APPLICATIONS OF SIMULATION IN DESIGN AND ANALYSIS OF ROADSIDE SAFETY FEATURES

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Roadside safety features present many challenging design and analysis problems. Although full-scale crash testing continues to be the only method for certifying the performance of roadside safety features, engineers have come to rely on computer simulation programs for analysis of the performance of these systems(1). Computer simulation codes are generally lumped into two categories, vehicle handling programs and impact models. Vehicle handling codes are used to evaluate safety problems associated with roadway and roadside geometrics, such as slopes, ditches and curbs. Although these applications for computer simulation are generally considered to be less complicated than most impact problems, vehicle handling still poses some significant obstacles. Most notable of these obstacles is associated with tire/terrain interaction. Tire penetration into soft soils has been identified as a potentially major cause of rollovers in ran-off-road accidents(2). Tire interactions with near vertical surfaces, where sidewall scrubbing becomes an important factor, have also been difficult to analyze(3). Some vehicle suspension components, such as suspension bumper stop systems and shock absorber systems, can create problems for computer simulation efforts when high velocity suspension deflections are encountered(4).

Impact models are used to evaluate the safety performance of numerous safety hardware systems such as longitudinal barriers, crash cushions, barrier terminals, and breakaway structures. Simulation modeling of longitudinal barrier impacts must be capable of evaluating barrier strength, vehicle stability, vehicle/barrier interlocking forces, and snagging potential. Barrier strength analysis is required when evaluating the potential for barrier penetrations. Component and connection strength and ductility requirements are often key factors in the design and analysis of longitudinal barriers. Vehicle stability becomes important when rollover is a possibility such as during automobile impacts with safety shaped barriers and any truck/barrier impact. Vehicle/barrier interlocking forces often prevent vehicles from overriding flexible and semi-rigid barriers such as cable and strong-post W-beam guardrails. Snagging of tires and vehicle hard points on longitudinal barriers can create safety problems during impacts with rigid barriers and barrier transitions.

Most crash cushions and many barrier terminals are designed to capture impacting vehicles and bring them to a controlled stop(5,6). Simulations of such impacts must accurately analyze the energy management of these safety systems and the interlocking forces that allow cushions and terminals to capture impacting vehicles. Vehicle/hardware interaction forces are also important to the analysis of breakaway structures since most of these systems are force activated. Simulations of breakaway devices must also track free-missile components of the breakaway systems to evaluate the possibility of occupant compartment intrusion(4).

Although numerous computer simulation models were developed over the last three decades, only a few of these programs have been widely used. The Highway Vehicle Object Simulation Model, (HVOSM), is probably the most widely used computer simulation code developed to date(3,4,7). This program was originally developed as a vehicle handling model and incorporates a relatively sophisticated three-dimensional lumped-parameter vehicle model. The vehicle model incorporates a total of 11 degrees of freedom (DOF), including a 6-DOF sprung mass, 1-DOF for each of 4 tires, and a steer DOF. HVOSM has not only been used by many researchers, it has been revised and upgraded by many users. Some of these modifications have greatly improved the versatility of the code. For example, sprung-mass/terrain impact models have enhanced the program's capability for modeling vehicles traversing deep ditches and steep embankments where a vehicle's undercarriage contacts the ground(4). HVOSM has been widely validated for modeling limit handling maneuvers where vehicle stability and controllability are important considerations(4,8,9). Although the program has some limitations, such as an inability to model tire penetrations into soft soil and rim gouging during hard cornering events, HVOSM has proven to be adequate for most vehicle handling applications.

HVOSM's capacity for modeling barrier impacts is much more limited. The program incorporates a brick shaped vehicle crush model that utilizes uniformly spaced deformation tracking points. Crush forces are assumed to be related to the volume and rate of change in volume of the region encompassed by the deformation tracking points. Although this procedure has been capable of successfully modeling a number of rigid barrier crash tests, it continues to have some nagging problems. For example, stability problems can develop when the directions of vehicle rotation change during a single impact event(4). This limitation is not normally

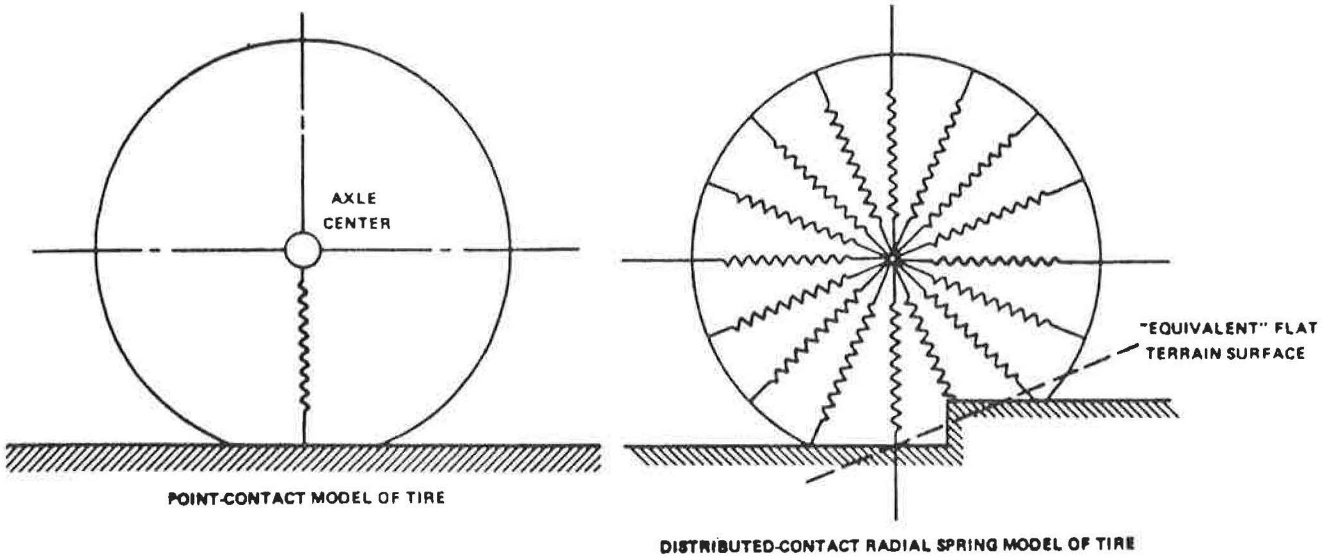


FIGURE 1 HVOSM's thin-disk tire model.

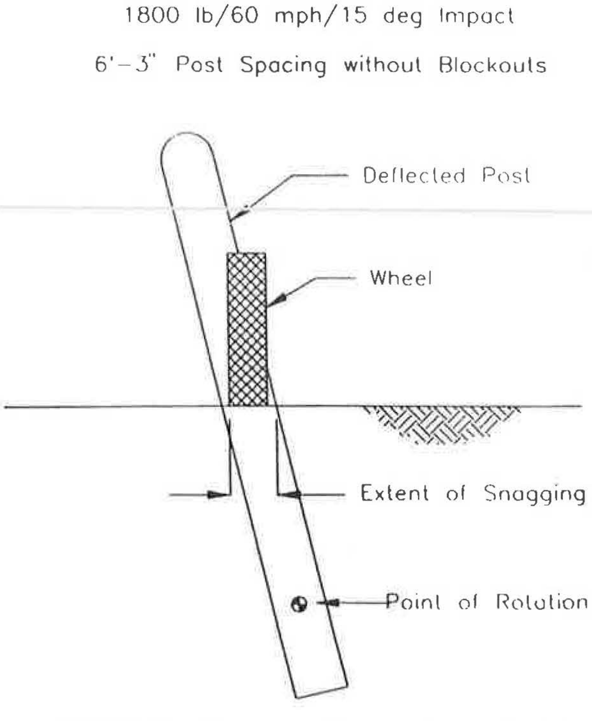


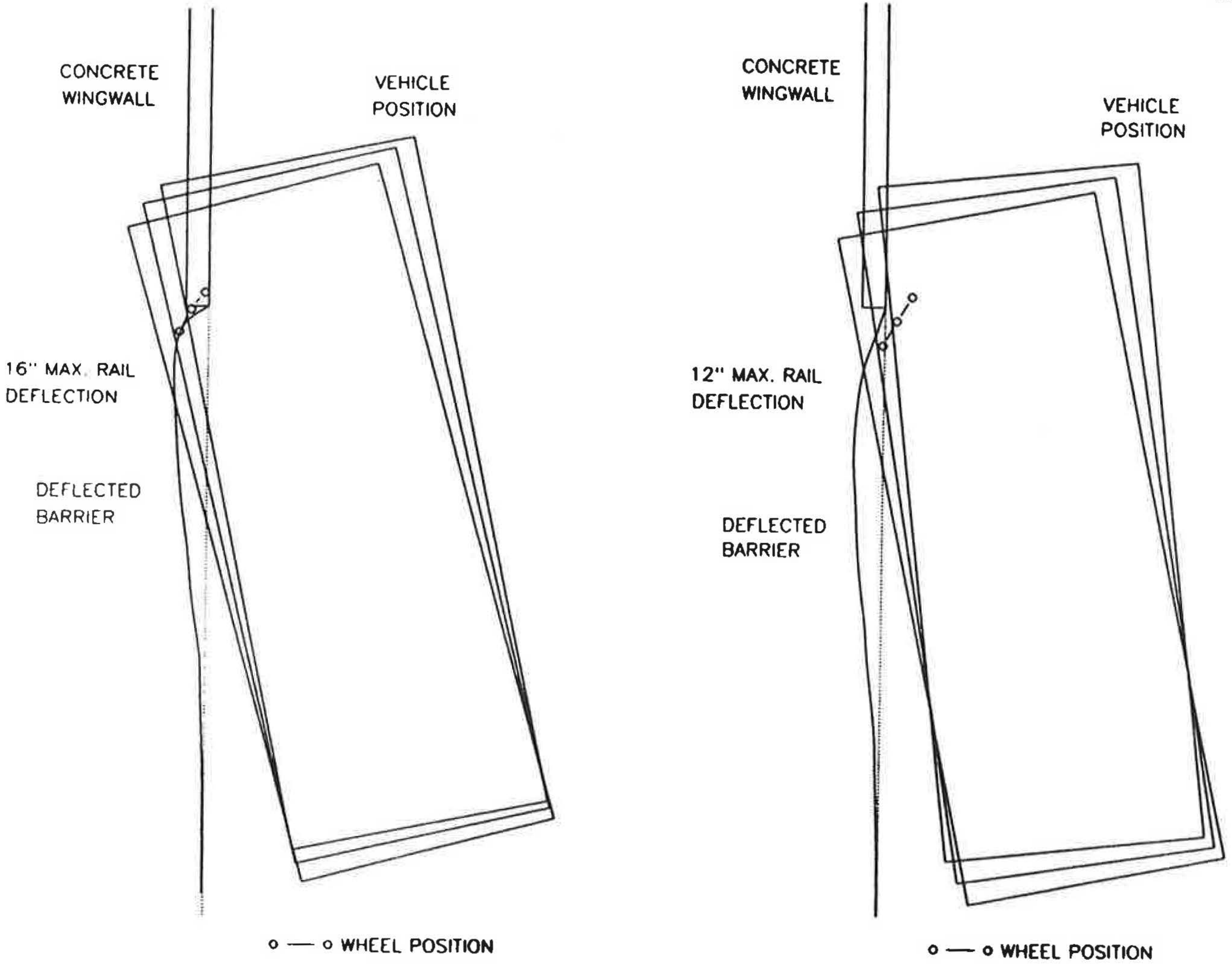
FIGURE 2 Predicting relative snagging potentials.

encountered during traditional tracking vehicle impacts. However, changes in the rotational direction are to be expected when vehicles are rotating prior to impact with the barrier, such as during non-tracking impacts.

Other problems associated with HVOSM's rigid barrier impact model include a relatively crude model of wheel rim and barrier contact, thin-disk tire model, and an inability to model suspension damage(3,4). Direct contact between wheel rims and rigid barriers often has an important effect on vehicle stability. Rim contacts during small car impacts with rigid barriers tend to reduce the extent of vehicle roll away from the barrier while similar contact increases roll angles during large car impacts. The thin-disk tire model, shown in Figure 1 (HVOSM's Thin-Disk Tire Model), does not have any lateral flexibility.

This problem prevents the model from accurately predicting tire deflections and the resulting tire/barrier contact forces when the angle between the plane of the tire and the barrier surface becomes small. In this case, real world tire forces are reduced when a vehicle's tire flexes outward away from the barrier. Finally, vehicle suspensions are frequently damaged during rigid barrier impacts. In this case a vehicle's wheels can act as a tripping mechanism and cause the vehicle to rollover after leaving the barrier

Barrier VII is probably the second most widely used roadside safety hardware simulation program(8). This code incorporates 2-dimensional beam and column finite element barrier and planar vehicle models. The program properly accounts for material and geometric nonlinearities and has a fairly wide selection of physical models including rails, posts, cables, hinges, sliders and springs. Vehicle crush is modeled with a series of nonlinear crush nodes. These nodes can interact with rail elements but cannot be used to interact with barrier posts or other elements that would cause snagging.



Predicted snagging for 16-in barrier deflection

Predicted snagging for 12-in barrier deflection

FIGURE 3 Barrier VII predictions of wheel snagging.

Barrier VII has been successfully used to model a large number of flexible barrier impacts$^{(9)}$. The program is best suited for predicting maximum barrier deflections, element loads, and plastic strain in barrier components. However, the program can also be used to predict snagging of vehicle hard points and wheels on barrier components as shown in Figures 2 (Predicted Relative Snagging Potentials) and 3 (Barrier VII Predictions of Wheel Snagging). Further, the program can be used to support crash testing by identifying critical impact locations and minimum lengths of barrier for proper performance$^{(1)}$.

Unfortunately, 2-D barrier models, such as Barrier VII, do have a large number of limitations. The program is not capable of predicting vehicle vaulting or underriding of a barrier. The program also becomes unstable when extremely large deformations are predicted. Further, it is not capable of simulating vehicle components snagging on barrier elements.

Several attempts have been made over the last 15 years to develop more sophisticated vehicle/barrier interaction models. These efforts led to the Guard, Crunch, and NARD programs$^{(9,10,11)}$. All of these programs incorporate three-dimensional finite element barrier models with a lumped parameter vehicle model similar to that used in the HVOSM program. Unfortunately, these programs all incorporated beam and column FEM barrier models without any mechanism for condensing out degrees of freedom. This basic problem prevents these programs from accurately modeling barriers with very poorly conditioned stiffness matrices such as W-beam guardrails. W-beam guardrail has high stiffness components in the extensional mode and has virtually no resistance to torsion. These wide stiffness variations cause the program to become unstable for high guardrail/vehicle interaction forces.

NEXT GENERATION OF SIMULATION MODELS

The common thread in the prior discussion of simulation program limitations is that all of the existing programs do not have sufficiently detailed models for predicting many aspects of vehicle/hardware interactions. The only solution to this problem is to incorporate much more detailed models of both the vehicle and roadside safety hardware. For example, if a simulation code is to accurately model vehicle/barrier interlocking forces, it must be capable of accurately predicting the local stiffness and deformed shape of a vehicle's sheet metal throughout an impact event. The only mechanism for obtaining this level of modeling detail is to incorporate large numbers of small plate, shell, and brick elements to build models of all relevant vehicle and safety hardware components. FEM vehicle models constructed in this manner contain as many as 30,000 elements as shown in Figure 4 (FEM Idealization of a 1991 Ford Taurus). Roadside hardware models can contain similar numbers of elements as shown for a turned-down guardrail terminal in Figure 5 (FEM Idealization of Turned-Down Guardrail Terminal).

Avantages of using sophisticated models such as DYNA3D(12) include greatly enhanced versatility and an opportunity for greatly improved accuracy. These simulation programs will have few limitations. For example, each individual vehicle suspension component is accurately modeled and the programs can therefore not only predict when suspension failure occurs, but also its effect on vehicle stability. These models should also be capable of accurately analyzing tire penetrations into soft soils as well as vehicle/barrier interlocking forces. Detailed hardware models will allow accurate prediction of soil/structure interactions as well as prediction of component stresses.

The refined models can provide a much higher level of confidence when using computer simulation models to extrapolate safety hardware performance beyond normal crash test conditions. Sophisticated FEM vehicle models should be capable of accurately predicting safety hardware performance for higher impact speeds and angles. Further, these codes will, for the first time, give researchers an opportunity to investigate the effects of non-tracking impacts on performance of roadside safety features. Some accident analysis studies have indicated that almost half of all safety hardware impacts involve non-tracking impacts. Other studies have identified non-tracking impact conditions as a potentially important cause of vehicle rollovers during ran-off-road accidents and longitudinal barrier impacts.

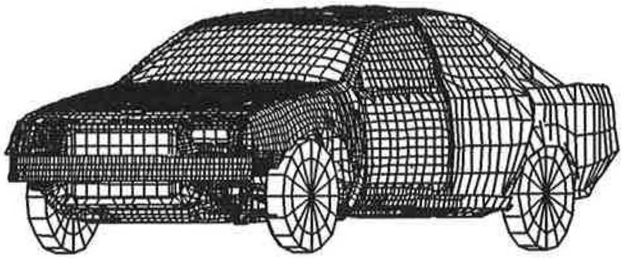


FIGURE 4 FEM idealization of a 1991 Ford Taurus.

The programs also offer a mechanism for evaluating the differences between safety performance in a full-scale crash test program and real world installation situations. Although practically all safety hardware is tested on flat ground with smooth/level approaches, few real world installations actually replicate this situation. Safety devices are commonly installed on modest roadside slopes or over curbs. Further, longitudinal barriers are placed around curves and gating barrier terminals, such as the Breakaway Cable Terminal, are seldom installed exactly as they were tested. Detailed FEM simulation models offer the potential for analyzing a wide variety of potentially hazardous impact conditions that have never been investigated before.

LIMITATION OF SOPHISTICATED MODELING TECHNIQUES

The long list of potential benefits from sophisticated FEM analyses is not easily obtained. Highly sophisticated vehicle models come with a very high price tag. The geometry of each vehicle component must be accurately determined and reduced to an appropriate finite element mesh. The behavior of materials used in the vehicle must also be accurately modeled. These models must include nonlinear material properties such as strain hardening behavior and strain rate sensitivities as well as conventional strength characteristics such as yield and ultimate stresses. Figure 6 (Strain Rate Sensitivity of a Mild Steel) shows typical strain rate sensitivities for steels commonly used in automobiles.

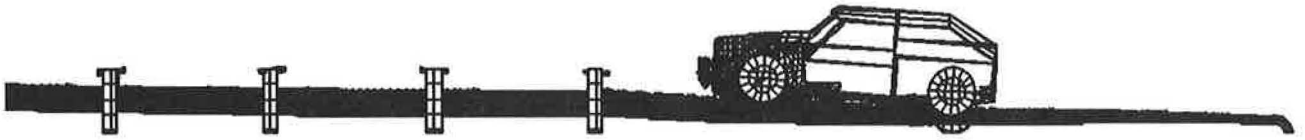


FIGURE 5 FEM idealization of turned-down guardrail terminal.

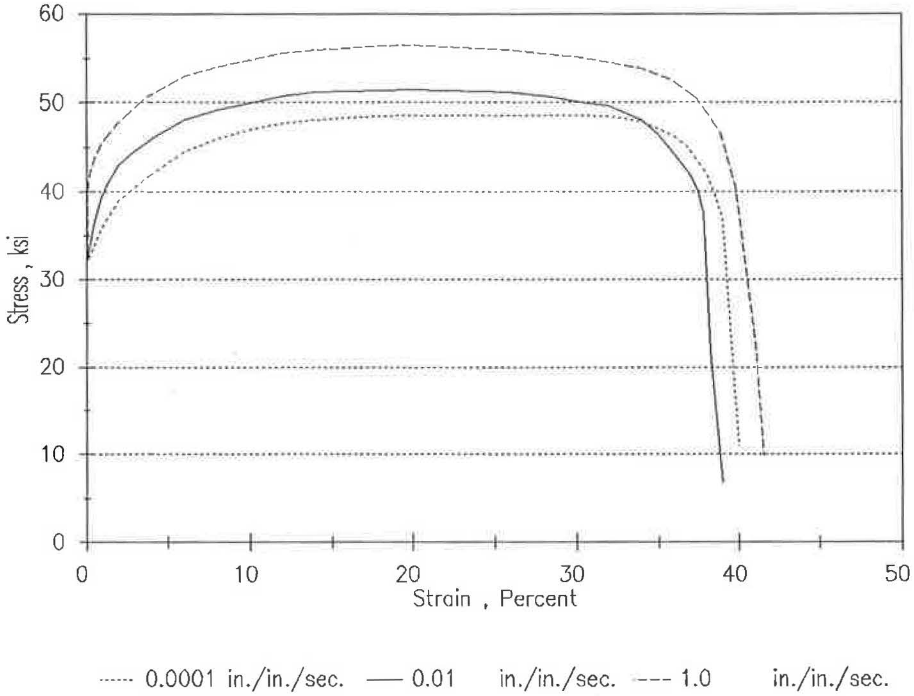


FIGURE 6 Strain rate sensitivity of a mild steel.

As shown in this figure, rate effects can be expected to account for an approximate 20% increase in the yield stress of steels commonly used in automobiles. Although existing FEM models incorporate mechanisms for modeling strain rate sensitivities, the material properties needed to implement these characteristics have yet to be determined. This problem is aggravated by the fact that a typical automobile is fabricated from as many as 16 different types of steel. Therefore, the vehicle modeling process should include identification of the type of steel used in each component as well as determination of the associated material properties. Mechanisms for attaching vehicle components can also have an impact on the energy management of an automobile. Thus, locations and sizes of such items as spot welds, rivets, and bolts can be important. A refined FEM mesh that includes only component geometry and element descretization costs approximately $100,000 to develop. These basic models must then be supplemented with material property information and extensively validated and refined before they can be used with confidence to simulate impacts with roadside hardware.

Roadside hardware models must be described with similar levels of detail. Although geometric descriptions of roadside hardware are generally easier to obtain, dimensional tolerances on these components are often much larger. Further, large variations in material properties are encountered in many safety hardware components such as W-beam guardrails, sign supports, and all wooden elements. Thus, if roadside hardware models are to be representative of a large number of installations, the extent of variations in component geometry and material properties must be identified. As a result, development of roadside hardware models is also relatively costly. This process may initially cost as much as $40,000 per system to obtain adequately validated models.

Computational demands for sophisticated FEM models of vehicles and roadside hardware systems are also very high. For example, simulations of frontal impacts with a rigid pole or barrier require from 3 to 10 hrs of cpu on a Cray-YMP super computer. This would translate into between 12 and 40 hrs of cpu in a workstation environment. Unfortunately simulations of impacts with roadside safety hardware involve many more elements and the events last much longer than rigid barrier impacts. These factors lead to much longer processing times. For example, a rigid pole can be modeled with a relatively few elements and the impact event is completed within 150 ms while a guardrail terminal model would be expected to require several thousand elements and the associated impact generally lasts more than 600 ms. Therefore, most safety hardware simulations will require more cpu time than rigid barrier impacts, perhaps as much as 250 hrs on workstation computers(13).

Many problems remain to be solved before DYNA3D can be effectively used in the design and analysis of roadside safety features. The high cost of developing vehicle models has greatly restricted the numbers of models available. Currently there are only two such models, a 1983 Honda Civic and a 1991 Ford Taurus. Unfortunately development of these models was undertaken more than 2 years ago and they are still in the validation process. Some agencies are now in the process of developing more expedient procedures for developing vehicle mesh information. These processes generally involve incorporating less sophisticated FEM meshes and/or deleting some of the less critical vehicle components. Although some of these procedures will undoubtedly generate less costly FEM meshes, the value of these models has yet to be accurately determined.

Regardless of the outcome of these efforts, the number of validated vehicle models is expected to be extremely limited for the foreseeable future. Automobile manufacturers are perhaps the most promising source of validated vehicle models. The National Highway Traffic Safety Administration is now seeking several "generic" vehicle models from domestic manufacturers. Although these models may not accurately represent any single vehicle, they could be expected to be representative of general classes of vehicles.

There is also a need to determine the required level of modeling detail for analysis of vehicular impacts with each type of roadside safety device. Large savings in cpu times could be realized if the refined finite element meshes now in use are found not to be necessary during most impact scenarios. This effort could also lead to a major reduction in the cost of developing vehicle models. Unfortunately a great deal of experience with DYNA3D models of roadside safety hardware impacts is needed in order to accurately assess the level of modeling detail required for these types of simulations. Highway safety designers should be able to shorten this process by identifying the vehicle and hardware components that are most important to the performance of roadside safety hardware.

Very few safety hardware models have been developed and none of these have been adequately validated to date. The validation process itself is another major obstacle. Although large numbers of documented crash tests are available for use in the validation process, very few of these have been conducted with a 1991 Ford Taurus or a 1983 Honda Civic. The limited data collection efforts associated with most crash test programs also reduces the value of previous testing efforts.

The validation process should be conducted in stages. The first stage of validation should involve modeling of the behavior of individual vehicle and hardware components and/or materials. The process should then progress into models of vehicle and hardware subsystems and eventually into full-scale crash testing. The process of validating mathematical models as large and complex as the DYNA3D simulations envisioned for roadside safety hardware analysis cannot begin with the final stage, i.e. modeling of a full-scale crash test. The validation process must be a process that builds confidence in the accuracy of simulation procedure. The highway safety community cannot be expected to accept these highly sophisticated simulation programs without a confidence building validation process similar to that outlined above.

Finally, existing material models may not be adequate for simulating the performance of roadside safety features. For example, fiber reinforced plastic and polymer based materials are often used in the construction of modern automobiles and are beginning to be used in roadside safety hardware. Existing material models are not believed to be capable of predicting the dynamic behavior of these materials.

Although sophisticated finite element procedures, such as DYNA3D are expected to bring major advancement to the design and analysis of roadside safety features, many significant obstacles remain. Even though the process of resolving these problems will likely involve a number of years and a large financial commitment, the potential benefits far outweigh the foreseeable costs. These procedures offer the only method for accurately determining the performance of roadside safety hardware systems for the entire range of impact conditions experienced along the nations highways. Comprehensive evaluation of the impact performance of existing roadside safety hardware will lead to the development of improved designs and allow highway agencies to make informed decisions regarding the merits of competing systems.

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