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Crashworthiness Analysis and Simulations of Vehicles Impacting a Roadside Guardrail

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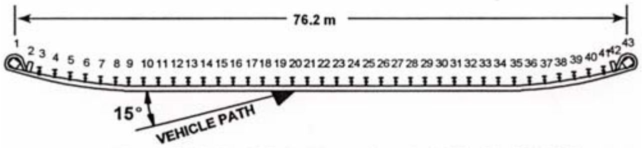
Abstract: This paper presents the results of a three-dimensional finite element study to simulate impacts of the models of a car and a pickup truck against a model of modified thrie-beam guardrail and to analyze the crashworthiness of the roadside guardrail. Nonlinear springs were used to simulate the rotation of the post below ground level. The simulation results of an event of a pickup truck impacting the modified thrie-beam guardrail model are presented. The "reduced" version of the pickup truck model is redirected after impact and leaves the guardrail without any significant problem. These results compare well with the results of a simulation of the impact of a "detailed" version of the pickup truck model. The simulation results indicate that the roadside guardrail model is performing properly and as expected.

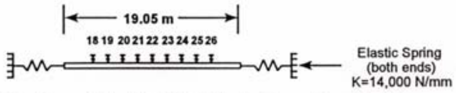
keyword: Finite element, simulation, vehicle, impact, thrie-beam, guardrail, pickup truck.

1 Background and objectives

Vehicle impacts with fixed roadside appurtenances such as roadside guardrails and bridge rails, median barriers, roadway signs and bridge abutments result in serious injury or death in many instances. The crashworthiness of some of these roadside safety structures has been evaluated through full-scale field testing for a number of years, but at considerable expense. If accurate finite element computational models can be developed and then used to predict the effects of vehicle-roadside structure collisions, enhanced design of such hardware systems can be more efficiently achieved. A series of crash tests, carried out by the Federal Highway Administration (FHWA) involving various different designs of the roadside guardrail, demonstrated that the modified thrie-beam guardrail performed better than the conventional W-beam and thrie-beam guardrails in its ability to safely contain and redirect the smaller class of vehicles, such as the 1975 Honda Civic, as well as the larger class of vehicles, such as school buses and intercity buses [Ivey, Robertson, and Buth (1986)]. Figure 1 illustrates the modified thrie-beam guardrail system modeled in the study, which consists of 12,101 shell elements with three integration points through the thickness.



Plan View of Modified Thrie-Beam Guardrail Used in Field Test



Modeled Portion of the Modified Thrie-Beam Guardrail

Figure 1 : Modified thrie-beam guardrail system (total length and modeled portion)

In an earlier phase of this study, a model of a compact automobile (model 820C vehicle, provided by the FHWA) impacting a modified thrie-beam guardrail (developed at the University of Mississippi) has been employed. The nonlinear, explicit, three-dimensional finite-element computer code LS-DYNA3D (1995), the preprocessors INGRID and LS-INGRID [Christon and Dovey (1992)], and the post-processor LS-TAURUS (1995) are used in this study. The 820C vehicle simulations have been carried out on Cray Y-MP and Cray J916 supercomputers located at the University of Mississippi. The simulation results have been compared with the results of a car crash event, which was previously conducted in a full-scale field crash test of the modified thrie-beam guardrail [Ivey, Robertson, and Buth (1986)].

The results of the previous phase of the simulation study involving the impact of the 820C vehicle model have indicated the following key points [Plaxico, et al. (1997a, b)]:

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- The DYNA3D models of roadside safety structures must be highly detailed in the impact zone to accurately simulate the complex interaction of a vehicle impacting into a roadside structure.
- It is necessary to model the structure-soil interaction into the LS-DYNA3D nonlinear models to simulate possible structural failures occurring during impact.
- More detailed LS-DYNA3D vehicle models may be required in order to accurately model the motions of the vehicle during the impact simulations. Factors, which have been shown to have more influence on simulation results than had been previously postulated, include the vehicle suspension model, tire model, and material model parameters.

The primary objectives of the later phase of simulation study were: (a) evaluation of the crashworthiness of the guardrail by conducting the simulation of a “reduced” version of a pickup truck model impacting the guardrail model, (b) crash simulation of a “detailed” version of the pickup truck model, and (c) comparison of the simulation results of the two models of the pickup truck with the results of a field crash test. The improved “reduced” and “detailed” versions of C2500 pickup truck models have been developed by the researchers of the National Crash Analysis Center (NCAC) and posted on the NCAC Internet site. The pickup truck impact simulations were carried out on the SGI Power Challenge workstation at NCAC, George Washington University.

2 Modeling of the modified thrie-beam guardrail

The dimensions of the modified thrie-beam guardrail system are based upon the latest specifications contained in the guide prepared by the AASHTO-AGG-ARTBA Joint Committee (1994). The total length of the guardrail is 76.2 m (250ft). The portion of the guardrail that was modeled is a 19.05 m (62.5ft) section located between post 17 and post 27, as shown in Figure 1, with nine W6x8.5 steel posts (spaced at 1,905 mm center-to-center) and nine M14x17.2 blockouts modified as is designated by Plaxico, et al. (1997b).

The finite-element model of the modified thrie-beam guardrail, developed using the preprocessor INGRID, consists of 12,101 shell elements, with three integration points through the thickness. Splice connections and rail overlaps are not simulated in the guardrail model. Linear springs are attached to the ends of the guardrail to simulate its continuation in both directions, as described by Plaxico, et al. (1997b) and shown in Figure 1.

All of the components of the guardrail are steel and are modeled using a piecewise linear stress-stain curve, with isotropic plasticity. The material properties of the guardrail used in the simulation correspond to AASHTO M-180 Class A Type II steel, as listed in Table 1 [Plaxico, et al.(1997b)].

The connection of the spacers to the posts is modeled by merging the nodes of the two parts. The bolted connection between the thrie-beam and spacers has been also modeled by merging of nodes. For simulations of the pickup truck in the second phase of the study connections are modeled using the “Spotweld Cards” in LS-DYNA3D.

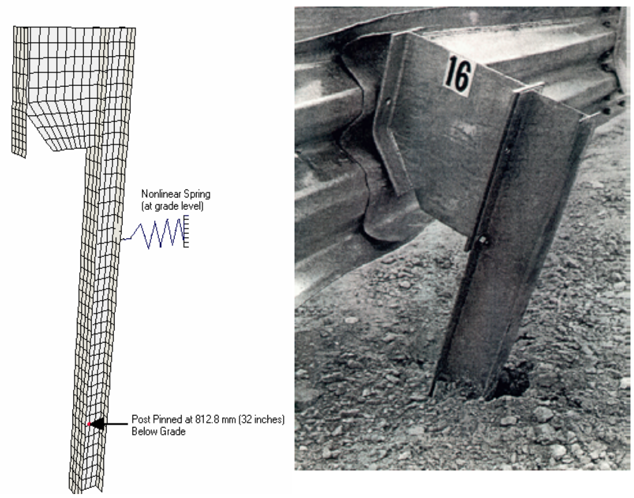
Table 1 : LS-DYNA Material parameters for modeling AASHTO M-180 Class a Type II Steel

Density (Mg/mm^3)	7.86E-09
Young’s Modulus (MPa)	200.E+03
Poisson’s Ratio	0.33
Yield Stress (MPa)	415.0
Strain Rate Effects	none
Plastic Strain at Failure	0.66
Increments of Strain	0.0 0.020 0.080 0.165 0.330 0.495 0.660 1.00
Increments of Stress (MPa)	0.0 415.0 548.0 585.0 591.0 95.0 600.0 0.00

3 Modeling of soil-post interaction

The modeling of the soil-post interaction, which plays a vital role in the response of the guardrail during an impact event, involved the use of a nonlinear spring to simulate the soil response. The data used in the development of the nonlinear spring came from a field-test study conducted by the Texas Transportation Institute (TTI) in which data were recorded during static loading tests of W6x8.5 steel posts buried 1,117.6 mm (44 inches) below grade [Dewey, et al. (1983)].

The results of those tests demonstrated that during loading, the W6x8.5 steel guardrail posts rotated at 686 mm (27 inches) and 813 mm (32 inches) below grade for non-cohesive and cohesive soils, respectively. Based upon the results of those test, a pivot point was set at 813 mm below grade, for the simulation of the rotation of the W6x8.5 steel guardrail posts during loading.



(a) (b)

Figure 2 : (a) Guardrail post-soil interaction modeled using nonlinear spring and (b) a record of the damage to guardrail after crash test 471470-30 [Dewey, et al. (1983)]

The response of the post in cohesive soil was reproduced by means of a finite-element sub-model of the post with a nonlinear spring attached to the post at grade level, as shown in Figure 2. Figure 2 also shows the post rotation recorded in a recent pickup crash test conducted at TTI [Mak, Bligh, and Menges (1995)].

The accuracy of simulation results were significantly improved after implementing the nonlinear post in the guardrail model, therefore, the nonlinear post was incorporated in subsequent simulations of the impact of the pickup truck model. Since the first presentation of this soil-post model by Plaxico, et al. (1997b), other researchers also have used nonlinear spring to model soil-post interaction.

4 The vehicle models

4.1 Passenger car model

The finite element model of 820C passenger car, provided by the FHWA, was used in the first phase of the study. The 820C model is of a 1989 Ford Festiva and contains 4,014 shell elements, 107 beam elements, and 745 solid brick elements.

This vehicle model has a total mass of 826 kg, compared to the total mass of 956 kg (including the mass of the telemetry equipment and crash dummies) of the 1975 Honda Civic car used in the field crash test at 18-degree impact angle [Ivey, Robertson, and Buth (1986)].

The problem of the “Nodal Constraint” option in the initial public domain DYNA3D simulations related to redirection after impact and the effects of the alternative method of modeling the connection of parts by the merging of the nodes on satisfactory redirection of the vehicle after impact were identified earlier in the study by Plaxico, et al. (1997a, b). For example, a consequence of merging nodes between certain parts of a model is the warpage of some of the elements. The accelerometer on the 820C vehicle is located at the center of gravity of the vehicle, between the driver’s and passenger’s seats; it is modeled as a rigid body in LS-DYNA3D.

During the simulation, the vehicle redirects from its original path of impact, hence a local coordinate system to rotate with the vehicle and gather velocity and acceleration data is defined. These data are collected via the RBDOUT (rigid body data output) option. This ASCII format file contains all of the displacement, velocity and acceleration data of the “rigid bodies” in local, as well as, in global coordinates.

4.2 Pickup truck model

The second phase of the study involved the simulation of an impact of a C2500 pickup truck model against the guardrail model at the same impact angel and same impact velocity used in the successful 820C impact simulation. The C2500 pickup truck models have been developed by the NCAC researchers at the George Washington University [Zaouk, et al. (1997)]. Some preliminary runs were made with version 7 of the “reduced” C2500 pickup truck model impacting a model of the modified thrie-beam guardrail. The release of version 7 of the reduced pickup truck model incorporates an accelerometer (material 50) at the center of gravity of the vehicle and many significant improvements in material properties, tire model, suspension model, rigid body constraints, and contact elements. The reduced version model consists of 10,514 elements and is considered a low-fidelity bullet model of the “detailed” C2500 pick up truck model. The “detailed” C2500 pickup truck model is a high-resolution model of the Chevy C1500/2500 pickup truck. The detailed vehicle model is composed of 54, 873 elements.

Model parameters are compared in Table 2.

Table 2 : Comparison of the “reduced” and “detailed” truck models

Model Parameters	C2500 "Reduced" Model Version 8c	C2500 "Detailed" Model Version 4f
Model mass	0.1838E+01 tons	0.1900E+01 tons
Total parts	59	224
Total number of elements (shell, solid, and beam)	10,514	54,873
Shell elements	10,028	51,244
Solid brick elements	437	3,458
Beam elements	49	171
Total nodes	11,060	62,402

5 The 820C Vehicle/Guardrail Impact Simulation

The finite-element model of the 820C vehicle was incorporated into the impact simulation of the modified thrie-beam guardrail. Th 826 kg model impacted the guardrail at a speed of 27, 538 mm/second (61.6 mph) and at an angle of 18 degrees. Another impact simulation was carried out at an angle of 15 degrees. The tire-pavement interaction is modeled using the ”stone wall” option in LS-DYNA3D with orthotropic friction. The transverse coefficient of friction between the tire and “stone wall” was taken as 0.2 and the longitudinal coefficient of friction was set to zero in order to simulate the tires sliding freely. These direction-dependent coefficients are defined to rotate relative to a defined local coordinate system located on the vehicle model.

A significant effort has been made to understand the redirectional problems involving autocontact definition during an impact simulation. There is the possibility of contact among many of the associated parts. Depending upon the complexity of the models, it may be difficult to model and define the contacts explicitly. The autocontact option provided in LS-SYNA3D considers only nodes impacting segments; as a result, sharp corners can penetrate without any contact being detected [Plaxico, et al. (1997b)]. This problem is of major concern in simulations such as the current study, where a significant amount of sliding between the vehicle and the guardrail is expected to occur. During such a simulation, the front of the vehicle may come into contact with the guardrail in the direction of the velocity vector, with, due to the penetrating nodes, further motion of the front of the vehicle in this direction prevented; this imparts a counter rotation to the vehicle. Consequently, different meshes may lead to inconsistent and even near-random results, making prediction of the vehicle’s motion impossible. This crucial problem and its solution, defining three sliding interfaces to model all possible contacts, are discussed in detail by Plaxico, et al. (1997b). Based on the results of the first phase of the study, Type 5 contact option is used to model contact between the vehicle and the guardrail, with the guardrail being defined as the master surface. The “autocontact” definition is used to define the contacts among parts of the vehicle with other parts of the vehicle, as well as to define the contacts among parts of the guardrail with other parts of the guardrail.

Vehicle acceleration history plots (100 Hz filtered data) from the actual crash tests at impact angles of 18, 16 and 15 degrees shown in the Federal Highway Administration (FHWA) report [Ivey, Robertson, and Buth (1986)] were digitized and processed for comparison with the simulation results. Results of acceleration histories from the simulations of the 820C vehicle impacting angles of 18, 16 and 15 degrees against the modified thrie-beam guardrail model were processed using 100 HZ filter to compare with the filtered field crash test data. During the field test 4098-5 at 18–degree impact angle, the vehicle paralleled to the guardrail at 0.145 seconds and, at that point, had decreased in speed to 88.5 km/hr (55mph). The vehicle remained parallel to the guardrail until leaving it at 0.375 seconds at an angle of 1 degree and a speed of 79.8 km/hr (50mph). The maximum deflection experienced by the guardrail occurred at 0.172 seconds and was 310 mm(12.2 inches). Based on comparisons with the field crash test results, the impact simulation at 15 degree and 100.6 km/h (62.5mph) corresponding to Test 4098-4 at 15-degree impact angle are compared to the results of the full-scale field test in Figure 3 and Table 3.

The response of the vehicle model during the simulation corresponds well with the response of the vehicle during the field test. During the simulation, the vehicle parallels to the guardrail at approximately 0.150 seconds, at which point it has decreased in speed to 83.7 km/hr (52 mph). The guardrail reached a maximum deflection of 340 mm (13.4 inches) at approximately 0.100 seconds and again

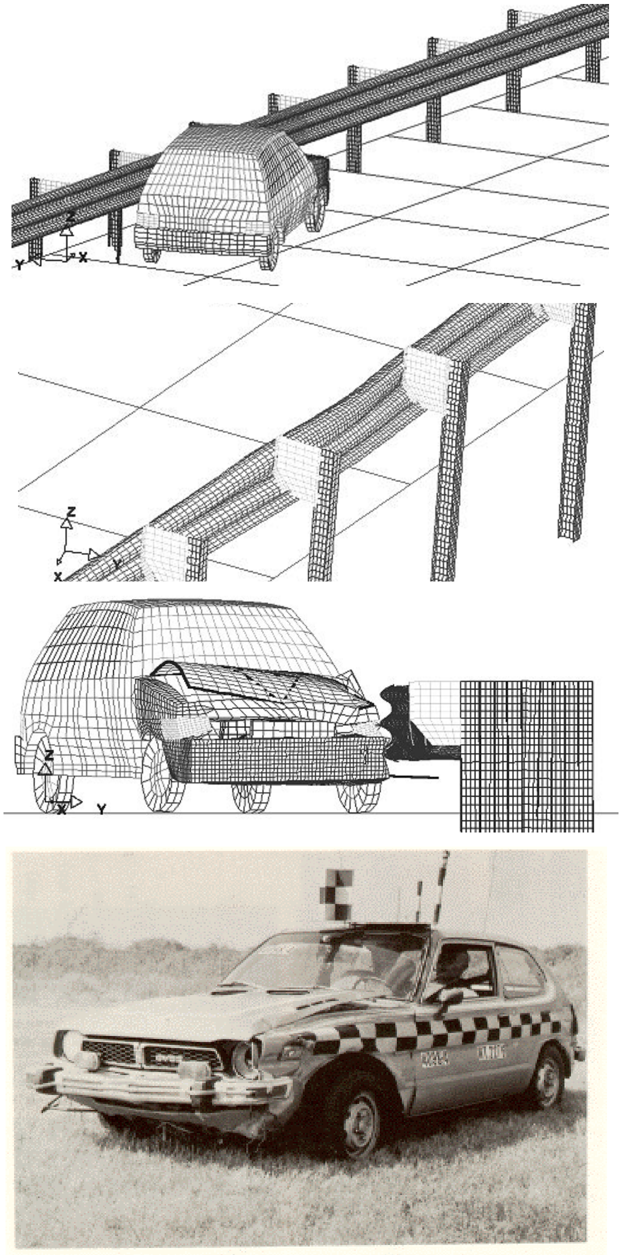


Figure 3 : Selected events of simulated results for the 820C impact versus the field test

reached a maximum deflection of 307 mm (12.1 inches) between post 21 and post 22 at o.200 seconds after the rear of the vehicle made contact with the rail. The vehicle exited the guardrail during the simulation at approximately 0.290 seconds at an angle of 2 degrees and at a speed of 79.5 km/hr (49 mph). Plots of acceleration verses time histories of the vehicle for the simulation and field measurements, using 100 Hz filtered data, are shown in Figure 4.

Table 3 : Comparison of the passenger car simulation and field crash test results

Comparison	Measurement	Simulation
Vehicle is	1976Honda CVCC	Model 820C
Vehicle mass is	1,032 kg (2,276 lb.)	826 kg (1,822 lb.)
Vehicle impacts the guardrail at	15 degree and 100.6 km/h (62.5mph)	15 degree and 100.6 km/h (62.5 mph)
Vehicle parallels the guardrail at	0.126 second	0.150 second
Speed decelerates to	94.4km/h (57mph)	83.7 km/h (52mph)
Vehicle leaves the guardrail at	2.7 degree and 89 km/h (55 mph) at 0.272 second	2.0 degree and 79.5 km/h (49 mph) at 0.290 second
Maximum deflection of the guardrail is	240 mm (9.5 in) at 0.16 second	307 mm (12.1 in) at 0.20 second

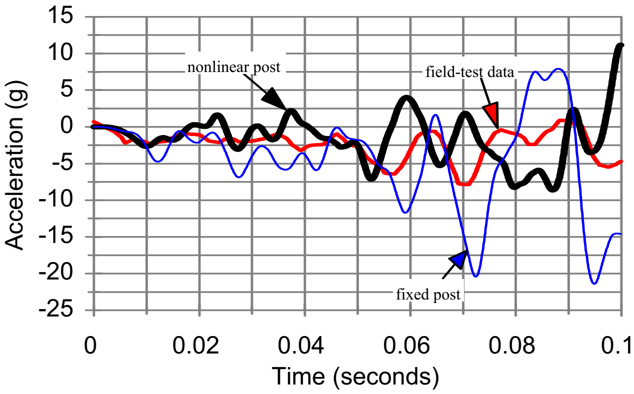


Figure 4 : Comparison of acceleration history plots of the car field test and simulation

The simulation results involving nonlinear posts (with the nonlinear spring) compare better with the acceleration histories of the actual crash test results in the first 0.03 seconds. Comparisons of the acceleration histories of the simulation and field crash results using the validation procedures “Valid” proposed by the National Crash Analysis Center (NCAC) were also conducted. The time domain analysis shows (a) a correlation measure of 0.6, (b) relative moment difference less than 3 percent for moments 1 through 5, and (c) root mean square (RMS) log measures of 11.3 (for RMS log difference r3) and 8.0 (for RMS log difference r3). The 820C vehicle model is based on the specifications of a 1989 Ford Festiva, whereas a 1976 Honda CVCC was used in the actual crash test at an impact angle of 15 degree. Therefore, it is no surprise to obtain a lower correlation between the acceleration histories from the simulation and field crash test results.

It should be noted that the 820C vehicle model was originally created and validated for head-on frontal impact with a rigid pole [Cofie (1995)]; that being the case, the developers of the vehicle model were not primarily concerned with the detailed modeling of the sides of the vehicle, the suspension system, or the effects of tire friction.

Though these factors may not have a significant influence on the response of the vehicle during a head-on collision with a rigid barrier, they have a considerable effect upon the vehicle's response during a redirection impact.

It is recognized that the criteria for acceptable comparison of acceleration time histories are still evolving and there is always some variance in the crash test results. Moreover, pavement-tire interaction is not appropriately considered in the vehicle simulation model where tires slide on a perfectly level rigid surface.

Note that in real field test situations vehicle tires roll on the pavements surface which is never perfectly smooth and, therefore, it imparts excursions to the vehicle axles which is well known from pavement longitudinal roughness studies [Hudson, Haas, and Uddin (1997)]. Considering the above limitations of the vehicle simulation model and differences in the mass of the simulation and field test vehicles, the overall comparison of the results of the simulation with the measurements is reasonable. Some results of the simulation and field test are shown in Table 3.

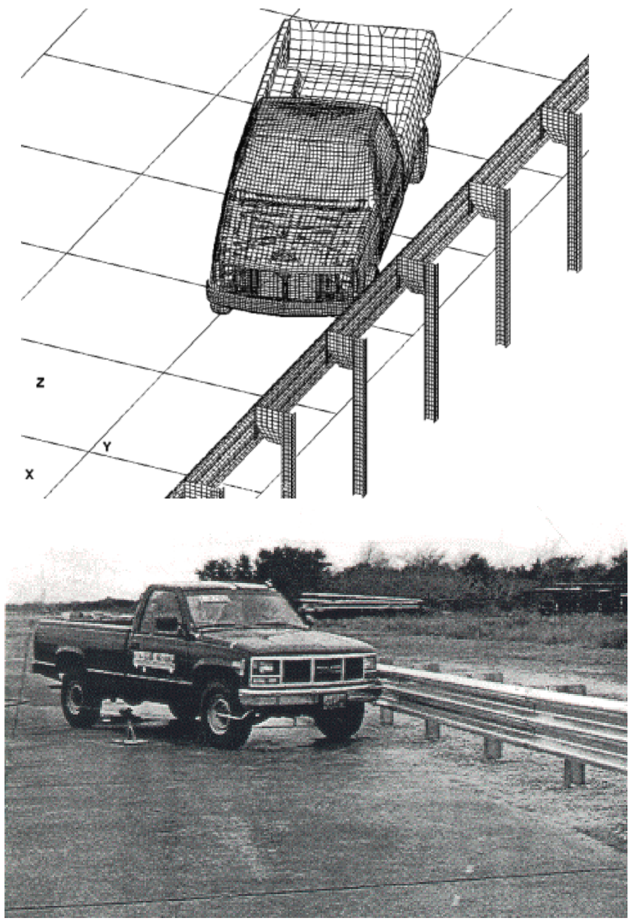


Figure 5 : A view of the reduced pickup truck and guardrail model

6 The Pick-up Truck/Guardrail Impact simulation

6.1 The "Reduced" Pick-up Truck Simulation

The simulation of the crashing of the reduced pickup truck model into the improved model of the modified thrie-beam guardrail was carried out at an impact angle of 15 degree and the impact velocity of 100.6 km/hr (62.5 mph) which was the same as used for the final 820C impact simulation. Figure 5 shows the reduced truck impacting the guardrail. Note the refined mesh in the impact region of the guardrail model.

The vehicle impacts the guardrail between posts 3 and 4, parallels the guardrail at 0.4 second, and leaves, the guardrail midway between posts 6 and 7 of the guardrail model. The maximum deflection of the guardrail at 0.24 second is 500 mm (19.7 inch). This maximum deflection is significantly more than the deflection recorded for the 820C passenger car (307 mm simulation at 0.2 second and 310 mm measured at 0.172 second), showing the higher impact energy exerted by the pickup truck model as compared to the passenger car. However, the guardrail has not completely failed during this simulation. Figure 6 shows the pickup truck model leaving the guardrail. Some elements of the guardrail model are removed from the model because these elements have failed, as shown in the close-up view in Figure 6.

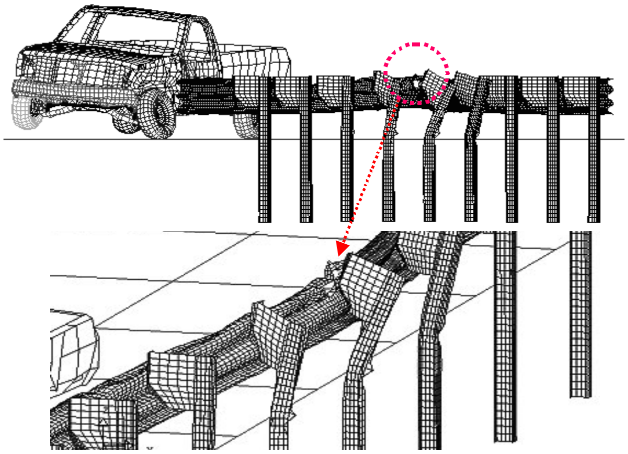


Figure 6 : A full view of the reduced pickup truck and guardrail model after vehicle redirection

6.2 Comparison with crash test results

A field crash test of a 1989 GMC pick up truck of a gross weight of 2, 076 kg (4,573 lb.) was conducted by TTI in November 1995. The truck impacted a modified thrie beam guardrail at a speed of 100.2 km/h and an impact angle of 25.1 degree. The truck paralleled at 0.264 seconds and left the guardrail at 0.56 seconds. The maximum deflection of the guardrail was 610 mm (24.0 inch). Moderate damage to the guardrail was recorded, however, the damage to the truck was severe. The left front assemble was torn from the vehicle's axle. These differences are expected because the impact conditions in the field crash were more severe. Two views of the damage guardrail are shown in Figure 7 and a damaged post is shown in Figure 2.

6.3 Comparison with simulation of "Detailed" pickup truck

A simulation of the impact of the detailed C2500 pickup truck model was carried out at a speed of 100.6 km/h (62.5 mph) and an impact angle of 15 degree, the same impact simulation conditions as used for the reduced truck model. The impact simulation was completed without any difficulty indicating that the guardrail model is performing properly and as expected. The results of the simulations of the two pickup truck models are similar.

A comparison of the simulations of the reduced and detailed pickup trucks is shown in Table 4. The CPU time taken to complete the detailed truck simulation was about 10 times the CPU time used in the reduced truck simulation.

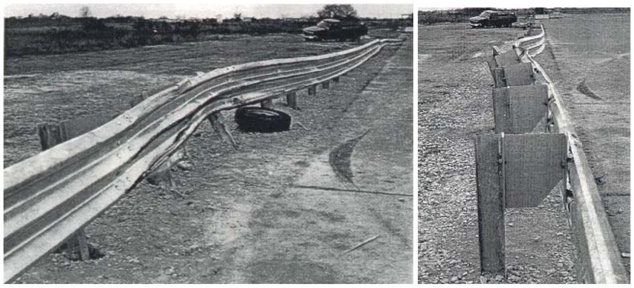


Figure 7 : The damage to the guardrail during the field crash test

6.4 Future work with the thrie-beam guardrail model

This study has validated the three-dimensional finite element model of the modified thrie-beam guardrail. The model provides a valuable simulation tool for assessing the impact damage to the guardrail model by the vehicle model under simulated impact conditions.

The thrie-beam guardrail model is available in public domain for future simulation research. This model should be used in a future study to simulate the impact of the pickup truck model at an impact angle of 25 degree and selected impact speeds to investigate the results of simulations when one of the wheels snags the posts. Although, not presented in this paper because the study is complete, the guardrail model is expected to perform well in this case. As shown in Figure 6, towards the end of the current simulation, some wheels leave the ground and the front left wheel is damaged.

The modified thrie-beam guardrail model is available on the NCAC Internet site. The input files for both the guardrail model and impact simulations with the pickup truck models are available for public use. The crash simulation community is encouraged to download these and several other vehicle and roadside hardware models for further simulations.

7 New development of meshless methods

The three-dimensional finite element modeling and simulation requires lots of labor-intensive hours to generate the finite element mesh, to ensure element connectivity, and to handle failed elements. This becomes extremely

Table 4 : Comparison of the "Reduced" pickup truck and "Detailed" pickup truck simulations

Items	"Reduced" Truck Model	"Detailed" Truck Model
Time steps used (sec)	4×10^{-6}	1×10^{-6}
Computer used for simulation	SGI Power Challenge	SGI Power Challenge
Total simulation time (sec)	0.5000	0.40
Total CPU time (hrs)	17 *	180
Angle of impact	15	15
Speed at impact (mm/sec)	2.79×10^4	2.79×10^4
Initial contact time (sec)	0.010	0.010
Initial contact location	mid-way between posts 3 and 4	mid-way between posts 3 and 4
Time at which vehicle parallels the guardrail (sec)	0.200	0.200
Location at which vehicle parallels the guardrail	center of truck at post 5	center of truck at post 5
Time at which vehicle leaves the guardrail (sec)	0.400	0.400
Location at which vehicle leaves the guardrail	mid-way between posts 6 and 7	mid-way between posts 6 and 7
Maximum deflection of the guardrail (mm)	500	470
Time at maximum deflection of the guardrail (sec)	0.240	0.215

complex in the three-dimensional nonlinear crash simulation contact problems presented in this paper for the crashworthiness analysis of vehicle-roadside structures. Although the cost of high performance computing has decreased substantially, the labor-intensive mesh generation tasks have not changed. A new generation of meshless methods is available to modeling and simulation community that can simplify the finite element input file and alleviate the difficulty of meshing and remeshing and element distortion problems as discussed by Atluri and Zhu (1998) and Cheng, et al. (2003). Several researchers have been active in this area in recent years, for example; Diffuse Element methods by Nayroles, et al. (1992), Element-Free Galerkin methods by Belytschko, et al. (1994), Kernal Particle method by Liu, et al. (1996), and Unity Finite Element method by Melenk and Babuska (1996). As stated by Atluri and Zhu (1998), "the major differences in these meshless methods, all of which may be classified as Galerkin methods, come from the techniques used for interpolating the trial fuction." These methods require the use of shadow elements. Recently, two truly meshless methods have been successfully developed, the meshless local boundary equation method and meshless local Petrov-Galerkin method for linear and nonlinear problems, as discussed by Atluri and Zhu (1998, 2000) and Atluri and Shen (2002a, 2002b). It is recommended that these meshless methods be used as an alternative computational approach for three-dimensional crash simulation problems.

8 Conclusions and recommendations

This study has produced significant improvement in the modified thrie-beam guardrail model, soil-post interaction, and crashworthiness analysis of the guardrail subjected to impacts by the finite element models of a passenger car and a pickup truck.

The 820C vehicle model is that of a 1989 Ford Festiva, which has a mass of 826 kg and is 20% lighter than the 1032-kg 1976 Honda CVCC (including telemetry equipment and crash dummies) used in the field test at an impact angle of 15 degree. During the simulation, there was minor damage to the vehicle model. It should be noted that the developers of the vehicle model were not primarily concerned with the detailed modeling of the sides of the vehicle, the suspension system, or the effects of tire friction; though these factors may not have a significant influence on the response of the vehicle during a head-on collision with a rigid barrier, they have a considerable effect upon the vehicle's response during a redirectional impact. The results of the simulations, however, are considered reasonable.

The simulations of the reduced and detailed pickup truck models impacting the improved model of the thrie-beam guardrail were carried out without any problem. A higher maximum deflection of the guardrail was computed in the pickup truck simulation, as compared to the maximum deflection in the car simulation. During these simulations the guardrail redirected the vehicle after the impact and performed as expected. The simulation results compare reasonably with the crash test results involving a C2500 pickup truck although the actual impact conditions were more severe. The refinements in the reduced and detailed models of the pickup truck have been successful, as observed in the simulations carried out in this study.

The results of the simulation of the pickup truck models impacting against the model of the modified thrie-beam guardrail are reasonable and demonstrate that the guardrail model is performing properly and as expected. Some of the problems in the finite element modeling of the guardrail and soil-post interaction modeling and their solutions identified in this study have advanced the knowledge of impact simulations of roadside guardrail. Further research is needed in the area of soil material modeling and pavement-tire interaction. It is recommended that more robust vehicle models be developed for correctly simulating the pavement surface-tire interaction, which plays a significant role in the acceleration history and impact forces because of the vehicle dynamics.

It is recommended that the new generation of meshless methods be used for three-dimensional crash simulation problems. This alternative computational approach can simplify the finite element input file and alleviate the difficulty of meshing and re-meshing and element distortion problems.

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The contents of this paper reflect the views of the author who is responsible for the facts, finding and data presented herein.

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