NHTSA'S CRASHWORTHINESS MODELING ACTIVITIES

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Paper #251

ABSTRACT

NHTSA uses a variety of computer modeling techniques to develop and evaluate test methods and mitigation concepts, and to estimate safety benefits for many of NHTSA's research activities. Computer modeling has been particularly beneficial for estimating safety benefits where often very little data are available. Also modeling allows researchers to augment test data by simulating crashes over a wider range of conditions than would otherwise be feasible. These capabilities are used for a wide range of projects from school bus to frontal, side, and rollover research programs. This paper provides an overview of these activities. NHTSA's most extensive modeling research involves developing finite element and articulated mass models to evaluate a range of vehicles and crash environments. These models are being used to develop a fleet wide systems model for evaluating compatibility issues.

INTRODUCTION

NHTSA utilizes a variety of simulation methods to support its regulatory and research activities. In crashworthiness research, simulations are often used to evaluate the feasibility, effectiveness, and potential limitations of proposed test procedures and safety countermeasures. Within crashworthiness research, the simulations tend to focus less on the performance of an individual vehicle or safety system, and more on the characteristics of a vehicle class or a type of restraint. One of the biggest challenges for crashworthiness research is to develop reasonable estimates of the consequence of regulatory changes on the frequency and distribution of injury within the U.S. fleet crash environment. These estimates must consider the range of vehicle types, crash configurations, restraint types and restraint usage levels among the many significant factors affecting the safety of the U.S. driving population.

One of the first fleet wide evaluation tools for evaluating vehicle crash performance was the Safety Systems Optimization Model (SSOM) developed by Ford Motor Company and later enhanced by the University of Virginia [1,2]. The SSOM was able to make remarkably useful predictions regarding fleet safety using some simple approximating functions for crash pulses from vehicle-to-vehicle crashes. These crash pulses were then combined with a known or predicted distribution of crashes to estimate the overall injury and fatality rates.

NHTSA has initiated a research program to extend the SSOM techniques using more current modeling techniques and updated fleet statistics [3]. This research is intended to produce a large scale systems model to evaluate vehicle crashworthiness based on the safety performance of the vehicle when exposed to the entire traffic crash environment, i.e., across the full spectrum of expected collision partners, collision speeds, occupant heights, occupant ages, and occupant injury tolerance levels. Starting with SSOM as a foundation, the Vehicle Research Optimization Model (VROOM) computer model, as described below, takes full advantage of recent dramatic improvements in vehicle and occupant models, newly developed injury criteria, and a comprehensive projection of the crash environment for the years 2000-2005. Where possible, VROOM also will explore the feasibility of implementing promising algorithms from the Volkswagen ROSI system-wide optimization model [4].

This research project was in the early phases of development when President Clinton, Vice President Gore, and the Chief Executive Officers of Chrysler, Ford, and General Motors announced the formation of a historic, new partnership aimed at strengthening U.S. competitiveness while protecting the environment by developing technologies for a new generation of vehicles. Tabbed the "Partnership for a New Generation of Vehicles" (PNGV) [5], the program's long-term objectives include developing a range of technologies to yield automobiles with a threefold improvement in fuel efficiency and reduced emissions. The implications of the fuel efficiency goal is that a 40 percent reduction of the vehicle mass will be required to meet the fuel economy requirements. If successful, the PNGV program will introduce a new class of vehicles that greatly increase the mass incompatibility of the vehicles in the U.S. fleet. The systems model under development was extended to include the three baseline vehicles for the PNGV program.

In vehicle-to-vehicle crashes the PNGV vehicles, due to their light weight, will encounter a higher change in velocity, and potentially a higher probability of injury. However, vehicles that are struck by a PNGV vehicle will have a much lower probability of injury, due to the low mass of the PNGV vehicle. The systems model is intended to evaluate the overall safety implications for introducing a new PNGV class of vehicles. It should also provide a method to examine safety countermeasures to optimize the safety of the PNGV vehicles and their effect on fleet wide safety.

SIMULATION METHODOLOGY

Toward meeting the aforementioned objectives, detailed finite element models are being developed for the three PNGV baseline vehicles and for vehicles representing the major vehicle categories within the fleet. This activity involves the tear down of the vehicles for scanning and measurement, as shown in Figure 1. This information is used to develop the geometric and inertial data necessary to prescribe a finite element mesh for the vehicles. Crash test data is used wherever possible to provide baseline validation for the finite element (FE) models. Additional material tests were conducted on the disassembled components to establish vehicle characteristics.

Figure 1. Vehicle teardown and measurement.

The vehicle FE models are being used in two ways. First, the models are used to study specific crash configurations, with specific collision partners, and specific impact speeds (see Figure 3). These crash simulations are useful for examining potential test configurations, measurement locations, and for extending the limited crash test data by simulating different crash conditions. However, while FE models are potentially very accurate and geometrically fidelic, FE models are prohibitively expensive to execute for fleet systems models. A typical VROOM run may require over ten thousand simulations, using different vehicle pairs, impact speeds, crash conditions, and occupants. The second application for the FE models will be to generate sophisticated, yet simpler and faster running articulated mass models using MADYMO [6]. These models require less computer time and it is easier to conduct the necessary simulations. Analyzing the load transfer from the finite element models, as shown in Figure 2, provides the data to develop the MADYMO models. The articulated mass models provide occupant injury measures that can be used to estimate probability of injury and predict fleet wide safety performance. Crash configurations that show unusual performance or injury measures can be studied in greater detail using the previously developed finite element models.

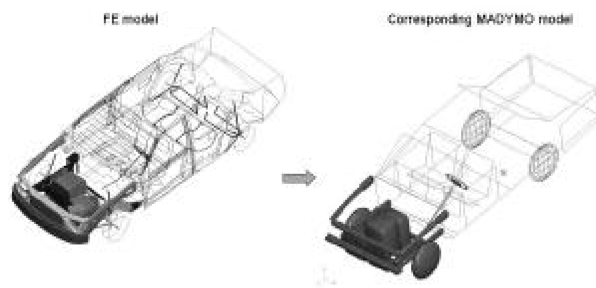

Figure 2. Developing MADYMO models from FEA models.

The approach to crashworthiness optimization may be stated formally as the following non-linear problem:

$$\text{Minimize Inj}(x,u) = p_i\, s_i(x,u) \quad \text{(Equation 1.)}$$

subject to

Wgt (x) Wgtmax

Cost (x, w(x)) Costmax

xmin x xmax

where:

x - Vector of Design Variables

u - Belt Usage Rate

Inj (x,u) - Total Injuries

Wgt(x) - Incremental weight for with design 'x'

Cost - Incremental cost for x and Wgt(x)

Wgtmax - Upper Constraint on incremental weight

Costmax - Upper Constraint on incremental cost

p_i - Probability of Event i

s_i - Injuries resulting from Event i

The objective expressed in Equation (1) is to determine that vector of design variables which minimizes total injuries or some measure of societal cost of total injuries [7]. The simulations will attempt to minimize normalized harm, defined as total harm in dollars normalized by the harm associated with an

AIS 6 injury level. Total harm is computed by summing the harm incurred in each of crash encounters i weighted by p_i, the annual expected probability of event i.

The incremental weight penalty associated with any proposed design modifications w(x) is limited to the upper constraint Wgtmax. Similarly, the incremental cost of the proposed design modifications is limited to an upper constraint of Costmax. The incremental cost in this context includes both the additional cost of design modifications and an estimate of the cost of material substitution to reduce weight. To ensure that design modifications lie within realistic ranges, the design variable vector is constrained by lower and upper limits on each design modification. The annual expected probability of a crash event i, sometimes referred to in the literature as exposure, is computed based on historical real world crash data. For the model, a crash event i is completely characterized by prescribing the crash speed, the impacting vehicle weight, the occupant seating location, the occupant height, the occupant gender, and the occupant restraint type. Additional information and results of system modeling is presented in References 8-11.

PROJECT STATUS

Finite element analysis (FEA) models were developed for vehicles representative of nine categories of vehicles plus the three PNGV baseline vehicles. The vehicles were selected by sales volume, within their category, and by the availability of crash test data from NHTSA's NCAP and regulatory compliance test programs.. The vehicles selected and their categories are shown in Table 1 below.

Table 1.
Vehicles selected for finite element modeling.

Vehicle	Category
1997 Geo Metro	subcompact car
1996 Dodge Neon	compact car
1997 Honda Accord	midsize car
1997 Ford Crown Victoria	full size car
1998 Dodge Caravan	minivan
1998 Chevrolet S10	compact pickup
1994 Chevrolet C1500	full size pickup
1998 Ford Econoline Van	full size van
1997 Ford Explorer	sport utility vehicle
PNGV baseline vehicles	
1995 Chevrolet Lumina	
1994 Dodge Intrepid	
1994 Ford Taurus	

Recently, NHTSA initiated the development of a 2000 Toyota Rav4 finite element model to represent a small sport utility vehicle category. NHTSA has contracted the development of the FE models to several academic, government, and commercial organizations, as shown in Table 2.

Table 2.
Organizations responsible for the FE models.

George Washington University, National Crash Analysis Center	Metro, Neon, Caravan, S10, C1500, Econoline
EASi Engineering Inc.	Lumina, Taurus, Intrepid
Oak Ridge National Laboratories	Explorer
SRI International and Applied Research Associates	Crown Victoria
University of Virginia	Honda Accord

Preliminary finite element models have been completed for each of the vehicles, and all but two of the models, the S10 and Econoline, have been extensively tested. LS-DYNA3D data sets for the models can be downloaded from the www sites in Table 3 or by sending an email request to NRD.OcrSoftDev@nhtsa.dot.gov.

Table 3.
Web address for downloading FE models.

http://www.ncac.gwu.edu
http://mpm22.ms.ornl.gov/newexplorer
http://auto-safety.mech.Virginia.edu
http://www.arasvo.com/crown_victoria/crown_vic.htm

These FE models currently are being used to study the crash interactions between specific vehicle pairs and crash configurations, as shown in Figure 3 below. This particular simulation was used to establish test conditions and sensor locations for the test series discussed in Reference 12. Reference 13 presents a study using the FE models to evaluate alternate crash conditions.

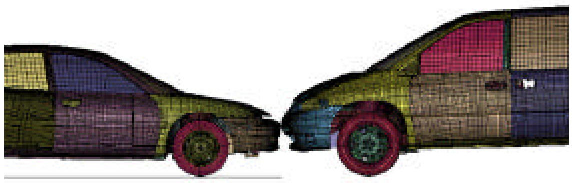

Figure 3. Vehicle-to-vehicle finite element crash simulation.

The FE models are also being used for the development of MADYMO lumped parameters models. To date, MADYMO models have been developed for six of the vehicles shown in Table 4 below. The FE models are sectioned to approximate the force and moments transferred across the sections. This data is used to develop a series of translational and rotational joints to approximate the behavior of the vehicles. The MADYMO models for the PNGV baseline vehicles were developed by EASi Engineering Inc. and the others are being developed by TNO / MADYMO North America.

Table 4.
List of MADYMO vehicle models under development.

1995 Chevrolet Lumina
1994 Dodge Intrepid
1996 Ford Taurus
1997 Geo Metro
1996 Dodge Neon
1997 Honda Accord
1997 Ford Crown Victoria
1997 Ford Explorer

MADYMO models for the remaining vehicles will be developed in future years if the results continue to look promising. At least three separate models have been generated for each vehicle category, one each for full frontal, frontal offset, and side impact crashes. These models are intended to simulate crashes with impact speeds ranging from 16 to 80 kmph between the vehicle pairs. The interface between the MADYMO models and the reliability of the simulation outcomes for all possible configurations is an area of active research. The goal of the MADYMO models is to predict occupant injury measures that can be used for analysis of the fleet wide vehicle performance.

Figure 4. MADYMO vehicle-to-vehicle crash simulation.

The fleet systems model is intended to simulate a subset of the vehicle-to-vehicle and vehicle-to-fixed object crashes representative of the U.S. crash environment. Preliminary systems models have been developed and are discussed in references 8 through 11. The results to date have been encouraging. The systems models have simulated the current crash environment and generated good approximations to the current harm and injury distributions.

VALIDATION

Staff members at the Volpe National Transportation Systems Center independently evaluate each of the FE and MADYMO models. The finite element models are evaluated against the measured vehicle accelerations and intrusion distances. The MADYMO models are evaluated on the basis of the injury measurements and the supporting acceleration data, e.g. head resultant acceleration, chest resultant acceleration etc. The definition of a “validated” computer model is an intentionally vague concept. However, the guidelines in Table 5 are used as a general aid in the comparison of two time history signals.

Table 5.
Criteria for evaluating simulation results.

Standard Deviation between signals	< 10%
Average Error between signals	< 5%
Correlation Coefficient	> 0.95
Percent of simulation result within 4G of test acceleration	> 90%

FUTURE PLANS

NHTSA intends to continue the development and refinement of the fleet systems model. If the systems model continues to perform well and can demonstrate contributions to our safety evaluations, the fleet models will be slowly, but regularly updated to reflect the changing nature of the U.S. fleet.

CONCLUSIONS

This is an overview of a research project in progress. The initial results look promising and the project has already contributed some benefits. However, the overall feasibility and reliability of the systems model has yet to be demonstrated. Based on the earlier successes of the SSOM model, NHTSA is encouraged by the progress of this research program.

REFERENCES

1. Ford Motor Company, Safety Systems Optimization Model, Final Report, U.S. Department of Transportation, Contract No. DOT HS-6-01446, November 1978.

2. White, K.P., Gabler, H.C., Pilkey, W.D., and Hollowell, W.T., "Simulation Optimization of the Crashworthiness of a Passenger Vehicle in Frontal Collisions Using Response Surface Methodology," SAE Paper No. 850512, March 1985

3. Gabler, Hampton C., Hollowell, William T., and Hitchcock, Ralph J., "Systems Optimization of Vehicle Crashworthiness," Fourteenth International Technical Conference on Enhanced Safety of Vehicles, Munich, Germany, May 1994.

4. Zobel, R., "Economically Justified Passenger Protection Results of Simulation," SAE Paper No. 850516, 1985

5. National Research Council, "Partnership for a New Generation of Vehicles Program Plan," United States Department of Commerce, Washington D.C., 1994.

6. MADYMO User's Manual 3D, Version 5.4, TNO Automotive, May 1999.

7. Blincoe, L.J., "The Economic Cost of Motor Vehicle Crashes 1994", Washington D.C., DOT HS 808 425, July 1996

8. Kuchar, A.C. (2000). A Systems Modeling Methodology for Estimation of Harm in the Automotive Accident Environment. Master's Thesis, Department of Mechanical Engineering, Tufts University.

9. Kuchar, A.C., Greif, R., and Neat, G.W. (2001). "A Systems Modeling Methodology For Evaluation of Vehicle Aggressivity In The Automotive Accident Environment", SAE Paper 2001-01-1172.

10. Kuchar, A.C., Greif, R., and Neat, G.W., "A Systems Modeling Methodology for Estimation of Harm in the Automotive Accident Environment", The 2000 ASME Crashworthiness, Occupant Protection and Biomechanics in Transportation Systems, Orlando FL; Nov. 2000; AMD-Vol. 246.

11. Kuchar, A.C. (2001). "A Systems Modeling Methodology For Estimation Of Harm In The Automotive Crash Environment", Proceedings of the 17th International Technical Conference on Enhanced Safety of Vehicles, Paper No. 354

12. Summers, Prasad, Hollowell, "NHTSA's Vehicle Compatibility Research Program", SAE Paper 2001-01B-257

13. Brewer, John, "Effects Of Angles And Offsets In Crash Simulations Of Automobiles With Light Trucks", Proceedings of the 17th International Technical Conference on Enhanced Safety of Vehicles, Paper No. 308