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Development and Validation of High Fidelity Vehicle Crash Simulation Models

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ABSTRACT

A program was performed to develop and validate a high fidelity finite element model of a full size car for crashworthiness analysis. This study is part of an overall program to develop a set of crash models for various vehicles that represent the range of vehicle types currently on the road. The resulting set of vehicle models can then be used to study the effect on the overall crash safety of the introduction of future light-weight vehicles or other changes in the current highway vehicle fleet composition.

The representative full size car selected for this program was the Ford Crown Victoria. The model developed required the tear-down and digitization of a vehicle to characterize the geometry and material testing to measure the mechanical properties. The digitized structural component surfaces were then used to generate the finite element model.

An important step in the overall model development is the validation of the model. Vehicle frontal and side impact tests had been performed on the Crown Victoria. Data from these full vehicle crash tests provided a primary set of measurements for validating the crash model. However, complete validation of the model based only on the existing vehicle crash tests is difficult because of the complexity of the crash responses and the limited number of measurements in the tests. Correct simulation of the crash responses requires modeling both the responses of the individual structural components and the interaction of those components to obtain the complete vehicle crash behavior. To assist in the model validation additional component tests were performed. The component tests included bumper and door rigid pole impact tests and a vehicle frame rigid wall impact test. The model validation using both the component tests and full vehicle crash tests is shown to illustrate the approach.

INTRODUCTION AND BACKGROUND

In 1993 the U.S. Government and U.S. Auto manufacturers formed a new partnership aimed at strengthening U.S. competitiveness while protecting the environment by developing new technologies for vehicles. This Partnership for a New Generation of Vehicles (PNGV) set the goal of developing a vehicle that can achieve up to three times the fuel efficiency of today's comparable vehicle while maintaining cost, performance and utility standards. To meet these goals it is expected that the PNGV vehicles will have a substantial reduction of weight compared to current vehicles.

The National Highway Traffic Safety Administration (NHTSA) is supporting the PNGV to ensure that the new generation vehicles meet existing and anticipated safety standards. As part of this effort, NHTSA has a program to develop a set of finite element models for various vehicles that represent the full range of vehicle types currently on the road from a subcompact car up to a sport utility vehicle and full size truck. This set of vehicle models will be used to establish the crash safety of future light-weight vehicles developed under the PNGV program.

The goal of the project described in this paper is to develop a high-fidelity crash simulation model for the 1997 Ford Crown Victoria in support of NHTSA and PNGV. This is a combined effort of MGA Research Corporation and SRI International under the management of the Volpe National Transportation Systems Center (VNTSC). MGA is performing component validation tests on the Crown Victoria and had previously performed vehicle frontal and side impact tests. SRI is developing the finite element model for vehicle crash simulations.

The finite element model is being developed to analyze full frontal, frontal oblique, and side impacts. Mass, geometry, and physical characteristics of the vehicle and major sub-components will be modeled with a high degree of detail for the portions of the vehicle involved in full frontal impact, frontal oblique impact on the driver's side, and side impact of the driver's side. All other portions of the vehicle will be geometrically accurate but with less precision. The resulting model will be verified against test data supplied by the government for each of the impact conditions.

The model development required both vehicle tear-down and digitization and model generation. NHTSA supplied SRI with the vehicle for use in vehicle tear down, scanning, and component measurement and digitization. A description of both the vehicle tear-down and digitization are given below.

After completion of the vehicle tear-down and digitization, components of the vehicle were used in dynamic testing. The objective of the tests was to gain additional dynamic test data on components that can be used for model validation. These tests included impact tests on the front bumper, the driver's side front door and the stripped car frame including the frame rails. The results of these component crash tests are given in References 1-3. Collision tests with complete vehicles were performed under the U.S. Department of Transportation New Car Assessment Program (NCAP).

VEHICLE TEAR-DOWN AND DIGITIZATION

A government-furnished 1997 Ford Crown Victoria was used as the prototype vehicle for developing the high-fidelity crash simulation model. This vehicle was delivered to SRI International in late March, 1997, as shown in Figure 1(a). Subsequently, the mass and center of mass of the as-received vehicle were determined. Next, the non-structural components of the vehicle were identified, and their positions were measured and recorded. These components were removed from the vehicle, weighed, and catalogued. After the tear-down process was completed and the vehicle was stripped down to its structural components, the surfaces of the vehicle were digitized and the information was transferred to a computer where it was used to define the geometry of the high-fidelity crash simulation model.

The mass and center of mass of the vehicle using a set of wheel weighers. The total mass of the vehicle as received was 1705 kg. The center of mass was then determined from comparison of mass measurements with the vehicle supported horizontally on level ground and at an inclined angle of 10.8° to the horizontal.

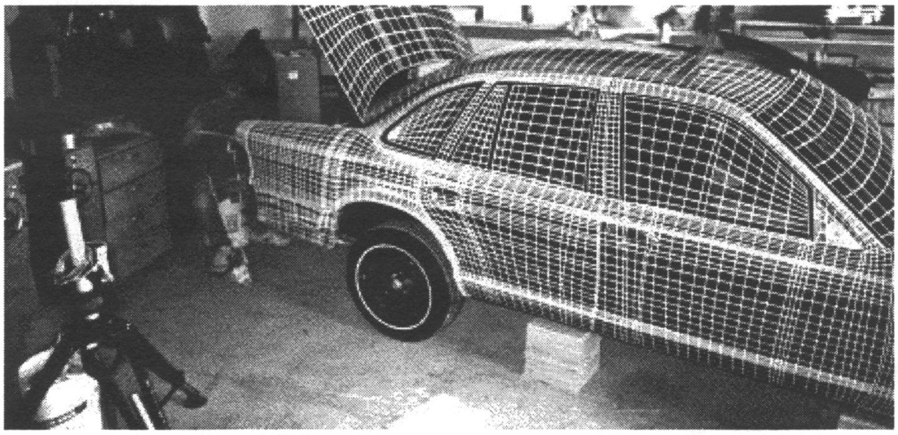
The objective of the tear-down and digitization is to characterize the geometry of the structural components that have a significant effect on the crashworthiness of the vehicle. During the early portion of this phase, parts and components that have a negligible effect on the crashworthiness of the vehicle were detached and removed. As parts were removed from the vehicle, they were weighed, cataloged with part number, and the position on the vehicle was recorded [Reference 4]. This information can be used later in the model development to ensure a proper mass distribution in the vehicle model. Examples of parts and components removed from the vehicle during the initial vehicle tear-down phase include plastic bumper covers, lights and light fixtures, hub caps, and interior trim components.

After the tear-down phase was completed, the geometry of the vehicle structural components were digitized. The vehicle digitization was performed using a FaroArm, a portable 3D coordinate measurement instrument (The FaroArm is a registered trademark of FARO Technologies, Inc.). The FaroArm is a counter-balanced, temperature compensated, six degree of freedom measurement arm constructed of anodized, aircraft aluminum with precision bearings. The FaroArm used in the present study was a bronze series B10-02 model having a diametrical range of 3.05 m (10 feet) and a measurement accuracy of ±0.4-mm. Proprietary, hybrid analog/digital transducers at each of six joints combine to provide complete point position and orientation. The 3D data captured by the FaroArm is analyzed by a digital signal processing (DSP) controller which communicates the information to a host computer. The Caliper 3D utility software package was used to control the FaroArm operations and to acquire data.

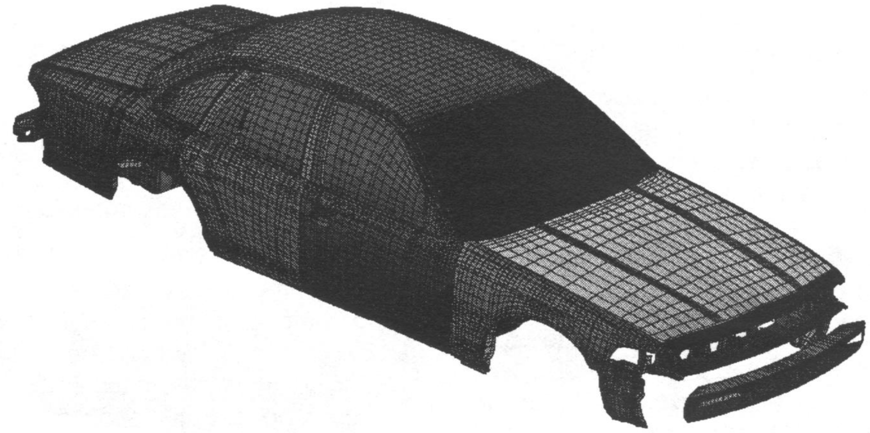
The first step in the vehicle digitization phase was to establish a global coordinate system to which all measurements could be referenced. This is important because the FaroArm had to be repositioned many times during the vehicle digitization phase to reach all locations on the inside and outside of the vehicle. The vehicle was placed on four blocks, inserted directly under the steel frame, for support while establishing the global coordinate system and remained on blocks throughout the vehicle digitization phase. This method gives more rigid support to the vehicle than would the suspension system of the vehicle, and unlike the suspension system, is not affected by the ever changing mass of the vehicle as various components are removed from the vehicle during the digitization phase. The global coordinate system was established using a reference triad on the vehicle. The triad consisted of three well-defined, permanently-marked, non-collinear points spaced as far apart as practically possible. The points for the global coordinate triad were located on the body floor pan along the vehicle centerline and at the base of the b-pillar.

Portions of the vehicle components were not accessible for digitization in their original positions. This was particularly true for multi-layered panels with accessible exterior surfaces and inaccessible interior surfaces such as doors, hood, trunk, and fenders. These panels had to be removed from the vehicle and repositioned to make their interior surfaces accessible for digitization. To ensure that all the measurements made before and after repositioning of the panels were in the same global coordinate system, a coordinate triad, referenced back to the global coordinate system was established on each removable panel, and on the engine, the frame, and the roof of the vehicle. These coordinate triads were used to reestablish the coordinate system for digitization of components removed from the vehicle. Similar coordinate triads placed around the vehicle were used to reestablish the coordinate system each time the FaroArm was moved to a new position.

(a) Initial condition - 1997 Ford Crown Victoria.



(b) Vehicle teardown and digitization.



(c) Digitized vehicle exterior surfaces.

Figure 1. Vehicle tear-down and digitization of the 1997 Ford Crown Victoria.

The vehicle digitization was performed using a structured format. This format minimizes the downstream processing required to convert the surface data into a format compatible with the TrueGrid mesh generation program used to develop the high-fidelity crash simulation model [Reference 5]. A grid of thin tape was applied to the vehicle surfaces as shown in Figure 1(b). The grid spacing varied depending on the local surface features. The spacing was adjusted as needed to accurately capture all the important geometric features of the vehicle.

The vehicle surfaces were defined by digitizing the intersection points of the horizontal and vertical grid lines. Each body panel or component of the vehicle was divided into subregions containing horizontal and vertical grid lines. Systematically, the subregions were digitized row by row in a sequential fashion, and the 3D coordinate data generated during this process were stored in a data file. The data files were then processed through a computer program written especially for the purpose of converting the FaroArm digitization data into a format compatible with TrueGrid. The program was written in FORTRAN and it performed the following data manipulation processes:

- **Reflect the data about a symmetry plane:** Whenever possible, symmetry about a vertical plane passing through the centerline of the vehicle was used to reduce the digitization effort.
- **Combine data points in adjacent surface regions:** Each surface or body panel of the vehicle was divided into smaller subregions. These subregions are combined to reconstruct the complete surfaces and body panels they represent. Redundant points within a user-specified tolerance are eliminated.
- **Apply rotational and translational coordinate transformations:** Apply geometric transformations to the digitized surface data to convert from the global coordinate system of the vehicle to the coordinate system used in the finite element model generation.
- **Generate Viewpoint data files:** The Viewpoint data file format was used throughout the present study as a format compatible with the TrueGrid mesh generation program.

The Viewpoint data files generated by the data manipulation program were imported directly into TrueGrid to define the various surfaces of the vehicle, such as the exterior body surfaces shown in Figure 1(c). Although the digitized surfaces have the appearance of a finite element mesh, the surfaces shown are collections of geometric polygons rendered using TrueGrid. Additional processing is required to develop a finite element model from the surface data. The finite element model generation is described below.

After the exterior surfaces were digitized, all removable body panels were detached from the vehicle thus making the remaining portions of the body of the vehicle more accessible for digitization. At this stage, a grid was applied to the newly exposed internal surfaces of the vehicle and the surfaces were digitized using the same procedures as the exterior body surfaces. With the new surfaces of the panel exposed, the panel was held in a rigid fixture in close proximity to the FaroArm. The arm position was referenced using the coordinate triad on the exterior surface of the panel, thus tying the measurements to the global coordinate system of the vehicle. The data was then processed through the data manipulation program to combine the geometry of the internal surfaces with the exterior surfaces.

In the final stages of digitization, the vehicle body was detached from the frame to fully expose the surfaces of the engine, the suspension, and the transmission. Many of these components were not digitized to the same level of detail as the structural components which are more actively involved in the crash deformation process. For example, In the finite element model the engine will be represented by a rigid body, so that only a coarse exterior geometry definition and the correct engine mass is required. These drivetrain components were digitized, then removed to expose all the surfaces of the frame for digitization.

After the frame of the vehicle was digitized, the engine, the transmission, and the suspension were mounted back in their original positions. The reassembled frame, suspension, engine, and drivetrain were used for the dynamic component testing. The component tests and associated analyses are described below.

MODEL GENERATION

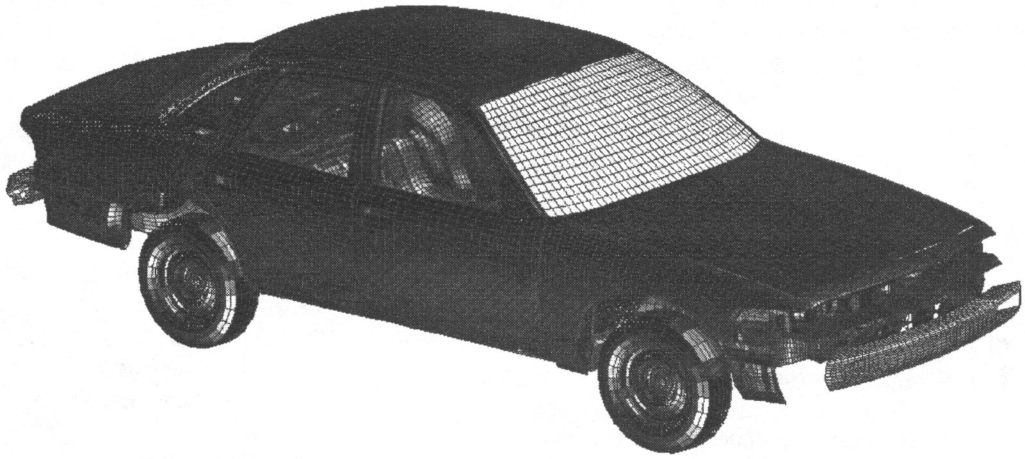
The model development was performed using the TrueGrid mesh generation program. TrueGrid is a powerful interactive mesh generation program with a graphical user interface. TrueGrid allows generation of complete input files for a variety of analysis programs including the LS-DYNA3D finite element code used in this program [Reference 6]. TrueGrid generates multi-block structured meshes of primarily solid hexahedron and/or structural quadrilateral shell elements. Discrete elements and beam elements can also be generated with TrueGrid.

As described above, the digitized vehicle surface data was input into TrueGrid by converting to a Viewpoint file format which can be read directly by TrueGrid. Parts are generated in TrueGrid by first defining a block of brick and/or shell elements. Vertices or edges of the element block can then be attached to the points or lines on the digitized surfaces. Next, the faces of the element blocks can be projected onto the surface definitions. Finally, the appropriate boundary conditions and initial conditions for the block are specified.

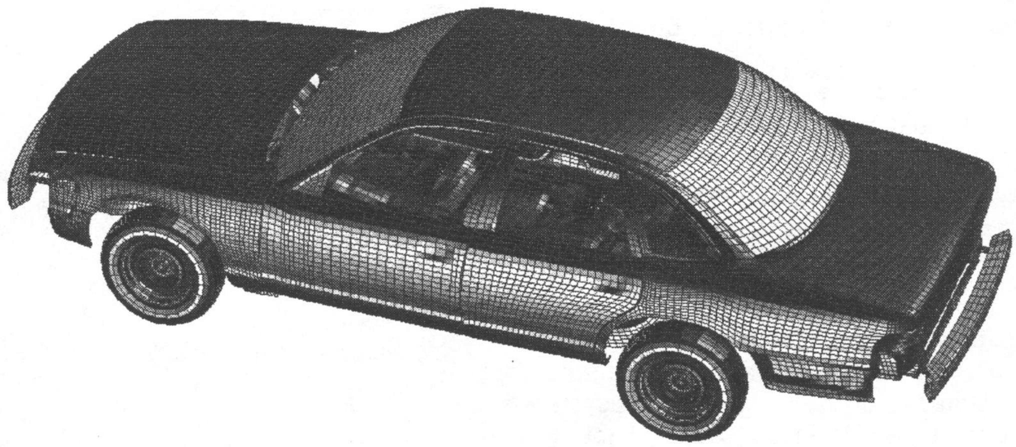
The finite element model of the Crown Victoria developed in this program is shown in Figure 2. The model includes the vehicle frame, drivetrain components, and the majority of the vehicle body structural components. To date, the approach used in the model development has been very successful. Some additional work is needed to complete the body model and include all connections and mounting points between the body and frame components to allow for the full vehicle simulations.

COMPONENT TESTS AND SIMULATIONS

As part of the model validation effort, impact tests and simulations of vehicle components were performed. The dynamic destructive tests included a rigid barrier impact test on the rolling chassis and drivetrain, and rigid pole impact tests on the front bumper and the driver's side front door. The component crash tests for the Ford Crown Victoria were performed by MGA Research Corporation. Corresponding simulations were performed to validate the model development on these components.



(a) Vehicle front view.



(b) Vehicle rear view.

Figure 2. Vehicle finite element crash model of the 1997 Ford Crown Victoria.

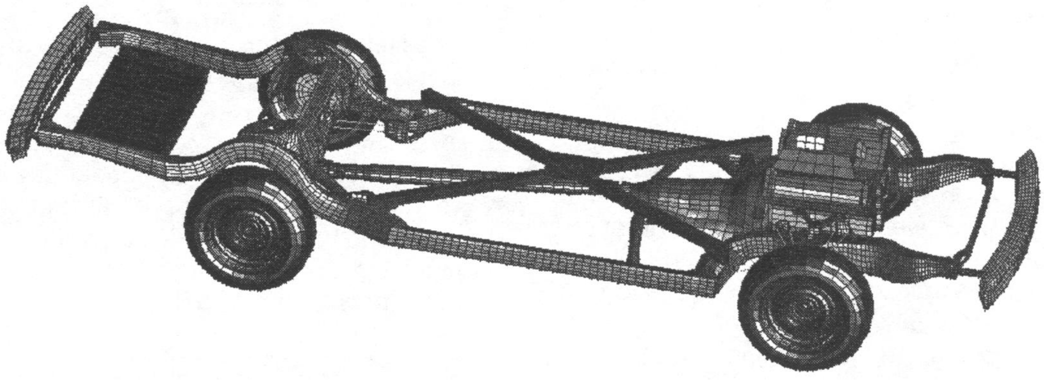


Figure 3. Model of the of frame and drive train used in the 35 mph rigid wall impact test.

The advantage of the component tests is that it is much easier to isolate and examine the discrepancies between test results and simulations at the component level. For the frame impact test, we can examine whether the discrepancies in the calculated response come from the modeling of the suspension components, engine mounts, or resolution of the frame mesh. If the full vehicle test was the only available crash data these discrepancies would be much more difficult to determine because of the added complexity.

The most critical component test for model validation in frontal collisions is the frame impact test. The model for the frame and suspension used to simulate the frame impact validation test is shown in Figure 3. The test conditions are a 15.6 m/s (35 mph) frontal impact with a rigid wall of the 957 kg (2110 lb) vehicle frame as tested. The model includes the frame, engine, transmission, drive train, and suspension components. In addition, a cross brace was added in the experiment and model to prevent uncharacteristic frame collapse modes. A representation of the instrumentation package attached to the rear section of the frame behind the rear axle was added to correctly model the overall mass distribution in the impact test.

The advantage of this test is that it can be compared with a corresponding NCAP frontal impact test that had been performed on a complete vehicle under the same test conditions. A comparison of the vehicle and frame barrier force histories for the frontal impact tests are shown in Figure 4. Much of the character of the vehicle collision force history is reproduced in the frame test. The comparison of these tests indicate that approximately one-half of the vehicle frontal collision response is attributed to the frame collapse behavior. Thus, the frame is an important component that needs to be modeled correctly in the full vehicle crash response.

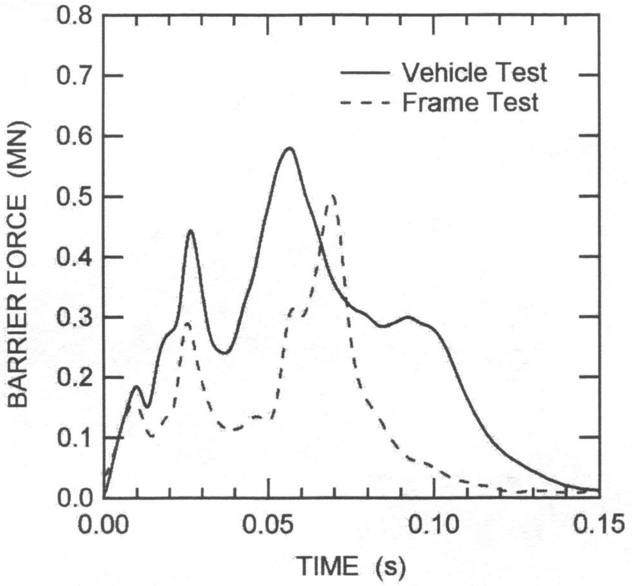


Figure 4. Comparison of the vehicle and frame frontal barrier impact tests.

The calculated frame collapse is dominated by the formation of two plastic buckles in each of the forward frame rails as observed in the experiment. The final state results in the forward frame crushed up to the front of the engine block. This peak frame displacement is reached at a time of approximately 70 ms. The calculated and measured wall impact force histories are compared in Figure 5. The magnitude and time of the peak force agrees quite well and corresponds to the time the engine impacts the forward frame and bumper against the wall. The early time response shows some discrepancy in timing of the force peaks, which result from the approximations in the modeling of the bumper isolators and failure of the isolator connections.

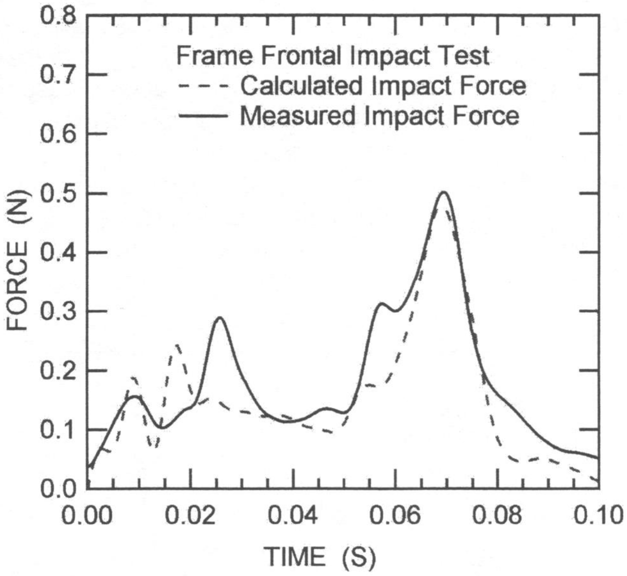


Figure 5. Measured and calculated wall impact force in the frame frontal impact test.

The calculated engine longitudinal acceleration is compared to measurements on the upper and lower engine in Figure 6. The overall agreement of the measured and calculated responses is good. The magnitude and time of the peak acceleration agrees quite well and corresponds to the time the engine impacts the forward frame and bumper against the wall. The calculated response has a larger magnitude cyclic response than measures during the first 20 ms. This discrepancy in the early engine accelerations could result from the engine mount modeling coupling the early frame motion too strongly to the engine.

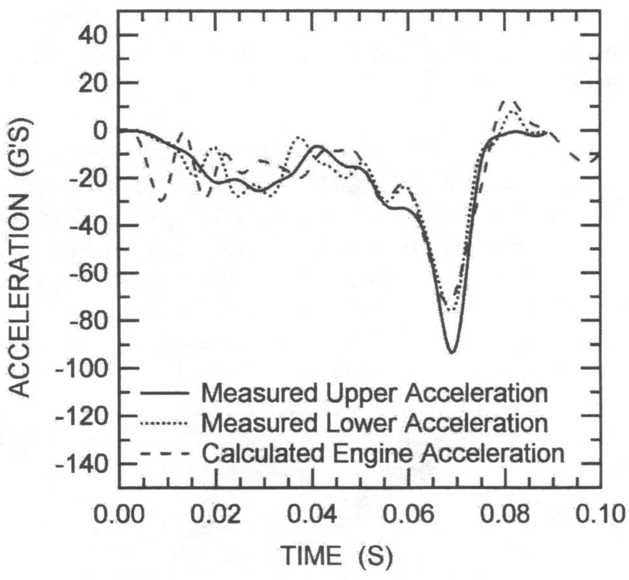


Figure 6. Measured and calculated engine accelerations in the frame impact test.

The calculated and measured accelerations in the frame rail at the intersection of the engine cross member is shown in Figure 7. Again the overall character of the calculated response is similar to the measured response. The calculated peak acceleration is approximately 20% higher than the measured value at a time of approximately 70 ms when the engine is rapidly decelerated. Both the measured and calculated response show a behavior with significant oscillations at approximately 120 Hz.

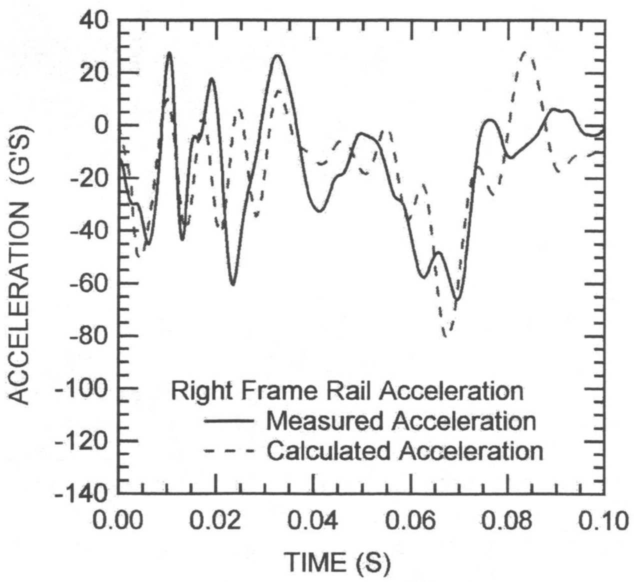


Figure 7. Measured and calculated frame accelerations in the frame impact test.

The configuration for the bumper test is a rigid pole pendulum impact test with the bumper attached to a rigid frame by the bumper isolators. The test conditions were an 2.68 m/s impact of a 356-mm-diameter pole attached to a 1706 kg pendulum mass. The pole impact was centered on the bumper. The loading conditions were chosen to produce significant plastic deformations without exceeding ultimate failure strength of the bumper. Failure of the bumper would make the experimental measurements difficult. The importance of this type of component test is to validate the model behavior for lower velocity frontal impacts. For example, accurate modeling at this level of response would be important for using the vehicle model to simulate impacts with various types of roadside hardware such as breakaway luminaire support poles or guardrails. The bumper behavior could also play a significant role in the collision behavior when impacting the side of a lighter vehicle.

The front bumper on the Crown Victoria is a curved box beam made of extruded aluminum with three approximately rectangular cells stacked vertically. As part of the model development, tensile tests were performed to measure the bumper aluminum material properties and compression tests were performed on the isolator to characterize its force-displacement behavior. The bumper aluminum was found to have a yield stress of 345 MPa and a hardening modulus of 450 MPa. The isolators were found to have a viscous damping behavior with an average resistance force of approximately 10 kN at 1.27 mm/s and 15 kN at 12.7 mm/s.

The bumper impact simulations were performed using the measured material properties and an accurate representation of the isolators and reaction frame. The maximum displacement at the bumper center was approximately 150 mm at a time of approximately 80 ms after impact. In this calculation, the isolator stroke was approximately 50 mm, contributing to the overall bumper displacement. A comparison of the measured and calculated impactor acceleration for the bumper test is shown in Figure 8. The overall agreement between the measured and calculated responses is quite good. A comparison of the final deformed shape of the bumper also shows good agreement between the calculated and measured response.

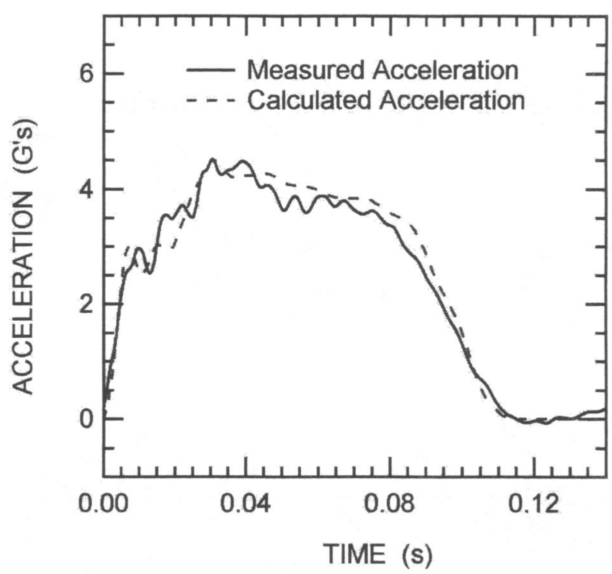


Figure 8. Measured and calculated pendulum accelerations in the bumper impact test.

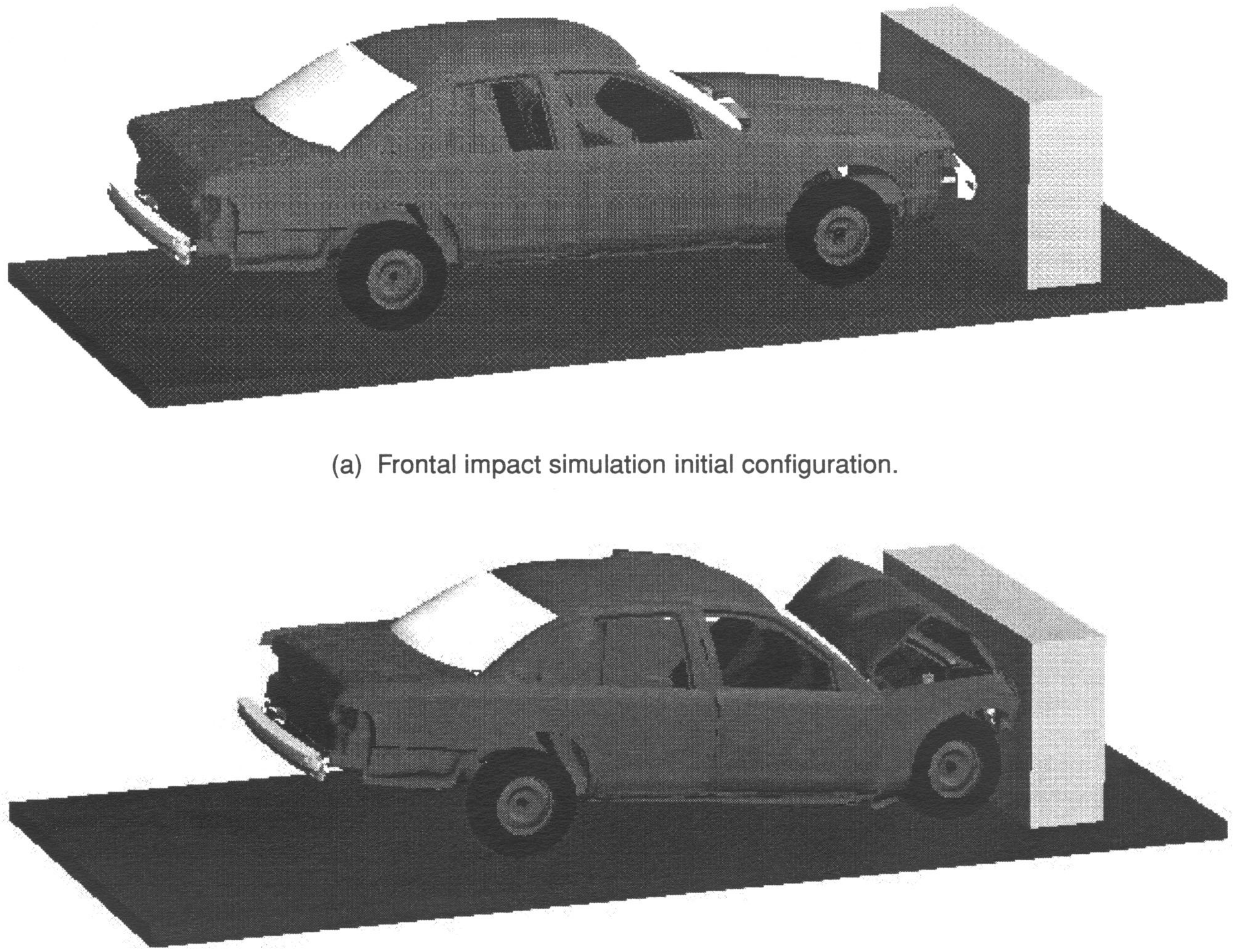
VEHICLE TESTS AND SIMULATIONS

Full vehicle crash test data were available for the Ford Crown Victoria from testing performed under the New Car Assessment Program (NCAP). MGA Research Corporation had previously performed these vehicle crash tests for NHTSA. Both frontal and side impact tests had been performed. A suitable model for the Movable Deformable Barrier (MDB) used in side impact testing was not yet available at the conclusion of this effort. Therefore, the frontal impact test is the only simulation performed with the full vehicle model at this time. This frontal impact condition is a 15.6 m/s (35 mph) impact of the vehicle into a rigid wall.

The current vehicle model has approximately 125,000 nodes with 25,000 brick elements and 88,000 shell elements. The calculated vehicle response in the frontal impact simulation is shown in Figure 9. Many of the characteristics observed in the tests are reproduced in the simulation. The overall collision response produces a pitching motion of the vehicle with a noticeable downward motion forward of the passenger compartment and a lifting of the rear of the vehicle. The hood is folded upward in the middle and the deformations are small in the vehicle behind the firewall.

The calculated and measured wall impact force histories, for the NCAP frontal impact test, are compared in Figure 10. The magnitude and time of the peak forces agree quite well. The maximum impact force occurs at a time of approximately 55 ms and corresponds to the time the engine is directly loaded through the crushed forward vehicle components against the wall. The late time impact force history drops off more rapidly in the simulation than in the experiment. This discrepancy may result from additional mass in the test such as crash dummies and instrumentation that were not included in the simulation.

The calculated and measured engine longitudinal accelerations are compared in Figure 11. The magnitude of the calculated peak acceleration is approximately 30% higher than that in the test with a shorter pulse width. Additional analysis is required to determine the source of these discrepancies. As in the frame component simulation, the calculated engine response has a larger magnitude cyclic response than measures during the first 20 ms. This discrepancy in the early engine accelerations could result from the engine mount modeling coupling the early frame motion too strongly to the engine.



(a) Frontal impact simulation initial configuration.

(b) Calculated vehicle deformations for 35 mph frontal impact.

Figure 9. NCAP frontal impact simulation with the 1997 Ford Crown Victoria model.

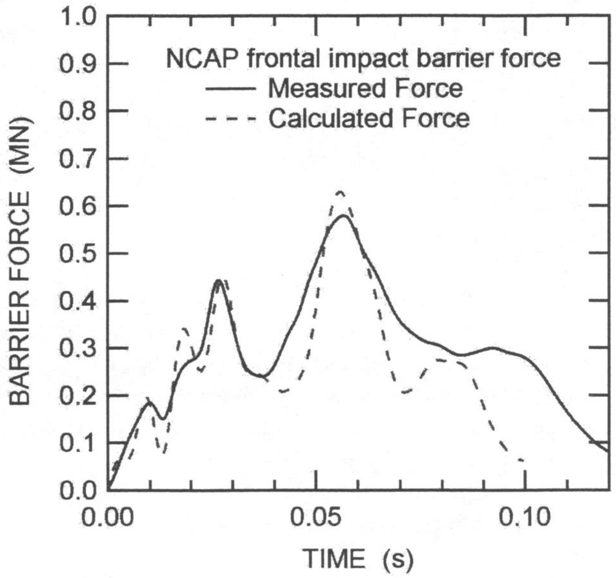


Figure 10. Measured and calculated wall impact force in the NCAP frontal impact test.

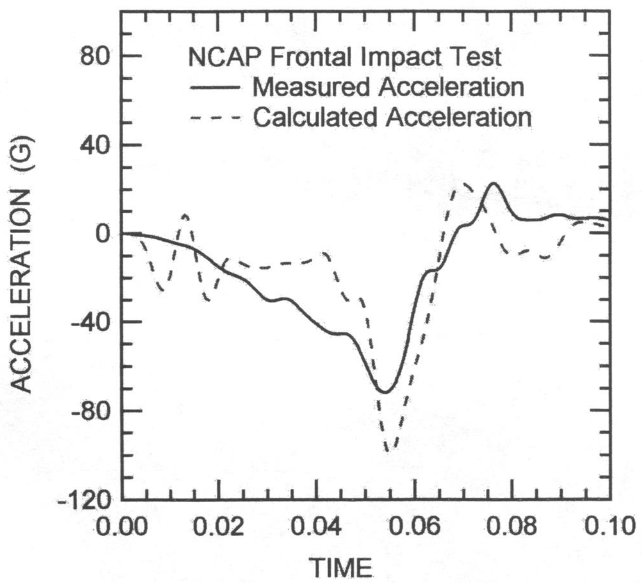


Figure 11. Measured and calculated engine accelerations in the NCAP frontal impact test.

CONCLUSIONS

The overall objective of the program is to develop and validate a computational model for the Ford Crown Victoria to predict the vehicle response to crash loading. The approach used was to tear-down a vehicle, digitize the vehicle with a FaroArm using a structured grid of single point measurements, convert the geometric data to a Viewpoint file format, and generate the model using the TrueGrid mesh generation program. The resulting crash simulations are performed using the LS-DYNA3D finite element code. This approach has been successful for the first phase of development of a detailed vehicle model.

The Crown Victoria model development is currently being completed to make it applicable for full vehicle crash simulations. Some additional multi-layer body structures, such as the cross-sections of the body pillars, need to be further characterized to ensure accurate representation in the model. Some additional material testing is also needed for primary components such as body panels, vehicle frame, and door beams. In addition, the modeling of various connections between components needs to be verified in the model to ensure correct simulation of collision responses.

Validation of this type of detailed vehicle crash simulation model is a difficult task. The overall crash response is made of contributions from the vehicle frame, body components, as well as loads transmitted through components such as the engine, suspension, and drivetrain. To validate the model, the crash responses of the vehicle and components need to be correctly modeled. This includes both the deformation characteristics of the components as well as the time histories of the response. To assist in this process, component crash tests were performed to allow validation of model components prior to validation of full vehicle behavior. We believe these component level tests and simulations are valuable components for the overall vehicle model validation.

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