental Examination of Selected Maneuvers That May Induce On-Road Untripped, Light Vehicle Rollover -Phase II of NHTSA's 1997-1998 Vehicle Rollover Research Program," NHTSA Vehicle Research and Test Center, Report No. DOT HS 808 977, January, 1999.

17. Wielenga, T.J., "A Method for Reducing On-Road Rollovers — AntiRollover Braking," SAE Paper No. 1999-01-0123, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, March, 1999.

18. Chace, M.A., Wielenga, T.J., "A Test and Simulation Process to Improve Rollover Resistance," SAE Paper No. 1999-01-0125, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, March, 1999.

19. Wielenga, T.J., "Tire Properties Affecting Vehicle Rollover," SAE Paper No. 1999-01-0126, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, March, 1999.

20. *ADAMS* User Documentation, Mechanical Dynamics, Inc., Ann Arbor, MI, 1998.

21. Renfroe, D.A., Partain, J., Lafferty, J., “Modeling of Vehicle Rollover and Evaluation of Occupant Injury Potential Using MADYMO,” SAE Paper No. 980021, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1998.

22. Cheng, H., Rizer, A.L., Obergefell, L.A., “Pickup Truck Rollover Accident Reconstruction Using the ATB Model,” SAE Paper No. 950133, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1995.

23. Cheng, H., Rizer, A.L., Obergefell, L.A., “ATB Model Simulation of a Rollover Accident with Occupant Ejection,” SAE Paper No. 950134, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1995.

24. Cooperrider, N.K., Thomas, T.M., Hammoud, S.A., “Testing and Analysis of Vehicle Rollover Behavior,” SAE Paper No. 900366, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1990.

25. Cooperrider, N.K., Hammoud, S.A., Colwell, J., “Characteristics of Soil-Tripped Rollovers,” SAE Paper No. 980022, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, February, 1998.

26. Thomas, T.M., Cooperrider, N.K, Hammoud, S.A., Woley, P.F., “Real World Rollovers — A Crash Test Procedure and Vehicle Kinematics Evaluation,” Proceeding of Experimental Safety Vehicle Conference, Gothenburg, June, 1989.

27. Wilson, R.A., Gannon, R.R., “Rollover Testing,” SAE Paper No. 720495, Society of Automotive Engineers, Inc., Warrendale, PA, 1972.

28. Orlowski, K.F., Bundorf, R.T., Moffatt, E.A., “Rollover Crash Tests - The Influence of Roof Strength on Injury Mechanics,” SAE Paper No. 851734, Society of Automotive Engineers, Inc. Warrendale, PA 1985.

29. Segal, D.J., “Highway-Vehicle-Object Simulation Model -1976, Volume 2: Validation,” Calspan Corporation, DOT Contract No. DOT-FH-11-8265, FHWA Report No. FHWA-RD-76-165, Buffalo, 1976.

30. *HVE Generic Vehicle Database*, Engineering Dynamics Corporation, Beaverton, OR, 1999.

31. *EDVDB (Engineering Dynamics Vehicle Database, Version 2.1,* Engineering Dynamics Corporation, Beaverton, OR, 1999.

32. *HVE User’s Manual, Third Edition,* Engineering Dynamics Corporation, Beaverton, OR, July, 1999.

33. York, A.R., Day, T.D., “The DyMESH Method for 3-Dimensional Collision Simulation,” SAE Paper No. 1999-01-0104, presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, March, 1999.

34. Day, T.D., York A.R., “Validation of DyMESH for Vehicle vs Barrier Collisions,” SAE Paper No. 2000-01-0844, to be presented at the Society of Automotive Engineers International Congress and Exposition, Detroit, March, 2000.

35. *HVE Developer’s Toolkit, Version 2,* Engineering Dynamics Corporation, Beaverton, OR, 1999.

36. Federal Motor Vehicle Safety Standard No. 208, Occupant Crash Protection, Part 571, S208.

Reviewer's Discussion
By Michael P. Holcomb, M.P.H Engineering
SAE # 2000-01-0852
Applications and Limitations of 3-Dimensional Vehicle Rollover Simulation
Terry D. Day, J. Travis Garvey, Authors

Rollover crashes are of considerable interest today. Rollovers are, by nature, chaotic events, and extremely difficult to analyze. Earlier GM work in rollover testing (Malibu I, II) has clearly shown the widely varying physical results seen where essentially identical starting conditions are used. It is a mistake to expect a simulation to completely address this very complex event. Validation or match of a simulation model against a specific rollover test would not likely be applicable to a specific rollover accident, because of the chaotic nature of rollovers. With respect to reconstruction of an actual rollover accident, even the most careful analyst takes the risk of finding only one of several sets of apparently "satisfactory" input conditions. Even then, the appropriate solution may be missed.

I am very concerned about the enthusiastic novice analyst who jumps in with both feet, plugs in some generic estimated values, and reaches vast conclusions without regard to the various limitations of the model and the input data. If the user does not well understand these constraints and limits, such simulations become little more than cartoons of the user's imagination.

The better application for such tools is in attempting to learn more about simulation, and more about rollover dynamics. In that regard, this particular simulation application offers much to the field, since it can provide a relatively fast response for parametric work.

A tool such as this, with the potential to advance the understanding of a very complex crash event is welcomed, even if with caution and trepidation. The authors clearly recite the various necessary estimates, simplifications, and limitations of their analysis approach. They discuss applications which could prove valuable in areas of research and analysis.

It will be interesting to see the various efforts to apply this approach. I suspect that the stiffness estimation process will attract much discussion, along with observations that numerous sets of starting conditions can be found to produce "satisfactory" results. I can only repeat my caution, and temper the natural enthusiasm with restraint and a need for truly better understanding. My thanks to the authors for their efforts in developing a potentially useful analytical tool.

Reviewer's Discussion
By Charles P. Dickerson, Dickerson Technical Services
SAE # 2000-01-0852
Applications and Limitations of 3-Dimensional Vehicle Rollover Simulation
Terry D. Day, J. Travis Garvey, Authors

The increasing interest in understanding and preventing occupant injuries in rollover crashes has resulted in a corresponding increase in the complexity of rollover crash reconstructions. In many cases it is no longer acceptable to just determine the speed and the number of rolls. The authors present an analytical tool that can be used to increase the resolution of a rollover crash reconstruction.

The paper describes a tool for modeling both the loss of control and the actual rollover. It is important to distinguish between these two phases of the overall crash event. Modeling the loss of control requires a sophisticated vehicle dynamics model that adequately predicts vehicle behavior in the non-linear handling regime. After the vehicle trips, it is then necessary to model the three dimensional interaction of the vehicle body and the ground. This appears to be the first tool that does both.

As with any sophisticated tool, it is important that the user fully understand the model and its limitations in order to appropriately use it in an analysis. This paper provides some insight into this new model as well as some helpful tips. Any reader interested in rollovers is encouraged to review the materials presented in the reference section.