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Three-Dimensional Reconstruction and Simulation of Motor Vehicle Accidents

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Three-Dimensional Reconstruction and Simulation of Motor Vehicle Accidents

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ABSTRACT

This paper describes the use of 3-D technologies for reconstructing and simulating motor vehicle accidents involving humans (occupants and pedestrians) and vehicles (passenger cars, pickups, vans, multi-purpose vehicles, on-highway trucks and vehicle-trailers). All examples involve three-dimensional environments, including road crowns, hills, curbs and embankments - any geometrical feature resulting in three-dimensional motion. Various reconstruction and simulation models are illustrated. The features and limitations of each model are addressed. Issues involving data requirements, preparation of 3-D models and presentation techniques (numeric, graphic and video animation) are also explored.

PERHAPS NO FIELD is more affected by the "state of the art" as the field of accident reconstruction, where researchers often assume the accident environment is a flat, horizontal surface in order to use the available reconstruction and simulation models. Until recently, no tools existed which could easily and conveniently consider the effects of a *truly* 3-dimensional environment which included road crown and superelevation, curbs, culverts, and embankments. The assumption of a flat environment is often acceptable, but there are times when it is not.

The purpose of this paper is to examine several common situations which are affected, to varying degrees, by the flat environment assumption. Examples are provided wherein the flat environment assumption seems reasonable, yet the outcome is different when a 3-D, non-planar environment is used. Other examples are provided wherein the flat environment assumption is clearly invalid, and 3-D simulation is employed in order to analyze and visualize the accident sequence. The differences between animation and dynamic simulation are addressed. Finally, a discussion of the limitations in the current 3-D technology is presented.

EXAMPLES

To illustrate various 3-D analysis techniques, the following examples are provided:

- Crown and super-elevation
- Post-impact rollout on sloped surface
- Occupant motion
- Highway median
- Low-speed Rollover

These examples all use simulation as the basic analysis method.

Crown and Super-elevation

Most road surfaces have some degree of crown to accomodate precipitation runoff. Nearly all curves have super-elevation to help reduce the effect of centripedal force on the vehicle occupants. Crown and super-elevation are normally rather small and are often ignored for purposes of simulation.

The following example illustrates the effect of road crown on locked-wheel braking. The road was straight, but included an average crown of 0.05 ft/ft in the outside lane. The driver of a pickup travelling northbound in that lane applied

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

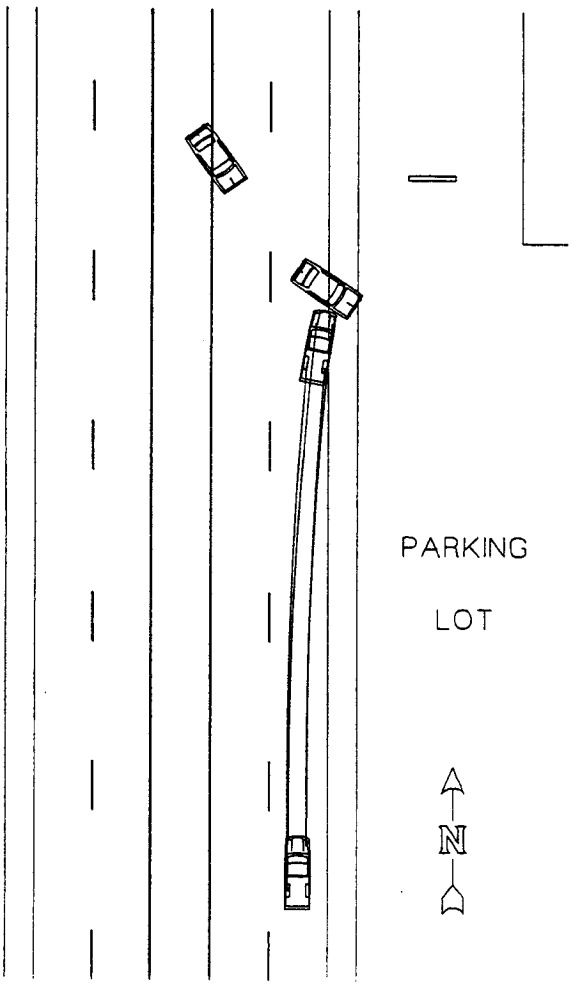

Figure 1 - 2-D simulation which includes steering to the right illustrated the hypothesis that the driver steered to the right to avoid impact.

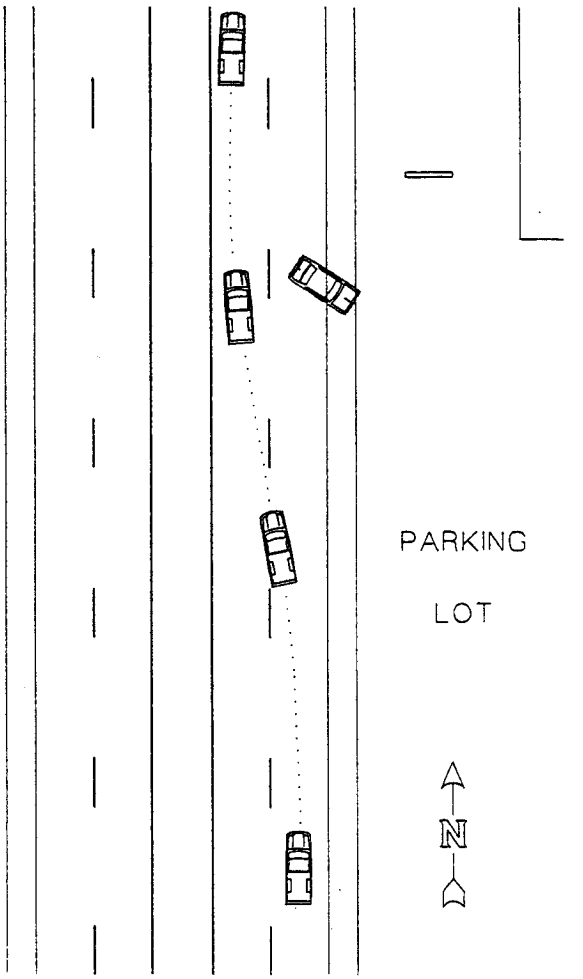

Figure 2 - Avoidance study using 2-D simulation showed that impact would not have occurred if the vehicle had steered slightly to the left.

the brakes hard enough to lock its wheels, in order to avoid another vehicle which turned left in front of it.

Because the pickup's skidmarks veered off to the right, it was initially assumed the driver steered to the right to avoid impact, and it was postulated the driver could have avoided the accident by turning slightly to the left. 2-D simulation results supported this conclusion, as shown in Figures 1 and 2. However, a 3-D simulation which included the effect of the road revealed the pickup's movement to the right was caused by locked wheel braking on the crowned road, as shown in Figure 3; steering was not a factor. In fact, 3-D simulation showed steering would have no effect (locked wheels do not produce a steering force).

When an empty pickup locks its rear brakes (note that unloaded pickups without anti-lock tend to be over-braked at the rear wheels in order to have sufficient braking power when fully loaded), 2-D simulation will show either a straight path or yaw instability. Because of the road crown, 3-D simulation was required to understand what actually happened: The vehicles rear wheels slid down the crown (to the right), causing the vehicle to rotate *counter-clockwise*. When the brakes were released, the vehicle took off in the direction of its heading vector (to the left). Modeling this type of behavior is beyond the scope of 2-D simulation.

Rollout on Sloped Surface

After impact, vehicles often leave the road and travel on sloped surfaces. The following example is actually a continuation of the previous example, and illustrates an interesting case that was carefully investigated by the police. Scene data were well documented, including impact positions (from pre-impact skidding and a collision scrub) and rest

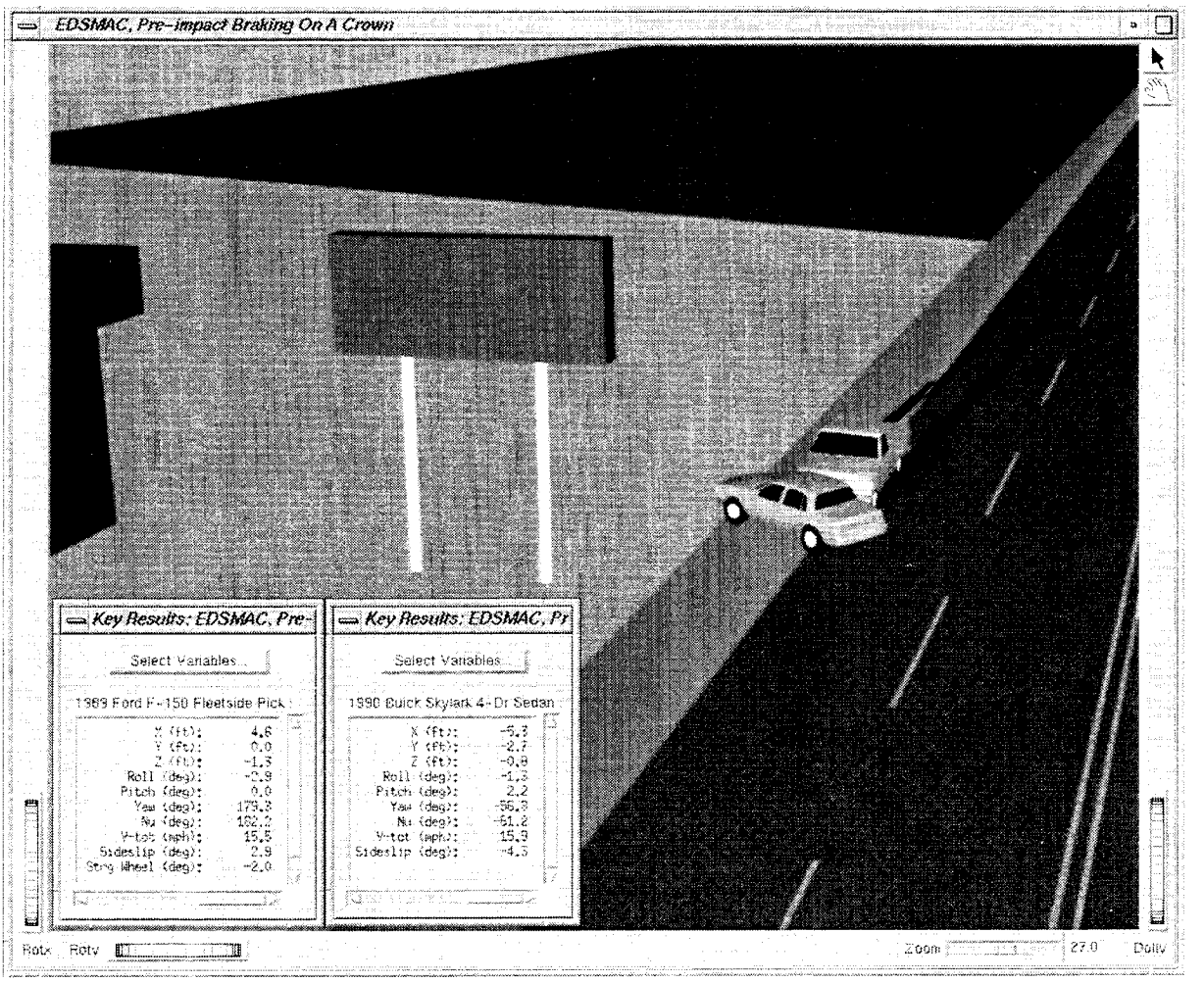

Figure 3 - 3-D simulation of the same event shown in Figure 1. This simulation included the effects of the road crown. Under normal driving conditions, the driver steers 3 degrees (at the steering wheel) to the left in order to offset the force due to the road crown. Locking the brakes on this surface, as shown below, causes the vehicle to veer slightly to the right.

positions (the investigating officer marked the earth-fixed wheel positions at rest). A scaled site diagram is shown in Figure 4. Note the vehicles came to rest next to each other (in fact, they were actually *touching* each other).

Reconstruction methods were employed to estimate impact speeds of about 10 mph for both vehicles (see Table 1). However, several diagnostic messages were issued, indicating a significant discrepancy between the momentum-based and damage-based results: The damage-based results showed significantly higher delta-Vs and, therefore, impact speeds when compared to the momentum-based results (see Table 1.). 2-D simulation results (see Figure 5) confirmed the speeds produced by the momentum analysis, but the results were still inconsistent with the damage severity.

3-D simulation (see Figure 6) revealed the source of the error: After impact, the passenger car rolled up a slight (8 percent) incline in the parking lot (it actually *struck* the building), and then rolled back onto the street, coming to rest next to the pickup. In fact, the vehicles actually had a second collision as the car rolled back out towards the street; this second collision with the pickup brought the car to rest. When the law enforcement officers arrived at the scene, they marked the rest positions of the vehicles but were unaware the car had travelled a significant distance after impact. 3-D simulation revealed the impact speed was approximately 15 mph for both vehicles (see Figures 3 and 6).

If the sine of the grade is greater than the combined rolling resistance (in the direction of rolling), the vehicle will roll downhill until it is stopped by another object (or until the grade changes again).

OCCUPANT MOTION

Occupant motion is obviously three-dimensional. During a crash, occupants tend to move in a direction opposing the PDOF. This fact helps determine who was driving at the

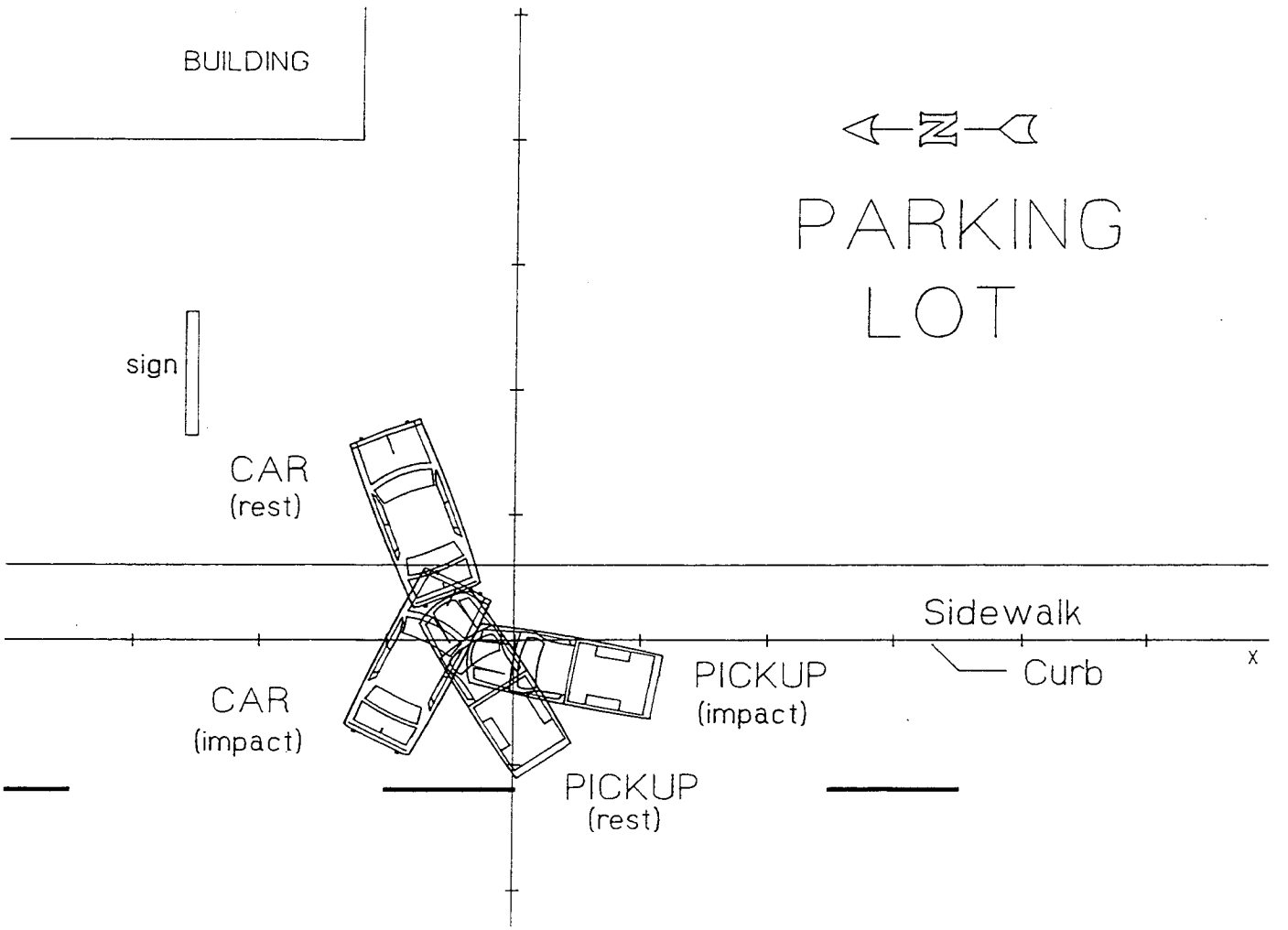

Figure 4 - Scaled accident site drawing showing the vehicles at impact and rest. Positions were well documented by the at-scene investigation.

Table 1. EDCRASH Reconstruction results

SAE Collision w/ Sloped Rollout

SUMMARY OF RESULTS

IMPACT SPEED (TRAJECTORY AND CONSERVATION OF LINEAR MOMENTUM)

	TOTAL	FWD.	LAT.	SIDESLIP
VEH #1	10.4 mph	10.4 mph	0.0 mph	0.0 deg
VEH #2	10.2 mph	10.2 mph	0.0 mph	0.0 deg

SPEED CHANGE (DAMAGE)

	TOTAL	FWD.	LAT.	PDOF
VEH #1	24.0 mph	-12.0 mph	-20.8 mph	60.0 deg
VEH #2	16.7 mph	-16.2 mph	4.0 mph	-14.0 deg

SPEED CHANGE (LINEAR MOMENTUM)

	TOTAL	FWD.	LAT.	PDOF
VEH #1	6.0 mph	0.6 mph	-6.0 mph	95.6 deg
VEH #2	4.2 mph	-3.9 mph	-1.5 mph	21.6 deg

ENERGY DISSIPATED BY DAMAGE

VEH #1	6665.8 ft-lb
VEH #2	104755.4 ft-lb

time of an accident. This rather simple example illustrates the use of 3-D simulation to visualize occupant motion in order to determine who was driving.

Two unbelted occupants were involved in an intersection collision. Only one head strike was recorded; it was located on the right side of the windsheld, in front of the passenger's seat position. The collision, which occurred on a level road, was reconstructed and simulated, as shown in Figure 7. The resulting impulse was supplied to a 3-D occupant simulator for purposes of visualizing the occupants' motion during impact. 3-D simulation of the occupants, also shown in Figure 7, revealed the driver had travelled at an angle within the occupant compartment and struck the windshield in front of the passenger's seat, resulting in forehead lacerations. Interestingly, the passenger also had facial lacerations, caused by impact with the side window glass, also shown in Figure 7

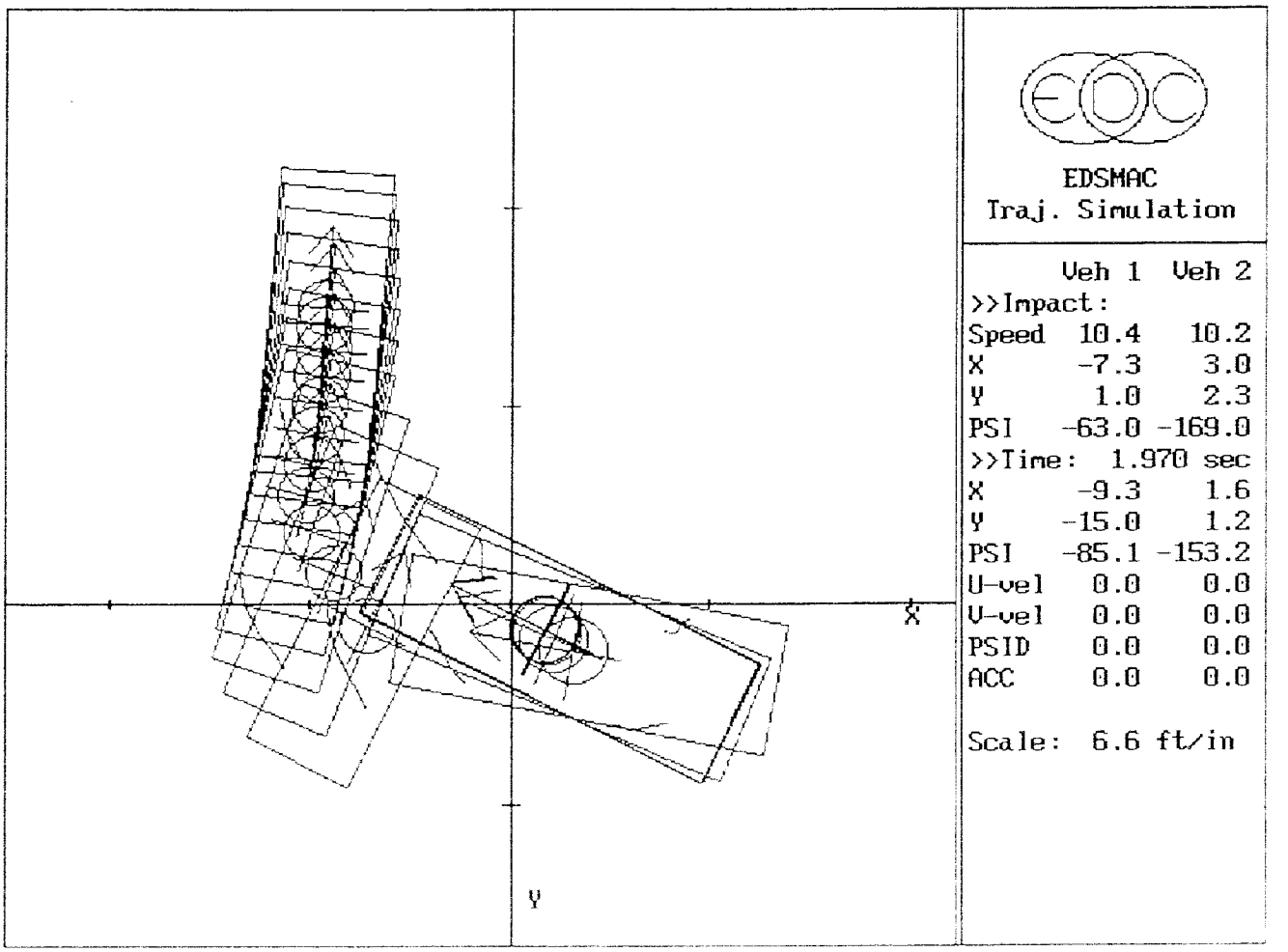

Figure 5 - 2-D simulation of rollout (above) that did not include the effects of the sloped surface.

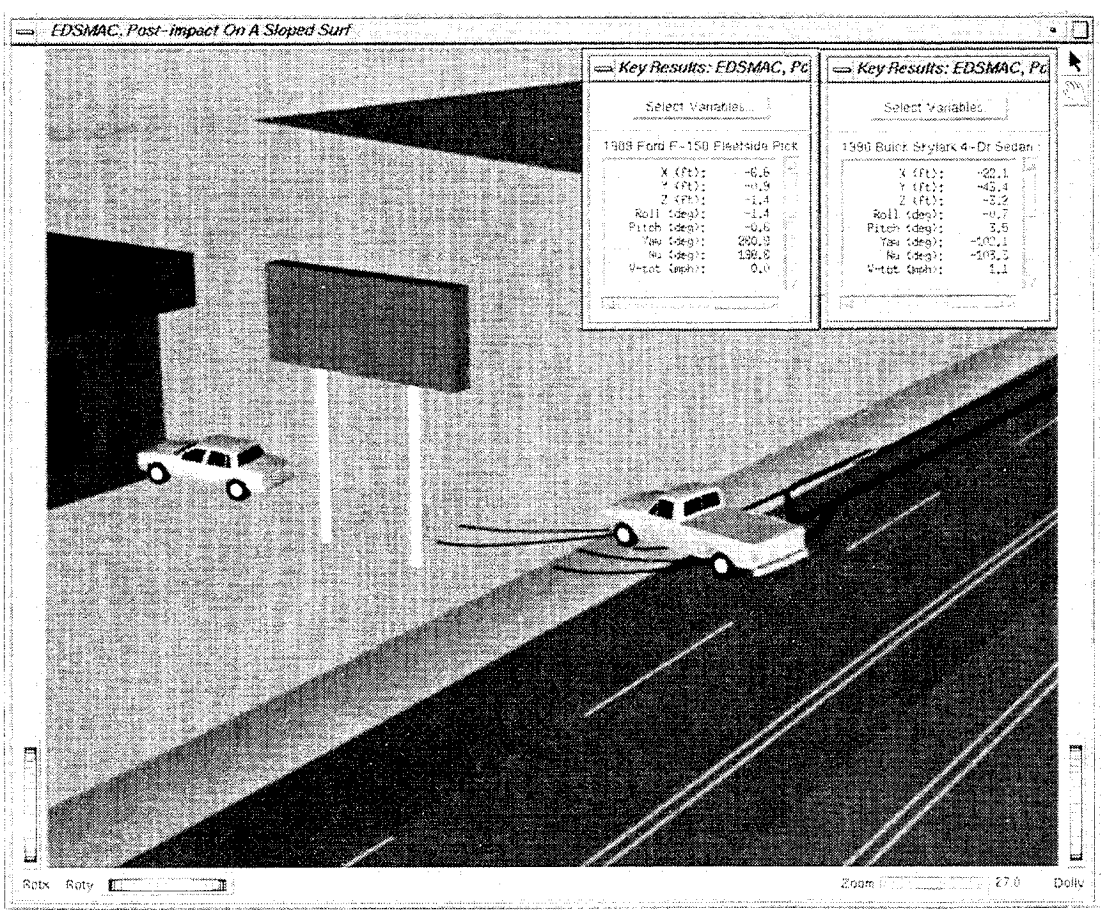

Figure 6 - 3-D simulation of post-impact rollout on a sloped surface (left). The passenger car, struck at a higher speed than originally estimated, rolled up the slope and actually touched the building at a low speed (about 1 mph), then rolled back to its rest position.

The tempered glass shattered, leaving no evidence of a head strike.

The above analysis technique is quite useful and easy to perform. The technique lends itself well to intersection-type collisions without rollover. If rollover occurs, the technique becomes much less reliable because the 3-dimensional nature of the motion is more difficult to predict; small changes in vehicle motion may influence the outcome.

HIGHWAY MEDIAN

Most rural interstate freeways use a median to separate opposing lanes of traffic. Although not excessively sloped, the median is rarely level.

In this example, a full-size passenger sedan left the highway to avoid a stalled vehicle blocking the lane ahead After entering the median, the driver attempted to bring the vehicle back onto the highway. However, due to a combination of speed (initially about 65 mph; about 60 at the time of rollover), steering , slope and soft dirt, the vehicle rolled over, as shown in Figure 8.

2-D simulation showed the tendency for wheel lift-off due to steering on a soft, furrowing surface (additional friction was added to simulate the increased lateral tire force). However, the 2-D simulation concluded the speed was much higher based on where the rollover took place (several hundred feet after leaving the road). However, the 3-D simulation revealed the rollover occurred late in the maneuver because, owing to the sloped surface, the wheels were unweighted during the first portion of the maneuver. Thus, the tire forces were insufficient to cause rollover until the vehicle travelled a significant distance - at the same time the driver was attempting to steer back onto the highway.

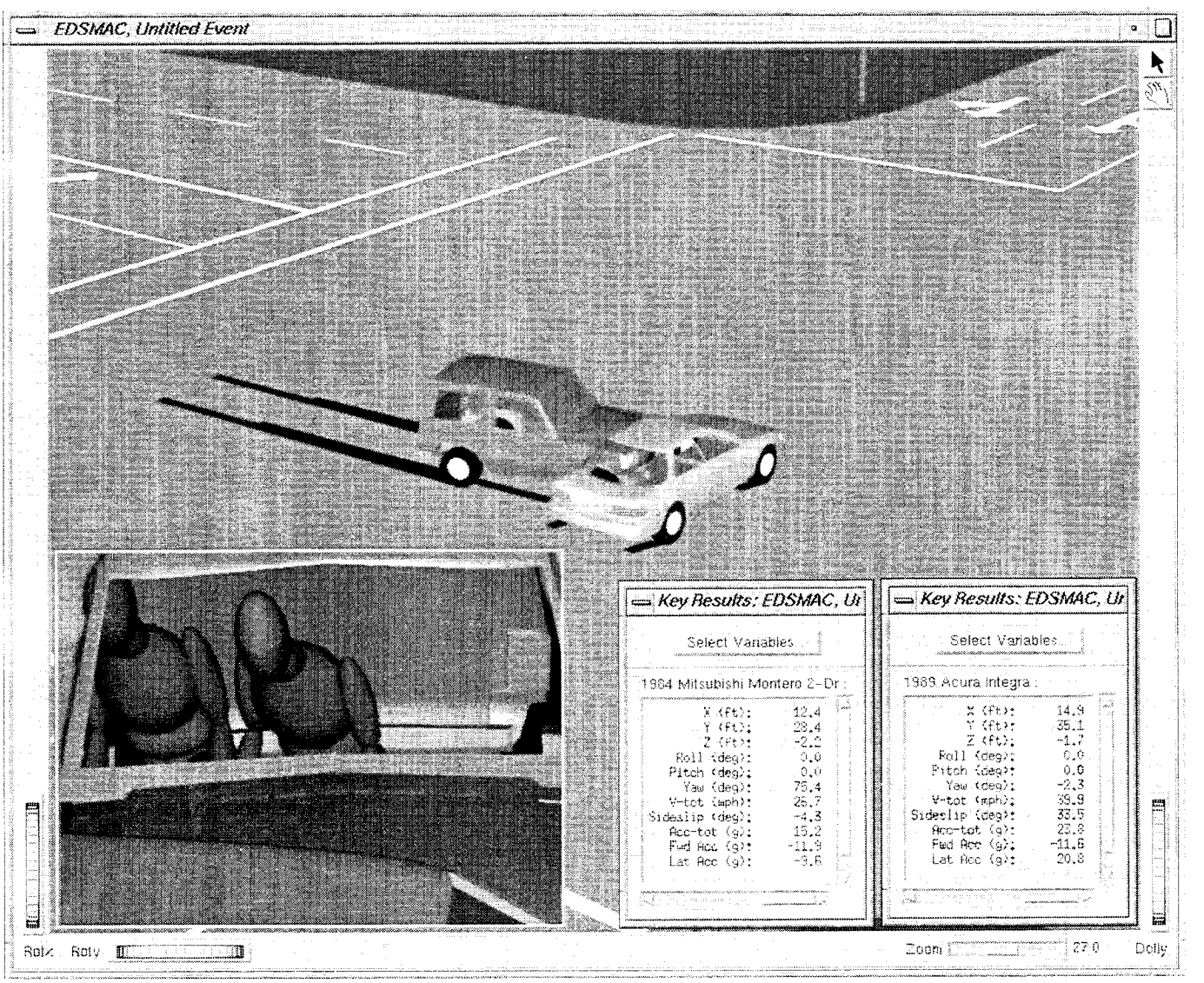

Figure 7 - 2-D simulation of an intersection collision. Inset shows the 3-D motion of the occupants during impact.

ROLLOVER

On-highway trucks often carry heavy loads, inherently resulting in a high center of gravity. These vehicles sometimes roll over while negotiating a curve, leading to the conclusion of excessive speed.

In this example, a truck carrying a load of plywood rolled over while negotiating a rather tight turn onto a freeway access road. Due to existing environmental considerations, the entrance to the access road had a negative superelevation of 5 to 8 percent. 2-dimensional simulation showed wheel lift-off for speeds greater than 26 mph, slightly greater than the posted speed. However, 3-D simulation which included the effects of the negative super-elevation, revealed the truck would roll at speeds as low as 17 mph, as shown in Figure 9.

ANIMATION VS SIMULATION

Animated sequences provide a useful visualization of an accident sequence. However, the resulting motion may or may not obey Newton's laws of motion, depending on how the animation was produced. Simulation inherently uses the laws of motion because it integrates the accelerations calculated directly from forces and moments computed using a physical model. All the motion visualized in the preceding examples was produced directly from 3-D simulation.

LIMITATIONS

The limitations imposed on the 3-D analyses described in this paper are all imposed by the physics models. A complete discussion of these limitations requires an

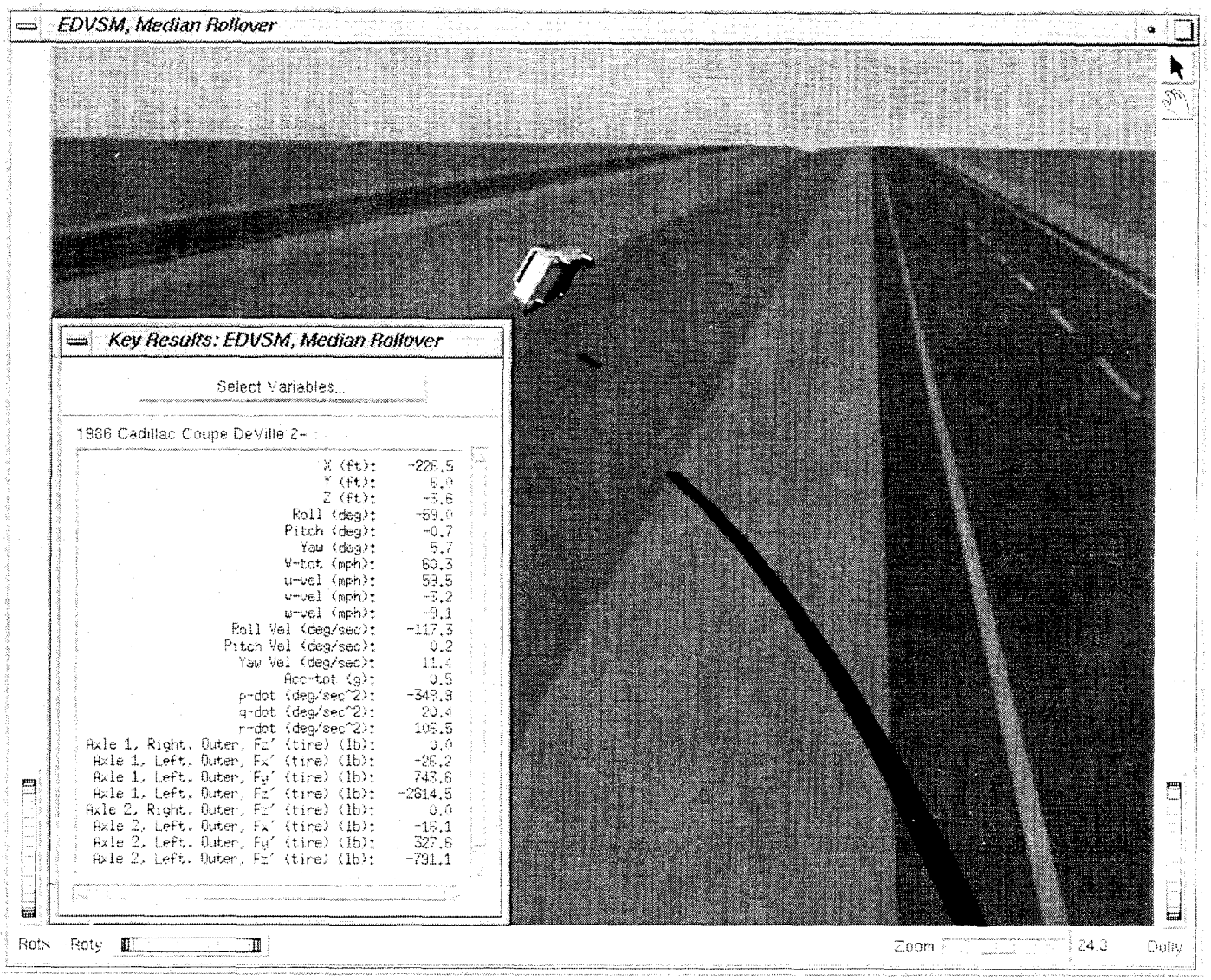

Figure 8 - 3-D simulation of a rollover on a highway median.

understanding of the assumptions used to develop the simulation model. The primary limitations of each of these models are outlined below.

No Full Vehicle Roll-over Model

All the vehicle simulators used in this paper model three-dimensional motion to varying degrees. Tire forces, aerodynamic forces and collision forces are incorporated into the various models. However, none of these simulators models the force between the vehicle body and the road. Therefore, when a vehicle rolls over and its body contacts the ground, no forces are predicted. As a result, when the simulated vehicle body contacts the ground, it sinks into the ground until the top of a tire makes contact. Then, tire forces are predicted, even though the top of the tire may actually be inside a fender well.

Human vs Environment Interaction (Pedestrian)

The human simulator used in these studies predicts the force between human ellipsoids and vehicle contact surfaces. It does not include the capability of calculating forces between human ellispoids and the environment (highway and roadside surfaces). As a result, human pedestrians not affected by other forces will sink into the ground.

3-D Collision Force vs Time Integration

None of the simulations cited in this paper incorporates a 3-D, time-based collision simulation model. Vehicle pitch and roll produced by the collision force are absent.

Environment Surface Compliance/Furrowing

The current HVE Environment Model includes 3-D surface geometry and friction attributes. However, surface compliance is absent. Thus, a rigorous model of tire forces

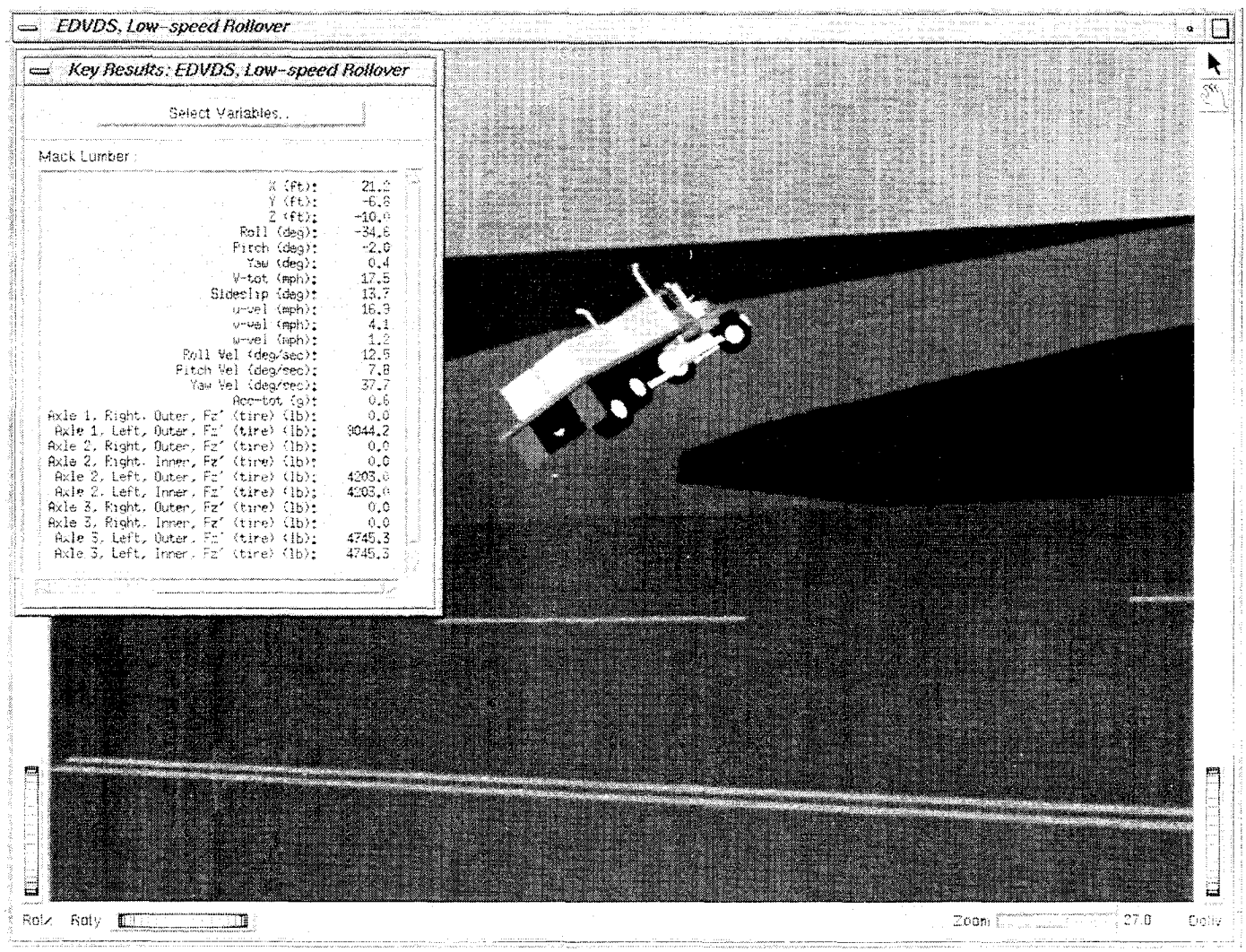

Figure 9 - 3-D simulation of a rollover due to a combination of high center of gravity and reverse slope.

resulting from furrowing on a soft, deformable surface is absent. Such forces may be approximated using the HVE Vehicle's tire modeling capability and the Environment's surface modeling capability.

FUTURE WORK

Obviously, the main thrust of future development effort is aimed at reducing or eliminating the above limitations.

Full, 3-D Rollover

The HVE simulation environment used in these studies allows up to 25 contact surfaces per vehicle, and the environment surfaces currently have the capability to supply geometry and friction attributes for an unlimited numger of polygons. Full, 3-D rollover capability can be added to the existing 3-D models by extending them to model the force between interacting vehicle contact surfaces and environment surfaces polygons.

One approach considered was simply allow the user to supply an impulse (table of force vs time) to any portion of the vehicle. This option was not chosen because it is contrary to the basic premise of simulation: that forces and moments should be calculated using a modeling paradigm, not simply entered by the user. This fact is illustrated by the fact that it would not be possible to validate such an approach.

Human vs Environment Interaction

Modeling the forces between human ellipsoids and environment surfaces requires similar extensions to those required for 3-D rollover, described above. Again, the HVE environment allows for it; the human simulator must be extended to included it.

3-D Collision Force

To perform fully 3-D collision force calculations is possible using finite element methods. However, with current levels of computing power, such an approach is impractical. An intermediate approach might be to use the 3-D vehicle mesh which describes the vehicle exterior (and is used to visualize it). Preliminary computation requirements reveal this, too, is impractical for real-time, general purpose simulation. A simplified approach using the HVE Vehicle Model's impulse center location (which has a 3-D location relative to the vehicle CG), along with existing simulation models which produce collision force calculations might be a practical alternative. This approach is under consideration.

SUMMARY

1. Two important applications for 3-D simulation were identified in this paper: (1) to model 3-dimensional phenomenon not amenible to analysis if the 3rd dimension is ignored, and (2) the ability to visualize three-dimensional events involving accident causation and avoidability.

2. Although this paper focused on accidents requiring a 3-D analysis tool, it must be stressed that 2-D methods are useful and sufficient for a large number of conditions.

3. The HVE simulation environment includes physical surface models for humans, vehicles and environments that are not being utilized by any current simulators. Opportunities exist for the development of new simulators that model the 3-dimensional interactions between vehicle exteriors and the highway environment, the 3-dimensional interaction between colliding vehicles and the 3-dimensional interaction between humans and the highway environment.

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SAE #960890
Discussion
By Lynn B. Frock
Fricke Cooper Engineering
Three-Dimensional Reconstructional and Simulation of Motor Vehicle Accidents Using HVE
Terry D. Day, Author

Mr. Day has present several examples where it has been clearly shown that 2-D simulations do not consider the required variables for a complete analysis. However, a 3-D simulation enabled the accident situation to be successfully modeled. As he has pointed out, many time, if not most times, a 2-D analysis is quite adequate. However, when vehicles travel over surfaces with significant elevation changes, a 3-D analysis may be necessary, Other 3-D tools in HVE such as EDHIS, which models occupant motion, will prove to be valuable analytic tools to the accident reconstructionist.

SAE #960890
Discussion
By Wesley Grimes
Collision Engineering Associates
Three-Dimensional Reconstructional and Simulation of Motor Vehicle Accidents Using HVE
Terry D. Day, Author

This paper is a fundamental look at the advantages of using 3-dimensional analysis methods in collision reconstruction. The examples presented show that in some cases the simplifying assumptions made in 2-dimensional simulations are simply not acceptable. In every vehicle simulation there are basic assumptions that allow the event to be modeled. The most common assumption is that the roadway or terrain is flat and level. As this paper shows, there are some instances where this assumption inhibits the analysis.

Unfortunately, there are times when a 2-dimensional analysis will produce results that are incorrect and without checking the results carefully it may not be obvious. The collision example presented is an excellent example of continued analysis until the results make sense. It is very important for the analyst to examine every simplifying assumption and confirm that 2-dimensional analysis is valid. If the problem requires 3-dimensional analysis, then a 2-dimensional analysis should not be presented.

The paper reminds us that there are still many, and in fact most, collisions that can be modeled accurately with 2-dimensilan simulations. The HVE program is an extension to existing technology. It is not the total answer to all simulation problems, but will handle more problems, more accurately than 2-dimensional analysis in many cases.