

# THE USE OF FINITE ELEMENT ANALYSIS IN ROADSIDE HARDWARE DESIGN

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**ABSTRACT** — Finite element analysis has been used in roadside safety research for nearly three decades. Early applications used simple discreet-element special-purpose codes to predict gross deflections of guardrails and bridge rails in collisions with motor vehicles. More recently general purpose nonlinear explicit finite element programs have been integrated into the analysis and design of roadside safety hardware. This paper reviews the history of the use of finite element methods in roadside safety research and presents the current status of many of the vehicle, occupant and roadside hardware models that have been developed to date.

## INTRODUCTION

Roadside safety research has progressed through several phases during the past 40 years. The first phase, accomplished in the years around 1960, was to recognize that there was a problem and that it was possible to improve the safety of roadways using engineering design.

In the infancy of roadside safety research it was possible to make significant improvements in safety just by using common sense and basic engineering judgement: keep the vehicle from leaving the road, rolling over, or under-riding the barrier; make sure the occupant stays inside the vehicle and nothing harmful penetrates into the occupant compartment. Many of the most common guardrail systems date from this early phase.

The next stage took place in the 1970's and 1980's when more difficult problems were addressed like developing guardrail terminals, transitions and crash cushions. Roadside hardware was developed to address a broad range of specific applications and site conditions. While judgement and intuition were still valuable tools, full-scale crash testing became the primary method for exploring the collision performance of barriers. Designers, using their intuition about impact events, were able to produce many useful designs, many of which are still in service today.

Unfortunately, the era of intuitive design in roadside safety is over. The problems that have persisted over the past several decades are the most difficult, most complex and most demanding problems -- guardrail terminals, side impacts, and non-tracking impacts and vehicle-barrier interaction problems to name just several. The roadside safety community is now entering a new phase of research where the effort and resources required to produce a successful roadside hardware design have increased dramatically as have the expectations of the public. Further improvements in roadside safety will require the use of the best analytical tools available in addition to crash testing and engineering intuition. This paper discusses one particular analytical method that holds great promise for roadside safety research: non-linear dynamic finite element analysis.

## BACKGROUND

### History

Although full-scale crash testing has been the most prominent method, the use of analytical methods are not new to roadside hardware design. Perhaps one of the most successful applications of finite element technology to roadside safety was the very first. Researchers at Cornell Aeronautical Laboratory investigated the mechanics of vehicle-barrier collisions for the New York Department of Public Works in the early 1960's.[1] Simple analytical models were developed using springs, dash-pots, beams and links to examine the dynamics of vehicles and the strength of barriers. This study was very successful, resulting in evaluations of many at-the-time common guardrail systems. Many now-commonly recognized safety

problems with guardrails were first observed in this study like (1) the importance of the rail separating from the post to prevent vehicle vaulting, (2) the potential for wheel snagging to occur on strong post guardrails and (3) the potential for pocketing when strong posts are combined with relatively weak rails. This research project was instrumental in improving the designs of the W-beam median barrier and the box beam guardrail designs used in New York to this day as well as the elimination of some poor designs like strong-post cable guardrails.[2] [3]

The New York Department of Public Works and the Cornell Aeronautical Laboratory also collaborated on using analytical methods for predicting the response of vehicles in a variety of vehicle handling situations.[4] This work eventually led to the development by McHenry of the Highway Vehicle Object Simulation Model (HVOSM) which has been widely used in the roadside safety community.[5] While this code is primarily a vehicle handling code subsequent extensions (e.g., HVOSM-RD2) have been used with some success to examine vehicle collisions with rigid barriers like concrete safety shapes.[6]

The BarrierVII program was developed by Powell in the 1970's and has been widely used to simulate impacts with flexible barrier systems.[7] The program is a two-dimensional code that contains a variety of simple elements like springs, dash-pots, links, posts, and beams. Barrier VII has been used with good success to predict the dynamic deflection of a variety of roadside safety systems. Bligh used BarrierVII to evaluate a box-beam to bridge railing transition design.[8] Ray used BarrierVII to develop design curves for establishing the required depth and width of concrete anchors used in guardrail to bridge rail transitions.[9] Calcote used BarrierVII to develop cost effectiveness criteria based on guardrail dynamic deflections predicted by BarrierVII.[10] BarrierVII is still being used to predict dynamic deflections for transition designs as is evident by recent work by Faller and Sicking.[11] While the relative simplicity of the code and its models made it very useful for many types of impacts, there were significant limitations to the types of simulations that could be performed because the code represented only two dimensions and the geometry of the barrier and vehicle were only coarsely represented.

A series of ill-fated projects were initiated in the 1980's to try and develop the next generation of special-purpose barrier analysis finite element codes. The codes GUARD, CRUNCH and NARD were the result of these efforts.[12] [13] [14] Some researchers were able to use GUARD for studies of bumper performance in impacts and optimization of guardrail design features.[15] [16] [17] Unfortunately, none of these codes ever gained the confidence of analysts due to a variety of problems including coding errors, poor analytical formulations, and restrictive assumptions. The roadside safety community's negative experience with the NARD and GUARD programs has left a lasting pessimism with some about the utility of analytical methods in roadside safety hardware design and evaluation.

In 1991 the Federal Highway Administration (FHWA) sponsored three projects to recommend a plan for developing improved capabilities for analytical simulations of roadside hardware collisions.[18] [19] [20] All three plans recommended abandoning special-purpose analysis codes like NARD, GUARD, BarrierVII and HVOSM in favor of the general-purpose non-linear finite element program DYNA3D.[21] In a relatively short period of time, the roadside safety community has gone from having virtually no capabilities and experience with general-purpose codes like DYNA3D and LS-DYNA3D to building a capable network of universities, laboratories, governmental research organizations, software developers and private researchers.

### **Benefits of Safety Research**

Despite the increasing difficulties, there is still a need for further roadside safety research. Two particular results of safety research demonstrate its continued utility:

- Reductions in the fatalities and injuries experienced on the roadside and a consequent reduction of

- accident costs, and
- Protecting the public's investment in roadside safety hardware.

Both FHWA and the National Highway Traffic and Safety Administration (NHTSA) share the goal of reducing the number, severity, and cost of highway accidents. In the past, NHTSA has concentrated on vehicle-to-vehicle collisions and occupant protection technology, leaving single-vehicle roadside accidents largely to FHWA to address. Single-vehicle accidents occurring off the roadway accounted for 1.4 million accidents in 1992, this represents more than 20 percent of all motor vehicle accidents.[22] Accidents occurring on the roadside represent a significant segment of all motor vehicle accidents. FHWA and NHTSA, therefore, share responsibility for 20 percent of the motor vehicle accident problem. Some emerging accident types, like side impacts with narrow objects and the interaction of wedge-shaped vehicles with roadside hardware, probably cannot be improved without a joint effort by both the roadside and vehicle design community.

Once installed, roadside hardware has a service life of 20 or even more years. Vehicles, in contrast, generally do not last more than 10 years and automobile manufacturers can radically change the characteristics of the vehicle population very quickly. The vehicle manufacturing industry can build vehicles that meet all applicable NHTSA safety standards but may not perform correctly with the majority of guardrails, bridge rails and other roadside hardware. For example, recent testing has shown that full-size pickup trucks roll over in 25 degree, 100 km/hr impacts with some strong-post W-beam guardrails. The light truck class of vehicles is rapidly approaching 50 percent of the vehicle fleet.[23] This type of longitudinal barrier is the primary guardrail in nearly every state in the United States, lining hundreds of thousands of miles of roadway. Minivans were just introduced to the vehicle population a decade ago yet now they represent about 10 percent of the vehicle population.<sup>(23)</sup> No crash tests of minivans and roadside hardware have ever been performed so the roadside design community has no clear understanding of how such vehicles are performing in the field in impacts with roadside safety hardware. Public agencies cannot afford the investment required to modify hundreds of thousands of miles of longitudinal barrier to continuously chase the moving-target of vehicle characteristics. Even if public agencies could afford it, the time required to retrofit this much hardware would be enormous and the changes could be obsolete before they were completed. Finite element analysis provides roadside safety researchers and policy makers with one more valuable tool that can be used to assess the performance of roadside hardware in a wide variety of impact conditions with a wide variety of vehicles.

### **Vehicle-Barrier Interaction**

Occasionally, roadside safety researchers run a full-scale crash test and observe an unexpected catastrophic failure that, after further investigation, seemed to be caused more by some feature of the test vehicle than the roadside hardware. This would prompt the question, "what is being tested, the hardware or the vehicle?" These types of vehicle-related failures have been observed more frequently during the past several years as researchers began to perform more tests with pickup trucks to comply with NCHRP Report 350 and as tests with vehicles other than passenger cars became more common.[24] It is becoming increasingly difficult to treat the vehicle, the roadside barrier and the roadside geometry as independent elements that can be designed with little thought about the other two.

Side impacts with narrow objects like trees and utility poles accounted for more than 8 percent of all traffic related fatalities and 20 percent of all single-vehicle run-off-road accidents in the period between 1980 and 1985.[25] Better warrants for removing selected trees and relocating utility poles would reduce this somewhat but significant improvement will require the attention of both the vehicle design community, the roadside safety and the roadway design communities. Side impacts are also a problem with breakaway

hardware like luminaire supports, small signs and guardrail terminals.[26] Testing has shown that it is nearly impossible to weaken a guardrail terminal sufficiently to improve side impact performance without destroying the terminal's effectiveness in end-on impacts. Improved performance for side impacts with guardrail terminals (thought to be about 1/3 of all guardrail terminal collisions) will require improvements to the side structure of vehicles as well as better terminal design.<sup>(25)</sup>

Poor performance has been observed recently in pickup truck impacts with guardrails and guardrail terminals.[27] A preliminary evaluation of these tests suggests the problem may be caused by (1) the inertial and stability properties of the truck, (2) particular aspects of the suspension design that promote failure in barrier collisions, and (3) the tendency for the wheels to contact guardrail posts causing serious snagging and potential rollover. While improvement in the performance of some roadside hardware devices can probably be achieved for some specific impact conditions, this class of vehicles appear to have serious performance problems in barrier impacts that might only be solvable by improving the design of the vehicle or at least better understanding the interaction between the vehicle and barrier. Problems with the pickup truck suggest that there may be similar problems with the new cab-forward passenger car designs as well.

Aerodynamically shaped front ends on most new vehicles have been shown to perform catastrophically in end-on impacts with terminals.[28] Modifications to guardrail terminal noses have not yet significantly improved the results. Anecdotal evidence has appeared in the literature to show that there can be problems with aerodynamically styled vehicles under-riding some types of guardrails.[29]

These are just a few examples where the changing geometry and properties of vehicles have made obsolete barriers that once performed quite well with the vehicle fleet of five and ten years ago.

### Roadside Hardware Design

Finite element analysis should be an integral part of the roadside safety hardware design process. In today's funding climate, with today's difficult research problems it is not feasible to evaluate every impact scenario using full-scale crash tests. Figure 1 shows a representation of the roadside safety research cycle: design, simulation, test, implement, and in-service evaluation. Currently a researcher designs a roadside safety appurtenance and tests it, repeating and refining the design until either a successful design is produced or funding runs out. Crash tests are performed according to the guidelines in National Cooperative Highway Research Program Report 350 (Report 350), the latest in a long series of roadside hardware crash testing recommendations.[30] Hardware is installed based on the results of these research and development tests. Even though the need for in-service evaluation is universally recognized, an effective means of accomplishing an in-service evaluation has yet to be found so the "loop" in practice is seldom ever closed. The subject of this paper, however, is the increasing importance and utility of the analysis phase of the roadside hardware development cycle. When designs are simple an analysis phase is often unnecessary. As designs become more complicated, however, an explicit analysis step should be performed.

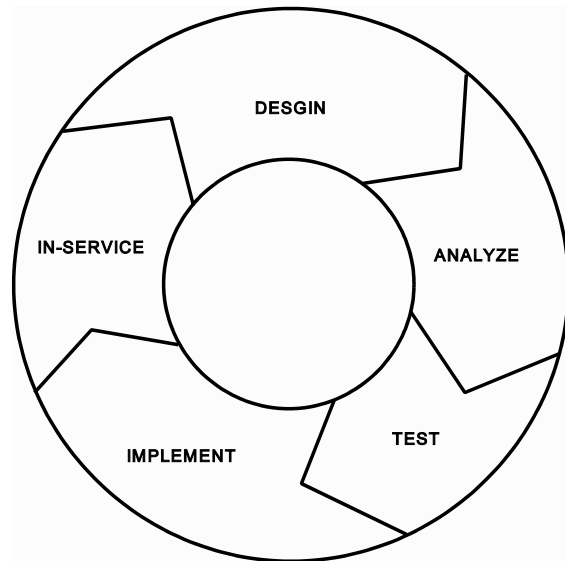


Figure 1. The roadside safety hardware development cycle.

Analysis can help identify and correct problems in the design prior to testing. Several issues will necessitate

the increased use of analytical methods in roadside safety research: (1) tests cannot provide enough information about the loads, accelerations, stress and strains of barrier components to develop designs based on the mechanical behavior of barrier components, (2) repetitive tests are expensive and not well suited to parametric analysis, (3) it is impractical to test with the full range of vehicles that should be examined and (4) it is not possible to examine the affects of a variety of test conditions like non-tracking pre-impact trajectories, side impacts, and driver braking and steering during impact.

There are three stages in integrating finite element analysis into the roadside safety evaluation and design process. The first step is to use finite element analysis to examine tests that have already been run. Such analysis can be used to examine the stresses and strains, accelerations and velocities, and failure mechanisms in a particular impact scenario in order to gain a better understanding of the impact event. This improved understanding can then be used to develop better design alternatives, examine the sensitivity of particular design elements to impact conditions or variations in material properties, or to estimate evaluation criteria. Currently, most of the work in using finite element methods in roadside hardware falls into this category.

The second stage is to use finite element analysis to predict the likely outcome of a full-scale crash test before the test is performed. This might be used to pick the most promising of several possible design alternatives, to identify the most critical crash test impact conditions, or to identify the worst-case test vehicle for a particular piece of hardware.

The third and ultimate stage is to use finite element analysis to evaluate the performance of hardware in situations that cannot be tested. Examples of this type of use include examining non-standard impact conditions like yawing prior to impact, braking and steering during impact, traversing a non-level terrain prior to impact. Simulations could also be used to test non-standard vehicles or proto-type vehicles. This use of finite element analysis will enable engineers to examine collisions that would be impossible to test and thereby design hardware that performs more reliably under a wide range of real-world conditions.

The emerging roadside safety environment will require roadside hardware that performs with a wide range of vehicle types over a wide range of impact conditions. While full-scale crash testing will always be a crucial part of roadside safety research it can no longer remain the sole tool for exploring the performance of the roadside.

## **ANALYSIS**

### **Codes**

The use of the finite element method to solve non-linear dynamic contact problems is just over twenty years old but it has evolved rapidly into a powerful method for performing realistic analyses of dynamically loaded structures.[31] Halquist began the development of DYNA3D at Lawrence Livermore National Laboratory in the 1970's and has continued its development in the code LS-DYNA3D. [32] FHWA and NHTSA have actively promoted integrating nonlinear finite element technology into the roadside hardware design and evaluation process. In general, any crashworthiness model is composed of material models, geometric finite element meshes, connections, and contact algorithms. These programs are available for nearly every type of computer hardware from PCs to massively parallel supercomputers. While it is beyond the scope of this paper to describe all the features of nonlinear dynamics finite element codes, some features that have been particularly useful in roadside hardware simulations include the development of automatic contact algorithms, the large selection of material types, the incorporation of material failure and element deletion and the development of parallel processor versions of the codes.

While there are a wide variety of material models available in codes like LS-DYNA3D, it is also necessary to develop the specific parameters needed to model particular materials used in roadside safety hardware like

guardrail steel, timber and soil. Wright and Ray have recommended values for typical guardrail steels and recently Plaxico, Patzner and Ray have recommended values for timber and soil material parameters that are useful in modeling roadside safety hardware systems.[33] [34]

Most roadside safety finite element models are constructed by building a model of the traffic barrier and using a public-domain vehicle model that was developed elsewhere. This is an efficient method of performing analyses since the development of vehicle models is itself a complex resource intensive task. This method leaves roadside safety hardware research free to concentrate on modeling roadside hardware rather than vehicles.

### Vehicle Models

Developing public-domain vehicle models that can be used in a wide variety of roadside safety hardware research studies is a challenging area of research. Table 1 shows all the vehicle models that are publicly available at this time for roadside hardware research along with some summary information. These models were developed by a variety of organizations for a variety of purposes so the size, complexity and speed vary considerably. Size in Table 1 is defined as the number of elements in the vehicle model. Although characterizing models by the number of elements alone does not give a complete picture of the model's likely performance, it does serve as a good first indicator of model complexity. The model speed is perhaps the best characteristic to examine, where speed is the amount of event time (in msec) that is simulated in one CPU hour of computation. As shown in Table 1, speeds of the available models vary from 0.67 msec/CPU hrs for the C-2500 pickup truck to 100 msec/CPU hrs for the Saturn. Clearly an analyst pays a heavy price in increased computation time when using the larger vehicle models. While a high degree of complexity may be required for designing vehicles, evaluating occupant restraint systems or assessing the likelihood of occupant compartment intrusion, it is still unclear how complex a vehicle model must be to provide good results in roadside hardware simulations.

Table 1. Vehicle models developed for used in roadside hardware analysis.

Model	Size <sup>¶</sup>	Speed <sup>§</sup>	Preprocessor
Saturn	2,260	100	Ingrid
Honda	10,100	8	Ingrid
820C	4,710	20	Ingrid/TrueGrid
Taurus	28,350	2	Patran
Full C-2500	54,366	0.4	Patran
Reduced C-2500	9,412	0.7	Patran

¶ Size is the size of the model in terms of the number of elements.  
 § Speed is the estimated amount of simulated time in msec per processor hours on a typical Unix workstation with a 120 MHz processor.

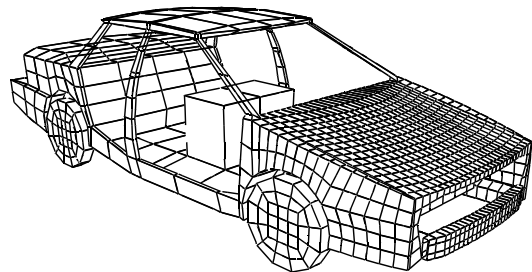


Figure 2. Model of a 1991 GM Saturn.

The first model intended specifically for roadside hardware research was the simple model of a 1991 GM Saturn developed by Wekezer shown in Figure 2.[35] This model was developed for FHWA by physically measuring the vehicle and building a simple mechanical analogue. The model was used to simulate a frontal impact with a slip-base luminaire support, a rigid wall, and a U-post sign support to demonstrate the utility and feasibility of using nonlinear finite element analysis. This model was the first successful application of DYNA3D to a roadside safety hardware problem.

Concurrently with the effort to develop the Saturn model, the FHWA sponsored the development of a frontal impact model of a 1981 Honda Civic, a vehicle frequently used in past crash tests. The model, shown in Figure 3, was developed by Mendis, Mani and Shyu using a forensic approach: the vehicle was taken apart, photographed, scanned, measured and otherwise documented.[36] These data were then used to build the geometric representation and material characterization of the vehicle. Additional efforts were made by Lee to improve the model and reduce the run time so that it would be a more useful roadside safety design tool.[37] Since the vehicle model only has detail in front of the firewall, this model is limited to frontal collision applications like sign support, luminaire or crash cushion collisions. A full-scale crash test program was also performed to obtain data that could be used to compare the model response with physical crash tests. [38]

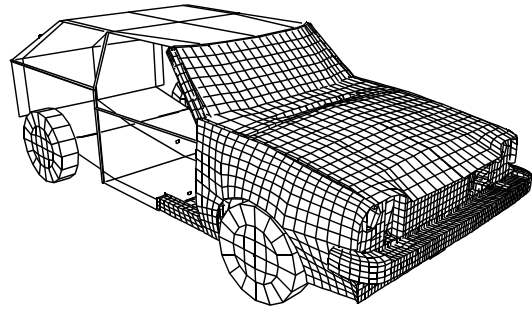


Figure 3. Model of a 1981 Honda Civic.

A simple model of an NCHRP Report 350 820-kg small passenger vehicle, shown in Figure 4, was developed for FHWA by Cofie and Ray.[39] Unlike the forensic approach, this vehicle model was never intended to be an exact replication of the vehicle geometry nor was it intended to include explicit models of all the parts and connections in the physical device. The intent was to have a simple model that had the correct inertial properties such that good center of gravity time history information could be obtained and compared to full-scale crash tests. The model was intended to be relatively generic although it was largely based on a 1990 Ford Festiva. The model was initially developed for frontal impacts into narrow objects but it is also being used for frontal impacts with guardrail terminals and re-directional collisions with guardrails and bridge railings. A series of full-scale crash tests involving Ford Festivas and rigid poles in the literature were used to assess the accuracy of the model for frontal impacts with objects like signs, luminaire supports and guardrail terminals.[40]

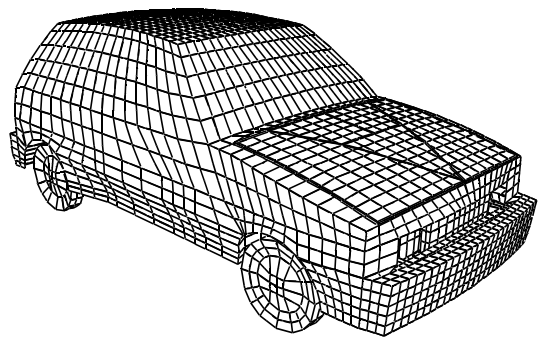


Figure 4. Model of an 820-kg passenger car.

NHTSA sponsored the development of a model of a 1991 Ford Taurus.[41] This model, originally developed by Varadapp and Shyo for frontal rigid-wall impacts, has been extensively modified for many other types of impacts including simulations of frontal rigid wall impacts, off-set frontal vehicle-to-vehicle impacts, and frontal narrow object impacts and occupant compartment intrusion studies.[42] [43] It has not yet been used in roadside hardware simulations. There is also a version of this model available for narrow-object side impact collisions that is expected to be widely used in developing and evaluating roadside hardware for side impact collisions.

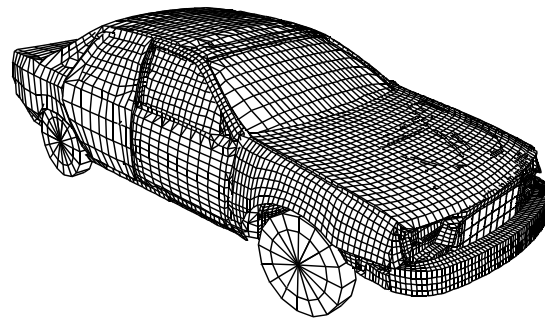


Figure 5. Model of a 1991 Ford Taurus.

The most recent vehicle model to be developed, shown in Figure 6, is a 1994 Chevrolet C-2500 pickup truck developed by Zaouk, Bedewi, Kan and Marzouigui.[44] This model, which was jointly developed by NHTSA and FHWA, was also developed using a forensic approach where the vehicle was disassembled, scanned and connections were meticulously documented. Two versions of the model have evolved: one large and complicated model that can be used for vehicle design and occupant restraint simulations and a reduced version that is intended for use in roadside hardware applications. The reduced version is being used for a variety of guardrail and guardrail terminal studies. This model is one of the more important contributions to the roadside safety research effort since many of the most pressing contemporary issues involve the performance of pickup trucks in collisions with roadside hardware.

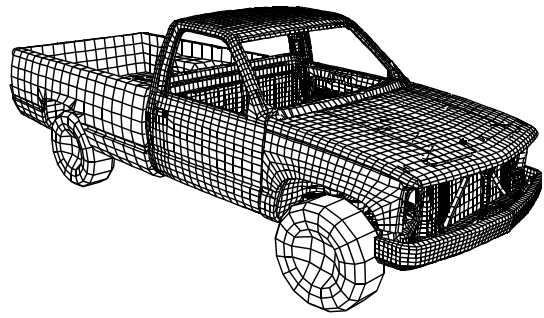


Figure 6. Model of a 1994 Chevrolet C-2500 pickup truck.

As the forgoing descriptions illustrate, a variety of vehicle modeling techniques have been used in simulating collisions with roadside safety hardware. The forensic approach has generally resulted in large geometrically precise models like the C-2500 pickup truck and the Taurus that provide a detailed representation of the vehicle but at a significant computational expense. On the other hand, models like the 820-kg and the Saturn were never intended to be high-fidelity models but rather simple models that could be used to represent the gross response of the vehicle at a modest computational expense. At this time it is still unclear what types of models are best suited to roadside safety research. Some types of research, for example studying the toe-pan intrusion in a vehicle, will require large complex models of the vehicle. Other types of impacts, for example the glancing-blow impact of a guardrail terminal, depend almost completely on inertia and kinematics so a very simple model may be appropriate. Determining what types of model are appropriate in different situations and how to develop and maintain these models will doubtless be a point of debate for some time.

There will be a need in the future for other types of vehicles as well in the coming years: minivans, sport utility vehicles, and cab-forward vehicles to name just several. At some point the roadside hardware community must determine what types of models are required to evaluate the performance of roadside appurtenances and how best to develop them.

### Roadside Hardware Models

There have been a variety of efforts to model roadside safety hardware during the past several years. The first several roadside hardware applications of DYNA3D were of small car frontal impacts like the rigid pole and U-channel post simulations shown in Figure 7 and Figure 8. Rigid pole simulations like those performed by Cofie and Ray are very useful for validating frontal-impact vehicle models for narrow object impacts.<sup>(39)</sup> Flanged-channel post simulations have been performed by Ray and by Marzouigoui using the Honda Civic and 820C vehicle models.[45] The flanged-channel sign support model has been investigated most recently by Lee with respect to

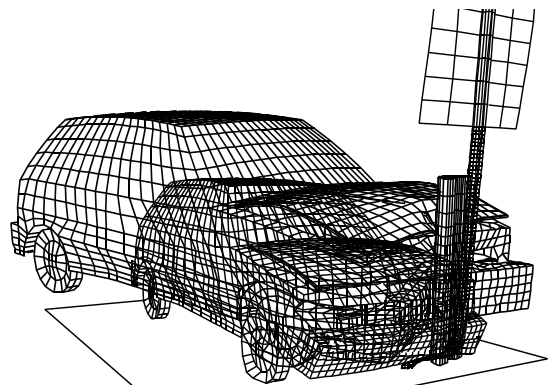


Figure 8. 32 km/hr impact of an 820C vehicle with a flanged-channel sign support (Test 3-60).  
 Figure 7. 32 km/hr impact of an 820C vehicle with a rigid cylindrical pole.



finding an appropriate method for modeling the soil.[46]

Other researchers have taken advantage of the frontal-impact vehicle models to investigate the performance of several luminaire supports. Abu-Odeh and Bligh have modeled the interaction of a small 820-kg vehicle with a slip-base luminaire support.[47] While modeling the slip and fracture behavior of the slip-base proved to be a complex task, the authors were also interested in assessing the risk to occupants when the pole strikes the top of the vehicle. Willam and Munz have examined the dynamic fracture of cast aluminum transformer bases in impacts with small passenger cars.[48]

Developing improved guardrail terminals has been an active area of roadside research for many years. In recent years Ray and Patzner have used finite element modeling to simulate a variety of collision scenarios involving the modified eccentric loader breakaway cable terminal (MELT).[49] The small 820-kg car model was first used to simulate the Report 350 Test 3-30 conditions (820 kg-100 km/hr-0 degrees) and compare the simulated results to the physical tests as shown in Figure 9. After the model of the MELT was found to perform well in small car impacts, the Chevrolet C-2500 pickup truck model was combined with the MELT model to simulate the test 3-31 conditions (2000 kg-100 km/r - 0 degrees) as shown in Figure 10. Ray and Patzner have gone on to simulate other Report 350 tests like the re-directional impacts with both the small 820-kg car and the 2000-kg truck. They were able to use the finite element simulations to demonstrate that the MELT is very sensitive to the strength of the soil and the strength of the timber material used in the wood posts. The results of the simulation effort helped to explain several anomalous tests where pickup trucks experienced very different responses in nearly identical full-scale crash tests.

Performance problems have also been observed in pickup truck impacts with common guardrails like the strong-post W-beam guardrail, the weak-post W-beam guardrail and the modified thrie beam guardrail. Ray has modeled an 820-kg vehicle impacting a strong-post W-beam guardrail under Report 350 Test 3-10 conditions (820 kg-100 km/hr-20 degrees) as shown in Figure 11. Plaxico, Hackett and Uddin have developed a model of a modified thrie beam guardrail that has been used to simulate the impact of an 820-kg small passenger car in a 100 km/h redirection collision.[50] This model was compared to full-scale crash tests in the literature and is now being used to simulate impacts with a 2000-kg pickup truck. Wekezer and others have also developed models of guardrails that have been used to simulate collisions with small vehicles.

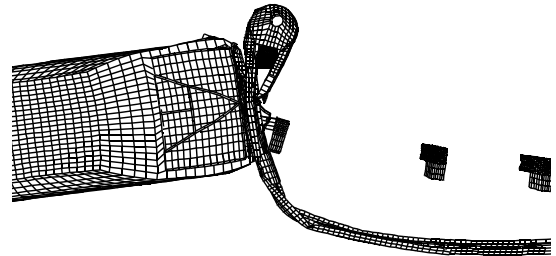


Figure 9. 100 km/hr impact of an 820C and a MELT guardrail terminal (Test 3-30).

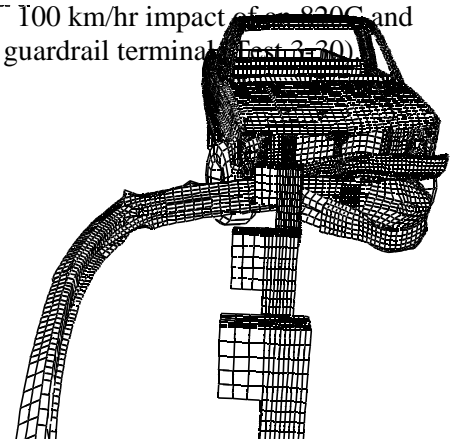


Figure 10. 100 km/hr impact of a C-1500 pickup truck and a MELT guardrail terminal (Test 3-31).

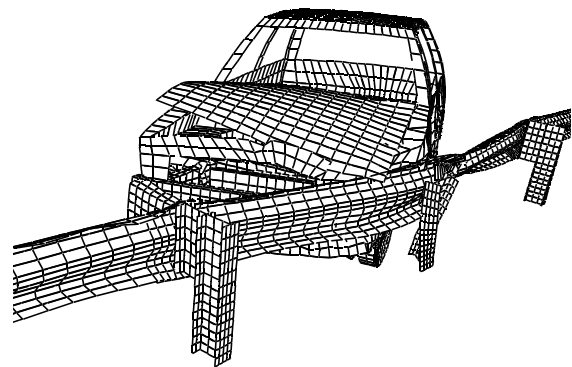


Figure 11. 100 km/hr impact of an 820C vehicle and a G4(1S) guardrail (Test 3-10).

A model of the weak-post W-beam guardrail was developed and used to assess the impact of an 820-kg passenger vehicle and is now being used to assess the performance of a 2000-kg pickup truck.[51] All these models have been developed to explore the performance characteristics of common guardrails with problem-vehicles like the small 820-kg passenger car and the 2000-kg pickup truck.

Although the majority of finite element applications to roadside safety have involved guardrails, guardrail terminals and luminaire supports, Carney has used this technique to develop a crash cushion made of high-molecular weight high-density polyethylene.[52] Since polyethylene is a temperature sensitive material, it was important to fully understand the effect of temperature on the performance of the crash cushion. Carney developed material properties for the polyethylene and then validated the material response at a variety of temperatures in the laboratory. These validated material properties were then used in a simulation of the whole crash cushion device in an impact with a small car to determine the performance of the system in a variety of temperature conditions. The simulations were able to demonstrate that the crash cushion would perform acceptably under atmospheric conditions that would have been very difficult to replicate in a full-scale crash test.

Figure 12 shows an example of a turned-down guardrail terminal being impacted by the Honda Civic model at 100 km/hr in Report 350 Test 3-10 conditions.[53] This simulation was performed by Reid, Sicking and Paulsen as a part of a State-sponsored research effort to find a crashworthy retrofit for the once-popular turned-down guardrail terminal. This research was the first where nonlinear finite element analysis was used to examine a variety of design options that were then tested in a full-scale crash test. Reid and Sicking have continued to use finite element analysis as a design tool and have been successful in developing a new type of guardrail profile, an improved dual-leg slip-base fuse plate and a mailbox support connection detail using finite element analysis.[54] [55] [56] [57] These projects are good examples of using the analytical power of finite element analysis to learn about the mechanics of a collision and then using full-scale crash tests to validate the concept. This type of project, where finite element analysis is used as an integral part of the design-test-evaluation cycle, will become increasingly common in the coming years as finite element analysis becomes more widely accepted in the roadside safety community.

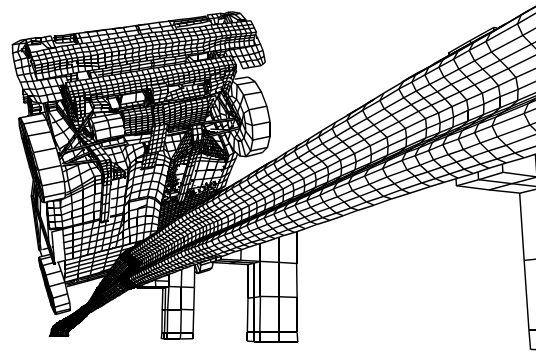


Figure 12. 100 km/hr impact of an 820C vehicle with a turned-down guardrail terminal (Test 3-30).

### Occupant Models

While occupant models have not been widely used in roadside safety simulations to-date, they have been used in occupant restraint and vehicle design research. NHTSA has sponsored the development of several finite element dummy models that may become more prominent in roadside safety research in the coming years.

Finite element models of the Hybrid III and components of the Hybrid III have been developed by several researchers. Khalil and Lin developed a thorax model for investigating occupant impacts with steering columns and Yang and Ye

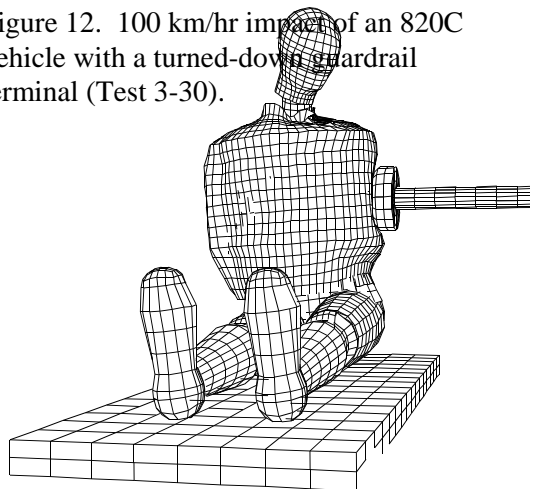


Figure 13. Simulation of a side impact dummy calibration test.

developed a head-neck model.[58] [59] More recently Nouredine and others have used a Hybrid III model to investigate the deformation-based chest injury criteria in frontal collisions.[60] There are numerous other examples of the development and refinement of the Hybrid III model but to-date it has not been used in a roadside safety hardware research. One reason that occupant models have not been used in roadside safety research is the unavailability of vehicle models where the interior is modeled.

In separate efforts Kirkpatrick and others developed a model of the side impact dummy (SID) for NHTSA in 1993 (Figure 13) while Midoun and others developed a SID model for Ford.[61] [62] [63] While results from these models were encouraging, comparisons to physical tests were not as good as desired because of a lack of validated parameters for many of the material models. Dummy models present a number of material modeling and contact challenges since an accurate model must correctly account for interactions between very soft foams and rubbers and very stiff materials like steel. NHTSA is continuing work to develop better material model parameters, refine the contacts and make other refinements.[64] The SID model is now being used to assess the risk of occupant injury in side impacts with narrow roadside objects like luminaire supports and guardrail terminals. It is likely that finite element models of anthropomorphic test devices like the SID will become increasingly important in roadside safety research especially in areas like side impact.

### Validation

Since there is a strong tradition of full-scale crash testing in roadside safety research it has been important to compare finite element simulation results with full-scale crash test results. Validating simulation models with physical tests has necessitated an examination of the repeatability of physical tests and an exploration the methods that can be used to compare physical and simulated events. Full-scale tests have always been evaluated largely on the basis of acceleration time histories. In 1982 Basu and Haghghi published a validation procedure for the FHWA that involved calculating a variety of time-domain and frequency domain characteristics of acceleration time histories.[65] This procedure was an important contribution since it demonstrated the importance of using quantifiable comparison techniques rather than qualitative techniques. Recently Meczkowski and Kan used the NARD Validation procedures to assess the fidelity of a finite element model of a Chevrolet C-2500 pickup truck.[66] In 1996 Ray suggested a series of simple statistical tests based on an analysis of the variance of the residuals (differences) between repeated crash test acceleration histories.[67] Figure 14 shows a plot of five physical tests compared to one simulated impact event. These repeated crash tests were used to both assess the repeatability of crash tests as well as develop comparison criteria. Recently Ray and Hiranmayee have further refined the technique and used it and the NARD validation procedure to assess the fidelity of a variety of public-domain vehicle models.[68] Although the research community has not formed a consensus on the best method to use, these efforts to establish quantifiable comparison measures are an important part of establishing the accuracy of finite element methods.

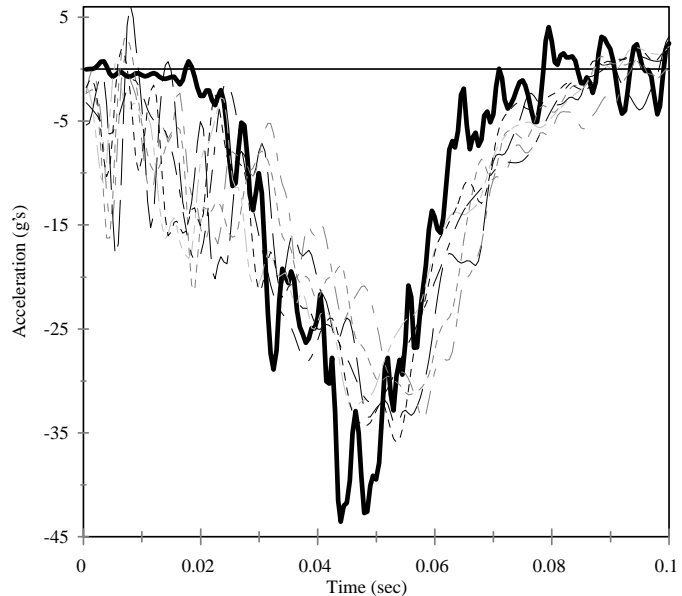


Figure 14. Comparison of simulated (bold line) and physical (all other lines) acceleration time histories of a 820-kg vehicle impacting a rigid pole at 32 km/hr.

## CONCLUSIONS

A great deal of progress has been achieved during the past several years in integrating non-linear finite element analysis into the roadside hardware design process. There is still, however, much work remaining before analytical methods achieve their full potential in roadside safety research. The computer software tools are available and computing hardware continues to improve at a rapid rate making these analyses increasingly more feasible. As the examples described above illustrate, the use of finite element analysis has steadily progressed from relatively simple impact scenarios to quite complicated, realistic impact scenarios. With continued progress finite element analysis is likely to play a very important role in the design and evaluation of roadside safety hardware in the coming decades.

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