ROADSIDE SAFETY HARDWARE — TIME FOR A NEW PARADIGM?

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INTRODUCTION

TRB has recently published *(1)* a number of papers that were presented at the summer meeting of the Transportation Research Board Roadside Safety Features Committee (A2AO4) in August 1994. One of the presenters *(2)* discussed the evolution of roadside safety features focusing on the major milestones that have occurred in roadside safety in the last 35 years. This presentation should be required reading for all professionals involved in roadside safety issues. It is an example of how a significant safety problem was identified and the efforts of highway safety professionals to correct the problem. Although thousands were ultimately involved in the implementation of the roadside safety features, the bulk of the research and development was done by a relatively small group. Roadside safety features have been significantly improved and those involved in these efforts deserved our thanks.

This article only deals with one particular type of roadside safety feature - roadside safety hardware.

A number of events have occurred since the initial assumptions were made in the 1960s that affect these early decisions about how safety hardware should be designed, tested and evaluated. A short list would include the following:

- The efforts of the National Highway Traffic Safety Administration (NHTSA) to improve vehicle crashworthiness.
- The Corporate Annual Fuel Economy (CAFE) standards *(3)* which have led to a reduction in vehicle size and weight.
- The emergence of light duty pickups and vans as a significant part of the passenger vehicle fleet.
- The rapid increase in the computational power of desktop computers.
- The Program for the Next Generation of Vehicles (PNGV) *(4)* program.

In view of these events and our safety experience with roadside safety hardware over the last 35 years, there is a need to reexamine the philosophy upon which the evaluation of the safety performance of roadside safety hardware is based.

CURRENT ROADSIDE SAFETY PHILOSOPHY

Each decade since the 1960 has produced at least one written procedure for evaluating the *safety performance* of roadside safety hardware. *(5, 6, 7, 8, 9)* These procedures are based upon several assumptions made in the early 1960s: roadside safety hardware was to (1) smoothly redirect the vehicle; (2) breakaway upon vehicle impact or (3) bring the vehicle to a controlled stop. Evaluation of the performance of the hardware would be based on the results of crash tests. Since it would be impossible to test all vehicles under all impacts conditions, "practical" worst case scenarios were developed. Two classes of automobiles were chosen to bracket the range of all light motor vehicles. It was felt that by testing vehicles at the extreme ends of the vehicle fleet, all vehicles would be covered. Impact speed and angles where chosen for crash tests that were also "practical" worst case scenarios. Most of the safety advances since the 1960s have been evolutionary - they built on and refined the original safety feature concepts.

CURRENT PROCEDURE FOR DEVELOPING ROADSIDE SAFETY HARDWARE

This discussion is limited to the current procedure for approving roadside safety hardware discussed in NCHRP Report 350. The document was prepared by contract under the supervision of an NCHRP committee. The committee consisted of representatives from 3 State DOT's, one county representative, one city representative, 2 FHWA employees, one representative from the hardware manufacturers, one international representative, one member from academia and two staff members from TRB. There were no representatives from either the automobile industry or the NHTSA. NCHRP Report 350 is an update of NCHRP Report 230. It is a consensus document based largely upon experience and engineering judgement.

NCHRP 350 establishes three criteria for evaluating the *safety performance* of roadside safety hardware - structural adequacy, occupant risk and post-impact vehicle response. These criteria are summarized below.

1. Structural adequacy
   a. Test article contains and redirects the vehicle.
   b. Test article activates in a predictable manner.
   c. Test article redirects, controls penetration or brings vehicle to a controlled stop.
2. Occupant risk
   a. Debris from test article should not pose a threat to driver or bystanders.
   b. Debris from test article should not block the driver's vision.
   c. Vehicle shall remain upright.
   d. Preferred and maximum occupant impact velocities (m/s) based upon an unrestrained, front seat occupant calculated from vehicle accelerations.
   e. Preferred and maximum occupant ridedown accelerations (Gs) based upon an unrestrained, front seat occupant calculated from vehicle accelerations.
   f. Hybrid III dummy (optional) test for frontal or head-on impacts.
3. Post-impact vehicular response
   a. Vehicle does not intrude into adjacent traffic lanes.
   b. Occupant impact velocity (nte 12 m/s in the longitudinal direction) and occupant ridedown acceleration (nte 20Gs in the longitudinal direction).
   c. Exit angle from test article (nte 60% of impact angle).
   d. Vehicle trajectory behind the test article is acceptable.

The vehicle moves through three phases: pre-impact, impact and post-impact. Currently the evaluation criteria ignores the pre-impact conditions by assuming the vehicle is stable, not skidding and moving straight ahead. The impact phase deals with the interaction between the vehicle and the hardware and the effect of the collision on the occupant. The post-impact phase looks at vehicle trajectory after it leaves the hardware and subjectively assesses the risk of accidents resulting from re-entering the traffic stream. The evaluation criteria deal with the impact and post-impact condition. The final evaluation is somewhat subjective and based largely on the kinetic response of the vehicle rather than on the occupants's chance of inury.

Evaluations of the safety performance of roadside hardware are based upon crash tests. NCHRP Report 350 describes the vehicles to be used in testing, the test conditions, and the instrumentation that will be used in testing the hardware. The testing criteria are hardware specific - longitudinal barriers; terminals and crash cushions; and support structures. A brief outline is shown below.

1. Table 3.1 *Test matrix for longitudinal barriers:* 6 tests levels; two types of barrier sections; 3 impact conditions (3 vehicles, speed, and angle); and 1 impact point.
2. Table 3.2 *Test matrix for terminals and crash cushions:* 3 levels; 2 categories — terminal and redirective crash cushions or non redirective crash cushions; 2 feature types — gating or nongating; 3 impact conditions (3 vehicle types, speed, angle); and 1 or more impact points.
3. Table 3.3 *Test matrix support structures, work zone traffic control devices and breakaway utility poles*: 2 test levels; 3 features; 3 impact conditions (3 vehicles, different speeds, same angle); 1 impact point.

There are a number of problem areas associated with using full scale crash tests to evaluate the performance of roadside safety hardware. These include

1. Crash tests are not completely reproducible. The results may vary because of changes in impact speeds, angles, etc. Even under identical test conditions, different vehicles, within the same platform, may produce different results.
2. A method of assessing the severity of a collision with roadside safety hardware does not exist. Recent efforts *(10)* to do this by using the results of controlled crash tests and data from accident files have been unsuccessful.
3. Impact conditions — Accident studies suggests that many vehicle are yawing, rolling and pitching at the time of impact. In the current testing procedure the vehicle is stable and moving straight ahead.
4. Test vehicles are chosen to bracket the passenger vehicle population. The variety of vehicles on the road make this difficult, if not impossible. The spread in vehicle types is even greater today than in the past.
5. The test procedures do not encourage the use of new vehicles for crash tests. New hardware is being evaluated by crash test that use vehicles that can be 6 years old. By the time the new hardware is installed these vehicles are no longer in the fleet.
6. Changes in vehicle fleet can quickly make the safety hardware obsolete. For example, the Breakaway Cable Terminal (BCT) terminals (about 500,000 have been installed) do not work well with wedge shaped vehicles or with light vehicles and have not passed the NCHRP 350 criteria when tested with the 2000P vehicle.
7. Testing and development of hardware is done in isolation. The automobile and roadside safety hardware are a design system. Current procedures ignore the design system.

8. Testing is done under "practical worst" conditions. There is some evidence that the critical impacts conditions may be vehicle specific. In addition, vehicle in the middle of the bracket (the most popular models) are not tested at all.

Historically there has been some interest in using finite element analysis (FEA) to design and evaluate roadside safety hardware. HVOSM *(11)* was developed in the 1960s and the BARRIER VII *(12)* program in the 1970s. However FEA to date has focused on replication of crash tests in an effort to better understand the crash phenomenon. The use of FEA to analyses specific hardware and identify design changes that will improve the performance has been limited. The use of FEA as a tool for evaluating the safety performance and accepting the hardware for use has not been done. Past FEA models can be divided into two categories *(13):*

- Impact Models — WRECKER, Barrier VII, GUARD, CRUNCH, NARD.
- Handling Models — HVSOM, RD2 and VD2 versions.

These specialized models had several serious limitations — the limited computational power available in the 1970s required many simplifying assumptions. Due to their specialized nature there were few users of these models.

In summary the current procedure for the evaluating of roadside safety hardware is based upon crash tests conducted in accordance with NCHRP 350 and comparing the crash tests results with the evaluation criteria contained in NCHRP 350. NCHRP 350 is based upon a "practical" worst case scenarios. Two vehicles are used to try and bracket the light duty fleet as a whole and the impact conditions chosen are for extreme conditions.

FUTURE PROCEDURES

Although it is difficult to define what future procedure will be used to design roadside safety hardware, it is possible to identify trends that will continue. The new procedures should recognize (1) computer power will continue to increase making analytical methods more feasible and (2) the uncertainty in predicting vehicle characteristics of the future.

The future procedures should build on our existing knowledge and to the extent possible, eliminate past problems. The future procedure for evaluating the safety performance of roadside safety hardware will resemble the current program in many respects. It will be based upon assumptions, it will require some sort of performance standards, it will involve full scale crash tests and finite element analysis. There are many factors that must be discussed and resolved.

The assumptions of the 1960s need to be reexamined. Currently the assumptions are that hardware should either redirect the vehicle, breakaway upon impact or bring the vehicle to a controlled stop. Are these still good assumptions? Are there better assumptions? Recent work *(14)* indicates that guardrail ends are 40% more hazardous than the line-of-run guardrail. It appears, based on this evaluation, that specific attention needs to be focused on terminals. Currently terminals are described in NCHRP 350 as either "Terminals and Redirective Crash Cushions" or "Nonredirective Crash Cushions". Which type of terminal is safer? Should there only be one type?

Line-of-run guardrail is designed to redirect the vehicle. Vehicles are either redirected parallel to the barrier or back into the traffic stream. What hazards does this posed to the vehicle occupants? What hazards does this pose to other users of the highway? Is there anything we can learn from accident data that provides insight into these problems? Should all errant vehicles that impact hardware be brought to a controlled stop?

These are key issues that deal with the performance of the hardware. Equally important is the design system — the vehicle and the hardware. As noted earlier NCHRP 350 specifies crash tests that use an 820C or a 2000P vehicle. These vehicles were chosen because they appear to bracket the existing vehicle fleet. Are these good choices? The risk of occupant injury during impact depends to a large extent upon the crashworthiness of the impacting vehicle. Should the most popular vehicle be used for evaluation and relative ranking developed for all other vehicles?

Observation of recent crash tests films have raised serious questions about the test vehicles themselves. In recent tests using pickup trucks (2000P), it appears that subsequent rollovers are caused by a damaged wheel system. What is being tested - the hardware or the test vehicles? Should crash tests be used to evaluate roadside safety hardware? Should NHTSA have a standard barrier test (similar to NHTSA's deformable barrier test) that vehicles must satisfy? Should we develop a surrogate vehicle/s and use then to test the system?

How do we optimize the vehicle/hardware system. Are there characteristics of the vehicle and characteristics of the hardware that should be optimized to minimize injury severity? Should vehicles and hardware be designed so that the cars are "caught" by the hardware?

All of these questions indicate there is a serious need to rethink the current procedures for designing roadside safety hardware. The development of new procedures must involve all of the parties responsible for vehicle crashworthiness and roadside safety.

It now appears that one of the most promising techniques for evaluating (and designing) roadside safety hardware is finite element analysis (FEA). Today FHWA and NHTSA use non-linear finite element codes, LLNL's DYNA3D and Livermore Software Technologies' LSDYNA, to study crash impacts. The motor vehicle industry also uses (among other methods), these same tools to evaluate motor vehicles impacts. Preliminary findings would indicate that FEA has the potential to both improve the design of roadside safety hardware and evaluate the safety performance. Given the difficulties associated with crash tests, is FEA a better technique? Is it affordable? Does it provide consistent and accurate data? How should the NHTSA's program on crashworthiness be factored into the development of roadside safety hardware?

One of the major problems associated with FEA is the development of FE models of motor vehicles. A limited number of FE vehicle models have recently been developed to replicate small cars. The Saturn and more recently two 820C small cars (Honda and Ford Festiva). A 2000P (pickup) is under development at GW University. These are very complicated models. It has been suggested that FHWA only needs a simple FE model to design hardware while NHTSA needs a detailed model to look at occupant injuries. Should FHWA and NHTSA use the same vehicle models? Can the automobile manufacturers supply FE models for testing? Should testing be done with future prototype models, perhaps from the PNGV program?

Finally, in the development of a new procedure for the evaluation of the safety performance of roadside safety hardware, collaboration must be sought from all of those involved in the motor vehicle/roadside safety hardware design problem. The vehicle manufacturers must develop safer vehicles that can compete in a global economy. NHTSA is involved in research to improve the crashworthiness of the motor vehicle, the Federal Highway Administrator and the States develop standards for highway design and operation. Manufacturers of roadside safety hardware are challenged to develop hardware that provide safe operation for a multitude of vehicle platforms. Any future program should recognized the contributions that each of these groups make and build upon the strengths of each group.

FUTURE EVALUATION PROCEDURE

Assumptions

All roadside safety hardware will be designed to bring the impacting vehicle to a controlled stop. Finite element analysis methods will be used to develop performance standards based upon the potential of occupant injury. FE models will be developed for each vehicle platform. Crash tests will be used primarily to validate vehicle models. Severity indices or rating will be developed for different for roadside safety hardware based on a standard test.

Evaluation Criteria

1. Structural. Performance specifications for a test article that require that the test article contains the vehicle. (Test article cannot redirect or breakaway and must bring the vehicle to a controlled stop.)

2. Occupant risk. Numerical values based on vehicle crashworthiness (predicted probability based on crash tests) and severity indices (criteria based on FEA analysis and real world injury data).

3. Post-impact vehicular response. Vehicle brought to a controlled stop. It will not be allowed to encroach on the roadway and not allowed to roll over.

Evaluation Techniques

1. Analytical techniques (FEA)

a. Structural. There will be a series of "generic" FE models of vehicles representative of existing vehicle platforms as well as future prototypes. There will be FE models of systems of roadside hardware. Libraries of vehicles and hardware will be maintained by FHWA. These models will have evolved to the point, and been validated to the extent that FEA can be used as a predictive tool.

b. Occupant risk. MADYMO is being incorporated into the Lawrence Livermore version of DYNA. It exists already LSDYNA. NHTSA is developing FE models of crash test dummies. Currently FHWA is using the NCHRP 350 flail space calculations.

c. Post-impact vehicular response. Work is underway with LSDYNA to handle vehicle trajectory after impact. The current effort is focused on making the finite elements rigid after the vehicle impacts the hardware. Initial efforts to have LLNL develop a capability to switch between DYNA and NIKE or perhaps from DYNA to a rigid body code such as VANDL has been delayed and may not be pursued.

2. Crash tests (model validation and severity assessment)

a. Validate FE models of vehicle.

(1) Joint test program with NHTSA to evaluate new vehicle performance characteristics with respect to safety ardware.

(2) FHWA/NHTSA will cooperate to define appropriate performance specifications for vehicles.

b. Develop severity assessments for vehicle/hardware impact.

(1) Joint FHWA/NHTSA severity assessment procedures.

(2) Standard test by NHTSA to assess vehicle barrier performance.

CURRENT FHWA RESEARCH ACTIVITIES

The FHWA role has been to continue to support and coordinate the development of FEA as a tool for developing safer roadside safety hardware. The current approach is dictated by limited resources, both staff and fiscal. It is based upon a joint effort with NHTSA to further conserve funds and share technical data. Progress has been slow for several reasons - (1) general lack of technical expertise in using finite element methodologies such as DYNA to model crash impacts, (2) the difficulty in building finite element models of motor vehicles, (3) limited access to computer with the necessary computational power, and (4) some analytical problems that have yet to be resolved.

FEA models - FHWA will continue its efforts to improve the public domain version of DYNA. However, other tools may be necessary. For example, NCHRP 350 has a rollover provision that the public domain version of DYNA cannot address. We must also use the tools that industry uses. Example, if an automobile manufacturer gave us a vehicle model in PATRAN or HYPERMESH we must be able to use it.

FE models of vehicles - This will continue to be a joint project with NHTSA at the NCAC. NHTSA is responsible for crashworthiness and is involved in numerous activities (such as the Program for the Next Generation of Motor Vehicles (PNGV). Hopefully industry will supply some models. Because of the cost of developing FE models only a limited number will be developed. FHWA and NHTSA must jointly use some of the same vehicle models to address common problems, ie. impacts into narrow objects. The vehicle models are now available from FHWA though the INTERNET. I would hope as people use these models, the improvements would be reported to NCAC so the models can be updated. I'm somewhat skeptical about this.

Roadside safety hardware - This effort will be coordinated from the TFHRC. The program will probably evolve as a series of cooperative agreements with colleges and universities and industry. Future cooperative agreements will not be restricted to just colleges. The models developed will be reviewed and made available to the public from FHWA (TFHRC) through the INTERNET. This will broaden the technical base and provide developers of roadside safety hardware a new tool. I hope improvements to the models would be shared with FHWA. Again I am skeptical that this sharing will occur .

The analysis programs, FE models of vehicles and roadside safety hardware FE models will improve as they evolve. The day will come when FE methods will be the dominant tool in developing new roadside safety hardware.

Finally, the window of opportunity is closing. I expect funding for this program to decrease significantly. The TRB has established NCHRP Project Panel G17-13, whose charge is to develop "A Strategic Plan for Roadside Safety." Such a plan would prioritize our research needs on all roadside issues of which FE analysis is only one issue. However, it may be that analytical methods may be the best way to address other roadside issues.

WHO IS INVOLVED IN ROADSIDE SAFETY HARDWARE?

The vehicle industry has to developed motor vehicles that are competitive in a global market. These vehicle have to be saleble and safe. The vehicle have to comply with a number of Federal Motor Vehicle Safety Standards (FMVSS). Based upon current literature and information supplied in trade magazines, a major effort is underway to shorten the time needed to bring a new car from concept into production and to make it safer. The US automobile industry in using a general purpose, non-linear, finite element codes similiar to DYNA3D to do vehicle modeling and analysis. Manufacturers also conduct crash tests to evaluate the performance of motor vehicles. Because of its competitive nature, the design and development of a new vehicle is a closely guarded secret.

NHTSA has the responsibility (National Traffic and Motor Safety Act of 1966) of developing FMVSS. A number of FMVSS have been promulgated by NHTSA. *(15)* In addition NHTSA developed and implemented the New Car Assessment Program (NCAP). The NCAP program provides consumer with information with a relative measure of the safeness of the vehicle. Both the FVMSS and the NCAP program are formally coordinated through the Federal register. NHTSA also publishes the R&D findings as they become available.

The Federal Highway Administration sets standards for highway design. In the case of roadside safety hardware, the FHWA has adopted NCHRP Report 350 and two AASHTO specifications *(16, 17)* as the standards for developing roadside safety hardware. To the best of my knowledge neither the vehicle industry nor NHTSA has been involved although the opportunity for involvement exist through the Federal Register process. The FHWA also certifies roadside safety hardware. This is a voluntary program provide by FHWA's Office of Engineering. This office review the information supplied by the manufacturer and decides if the hardware satisfies the requirement of NCHRP 350. If Engineering finds that the hardware meets all requirements of the standards, a memorandum is issued to the field indicating that it is approved for use on the Federal-aid system. This is a valuable service in that this finding is only done once.

AASHTO is involved because they promulgate specifications that the States follow and conduct research. The standards are developed by appropriate AASHTO committees. These committees are largely made up of State users who volunteer their time, and the standards are generally based on the state-of-the-practice considerations. The standards are reviewed by all States before their adoption and in reality are consensus standards. In 1962, highway administrators of the American Association of State Highway and Transportation Officials initiated a highway research program . This research program is administered by the TRB as the NCHRP. The States provides research problem statements and funds to Transportation Research Board to conduct an objective research program. NCHRP Report 350 was developed by a task committee selected by the Transportation Research Board.

The roadside safety manufacturers, like the automobile industry, operate in a competitive environment. The hardware they development must meet the criteria contained in NCHRP 350. As noted above, hardware that successful meets all test is sent to FHWA for certification.

State and Local governments are responsible for the location, selection, and maintenance of the barriers. Several States also have an active research program developing hardware for use within their State.

CONCLUSIONS

FEA will be the dominant technology in developing future roadside safety hardware. It is the only methodology available that could allow

- Analysis of hardware systems for a wide variety of different vehicles, speeds and impact angles, including non-tracking vehicles. Example - the designer could build an envelop of performance limits and identify critical crash characteristics.
- Allow the designer to solve problems through stress analysis. Example - some current guardrails terminals develop a hinge about 10 -15 meters from the terminal nose. Is there something that could be done at this location to improve the performance of the hardware?
- Develop severity indices and evaluate injury in complex collision scenarios. Example - MADYMO dummy models have been incorporated into DYNA models.
- Allow designer to evaluate vehicle prototypes. We are shooting at a moving target Example - develop FE models based on projections from Delphi studies.
- Develop simpler roadside safety hardware. Example - there are numerous instances where roadside safety hardware has been installed wrong.
- Evaluate different types of materials for use in roadside structures. Example - FHWA is developing a traffic barrier system using composites.

REFERENCES

1. *Roadside Safety Issues*, Transportation Research Circular 435, Transportation Research Board/National Research Council, Washington, DC, January 1995.
2. Ross, Jr., H.E., *Evolution of Roadside Safety Features*, Transportation Research Circular No. 435, Transportation Research Board/National Research Council, Washington, DC, January 1995.
3. *Automotive Fuel Economy Program, Nineteenth Annual Report to the Congress Calendar Year 1994*, DOT HS 808 254, National Highway Traffic Safety Administration, Washington, DC.

4. *Review of the Research Program of the Partnership for a New Generation of Vehicles*, National Research Council, National Academy Press, Washington, DC 1994.
5. "Proposed Full-Scale Testing Procedures for Guardrails, Highway Research Board, Circular 482, September 1962.
6. Bronstad, M.E. and Michie, J.D., *Recommended Procedures for Vehicle Crash Testing Highway Appurtenances*," NCHRP Report 153, 1974.
7. "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances," Transportation Research Circular 191, Transportation Research Board, 1978.
8. Michie, J.D., "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances," NCHRP Report 230, 1981.
9. Ross Jr., H.E., Sicking, D. L., Zimmer, R.A., and Michie, J.D., "Recommended Procedures for the Safety Performance Evaluation of Highway Features," NCHRP Report 350, 1993.
10. Council, F.M. and Stewart, J.R., *Attempt to Define Relationship between Forces to Crash-Test Vehicles and Occupant Injuries in Similar Real World Crashes*, Transportation Research Record 1419, TRB, pp. 78-85, Washington, DC 1993.
11. McHenry, R.R. and Delays, N.J., "Automobile Dynamics - A Computer Simulation of Three-Dimensional Motions for Use in Studies of Braking Systems and the Driving Task," Calspan Report No. VJ-2251-V-7, August 1970.
12. Powell, G.H., "General Computer Program for Analysis of Automobile Barriers," Highway Research Board, Record No. 343, 1971.
13. McCulough, M., "An Upgrade Plan for FHWA Roadway Safety Simulation Models", FHWA-RD-93-189, FHWA, Washington, DC, December 1994.
14. Viner, J.G., "The Roadside Safety Problem", Transportation Research Circular Number 435, TRB/NRC, Washington, DC, January 1995.
15. Hollowell, W.T. and Hackney, J.R., *Evolution of Vehicle Crashworthiness as Influenced by the National Highway Traffic Safety Administration*, TRB Circular 435, Transportation Research Board/National Research Council, Washington, DC, January 1995.
16. "Standard Specifications for Structural Supports for Highway Signs, Luminaries, and Traffic Signals", AASHTO, Washington, DC 1985.
17. "Guide Specifications for Bridge Railings", AASHTO, Washington, DC, 1989.