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TABLE OF CONTENTS

PART 1 INTRODUCTION

This *Transportation Research Circular* documents the activities of a workshop held at the National Academy of Sciences's J. Erik Jonsson Center in Woods Hole, Massachusetts on August 11-13, 1994. The workshop, sponsored by the Transportation Research Board Roadside Safety Features Committee (A2A04) and the National Cooperative Highway Research Program, was organized to bring together transportation professionals to discuss the current status of roadside safety research and explore new approaches and methods that could produce safety benefits in the coming decade.

Many tasks are underway with the FHWA, TRB, the states, and others to address issues related to roadside safety. These include efforts to analyze accident trends, formulate improved analysis procedures, develop better hardware, and promote a firmer understanding of the applicability of specific roadside improvements. A fundamental need exists to coordinate these activities on the basis of a common vision of the most critical needs and expected products. It is therefore imperative that the current state-of-the-art be reviewed, gaps or weaknesses in current knowledge be identified, current trends be assessed, research opportunities be explored, products be conceptualized, and consensus be reached on an agenda to improve the processes related to addressing roadside safety problems at federal, state, and local levels. In addition, the influences of the extent and design of the existing infrastructure, agency resources, new national policies, changing vehicle designs, the emergence of innovative materials and technologies, and other factors, must be considered in evaluating the research needs in roadside safety.

This workshop laid the groundwork for the development of a strategic plan for roadside safety research by assembling prominent professionals to identify research needs, define the critical factors and their range of values, assess the advantages and disadvantages of alternative means to resolve persistent safety problems, and producing a document which can promote debate over the issues leading to the adoption of a strategic plan in the future.

Featured at the workshop were six invited papers/presentations on:

- Evolution of Roadside Safety;
- The Roadside Safety Problem;
- The Evolution of Vehicle Safety and Crashworthiness;
- Evolution of Vehicle Crashworthiness as Influenced by the National Highway Traffic Safety Administration;
- Methods for Analyzing the Cost-Effectiveness of Roadside Features; and
- Applications of Simulation in Design and Analysis of Roadside Safety Features;

Following these presentations, the workshop participants were divided into four breakout groups. These groups addressed the following issues:

- Data and analysis needs;
- Selection and design of roadside safety treatments;
- Efficacy of simulation methods; and
- Assessing and developing roadside hardware;

This Digest contains the six invited papers, summaries of the findings of each discussion group, and selected comments by workshop participants. The Roadside Safety Features Committee (A2A04) plans to hold a follow up meeting during the summer of 1995 to formulate a common vision of the roadside safety research agenda for the coming decade.

John F. Carney III
Vanderbilt University and
Chair, TRB Committee on Roadside Safety Features (A2A04)
Kenneth S. Opiela
Transportation Research Board
January 1995

PART 2 PRESENTATIONS

EVOLUTION OF ROADSIDE SAFETY

Hayes E. Ross, Jr.
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Motor vehicle fatality rates have been on a general decline over the past twenty five years. In 1965, rates of 25 deaths per one hundred thousand population and 5 per one hundred million vehicle miles traveled were occurring; 1992 rates were 15.4 deaths per one hundred thousand population and 1.8 per one hundred million vehicle miles traveled. While the trends are noteworthy and very encouraging, approximately 40,000 people are still being killed annually in motor vehicle accidents. Of this total, approximately 30% result from single-vehicle, run-off-the-road accidents.

Unquestionably, improvements in roadside safety design have contributed significantly to these rate decreases, especially during the past 30 years. Safety advancements have resulted from the development of cost effective and crashworthy hardware, improved geometric features, use of safe recovery areas, improved guidelines for the design, selection, and maintenance of safety features, and general acceptance of the "forgiving roadside" philosophy.

This paper presents an overview of progress made during the past 30 years or so and identifies problems and key areas that need to be addressed in the near future. Selected references and accomplishments thought to be fundamental to the advancement of roadside safety are identified. However, the paper is by no means exhaustive and in all likelihood some major omissions have inadvertently been made.

MILESTONES

The vast majority of improvements in roadside safety have occurred since 1960. Prior thereto little attention was given to safety of the roadside; run-off-the-road accidents were attributed to "the nut behind the wheel." This philosophy resulted in unyielding sign and luminaire supports, untreated guardrail ends, non-traversable ditches, untreated culvert ends, etc.

An effort is made in this section to briefly describe selected publications, documents, activities, events, etc. since 1960 that have contributed significantly to roadside safety.

1960's

The decade in which serious concerns about roadside safety emerged.

- *"Roadside Design for Safety,"*(1) This paper identified common roadside hazards such as blunt guardrail ends, rigid supports for light poles and signs supports, trees, utility poles, steep side slopes, and unsafe ditch sections. Potential solutions to these problems were presented which were subsequently developed and implemented by the states, such as sloping and burying the end of the guardrail, use of breakaway supports, clearing the roadside of unnecessary obstacles, and flattening and rounding slopes and ditches.
- *"Proposed Full-Scale Testing Procedures for Guardrails,"*(2) This was the first formalized set of guidelines for testing guardrails, and was contained on one page.
- *"Highway Guardrail: Determination of Need and Geometric Requirements, with Particular Reference to Beam-Type Guardrail,"*(3) This study provided guidelines establishing where guardrail was needed and how it should be installed dimensionally and geometrically. There were no comprehensive guidelines prior to its publication.
- *Development of the slip-base breakaway system* - Through support from the Texas Highway Department, the Bureau of Public Roads, and other states, Texas Transportation Institute (TTI) researchers developed workable slip-base breakaway systems for sign and luminaire supports. Major safety benefits have been derived from extensive use of these designs.
- *National Traffic and Motor Vehicle Act of 1966* - This act required the establishment of minimum safety performance standards for motor vehicles and motor vehicle equipment.
- *Highway Safety Act of 1966* - This act intended to strengthen state and local safety programs, and for the first time placed the federal government in a leadership role to help guide and finance state programs.
- *"Highway Design and Operational Practices Related to Highway Safety,"*(4) This was the first of the two so-called "Yellow Books" that addressed highway safety issues. It pointed out the increasing number of "run-off-the-road" accidents and identified ways to mitigate roadside hazards. It established the 30 ft. clear recovery area, currently denoted the clear zone.
- *Development of initial crash cushion designs* - The 1960's saw the development of the steel drum crash cushion at TTI, the water-filled plastic tubes at Bringham Young University, and the sand-filled plastic drums by John Fitch of Connecticut. Major safety benefits have been derived from extensive use of these and other cushion designs subsequently developed.
- *"Guardrails, Barriers and Sign Supports,"*(5) Included in this record were fundamental papers dealing with tests and further development of the W-beam barrier(J. L. Beaton, et al), development of new highway barriers

(M. D. Graham, et al), and development of guardrail warrants (J. C. Glennon et al). The study by Beaton, et. al., established basic height and post spacing requirements for W-beam guardrail still in use today. The paper by Glennon, et. al., developed warrants for guardrail to shield embankments still in use today. The paper by Graham, et. al., presented results of an extensive theoretical and experimental study in which new barrier designs were developed, including the strong-beam, weak-post guardrail, median barrier, and bridge rail systems; improvements were also made in the cable guide rail system.

- *"Location, Selection and Maintenance of Highway Guardrails and Median Barriers,"*(6) This report provided recommended standards for nationwide consistency of practice by highway design engineers as related to warrants, design, and maintenance.
- *Development of median barriers* - Adoption of the New Jersey and General Motors concrete safety-shaped barriers (CSSB) by a number of states began in the 1960's. By the end of the decade, most of the states had installed CSSB's to some extent, and their use was on the increase. Eventually the New Jersey shaped proved to be the preferred design, and it is now the most widely used median barrier in the U.S. Precast segments of the New Jersey CSSB are also widely used to shield workers and hazardous areas from traffic. Other median barriers developed and/or refined during this decade included the widely used back-to-back W-Beam design, the box-beam design, and the cable design.
- *Development of the Highway-Vehicle-Object-Simulation-Model (HVOSM)* - HVOSM, which was originally known as the Cornell Aeronautical Laboratory Single Vehicle Accident model(CALSVA) was developed during the 60's by Ray McHenry and other researchers at CAL (later to become Calspan Corporation)(7). It was used initially in the development of longitudinal barriers for the New York Department of Transportation. TTI researchers have made wide use of HVOSM in numerous studies involving vehicle-roadway and vehicle-barrier interactions. It has also been used by researchers at Southwest Research Institute and the University of Nebraska. When used properly and within its limits HVOSM provides valuable insight into these types of events, and has been used in the design and analysis of various safety features.

1970's

The decade in which the Federal government and FHWA emerged as a leading force in promoting and supporting highway and roadside safety.

- *Highway Safety Act of 1970* - This act established the National Highway Traffic Safety Administration (NHTSA) and separated the functions of the National Highway Safety Board between NHTSA and FHWA.
- *U.S. congressional hearings* - Comprehensive hearings were held early in the 1970's on highway safety issues. It was concluded that substantial improvements could be made if the Federal Highway Administration took a more active role in highway safety. These hearings led to the advancements made in the Highway Safety Act of 1973.
- *"Location, Selection, and Maintenance of Highway Traffic Barriers,"*(8) This report updated and superseded NCHRP Report 54. It presented a synthesis of existing information on warrants, service requirements, and performance criteria for all traffic barrier systems, including longitudinal barriers and crash cushions.
- *"Evaluation of New Guardrail Terminal,"*(9) This paper described development of the breakaway cable terminal (BCT) for W-beam guardrail. The BCT design, with subsequent modifications, became the most widely used end treatment for W-beam guardrail in the U.S. Other end treatment designs developed since, such as the eccentric loader terminal, the modified eccentric loader terminal, and the ET-2000® have utilized the breakaway cable feature of the BCT.
- *Highway Safety Act of 1973* - For the first time, this act required that a portion of the Highway Trust Fund be used for highway safety improvement programs (Highway Safety Act of 1966 provided no funding and was therefore ineffective). This act also created various funded safety improvement programs including rail-highway crossings, pavement markings, corrections to hazardous locations, removal of roadside hazards, and improvements on non-Federal aid highways.
- *"Highway Design and Operational Practices Related to Highway Safety,"*(10) This was a second edition of the "yellow book" report originally issued in 1967. This new edition represented both new knowledge and new priorities for highway safety efforts by highway and traffic departments. It incorporated results of research and field experience in the areas of design and operations.
- *"Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances,"*(11) This report updated the one-page guidelines provided in HRB Circular 482 and provided recommendations relative to the testing and evaluation of longitudinal barriers, crash cushions, and breakaway features.
- *"Guide for Selecting, Locating, and Designing Traffic Barriers,"*(12) This was the first publication by AASHTO that comprehensively addressed the subject of traffic barriers. Its purpose was to summarize the current state of knowledge and to present specific design guidelines that established conditions which warrant barrier protection, the type of barriers available, their strength, safety, and maintenance characteristics, selection procedures, and how the barrier should be installed dimensionally or geometrically. Also presented were a cost effectiveness analysis procedure and barrier design methodologies.
- *Further development of new crash cushion designs* - The 1970's saw the development and implementation of

several new and innovative crash cushion systems. Some of these systems employed sacrificial, energy-absorbing cartridges made of lightweight concrete, foam, and honeycomb type materials. Others made use of reinforced, large-diameter steel pipe. Specific designs included the Guardrail Energy Absorbing Terminal (GREAT®), the HEX-FOAM® Sandwich System, and the Connecticut Impact Attenuating System (CIAS).

- *Development of truck mounted attenuators (TMA)* - Initial efforts to develop a TMA were made at TTI and the design consisted of an array of steel drums mounted on a wheeled trailer. Subsequent efforts involved the use of reinforced steel pipe, vermiculite concrete cells, HEX-FOAM®, and aluminum honeycomb.
- *Development of bridge rails for heavy vehicles* - Multi-fatality accidents involving a school bus in Martinez, California in 1976 and an anhydrous ammonia truck in Houston, Texas in 1977 brought national attention to bridge rail designs. Subsequently, major efforts have been made to (a) develop railing designs capable of containing heavy vehicles, (b) develop impact performance guidelines for railings to contain heavy vehicles, and (c) develop warrants for railings that have heavy vehicle containment capabilities. However, to date, wide use of high containment railings has not occurred.
- *"General Computer Program for Analysis of Automobile Barriers,"*(13) This paper describes the BARRIER VII program. Wide use has been made, and continues to be made, of BARRIER VII in the design and analysis of numerous longitudinal barrier systems. It has proven to be a valuable tool when used properly and within its limits.

1980's

The decade which focused on development of safer features for mailboxes, drainage structures, guardrail ends, and utility poles.

- *"The Rural Mailbox: A Little-Known Roadside Hazard,"*(14) This paper focused national attention on the problem of hazardous mailbox installations and presented safe designs. Subsequent research sponsored by FHWA, the Texas Department of Transportation, Minnesota Department of Transportation, and others has resulted in vastly improved mailbox installations across the country.
- *"Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances,"*(15) This report updated and superseded NCHRP Report 153(11) and TRB Circular 191(16). It incorporated new procedures, updated the evaluation criteria (introduced the "flail-space" model), and brought the procedures up to date with available technology and practices.
- *"Safety Treatment of Roadside Drainage Structures,"*(17) This report described results of a study in which safety treatments for transverse and parallel drainage structures were developed. Results of this study have been applied across the U.S.
- *"Timber Pole Safety by Design,"*(18) This paper described a slip-base breakaway system for timber utility poles. Designs of this type are now being implemented on a select basis in various states.
- *"Roadside Design Guide,"*(19) This guide updated and superseded the 1977 AASHTO Guide for Selecting, Locating, and Designing Traffic Barriers. New items addressed included "Roadside Safety and Economics," "Roadside Topography and Drainage Structures," "Sign and Luminaire Supports and Similar Roadside Features," and "Safety Appurtenances for Work Zones."
- *Development of new end treatments* - A number of new and innovative end treatments for roadside and median barriers were developed in the 80's, most of which are proprietary designs. These included the Safety End Treatment (SENTRE®), modifications to the turned down W-beam guardrail, the Transition End Treatment (TREND®), the Vehicle Attenuating Terminal (VAT), now referred to as the Crash-Cushion/Attenuating Terminal (CAT®), and the guardrail extruder terminal (GET), now referred to as the ET-2000®.
- *"Guide Specifications for Bridge Railings,"*(20) This document, which may be used in lieu of the AASHTO "Standard Specifications for Highway Bridges," required full-scale crash testing of all railings used on new construction. It also provided guidelines identifying roadway conditions for which railings of differing performance levels have application.

1990's

The decade of changing design vehicles, major advancements in computer simulation of vehicle/roadway/occupant interaction in crashes, and international cooperation and harmonization.

- *Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA)* - Among other things, this act "...requires that the Secretary of Transportation shall ... issue a final rule regarding the implementation of revised guidelines and standards for acceptable roadside barriers and other appurtenances, including longitudinal barriers, end terminals, and crash cushions. Such revised standards shall accommodate vans, mini-vans, pickup trucks, and 4-wheel drive vehicles and shall be applicable to the refurbishment and replacement of existing roadside barriers and safety appurtenances as well as to the installation of new roadside barriers and safety appurtenances..." (Section 1073, Public Law, 12/18/91). In response to this section of the act, FHWA has officially adopted NCHRP Report 350 for the testing and evaluation of safety features to be used on highways receiving federal aid. In consideration of the act, a 3/4-ton pickup was selected as one of the test vehicles in Report 350 for evaluating safety features. Also, NCHRP Study 22-11 is now underway at TTI for the "Evaluation of Roadside Features to Accommodate Vans, Mini-Vans, Pick-Up Trucks and 4-Wheel Drive Vehicles."

- *"Single-Slope Concrete Median Barrier,"*(21) This paper describes the development of a new type of concrete median barrier, incorporating a single sloped face. The barrier is thought to have improved impact performance, especially for small vehicles, in comparison to the New Jersey shape. Also, another advantage is that it will not be necessary to reset the barrier each time the adjoining pavement is overlaid. Use of the barrier is increasing across the U.S.
- *"Recommended Procedures for the Safety Performance Evaluation of Highway Features,"*(22) This report updated and superseded NCHRP Report 230. Key changes included guidelines for evaluating a wider range of features, adoption of the pickup truck to represent the upper end of the passenger vehicle spectrum, provisions for testing to a wider range of levels from which different service level systems can be developed, provisions for optional test methods for side impact testing, and adoption in total of the SI units of measure.

FORGIVING ROADSIDE CONCEPT

While the person who coined the term "forgiving roadside" is unknown, the concept or philosophy is thought to have originated in the 60's. K. A. Stonex, Paul Skeels, and others at the General Motors Proving must be given considerable credit for recognizing the need for such a concept, and for conveying that need to highway engineers across the U.S. There were many other roadside safety pioneers of that era who also fostered the concept, some of which were: John Beaton, Eric Nordlin, and others at the California Department of Transportation, Malcolm Graham, William Burnett, and others at the New York Department of Transportation, T. J. Hirsch, Thomas Edwards, and others at the Texas Transportation Institute, Jarvis Michie, Maurice Bronstad and others at the Southwest Research Institute, Leon Hawkins, Paul Tutt, and others at the Texas Highway Department, and Flory Tamanini, John Eicher, W. J. (Red) Lindsay, and others at the Bureau of Public Roads.

Basically, a forgiving roadside is one free of obstacles that could cause serious injuries to occupants of an errant vehicle. To the extent possible, a relatively flat, unobstructed roadside recovery area is desirable, and when these conditions cannot be provided, hazardous features in the recovery area should be made breakaway or shielded with an appropriate barrier. The key question highway engineers have grappled with for years is the lateral extent to which the recovery area or "clear zone" should extend.

A clear zone width of 30 ft. was first recommended in the 1967 AASHO Yellow Book(4). This was based primarily on studies of the lateral extent of movement of vehicles inadvertently leaving the General Motors Proving Ground test track. The 30 ft. zone became the unofficial standard, and highway agencies attempted to meet this width, especially for high-speed facilities, regardless of operating conditions, roadside conditions, or roadway alignment. Publication of the 1977 AASHTO "Guide for Selecting, Locating, and Designing Traffic Barriers"(12) brought major changes in recommended clear zone widths. Factors such as side slope, operating speed, traffic volume, and horizontal curvature of the road influenced the clear zone width. Depending on these factors the width could be greater or less than 30 ft. Current clear zone criteria, as given in the 1989 AASHTO "Roadside Design Guide," are based on information in the 1977 Barrier Guide(19).

Clear zone criteria have been based on limited empirical data and the collective judgement of researchers and highway engineers. Little is known as to the relation between clear zones and benefits derived therefrom. AASHTO will seek to address these shortcomings through NCHRP Project 17-11 entitled "Recovery-Area Distance Relationships for Highway Roadsides." As stated in the 17-11 project statement, "Updated guidelines are needed to aid designers in determining safe and cost-effective recovery areas, while recognizing the constraints associated with building or improving the highway system." A primary element which has not been given adequate attention in selecting clear zone criteria is the cost-effectiveness factor. What are we buying in terms of benefits (reduction in number and severity of accidents) for increased recovery areas, when considering factors such as service level of facility, traffic operating conditions, roadway alignment, roadside conditions, cost of right-of-way, and hazards beyond the recovery area?

DESIGN

Design of a roadside safety feature is typically fraught with difficulties and pitfalls, and often involves a long arduous process. This should be expected when one realizes that most safety features are highly non-linear structural systems, usually supported by highly non-linear soils, being struck by speeding, highly non-linear vehicles. Both material and geometrical non-linearities usually exist. Furthermore, the design desirably should be aesthetically pleasing, meet environmental requisites, have a long design life, require minimal maintenance, and not cost too much. Despite the many obstacles, numerous advancements have been made in roadside safety design over the past 30 years.

Figure 1, taken from NCHRP Report 350, illustrates the design process required from initiation to completion of a safety feature. A summary of the methodologies used in the design process and key hardware developed follows.

Methodologies

Early designs were generally conceptualized through application of basic principles of mechanics coupled with retrospective data, and the experience and judgement of the designer. Then the design was hopefully finalized through an iterative crash testing program. In fact, this methodology is still widely used.

Up to the 1980's, bridge railings were designed to support a set of static loads, and it was not necessary to evaluate designs via crash testing. Following several multi-fatality accidents in which vehicles breached bridge railings, national pressure resulted in the adoption of impact performance specifications for bridge railings.

Although computer simulation programs have provided insight and served as design tools in recent years, they often lack the sophistication needed to accurately predict behavior and failure modes observed in crash tests. As a consequence, crash testing, with all its limitations, remains the ultimate proof of a features' acceptability.

Appendix D of NCHRP Report 350 summarizes useful techniques, methodologies, and sources of information for designing a safety appurtenance. It also summarizes computer simulation models that can be used in design of selected features. Table 1, taken from Appendix D of NCHRP Report 350, summarizes available techniques, area of their application, and their limitations.

Hardware

As illustrated in the "MILESTONES" section of this paper, major accomplishments have been made in roadside safety design over the past 30 years. Much of this can be attributed to new and improved "roadside furniture," including traffic barriers, breakaway/yielding supports, drainage structures, and traffic control devices used in work zones. A summary of principal contributions in hardware development during the past 30 years follows Items are not necessarily listed in any chronological or prioritized order.

Longitudinal Barriers - Roadside and Median Barriers and Bridge Railings

- Strong-post (wood or steel), W-beam, 6 ft-3 in. post spacing, 27 in. high rail for roadside applications - This is the most widely used roadside barrier and it replaced a similar system with 12 ft.-6 in. post spacing with a 24 in high rail. A 30 in. high version of the same barrier with back-to-back W-beams, and a rub rail has been used for median barriers.
- Concrete safety shaped barrier (CSSB) (often called the New Jersey barrier) - The CSSB is now the most widely used median barrier in the country, and is widely used as a bridge railing. Precast, segmental CSSB's are also widely used in work zones.
- Single slope concrete barrier (SSCB) - The SSCB was recently developed but it is gaining in popularity and use as a median barrier. Impact performance is as good or better than the CSSB and it has operational advantages over the CSSB.
- Thrie beam roadside and median barriers - Thrie beam barriers are widely used by some states, both on the roadside and in the median. Depending on their performance in comparison to W-beam barriers for Report 350 criteria, and for light trucks in general, thrie beam barriers may be in greater demand in the near future.
- Bridge railings in general - Since adoption of impact performance specifications for bridge railings by AASHTO, considerable efforts have been made to ascertain the adequacy of existing railings and to develop new railings to meet the AASHTO multi-performance level specifications. This process has eliminated some substandard systems and has resulted in a set of good performers. It has also resulted in railings capable of containing moderate size trucks. Many feel however that there are still too many designs and that only a few, standard, good performing designs are needed.

Longitudinal Barriers - End Treatments

- Turned down guardrail - Following recommendations of engineers at the General Motors Proving Grounds, highway engineers developed the turned down W-beam end treatment for guardrail to reduce the severe hazard of the blunt guardrail. Although later designs proved to be superior, the turned down treatment advanced roadside safety.
- Breakaway cable terminal (BCT) - The BCT was developed as an alternative to the turned down treatment, and its use grew dramatically during the 70's and 80's. Its performance has generally been good when

installed properly. However, its performance with small vehicles has been a problem, and for this reason other designs have been developed, including the "eccentric loader terminal" (ELT), and more recently the modified eccentric loader terminal (MELT).

- Proprietary systems - Several new and innovative proprietary end treatments have been developed and implemented, including the Safety End Treatment (SENTRE®), the Transition End Treatment (TREND®), the Vehicle Attenuating Terminal (VAT), now referred to as the Crash-Cushion/Attenuating Terminal (CAT®), and the guardrail extruder terminal (GET), now referred to as the ET-2000®.

Crash Cushions

- Steel drum crash cushion - The steel drum crash cushion is believed to be the first operational cushion. It has performed well and is still in wide use in Texas. Its use in other states has diminished, due primarily to maintenance difficulties.
- Proprietary systems - Several innovative proprietary crash cushions have been developed and implemented over the past 30 years, including the Fitch sand filled plastic barrels, the water filled tubes, Guardrail Energy Absorbing Terminal (GREAT®), the HEX-FOAM® Sandwich System, and the Connecticut Impact Attenuating System (CIAS).

Breakaway Supports

- The breakaway feature was a key factor in making the forgiving roadside concept a reality. It has been widely used on sign and luminaire supports, barrier end treatments, and utility poles.

Drainage Structures

- Safety treatment of transverse and parallel drainage structures - Improvements in the safety of blunt culvert ends and large culvert openings have been successfully treated with sloped ends and safety grates, without significantly compromising the hydraulic efficiency of the culverts. These designs are now widely used across the country.

Traffic Control Devices

- Construction of new highways has rapidly declined, whereas reconstruction and rehabilitation of existing facilities has dramatically increased. Safety of motorists and workers in work zones has become a leading concern. Consequently, development of safe traffic control devices has evolved, especially during the past 15 years. Traffic safe signs and channelizing devices, including barricades, cones and tubular markers, drums, and vertical panels have been developed and are now being widely used. Research is continuing in this area.

Truck Mounted Attenuators (TMA)

- With expanding maintenance and work zone activities, development and use of TMA's have increased. Several commercially available systems are in use, including the HEXFOAM TMA, the HEXCEL TMA, and the Connecticut Impact Attenuation System TMA.

Geometric Features

- Embankments, ditches, driveways, and crossovers - Research using computer simulation models, coupled with limited crash testing has led to recommended guidelines for these features.
- Curbs - Curbs along the edges of high-speed roadways have been in disfavor for a number of years. Analysis and field experience have show that a curb can be detrimental to safety since it may trip and overturn an errant vehicle, or it can cause the vehicle to become airborne, adding to vehicular instability and to the possibility of adverse behavior of a barrier or breakaway support behind the curb.

Other Features

- Mailbox supports - Noteworthy advancements in the safety of mailbox supports have been made in the past 15 years. Traffic safe supports are now available and being used for single and multiple mailbox installations.

- Emergency call box supports - Traffic safe supports for emergency call boxes are now widely used.

EVALUATION

Evaluation procedures for safety features have evolved over the past 30 years. However, full scale vehicular crash testing has been, and continues to be, the primary methodology by which impact performance of a safety feature is assessed. Bogie vehicles and pendulums have also been used to evaluate breakaway supports. Once proven acceptable via crash testing the feature is treated as an experimental device and is usually installed in the field on a limited basis, and its performance monitored for a period of time. If it performs as intended in the field, it normally will be treated as an operational system, and is ready for widespread use. However, some degree of ongoing monitoring is desirable. This process is illustrated in Figure 1.

Initial test guidelines applied only to longitudinal barriers, and results of the tests were evaluated primarily by subjective means. It was realized that vehicular accelerations were indicators of occupant risks, and effort were made to minimize accelerations. In early breakaway support development, change in vehicular momentum was used as an indicator of occupant risks. It was subsequently realized that change in vehicular velocity was a better indicator of occupant risk since it was not dependent on the vehicle's mass.

In the late 60's and early 70's, an acceleration severity index (ASI) was adopted for use in evaluating vehicular response to encroachments onto roadside geometric features such as ditches, embankments, and median crossovers. It was an interaction relationship involving the ratios of average vehicular accelerations in the x, y, and z directions, to tolerable accelerations in those directions. Although this approach was abandoned by U. S. A. researchers many years ago, some European countries still use it to evaluate tests of various roadside features. In fact, the ASI will be included in test standards for "road restraint systems" by the Committee on European Normalization (CEN).

NCHRP Report 153, published in 1974, contained state of the art test and evaluation guidelines for longitudinal barriers, crash cushions, and breakaway features.(11) Impact severity of longitudinal barriers was evaluated by limiting values of vehicular acceleration in the longitudinal and lateral directions. Direct, head-on impacts with crash cushions were evaluated by limiting acceleration in the longitudinal direction computed over the stopping distance.

NCHRP Report 230, published in 1980, updated Report 153(15). Among other things, it completely revised the occupant risk evaluation criteria by introducing the "flail space model." It represented the occupant as an unrestrained lumped mass, free to flail in the vehicular x-y plane, within a given "occupant compartment." The velocity at which the occupant struck the compartment, and the ridedown accelerations subsequent to contact, were measures of occupant risk.

NCHRP Report 350, published in 1993, updated Report 230(15). Although some changes were made in the "structural adequacy" and the "vehicle trajectory" evaluation criteria, only minor changes were made to the occupant risk criteria, and the basic flail space model was retained. Other changes in Report 350 relative to Report 230 included changes to test vehicles, changes to the number and impact conditions of tests required to evaluate a feature, adoption of the concept of "test levels" as opposed to "service levels," inclusion of test guidelines for additional features, and adoption of the International System (SI) of units.

Both Reports 230 and 350 pointed out that field evaluation was the final and perhaps the most important step in the evaluation of a feature. Both reports provided guidelines by which a feature could be field evaluated. However, to a large extent, field evaluation remains the weak link in the assessment of a feature's performance and suitability for use. Notable exceptions to this are the field studies the New York DOT conducted on many of its barrier systems, studies by the Kentucky DOT on end treatments, studies by California DOT on median barrier performance, studies by Texas DOT on end treatments, and studies by FHWA on selected safety features. Proprietary systems are often closely monitored by their suppliers/manufacturers, especially during the period of their initial use. Problems that arise in proprietary systems are usually quickly corrected; also, changes that will improve performance and reduce costs are also incorporated.

The FHWA has also played a key role in the evaluation and implementation of new safety features. The FHWA has served as an arbiter in establishing acceptability and operational status of new features to be used on federal-aid highways. An assessment is made based on design details, specifications, and crash test results. State highway agencies typically rely heavily on this assessment in their review and possible use of the approved feature on *all* highways in their system.

INSTALLATION AND MAINTENANCE

Proper installation and maintenance of a safety feature is usually critical to its proper performance. The BCT has been one of the most widely used safety features, and one that has often been improperly installed. Frequently it has been installed without the recommended flare and end offset, and the consequences have been alarmingly injurious. Another example concerns sloping culvert ends for parallel drainage structures. Typically, the culvert end has a 6 to 1 slope and it is intended that the slope of the driveway, entrance ramp, or crossover under which the culvert traverses, match the sloping culvert end. In many cases the sloping end has been either left exposed due to improper fill slopes for the driveway, entrance ramp, or

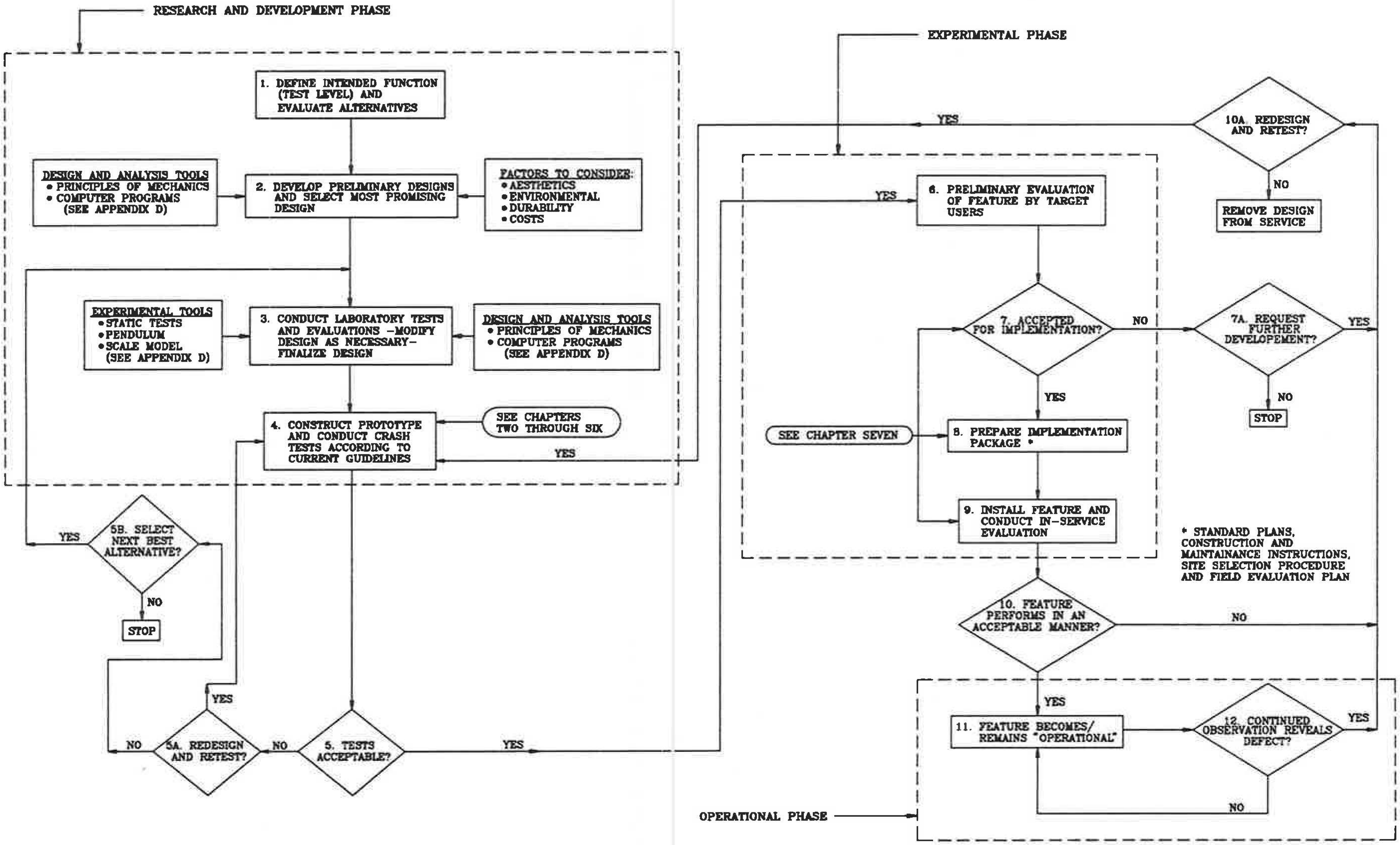

FIGURE 1 Flow chart for development of a safety feature.

TABLE 1 APPLICATION AND LIMITATIONS OF SAFETY FEATURE DEVELOPMENT TECHNIQUES

Development Technique	Principal Areas of Application	Possible Limitations
1. Structural Design Methods	• Preliminary and final design of feature for environment and non-collision performance • Preliminary design of feature for vehicle collision performance • Analysis of connections, material properties requirement and foundation design	• Dynamics and kinematics of feature and collision vehicle are not addressed • Collision severity in terms of occupant injuries and fatalities is not addressed
2. Static Tests (quasi-static)	• Mechanical properties of unique shapes, connections, new materials • Validation of structural design features • Quality control of critical material properties • Develop input values for computer programs	• Dynamic properties not examined • Generally applicable to samples, connections, and small subassemblies; entire system is not accommodated
3. Computer Simulations	• Study interrelations of feature and vehicle dynamics and kinematics • Study interrelations of vehicle dynamics and occupant dynamics • Study sensitivity of feature, vehicle and site conditions on vehicle/feature dynamic interactions	• Program should be validated by full-scale crash tests for specific conditions that bracket the conditions under study • Input parameters are sometimes not available and must be estimated • For practical and economic reasons, programs model only major feature/vehicle properties • Sometimes minor features decide the performance
4. Laboratory Dynamic Tests		
A. Gravitational Pendulum	• Compliance test for luminaire and single-leg sign breakaway supports • Evaluation of breakaway mechanisms • Force/deformation properties of guardrail post/soil interaction • Dynamic strength of anchor systems • Dynamic properties of barrier subsystems	• Impact speed 40 km/h or less • For dual-leg supports, upper-hinge mechanism are not examined • Does not simulate off-center impacts • Trajectory of article not reproduced • Base-bending support not applicable • Crushable nose must be tuned for type and width of specimen and recalibrated periodically • Cannot properly evaluate criterion D, Table 5.1
B. Drop Mass	• Quality control test of breakaway component • Test can be performed in a confined, indoor space	• Same limitations as for pendulum • For breakaway base, attached pole introduces artifact moment into base due to gravity
C. Scale Model	• Development testing of feature	• Difficulties and uncertainties in modeling vehicle and safety feature components
C. Bogie Vehicle Test	• Compliance test for single or multi-leg breakaway support • Repeatable test vehicle suspension, nose crash, and other dynamic properties • Low-cost, high-speed (0-60 mph) experiments	• Must be carefully designed and calibrated to represent vehicle characteristic of interest, which is often a long and expensive process • Designs have been appropriate for testing only limited variations in feature • Must be updated and recalibrated periodically.
D. Vehicle Crash Test	• Compliance test for all features • Investigation of unusual conditions • Most direct tie to actual highway collisions • Final proof test	• Relatively expensive to perform • Requires extensive capital facilities • Deliberate and slow to perform • Test results pertain to the specific vehicle model tested and may not be applicable to other vehicles

crossover, or fill has been added only in the immediate area adjacent to the sloped end.

Another common problem transportation agencies face is the expertise and attention to detail required in proper maintenance of many safety features. The initial installation may be by well trained and experienced contractors, while maintenance and restoration may be the responsibility of agency personnel. Both contractors and maintenance personnel must know the importance of proper installation and maintenance procedures, and the consequences if these procedures are not followed.

FUTURE CONCERNS

While major advancements have been made in roadside safety design, challenges and opportunities for further advancements remain. Following are selected issues relative to the design, evaluation, and maintenance of safety features for future consideration.

- *Multi-Performance Level Features and Warrants for Their Use* - NCHRP Report 350 provides guidelines for evaluation of safety features/hardware for up to six test levels (note that test levels imply performance levels). However, Report 350 provides no warrants or guidelines that establish highway conditions for which a specific "test level feature" would have application. Many of the operational safety features developed to date were designed to meet test level 3 requirements of Report 350. Thus, there is a need to (a) develop other features meeting the array of test levels in Report 350, and (b) to develop guidelines for their use. NCHRP Project 22-12, soon to be awarded, will address part b. In the absence of a wide array of operational, multi-performance level safety features/hardware, the study may have to approach the problem from another perspective. In this case, the project may have to develop guidelines for a family of "hypothetical, multi-performance level features," having assumed characteristics such as impact performance parameters and costs associated with purchase, installation, and maintenance. It would then remain to be determined if such features could be feasibly produced.
- *Vehicle mix* - There is a clear trend toward increased use of pickups, vans, and sport/utility motor vehicles. The ISTEA of 1991 recognized this trend, and mandated that highway safety features be designed to accommodate these vehicles. Project 22-11, which began June 1, 1994, will address many concerns relative to roadside safety design for light trucks. An FHWA study soon to be awarded will also address the light truck problem by estimating future trends in vehicular design and by developing a limited number of vehicular platforms representative of a group or class of vehicle types. Are there areas not covered in either of the above mentioned studies that need attention?
- *Performance guidelines/standards* - Future updates to NCHRP Report 350 need to consider:
  a) *Impact conditions* - In a significant percentage of accidents with safety features the vehicle is yawing and not in a tracking mode. All compliance test guidelines to date use a tracking vehicle. Should non-tracking tests, including full side impacts, be included in future test guidelines? How would identification of standardized non-tracking tests be made? Can such tests be conducted with a high degree of control and repeatability? Can hardware be cost effectively developed to accommodate these types of impacts.
  b) *Test vehicles* - For test levels 1 through 3 of Report 350, two passenger vehicles are used to evaluate safety features. For test levels 4 through 6 the small car and three different size trucks are used. The two passenger vehicles and three trucks used in these tests are intended to bracket the wide spectrum of vehicle types on the road, and as such it is assumed that they reflect the extremes in vehicle/feature performance expected in the field. Are safety features being properly designed to accommodate the wide range of vehicles in the mix? Do the design vehicles of Report 350 adequately represent the mix? What about motorcycles? What is a realistic tradeoff between the cost of requiring additional tests to represent a wider vehicular mix and added safety benefits which may result therefrom?
  c) *Occupant compartment deformation/ intrusion criteria* - Criterion D, Table 5.1, of Report 350 addresses occupant compartment integrity, but assessment thereof must of necessity be subjective. An occupant compartment deformation index (OCDI) is to be computed and reported, which gives a quantitative measure of the change in occupant compartment dimensions. However, limiting values for the OCDI are not given, and it is used for information only. Should limiting, quantitative values be established for this criterion? If so, how can this be accomplished?
  d) *Occupant risk criteria* - Surrogate measures such as the flail space approach of the U.S.A, the THIV and PHD approach employed by CEN (which is very similar to the flail space approach), and the ASI approach also used by CEN, are at best only indicators of occupant risks. Furthermore, they cannot account for factors such as occupant restraint systems, air bags, crashworthiness of the occupant

compartment, effects of driver/passenger size, etc. Advances in computer technology and in the development of sophisticated dummies and collision victim simulation models are such that quick and accurate determination of occupant response in a crash test or simulation is feasible. Should future occupant risk indices include application of these technologies?

e) *Use of surrogate test vehicles* - Bogie vehicles and pendulums have frequently been used for development and compliance testing of breakaway supports, especially luminaire supports. Efforts are being made to extend the range of application to other features such as crash cushions, yielding signs, and longitudinal barriers. Have these devices performed in an acceptable manner? What efforts and costs are involved in development of a validated surrogate? Heavy roof damage was observed in recent tests of light poles with production model vehicles. Bogies and pendulums generally cannot assess roof crush. Should a compliant roof be required in these surrogate devices?

- *Work zone safety features* - Are there still problems with work zone safety features and traffic control devices? Are new designs needed? Potential candidates include highly portable barriers that can be quickly deployed and retrieved, truck mounted attenuators for high speed impacts (100 km/h), and safe changeable message sign systems.
- *New Materials* - Advanced and recycled materials are being used in various transportation areas, including composites, high-strength concrete, and recycled rubber and plastics. Which new materials and recycled materials are candidates for use in roadside safety features? What is the current state of knowledge relative to the use of these types of materials in roadside safety design? Can these types of materials be cost-effectively used in roadside safety design, and if so how? Do we need basic studies to better define the properties and characteristics of these materials necessary for their use in roadside safety design?
- *Railing design* - The W-beam rail, and to a lesser extent the thrie-beam rail, have been widely used as basic elements in longitudinal barrier systems in the U.S.A. and other countries for many years. How did this come to be? Are these shapes optimum? Can we do better considering factors such as performance, cost, design flexibility, cost effectiveness?
- *Safety feature installation and maintenance procedures* - Proper installation and maintenance of safety features remains a concern. Installation and maintenance problems are generally proportional to the degree of design complexity. Keeping designs simple, and use of readily available, standard parts is highly desirable. What, if anything, can and should be done to improve the quality of installation and maintenance of safety features?
- *International cooperation and harmonization* - Considerable progress has been made in international cooperation and harmonization relative to roadside safety. The European community was represented on the advisory panel for NCHRP Project 22-7, in which Report 350 was prepared. U.S.A. representatives attend and participate, as observers, in CEN technical working groups responsible for writing test standards for road restraint systems. Further, subcommittee A2A04(2), International Research Activities, has been very active and successful in promoting technology exchange in the roadside safety area and in promoting harmonization of impact performance guidelines/standards internationally. It is certainly desirable to continue and expand these efforts.

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THE ROADSIDE SAFETY PROBLEM

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The best picture of the nature of the roadside safety problem requires an appropriate use of information of crashes of all severity outcomes - fatality, injury, and property damage only crashes. Comprehensive crash costs present a rational way to combine this information into an overall measure total crash loss by crash type.

Research by Dr. Ted Miller for the Federal Highway Administration (FHWA) to develop comprehensive crash costs is widely recognized (FHWA, NHTSA, NSC, CDC) as providing the best current crash costs.(1) The Tables in this section use these costs (in 1988 dollars) along with 1985 data for: counts of fatalities from the Fatal Accident Reporting System (FARS); and injury and property damage only (PDO) data from the Continuous Sampling System (CSS) of the National Accident Sampling System (NASS). NASS data are from in-depth investigations of a statistical sample of all crashes in the United States. The level of detail in describing fixed objects in the CSS is better than most State accident data, the reliability is much higher due to case quality review procedures used, and of course the data is nationally representative. Data for 1985 were used as this is the last full year of operation of the NASS CSS.

Counts of fatalities, estimates of injuries and PDO vehicles by most harmful event (MHE) are given in Table 18 (Appendix) along with the percent of loss (or harm) based on the comprehensive costs of reference 1. The overturns shown are limited to cases in which the first harmful event (MHE) occurred outside the shoulder.

Examination of this data for all crashes (not just the ran-off road crashes reported here) reveals that unreported accidents are not likely to change the relative importance of crash losses by crash type shown in these Tables. Most unreported crashes are likely to be PDO crashes. Reported PDO crashes were found to account for just 4 percent of overall crash costs (fatalities 41 percent and injuries 55 percent)(2). If there are twice as many unreported crashes as reported, as thought by some, only about 8 percent of the true crash costs are not accounted for in police reported crashes. Clearly, unknown crash type losses of around 8 percent due to unreported crashes have no practical effect on these findings.

Tables 1-3 summarize the findings of the ran-off-road crash losses of Table 18:

- Table 1 shows six crash types responsible for 77 percent of crash losses,
- The remaining 24 percent of losses are spread out over 14 crash types (Table 2), and
- Roadside safety devices account for only 10 percent of crash losses (Table 3).

The goal of a strategic plan for roadside safety research should be to reduce, in the best possible way, the losses from ran-off-road crashes. Tables 1-3 can serve as a central guide in this effort.

The remainder of this white paper explores: the leading (and rather amorphous at this point!) loss - overturn; the leading roadside safety device loss - guardrails; and emerging trends which may change these 1985 loss figures (increase in light trucks and vans, airbags, anti-lock brakes, and aerodynamically styled vehicle front ends).

OVERTURN - THE LEADING RAN-OFF-ROAD LOSS (27.5 PERCENT OF LOSS)

Crash Types

For practical purposes, ran-off-road crashes can be classified as either: rollover on slopes and ditches; or fixed object crashes which may or may not involve rollover. With the exception of immersion, all other ran-off-road crash types (parked car, non-fixed object, pedestrian, etc.) are of no interest in roadside safety design.

National fatality counts and estimates of crashes in this section are 1991 data.(3) Fatalities are driver fatalities from FARS data, and crashes are from General Estimate System (GES) data.

GES is a statistical sample of police reported crashes. GES can be used to compare overall fixed object crashes with other crash types like rollovers on slopes and ditches. However, specific object struck codes are of limited use as they represent the lowest common denominator of these codes between the State data in the GES. For example, utility pole, sign support, luminaire support, and other poles are all combined into one GES data element.

Slope Rollovers

Table 5 shows slope rollovers to be 3/4 of all ran-off road rollovers and to account for 1/2 of driver fatalities in ran-off-road rollovers. Fixed object rollovers account for the remainder - 1/4 of rollovers, and the other 1/2 of rollover fatalities. These severe fixed object-rollover crashes are of course split over a wide range of specific

TABLE 1 CRASH LOSSES BY MOST HARMFUL EVENT (MHE) FOR MHES LARGELY ASSOCIATED WITH ROADSIDE OCCURRENCES -1985 (OVERTURNS LIMITED TO THOSE WHICH OCCURRED ON ROADSIDE)

Most Harmful Event	Fatalities	Injuries	PDO Vehicles	Total $Millions	Percent of loss
Overturn	4,820	134,000	32,000	17,786	27.5%
Tree	3,497	88,000	26,000	12,485	19.3%
Utility pole	1,522	110,000	33,000	8,769	13.6%
Embankment	668	95,000	18,000	6,004	9.3%
Guardrail	600	21,000	17,000	2,435	3.9%
Other traffic rail	18	N/A	N/A	43	
Ditch	353	23,000	16,000	1,932	3.0%
Other fixed object	279	20,000	25,000	1,632	2.7%
Fire hydrant	12	N/A	N/A	29	
Impact attenuator	7	N/A	N/A	17	
Mail box	N/A	2,000	7,000	104	
Other post	277	13,000	19,000	1,295	2.5%
Traffic signal pole	N/A	5,000	3,000	235	
Overhead sign post	15	N/A	N/A	36	
Other noncollision	121	5,000	18,000	551	2.4%
Immersion	394	N/A	N/A	946	
Culvert	302	17,000	4,000	1,514	2.3%
Bridge rail	151	15,000	11,000	1,071	2.1%
Bridge end	115	N/A	N/A	276	
Luminaire support	115	N/A	N/A	427	2.1%
Nonbreakaway	N/A	14,000	3,000	649	
Breakaway	N/A	5,000	5,000	239	
Curb	193	13,000	24,000	1,078	1.7%
Bridge pier	296	4,000	3,000	900	1.4%
Building	174	10,000	4,000	884	1.4%
Concrete barrier	100	N/A	N/A	240	1.3%
Conc. Median	N/A	7,000	4,000	329	
Conc. Non-median	N/A	3,000	5,000	147	
Median barrier	N/A	3,000	2,000	141	
Fence	192	8,000	16,000	856	1.3%
Wall	159	7,000	7,000	716	1.1%
Signpost	123	N/A	N/A	295	0.8%
Large sign	N/A	3,000	1,000	140	
Small sign	N/A	1,000	5,000	55	
Shrubbery	15	16,000	12,000	324	0.5%
Total	14,571	642,000	320,000	$64,578	100%

TABLE 2 LEADING ROADSIDE CRASH LOSSES (1985)

	%
Overturn	27.5%
Tree	19.3%
Utility Pole	13.6%
Embankment	9.3%
Guardrail	3.9%
Ditch	3.0%
Totals	76.6%

TABLE 3 OTHER ROADSIDE CRASH LOSSES (1985)

	%
Other fixed object	2.7%
Other post	2.5%
Other noncollision	2.4%
Culvert	2.3%
Bridge rail/end	2.1%
Luminaire support	2.1%
Curb	1.7%
Bridge pier	1.4%
Building	1.4%
Median barrier	1.3%
Fence	1.3%
Wall	1.1%
Sign post	0.8%
Shrubbery	0.5%
Totals	23.6%

TABLE 4 ROADSIDE SAFETY HARDWARE LOSSES (1985)

	%
Guardrail	3.9%
Bridge rail/end	2.1%
Luminaire support	2.1%
Median barrier	1.3%
Sign support	0.8%
Impact attenuator	0.01%

crash types such as guardrail end crashes and off-center impacts with trees.

Table 6 compares slope rollover fatalities with specific fixed object (rollover and non-rollover) fatalities. Slope rollovers are seen to be the leading cause of ran-off-road fatalities.

Two-Lane Rural Roads

Table 7 shows slope rollover fatalities to be disproportionaly on rural 2-lane roads - 72 percent of slope rollovers compared to 55 percent of fixed objects. Table 8 shows curves to be a special problem on 2-lane rural roads for both slope rollovers and fixed object crashes - 35 percent of crashes and 1/2 of fatalities occur on curves for both crash types.

Utah Highway Safety Information System (HSIS) data is being examined in an ongoing FHWA staff research study to examine ran-off-road crash risk by horizontal curvature. Slope rollovers and fixed object crashes are combined in this data.

Figure 1 shows the increase in ran-off-road crash risk (crashes per MVMT) on rural 2-lane roads as curvature increases based on 4,676 crashes and over 6 billion vehicle-miles of travel based on the data in Table 9. For comparison, the curvature adjustments of the Roadside Design Guide, based on much more limited data, are also shown. Utah data cannot separate inside of curve and outside of curve crashes, however Hall and Zador found 2/3 of fatal rollovers on curves to be on the outside of the curve.(5)

Vehicle Pre-Crash Orientation

Computer simulation using vehicle dynamics programs is a useful tool to examine the risk of rollover on specific slope and ditch combinations. Such simulations require knowledge of vehicle trajectory characteristics in actual slope rollover crashes.

Vehicle orientation at crash impact is available in 1,000 single vehicle NASS cases reconstructed by Terhune.(4) Figure 2 was developed from this data and shows around 70 percent of slope rollover vehicles to be in a lateral skid at the point of tripping with less than 15 percent of fixed impact vehicles in a lateral skid.(3) Additional trajectory data are shown in reference 3.

TABLE 5 RAN-OFF-ROAD CRASH TYPE BY DRIVER INJURY SEVERITY

Most Harmful Event			All Crashes	Driver Fatalities
	No.	%	No.	%
Slope - Rollover	148,000	15%	2,186	26%
Fixed Object - Rollover	50,000	5%	2,025	25%
Fixed Object - No Rollover	769,000	80%	4,054	49%

Summary

Most ran-off-road rollovers occur on sideslopes and ditches. This specific crash type is the leading cause of roadside fatalities. The outside of horizontal curves on rural 2-lane roads are areas worthy of special attention in efforts to reduce slope rollovers. Research is needed to re-examine both (1) slope design guidelines, and (2) guardrail warranting criteria to address this problem. Valuable insight on specific slope and ditch combinations can be obtained through computer simulation.

GUARDRAIL - THE LEADING ROADSIDE SAFETY DEVICE LOSS (3.9 PERCENT OF LOSS)

End vs. Length of Need

Tables 10-12 examine guardrail end vs.length of need (LON) crashes. Utah data is from HSIS, North Carolina data was provided by the Highway Safety Research Center, LBSS data are from reference 6 and Texas data are from reference 7.

Table 10 shows the percent of end impacts on guardrails from four sources. The LBSS data are from an in-depth study and end impacts shown are upstream end impacts. Texas data are from a review of hard copy of police reports, while Utah and North Carolina data are coded data from police reports. The Utah data is seen to be an outlier. The data seem to suggest a best current estimate of something like 1/4 of guardrail crashes being end impacts. The median length of guardrail in the LBSS file is 370 ft., illustrating the disproportionate involvement of guardrail crashes on ends based on the relative lengths of ends and LONs.

Table 11 shows crash severity in terms of percent of fatal plus incapacitating injuries from the two States with known guardrail end types. The risk of fatal or incapacitating (K+A) injuries in end impacts with these end types are seen to be about 40 percent higher than LON impacts as shown in Table 12 which summarizes these findings.

Summary

Guardrail end impacts represent a disproportionate risk of crash involvement compared to LON based on installed lengths, and the severity of crashes with the most commonly installed end types is higher than LON crashes. Available data are not adequate to determine the relative contributions of specific end design, termination points, and clear zones behind the rail ends in contributing to injuries.

EMERGING TRENDS

Vehicle Fleet Changes

Light Trucks and Vans - In response to the increase in light trucks and vans in the vehicle fleet, NCHRP Report 350 uses a 3/4 ton pickup truck as a replacement test vehicle for the no longer available 4,500 lb car. Examination of six years of accident data involving roadside safety devices in two States (North Carolina - 5,008 crashes, and Michigan - 13,554 crashes) shows no difference in risk of (K+A) driver injury between cars, and light trucks and vans in either State as shown in Tables 13 and 14.(8) Also, no statistically significant differences in risk of K+A injury were found between car and pickup drivers when examined by specific object struck. Table 15 shows the objects closest to showing statistically significant K+A injury risks and an overall comparison of car and pickup truck driver risks.

However, analysis of FARS data in this same study shows drivers in pickups to be at greater risk of fatality in crashes with roadside safety devices than car drivers, Table 16. Ejections in rollovers may explain the differences found in fatalities - 53 percent of pickup driver fatalities were total ejection rollovers compared to 36 percent of car driver fatalities. Seat belt observations in North Carolina indicate pickup drivers have a 20 percent lower belt use rate than car drivers.(9)

Thus, lower belt use rates, combined with the known greater risk of rollover of pickups as compared to cars

TABLE 6 RAN-OFF-ROAD DRIVER FATALITIES BY MOST HARMFUL EVENT

Most Harmful Event	No.	%
Slope-Rollover	2,186	26%
Tree	1,901	23%
Utility Pole	746	9%
Guardrail	576	7%
Slope-No Rollover	457	6%
Culvert	370	4%
Fence	291	4%
Other Objects	1,738	21%
Totals	8,265	100

TABLE 7 DRIVER FATALITIES BY LAND USE AND ROADWAY TYPE

	Rural 2-Lane	Rural Interstate	Rural Other	Urban
Slope Rollover	72%	14%	2%	12%
Fixed Object	55%	6%	3%	37%

TABLE 8 HIGHWAY FEATURE INVOLVEMENT ON 2-LANE RURAL ROADS

	Involved Vehicles		Fatalities	
Highway Feature	Slope Rollover	Fixed Object	Slope Rollover	Fixed Object
Not at junction	94%	85%	97%	96%
55 mph or > speed limit	73%	58%	78%	68%
Dry pavement	60%	57%	85%	81%
Curves	35%	35%	53%	48%
Grades	32%	27%	37%	35%
Construction zone	N/A	N/A	1%	1%

TABLE 9 RUN-OFF-ROAD ACCIDENTS, 2-LANE RURAL ROADS, BY CURVATURE: UTAH, 1985-1987

Degree of Horizontal Curvature	Accidents		Roadway Mileage		Million Vehicle Miles of Travel (MVMT)	Accidents / MVMT
	Total	Percentage	Total	Percentage		
Missing	995	21.3	2204.2	35.8	797.5	1.25
0	2826	60.4	3435.6	55.8	4817.7	0.59
0 - 1	2	0	4.1	0.1	6.3	0.76
1 - 2	7	0.1	12.1	0.2	21.4	
2 - 3	33	0.7	43.4	0.7	46.9	
3 - 4	102	2.2	86	1.4	114.5	
4 - 5	76	1.6	69.2	1.1	80.1	1.09
5 - 6	79	1.7	52.7	0.9	62.4	
6 - 7	71	1.5	47.2	0.8	54.2	1.37
7 - 8	50	1.1	32.3	0.5	34.3	
8 - 9	38	0.8	25.7	0.4	28.8	1.63
9 - 10	45	1	19.6	0.3	22	
10 - 20	231	4.9	87.1	1.4	107.4	2.15
20 - 30	73	1.6	23.1	0.4	21.8	3.2
30 - 40	18	0.4	6.8	0.1	5.3	
40 - 50	15	0.3	4.3	0.1	4	
> 50	15	0.3	6.3	0.1	6.7	
Total	4676	100.0	6159.6	100.0	6231.2	0.75

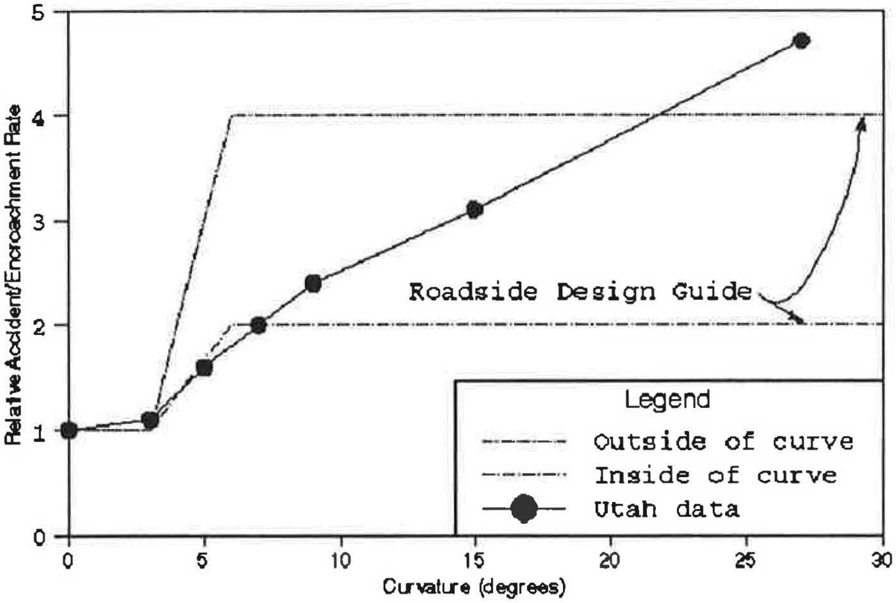

Figure 1 Utah 2-lane rural roads (4676 Accidents/6231 MVMT).

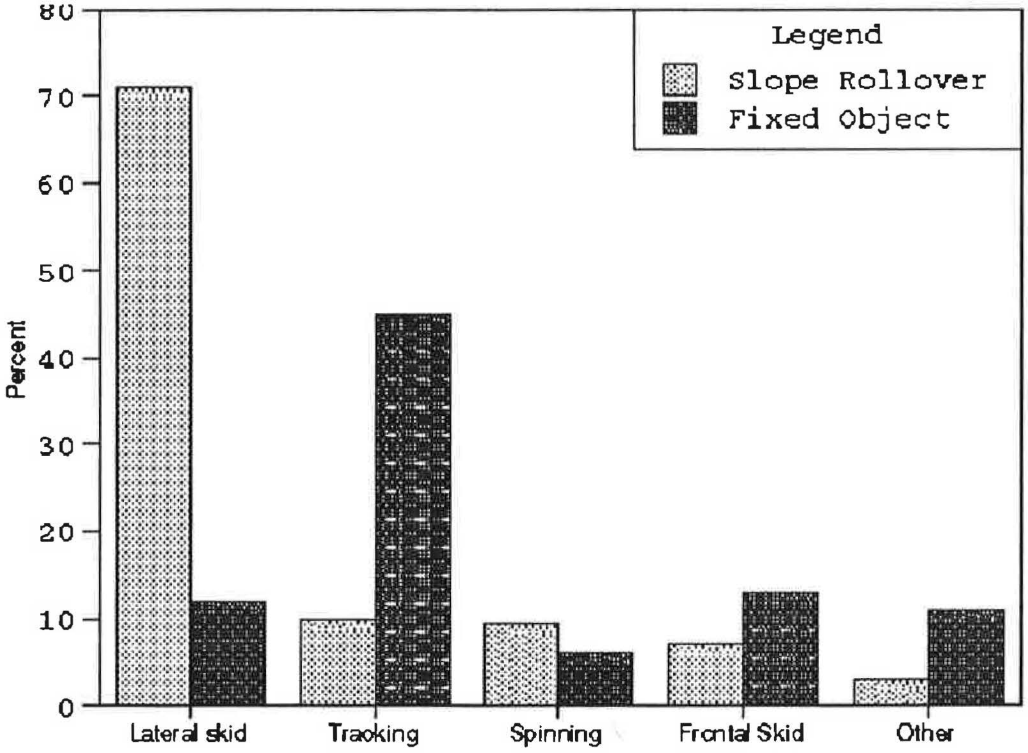

Figure 2 Vehicle pre-crash orientation.

may well explain the differences seen in fatality risk. Redesigning roadside safety hardware to reduce pickup rollover risk may not be cost effective.

Air Bags and Anti-Lock Brakes

Complete conversion of the car, light truck and van fleet to driver and right front air-bags is now well underway. Crash severity reduction achieved by this major change will probably differ by crash type. Air bags are likely to reduce the severity of object crashes more than rollovers.

Currently, 40 percent of new cars are equipped with anti-lock brakes which reduce skidding risk. The NHTSA has published an advanced notice of proposed rulemaking on the issue of requiring antilock brakes to reduce rollover risk.(10) Figure 2 shows that anti-lock brakes have the potential to reduce slope rollovers more than fixed object crashes.

Aerodynamic Vehicle Front End Styling

Wedge-shaped front profiles of cars, a style once seen only in sports cars, are an increasingly large segment of new car sales. These vehicles can present underride problems in crashes with traffic rails such as the G1 cable guardrail, and guardrail ends such as the BCT or eccentric loader terminal, figures 3 and 4.(11,12)

Emerging trends such as the compatibility of wedge-shaped cars with these specific safety hardware types are topics worthy of research, however it is impractical to answer these kinds of questions through any kind of accident research.(13)

Summary

The "practical worst case" test philosophy of NCHRP Report 230 has provided about the same level of protection to drivers of pickups, vans and cars if the measure of safety is likelihood of serious (K+A) injury. It may prove impractical to provide equal levels of protection against fatality as differences in inherent vehicle stability combined with belt use rates seem to be the major factor in these differences. This then raises the question, will the resources spent to comply with the NCHRP Report 350 pickup tests improve safety?

An air bag equipped vehicle fleet with a growing percentage of anti-lock brakes will change the current ran-off-road loss picture. Ran-off-road losses should be re-examined in a few years when enough data becomes available. Also, the injury tolerance standards of NCHRP Report 350 may need to be revised as they assume unbelted vehicle occupants. Put another way, will decisions based on the injury criteria of NCHRP Report 350 prove to be cost effective as cars and light trucks become driver and right front air-bag equipped by the time these devices are deployed in any number?

TABLE 10 GUARDRAIL END CRASHES PERCENT OF ALL GUARDRAIL CRASHES

	All	Percent on Ends
Utah	2,482	5
North Carolina	2,360	26
LBSS	993	33
Texas	834	21

TABLE 11 GUARDRAIL CRASH SEVERITY PERCENT (K+A) INJURIES

	End	LON
Turned Down (TX)	14.3%	10.6%
BCT/Blunt (NC)	13.5%	9.1%

TABLE 12 GUARDRAIL END VS. LENGTH OF NEED

	End	LON
Number	1/4	3/4
(K+A) Injuries	14%	10%

TABLE 13 DRIVER INJURY BY VEHICLE TYPE, NORTH CAROLINA

	Car	Pickup	VanUtil.
K	0.7%	1.2%	1% 2%
A	6.9%	7.0%	7% 8%
B	13.1%	12.1%	16% 9%
C	17.1%	16.4%	13%18%
O	62.2%	63.4%	63%62%
Nδ,687	887	141	109
		p=0.38 NS	

TABLE 14 DRIVER INJURY BY VEHICLE TYPE, MICHIGAN

	Car	Pickup	Util.Van
K	0.4%	0.5%	1% 0
A	3.5%	3.2%	2% 2%
B	7.0%	7.8%	6% 5%
C	10.1%	10.4%	9% 8%
O	78.9%	78.1%	83%84%
No.	10,731	2,388	244191
		p=0.50 NS	

TABLE 15 CARS VS. PICKUP TRUCKS BY OBJECT STRUCK, NORTH CAROLINA

Object	Vehicle	(K+A)	Number	p
Guardrail face	Car	6.1%	1,623	0.14
	Pickup truck	8.2%	429	
Guardrail end	Car	18.7%	475	0.16
	Pickup truck	13.0%	93	
Median barrier	Car	5.0%	185	0.16
	Pickup truck	12.0%	42	
All	Car	7.5%	3,687	0.68
	Pickup truck	8.2%	887	

TABLE 16 RURAL DRIVER FATALITIES (FARS) AND CRASHES (GES) GUARDRAIL, MEDIAN BARRIERS, IMPACT ATTENUATORS

	Fatalities		Crashes	
	Number	Percent	Number	Percent
Cars	223	70%	46,600	88%
Pickup	75	24%	4,600	9% (1)
Van	12	4%	1,500	3%
Utility	9	3%	500	1%
Totals	319	100%	53,200	100%

(1) 95% confidence limits -- 4.4% to 13.3%

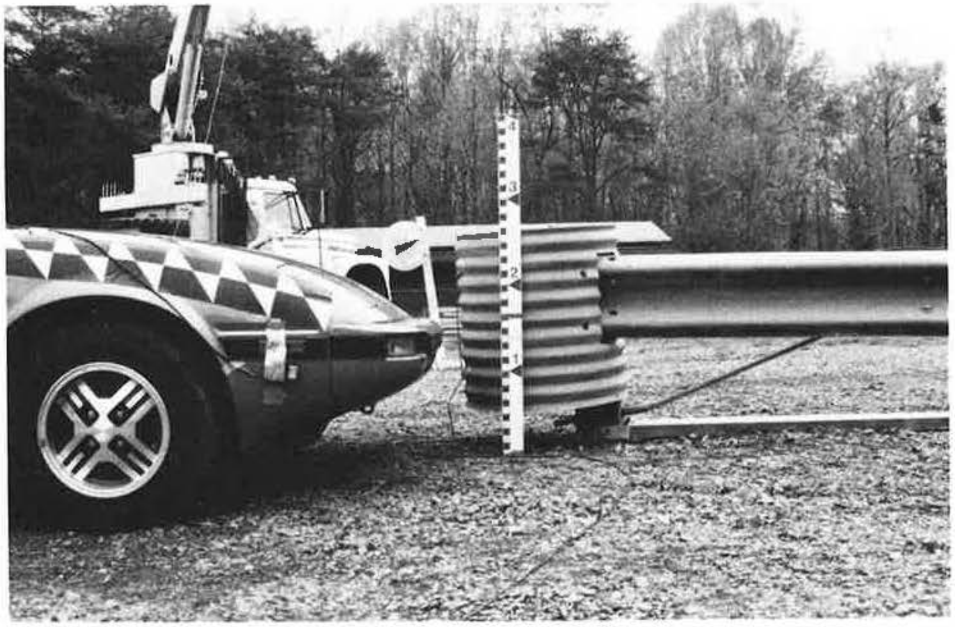

Figure 3 Wedge-Shaped Vehicle and Eccentric Loader Terminal.

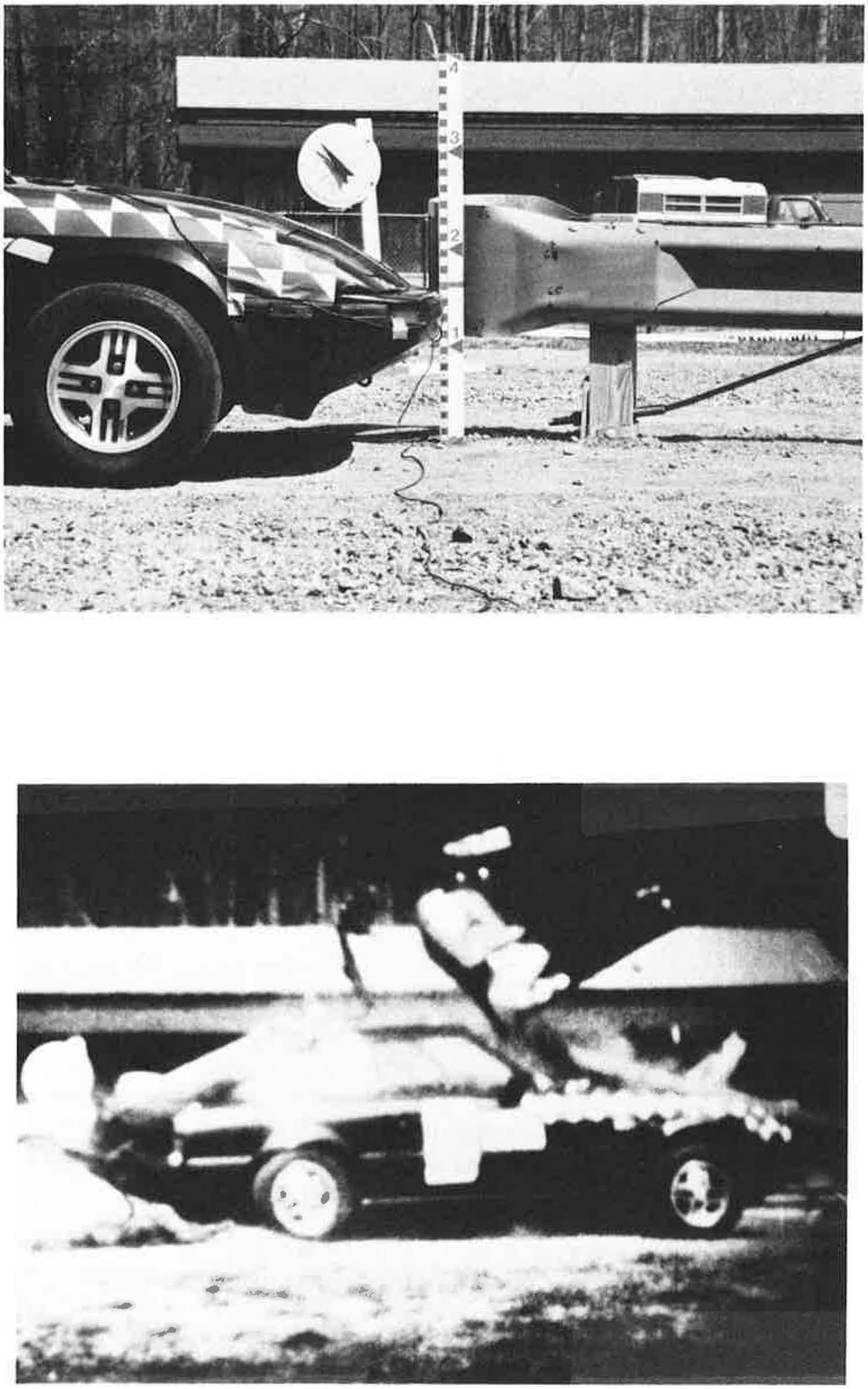

Figure 4 Wedge-Shaped Vehicle and Breakaway Cable Terminal.

TABLE 17 MEASURES TO ADDRESS THE LEADING RAN-OFF-ROAD-CRASH LOSSES

Overturn	27.5%
●Rollovers on sideslopes and ditches (3/4 of overturns)	
- Slope design standards	
- Guardrail warrants	
Tree	19.3%
●Review clear zone standards	
Utility pole	13.6%
●Implementation - bury, relocate, make breakaway	
Embankment/Ditch	12.3%
●Slope design standards	
●Guardrail warrants	
Guardrail	3.9%
●End impacts	
- Termination points - clear zones	
- In service performance of existing designs	

TABLE 18 ROADSIDE SAFETY HARDWARE LOSSES

Guardrail	3.9%
Bridge rail/end (includes unshielded ends)	2.1%
Luminaire support (includes non-breakaway supports)	2.1%
Median barrier	1.3%
Sign post (includes non-breakaway supports)	0.8%
Impact attenuator	0.01%
Total	10.2%

TABLE 19 EMERGING ISSUES

Air bags in 100% of vehicle fleet - revising crash severities
●Updated severity indices needed
●Reduce severity of object crashes more than rollovers?

Anti-lock brakes - 40% of new cars
●Reduce number of rollovers more than fixed object crashes?

More light trucks and vans in fleet
●Will resources spent to comply with NCHRP Report 350 improve safety?

A PROGRAM TO ADDRESS THE PROBLEM

Tables 17-19 address, in outline form, findings and recommendations from this look at the roadside safety problem. Table 17 presents suggestions to address the leading losses of Table 2.

Both re-examining slope and ditch design standards and guardrail warrants are recommended to identify cost effective solutions to the leading roadside safety problem - slope rollovers. These efforts might also be helpful for crashes coded as embankment or ditch.

Updating clear zone standards is a suggested way to address the tree problem. NCHRP Project 17-11 is currently soliciting proposals on this topic.(14) Due to funding limitations of this effort, a follow-on study may be needed in this area.

The utility pole problem might be best addressed by implementing what we already know. Burial of utility lines creates aesthetic as well as safety advantages, relocation and collocation of poles and breakaway supports are other safety options.

Research needed to make meaningful improvements to roadside benefit/cost models such as NCHRP Project 22-9 and FHWA's Interactive Highway Safety Design Model research program should aid implementation efforts to reduce these losses.(15,16)

Altogether, roadside safety structures account for an estimated 10.2 percent of ran-off-road crash losses (Table 18). Overturns subsequent to impact with these structures are not included in this estimate and would increase these totals. However, unshielded bridge ends, and non-breakaway sign and luminaire support crashes are unavoidably included in these figures and would reduce this estimate. Study of termination points, clear zones and in-service performance of newer guardrail end designs would seem to be the highest priority to reduce these losses.

Excluding guardrail, roadside safety device losses account for 6.3 percent of ran-off-road crash losses. Clearly research in this area should be focused on specific identified problems such as those relating to emerging wedge-shape car front profiles.

Emerging issues are summarized in Table 19. Introduction of airbags and anti-lock brakes will create a need to update crash test injury evaluation criteria, severity indices and to re-examine overall ran-off-road crash losses. Compliance testing to meet the pickup test requirements of NCHRP Report 350 may not improve safety.

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THE EVOLUTION OF VEHICLE SAFETY AND CRASHWORTHINESS

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The current fatality rate is 1.8 fatalities per 100 million miles driven and continues to improve even though travel is increasing. On average the U. S. has the safest roads among industrialized countries.

However, injury is the fourth leading cause of death in the U.S. following heart disease, cancer, and strokes. The largest cause of injury is motor vehicle crashes.

Research shows that most accidents are avoidable and the driver has the primary responsibility in avoiding fatal crash situations. Two thirds of fatal crashes were caused by a driver's mistake. The largest fraction of these - 45 percent - could be characterized as inadvertent errors. Another 21 percent of those crashes could be attributed to aggressive driving.

In the 1930's, as the automobile became more prominent in meeting a mobile societies transportation needs, automobile crashes began to occur on a regular basis as did related injuries and fatalities.

U.S. fatalities per 100,000,000 miles reached 15.6, compared with 3.5 in 1980 and 1.8 today. Thankfully, the figure is still falling. However, automobile transportation safety efforts must continue, and they will, but the challenges to achieve continued reductions become more and more complex. In the very simplest of terms, those reductions are twofold and involve avoiding a crash altogether or increasing the opportunity to survive a crash. Both aspects have posed, and continue to pose, enormous challenges to the automotive safety engineer.

So then, the first challenge is to design cars and road infrastructures that are sufficiently adequate in every sense to significantly reduce the opportunity for a crash to occur. These designs embrace a whole raft of technologies, from ABS brakes and radial tires to Near Obstacle Detection systems that can cause a vehicle to pre-brake and avoid obstacles, to improved road surface materials and the use of computers in the control of city traffic flow.

The second challenge is to design and build cars that enhance the protection of the occupants in the event of a crash. These two mainstream aspects of safety exist in parallel, each complimenting the other while remaining essentially independent of the other.

However, it should be noted that there is a third element to crash reduction that is significant. It involves drivers and their behavior while driving a vehicle. In addressing driver behavior issues, training and disciplining are arguably two of the most ideal and cheapest paths to enhancing effective road safety. Tremendous gains in reducing death and injury as a result of driver error have been made. And much credit for this must be given to MADD, SADD, and other such organizations, as well as NHTSA's efforts regarding driver awareness. However the sad realism is that these efforts are never likely to be thoroughly effective. Therefore, efforts to apply new technology that will enhance total roadway safety must continue.

In the short space of the past 30 years, research into, and the development of automotive safety systems and equipment truly accelerated. Important to this progress were events that occurred peripheral to vehicle engineering innovation.

One of the more significant of these events was passage by Congress of the National Traffic and Motor Vehicle Safety Act of 1966 which brought the National Highway Safety Bureau, now the National Highway Traffic Safety Administration, into existence. The Safety Administration also was instrumental in putting into place a national accident data gathering system that permits a more accurate description of the accident scene.

However, it should be noted that the automotive industry had been expending much effort in reducing death and injury resulting from vehicle crashes before the passage of the safety act. For example, in 1955 GM installed front-seat lap belts on Cadillacs and in 1956 Buick developed finned aluminum brake drums for faster brake cooling. Also of note at this time was GM's efforts to gather field accident data into a data base to focus on vehicle crash performance.

Other significant events have been the automotive industry's invention of a vast array of safety test equipment, including improved test dummies, and an increase in understanding the tolerance of the human body to injury.

General Motors Research Laboratories are one of the prime contributors to the advancement of highway safety. In depth studies in the areas of biomedical science and the expertise and advice of the men and women involved in this area of GM research have been crucial to the building and selling of safe and efficient automobiles. Additionally, this area of research has provided a leadership role in developing test dummies, and in enhancing test dummy ability to simulate the response of human beings - to make test dummies more human-like in their response.

As a result of the development industry-wide of more critical tests and test evaluations vehicle interiors have experienced a dramatic increase in vehicle safety.

Many new occupant protection features have been introduced into the passenger cars since the early 60's, a tribute to engineers working with tools developed over the past 30 years.

In 1960, GM designed its initial crash decelerator sled which was installed at Wayne State University medical center in Detroit. For the first time occupant dynamics and impact could be simulated and measured.

By 1963, the first series of tests using cadavers took place. Deceleration forces were increased and measured to determine tolerance. It was found that 340kg could be tolerated if the force was concentrated, or 950kg if spread by the steering wheel and hub. This data was pivotal to engineering. It set the parameters for padding, but material and components had to be carefully designed for energy management.

By 1967, all GM cars used high-penetration resistant glass. Other manufacturers were also adopting it and it is regarded as one of the most significant contributions to automotive safety. Not only has it helped improve driver and passenger survivability but it has also helped reduce pedestrian injuries when struck by a car.

Also introduced during this time frame were the energy absorbing instrument panel, cushioned armrests and door interiors, energy absorbing front seat back tops, and head restraints.

Passenger guard inside door locks made their initial appearance. Folding front seat back locks, first appearing in 1958, now became standard equipment. Also in 1967, the energy absorbing steering column had its debut.

The inside rear view mirror received a day/night mirror glass encased in vinyl backing to resist shattering in an accident, and was mounted on a breakaway pedestal. And, of course seat belts were standard. In 1986, GM introduced the first rear seat lap/shoulder belts in the U.S. domestic automotive industry.

While not subject to as substantial change as the body structure or vehicle interior, the chassis and drive train too have experienced safety improvements since the late 50's. Brakes, fuel tanks, and tires have led the way. Standardization of the dual master cylinder and warning in 1967, for example, ensured that a passenger car would have effective braking if damage occurred to one of the brake lines.

Two years later cars with manual transmissions received a safety start switch to prevent them from being started while in gear, and fuel system integrity and security were increased.

By 1971 front disc brakes, with their improved capacity to resist fade and the effects of water, had made a successful engineering transition from racing car to passenger. The pressure lock radiator cap and maintenance free, sealed battery made their appearance.

The following year the disc brake lining wear audible indicator was introduced by Oldsmobile and soon spread to all car models. In 1973 tires with Tire Performance Criteria (TPC) number which made it possible for customers to order a replacement tire that duplicated the specifications of the original equipment tire became possible. That same year the pressure relief gas cap was also introduced.

In 1974, GM became the first automaker to offer air bag restraints as options on selected vehicles. Now new generations of air bags are being worked on to reduce any side effect issues that may occur such as bruising or abrasions.

Combined with all of this was the development of the "safety cage" occupant protection approach. Much engineering goes into designing the passenger compartment so that it helps to maintain its integrity during a collision. A reinforced safety cage surrounds passengers with a rigid, high strength structure. This reinforced safety cage is then combined with front and rear "crumple zones" that are designed to absorb crash energy and minimize intrusion into the passenger compartment.

The best way to survive a crash is to avoid it altogether. Many crash avoidance features have been incorporated into automobiles to improve this capability.

In 1984 the center-high-mounted stop lamp was introduced as standard equipment. By making cars more visible from the rear, the intent is to reduce rear end collisions. Data indicates rear end collisions are reduced by up to 17 percent.

Other accident avoidance options like Anti-lock Brakes and traction control help the driver maintain steering control under various types of adverse roadway conditions. Brakes, suspension, tires are all engineered as a system to maximize vehicle control.

And soon it will be easier to avoid GM cars and trucks. That's the advantage of daytime running lights. Daytime running lights are special headlights that come on whenever you start your engine. Cars that have them are often easier to see, and that can help other drivers avoid collisions. This fall, General Motors will be the first automaker to offer low intensity daytime running lights as standard equipment on thousands of its U.S. cars and trucks.

As you can see, what has been occurring regarding the safety of vehicle occupants over the past 30 years is substantial. But what does the future hold regarding further advancement in vehicle occupant protection and crash avoidance? Where do we go from here?

In the realm of test tools, safety researchers from GM and the University of Michigan are developing and refining the world's first "pregnant" crash test dummy as a new tool to help study the effects of vehicle crashes on pregnant women and their unborn infants. What makes the pregnant dummy unique is that it carries a special fetal insert consisting of a simulated seven-month-old fetus suspended in a special urethane gel that closely approximates the specific gravity of amniotic fluid.

Cars and trucks of the future will become smarter and most future crash avoidance technologies will be aimed at extending the driver's senses.

Obstacle detection systems, using radar and/or sonar, are under development. These systems warn the driver of objects behind the vehicle or in "blind" spot areas.

Adaptive cruise control is a radar based system which assists drivers to maintain proper separation from vehicles detected ahead and alerts the driver when necessary.

GM is developing a lane sensing system called "Lane Lok" which is a real time computer vision system. The system identifies road markers without the need for special markings as well as curvatures. It then calculates the vehicles position to provide a warning to the driver when the vehicle starts to go off course.

Night vision enhancement is another technology taken directly from military applications. The system uses infrared (heat) sensing and display technologies. Night vision aide in defining vehicle position on dark roadways and provides a distinct advantage in low visibility situations such as when rain or fog exists. All of these systems may eventually find their way into the vehicle of the future.

Navigational aid systems use satellite navigation or other methods to locate the vehicle and communication systems to route drivers from where they are to where they want to go. They do this while helping them avoid areas of congestion. GM was directly involved in such programs as "Travtek" and "Pathfinder" to test navigation systems in Florida and California.

As a result, GM is now able to offer a production system as an option on 1994 Oldsmobile and 88 LSS models sold in California. The system will be made available country-wide within the next two years, as roadway data bases are completed.

Improvements in vehicle technology will come as a result of looking at the vehicle as an integrated system of crash avoidance and crash protection features. These diverse technologies all work together to provide incremental benefits and come into play at the moment when needed. Along with this technology, we must not forget to keep a constant focus on enhancing resolution of issues involving driver behavior as well.

EVOLUTION OF VEHICLE CRASHWORTHINESS AS INFLUENCED BY THE NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

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The design, development, and production of an automobile is an extremely complicated, difficult, and competitive process. Not only must good judgements about the design, size, cost, market segment, and many other characteristics of a vehicle be made many years in advance of its first public appearance, the many processes that merge the initial decisions and ideas into a viable product must be efficient and functional for a manufacturer to create a marketable product. As the nation's concerns for protecting the environment, conserving natural resources, and improving public safety continue, each of the technologies that direct, develop, and evaluate these various aspects of a vehicle's design should also become more effective, efficient, and timely(1).

One aspect of vehicle design, the safety afforded by the vehicle, provides no exception to the above statement. Reducing the human losses from highway crashes is a complex challenge to both the vehicle manufacturing industry and to the government. Motor vehicle crash injuries result from unfortunate coincidences of many human, technological, and environmental factors. Eliminating injuries and fatalities requires effective and balanced strategies and actions.

The Department of Transportation (DOT) is charged with the responsibility for reducing losses from motor vehicle crashes on U.S. highways. One agency of DOT, the Federal Highway Administration (FHWA), sets standards for highway design; another agency, the National Highway Traffic Safety Administration (NHTSA), sets standards for motor vehicle safety performance; and both agencies implement a variety of highway and traffic safety programs. The Department works in many constructive ways with state and local governments, industry, and other private groups to improve safety on our roads(2).

This paper presents an overview of safety technologies introduced into motor vehicle designs that have been realized as a result of actions taken by the National Highway Traffic Safety Administration in meeting its safety mandate.

SAFETY PROBLEM

Before discussing the technologies that have been introduced into vehicle designs to improve vehicle safety, it is important to understand the magnitude of the safety problem associated with motor vehicle crashes. This section provides that overview.

The historical magnitude of the motor vehicle safety problem may be grasped by comparing the number of deaths that have occurred on U.S. roads (2,766,590) from 1900 to 1989 with the total number of deaths of Americans that have occurred in all U.S. wars since the nation was founded in 1776 (1,186,654) [3]. Each year in this nation, about 40,000 people die as a result of motor vehicle crashes, For example, in 1992, there were 39,235 fatalities (32,869 vehicle occupants, 6,366 nonmotorists) in 34,928 motor vehicle crashes [2]. This is the equivalent to the losses that would be incurred if a major commercial airline were to crash every day, 365 days a year.

In addition to the fatalities suffered in 1992, there were 416,000 persons injured with incapacitating injuries (i.e., an injury, other than a fatal injury, which prevents the injured person from walking, driving, or normally continuing the activities the person was capable of performing before the injury occurred), 863,000 persons injured with nonincapacitating injuries (i.e., an injury, other than a fatal or incapacitating injury, which is evident to observers at the scene of the accident), and 1,790,000 other injuries (i.e., injuries claimed by an individual but not evident to an observer). These add up to 3,070,000 total injuries in 1992. Each year, the years of potential life lost amount to 1.4 million and the related economic losses total $75 billion(3).

SAFETY IMPROVEMENTS

The NHTSA has been very instrumental in introducing safety technologies into vehicle design. Figure 1 provides a summary look at these technologies. Over the years, crashworthiness improvements to passenger cars have been implemented due to standards issued for roof crush resistance, seat belts and automatic protection, head restraints, steering wheel impact protection, padded dash and interior protection, side door impact protection, child safety seats, fuel system integrity, door locks, window glazing, and bumper requirements. The next section provides a summary of the crashworthiness related Federal motor vehicle safety standards. Another agency program, the New Car Assessment Program (NCAP), provided motivation for manufacturers to improve some aspects of safety design beyond that required by the safety standards. This program is summarized as well.

FEDERAL MOTOR VEHICLE SAFETY STANDARDS

In September of 1966, the National Traffic and Motor Vehicle Safety Act was signed into law. The law directs the Secretary of Transportation to issue Federal motor vehicle safety standards (FMVSS) to which motor vehicle manufacturers must conform. The first such standards became effective on all vehicles manufactured on or after January 1, 1968, for sale or use in the United States, with the exception of FMVSS No. 209, which was effective upon issuance on March 1, 1967. Additional standards have been added and others are in the process of being developed and issued. The following provides a brief description of the crashworthiness related standards.

Standard No. 201, Occupant Protection in Interior Impact, specifies requirements for padded instrument panels, seat backs, sun visors, and armrests. Additionally, glove compartment doors are required to remain closed during a crash. Over a wide range of speeds, injuries suffered by occupants are largely determined by how well the structures on the inside of the vehicle cushion the human body striking them.

Standard No. 202, Head Restraints, specifies requirements for head restraints to reduce the frequency and severity of neck injuries in rear end and other collisions.

Standard No. 203, Impact Protection for the Driver from the Steering Control System, specifies requirements for minimizing chest, neck, and facial injuries by providing steering systems that yield forward, cushioning the impact of the driver's chest by absorbing much of the driver's impact energy in frontal crashes. Such systems are highly effective in reducing the likelihood of serious and fatal injuries.

Standard No. 204, Steering Control Rearward Displacement, specifies requirements limiting the rearward displacement of the steering column into the passenger compartment to reduce the likelihood of chest, neck, or head injuries.

Standard No. 205, Glazing Materials, specifies requirements for all glazing materials used in windshields, windows, and interior partitions of motor vehicles. Its purpose is to reduce the likelihood of lacerations and to minimize the possibility of occupants penetrating the windshield in collisions.

Standard No. 206, Door Locks and Door Retention Components, requires locking systems and specifies load requirements for door latches and door hinge systems to minimize the probability of occupants being thrown from the vehicle as a result of impact forces encountered by the vehicle during a crash.

Standard No. 207, Seating Systems, establishes requirements for seats, their attachment assemblies, and their installation to minimize the possibility of failure as a result of forces acting on the seat during a vehicle crash.

Standard No. 208, Occupant Crash Protection, specifies requirements for both active and automatic occupant crash protection systems. The most recent upgrade required that vehicles be equipped with air bag systems. With this requirement, improved knee bolsters were necessary to control occupant kinematics and femur loadings.

Standard No. 209, Seat Belt Assemblies, specifies requirements for seat belt assemblies. The requirements applies to straps, webbing, or similar materials, as well as to all necessary buckles and other fasteners and all hardware designed for installing the assembly in a motor vehicle, and to the installation, usage, and maintenance instructions for the assembly.

Standard No. 210, Seat Belt Assembly Anchorages, specifies requirements for seat belt assembly anchorages to ensure effective occupant restraint and to reduce the likelihood of failure in collisions.

Standard No. 211, Wheel Nuts, Wheel Discs, and Hub Caps, requires that "spinner" hub caps and other winged projections (both functional and nonfunctional) be removed from wheel nuts,wheel discs, and hub caps. Its purpose is to eliminate a potential hazard to pedestrians and cyclists.

Standard No. 212, Windshield Mounting, requires that each windshield mounting must be anchored in place and retain specified percentages of its periphery in a crash situation. The purpose of this standard is to keep vehicle occupants within the confines of the passenger compartment during a crash.

Standard No. 213, Child Seating Systems, specifies requirements for dynamic testing of child seating systems to minimize the likelihood of injury and/or death of children in vehicle crashes or sudden stops. The standard also includes requirements for providing information regarding proper installation and use of the child seats.

Standard No. 214, Side Impact Protection, specifies requirements for crush resistance levels in side doors of passenger cars to minimize the safety hazard caused by intrusion into the passenger compartment in a side impact accident. More recently, the standard has been updated to incorporate occupant protection requirements from a dynamic side impact test procedure. This new requirement is leading to improved door paddings and upgraded vehicle side structures.

Standard No. 216, Roof Crush Strength, sets minimum requirements for roofs to reduce the likelihood of roof collapse in a rollover accident. This standard provides an alternative to conformity with the rollover test requirements of Standard No. 208.

Standard No. 219, Windshield Zone Intrusion, regulates the intrusion of vehicle parts outside the occupant compartment into a defined zone in front of the windshield during a frontal barrier crash test. Its purpose is to reduce crash injuries and fatalities that

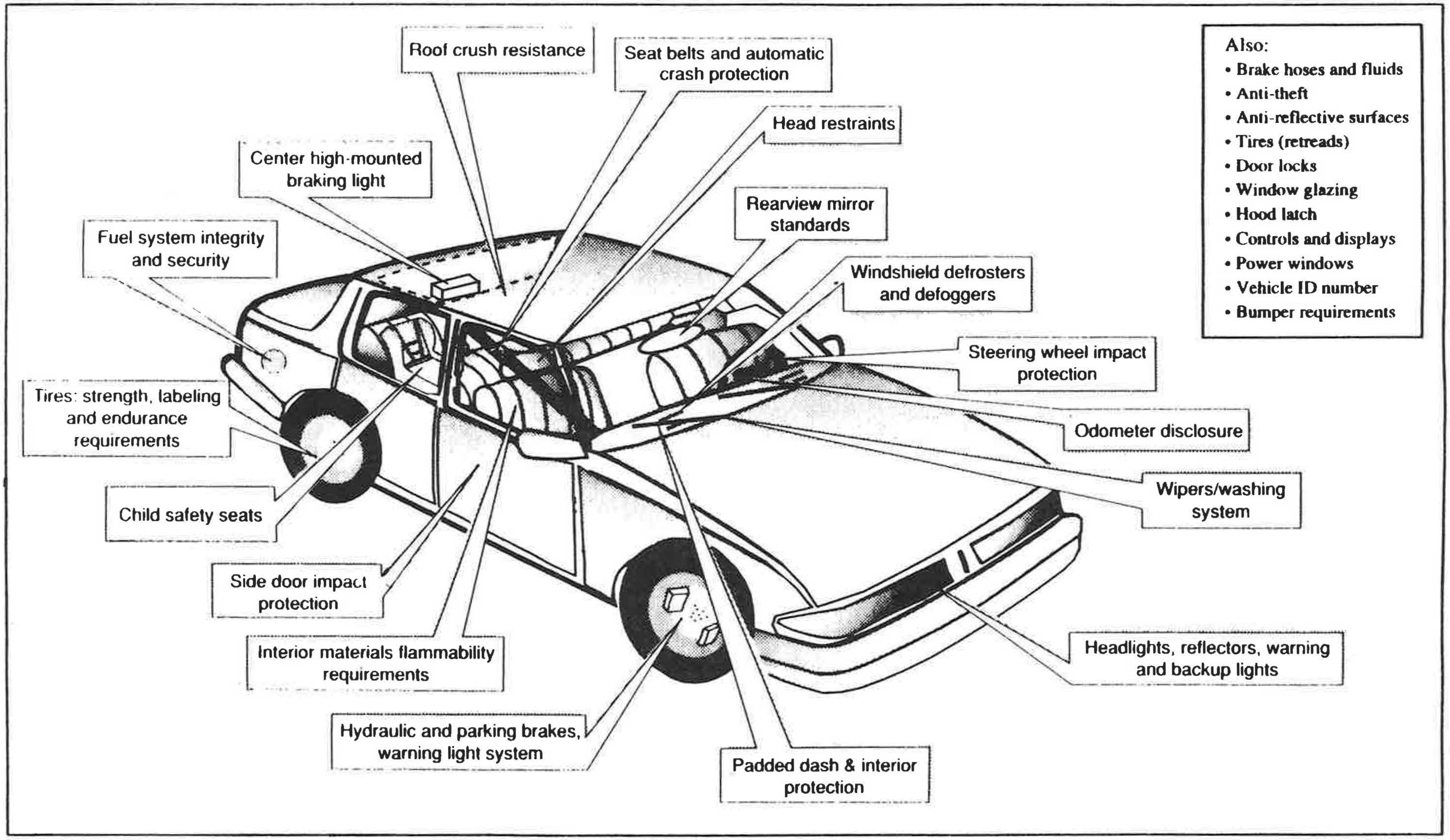

FIGURE 1 NHTSA's motor vehicle safety standards.

result from occupants contacting vehicle components displaced near or through the windshield.

Standard No. 301, Fuel System Integrity, specifies requirements for the integrity of the entire fuel system, including the fuel tanks, fuel pump, carburetor, emission controls, lines, and connections in severe front, rear, or lateral barrier impact crash tests. Manufacturers must also be able to demonstrate that fuel loss will not exceed one ounce per minute in s static rollover test following these barrier crash tests, as well as not exceeding these limits after, and incidental to, the crash tests.

Standard No. 302, Flammability of Interior Materials, specifies burn resistance requirements for materials used in the occupant compartment of motor vehicles in order to reduce deaths and fires causes by vehicle fires.

NHTSA has evaluated several of the crashworthiness safety standards including those pertaining to side door strength, restraint systems, roof crush resistance, and steering assemblies. As part of these evaluations, benefit estimations were developed. These are summarized in Table 1. Note that the benefits are representative only of the year on which the evaluation was based.

Historical and cumulative effects of safety standards can be estimated by adjusting the full fleet estimates in Table 1 for model year safety equipment content and fatality experience(4). Table 2 summarizes such estimates by year for each of the crashworthiness standards evaluated since 1967. Note that in some instances safety equipment was installed on some vehicles prior to the effective date of the standard. Therefore, although these estimates represent savings from the safety equipment that is required to meet safety standards, they do not necessarily correspond with the effective date of the standard.

NEW CAR ASSESSMENT PROGRAM

In 1978, the NHTSA began the crashworthiness assessment of new cars by conducting high speed 35-mph frontal barrier crash tests. The New Car Assessment Program's (NCAP's) primary goals are to provide consumers with a measure of the relative safety potential of automobiles and to establish market forces which encourage vehicle manufacturers to design higher levels of safety into their vehicles. NCAP represents the first program ever initiated to provide relative crashworthiness information to consumers on potential safety performance of passenger vehicles(5).

The test conditions for NCAP are based on years of development work conducted by NHTSA, the automobile industry, and others to develop the test devices and test procedures used in measuring compliance to the passive restraint requirements of FMVSS No. 208. For these requirements, certain injury criteria, as measured by the anthropomorphic dummies, are not to be exceeded in a 30 mph frontal barrier crash. The injury criteria apply to the head (as measured by a composite of acceleration values known as the Head Injury Criterion, or HIC), chest (as measured by chest deceleration, chest Gs), and upper leg (as measured by femur axial compression loads). These criteria are used to evaluate the compliance of vehicles to the safety standard and to assess the performance of the vehicles in the NCAP tests.

The major differences between the NCAP tests and the FMVSS No. 208 tests, which have been conducted for model year (MY) 1987 through 1994 passenger cars, are the nominal speed at which the tests are conducted (i. e., 30 versus 35 mph) and the use of all available restraint systems in the NCAP tests as compared to only the use of the passive restraint systems in the FMVSS No. 208 tests. (Note: The exception to this is the condition in which the vehicle has a driver air bag and a manual safety belt system for the right front passenger. In the FMVSS No. 208 test, the vehicle is then tested with the air bag as the restraint for the driver and the manual system for the passenger)[1]. Other minor variations between the two test conditions include that for the NCAP tests, dummies are not calibrated as often as in the FMVSS No. 208 tests, a load cell barrier is attached to the fixed rigid barrier, and additional instrumentation is used (e.g., load cells on the safety belts).

The NCAP crash tests are conducted at 35 mph in order to provide a level of impact severity sufficiently higher than the 30 mph FMVSS No. 208 test speed so that possible differences in frontal crash safety performance can be observed. As calculated from the kinetic energy, a 35 mph crash is about one-third more severe than a crash at 30 mph.

In these 35 mph crash tests, the vehicle experiences a total change in velocity, including rebound from the barrier, of approximately 40 mph. In a 30 mph crash test, the change in velocity is approximately 33 mph. From examination of the National Accident Sampling System (NASS) files, the fatality and injury rates for restrained front seat occupants are two to three times greater in a crash with a 40 mph change in velocity than in a crash with 33 mph change in velocity. For events in which crash severity is determined, the NASS files also show that more than 40 percent of the life-threatening (AIS 4 and greater) injuries and fatalities of occupants in frontal collisions occur in crashes with a change in velocity greater than 33 mph.

NHTSA has now conducted over 400 NCAP crash tests of different passenger cars, light trucks, and vans. The

TABLE 1 ANNUAL FLEET BENEFITS OF MAJOR CRASHWORTHINESS FEDERAL MOTOR VEHICLE SAFETY STANDARDS(4)

FMVSS	Fatalities	Injuries
201 Interior Impact	Up to 700	
202 Head Restraints		64,000
203,204 Steering Assemblies	1,300	
205,212 Windshield Glazing Installation	105	47,000
206,216 Door Locks & Roof Crush Resistance	510	
207 Seat Back Locks	None	None
213 Child Safety Seats	192	
214 Side Impact	480	9,400

data from the driver and passenger dummies are regularly released as part of NHTSA's Consumer Information Program as required by Title II of the Motor Vehicle Information and Cost Savings Act (15 U. S. C. 1942 et seq.).

With MY 1987 automobiles, the mandatory passive safety requirements of Federal Motor Vehicle Safety Standard (FMVSS) No. 208, "Occupant Crash Protection," were phased in. Prior to 1987, only a few vehicles had been voluntarily produced with passive restraint systems. These included General Motors, Ford, and Mercedes air bags and Volkswagen and Toyota passive belts. Beginning in MY 1987, the manufacturers selected either passive belts (2 or 3 point, non-motorized or motorized) or air bags to meet the FMVSS No. 208 requirements.

There are significant differences in the potential safety performance among passenger cars. Head Injury Criterion (HIC) values range from a low of 185 to a high of 4500. Even in model year (MY) 92 vehicles, these values range from a low of 282 to a high of 2021. This indicates that NCAP tests continue to provide consumers with occupant protection information which may be used in purchasing decisions.

Since 1979, significant measurable improvements have occurred in passenger car safety. The average for HIC has decreased by approximately 30 percent from a high of almost 1300 in 1980 to less than 1000 in 1992.

The percentage of passenger cars which meet FMVSS No. 208 requirements in the NCAP tests increased from less than 25 percent in 1979 to over 60 percent in 1992.

The percentage of passenger cars in the higher risk group (HIC exceeds 1250, and/or chest acceleration exceeds 70 gs, and/or femur loads exceed 3000 lbs.) has significantly declined from the early years of NCAP. In MY 1979, more than 50 percent of the passenger cars were in this higher risk group. In MY 1992, less than 25 percent are in this group. Accident data indicate that passenger cars in the lower risk group may expose restrained occupants to significantly lower fatality rates in frontal collisions.

Positive actions have been taken by the manufacturers to institute significant improvements in passenger car safety performance. Many specific examples of vehicle makes and models which were improved after initial NCAP tests can be cited. In some cases, the manufacturers modified the existing model and in other cases the improved safety was incorporated in a complete redesign of the model. Changes incorporated into specific makes and models by the manufacturers reduced high dummy responses by as much as 75 percent.

In addition to the overall trends which have shown the influence of NCAP in improving vehicle safety performance, many specific examples of vehicle makes and models which were improved after initial NCAP tests can be cited.

Two early examples in the program occurred with Volvo and Mercedes models. Each of these manufacturers have traditionally advertised the safety aspects of their vehicles. In 1979, a Volvo 244 DL and, in 1980, a Mercedes 240D, were tested in NCAP. Surprisingly, both of these vehicles had high driver and passenger HIC values. Examination of the safety belts of these vehicles indicated unsatisfactory belt reel-out from the retractors due to excessive belt lengths. This

TABLE 2 ESTIMATED ANNUAL AND TOTAL FATALITY BENEFITS RESULTING FROM CRASHWORTHINESS SAFETY STANDARDS, 1967-1990[(4)]

Year	201	203, 204	205, 212	206, 216	208, 209 210, 213	214	Total
1967					520		520
1968	82	140	7		777		1,005
1969	116	198	17	36	1,081	60	1,508
1970	297	506	32	90	1,334	48	2,307
1971	381	649	47	139	1,614	102	2,932
1972	488	830	65	197	2,296	142	4,018
1973	561	955	80	242	2,425	203	4,466
1974	517	868	75	240	2,501	186	4,387
1975	539	903	79	272	2,163	243	4,199
1976	590	980	97	314	1,936	285	4,202
1977	645	1,065	98	359	1,882	334	4,383
1978	726	1,174	110	411	1,445	391	4,257
1979	744	1,202	113	445	1,250	417	4,171
1980	752	1,215	116	465	1,280	439	4,267
1981	742	1,196	115	467	1,297	442	4,259
1982	666	1,059	102	418	1,138	402	3,785
1983	690	1,096	106	423	1,370	423	4,108
1984	698	1,109	111	447	1,696	441	4,502
1985	681	1,080	106	464	2,506	438	5,275
1986	733	1,182	118	508	3,495	482	6,518
1987	738	1,190	119	512	4,234	497	7,290
1988	757	1,223	122	537	4,823	515	7,977
1989	736	1,186	118	527	4,813	500	7,880
1990	710	1,145	114	507	5,000	482	7,958
Total	13,588	22,151	2,067	8,020	52,876	7,472	106,174

condition allowed severe head contacts to occur between the driver dummies and the steering assemblies, and between the passenger dummies and the instrument panels. Both manufacturers made significant design changes to eliminate these safety problems. Results of their models in succeeding years indicate the success of their changes.

Notable examples occurred when initial tests of several Japanese models resulted in very high dummy responses. These models included the Honda Civic and Prelude, the Mazda 626 and RX-7, and the Toyota Celica, Corolla, and Cressida. Factors which contributed to the poor performance of these models in these initial tests may have included inadequate energy management of

TABLE 3 NCAP EXAMPLES OF VEHICLE SAFETY IMPROVEMENTS

VEHICLE IDENTIFICATION			DUMMY RESPONSE PARAMETERS							
MAKE	MODEL	MY	HICD	HICP	CGD	CGP	LFEMD	RFEMD	LFEMP	RFEMP
VOLVO	DL	79	1782	1889	52	61	320	900	700	320
VOLVO	DL	82	550	381	45	35	154	1147	892	227
VOLVO	DL (SW)	85	621	262	33	31	100	1005	630	615
VOLVO	DL	85	651	310	36	25	350	1020	590	
MERCEDES	240D	80	1262	1369	54	44	674	1687	666	1449
MERCEDES	300SD	84	890	734	63	44	1410	1150	295	490
MERCEDES	190E	90	800	833	60	58	705	1028	582	331
DODGE	COLT	82	932	1730	72	44	517	782	506	276
DODGE	COLT	85	787	741	42	32	480	460	1090	370
RENAULT	MEDAL.	88	1656	873	57	38	205	617	411	1193
EAGLE	MEDAL.	89	745	589	41	39	1721	1738	1574	1670
FORD	GRANADA	79	1442	1279	61	56	1750	350	390	570
FORD	GRANADA	82	860	1050		52	980	800	460	340
FORD	TAURUS	86	1209	695	53	37	828	1485	566	502
FORD	TAURUS	88	707	359	38	47		775	455	438
FORD	TEMPO	84	2955	1104	63	45	750	480	675	370
FORD	TEMPO	85	1207	932	52	40	870	580	440	310
FORD	TEMPO	88	721	470	47	50	1113	1773	1037	702
HONDA	CIVIC	79	2030	2093	93	46	1080	838	1520	1460
HONDA	CIVIC	80	2626	1506	54	47	1006	3118	418	218
HONDA	CIVIC	81	607	492	41	35	200	500	1100	540
HONDA	CIVIC	84	563	846	37	43	1067	602	1566	1275
HONDA	PRELUDE	80	2904	1759	52	45	445	1057	465	277
HONDA	PRELUDE	84	659	475	43	31	600	510	690	980
HYUNDAI	EXCEL	86	999	2662	73	55	2248	785	1597	520
HYUNDAI	EXCEL	87	757	345	54	46	2408	1794	1187	1006
HYUNDAI	EXCEL	87	716	1003	55	43	790	345	1360	775
HYUNDAI	EXCEL	90	696	419	41	39	1385	1921	1682	964
MAZDA	626	82	969	1693	47	50	575	1215	550	250
MAZDA	626	83	1196	1087	45	56	450	350	260	360
MAZDA	626	87	846	801	52	46	820	1300	1487	1255
MAZDA	RX-7	85	921	1345	40	42	369	476	604	809
MAZDA	RX-7	88	921	614	39	48	186	1135	268	650

TABLE 3 (continued)

VEHICLE IDENTIFICATION			DUMMY RESPONSE PARAMETERS							
MAKE	MODEL	MY	HICD	HICP	CGD	CGP	LFEMD	RFEMD	LFEMP	RFEMP
VOLVO	DL	79	1782	1889	52	61	320	900	700	320
MERCURY	SABLE	86	1237	680	48	44	1039	1780	671	465
MERCURY	SABLE	88	712	410	51	35		1512	862	913
PONTIAC	FIREBIRD	79	965	1297	42	47	582	472	503	717
PONTIAC	FIREBIRD	83	408	376	34	32	900	480	100	125
AAB	9000	86	773	1443	71	46	484		541	421
SAAB	9000	87	584	440	37	35	120	346	435	638
TOYOTA	CELICA	79	849	1862	61	59	2920	435	400	520
TOYOTA	CELICA	82	702	530	36	45	456	448	360	359
TOYOTA	CELICA	86	627	430	42	40	382	721	439	593
TOYOTA	CELICA	90	834	685	50	37	1071	1190	406	609
TOYOTA	COROLLA	80	838	1162	69	92	740	775	200	270
TOYOTA	COROLLA	82	842	828	59	40	1400	1178	888	507
TOYOTA	COROLLA	84	630	611	41	42	1320	730	340	395
TOYOTA	COROLLA	89	994	546	49	45	1101	894	451	681
TOYOTA	COROLLA	84	432	602	37	47	1100	450	580	300
TOYOTA	COROLLA	88	593	397	42	40	719	1162	300	393
TOYOTA	CRESSIDA	81	1980	771	55	50	1710	1982	1644	1807
TOYOTA	CRESSIDA	85	883	914	50	58	1725	1820	1355	1820
TOYOTA	CRESSIDA	89	790	544	51	51	1632	1554	1246	1107
VW	JETTA	81	1210	1272	68	52	1276	1191	1559	1286
VW	JETTA	85	898	1008	50	51	362	396	711	516
AUDI	4000	80	1322	1428	70	45	408	353	1030	527
AUDI	5000	85	2105	557	39	31	362	357	292	326
AUDI	100	89	185	710	35	31	998	571	894	757

the crash forces (i. e., poor structural design), excessive intrusion and inappropriate collapse characteristics of the steering assembly and instrument panels, and inferior safety belt parameters. The data in Table 3 indicate the manufacturers' positive reactions to improve the safety performance of these models. In some cases, the manufacturers modified the existing model, and in other cases the improved safety was incorporated in a complete redesign of the model. Relative to the improvements in potential occupant protection, the results, as shown in the table, were exceptional. HIC values were reduced by as much as 75 percent and chest Gs and femur loads were reduced by 50 percent or more.

Other interesting examples have occurred with the beginning of the New Car Assessment "Optional Test"

Program in 1986. This program gives to the manufacturers the option to request a test or retest of a particular vehicle model, based on design changes to a previously tested model or the introduction of innovative safety features. This optional test is sponsored by the manufacturer but conducted by following the NCAP test procedures under NHTSA control at a NHTSA approved test site.

The Mercury Sable, the Ford Taurus, and the Audi 100 are examples of models which have been tested in this optional program. For the Sable and the Taurus, the manufacturers incorporated design changes after the initial NCAP tests were conducted. The retests indicate the potential for improved occupant protection.

For the Audi 100, the manufacturer requested the optional test because of innovative safety features, which included a driver air bag and unique safety belt pre-tensioning devices. All dummy responses were low in the Audi 100 test with the driver HIC of 185 being the lowest HIC ever recorded in the NCAP 35 mph test. The manufacturer (Audi) has used these data extensively in advertising campaigns to inform consumers of the occupant safety provided by the Audi 100. Data are shown in Table 3 of other Audi models. These data show the inferior NCAP performance of previously tested Audi models. The comparison between the previous Audi models and the new Audi 100 and the use of the Audi 100 NCAP results in the advertising campaigns may represent a change in philosophy by the manufacturer toward NCAP safety performance.

Table 3 contains several other examples from different manufacturers which illustrate the capabilities to introduce improvements in safety performance in particular makes and models.

SUMMARY

Over the years, crashworthiness improvements to passenger cars have been implemented due to standards issued for roof crush resistance, seat belts and automatic protection, head restraints, steering wheel impact protection, padded dash and interior protection, side door impact protection, child safety seats, fuel system integrity, door locks, window glazing, and bumper requirements. Another agency program, the New Car Assessment Program (NCAP), provided motivation for manufacturers to improve some aspects of safety design beyond that required by the safety standards. In responding to NCAP, manufacturers have improved the poorer performance resulting from inadequate energy management of the crash forces (i.e., poor structural design), excessive intrusion and inappropriate collapse characteristics of the steering assembly and instrument panels, and inferior safety belt parameters.

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METHODS FOR ANALYZING THE COST-EFFECTIVENESS OF ROADSIDE SAFETY FEATURES

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Highway agencies are continually faced with decisions relating to roadside safety, from the use and selection of specific roadside safety features and appurtenances at specific locations to the development of warrants, policies, and guidelines on a system-wide basis. In today's environment of ever increasing demand and decreasing resources, it is crucial to make sure that the best use is made of the limited funds available. Cost-effectiveness analysis provides a logical and systematic approach to these decisions, from comparing alternatives and selecting the most cost-beneficial alternative to the development of warrants, policies, and guidelines.

This presentation provides brief descriptions of various existing cost-effectiveness analysis procedures and how the procedures are used in actual applications, followed by an overview of the cost-effectiveness analysis methodology. Some future research needs to improve on existing cost-effectiveness analysis procedures are then suggested as a starting point for discussions in the breakout group sessions.

OVERVIEW OF COST-EFFECTIVENESS ANALYSIS

Most existing cost-effectiveness (C/E) analysis procedures are based on the benefit/cost (B/C) methodology and the two terms, cost-effectiveness and benefit/cost analysis, are often used interchangeably. The basic concept behind the benefit/cost analysis is that public funds should be invested only in projects where the expected benefits would exceed the expected direct costs of the project. Benefits are measured in terms of reductions in accident or societal costs from decreases in the frequency or severity of accidents. Direct highway agency costs are comprised of initial installation, maintenance, and accident repair costs. An incremental benefit/cost ratio between the additional benefits and costs associated with an improvement option over the existing conditions or another improvement option is normally used as the primary measure of whether or not a safety improvement investment is appropriate. The formulation of the incremental benefit/cost ratio is expressed as follows:

$$B/CRatio_{2\text{-}1} = \frac{B_2 - B_1}{C_2 - C_1} \tag{1}$$

where

$BC_{2\text{-}1}$ = Incremental B/C ratio of alternative 2 compared with alternative 1
B_1,B_2 = Annualized accident or societal cost of alternatives 1 and 2
C_1,C_2 = Annualized direct cost of alternative 1 and 2

When the incremental benefit/cost ratio is greater than 1, the analysis indicates that, comparing safety improvement alternative 2 to alternative 1, the benefits of alternative 2 are greater than the increased costs associated with that improvement.

A variety of cost-effectiveness analysis procedures have been developed over the years. These procedures can be classified as either encroachment probability based or accident data based models. Brief discussions on these two types of cost-effectiveness analysis procedures are outlined below.

ENCROACHMENT PROBABILITY BASED PROCEDURES

All encroachment probability based cost-effectiveness procedures are predicated on the concept that run-off-road accident frequency can be linked to roadside encroachment frequency through a probability model. McFarland and Ross(1) developed the first encroachment probability model to estimate the frequency of luminaire impacts. The authors proposed most of the major components of modern encroachment probability models. However, due to data limitations, this early model was somewhat simplistic in that all vehicles were assumed to encroach onto the roadside at the same speed and angle. Further, the model was developed for the specific purpose of predicting impacts with point hazards and therefore was not general in nature. Glennon(2)generalized and refined this procedure for application to any run-off-road situation.

The first cost-effectiveness procedure to be widely used by practicing engineers was published in the 1977

AASHTO *Guide for Designing, Selecting, and Locating Traffic Barriers*.(3) This model was very similar to previous procedures in that it assumed constant encroachment angles and speeds. Accident severity estimations were based on the collective judgement of a panel of highway safety experts. Although the survey requested information regarding average severity, most respondents envisioned high speed impacts when assigning the severity. Thus, resultant severity for most hazards was very high. The 1977 AASHTO Barrier Guide procedure was originally presented in a graphical format, but many highway agencies developed computer programs to simplify its use.(4) Major limitations associated with this procedure include overestimated impact severity, high encroachment frequencies, and a cumbersome analysis procedure.

Many of these problems were addressed in a comprehensive benefit/cost model, called ABC, developed by the Texas Transportation Institute.(5) Specific improvements included a hazard imaging system, velocity-dependent accident severity, real-world impact conditions, and a distribution of vehicle sizes. The hazard imaging system was designed to consider the effect of one hazard shielding another so that the program could properly evaluate the effectiveness of shielding hazards with barriers. Before this technique was implemented, every guardrail, regardless of length, was assumed to eliminate all accidents involving the shielded hazard.

The TTI ABC program also linked accident severity to impact speed and angle. Accident severity for specific impact conditions was estimated using data from full-scale crash tests and computer simulation. Distributions of impact speed and angle were identified from computerized reconstructions of real-world accidents. A distribution of vehicle sizes was also incorporated into the TTI ABC program in an effort to further refine severity estimates. This approach linked safety hardware performance to both vehicle size and accident severity. In this manner, performance limits of barriers or crash cushions were predicted based on vehicle size, impact speed, and impact angle and accident severity estimates were then revised when the performance limit was exceeded.

The TTI ABC program resolved many of the problems associated with previous benefit/cost analysis procedures, including the ability to study the effects of different barrier configurations and parameters, such as runout length and flare rate. However, due to the lack of a user friendly interface and proper distribution, the program never gained wide acceptance. Another problem associated with this program is the relatively coarse speed, angle, and vehicle size distributions used in the model. This limitation prevented the program from identifying small geometric differences between two guardrail treatment alternatives.

The Federal Highway Administration (FHWA) revised the TTI ABC program to develop the Benefit Cost Analysis Program (BCAP).(6) The BCAP program incorporated several unique features, including an algorithm to allow encroaching vehicles to decelerate after leaving the road, acceleration-based accident severity estimates, and refined vehicle type and encroachment speed and angle distributions. The BCAP program's encroachment model assumed that all vehicles would decelerate at a constant rate after encroaching into the roadside. The program also incorporated procedures for predicting the average lateral accelerations during longitudinal barrier impacts and using them to predict accident severity. One area of the program that was significantly improved over previous procedures was the refinement of the encroachment speed and angle and vehicle size distributions. This refinement eliminated some of the inconsistencies observed with the TTI ABC program.

Although the BCAP program was distributed with an ostensibly user friendly preprocessor, the user interface was so cumbersome and difficult to use that most users found it worse than conventional batch processing. A comprehensive review of the BCAP program recently identified several problems with the code that caused the program to overpredict the numbers of barrier penetrations and underestimate vehicle rollovers.(7) Also, the distributions of encroachment speed, angle, and lateral extent of encroachment were found to be somewhat different than those found in encroachment and accident studies.

The FHWA developed the ROADSIDE program, which is included as an Appendix to the 1988 AASHTO *Roadside Design Guide*(8), in an effort to provide highway agencies with a simplified cost-effectiveness analysis procedure that did not require as much input data as the more sophisticated BCAP program. The ROADSIDE program is a simplified version of the BCAP program and retained many of the basic features. Unfortunately, the ROADSIDE program did not retain the encroachment speed and angle distributions nor the algorithm for predicting impact conditions contained in the BCAP program. Instead, average impact severity was used in the same manner as the procedures contained in the 1977 AASHTO Barrier Guide. These simplifications severely limited the usefulness of the program since it could no longer predict when the performance limits of safety hardware were exceeded. Also, the impact severity had to be estimated from police level accident data or engineering judgement. Sensitivity analyses on the TTI ABC and BCAP programs demonstrated that benefit/cost analysis procedures are most sensitive to impact severity estimates. Thus, the accuracy of the ROADSIDE program is greatly diminished due to the relatively crude impact severity estimation algorithms.

An effort to develop improved cost-effectiveness analysis procedures is currently underway in NCHRP Project 22-9 conducted by TTI.(9) The procedures will be based on the encroachment probability model and will include the best features from the existing procedures plus new additions and improvements.

ACCIDENT DATA BASED PROCEDURES

Benefit/cost analysis procedures based on accident data utilize statistical models developed from analysis of police level accident data to predict accident frequencies and severity. These procedures fall into two general categories: site specific and feature specific models. Site specific techniques utilize the accident history at a specific site to predict future accident occurrences.(10) The basic approach is to use statewide accident data bases to determine average severity of various types of roadside accidents and accident reduction factors for different safety treatment options. The benefits of an accident countermeasure are merely differences in the historical accident costs and the expected future accident costs associated with a proposed safety improvement. These procedures are widely used to evaluate safety improvements on existing highways, especially in hazard elimination programs. The primary advantage of this technique is that the accident experience pertains to the specific site and includes the effects of the specific roadway and roadside features. Unfortunately, these techniques often rely on a very limited number of accidents and therefore their accuracy is sometimes questioned. However, these procedures continue to be the most appropriate means of identifying accident loss reductions that can be expected from roadside safety improvements at sites where significant accident history is available.

Benefit/cost analysis procedures based on feature-specific accident data are generated through statistical models developed from analysis of large accident data bases. These data bases must contain a great deal of roadway and roadside information so that the resulting accident prediction models can include such important variables as traffic volume, highway alignment, and hazard size and location. Police level accident records do not contain all of this information and therefore must be supplemented with roadway inventory data and/or information collected from field investigations. Unfortunately, roadway inventory files maintained by highway agencies seldom contain information concerning the roadside such as sideslope, or type, quantity and characteristics of roadside hazards and features. Thus, field investigations are often necessary to obtain the data required for analysis.

Accident data based accident prediction algorithms involve correlating roadway and roadside conditions with the observed accident frequencies using some form of regression analysis techniques. One of the major problems with police level accident data is the extent of unreported accidents, i.e., accidents that are not reported to law enforcement agencies for whatever reasons. Some roadside features, such as breakaway sign and luminaire supports, have a very high incidence of unreported accidents while other hazards, such as utility poles, have a relatively low rate of unreported accidents. As a result, accident prediction algorithms must be developed separately for each roadside hazard or feature type. This greatly complicates the process of developing general accident prediction routines necessary for a benefit/cost analysis model used to evaluate roadside safety improvements.

Other problems associated with police level accident data include inaccurate and improper coding by the reporting officers, incorrect use of nomenclature, lack of detail on the reported variables, and inaccurate location coding of accidents.(11) The poor quality of police level accident data oftentimes raises questions about the accuracy and validity of the results from accident data based studies.

The extreme variability in accident rates and the large numbers of highway variables that could potentially affect run-off-road accident frequencies also presents major problems when developing accident prediction algorithms. Run-off-road accident rates are affected by a large number of factors, many of which are unrelated to roadway, roadside, and traffic conditions and cannot be properly considered in an accident data regression analysis, such as driver demographics, drinking establishment locations, and economic vitality of the local economy. As a result, even the best accident data based prediction models could seldom explain more than 50 percent of the variations in accident frequencies or rates based on roadway, roadside and traffic variables. Exposure, or the opportunities for an accident to occur, accounts for most of this correlation obtained in the regressions equations. When the effect of exposure is taken into account, such as using accident rate (i.e., accidents per million vehicle miles of travel) as the dependent variable, the resulting prediction models generally explain less than 25 percent of the observed variations.

Further, the number of roadway, roadside, or traffic variables that are found in regression models to have a significant effect on accident frequency or rate is typically very small, e.g., 5 or less, and most of these variables are exposure related. Beyond this handful of significant variables, the other variables would have very little effect on accident frequency or rate and are statistically insignificant. Variables of interest are oftentimes forced into the regression equations even though they are not significant in order to be included in the model. For example, in a major study to develop procedures for predicting utility pole accident frequency, the researchers found that only traffic volume, pole density, and pole offset had any significant effect on utility pole accident frequency.(12) Note that all of these variables are closely related to exposure. Traffic volume and pole density are the two variables that control the number of times that a vehicle passes by a utility pole and has the opportunity for an accident. Pole offset can also be considered an exposure factor since it strongly effects the chances that an errant vehicle will encroach far enough onto the roadside to cause an accident.

A computer program, called UPACE, was developed based on this accident prediction model to help engineers determine when utility pole countermeasures should be taken. The program has gained some distribution, but has not been widely implemented. The specificity of the program has tended to limit its usefulness. Most highway engineers do not encounter a utility pole safety analysis with enough regularity to develop a widespread interest in this code.

Another effort to develop accident data based prediction procedures involved an investigation of the effects of cross-sectional design parameters on accident rates.(13) Regression equations were developed relating accident frequencies and rate to various roadway and roadside parameters, such as lane width, shoulder width, traffic volume, roadside recovery distance, type of terrain, and roadside sideslopes. Note that roadside hazards and features were classified only in terms of a general hazard rating, with no specificity regarding the type or density of hazards or features. Accident reduction factors were derived from the regression models which may be used as inputs to benefit/cost analysis. The predictive power of the regression models is generally limited and some of the included parameters were apparently forced into the models with little statistical significance. Findings from this study would not be directly applicable to most roadside countermeasure evaluations.

APPLICATIONS OF COST-EFFECTIVENESS PROCEDURES

Cost-effectiveness analysis procedures are used for three general purposes, evaluation of safety improvements at a specific site, development of warrants, policies and guidelines, and establishment of multiple performance level selection guidelines. Both accident data based and encroachment probability based procedures are used to evaluate countermeasure effectiveness at specific sites. Many state highway agencies require a benefit/cost analysis of all projects to be funded using safety funds. Thus, these procedures are widely used. Accident data based procedures are believed to be the better approach for predicting future accident frequency provided sufficient accident data are available during which the roadway geometrics and traffic patterns were not changed significantly. As discussed previously, these procedures are based on the assumption that the accident experience will remain unchanged in the future.

It is sometimes appropriate to utilize encroachment probability based accident procedures even when the historical accident record indicates no accidents at that site. When very severe hazards are located close to the roadway, safety treatments can be justified even though a reported accident may only occur infrequently. Thus, some states use encroachment probability based analyses even when historical accident data is available.

Historical accident data are no longer meaningful when major changes occurred to highway geometrics or traffic patterns. For example, run-off-road accident frequencies would be expected to change significantly when a highway is realigned to straighten sharp curves. In this case, highway engineers can no longer evaluate roadside safety treatment options with an accident data based procedure since the conditions have changed significantly to render the historical accident pattern inappropriate. An encroachment probability based procedure would be the choice even though the procedure cannot accurately evaluate all of the local conditions at a specific site. The encroachment probability based procedure should be capable of predicting average accident frequencies for all sites similar to the one under consideration. Although the model would be expected to be in error for specific sites, it should select the appropriate safety treatment for the average site. Prior analysis of encroachment probability based models indicates that they are most sensitive to accident severity estimates and only moderately sensitive to accident frequency estimates.(7,14) Therefore, inaccuracies in the prediction of accident frequencies would have much less effect on the validity of the analysis results provided the severity estimates are appropriate.

As mentioned previously, accident data based prediction models are very specific in nature and cannot be readily extended for use with other roadside features. Thus, encroachment probability based models are currently the only available alternative for development of general use guidelines for roadside safety hardware. Development of safety improvement implementation guidelines involves conducting cost-effectiveness analysis of a limited number of typical roadside sites. The study sites are selected to be representative of common highway situations on various highway classes. A large number of runs are then conducted while varying pertinent highway and roadside parameters. The conditions under which a safety improvement is warranted can then be tabulated or graphed for all traffic and roadway conditions investigated.

Encroachment probability based cost-effectiveness procedures have been used to develop guidelines for the implementation of a number of roadside safety features. The 1989 AASHTO *Guide Specifications for Bridge Railings* is probably the most widely distributed of these efforts.(15) This research involved conducting a cost-effectiveness analysis of three different bridge rail performance levels for three different types of highways (four or more lane divided, two-lane undivided, and one-way). The analysis was used to determine the most cost-beneficial bridge railings on each highway type for a variety of highway design speeds, vehicle mix (percent truck), and bridge rail offsets. This information was then tabulated to form the bridge rail selection tables contained in the Guide Specifications. This process can again be expected to be most sensitive to accident severity assigned to various safety treatment alternatives.

In a survey of users of cost-effectiveness analysis procedures(9), including personnel from FHWA, state highway agencies, and research organizations, the most commonly used cost-effectiveness procedures are the 1977 AASHTO Barrier Guide and the ROADSIDE program. There was no specific mention of any of the accident data based procedures. Very few people are familiar with the BCAP program and it appears that the only major application of the program is in the development of the selection guidelines contained in the 1989 AASHTO *Guide Specifications for Bridge Railings*. The ABC program was used in a number of studies, but its use was limited to only work conducted by the Texas Transportation Institute.

COST-EFFECTIVENESS ANALYSIS METHODOLOGY

This section provides an overview on the encroachment probability based cost-effectiveness analysis methodology. The encroachment probability model is unique to roadside safety cost-effectiveness procedures. It is based on the concept that the ran-off-the-road accident frequency can be directly related to the encroachment frequency, i.e., the number of vehicles inadvertently leaving the traveled portion of the roadway, which is a function of roadway and traffic characteristics and that the severity of ran-off-the-road accidents is related to encroachment characteristics, such as the speed and angle of encroachment.

The basic formulation of the encroachment model is expressed by the following equation:

$$E(C) = \sum_{i=1}^{n} P(E) * P(A|E) * P(I_i|A) * C(I_i) \qquad (2)$$

where

$E(C)$ = Expected accident cost
$P(E)$ = Probability of an encroachment
$P(A|E)$ = Probability of an accident given an encroachment
$P(I_i|A)$ = Probability of injury severity i, given an accident
$C(I_i)$ = Cost associated with injury severity i
n = Number of injury severity levels

Figure 1 shows a schematic of the key modules and data parameters of the encroachment probability model based cost-effectiveness analysis procedure. As shown in Figure 1 (Overview of Encroachment Probability-Based Cost-Effectiveness Analysis Procedure), there are four major modules to the procedure:

1. Encroachment module,
2. Accident prediction module,

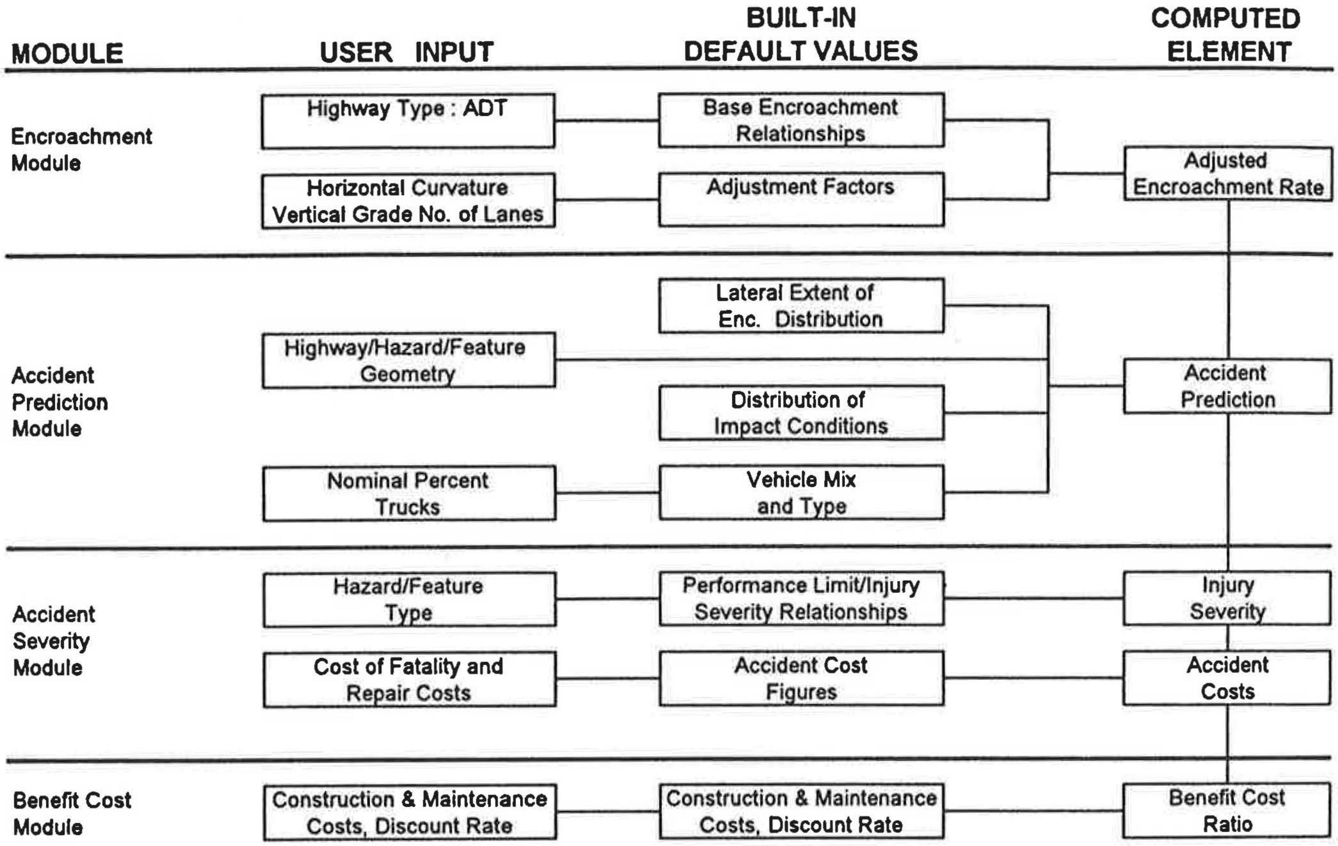

FIGURE 1 Overview of encroachment probability-based cost-effectiveness analysis procedure.

3. Accident severity module, and
4. Benefit cost module.

Brief descriptions of each of these modules are presented as follows.

Encroachment Module

The encroachment module, a flowchart of which is shown in Figure 2 (Flowchart of Encroachment Module), utilizes roadway and traffic information to estimate the expected encroachment frequency along any highway segment, P(E). A two-step process is used to estimate encroachment frequencies. The first step involves using basic highway type and traffic volumes inputs by the user to estimate a base encroachment frequency. The encroachment frequency-traffic volume relationships are established from available encroachment data.

There have been three previous efforts in collecting encroachment data: Hutchinson and Kennedy, Cooper, and Calcote(16-18). The first study of roadside encroachments was conducted by Hutchinson and Kennedy in the mid-1960's.(16) This research involved periodic observations of wheel tracks on snow covered medians on rural interstate highways. One major drawback of this study is that the researchers could not distinguish between controlled and uncontrolled, i.e., intentional and unintentional, encroachments. Although snow in the median is believed to be a significant deterrent to drivers intentionally leaving the roadway, some of the wheel tracks were undoubtedly from controlled excursions onto the roadside that would never have resulted in accidents. Overrepresentation of adverse weather conditions and the 70 mph (112.7 km/h) speed limit on rural interstate highways at that time would also have increased the observed encroachment frequencies. Thus, the encroachment frequency data from this study, as shown in Figure 3 (Encroachment Frequency Data), should only be considered as an upper bound. Also, the data were collected on sections of highways that are relatively straight and flat. Insufficient data were collected in this study on horizontal and vertical curves or grades to determine the potential effects of these elements on encroachment frequency.

A more comprehensive study of roadside encroachments was undertaken in Canada by Cooper

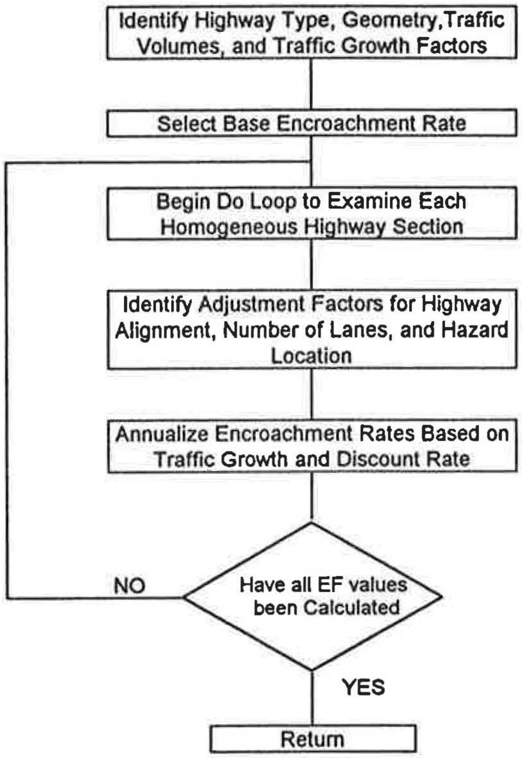

FIGURE 2 Flow chart of encroachment module.

during the late 1970's.(17) This study involved weekly observations of wheel tracks on grass-covered roadsides of rural highways. All of the encroachment data were collected during the summer months on highways with speed limits in the 50 to 60 mph (80.5 to 96.6 km/h) range. Thus, adverse weather conditions were underrepresented in this study and the speed limits were slightly lower than the 55 to 65 mph (88.6 to 104.7 km/h) range currently used in this country. This study also suffers from the inability to distinguish controlled from uncontrolled encroachments. Further, the grassy areas in the roadsides were occasionally used by farm equipment and other slow-moving vehicles. The effects of favorable weather conditions and lower speed limits on the encroachment rates are believed to be more than offset by the inclusion of controlled encroachments in the data. As expected, encroachment frequencies on straight and flat sections of highways observed by Cooper, shown in Figure 3, were somewhat lower than those measured by Hutchinson and Kennedy.

In another study of roadside encroachments, Calcote used time-lapse video photography and electronic monitoring to identify encroachments along urban freeways and rural highways, respectively.(18) The electronic monitoring approach failed to produce any useful results due to the use of the shoulder area by slow-moving vehicles to allow faster vehicles to pass and the propensity for false signals. The time-lapse video photography approach did record a large number of encroachments. However, despite the visual records of the encroachments, the researchers were still unable to determine whether or not encroaching vehicles were under control. Most encroachments involved vehicles moving slowly off of the roadway for some distance and then moving back into the traffic stream without any abrupt changes in vehicle trajectory. Researchers assumed that all encroachments were controlled unless the vehicle exhibited a rapid change in trajectory or hard braking. Using this relatively restrictive definition of uncontrolled encroachment, only 14 of the approximately 7,000 encroachments were judged to be uncontrolled, or a ratio of 500 to 1 between controlled and uncontrolled encroachments. The limited nature of the study and the high ratio between controlled and uncontrolled encroachments rendered the research results statistically insignificant and not too meaningful.

The various existing procedures use different base encroachment rates. For example, the 1977 AASHTO Barrier Guide uses the encroachment data collected by Hutchinson and Kennedy while the TTI ABC model uses the Cooper encroachment data. The BCAP and ROADSIDE programs use a constant encroachment rate of 0.0005 encroachments (to one side of the road) per mile per year per average daily traffic (ADT). which is not based on either the Hutchinson and Kennedy or Cooper encroachment data. The new cost-effectiveness

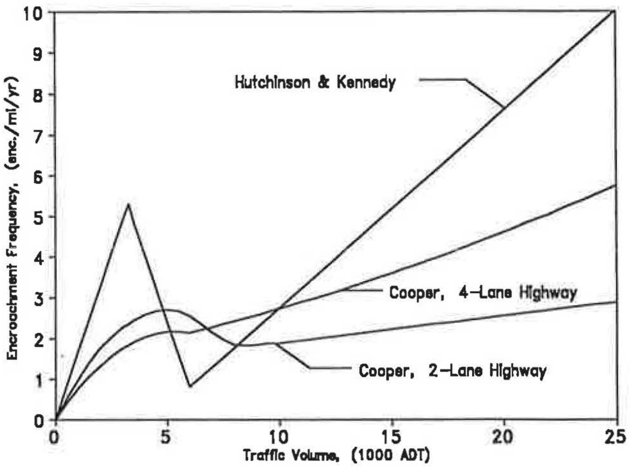

FIGURE 3 Encroachment frequency data.

procedure being developed under NCHRP Project 22-9 uses encroachment data from the Cooper study with breakdowns by highway type: two-lane undivided, four-lane undivided, and four lane-divided highways.

Base encroachment rates are then modified to account for specific highway characteristics, such as horizontal and vertical alignment, and number of lanes. The rationale for these adjustment factors is that encroachments are affected by certain geometric and roadway cross-sectional characteristics and the base encroachment rates should be adjusted to account for these characteristics. For example, previous studies have found that vehicle encroachments are more likely on the outside of curves and the encroachment rate should thus be increased to account for the presence and the degree of curvature of the horizontal curve.(19, 20)

The BCAP program provides adjustments for horizontal curvature and vertical grade, based on results from the study on fatal single vehicle accidents by Wright and Robertson.(19) It is believed that these adjustment factors are too high because only fatal accidents were included in the sample. There are also other concerns with the study, such as the small sample size, the lack of control for other potential covariates, e.g., area type, highway type, number of lanes, etc. Also, the effect of vertical grade on encroachment rate is questionable and not supported by data from other more recent studies, which found no significant relationships between vertical grade and accident rates.(12,20)

The 1989 AASHTO *Guide Specifications on Bridge Railings* also incorporates encroachment frequency adjustment factors to account for the effect of bridge deck height and water depth below bridge. These factors are designed as a surrogate to account for the increase in severity of bridge rail penetration accidents. Increasing the encroachment frequency would increase the number of accidents involving bridge rail penetration and rolling over the bridge rail, which in turn would increase total accident costs. Unfortunately, this approach also increases the frequency and costs associated with all other accident types, such as those involving redirection and rollover on the traffic side of the bridge railings. There is no supporting data or theoretical basis for these adjustment factors and they are not considered appropriate.

The new cost-effectiveness procedure being developed under NCHRP Project 22-9 will consider adjustment factors for horizontal curvature, vertical grade, number of lanes, and left versus right encroachments. The adjustment factors for horizontal curvature and vertical grade will be established from the more recent studies by Zegeer, et al. on two-lane rural highways(13) and horizontal curves(20). Adjustment factors for number of lanes and left versus encroachments are new additions. It is intuitively obvious that the encroachment rates are different from different lanes on multi-lane facilities. For example, a vehicle in the center lane is less likely to encroach into the roadside than a vehicle in the right lane since the vehicle will first have to cross the right lane before encroaching into the roadside, thus allowing more time for the driver to take corrective actions. Another consideration is that the traffic volume is not distributed equally among the lanes, e.g., the right lane tends to carry more traffic than the center lane. Also, in a study on single vehicle, ran-off-road accidents by Perchonok, et al.(21), it was found that the ratio between right and left encroachments was approximately 2 to 1.

The encroachment frequency algorithm will then consider the effect of traffic growth on encroachment frequencies. Since the cost-effectiveness analysis procedure will incorporate an annualized cost basis for comparing various safety treatment alternatives, estimated encroachment frequencies will be further adjusted to annualize the traffic growth effects. This process involves estimating encroachment frequencies in future years and annualizing those encroachments over the life of the treatment alternative using economic discounting procedures. This analysis is appropriate since all accident related costs are assumed to be directly proportional to the encroachment frequency. Thus, using economic discount factors to adjust encroachment frequency would yield the same result as converting encroachment frequency to accident costs and then annualizing the result.

Accident Prediction Module

The accident prediction module estimates the conditional probability than an accident will occur given an encroachment, $P(A|E)$. The basic process involves considerations for the lateral extent of vehicle encroachment, and the probability of the vehicle impacting with a roadside feature (which in turn are based on the encroachment characteristics, i.e., speed and angle, vehicle trajectory, i.e., steering and braking, and vehicle and hazard size, i.e., length and width). The impact conditions, i.e., speed and angle, are also determined as part of the accident prediction module.

The model first determines the probability that the vehicle would encroach far enough laterally to impact the roadside feature under consideration based on the

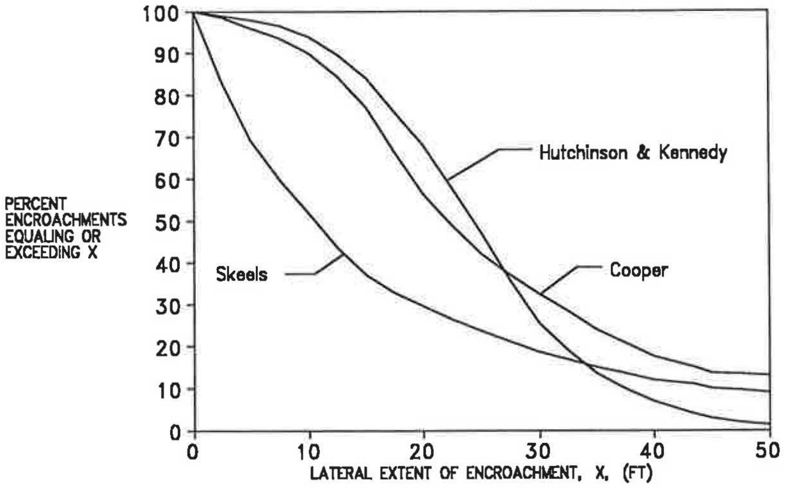

FIGURE 4 Lateral extent of encroachment data.

lateral extent of vehicle encroachment. In other words, the vehicle may stop or steer back to the roadway before encroaching far enough to impact the feature. Figure 4 (Lateral Extent of Encroachment Data) shows the distributions of lateral extent of vehicle encroachment from studies by Hutchinson and Kennedy(16), Cooper(17) and Skeels(22).

As may be expected, the percentage of vehicles encroaching beyond a given lateral distance decreases with increase in the lateral distance. In other words, a roadside feature located further away from the edge of the travelway is less likely to be impacted than one that is closer to the travelway. Note that the shape of the curve from the Skeels data is significantly different from that of the curves from encroachment studies by Hutchinson and Kennedy and Cooper. The difference is attributed to the presence of paved shoulders where tire tracks are not evident. Thus, only encroachments beyond the paved shoulders are included in the data.

The model then estimates the probability that the vehicle will impact the roadside feature if the vehicle encroaches far enough laterally. Existing encroachment probability models use an approach known as hazard imaging. An impact envelope, which is defined as the region along the roadway within which a vehicle leaving the travelway at a prescribed angle will impact the roadside object or feature, as shown in Figure 5 (Hazard Imaging). Given an encroachment by a vehicle of a particular type and size, the probability that the vehicle will leave the highway within the hazard envelope of a particular roadside obstacle is given by the equation shown below:

$$P(H^{w,i}_{v,\theta} \mid E^{w}_{v,\theta}) = \frac{1}{5280}\left(L_i + \frac{W_e}{\sin\theta} + W_i\cos\theta\right) \qquad (3)$$

where

$P(H^{w,i}_{v,\theta} \mid E^{w}_{v,\theta})$ = Probability that an errant vehicle of size, W, encroaching at speed, V, and angle, θ, will be within the impact envelope of hazard, i, given that a vehicle of size, W, has encroached at speed, V, and angle, θ.
L_i = Length of hazard i
W_e = Effective width of vehicle size W
θ = Encroachment angle (deg.).
W_i = Width of hazard i

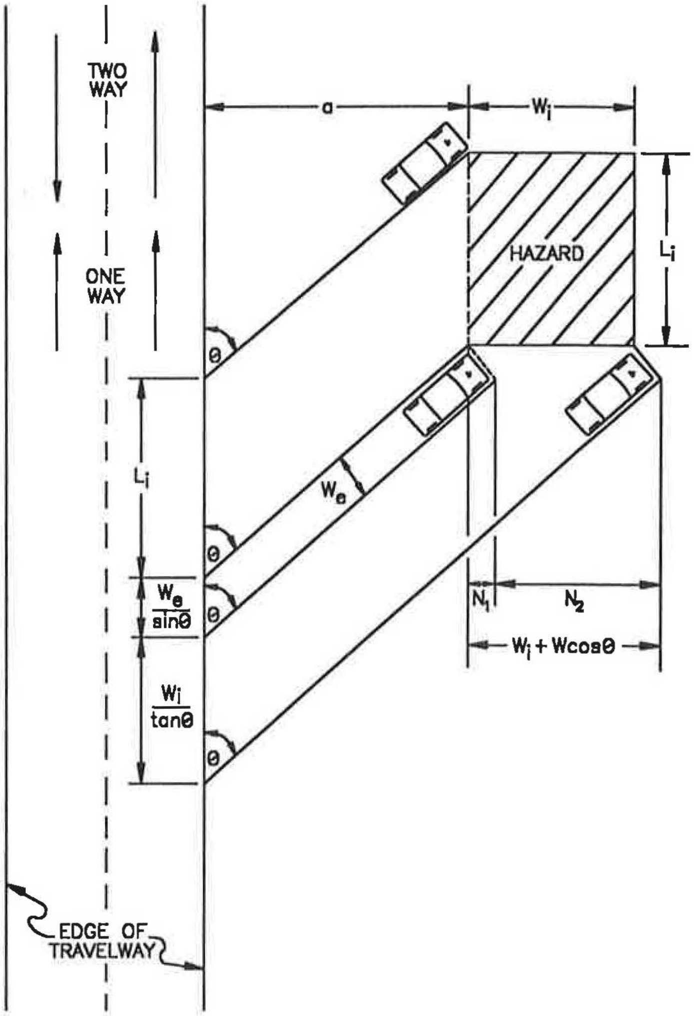

FIGURE 5 Hazard imaging.

The hazard imaging algorithm assumes that uncontrolled vehicles encroach along a straight path, i.e., no steering input. It takes into account the encroachment angle, the length and width of the hazard, and the vehicle size. The 1977 AASHTO Barrier Guide and the ROADSIDE programs use average encroachment angles and vehicle size. The BCAP and TTI ABC programs allow for a distribution of encroachment angles and different vehicle sizes.

The new procedure being developed under NCHRP Project 22-9 does not use the hazard imagining approach. Instead, a Monte Carlo simulation technique is planned for use with the new procedure. The Monte Carlo simulation technique involves using random selection processes to simulate vehicles running off of the road within the highway section of interest. As shown in Figure 6 (Flowchart of Accident Prediction Module), the first step in the accident prediction process is to define the geometry of roadside hazards and features. Random numbers are then generated to define the location and nature of an encroachment, i.e., vehicle type and size, impact speed and angle, vehicle orientation at impact, and lateral extent of encroachment. (Note that the inclusion of vehicle orientation at impact is another improvement incorporated into the new procedure.) The roadside region that the vehicle will traverse, vehicle traversal region (VTR), is then defined based on the encroachment point, the impact angle, vehicle size, and vehicle orientation, as shown in Figure 7 (Vehicle Traversal Region). Objects within this region are then identified according to proximity to the roadway and

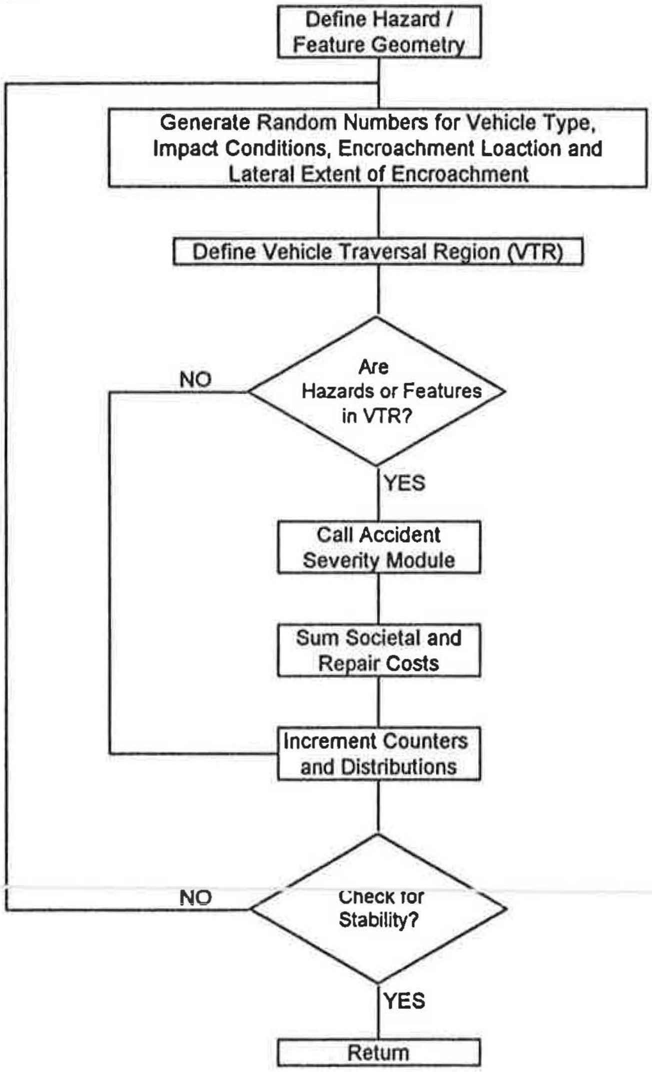

FIGURE 6 Flow chart of accident prediction module.

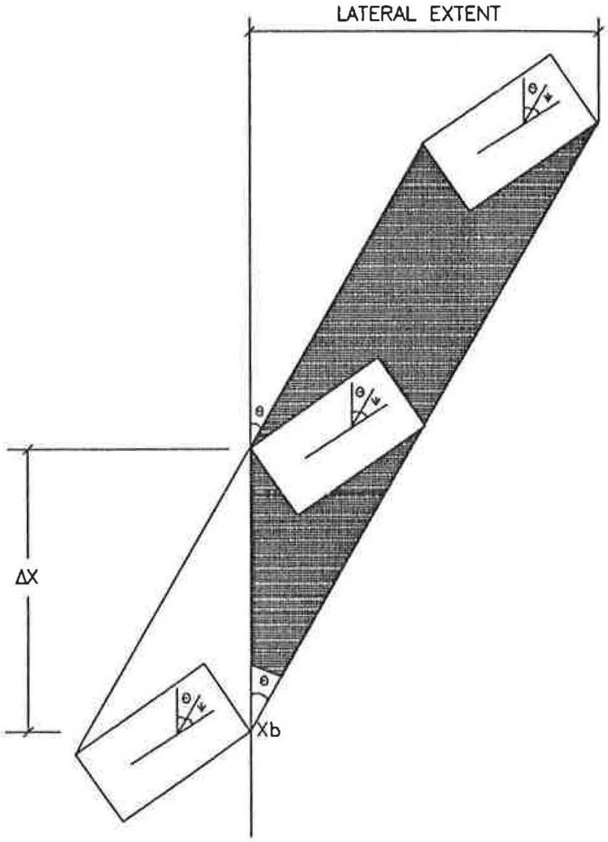

FIGURE 7 Vehicle traversal region.

compared to the lateral extent of encroachment to determine if an accident will occur. If an accident is predicted to occur, the program will then continue on to estimate the impact severity and the associated accident costs. A new set of random numbers is then generated and the process is repeated.

The stability and convergence of the solution will be checked every 10,000 simulated runs. The checks will include comparing the distributions of the simulated samples to the target distributions built into the model, such as impact speed, angle and orientation, lateral extent of encroachment, vehicle type and size, etc. If all of these checks are within acceptable levels of accuracy, the simulation effort will then terminate. Otherwise, another 10,000 iterations will be undertaken and the convergence checks outlined above are repeated.

The accident prediction module will also determine the impact conditions, i.e., impact speed and angle, for estimation of the accident severity. The 1977 AASHTO Barrier Guide and the ROADSIDE programs use average severity indices for accident severity and do not require the use of impact conditions. The BCAP program assumes certain encroachment speed and angle distributions, based on which the impact speed and angle distributions are estimated. It should be noted that the encroachment speed and angle distributions used in the BCAP program are based strictly on engineering judgement, with no theoretical basis of supporting data. With the assumption of straight path for the encroaching vehicles, i.e., no steering input, the impact angle would be the same as the encroachment angle. As for estimation of the impact speed, the BCAP program assumes braking with a constant deceleration rate and the impact speed is calculated by subtracting the speed loss due to braking from the encroachment speed.

The TTI ABC program and the new procedure being developed under NCHRP Project 22-9 do not use encroachment conditions to estimate impact conditions. Instead, the impact conditions are established from real-world accident data.(23-25) The advantage of this approach is that the impact conditions are from real-world accident data and not derived from some arbitrarily chosen theoretical distributions. The drawback is that the impact speed is independent of the lateral location of the hazard. Although intuition suggests that impact speeds should decrease as the distance from the roadway increases, both accident data and deterministic encroachment models indicate that the degree of speed reduction is relatively minor for hazards located within 30 ft (9.1 m) of the travelway. Since most roadside hazards of interest are located within a 30-ft (9.1-m) clear zone, this limitation is not believed to be a major source of error. However, the Monte Carlo technique proposed for use in the new cost-effectiveness procedure could be easily modified to link extent of lateral encroachment distributions to impact conditions, should the data become available in the future.

Accident Severity Prediction Module

The accident severity prediction module estimates the severity of the accident and associated costs given that an accident has occurred, $P(I_i|A)$. The severity of an accident is a function of many factors, including impact conditions (i.e., impact speed, angle, and vehicle orientation), the size and weight of the impacting vehicle, and the nature of the impacted roadside object or feature. For a given roadside object or feature and impacting vehicle, the conditions under which the vehicle impacts the roadside object or feature, i.e., speed, angle and vehicle orientation, determine the outcome and severity of the accident. In the case of a roadside safety device, e.g., guardrail, crash cushion, etc., the performance limit of the safety device should also be taken into account. When the impact conditions exceed the performance limit of the safety device, some catastrophic outcome could occur and the severity of the impact is usually a function of the catastrophic outcome. For example, if the impact loading on a bridge railing is greater than its structural capacity, the impacting vehicle would penetrate the bridge railing and fall into the river below. The severity of the accident is determined by not only the impact with the bridge railing, but also by the fall of the vehicle into the river.

Most existing encroachment probability models have used a severity index (SI) as a surrogate measure for accident severity. The severity index was developed as a tool when estimating severity of roadside hazards through surveys of transportation and law enforcement experts.(3) A probability of injury and fatality was arbitrarily assigned to each index as shown in Table 1. Survey respondents were then asked to consider the table when assigning a subjective SI value to each roadside hazard. This SI concept has continued to be used by most encroachment probability based procedures even though severity is no longer assigned through subjective evaluation.

Accident severity from police reports is normally recorded in terms of five severity levels: fatal (K), incapacitating injury (A), non-incapacitating injury (B), possible injury (C), and property-damage-only (PDO). A more accurate and detailed injury severity rating scheme, based on the Accident Injury Scale (AIS), is sometimes used. This scale has six levels (1 through 6) that are based on the medical evaluations of the injured parties. Unfortunately, the AIS scale is too sophisticated for use by police and therefore is available only from in-depth accident investigation studies where medical records of injured occupants are collected..

Neither of the accident severity reporting schemes fits conveniently into the Severity Index concept described previously. Further, accident data analysis indicates that the relationships between PDO, injury, and fatal accidents used in the severity index scale are seldom appropriate.(10) In other words, when the percentage of injury accidents reaches the level for any given severity index shown in Table 1, the percentage of fatal accidents seldom correlates with the appropriate SI value. Thus, there are no apparent advantages of continuing to incorporate severity indices as a means of expressing accident severity. Therefore, for the new cost-effectiveness procedures being developed under NCHRP Project 22-9, accident severity will be defined in terms of probability of injury or fatality. These probabilities will then be used to calculate accident costs directly, without the intermediate step of determining a severity index.

As mentioned previously, the 1977 AASHTO Barrier Guide and the ROADSIDE programs use average severity indices for accident severity and do not require the use of impact conditions. The BCAP and TTI ABC programs and the new cost-effectiveness procedures being developed under NCHRP Project 22-9 use a variety of severity estimation procedures tailored to the specific hazard or feature being struck. For example,

TABLE 1 SEVERITY INDEX AND PROBABILITY OF INJURY

Severity Index	% PDO Accidents	% Injury Accidents	% Fatal Accidents
0	100	0	0
1	85	15	0
2	70	30	0
3	55	45	0
4	40	59	1
5	30	65	5
6	20	68	12
7	10	60	30
8	0	40	60
9	0	21	79
10	0	5	95

procedures for predicting the severity of impacts with rigid objects would be very different from those used to predict crash cushion impact severity. Typically, severity for a few impact conditions are estimated from a combination of crash test results, computer simulation, and accident data. Severity indices or probabilities of injury are then assigned to these impact conditions and engineering judgement is used to extrapolate these severity indices to all other possible impact conditions.

Some of the severity estimation analyses are velocity-dependent.(5,26,27) Typically, these procedures used crash testing results or impact analysis techniques to estimate the severity of impact for one or two impact speeds and then extrapolated the data for all other impact speeds using a linear approximation. Other severity estimation procedures are based on vehicle accelerations or impact energy. For example, the BCAP model uses a simple analytical equation to estimate the average lateral acceleration during vehicle redirection in a longitudinal barrier impact. The severity was estimated for two levels of average lateral acceleration and then linearly extrapolated to all other acceleration levels. Crash cushions are a good candidate for energy dependent impact severity models. Such a procedure would involve estimating accident severity for two levels of impact energy and extrapolating the findings to other impact conditions.

The accident severity analysis procedures incorporated into the new cost-effectiveness procedure being developed under NCHRP Project 22-9 will also allow for separate consideration of the location of impact on the obstacle being impacted. The severity of impact with roadside hazards and safety devices are often a function of the point of impact with the obstacle. For example, the severity of an impact with the side of a redirective crash cushion is considerably different than the severity of impact with the front of the cushion. This is another of the improvements incorporated into the new procedure.

Vehicle behavior during and after impact is also included in the severity estimates for roadside obstacles and safety devices. For example, severity for guardrail or roadside slope impacts generally increase dramatically when the impacting vehicle rolls over. Therefore, the first step in estimating impact severity is to identify the expected vehicle behavior during impact. For roadside appurtenances, such as barriers and crash cushions, a performance limit check is first conducted to determine if the vehicle is properly contained. This check can take the form of a simplified theoretical analysis or empirically derived relationships between impact conditions and the structural capacity of the barrier or crash cushion. Impacts wherein the vehicle is predicted to penetrate through the barrier or to exceed the capacity of a crash cushion would then be assigned a much higher severity than impacts within the performance limit of the device.

A stability check is then conducted using simple impulse and momentum or energy based analyses to identify the propensity for vehicles to roll over during impact. For barriers or impacts on the side of redirective crash cushions, this check can be segregated into two categories: vehicles that roll over the barrier and those that roll over in front of the barrier. Impacts involving a vehicle that is predicted to roll over a barrier would then be assigned a severity similar to barrier penetration accidents. Impacts involving a vehicle rolling over in front of the barrier would be assigned a lower severity that is related to the original impact speed. Although not widely used in the past, a similar approach can be used for evaluation of vehicle stability during impacts with many other types of roadside obstacles, such as ditches and slopes. This approach may improve severity predictions for impacts with a number of roadside obstacles and features.

The accident severity is then converted to accident or societal costs, $C(I_i)$, based on some pre-selected accident cost figures. There are two sets of accident cost figures that are commonly used: the accident cost figures developed by the National Safety Council (NSC)(27) and the FHWA Comprehensive cost figures based on the "willingness to pay" principal(28), as shown in Table 2. Note that the current (1994) comprehensive cost figures are even higher than those shown in Table 2, e.g., the estimated cost for a fatality has increased from 1.7 to 2.6 million dollars.

Most States currently use the NSC accident cost figures, which include estimates of direct costs, such as wage loss, medical expense, insurance administration, legal/litigation cost, and property damage, but do not account for indirect costs, such as the consideration of a person's natural desire to live longer or protect the quality of one's life. The NSC cost figures were used as default values in the BCAP program and also adopted in the 1988 AASHTO *Roadside Design Guide*.

The FHWA has adopted the comprehensive cost figures, which are based on the concept of willingness to pay and include the indirect costs mentioned above. It should be noted that the NSC and the National Highway Traffic Safety Administration (NHTSA) has endorsed the use of the comprehensive cost figures for benefit-cost analyses.(27,29) It is evident from Table 2 that the FHWA comprehensive cost figures are substantially higher than those of the NSC, which could have a significant effect on the outcomes of specific cost-effectiveness analysis depending on which set of accident cost figures are used.

TABLE 2 ACCIDENT COST BY SEVERITY

Roadside Design Guide

Accident Severity	Accident Cost ($)
Fatality	500,000
Severe Personal Injury	110,000
Moderate Personal Injury	10,000
Slight Personal Injury	3,000
Property Damage Only (Level 2)	2,500
Property Damage Only (Level 1)	500
No Damage	0

Comprehensive (Willigness to Pay)

Accident Severity	Accident Cost ($)
Fatal	1,700,000
Injury (Overall)	14,000
ABC Injury Scale:	
A Injury - Incapacitating Injury	47,000
B Injury - Nonincapacitating Injury	10,000
C Injury - Possible Injury	3,000
Property Damage Only (PDO)	2,500

The cost of repairing roadside safety hardware will also be estimated by the accident severity module. This process will usually involve estimating extent of damage based on impact energy terms. The repair cost for any given accident is then estimated from the extent of damage and unit repair costs. For example, results from full-scale crash testing and computer simulations can be used to determine the relationship between impact energy terms and length of guardrail damage. The repair cost is then the product of the length of damaged rail and the unit cost for repair.

Benefit Cost Module

Benefits derived from a safety improvement are measured in terms of reduced accident or societal costs resulting from reduced accident frequency and/or severity. Costs associated with a safety improvement include increases in the cost for initial installation, normal maintenance, and repair of damages from accidents. Computation of the incremental benefit/cost ratios is very straightforward once the benefits and costs are determined. As summarized in Figure 9 (Flow chart

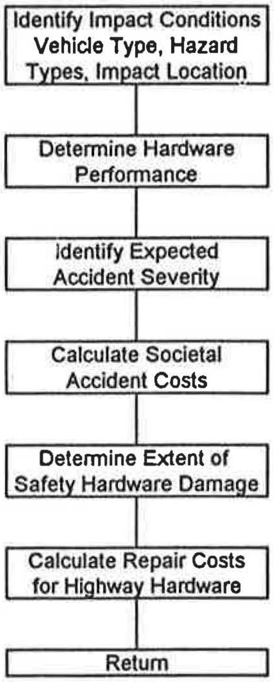

FIGURE 8 Flow chart of accident severity module.

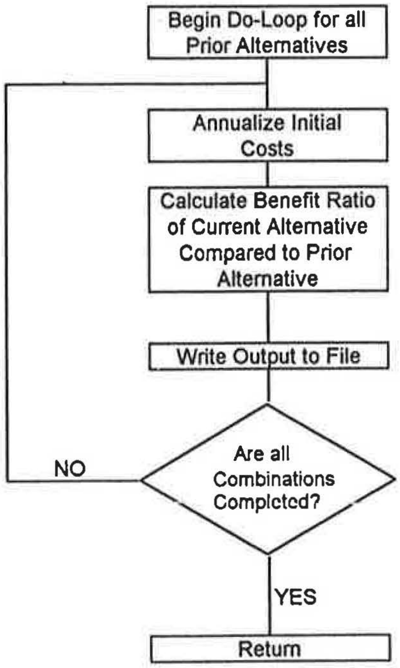

FIGURE 9 Flow chart of benefit cost module.

of benefit cost module), the benefit cost module will first annualize the accident or societal costs and the construction and maintenance costs and then ratio the benefits and costs of each pair of alternatives under consideration. The formulation for determining the incremental benefit/cost ratio between two alternatives is shown previously in Equation 1.

FUTURE RESEARCH NEEDS

The encroachment probability based cost-effectiveness analysis procedures, as briefly described above, is a sophisticated and complex program involving numerous algorithms, data sources, and assumptions. As such, there are numerous areas within the procedure where improvements are needed, ranging from updated or new data to revised algorithms and assumptions that better define the process. The new cost-effectiveness analysis procedure being developed under NCHRP Project 22-9 recognizes this need for continuing improvement of the procedure and is designed to be modular in nature so that future improvements can be incorporated with a minimum level of effort as new data and methodologies become available.

The most important area requiring improvement is perhaps the accident severity estimation procedures, which are shown to have the most effect on the outcomes of the cost-effectiveness analyses. Available data in this area are mostly comprised of full-scale crash test data which are limited to selected vehicle types and impact conditions. The crash test data can be supplemented with computer simulation studies, but there are severe limitations to the capability of existing computer simulation models. Available accident data are mostly limited to police reports which lack the level of detail and accuracy required to evaluate the safety and performance of roadside safety features. More detailed accident data and in-service evaluation are sorely needed.

Another major weakness with encroachment probability models is the limitations of the encroachment frequency data. Most encroachment frequency data were collected from observing tire tracks along the roadside left by encroaching vehicles. There is no means to determine whether the sets of tire tracks were left by vehicles encroaching in a controlled or uncontrolled manner. On roadways with paved shoulders, vehicles that encroached within the shoulder area do not leave any tire tracks. Also, there may be built-in biases in the encroachment data due to the weather and surface conditions of the highways during the data collection periods.

Other problems associated with encroachment probability models include difficulties in obtaining information regarding encroachment characteristics, such as encroachment speed and angle distributions, distributions of lateral vehicle movement, distribution of sizes of encroaching vehicles, the attitude of encroaching vehicles, and the trajectories of the encroaching vehicles. Numerous assumptions were made in formulating the algorithms built into the encroachment probability model. Due to the complexity of the encroachment probability model, it is very difficult to thoroughly validate the model and the existing procedures are basically unvalidated..

Gaps in the state-of-the-knowledge regarding the encroachment probability based cost-effectiveness procedures and potential research studies to fill in these gaps were identified in a recently completed study sponsored by FHWA(30) and the ongoing NCHRP Project 22-9(9). The following is a list of major data gaps identified from these two studies and are listed in order of relative importance to the procedure. These data gaps are by no means all inclusive, but serve to illustrate the major data gaps for the purpose of further discussions in the breakout group sessions.

- Performance limits of roadside safety features and - associated severity.
- Relationships of injury probability and severity to impact conditions.
- Distributions of impact conditions.
- Effects of sideslopes on extent of lateral encroachment.
- Severity associated with sideslopes.
- Validation of encroachment frequency/rate.
- Encroachment frequency/rate adjustment factors.
- Extent of unreported accidents.
- Vehicle trajectory after encroaching into roadside.
- Relationships of surrogate severity measures to Injury probability and severity.

For each data gap, brief background information and discussions of its importance to the new cost-effectiveness analysis procedure are presented as follows:

Performance Limits of Roadside Safety Features and Associated Severity

The results of cost-effectiveness analysis regarding roadside safety features are controlled to a large extent by catastrophic events, such as penetration of the barrier or rolling over the barrier by the impacting vehicle, particularly when comparing among multiple performance levels. The occurrence of catastrophic events is a function of the performance limit of the impacted roadside object or feature. In other words, when the performance limit of a given roadside object or feature is exceeded, e.g., loading is greater than barrier capacity, some catastrophic outcome would occur. Thus, the performance limit of the impacted roadside object or feature is an important factor to the determination of the severity of an impact. Currently, the performance limits of roadside objects and features and the potential outcomes of exceeding the performance limits are not well defined.

Although numerous crash tests are conducted with many types of roadside safety features each year, virtually all of these tests are limited to two or three vehicle sizes impacting in a tracking mode at speeds of 45 and 60 mph (72.4 and 96.6 km/h). These impact conditions were selected to be representative of relatively severe accidents or worst case conditions. Even so, the performance limits of various roadside safety features are often not defined by crash tests under these test conditions. There remains a need to more accurately define impact conditions that can cause safety hardware performance to become unacceptable.

The required data may be obtained from crash testing or computer simulation studies to include a wider spectrum of vehicle sizes and impact conditions. Full-scale crash testing is a very expensive endeavor and its use will necessarily be very limited in scope. Computer simulation study is a good and relatively inexpensive approach, provided accurate and validated computer simulation models are available. Unfortunately, existing computer simulation models have severe limitations and their use is confined to only selected roadside safety features and vehicle types. Another means of collecting the required data is through in-depth investigation of real-world accidents and the conduct of in-service evaluation. Efforts in this area have been very limited so far, but it is potentially a very promising approach worthy of further consideration.

Relationships of Injury Probability and Severity to Impact Conditions

For impacts where the performance limit of the impacted roadside object or feature is not exceeded, e.g., redirection for a barrier, severity is a function of the impact conditions, i.e., impact speed and angle and vehicle orientation at impact. These relationships between impact conditions and impact severity are particularly important when evaluating several safety treatment alternatives, such as different levels of performance. These relationships are currently not well defined, thus requiring some form of approximation or hypotheses in what the relationships are. For example, in a redirectional impact by a barrier, the severity is often defined as a linear function of the lateral acceleration experienced by the impacting vehicle. There is a definite need to better define these relationships between injury probability and severity to impact conditions for the various roadside safety features.

The study approaches would be similar to that for defining the performance limits of roadside safety features, i.e., crash testing, computer simulation, in-depth accident study, and in-service evaluation. Actually, the efforts for these two studies can probably be combined into a single study with the proper experimental design.

Distributions of Impact Conditions

An important factor to the outcome and severity of an accident involving a roadside object or feature is the impact conditions, i.e., speed, angle, and vehicle orientation at impact. The impact speed and angle determine whether the performance limit of the roadside safety features is exceeded and the associated injury probability and severity. Vehicle orientation at impact is also important since non-tracking impacts are believed to be of significance with regard to the severity of impacts with breakaway structures, narrow fixed objects, end terminals and crash cushions. Thus, the distributions of impact conditions are crucial to the accuracy and validity of the cost-effectiveness model. However, there is only limited information available on the distribution of impact conditions from studies such as Perchonok, et al.(21), Lampela and Yang(31), and Mak, et al.(23-25), and the data are somewhat dated. There is a need to obtain better more updated information on the distribution of impact conditions.

In order to determine the impact conditions, the data collected on the accidents has to provide sufficiently detailed information for the accidents to be reconstructed. This requires, as a minimum, information on the vehicle trajectory, impact sequence, nature of object(s) struck or harmful event(s), and damage to the vehicle and object(s) struck for each accident investigated. This detailed level of accident data is typically not available from police level accident data, but requires in-depth data collection by trained investigators. Also, the accidents will have to be reconstructed to determine the impact conditions. There have been very few in-depth accident studies conducted in recent years since they are relatively expensive to conduct. The most recent effort is the National Accident Sampling System (NASS) Longitudinal Barrier Special Study (LBSS), which resulted in a data file with in-depth data on over 1,000 longitudinal barrier accidents. However, these accidents were non-representative samples with bias toward the more severe accidents. The NASS Continuous Sampling System (CSS) data file may also provide some useful information, but the sample of fixed-object impacts is expected to be rather small.

Effect of Sideslopes on Extent of Lateral Encroachment

All previous encroachment probability models have not incorporated the effect of roadside conditions, e.g., sideslope, ditch configuration, etc., into the determination of impact probability and severity. Yet it is intuitively apparent that the steepness of the sideslope should have significant effect on the extent of lateral encroachment of an errant vehicle after it leaves the roadway and on the ability of a driver to maintain control of the vehicle and to recover from the errant path. The extent of lateral encroachment would in turn affect the probability of an errant vehicle impacting roadside hazards. In a study to assess the effect of sideslopes on the clear zone distance requirement, the responses of selected passenger cars on a range of sideslopes were studied for selected encroachment conditions and driver inputs.(32) The study results clearly indicate that the extent of lateral encroachment is significantly affected by the sideslopes. A study to evaluate the effect of sideslope on the lateral extent of encroachment is therefore recommended. Currently, a new study under NCHRP (Project 17-11) is planned to re-examine the clear recovery distance concept, part of which will involve studying the relationships between sideslopes and the extent of lateral encroachment.

Severity Associated with Sideslopes

In the cost-effectiveness analysis procedures, sideslope is typically considered as a traversable roadside feature with an associated severity rating. It can be argued that the severity associated with a sideslope is totally the result of rollover accidents, assuming that the errant vehicle does not impact with another roadside object or feature. In other words, assuming that the sideslope is of infinite width and totally free of other roadside objects or features, the only harm that could happen to an errant vehicle on the sideslope is for the vehicle to roll over. Studies by Zegeer, et al.(13,20) attempted to ascertain the severity associated with sideslopes, but the data are considered too gross for useful results. A study to determine the probability and severity of rollover accidents for various sideslopes is therefore proposed.

Validate Encroachment Frequency/Rate

The basic underlying assumption of an encroachment probability based cost-effectiveness analysis model is that the rate of roadside accidents is directly related to the encroachment rate. The model starts with an average or base encroachment rate and proceeds from there. Needless to say, the encroachment rate is important to the validity and accuracy of the cost-effectiveness model. Available data on encroachment rates are limited to three previous studies by Hutchinson and Kennedy(16), Cooper(17), and Calcote(18).

The approach employed by Hutchinson and Kennedy(16) and Cooper(17) involved periodic observations of tire tracks along the roadside and/or median areas of highways. A major limitation of this approach is that controlled encroachments, wherein the drivers intentionally leave the travelled portion of the roadway for whatever reason, cannot be distinguished from uncontrolled encroachments. Another problem is that most of the studied highways have paved or gravel shoulders. Vehicles encroaching only a short distance from the travelway, i.e, within the shoulder area, would not leave any evidence of an encroachment and thus could not be identified. On the other hand, the presence of paved shoulders reduces the likelihood that tire tracks observed beyond the shoulder areas are from controlled encroachments since controlled encroachments are more likely to occur on the shoulder areas. Existing encroachment data from observation of tire tracks are also biased by the effects of seasonal and weather changes on the encroachment rates. Much of the data studied by Hutchinson and Kennedy(16) were collected during winter months in Illinois where snowy and icy weather and surface conditions could significantly increase encroachment rates. Conversely, the data by Cooper(17) were collected only during the summer months when favorable weather conditions may produce encroachment rates that are lower than the annualized averages.

Calcote, et al.(18) used video monitoring or electronic surveillance of highway sections to collect encroachment data. The video monitoring did provide visual records of all encroachments along the highway sections under observation and the characteristics of the encroachments, but the researchers still had tremendous difficulty distinguishing between controlled and uncontrolled encroachments. Electronic monitoring was found to be highly unreliable. Also, the high costs of these approaches limited the study to only a few short sections of highways, resulting in a sample size considered too small to be reliable or statistically significant. Until better and less expensive data collection techniques and equipment become available, these approaches are considered impractical and not recommended for further consideration.

As described above, there are many unanswered questions regarding the validity of existing encroachment data. The most important of these questions centers around the effect of controlled encroachments on the estimated encroachment frequencies. However, these questions cannot be answered by collecting additional encroachment data using available techniques, such as observation of tire tracks. Video monitoring and electronic surveillance are too expensive to be a feasible alternative. Thus, some other means to check on the validity of the existing encroachment data is needed, such as approaches used in of NCHRP Report 77(1)and TRB Special Report 214(33), and approaches proposed in the report by Mak and Sicking.(30). Regardless of the approach used, a study to validate/ calibrate encroachment frequency/rate is needed and recommended for consideration.

Encroachment Frequency/Rate Adjustment Factors

Encroachment rate is believed to be affected by various geometric and roadway characteristics, such as horizontal and vertical alignments, number of lanes, etc. The base encroachment rates used as initial inputs to the cost-effectiveness analysis models are average values and do not account for variations of these characteristics at individual sites. Thus, it is necessary to adjust the base encroachment rates to reflect specific site conditions. One approach is the use of empirical adjustment factors. For example, the Benefit Cost Analysis Program (BCAP) uses empirical adjustment factors to account for horizontal curvature and vertical grade. The adjustment factor for horizontal curvature is a function of the location relative to the curve and the degree of curvature. The adjustment factor for vertical grade is a function of the type and degree of grade.

These adjustment factors are based on a study by Wright and Robertson(19) in which 300 fatal single-vehicle, ran-off-the-road, fixed-object accidents were studied. While the study was well designed, it has a very small sample size and the effects of horizontal and vertical alignment are likely over-estimated since the study included only fatal accidents. More recent studies by Zegeer, et al.(13,20) found the effect of horizontal curvature to be less than that indicated by the Wright and Robertson study(19) and vertical grade was found to have no significant effect on accident rates. Also, there may be additional roadway characteristics that could potentially affect encroachment rates that were not included in the adjustment factors. In order to account for roadway characteristics that may have significant effect on encroachment frequency and rate, there is a need to identify these roadway characteristics and to develop the appropriate empirical adjustment factors.

Extent of Unreported Accidents

Accident data is generally not a good means of adjusting encroachment data since only a fraction of the accidents involving roadside objects and features are actually reported to police. While the severity of these unreported accidents is likely to be minor in nature when compared to reported accidents, it is important to know the extent of these unreported accidents, especially for evaluation of the performance of safety devices. A number of studies have examined the extent of unreported accidents with widely varying results. For example, a study by Make and Mason on utility pole accidents(24) found that the approximately 60 percent of all utility pole accidents are reported while another study by Lampela and Yang on concrete barrier used in work zones reported that only 2 percent of accidents are reported(31). Such variations indicate that the extent of unreported accidents is affected by a number of factors, including type of roadside object or feature and location. A better understanding of the extent of unreported accidents could lead to improved accident data based benefit-cost procedures and allow accident data to be used for validation of encroachment probability models.

Trajectory of Vehicle after Encroaching into Roadside

There is currently very little information regarding the trajectory of an errant vehicle prior to leaving the roadway or after encroaching onto the roadside. For example, did the vehicle leave the roadway on the right, on the left, first right and then left, or first left and then right? Is the vehicle path straight or curved? How do the roadside conditions interact with the vehicle trajectory and the distance travelled by the vehicle prior to impact? Are drivers braking, steering, or both? How do driver actions affect the impact probability and impact conditions? All these vehicle trajectory parameters could potentially affect the impact probability and severity, but there are simply insufficient data to even speculate on the answers to these questions, not to mention incorporating them into a cost-effectiveness model. Better understanding and more information on the vehicle trajectory is needed and therefore proposed.

Relationships of Surrogate Severity Measures to Injury Probability and Severity

The severity of a given roadside object or feature is oftentimes determined from full-scale crash testing or simulation and is expressed in terms of surrogate severity measures, such as highest 50-msec average acceleration, occupant impact velocity, and highest average 10-msec ridedown acceleration. On the other hand, accident severity is defined by injury probability and injury severity for the cost-effectiveness analysis procedure. Existing relationships between these crash test severity measures and actual injury probability and severity are limited to longitudinal barrier impacts and are based on extremely limited data and are therefore suspect. However, such relationships are important to cost-effectiveness analysis in order to develop more accurate relationships between impact conditions and injury probability and severity. These relationships also provide an important method for evaluating the performance of safety hardware during the development process. Previous attempts to develop such relationships, such as the study by Calcote and Mason(34), have not been successful. There remains the need to establish the relationships between these surrogate severity measures used in full-scale crash testing or computer simulation to actual injury probability and severity.

SUMMARY

This paper provides an overview on the use of cost-effectiveness analysis and existing cost-effectiveness analysis procedures in the evaluation of roadside safety improvements. The major components of a cost-effectiveness procedure are outlined and discussed briefly. Various gaps in the state-of-the-knowledge regarding cost-effectiveness analysis procedures and suggested future research needs are identified to serve as a starting point for discussions in the breakout group sessions.

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APPLICATIONS OF SIMULATION IN DESIGN AND ANALYSIS OF ROADSIDE SAFETY FEATURES

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Roadside safety features present many challenging design and analysis problems. Although full-scale crash testing continues to be the only method for certifying the performance of roadside safety features, engineers have come to rely on computer simulation programs for analysis of the performance of these systems(1). Computer simulation codes are generally lumped into two categories, vehicle handling programs and impact models. Vehicle handling codes are used to evaluate safety problems associated with roadway and roadside geometrics, such as slopes, ditches and curbs. Although these applications for computer simulation are generally considered to be less complicated than most impact problems, vehicle handling still poses some significant obstacles. Most notable of these obstacles is associated with tire/terrain interaction. Tire penetration into soft soils has been identified as a potentially major cause of rollovers in ran-off-road accidents(2). Tire interactions with near vertical surfaces, where sidewall scrubbing becomes an important factor, have also been difficult to analyze(3). Some vehicle suspension components, such as suspension bumper stop systems and shock absorber systems, can create problems for computer simulation efforts when high velocity suspension deflections are encountered(4).

Impact models are used to evaluate the safety performance of numerous safety hardware systems such as longitudinal barriers, crash cushions, barrier terminals, and breakaway structures. Simulation modeling of longitudinal barrier impacts must be capable of evaluating barrier strength, vehicle stability, vehicle/barrier interlocking forces, and snagging potential. Barrier strength analysis is required when evaluating the potential for barrier penetrations. Component and connection strength and ductility requirements are often key factors in the design and analysis of longitudinal barriers. Vehicle stability becomes important when rollover is a possibility such as during automobile impacts with safety shaped barriers and any truck/barrier impact. Vehicle/barrier interlocking forces often prevent vehicles from overriding flexible and semi-rigid barriers such as cable and strong-post W-beam guardrails. Snagging of tires and vehicle hard points on longitudinal barriers can create safety problems during impacts with rigid barriers and barrier transitions.

Most crash cushions and many barrier terminals are designed to capture impacting vehicles and bring them to a controlled stop(5,6). Simulations of such impacts must accurately analyze the energy management of these safety systems and the interlocking forces that allow cushions and terminals to capture impacting vehicles. Vehicle/hardware interaction forces are also important to the analysis of breakaway structures since most of these systems are force activated. Simulations of breakaway devices must also track free-missile components of the breakaway systems to evaluate the possibility of occupant compartment intrusion(4).

Although numerous computer simulation models were developed over the last three decades, only a few of these programs have been widely used. The Highway Vehicle Object Simulation Model, (HVOSM), is probably the most widely used computer simulation code developed to date(3,4,7). This program was originally developed as a vehicle handling model and incorporates a relatively sophisticated three-dimensional lumped-parameter vehicle model. The vehicle model incorporates a total of 11 degrees of freedom (DOF), including a 6-DOF sprung mass, 1-DOF for each of 4 tires, and a steer DOF. HVOSM has not only been used by many researchers, it has been revised and upgraded by many users. Some of these modifications have greatly improved the versatility of the code. For example, sprung-mass/terrain impact models have enhanced the program's capability for modeling vehicles traversing deep ditches and steep embankments where a vehicle's undercarriage contacts the ground(4). HVOSM has been widely validated for modeling limit handling maneuvers where vehicle stability and controllability are important considerations(4,8,9). Although the program has some limitations, such as an inability to model tire penetrations into soft soil and rim gouging during hard cornering events, HVOSM has proven to be adequate for most vehicle handling applications.

HVOSM's capacity for modeling barrier impacts is much more limited. The program incorporates a brick shaped vehicle crush model that utilizes uniformly spaced deformation tracking points. Crush forces are assumed to be related to the volume and rate of change in volume of the region encompassed by the deformation tracking points. Although this procedure has been capable of successfully modeling a number of rigid barrier crash tests, it continues to have some nagging problems. For example, stability problems can develop when the directions of vehicle rotation change during a single impact event(4). This limitation is not normally

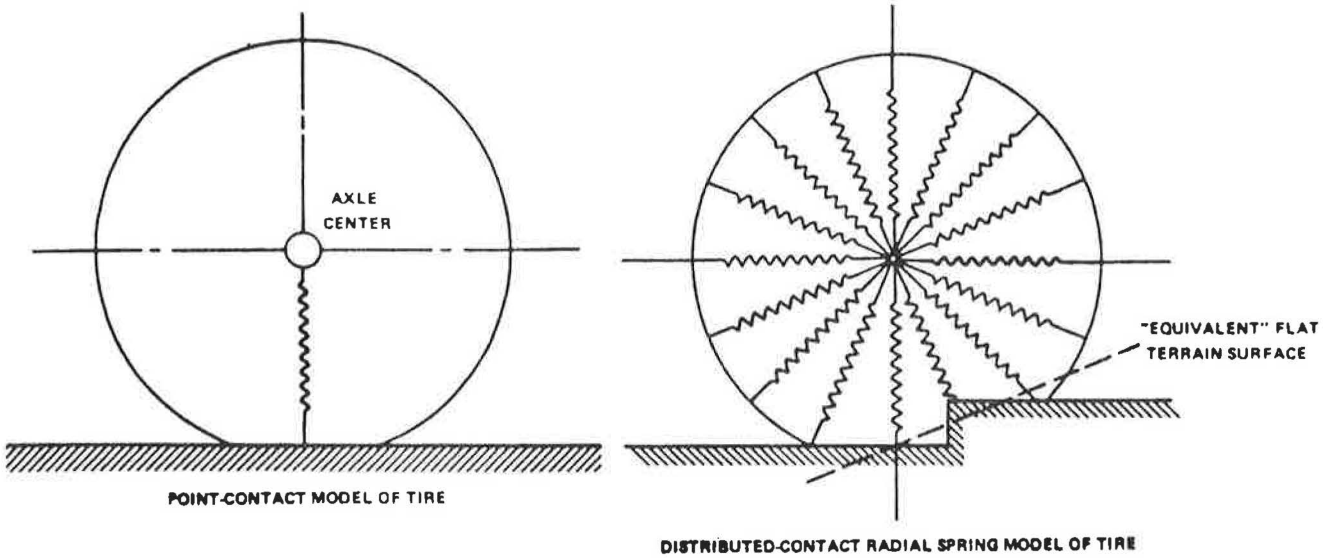


FIGURE 1 HVOSM's thin-disk tire model.

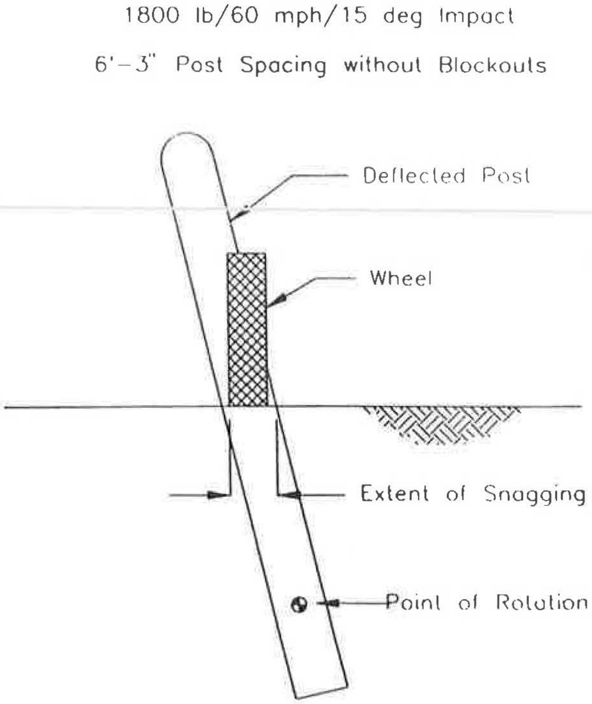


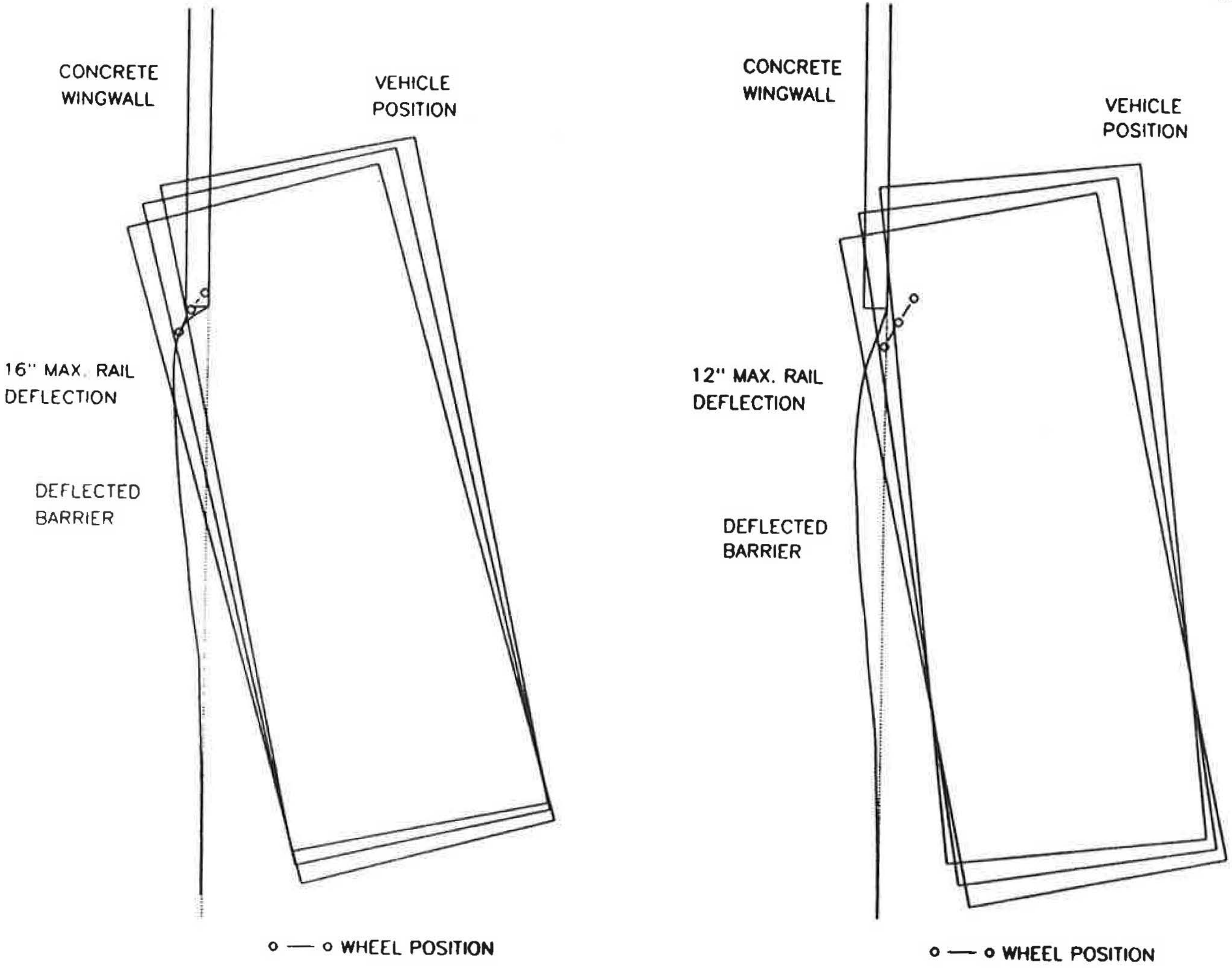
FIGURE 2 Predicting relative snagging potentials.

encountered during traditional tracking vehicle impacts. However, changes in the rotational direction are to be expected when vehicles are rotating prior to impact with the barrier, such as during non-tracking impacts.

Other problems associated with HVOSM's rigid barrier impact model include a relatively crude model of wheel rim and barrier contact, thin-disk tire model, and an inability to model suspension damage$^{(3,4)}$. Direct contact between wheel rims and rigid barriers often has an important effect on vehicle stability. Rim contacts during small car impacts with rigid barriers tend to reduce the extent of vehicle roll away from the barrier while similar contact increases roll angles during large car impacts. The thin-disk tire model, shown in Figure 1 (HVOSM's Thin-Disk Tire Model), does not have any lateral flexibility.

This problem prevents the model from accurately predicting tire deflections and the resulting tire/barrier contact forces when the angle between the plane of the tire and the barrier surface becomes small. In this case, real world tire forces are reduced when a vehicle's tire flexes outward away from the barrier. Finally, vehicle suspensions are frequently damaged during rigid barrier impacts. In this case a vehicle's wheels can act as a tripping mechanism and cause the vehicle to rollover after leaving the barrier

Barrier VII is probably the second most widely used roadside safety hardware simulation program$^{(8)}$. This code incorporates 2-dimensional beam and column finite element barrier and planar vehicle models. The program properly accounts for material and geometric nonlinearities and has a fairly wide selection of physical models including rails, posts, cables, hinges, sliders and springs. Vehicle crush is modeled with a series of nonlinear crush nodes. These nodes can interact with rail elements but cannot be used to interact with barrier posts or other elements that would cause snagging.



Predicted snagging for 16-in barrier deflection

Predicted snagging for 12-in barrier deflection

FIGURE 3 Barrier VII predictions of wheel snagging.

Barrier VII has been successfully used to model a large number of flexible barrier impacts(9). The program is best suited for predicting maximum barrier deflections, element loads, and plastic strain in barrier components. However, the program can also be used to predict snagging of vehicle hard points and wheels on barrier components as shown in Figures 2 (Predicted Relative Snagging Potentials) and 3 (Barrier VII Predictions of Wheel Snagging). Further, the program can be used to support crash testing by identifying critical impact locations and minimum lengths of barrier for proper performance(1).

Unfortunately, 2-D barrier models, such as Barrier VII, do have a large number of limitations. The program is not capable of predicting vehicle vaulting or underriding of a barrier. The program also becomes unstable when extremely large deformations are predicted. Further, it is not capable of simulating vehicle components snagging on barrier elements.

Several attempts have been made over the last 15 years to develop more sophisticated vehicle/barrier interaction models. These efforts led to the Guard, Crunch, and NARD programs(9,10,11). All of these programs incorporate three-dimensional finite element barrier models with a lumped parameter vehicle model similar to that used in the HVOSM program. Unfortunately, these programs all incorporated beam and column FEM barrier models without any mechanism for condensing out degrees of freedom. This basic problem prevents these programs from accurately modeling barriers with very poorly conditioned stiffness matrices such as W-beam guardrails. W-beam guardrail has high stiffness components in the extensional mode and has virtually no resistance to torsion. These wide stiffness variations cause the program to become unstable for high guardrail/vehicle interaction forces.

NEXT GENERATION OF SIMULATION MODELS

The common thread in the prior discussion of simulation program limitations is that all of the existing programs do not have sufficiently detailed models for predicting many aspects of vehicle/hardware interactions. The only solution to this problem is to incorporate much more detailed models of both the vehicle and roadside safety hardware. For example, if a simulation code is to accurately model vehicle/barrier interlocking forces, it must be capable of accurately predicting the local stiffness and deformed shape of a vehicle's sheet metal throughout an impact event. The only mechanism for obtaining this level of modeling detail is to incorporate large numbers of small plate, shell, and brick elements to build models of all relevant vehicle and safety hardware components. FEM vehicle models constructed in this manner contain as many as 30,000 elements as shown in Figure 4 (FEM Idealization of a 1991 Ford Taurus). Roadside hardware models can contain similar numbers of elements as shown for a turned-down guardrail terminal in Figure 5 (FEM Idealization of Turned-Down Guardrail Terminal).

Avantages of using sophisticated models such as DYNA3D(12) include greatly enhanced versatility and an opportunity for greatly improved accuracy. These simulation programs will have few limitations. For example, each individual vehicle suspension component is accurately modeled and the programs can therefore not only predict when suspension failure occurs, but also its effect on vehicle stability. These models should also be capable of accurately analyzing tire penetrations into soft soils as well as vehicle/barrier interlocking forces. Detailed hardware models will allow accurate prediction of soil/structure interactions as well as prediction of component stresses.

The refined models can provide a much higher level of confidence when using computer simulation models to extrapolate safety hardware performance beyond normal crash test conditions. Sophisticated FEM vehicle models should be capable of accurately predicting safety hardware performance for higher impact speeds and angles. Further, these codes will, for the first time, give researchers an opportunity to investigate the effects of non-tracking impacts on performance of roadside safety features. Some accident analysis studies have indicated that almost half of all safety hardware impacts involve non-tracking impacts. Other studies have identified non-tracking impact conditions as a potentially important cause of vehicle rollovers during ran-off-road accidents and longitudinal barrier impacts.

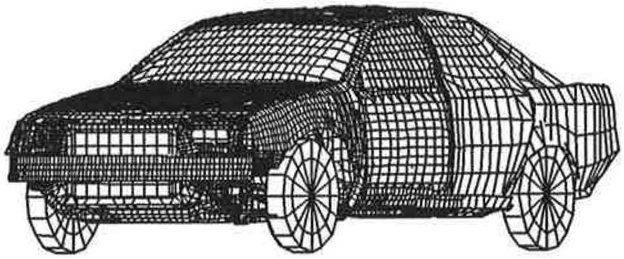


FIGURE 4 FEM idealization of a 1991 Ford Taurus.

The programs also offer a mechanism for evaluating the differences between safety performance in a full-scale crash test program and real world installation situations. Although practically all safety hardware is tested on flat ground with smooth/level approaches, few real world installations actually replicate this situation. Safety devices are commonly installed on modest roadside slopes or over curbs. Further, longitudinal barriers are placed around curves and gating barrier terminals, such as the Breakaway Cable Terminal, are seldom installed exactly as they were tested. Detailed FEM simulation models offer the potential for analyzing a wide variety of potentially hazardous impact conditions that have never been investigated before.

LIMITATION OF SOPHISTICATED MODELING TECHNIQUES

The long list of potential benefits from sophisticated FEM analyses is not easily obtained. Highly sophisticated vehicle models come with a very high price tag. The geometry of each vehicle component must be accurately determined and reduced to an appropriate finite element mesh. The behavior of materials used in the vehicle must also be accurately modeled. These models must include nonlinear material properties such as strain hardening behavior and strain rate sensitivities as well as conventional strength characteristics such as yield and ultimate stresses. Figure 6 (Strain Rate Sensitivity of a Mild Steel) shows typical strain rate sensitivities for steels commonly used in automobiles.

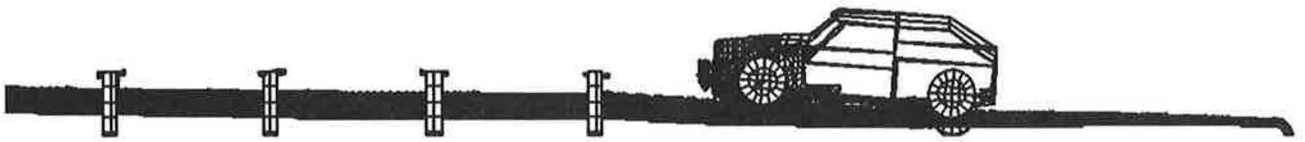


FIGURE 5 FEM idealization of turned-down guardrail terminal.

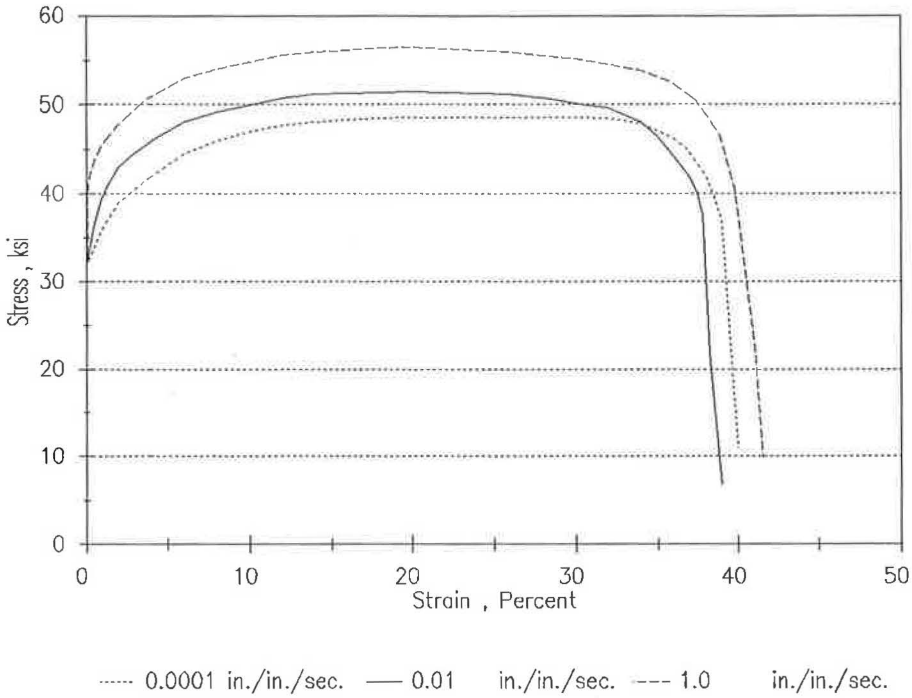


FIGURE 6 Strain rate sensitivity of a mild steel.

As shown in this figure, rate effects can be expected to account for an approximate 20% increase in the yield stress of steels commonly used in automobiles. Although existing FEM models incorporate mechanisms for modeling strain rate sensitivities, the material properties needed to implement these characteristics have yet to be determined. This problem is aggravated by the fact that a typical automobile is fabricated from as many as 16 different types of steel. Therefore, the vehicle modeling process should include identification of the type of steel used in each component as well as determination of the associated material properties. Mechanisms for attaching vehicle components can also have an impact on the energy management of an automobile. Thus, locations and sizes of such items as spot welds, rivets, and bolts can be important. A refined FEM mesh that includes only component geometry and element descretization costs approximately $100,000 to develop. These basic models must then be supplemented with material property information and extensively validated and refined before they can be used with confidence to simulate impacts with roadside hardware.

Roadside hardware models must be described with similar levels of detail. Although geometric descriptions of roadside hardware are generally easier to obtain, dimensional tolerances on these components are often much larger. Further, large variations in material properties are encountered in many safety hardware components such as W-beam guardrails, sign supports, and all wooden elements. Thus, if roadside hardware models are to be representative of a large number of installations, the extent of variations in component geometry and material properties must be identified. As a result, development of roadside hardware models is also relatively costly. This process may initially cost as much as $40,000 per system to obtain adequately validated models.

Computational demands for sophisticated FEM models of vehicles and roadside hardware systems are also very high. For example, simulations of frontal impacts with a rigid pole or barrier require from 3 to 10 hrs of cpu on a Cray-YMP super computer. This would translate into between 12 and 40 hrs of cpu in a workstation environment. Unfortunately simulations of impacts with roadside safety hardware involve many more elements and the events last much longer than rigid barrier impacts. These factors lead to much longer processing times. For example, a rigid pole can be modeled with a relatively few elements and the impact event is completed within 150 ms while a guardrail terminal model would be expected to require several thousand elements and the associated impact generally lasts more than 600 ms. Therefore, most safety hardware simulations will require more cpu time than rigid barrier impacts, perhaps as much as 250 hrs on workstation computers(13).

Many problems remain to be solved before DYNA3D can be effectively used in the design and analysis of roadside safety features. The high cost of developing vehicle models has greatly restricted the numbers of models available. Currently there are only two such models, a 1983 Honda Civic and a 1991 Ford Taurus. Unfortunately development of these models was undertaken more than 2 years ago and they are still in the validation process. Some agencies are now in the process of developing more expedient procedures for developing vehicle mesh information. These processes generally involve incorporating less sophisticated FEM meshes and/or deleting some of the less critical vehicle components. Although some of these procedures will undoubtedly generate less costly FEM meshes, the value of these models has yet to be accurately determined.

Regardless of the outcome of these efforts, the number of validated vehicle models is expected to be extremely limited for the foreseeable future. Automobile manufacturers are perhaps the most promising source of validated vehicle models. The National Highway Traffic Safety Administration is now seeking several "generic" vehicle models from domestic manufacturers. Although these models may not accurately represent any single vehicle, they could be expected to be representative of general classes of vehicles.

There is also a need to determine the required level of modeling detail for analysis of vehicular impacts with each type of roadside safety device. Large savings in cpu times could be realized if the refined finite element meshes now in use are found not to be necessary during most impact scenarios. This effort could also lead to a major reduction in the cost of developing vehicle models. Unfortunately a great deal of experience with DYNA3D models of roadside safety hardware impacts is needed in order to accurately assess the level of modeling detail required for these types of simulations. Highway safety designers should be able to shorten this process by identifying the vehicle and hardware components that are most important to the performance of roadside safety hardware.

Very few safety hardware models have been developed and none of these have been adequately validated to date. The validation process itself is another major obstacle. Although large numbers of documented crash tests are available for use in the validation process, very few of these have been conducted with a 1991 Ford Taurus or a 1983 Honda Civic. The limited data collection efforts associated with most crash test programs also reduces the value of previous testing efforts.

The validation process should be conducted in stages. The first stage of validation should involve modeling of the behavior of individual vehicle and hardware components and/or materials. The process should then progress into models of vehicle and hardware subsystems and eventually into full-scale crash testing. The process of validating mathematical models as large and complex as the DYNA3D simulations envisioned for roadside safety hardware analysis cannot begin with the final stage, i.e. modeling of a full-scale crash test. The validation process must be a process that builds confidence in the accuracy of simulation procedure. The highway safety community cannot be expected to accept these highly sophisticated simulation programs without a confidence building validation process similar to that outlined above.

Finally, existing material models may not be adequate for simulating the performance of roadside safety features. For example, fiber reinforced plastic and polymer based materials are often used in the construction of modern automobiles and are beginning to be used in roadside safety hardware. Existing material models are not believed to be capable of predicting the dynamic behavior of these materials.

Although sophisticated finite element procedures, such as DYNA3D are expected to bring major advancement to the design and analysis of roadside safety features, many significant obstacles remain. Even though the process of resolving these problems will likely involve a number of years and a large financial commitment, the potential benefits far outweigh the foreseeable costs. These procedures offer the only method for accurately determining the performance of roadside safety hardware systems for the entire range of impact conditions experienced along the nations highways. Comprehensive evaluation of the impact performance of existing roadside safety hardware will lead to the development of improved designs and allow highway agencies to make informed decisions regarding the merits of competing systems.

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PART 3 SUMMARY OF BREAKOUT GROUP DISCUSSIONS

BREAKOUT GROUP A
DATA AND ANALYSIS NEEDS

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Richard Foedinger	*Technology Development*
Mark Gieseke	*Minnesota DOT*
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Kenneth Opiela	*Transportation Research Board*
Jerry Reagan	*Federal Highway Administration*
John Viner	*Federal Highway Administration*

GOAL

The objectives of all roadside safety research and projects are to reduce the frequency and severity of run-off-road accidents. One major component of that effort over the past several decades has been the use of accident data to identify problems and to understand the mechanisms that cause accidents and contribute to their severity. The first step in any design process should be to understand as fully as possible the problem. Ideally the role of accident data is to supply some of this understanding. Unfortunately, current accident data rarely gives a clear unambiguous picture of a problem and therefore special data gathering effects and interpretations are required.

ACCIDENT DATA

Traditionally, accident data has provided crucial information for identifying roadside safety problems and evaluating the effectiveness of roadside safety treatments. The need exists for more detailed crash information, acquired primarily through bi-level crash investigations merged with other data bases, to provide meaningful insights on a number of critical roadside safety issues including:

- Vehicle specific encroachment trajectory characteristics including yaw angle and overturn data.
- Factors, characteristics, and causes of vehicle overturn in run-off-the-road crashes.
- Actual performance characteristics including injury severity, possibly using the CODES data base, to evaluate weak and strong post guardrail systems.
- Crash characteristics and performance of "new" guardrail end sections.
- Crash characteristics on 1:3 side slopes to determine level of actual traverseability.
- Adequacy of clear zone and median width criteria.

Bi-level crash investigations provide detailed data beyond that available in police accident reports for pre-defined specific crashes and crash characteristics. Currently, bi-level investigations related to roadside safety are not conducted on the national level but occur to a limited degree in a few states. Careful planning is necessary to insure that needed data is accurately acquired and an experimental design defines the magnitude and scope of effort. Different methods for funding and coordinating these types of bi-level investigations should be explored.

Although police accident data are widely available and can be obtained in statistically meaningful volumes, mechanisms for improving the accuracy and quality of crash data from police accident reports should include:

- Improved location accuracy.
- Better tie-in with other roadway data bases (e.g. maintenance records).
- More detailed information on the sequence of events in the crash.

The accuracy and quality of crash data extracted from police investigations and reports varies considerably. Efforts are needed to improve data quality including better training of police officers, heightened recognition of the importance of the data, and expanded uses of innovative technology such as GPS.

ENCROACHMENT DATA

Limited encroachment information from the 1960's and 1970's using labor-intensive survey techniques are the prime basis for many roadside design decisions. Unfortunately, the vehicle fleet, drivers, and the highway have evolved substantially since these studies, leaving the applicability of these encroachment data to existing conditions in question. The labor required to replicate and expand (not all functional highway classifications were included, for example) these studies is beyond the financial resources of organizations sponsoring roadside safety research. Efficient encroachment data gathered from emerging technologies needs further exploration. A feasibility study to determine the conceptual efficacy of utilizing present and emerging technology to acquire detailed roadside encroachment information without large scale, labor-intensive efforts should be performed.

The reasons why drivers leave the roadway and the root causes of roadside accidents are not well understood. Data is needed to more thoroughly understand the distribution and characteristics of why drivers leave the road and what drivers do in a roadside departure.

Human-factors expertise has not typically been brought to bear on roadside safety research. Professionals with expertise in the human factors and behavioral science fields should be more involved in determining information needs and research approaches. Departure from the roadway can occur from a variety of reasons including fatigue, degraded driver performance due to alcohol and/or drugs, speed too fast for geometric conditions, other crash avoidance evasive maneuvers, driver distractions and locked wheel slides especially on curves. The information is critical from at least three vantages:

- Determination of appropriate roadside design strategies — if a significant portion of drivers are falling asleep rather than losing control, shoulder rumble strips could be quite effective.
- Potential impact on test criteria — if a significant portion of drivers are steering in a certain direction and potentially braking, the results could impact hardware performance since crash testing assumes no steering and braking.
- Potential impact on driver education — virtually no information exists to coach the driver on safe actions to take once roadside encroachment initiates.

TEST AND EVALUATION CRITERIA

Data is needed to assess the relationship of roadside hardware test criteria to actual crash performance characteristics for various safety hardware. Crash data of safety hardware, particularly guardrail, indicates that severe injury and death still occur even though a hardware system meets the NCHRP 350 test requirements. A more thorough understanding of the mechanisms of barrier failure is needed to determine if the test criteria needs to be modified to reflect actual field conditions. Detailed crash information from bi-level crash studies of severe crashes involving specific safety hardware are a necessary foundation for the assessment.

Data is needed to assess the level and patterns of discrepancies between field installations and design requirements for various roadside hardware. The performance of roadside hardware can be substantially compromised if deviations in critical elements of the hardware are substantially changed. Examples include low or high guardrail and BCT end sections without a 4-foot flare. A need exists to identify critical elements, define those with frequent deviations of sufficient magnitude to affect performance, and define appropriate cost-effective corrective actions.

Research is needed to assess the performance of roadside hardware in common environments which deviate from test requirements. Field conditions vary such that some common conditions cannot be easily incorporated into the test criteria. Performance under some of these conditions may vary significantly from test conditions. Examples include guardrails on a 6:1 cross slopes or on moderate horizontal curves. Site conditions that differ substantially from test and evaluation criteria should be investigated using bi-level crash information, limited crash tests, and/or simulation.

The relationships between surrogate performance characteristics in the NCHRP 350 evaluation criteria (unbuckled occupants, no air bags) and actual injuries under similar test criteria when air bags are deployed and safety belts utilized should be examined. The evaluation criteria in NCHRP 350 are based on the worst case scenario for occupant protection. That is, no safety belts and air bags are considered. Five or ten years ago these may have been realistic assumptions. However, with very rapid introduction of air bags in the new fleet and the steadily rising usage rate of safety belts (approximately 70 percent usage in 1994), the test criteria may no longer be relevant to real accident conditions. The differences between injuries of belted and un-belted occupants and occupants in vehicles where air bag are deployed need to be better understood.

Considerable side impact research has been performed, test and evaluation criteria have not been formally adopted and specific guidelines for the hardware thatshould be tested for side impact performance has not been developed. Side impact performance is a special concern for guardrail end sections since:

- Data from FARS indicate that approximately 18 percent of all single vehicle crashes have collision points between two and four o'clock and eight and ten o'clock.

- Guardrail end sections are extensively deployed and vulnerable to a number of side impacts.
- Side impact tests of the BCT, ELT and MELT have shown in considerable intrusion into the passenger car compartment.

Due to the magnitude of the side impact problem, a need exists to acquire the data necessary to finalize the development of side impact test criteria and incorporate these into the basic test requirements. Such criteria will provide the basis for the design of safer end sections.

VEHICLE FLEET CHARACTERISTICS

Characteristics of the vehicle fleet need to be identified, projected into the future, and incorporated into the roadside testing and design process. Over the past ten years, the emergence of vans, mini-vans, utility vehicles, and pickup trucks has led to a diversified vehicle fleet, each with its own set of performance characteristics in collisions. In addition, the introduction of additional safety features such as air bags, anti-lock brake systems, and enhanced side impact protection will affect the severity and potentially the frequency of roadside crashes. A more thorough understanding of the existing and projected (ten year) vehicle fleet composition is needed in relation to the likely crash performance characteristics of new vehicles. This information could also be used for formulating roadside design policy.

HIGHWAY TYPE

The characteristics of single vehicle crashes on rural, two-lane roads need to be studied so that a better understanding of this type of accident is obtained. Such improved understanding could lead to more cost-effective strategies to minimize severe single vehicle crashes. Rural major and minor collectors and local highways (functional highway system) account for over 5,800 annual single vehicle highway fatal crashes (1992 FARS data) or over 60 percent of all rural single vehicle crashes. Yet because of the low volume and extensive mileage, the density of fatal crashes (deaths/100 miles) is very low (local rural roads have on average density of 0.1 fatal crash per 100 miles). Geometrics and roadsides are often inadequate throughout these systems and it is unrealistic to consider entire system-wide upgrades within existing financial constraints. Understanding the characteristics of these crash types could allow for the development of selective, cost-effective strategies for reducing crash loses in these types of collisions.

While at a somewhat lower priority, this same process should be undertaken for urban local streets, minor arterials, and collectors where over 2,000 annual, single-vehicle, fatal crashes occurred. This represents over 50 percent of all urban, single-vehicle, fatal crashes.

SEVERITY INDICES

The severity indices in the roadside design process need to be re-examined and possibly revised. The basic severity indices were developed nearly twenty years ago and reflect roadway conditions considerably different from current conditions. Changes like the availability of airbags, increased safety belt usage, anti-lock brake systems, reduced drinking and driving, and many other factors have probably changed the likely severity of roadside crashes. The severity indices for various roadside hardware and obstacles should be re-evaluated to determine if changes are needed to reflect current and near term conditions.

IN-SERVICE EVALUATION

More attention must be given to pre-define data requirements and specific methods of assessment for in-service evaluations of roadside safety hardware. Since real world crashes may differ considerably from test conditions, it is important to evaluate performance in a range of real-world collision situations. In addition, durability and repair and maintenance concerns can be more rapidly identified through a properly constructed in-service evaluation.

BREAKOUT GROUP B

SELECTION AND DESIGN OF ROADSIDE SAFETY TREATMENTS

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Bill Wendling	*Brown Traffic Products, Inc.*
Harry Taylor	*Federal Highway Administration*
Ed Paulis	*Maryland DOT*
Jim Hatton	*Federal Highway Administration*
Don Gripne	*Washington DOT*
Jim Kennedy	*Battelle*

IDENTIFYING PROBLEM AREAS

The first step in formulating solutions to any problem is to describe the problem accurately. Since the highway fatality rate in the United States has been decreasing steadily for three decades, it is getting more difficult to find areas where improvements can be made and the improvement later shown to have had positive results.

Thus, the first step in the cost-effective use of limited funds is to identify problems that still occur which can be effectively addressed by highway professionals. This relative lack of objective performance measures is perhaps the most serious shortcoming with which roadside safety engineers must deal. In many cases, the engineer simply does not know what is happening or what the effect of a particular treatment will actually be. Recent accident analyses indicate that vehicle rollover is a major problem and yet information available to policy makers and researchers on vehicle stability on slopes and ditches is probably 20 years out of date and all of that particular research was done with large cars. The effects of slope and ditch geometry on the stability of utility vehicles and smaller cars are not known. Intuitively we know that stability is harder to achieve for higher center of gravity vehicles and vehicles with shorter wheel bases, but we do not know how to design roadsides to accommodate them. A second area of concern is the effectiveness of the traffic barriers along the roadways. Unfortunately, it is difficult to assess how the current generation of barriers is performing with any confidence. The evidence of impacts with roadside hardware can be seen on many miles of roadway. It is apparent that the hardware was struck, but unless there was a concentrated effort to investigate what the actual result was, it is difficult to determine if there was a successful redirection or whether there were serious injuries and fatalities.

In the past, there was a concentrated effort to look at all fatal accidents on the Interstate system to determine if any roadway or roadside conditions contributed to the accident or to its severity. Few agencies presently conduct this type of reviews on an on-going basis. The only way to find out what is actually happening is to look at selected accidents in great detail. There is general agreement that police reports do not capture enough of the information needed to identify most roadside features accurately. In the field of accident reporting the policeman is a "fault finder", not a "fact finder". He/she often does not have the training to determine what might have contributed to the severity of a particular accident from an engineering viewpoint. Also, the police are not likely to be able to identify the exact type of hardware hit or the nature of the failure mechanisms (particularly in a damaged state). But a police officer can certainly say the accident resulted from driver error such as DWI, speeding, or simply inattention. Practically, little engineering insight can be gained from the typical police accident report.

EVALUATING HARDWARE PERFORMANCE

In addition to the problems inherent with reported accidents, there is virtually no information on the true extent of unreported accidents. Obviously when roadside hardware is hit and damaged, maintenance personnel have to repair it, so a significant amount of information should be available regarding how often barriers are repaired and the nature of those repairs. Ideally, maintenance forces should be aware that relocating hardware or replacing it with a more appropriate design may minimize future mishaps. Without the benefit of data on unreported accidents, it appears that guardrail or traffic barriers are the third-ranked fixed object killer in the country (trees and utility poles top the list), but when one looks at the number of times a barrier has actually been hit and the vehicle driven away with no severe property damage, the percentage of barrier-collision successes is probably very good.

Until recently, the Federal Highway Administration required new traffic barriers to be installed on an experimental basis and to be evaluated by the using agency. Most states were reluctant to put in experimental appurtenances because they did not want the added responsibility for evaluating the performance of the experimental barrier. They perceived the evaluation process to be cumbersome, requiring much time and effort when, in effect, a simple narrative report would normally have sufficed. This report would answer such questions as:

- How does the experimental feature perform when hit?
- What does the experimental feature cost compared to what would have been used otherwise?
- Are there any non-accident related problems with it?

In spite of the scaled-down reporting requirements, most State agencies remained reluctant to use and evaluate new products. For this reason, the FHWA delegated to the individual States the decision on whether or not to evaluate new products formally. Thus, this remains an area in which much useful information is not routinely collected or disseminated.

There are several specific instances where the lack of timely feedback has resulted in the creation of significant safety concerns. Collectively, State highway agencies installed numerous breakaway cable terminals (BCT's) throughout the country until some States began to get feedback that this treatment was contributing to a relatively high number of serious injuries. When actual field installations were examined, numerous problems were identified that compromised the performance of the BCT. Even a decade later it is still very hard to find a BCT in the field that looks like one of the ones that was crash tested. Many of them do not have the required parabolic flare. The ones that do have the flare seldom have a clear run out area behind the barrier even though it is known that the vehicle will normally come to rest in this area. Crash testing has demonstrated the importance of the correct parabolic flare and a clear run-out area, yet terminal after terminal is installed either without the flare or in an area where the area beyond the terminal is not traversable.

A second example where lack of definitive performance data creates uncertainty concerns the turned-down w-beam guardrail terminal. There are a few States that believe the turned-down terminal is still as good as anything else even though crash tests have demonstrated that this type of design invariably rolls small cars and it does not slow big cars very much. They are still going to either ride up on the barrier or end up 200 feet behind the barrier in the woods or over the embankment. There generally is not sufficient accident data to show statistically that these are poor performers in the field. Regardless of the crash test results there is still room for argument that this may be the best that can be done for some situations. A systematic review of guardrail terminal accidents could eliminate the uncertainty by documenting actual performance.

A more recent concern arises from the ISTEA requirement that States install a certain percentage of "innovative" median barriers annually. About half of the states that reported using innovative median barrier installed the single slope or constant slope barrier that was developed by the Texas DOT. It is not known whether the constant slope barrier is significantly better than a New Jersey safety shape of equal height. Unless someone is looking at the performance of these barriers in the field, hundreds of miles of constant-slope barrier may be installed on the highway system and before the roadside safety community discovers, as with the BCT, that a safety problem has been created. Responsible roadside safety professionals must find ways to determine the real-world performance of barrier but, unfortunately, there does not seem to be a national inclination to do so.

TRAINING FIELD PERSONNEL

Training of design, construction and maintenance personnel is also a major problem despite the fact that there are many technology transfer efforts underway. Most states have technology transfer centers primarily intended as a resource for city and county engineers who might not be privy to the most recent information available to (or through) State agencies. Despite these efforts, many designers in state highway departments are not aware of fundamental roadside safety concepts. When such personnel attend the National Highway Institute's Roadside Design Guide course they often see new barriers for the first time even though the FHWA may have sent out information earlier. This information does not always get down to the people who need to see it. In the late 1970's, the Federal Highway Administration had safety coordinators in each division office and most state highway agencies had a contact person who was concerned with disseminating this information. This staffing level no longer exists in many FHWA offices and many State highway departments no longer have a central safety engineer to review such information and get it to the right people. There is a large discrepancy between what researchers and policy makers know and what designers, installers and others charged with implementing the technology know. Training is one of the areas where big improvements could be attained at relatively modest cost. Training is often focused on the designer such that construction and maintenance personnel are ignored. The construction people should have enough knowledge of the design procedure and how an appurtenance is supposed to work to avoid installation mistakes.

Years ago the Federal Highway Administration implemented what were called "Yellow Book" reviews. FHWA personnel went out in each state with a group of people from the state and looked at projects that had recently been constructed from a safety perspective. Virtually every project had some features that were far less than optimal from a safety viewpoint. For example, multiple safety features that worked fine independently can be put in such proximity that they would probably interfere with each other or areas where a clear recovery area was needlessly shortened (e.g., by the construction of a vertical head wall at the minimum clear zone distance). Like the perfect BCT, the perfect project from a safety standpoint is very difficult to find.

UTILIZING NEW TECHNIQUES

New technology may provide improvements to roadside safety: electronic vehicle identification numbers to keep track of road use, the use of GIS/GPS systems to inventory and monitor roadside appurtenances and provide precise data on accident locations, on-board sensors that record pertinent vehicle dynamics information like an aircraft crash data recorder, weigh-in-motion and classification systems to improve understanding of the nature of road use, collision avoidance systems, aids to keep vehicles on the road, and so on. Research is needed to find the best way to apply these new technologies to real-world situations and evaluate their safety impacts.

The last two items are more specific. NCHRP Report 350 now has six performance limits for various traffic barriers. Appurtenances that fit into each of those categories need to be identified and guidelines for using such barriers need to be developed. Virtually all States do this in an ad-hoc manner already. If a location exists where a truck penetration is unacceptable, a San Antonio tall concrete wall could be used. Pennsylvania has a 2280-mm concrete safety shape where two interstates meet and the connecting loop ramp was the site of several tractor-trailer crashes. Maryland has built a wall similar to the Texas design to prevent trucks from going off a curve on the bottom of a downgrade. There would be more high-performance barriers at selected locations in the country if there were credible warrants that a state highway agency could use.

Rumble strips are an extremely effective way of alerting a motorist to the fact that an encroachment has begun and the vehicle may be heading off the road. Some states are using this technique extensively, some at selected locations, and some use it rarely. States that have conducted before-after studies have reported reductions in run-off-road accidents of up to 70 percent. This appears to be an extremely cost-effective safety treatment which should be widely adopted.

SUMMARY

Virtually everything discussed above should be included in the safety management system which is mandated by ISTEA. The first and most important step in this process is accurate problem identification. This requires refinements to the current accident record system so that information useful to the highway designer is available. It also requires on-going surveillance of the highway infrastructure to identify possible problem areas. Once problem areas have been clearly identified, specific objectives must be developed. Everyone involved in the safety effort must have the same understanding of what is to be accomplished. The next step is to establish a methodology, or specific approach, to meet the stated objectives. And the final step is evaluation; a systematic review of what has been or is being done to verify that all objectives are being met. An effective safety management system will include each of these elements.

BREAKOUT GROUP C
EFFICACY OF SIMULATION METHODS

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INTRODUCTION

The objective of the breakout group was to explore the state-of-the-art associated with computer simulation and to assess the feasibility of more widespread use of this approach in the design and evaluation of roadside safety features. Computer simulation programs are generally lumped into two distinct categories: vehicle handling models and finite element impact models. The discussions initially focused on the current capabilities and limitations in these two areas, how the existing limitations can be overcome, and what the potential benefits of such improvements would be to highway safety. These benefits might take the form of updated or improved guidelines/specifications, development of warrants for different service levels, improved hardware, and evaluation of existing hardware and features under conditions which have been untestable due to cost constraints or technical limitations.

VEHICLE HANDLING MODELS

It was generally agreed that existing vehicle handling models such as the Highway-Vehicle-Object Simulation Model (HVOSM) and the Vehicle Dynamics Analysis, Non-Linear (VDANL) simulation program do a credible job in simulating vehicular traversals of roadside features such as side slopes, ditches, driveways, and median crossovers on hard soils. HVOSM has been well validated and widely used in roadside safety research. VDANL has been used extensively by the National Highway Traffic and Safety Administration (NHTSA) and is currently being used by the Federal Highway Administration (FHWA) in its Interactive Highway Safety Design

Model (IHSDM) project. Table 1 lists some of the applications for these two vehicle handling codes and the limitations and capabilities of the current models in these areas.

One of the major limitations identified with existing vehicle handling models involves tire/soil interaction. Vehicle dynamics programs such as HVOSM and VDANL have validated tire models for hard soil or pavement, but they are not generally suitable for simulating soft soil conditions in which the tire ruts and/or plows into the soil. This type of interaction is of particular significance since it is believed to be a major contributing factor in many vehicle rollovers.

With appropriate validation and models of sufficiently fine detail, DYNA3D should be capable of accurately simulating this type of tire/soil interaction. However, a simplified approach to the problem is desirable so that large parametric studies can be conducted in a more cost-effective manner. Two approaches for addressing this problem were discussed. One approach involves using detailed finite element models as an intermediate tool to explore the phenomena and aid in the development of a simpler tire force model for soft soils that could be integrated back into existing vehicle handling codes. For example, it may be feasible to use a validated DYNA3D model to determine appropriate coefficients for modifying the friction ellipse of the carpet plot to serve as a surrogate measure of degree of soil penetration for different soil types. In this way, the fast run times of the handling models could be utilized for conducting parametric studies that would otherwise be too costly.

A second approach is to provide a real-time linkage between the vehicle handling code and DYNA3D for purposes of transferring tire forces. DYNA3D could be used to model the tire/soil and undercarriage/soil contact using optimized meshes and the resulting forces could be transferred to the handling model to determine the resulting vehicular behavior.

Driver modeling is another current limitation of all handling codes and it may also play an important role in collision analysis. The affect of driver inputs just prior to and during a roadside encroachment or collision are largely unknown. Recent live driver barrier collisions have shown that drivers can maintain contact with the steering wheel during impact, even when subjected to accelerations up to 5-g. In such cases, the driver's response can have a dramatic effect on vehicular trajectory.

In addition to studying the rollover problem, another benefit that can be derived by addressing some of the limitations presented in Table 1 is improved severity indices for input into benefit/cost models. Simulation

TABLE 1 APPLICATIONS, LIMITATIONS AND CAPABILITIES OF VEHICLE HANDLING SIMULATIONS

Applications	**Limitations**	**Capabilities**
Traversal of Slopes and Ditches • Research rollover problem • Develop guidelines (eg. clear zones, slopes) • Severity indices for benefit/cost analysis	• Tire rutting/plowing in soft soils • Undercarriage contact with terrain • Tire failure (blowout) • Tire roll-off rim due to soil plowing or hard cornering • Modelling rollover event	• Adequate suspension in normal operating range • Validated for hard soil and pavement • Predict *occurrence* of rollover (limited ability to simulate actual rollover event)
Pre-Impact Phase • Provide impact conditions for barrier design • Severity indices for B/C analysis	• All of the above limitations • Driver modelling	• Same as above • Non-tracking conditions on hard soils
Post Impact Phase • Barrier design • Prediction of rollover • Severity indices for B/C analysis	• All of the above limitations • Damaged suspension • Repeatability of tests.	• Same as above • Limited ability to model damaged suspension

models are often used to estimate the severity of roadside encroachments for ranges of impact conditions that could never be economically tested.

This is accomplished by relating indicators such as vehicular stability and occupant risk criteria to severity indices for input into the B/C model. Improved handling models capable of predicting and simulating rollovers will enable researchers to more accurately define these values which, in turn, will help to more optimally allocate billions of dollars of maintenance and design funds.

IMPACT MODELS

In recent years, impact modeling has focused on the DYNA3D finite element program. DYNA3D is a state-of-the-art nonlinear dynamic impact finite element code that has gained wide acceptance for its ability to model complex collision problems. This code is a vast improvement over formerly used codes like BARRIER VII, GUARD, and NARD. The general purpose nature of the code lends itself to a broad range of collision analysis domains, including vehicular impacts with roadside safety hardware.

However, although many roadside safety problems can currently be addressed using DYNA3D, there is a large amount of work that must be accomplished to extend its capabilities to more specifically address this area of analysis.

Much of this work will be accomplished through the Vehicle Impact Simulation Technology Advancement (VISTA) and PREVISTA programs. These are collaborative agreements among FHWA, NHTSA, and Lawrence Livermore National Laboratory (LLNL) through which the use of DYNA3D and associated codes are being explored for use in roadside hardware analysis, vehicle crashworthiness, and occupant biomechanics research. The PREVISTA project is an exploratory study whereas the full VISTA program will be a longer term effort. In addition, finite element vehicle and hardware models are being developed in support of these efforts through government grants and research contracts.

Table 2 identifies some of the applications for the DYNA3D impact code, along with existing limitations and capabilities in these areas. As indicated in the table, there is a need for detailed vehicle and hardware finite element models. Obtaining good vehicle models appropriate for use in roadside safety research has been a problem over the past several years. Research efforts in this area have primarily focused on developing and validating vehicle models for frontal impacts at a cost of approximately $100,000 per vehicle. Vehicle models

TABLE 2 APPLICATIONS, LIMITATIONS, AND CAPABILITIES OF IMPACT SIMULATIONS

Applications	**Limitations**	**Capabilities**
ISTEA Vehicle Performance with Longitudinal Barriers • Explore current barrier designs to identify potential problems	• No spinning wheel (may be important to simulating vehicle climb) • Lack of available vehicle models from which to choose • No vehicle models developed or validated for oblique impacts • Need for more sophisticated suspension models	• Can simulate broad range of impact conditions (eg. non-tracking).
Crash Cushion, Breakaway Support, and Guardrail Terminal Development and Evaluation	• Failure Criteria • Material properties	• "Validated" vehicle models for frontal and side impacts will soon be available. • Large suite of material models available in DYNA3D (approximately 40). • Good contact algorithms.
New Longitudinal Barrier Development	• Oblique-impact vehicle models need to be developed	• Same as above

which are currently available include a Ford Festiva, a Ford Taurus, and a Honda Civic. Work on a 1/2-ton pickup truck is expected to be completed in December 1994. This pickup model, which is being developed for both frontal and side impacts, will have approximately 20,000 elements.

There are several other efforts pertaining to the development of vehicle models currently underway at NHTSA and FHWA. It is anticipated that additional vehicle models representing the three major automobile manufacturers platforms will be available in November 1995. These will include a Chevy Lumina, a Dodge Intrepid, and an improved Ford Taurus. Obtaining models and/or information from the auto manufacturers would greatly reduce the cycle-time required for roadside-hardware/vehicle finite element model development. NHTSA routinely obtains information of this type from the manufacturers, but confidentiality agreements limit the distribution of this information. There are, however, some promising developments that suggest that NHTSA will obtain some generic or anonymous vehicle models from Ford and GM in the near future. In addition, increased public domain (FHWA/NHTSA) activity will probably encourage manufacturers to become involved so that they can have some influence over the development of these public domain models. Any participation or cooperation between the automobile manufacturers, NHTSA, and the roadside safety community should continue to be highly supported and encouraged.

One need in this area that is not currently being addressed is the development and validation of vehicle models for oblique impacts. As mentioned, modeling efforts are being directed toward frontal and side impacts in response to NHTSA test requirements. More detailed modeling of the wheel well area and, in particular, the suspension, is needed in order to accurately simulate oblique impacts into longitudinal barriers.

Hardware models are less time consuming and costly to construct because the material properties are typically easier to quantify and the geometrics are not as complex. It is estimated that validated models for most roadside appurtenances can be constructed for $25,000 to $40,000 each, depending on the level of complexity. To date, work has been conducted on the development of finite element models for the breakaway cable terminal (BCT), the turndown W-beam guardrail terminal, the G4(1S) steel post W-beam guardrail system, and a U-channel sign support. In addition,

TABLE 3 VALIDATION PROCEDURE

Model Type	Basis of Comparison	Validation Criteria
Material Models	static/dynamic tests of vehicle and barrier materials	• Match stress-strain diagrams to experimental results for different strain rates. • Match elongation at failure.
Components	static/dynamic tests of rail element, post, vehicle components, etc.	• Match force-displacement and/or force-time histories. • Demonstrate the correct deformation and failure modes.
Subsystem	post/block/rail connection, posts in soil, engine cradle and motor mount assembly, suspension system, etc.	• Same as Component validation. • Demonstrate proper energy balance. • Match time-event sequences and deformation phenomena. • Match acceleration and velocity time histories. • Match peak 10-ms average acceleration.
System	Roadside hardware systems subjected to rigid impactors (bogy, cart, etc.).	• Same as Subsystem validation. • Match both resultant and components of acceleration and velocity indicators.
	Vehicle subjected to rigid barrier and pole impacts.	• Same as Subsystem validation. • Force, velocity, and acceleration-time histories should be matched for c.g., engine, and maybe calipers.
Vehicle/Hardware Interaction	Vehicle/Hardware impacts under prescribed conditions.	• Same as System validation. • Match acceleration and velocity-time histories for c.g.

FHWA has initiated a university grant program for the purpose of developing and validating additional hardware models, and it is anticipated that 5-6 new models will be available in the spring of 1996. LLNL researchers have offered their support in assisting the universities in their modeling efforts.

Once these areas have been addressed, the DYNA3D code will begin to be able to function as a valuable tool for exploring numerous roadside safety issues. Areas which the program is expected to impact include the assessment of current hardware with ISTEA vehicles, the evaluation of hardware under alternate impact conditions including non-tracking scenarios, the optimization of current hardware for different service levels, and the development of improved hardware.

There are a variety of approaches to using and integrating vehicle handling and impact models. Some have suggested merging or combining the best features of these different codes into one over-arching code. Others believe the codes should remain separate and be linked or coupled externally. At one time it was thought that these codes could be packaged in a user-friendly interface such that they could be used by design engineers and State DOT personnel. This idea has been largely abandoned, at least for the present, in recognition that these types of analyses are very complex and require well trained and specialized analysts that will not normally be available to user agencies. The use of these codes, therefore, is primarily intended for research and development purposes.

VALIDATION ISSUES

Before any simulation code can be useful as a reliable design and analysis tool, it must first be properly and reliably validated. However, it should be understood that it is not practical to match every peak and valley during the validation process. Validation should be viewed as an accumulation of evidence that the simulation is realistically explaining physical phenomena; there is no one single metric that will assure the analyst that a model is sufficiently validated.

A generic validation procedure is shown in Table 3. This procedure has five distinct levels of validation. While it will not always be possible to validate a simulation to all of these levels, the analyst should attempt to validate all the critical portions of any finite element simulation. Initially, the validation process should be conducted in progressively complex stages, ranging from material models to the full vehicle and hardware systems. Many of these items will only need to be validated once, after which they can be used in subsequent simulations. For example, once the properties of AASHTO M180 Class A Type II guardrail steel have been fully validated for the expected range of strain rates, subsequent analysts can use those results with confidence that they are using a "validated" material model. Thus, over time, libraries of validated materials, standard barrier components, common barrier subsystems, and vehicle and hardware models can be assembled and used as a starting place for new analyses. As more materials, components, and assemblies are independently validated, the analyst can have more confidence in the predictions of the model.

GENERAL DISCUSSIONS

The finite element vehicle models which have been or are being developed provide the analyst with a level of detail and sophistication which was previously unavailable. These detailed models will unquestionably increase the level of accuracy of our simulation efforts. However, this increase in sophistication does not come without a price. As mentioned above, the development and validation of a finite element vehicle model represents a significant investment in time and effort. This reality raises several issues which must be addressed.

First, what level of detail is required to adequately simulate roadside impacts? Cost escalates quickly with an increase in complexity. This is true not only in regard to the initial modeling cost, but in CPU time as well. In order to reduce these costs it is necessary to determine how generalized the model can be without compromising the desired level of accuracy. For example, a distinction can be made among frontal, side, and oblique impacts. For each of these impact scenarios, what areas of the vehicle require precise detail and how many elements are necessary? These questions are perhaps best answered during the validation process by performing mesh sensitivity analyses and investigating different modeling schemes.

Second, how many different vehicle models are required to obtain an accurate representation of the vehicle fleet? Historically, roadside features and appurtenances have been evaluated with only two design vehicles: a small passenger car to measure occupant risk, and a larger passenger sedan or pickup truck to assess strength. The basic concept was to bracket the behavior of the vehicle fleet by using two vehicles at opposite ends of the spectrum. Ideally, researchers and designers would like to be able to consider the performance of other vehicle types, but cost has been a prohibiting factor. While simulation may provide more flexibility in this regard, it would not be practical to develop finite element models of every vehicle on the market. Thus, the question becomes how many vehicle models are necessary to establish a representative picture of the vehicle fleet? There are two research studies which will help address this question. A study sponsored by FHWA will soon be awarded in which current and future vehicle trends will be analyzed, and generic vehicle platforms will be developed. Additionally, as part of an ongoing NCHRP study which is investigating the performance of light trucks with current hardware, the suitability of the 2000P as a surrogate for the light truck population will be addressed.

Once the appropriate vehicle models have been selected and developed, how often should the models be updated to assure adequate representation of vehicle fleet behavior? One suggestion is to adopt the current 6-year time frame specified in NCHRP Report 350 for the acceptable age of design test vehicles. For instance, if a 1991 Ford Taurus model is developed, the model could be reviewed after six years and revised if it is found that the platform has undergone changes which may effect its impact performance. If generic models are used, the generic platform upon which the vehicle model is based could be reviewed. The aforementioned FHWA study should provide some guidance in this area.

RESEARCH NEEDS AND PRIORITIES

There are many possible improvements to simulation codes that could be pursued. Since the focus of FHWA,

TABLE 4 PERCEIVED RESEARCH NEEDS

	Priority	**Level of Effort**
● Better tire/soil models	High	High
● Oblique vehicle models	High	High
● Roadside hardware models	High	Medium
● Suspension models	High	Medium
● Vehicle handling linkages to FEM codes	High	Medium
● Material characterizations	High	Low
● Additional vehicle models	Medium	High
● Validation and testing	Medium	High
● Additional material models (e.g. composites)	Low	High
● Occupant models	Low	High

NCHRP and the roadside hardware community is developing safer roadsides, the improvements to simulation codes will be driven by practical problems that need solutions and will provide the most benefits. Existing codes are currently useful for evaluating many roadside safety problems, and further advancements and improvements to these codes will undoubtedly extend these capabilities and permit investigation of problems that cannot be cost effectively addressed through crash testing or analysis of accident data. Improved simulation codes are expected to be particularly useful in exploring the rollover problem, investigating the effects of non-tracking impacts, and performing parametric studies on the effects of variations in different vehicle and barrier parameters. Simulation can also be used to identify critical test conditions, improve existing hardware and/or roadside conditions, develop new hardware, and optimize policies and guidelines, thus producing safer roadsides.

To provide some direction toward attaining these goals, a variety of research needs were discussed. Table 4 presents a list of these needs which were compiled from the limitations identified earlier. Each research need was assigned a relative priority and level of effort using a range of high, medium, and low. The priority assignments were based primarily on the perceived level of benefits the research would provide. The level of effort is a relative estimate of the amount of resources required to address the issue. Of the two rankings, the priority assignment should be weighed more heavily than level of effort.

COMMENTS ON THE EFFICACY OF SIMULATION METHODS

Dale Schauer
Lawrence Livermore National Laboratory

I would like to stress that the DYNA3D finite element program is an excellent tool for doing roadside hardware impact simulations. Performing these analyses is going to require good computer hardware and experienced users.

Lawrence Livermore National Laboratory has distributed DYNA3D to over 300 different institutions around the world. DYNA3D is the basis of all the nonlinear finite element impact analysis codes that are being used by the automobile manufacturers to simulate their impact crashes.

I am afraid that the level of experience available in the roadside safety hardware community is not sufficient. The FHWA is entering cooperative agreements with about 10 universities performing various types of roadside safety simulations. I believe the Laboratory can help these universities and graduate students because they are going to be lacking in experience and the results are going to be worthless unless they have assistance.

If you can get both good computer hardware and experienced users, I know that you will get good results. We have used DYNA3D in the Laboratory for over 15 years in nuclear weapons design and we have extremely more difficult environments than the automobile crash environment.

We have used it very successfully even in simulating events for which we did not have a chance to set up a controlled experiment. When we have had time to set up a controlled test we have gotten very good comparisons. I know you will be able to obtain the same quality results given the proper experience and computing resources.

Where I think this community can use this tool is to simulate tested geometries. There is a lot of test data today. Once you can simulate these test geometries, you can ask the "what-if" questions. Several of these questions that were mentioned at the meeting are:

- Barrier capacity -- this type of problem is ideal for computer simulation studies. The simulation can be used to explore the limits of the barrier and then design a test, this can be designed just below and just above the expected "capacity" point. If your simulation confirms the test results you can put a great deal of faith in your ability to predict the barrier performance.
- Performance of poorly installed hardware -- Poor geometry and misinstalled hardware can be modeled just as "properly" installed hardware can. The attributes that cause poor performance can be identified using simulation.
- Vehicle performance -- The performance of small vehicles and large vehicles can be explored using simulation.

The key to successful simulation studies is getting experienced analysts, barrier designers and testers to work as a team in designing hardware. A lot of people who write computer codes do not have the slightest idea of what's going on in the field. You can not expect a computer scientist to do some calculations without any input from the test people. Likewise, testing people can not be expected to understand the arcane details of simulation. It is critical for the test people to work with the computer simulators.

Full-scale crash testing is not going to go away. Computer simulation is not going to put testing out of business. The biggest advantage of simulation is the ability to explore "what-if" situations. You can ask all these what if questions on the computer and it doesn't cost a lot of time and money. I believe this is the correct approach and I think we should proceed.

BREAKOUT GROUP D
ASSESSING AND DEVELOPING ROADSIDE HARDWARE

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Ken Stack	*General Motors*
Michael Kempen	*Roadway Safety Services, Inc.*
Arthur Dinitz	*Transpo Industries*
Bob Mileti	*Roadway Safety Services, Inc.*
Hayes Ross	*Texas Transportation Institute*

The purpose of this group was to analyze issues associated with the development, testing and application of roadside hardware and to prioritize lists of hardware development needs and opportunities to promote new concepts. Developing new, more effective roadside hardware involves a critical examination of the changes in the vehicle fleet, changing roadway operational conditions, and the need to maximize the benefit of allocating scarce resources to address safety issues.

One important concept that has evolved over the past decade is the multiple service level approach to roadside hardware. NCHRP Report 350 has identified testing levels that attempt to categorize barriers into groups with similar performance capabilities. Report 350 does not, however, suggest appropriate situations where these different test levels should be used. Much research needs to be done to link the test levels in Report 350 to criteria for locating and selecting roadside hardware at a particular site. The likely range of impact speeds and angles as well as the operational conditions on a particular roadway should be part of determining what service level is required at a specific site. NCHRP project 22-12, planned to start in 1995, is expected address many of these issues.

An important consideration in locating and selecting barriers is the underlying philosophy behind a barrier design. Many barrier systems have been designed with the so-called "redirect-the-vehicle" approach. While most roadside safety practitioners would probably agree it is generally preferable to use an "arrest-the-vehicle" strategy, the technology available when most of the common barrier systems were developed could not accommodate this approach.

Secondary collisions with fixed roadside objects and other vehicles can be even more harmful than the first collision with a roadside safety device. Some sites may be particularly prone to this type of multiple event collision. For example, high-volume roadways may be more prone to secondary collisions with other vehicles and two-lane rural roadways with limited shoulders may be more prone to second collisions with fixed objects like trees.

Some devices have been developed that exploit the "arresting" strategy. Unfortunately, sometimes this type of barrier creates a maintenance problem since the arresting action is usually supplied by causing extensive barrier damage. Many redirecting barriers, such as the concrete safety shape, can sustain many impacts without any repairs or maintenance. This issue, also depends largely on proper siting of roadside hardware. Roadside hardware should be designed to be an integral part of the roadside rather than an after-thought. Redirecting barriers may be superior in some situations where repairing damaged barrier in a timely manner would be a problem or where there is simply no room to decelerate a vehicle. Arresting barriers, however, are probably superior when properly located to allow them to decelerate and capture the vehicle. Research to identify the types of situations where an "arrest" strategy should be used rather than a "redirect" strategy is needed.

Arguably, developing better criteria for locating and selecting barriers would produce more of a safety benefit than developing new hardware. Much of the current generation of roadside hardware is not well matched to the sites or conditions of the roadside. While more improved training and technology transfer would help educate field personnel, current selection criteria are not well developed. Some European countries are using safety "audits" to try and identify and correct safety problems during construction. This requires a skilled safety auditor to examine the plans and examine the site. While this is an improvement over the current system used in the United States, it depends on the accumulated skill and experience of the auditor and may not help in developing general purpose criteria. The cost-benefit approach has been available for many years but has not been as widely adopted as once hoped. Practitioners have found cost benefit analyses unwieldy and there has been a shortage of dependable probablistic models. In addition, current cost-benefit models do not examine the whole roadside system but focus on just one particular feature. The fact that one can find improperly installed or located hardware on nearly any roadway in the country is ample evidence that there is not an adequate tie between the design of the roadway and the roadside.

The vehicle fleet in the United States has changed significantly over the last decade. New safety improvements such as anti-lock braking systems, airbags, active suspension systems, safety-cage bodies, side impact protection, and padded interior components have made the modern fleet of vehicles safer. The roadside hardware community has always reacted slowly to changes in the vehicle fleet due to the reliance on testing with 5 and 6 year old vehicles. By the time crash tests are performed, reported, and final results distributed to practitioners, it is not uncommon for the test vehicle to be 10 years old. Improvements in vehicle design also suggest a critical review of testing procedures should be undertaken. Is it still reasonable to design for unbelted occupants? Will a higher proportion of ABS equipped vehicles change the typical speed and angle at impact? What effect will ABS have on the non-tracking impact problem? These and many other fundamental questions need to be examined so that barrier designs can anticipate vehicle fleet changes.

In addition to safety-related improvements, many other vehicle changes have at least the potential for changing the way vehicles and barrier interact. Aerodynamic styling, lighter vehicles, and the ability to tear wheels from many small cars could all degrade the performance of once-adequate barriers systems. In addition, completely new types of vehicles like minivans and all-purpose vehicles have become a significant part of the vehicle fleet. What changes in barrier performance will the very different inertial properties of these vehicle cause? The breakaway cable terminal provides a good case study of vehicle fleet changes affecting the suitability of a barrier. While closer collaboration with the automotive design community will improve this situation, the roadside hardware community must also find ways to anticipate problems with current hardware, much of which was designed for vehicles produced more than 20 years ago.

Great strides have been made in making roadways safer. These improvements have resulted from efforts by roadway designs, the roadside hardware community, automobile manufacturers and law enforcement agencies. In the past these groups have tended to work alone on pieces of the overall safety problem. Continued improvements in safety, however, are requiring that these groups work more closely. The roadside hardware design community must find ways to work with the automobile design community to stay informed about vehicle design changes. These interactions can be partially accomplished through technical organizations like the Transportation Research Board, the Society of Automobile Engineers, and the Automobile Manufacturers Association. The degree of collaboration allowed by law is one barrier to information exchange that should be explored. While the roadside design community is relatively free of restrictions, the automobile industry is a highly competitive and highly regulated industry that may not be able to function as openly as the roadside design community would like. All roadside hardware collisions involve three key ingredients: the driver, the vehicle and the barrier. Focusing on one to the exclusion of the others is a short sighted policy for all involved in improving roadside safety.

"Real world" collisions are often not like the controlled tests performed when evaluating roadside barriers. Tests are performed with engines off, tracking vehicles, with no driver input. There should be a continuing effort to find better ways to perform tests as new technologies emerge. In addition to the testing conditions themselves, there is also a need to find better measures of performance. Is the occupant risk criteria really a good measure of the risk to occupants? Are the post-impact trajectory criteria used and are they meaningful? What should constitute an occupant compartment "intrusion"? The community should be open to finding better evaluation criteria and not become inflexible because "that is the way it has always been done."

Crash testing procedures currently identify reasonable "worst case" test vehicles. This has resulted in using a very small vehicle (the 700C or 820C passenger car) and a relatively large pickup truck (2000P pickup truck). The most common vehicle class, passenger cars in the 1300-kg range, have rarely been used in testing roadside hardware. The roadside testing community has tended to informally standardize on a few test vehicles like the Honda Civic in the 1980s and the Ford Festiva in the 1990s since it is easier to compare tests using similar vehicles. There is an ever present conflict between testing with "standard" vehicles that can be compared directly with each other and testing with "representative" vehicles that can be related to the vehicle fleet as a whole. Interestingly, NHTSA generally has used a "representative" vehicle approach in its research in contrast to the "standard" vehicle approach used in roadside design. Research should reexamine the philosophy behind selecting test vehicles.

The effect on barrier performance of a changing vehicle fleet may also have tort liability ramifications. For example, what would the liability consequences be of the standard W-beam guardrail not satisfying Report 350 test level three? When a barrier tears a wheel off a vehicle during a collision causing it to roll over, is this a failure of the vehicle or the barrier? Even if the answers to these types of were known, how could a State upgrade such common hardware and avoid litigation when serious accidents occur on the unupgraded portions of the network? Should guidelines or methodologies be developed for upgrading substandard sites in a roadway network?

Most roadside designers would agree that the best alternative for providing a safe roadside is to maximize the clearzone available to errant vehicles. Unfortunately, acquiring right-of-way is usually the most expensive component of roadway construction. Roadway designers, especially in rehabilitation work, try to minimize right-of-way takings since they tend to be expensive and time consuming. Despite these problems, however, additional clearzone is probably the most effective method for making a roadside safer. Not enough is known, however, about the benefit-cost implications of right-of-way acquisition. NCHRP Project 17-11 is expected to re-investigate the clearzone concept and should address some of these issues.

While much has been accomplished in roadside safety, there is still much to do. As long as vehicles and operational conditions continue to change, there will be a need to continually reexamine the existing roadside hardware and the criteria for its use.

PART 4 WORKSHOP SUMMARY

Malcolm H. Ray, Momentum Engineering, Inc.
John F. Carney III, Vanderbilt University
Kenneth S.Opiela, Transportation Research Board

Efforts to improve roadside safety have had a dramatic impact on the number of automobile fatalities during the past 30 years. In 1983 the annual traffic fatality rate was 2.6 fatalities per 100 million vehicle miles travelled. A decade later, in 1993, the fatality rate had dropped to 1.7 fatalities per 100 million vehicle miles travelled. This impressive accomplishment has been achieved through a dedicated effort by every segment of the highway transportation industry, including the roadside design community.

The Federal Highway Administration, the American Association of State and Highway Transportation Officials, the states, the Transportation Research Board, and others have initiated a variety of research activities to improve roadside safety. These have included analyzing accident trends, formulating improved analysis procedures, developing better hardware, and promoting better understanding of the accident environment. These activities must be coordinated on the basis of a common vision of the most critical needs and expected products to ensure continued improvement in roadside safety. It is, therefore, imperative that the current state-of-the-art be reviewed, the gaps in current knowledge be identified, current trends be assessed, research opportunities be explored, products be conceptualized, and consensus be reached on an agenda to improve the processes for addressing roadside safety problems at the federal, state, and local levels.

Issues related to roadside safety are influenced by the extent and design of the existing infrastructure, agency resources, new national policies, state and local initiates, changing vehicle designs, the emergence of innovative materials and technologies, and many other factors. These must be considered in evaluating the research needs in roadside safety.

This workshop has featured invited presentations by prominent researchers that established a common background on the major issues, recent and on-going research efforts, and expected opportunities for the future. The invited presentations included discussions of:

- Evolution of Roadside Safety,
- The Roadside Safety Problem,
- The Evolution of Vehicle Safety and Crashworthiness,
- Evolution of Vehicle Crashworthiness as Influenced by the National Highway Traffic Safety Administration,
- Methods for Analyzing the Cost-Effectiveness of Roadside Features, and
- Applications of Simulation in Design and Analysis of Roadside Safety Features.

After the presentations, the workshop participants were divided into four breakout groups to pursue additional discussions of research needs and opportunities for improving roadside safety. The four groups addressed:

- Data and analysis needs,
- Selection and design of roadside safety treatments,
- Efficacy of simulation methods,
- Assessing and developing roadside hardware.

Several common themes emerged from the four discussion groups: First, roadside safety involves much more than developing new roadside safety hardware. Recent analysis of accident data has indicated that such non-impact accident types as rollovers to steep side slopes are a major portion of all run-off-road accidents. The properties of the changing vehicle fleet bring into question the appropriateness of current slope standards. A number of higher center-of-gravity vehicles like mini-vans and pickup trucks have become popular alternatives to the traditional passenger car. In addition, the clear-zone concept, though it has been a feature of highway design for many years, often cannot be used on many State and local roadways because of right-of-way limitations. The result of these limitations is that collisions with fixed objects such as trees and utility poles continue to represent the largest group of fixed-object fatalities. Issues like these involve more than designing roadside barriers and evaluating thier performance in crash tests. Roadside safety should involve the whole range of possible harmful events that could take place on the roadside.

Second, the importance of properly selecting and locating roadside safety hardware was discussed by several breakout groups. The 1988 AASHTO *Roadside Design Guide* and the 1977 *Guide for Selecting, Locating, and Designing Traffic Barriers* are the preeminent guidelines for designing safe roadsides. Additional research is needed to refine certain aspects of these documents. NCHRP Project 22-12 is expected to address many of issues related to selecting and locating roadside hardware but a larger problem is getting field practitioners to use up-to-date standards. Hardware is frequently placed on the site in such away that it could never perform correctly and even when correctly located, hardware is often not installed correctly. For example, popular breakaway cable terminals, are sometimes placed just in front of steep untraverseable slopes where, even if the terminal activates correctly, the vehicle will be gated into an area where the vehicle may roll over or strike a fixed object.

The third common theme which emerged during the breakout sessions concerned the lack of quantifiable methods for identifying hazardous situations. The encroachment-collision-severity model of off-road accidents has been available since the publication of NCHRP Report 148, *Roadside Safety Improvement Programs on Freeways*. While this method is a crisp analytical statement in the language of probability, the lack of probablistic models has greatly hampered the utility of the method to actual roadside designers. The ROADSIDE program is based on the encroachment-collision-severity method but it depends heavily on unquantifiable assumptions about the likely severity of collisions and the likely effect on encroachments of site geometry and operational conditions. Many agencies are unable to develop quantifiable input values for these types of programs. As a result, decisions about what roadside hardware to select, where it should be located and how it should be replaced are often difficult to justify in objective, quantifiable terms. This lack of a quantifiable basis for roadside safety decision making leaves agencies vulnerable to tort litigation and hinders thier ability to focus scarce roadside safety resources on the most important problems.

The quality of accident data has been a persistant problem in roadside safety research for many years. Collecting high-quality data relavent to a specific roadside problem is prohibitively expensive. Relying on low-cost high-volume police level accident data severely restricts the level of detail that can be examined and police level data is notoriously prone to errors and ommisions. Technology may ofer some improvements; police officers could automatically log information into portable computers, global positioning systems could be used to identify precise locations, and a host of new technologies could be used to design new data acquisition hardware. The continued expansion and refinement of the FHWA's HIghway Safety Information SYstem should do a great deal to make a relatively consistant set of accident and roadway data available to researchers and policy analysts. Another fundamental problem with accident data, however, restricts agencies to reacting to perception of past problems rather than anticipating future problems because accident data is based on what has happened rather than on why it has happened.

The fourth common theme dealt with the need for better coordination between the automotive design and manufacturing community and the roadside design community. There has been relatively little interchange between these groups because of the competitive nature of automobile design, possible exposure to litigation, and possible violations of anti-trust laws. This has resulted in the roadside safety community reacting to automotive changes, sometimes long after the change has become wide spread in the vehicle population. Typical roadside hardware crash testing uses vehicles less than seven years old at the time of testing but, by the time the research is complete and the results are to be implemented in the field, the test vehicle may be 10 or more model-years out-of-date. For this reason, the roadside hardware community has been slow to recognize problems relating to changes in the vehicle fleet. The breakaway cable terminal provides another cautionary illustration: when the testing was originally being done (1972 through 1980) using the guidelines in NCHRP Report 153, the small test vehicle was a 1020-kg passenger vehicle. The oil embargo of 1973 quickly caused automobile manufacturers to start introducing smaller cars and by 1978 820-kg vehicles like the Honda Civic and the Volkswagen Rabbit were common. By the mid 1980s researchers were beginning to observe problems in the field with these newer, smaller vehicles. The result is that researchers have been trying for more than a decade to find an inexpensive retrofit to the BCT to rectify a problem that could have been avoided if testing was done using newer vehicles in the 1970's. Roadside safety hardware has a very long service life, far longer than a typical vehicle. It is imperitive that the roadside hardware community be able not only to keep pace with changes in the vehicle but to anticipate the performance of roadside hardware with the rapidly changing vehicle fleet.

The fifth theme which emerged was the need to employ modern analytical techniques like nonlinear finite element analysis to help to understand roadside collisions and allow designers to formulate more effective designs. Once a finite element model of a roadside appurtenance has been made, possible design changes can be examined quickly and with confidence. This will allow designers to concentrate full-scale crash testing efforts on the most promising alternatives. Another significant advantage of using finite element simulations is the ability to examine the performance of vehicles that have not even been built in impacts with roadside safety hardware. The 1990 ISTEA legislation has also mandated that vehicle types other than the traditional passenger car be examined to see how well they perform on the current generation of roadside safety hardware. Simulation also allows researchers to explore impact situations that are difficult or impossible to test. For example, there is no method for performing non-tracking side impacts with roadside features so simulation can provide a way to explore this important scenario. In addition to un-testable situations, simulation provides a way to parametrically search for the real worst case scenario. The standard crash test conditions in NCHRP Report 350, like all testing specifications before it, assume that they explore the worst case impact. There may be, however, other much more severe impact conditions that, because of the limitations on testing resources, are not explored in the "standard" tests. Simulation allows the researcher to explore these situations relatively quickly once a model has been developed. Developing a finite element model of a roadside hardware collision is not inexpensive, a full model may easily cost $100,000 to develop above the cost of the vehicle model. Once a model has been developed, however, it can be easily changed allowing the analyst to parametrically explore variations in the impact conditions or the design at very little cost. Hundreds of collisions scenarios can be examined using simulations during the barrier development or evaluation phase. While there will always be a need for full-scale crash tests to unequivocally demonstrate the performance of hardware, a careful balance of analysis and testing could greatly improve roadside hardware designs. While the current generation of nonlinear finite element analysis tools like DYNA3D can be used to address many roadside hardware collision scenarios, extensions and modifications will be required to investigate a wider range of roadside safety problems. Current finite element programs probably cannot be used to investigate situations like tires rutting into soft soils, long impact events like rollovers, trajectories of vehicles after impacting a barrier, and the effect of serious suspension damage. Addressing these types of problems is feasible but will require research into improving the computer programs and analytical techniques used in simulating roadside events.

Table 1 shows some of the research issues that were identified and discussed during the workshop. Several issues overlap and additional issues will certainly become apparent in the comming years, but the table provides a good illustration of the range of issues confronting the roadside safety community in the coming years.

This document is the first step in what is hoped to be a continuing dialog among the members of the roadside safety community. The TRB Roadside Safety Features Committee (A2A04) plans to hold a follow-up meeting during the summer of 1995 to formulate a common-vision of the roadside safety research agenda for the coming decade.

TABLE 1 ROADSIDE SAFETY RESEARCH ISSUES

Rollover on Slopes
What is the extent of the roadside slope rollover problem? What mechanisms cause slope-related rollover? What are the implications on slope standards?

Trees and Poles
Are there reasonable strategies that can be used to decrease the number and severity of tree and utility pole collisions while balancing safety with the needs of private land owners, municipalities, and utility companies?

Better Quality Accident Data
What methods can be used to obtain higher quality accident data? What types of in-depth accident studies could be designed, funded and implemented to address specific roadside safety problems?

Clearzone Concept
How effective are clearzone? Can clearzone be justified on a benefit-cost basis? What alternatives should be used if it is not possible to satisfy clearzone standards?

Changing Vehicle Fleet
What are the emerging trends in vehicle design and how will they effect the performance of the current generation of roadside safety hardware? What features should new hardware have to ensure good performance with these new vehicles?

Criteria for Selecting and Locating for Roadside Barriers
What criteria should be used to select a barrier for a specific location and how should that barrier be located? Are the recommendations in the 1977 AASHTO Barrier Guide and the 1988 AASHTO Roadside Design Guide adequate? How should the multiple test levels in NCHRP Report 350 relate to the selection of roadside hardware for a particular site?

Training of Roadside Designers and Installers and Maintainers
What can be done to more effectively transfer knowledge about roadside hardware and proper design, installation and maintenance practices to field practitioners?

Measures of Effectiveness for Roadside Design
How can the safeness of a roadway be quantified to form the basis for policy and economic decisions? What measures of effectiveness could be used and what would the underlying models be based on?

Better Encroachment Data
Are there new ways of collecting encroachment data so that models of encroachment could be developed as a function of roadway characteristics?

Quantifyable Severity Indices
Can a systematic method for assigning severity indices be developed for use in the ROADSIDE program?

Enhanced Coordination with the Automobile Manufacturers
What are the barriers to better cooperation between the automobile manufacturers, the roadside design community, the FHWA and the NHTSA? How can these barriers be overcome?

Performance of Vans, Pickup Trucks and Sport Utility Vehicles
How well do vehicles that have not typically been used in full-scale testing perform in collisions with typical roadside hardware?

Integrating Simulation into the Roadside Hardware Design and Evaluation Process
Can finite element collision simulation and vehicle dynamics simulation be integrated into the design and evaluation process such that it is a useful tools for improving hardware performance?

Extensions to Current Simulation Programs
Can capabilities be added to the current generation of simulation tools to address issues like traversing soft soil, long-duration impacts, and damaged suspension?

Non-standard Impact Conditions
Are the impact conditions recommended in NCHRP 350 actual "worst case" conditions? Are there other more demanding impact scenarios (e.g. side impact collisions and non-tracking impacts) that should be addressed during the development of roadside hardware.

Arrest versus Redirect Strategies
In what situations is it better to redirect an errant vehicle rather than arrest it? Can the difference in approaches be quantified in terms of severity? What types of locations would be appropriate for each strategy?

APPENDIX A WORKSHOP ATTENDEES

Batley, Joseph, Buffalo Specialty Products, Inc., Allentown, Pennsylvania
Bligh, Roger, Texas Transportation Institute, College Station, Texas
Bronstad, Maurice, Dynatech Engineering, San Antonio, Texas
Bryer, Thomas, Pennsylvania DOT, Harrisburg, Pennsylvania

Carney, John F., III, Vanderbilt University, Nashville, Tennessee

Dearasaugh, Bill, Transportation Research Board, Washington, D.C.
Denman, Owen, Energy Absorption Systems, Rocklin, California
Dinitz, Arthur, Transpo Industries, New Rochelle, New York
Durkos, John, Energy Absorption Systems, Chicago, Illinois

Fitch, John, Roadway Safety Services, Inc., Lakeville, Connecticut
Frank, Jon, Barrier Systems, Inc., Carson City, Nevada

Gieseke, Mark, Minnesota DOT, Stillwater, Minnesota
Gripne, Donald, Washington DOT, Olympia, Washington

Hatton, James H., Jr., Federal Highway Administration, Washington, D.C.
Hedges, Rex, Motor Industry Research Association, England
Hollowell, William Thomas, National Highway Traffic Safety Administration

Kay, Greg, Lawrence Livermore National Labs, Livermore, California
Kempen, Michael, Roadway Safety Services, Ronkonkoma, New York
Kennedy, Jim, Jr., Battelle Corporation, Columbus, Ohio

Lee, Tony, Lawrence Livermore National Labs, Livermore, California
Lewis, David, Consultant with Syro/Trinity, Canfield, Ohio

Mak, King K., Texas Transportation Institute, College Station, Texas
McDevitt, Charles, Federal Highway Administration, McLean, Virginia
McGinnis, Richard, Bucknell University, Lewisburg, Pennsylvania
Mileti, Robert, Roadway Safety Service, Inc., Ronkonkoma, New York

Opiela, Kenneth S., Transportation Research Board, Washington, D.C.

Paulis, Edward, Jr., Maryland DOT, Hanover, Maryland
Perkins, Arthur, New York State DOT, Albany, New York
Powers, Richard, Federal Highway Administration, Washington, D.C.

Ray, Malcolm, Federal Highway Administration/Momentum Engineering, McLean, Virginia
Reagan, Jerry A., Federal Highway Administration, McLean, Virginia
Ross, Hayes, Texas Transportation Institute, College Station, Texas

Saxton, Lyle, Federal Highway Administration, McLean, Virginia
Schauer, Dale, Lawrence Livermore National Labs, Livermore, California
Sicking, Dean, University of Nebraska, Lincoln, Nebraska
Stack, Ken, General Motors, Warren, Michigan

Stephens, Barry, Energy Absorption Systems, Inc., Rocklin, California
Strybos, John, Southwest Research Institute, San Antonio, Texas

Taylor, Harry, Federal Highway Administration, Washington, D.C.

Viner, John, Federal Highway Administration, McLean, Virginia

Wallace, Joe, Virginia DOT, Richmond, Virginia
Wendling, William H., Brown Traffic Products, Inc., Camdenton, Missouri
White, Tim, Virginia DOT, Richmond, Virginia

APPENDIX B FHWA ROADSIDE SAFETY HARDWARE RESEARCH PROGRAM

The Federal Highway Administration's Design Concept Research Division has played an important role in the development of new roadside safety hardware and the procedures for developing them. The attached flow chart shows the seven primary research thrust areas for the Design Concept Research Division:

(1) The use of composite and recycled materials in roadside safety hardware,

(2) The use of analytical methods and computer simulation in developing and evaluating roadside hardware designs,

(3) Maintaining an in-house crash test laboratory for exploring the performance of roadside safety hardware,

(4) Conducting full-scale crash tests to design and evaluate roadside hardware designs,

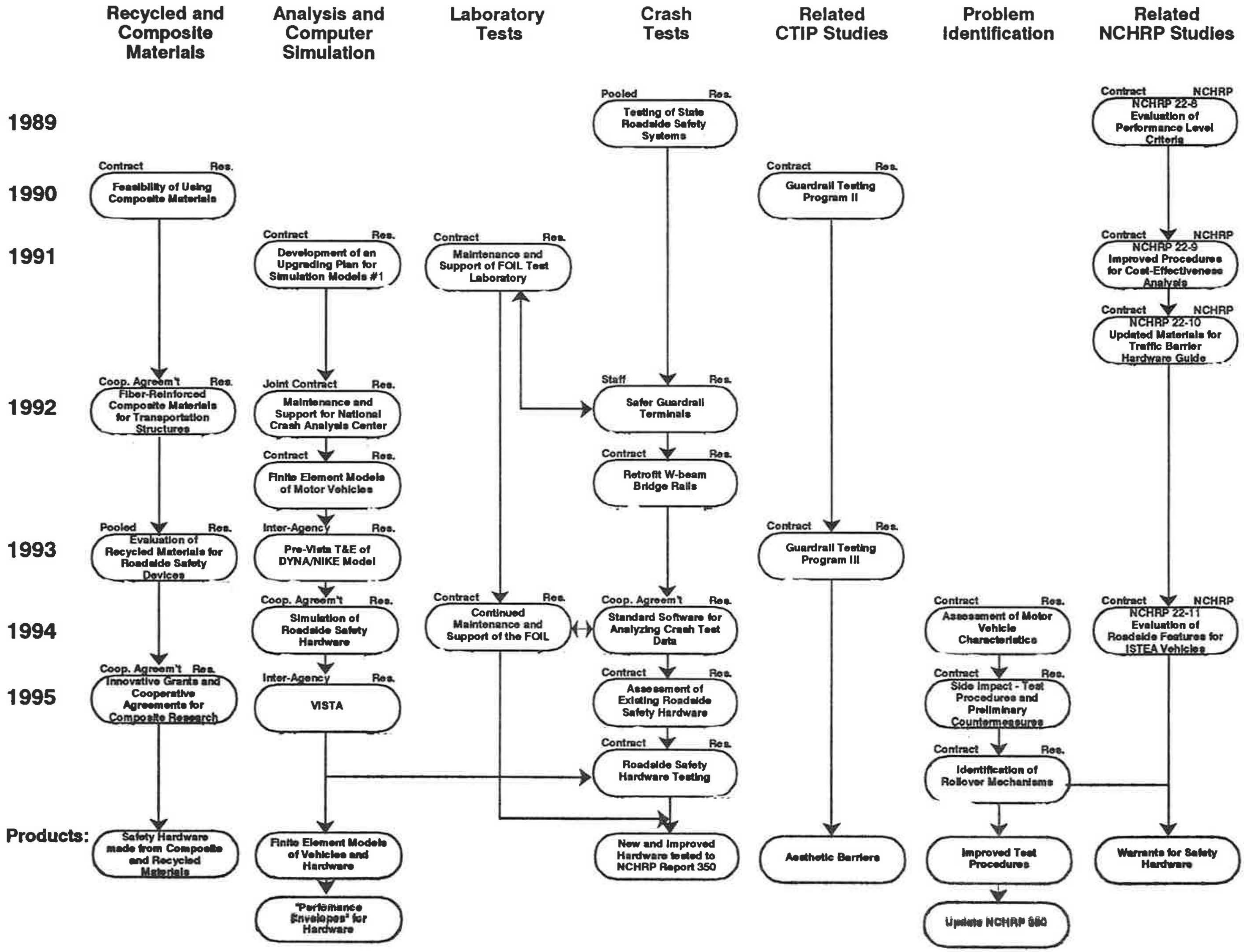
(5) Coordinating the development and evaluation of roadside barriers with other Federal agencies and the States,

(6) Identifying emerging problem areas like side impact accidents, addressing the needs of a changing vehicle fleet, identifying rollover mechanisms, and improving test and evaluation procedures.

(7) Coordinating with NCHRP to address important roadside safety issues.

The flow-chart shows the projects, internal staff studies, cooperative agreements and contracts planned in each of the seven thrust areas along with the expected fiscal year when each effort starts. At the bottom of the page, the expect products of these research efforts are listed. Although the chart shows a linear flow from research topic to research topic, there is a great deal of synergetic flow between thrust areas. For example, the computer simulation efforts are expected to assist in the roadside hardware design effort and likewise, the crash testing efforts will provide needed validation data for the simulation efforts.

ROADSIDE SAFETY HARDWARE



APPENDIX C Current NCHRP Research on Highway Safety

Current NCHRP Synthesis Efforts in Highway Safety

Project Title	Principal Investigator/Contractor	Start	End	Status Notes
Procedure for Determining Work Zone Speed Limits	Mr. James Migletz Graham-Migletz Enterprises, Inc.	11/15/89	6/30/93	Report being prepared for publication.
Effectiveness and Implementability of Procedures for Setting Work Zone Speed Limits	Mr. James Migletz Graham-Migletz Enterprises, Inc.	1/03/94	4/30/96	Continuation project set to begin.
Improved Traffic Control Device Design and Placement to Aid the Older Driver	Dr. Richard Lyles Michigan State University	4/15/92	10/15/94	Interim Report approved & field testing to begin in early 1994.
Effective and Safe Illumination Practices for Night Work Zones	Dr. Ralph Ellis The University of Florida	3/1/93	11/30/94	Research in progress.
Advance Warning Arrow Panel Visibility	Mr. Douglas Mace The Last Resource, Inc.	3/1/93	2/28/95	Interim Report approved and lab tests are underway.
Fatigue Design and Evaluation for Signal, Sign, and Light Support Structures	Mr. Mark Kuczinski Lehigh University	1/1/93	12/31/94	Interim Report under review.
Roadway Width for Low Traffic Volume Roads	Mr. Timothy Neuman & Mr. Charles Zegeer Jack Leisch & Assoc. - North Carolina HSRC	5/1/89	6/30/93	Report in preparation to be published as NCHRP Report 362.
Traffic Barrier and Control Treatments for Restricted Work Zones	Dr. Hayes E. Ross, Jr. TX A&M Research Foundation	6/1/88	6/30/93	Report in preparation to be published as NCHRP Report 357.
Effect of Highway Standards on Safety	Dr. Hugh W. McGee & Mr. Warren Hughes Bellomo-McGee, Inc.	2/15/92	12/15/93	Final report due 2/94.
Warrants for the Installation of Low Service Level Guardrail Systems	Louis B. Stephens, Jr. Wilbur Smith & Associates	5/1/90	1/31/92	Research completed & RRD in preparation.
Update of "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances"	Dr. Hayes E. Ross, Jr. Texas A&M Research Foundation	6/1/89	8/31/92	Research published as NCHRP Report 350.
Evaluation of Performance Level Selection Criteria for Bridge Railings	Mr. K.K. Mak & Mr. D.L. Sickling TX A&M Research Foundation	4/15/89	12/30/92	Revised final report due 12/93.
Improved Procedures for Cost-Effectiveness Analysis of Roadside Safety Features	Mr. King Mak & Mr. Dean Sicking Texas Transportation Institute	9/1/91	3/31/94	Revised Interim Report due 1/94.
Updated Materials for a Traffic Barrier Hardware Guide	Dr. Malcolm Ray Momentum Engineering	1/2/91	12/31/94	Research in progress.

Current NCHRP Synthesis Efforts in Highway Safety

Project Title	Principal Investigator/Contractor	Start	End	Status Notes
Development and Implementation of Traffic Control Plans for Highway Work Zones	Jerry Graham & James Migletz	6/01/89	8/31/93	95% complete.
Performance and Operational Experience of Truck-Mounted Attenuators	Not yet awarded			Published as Synthesis 182.
Accident Data Quality	Not yet awarded			Published as Synthesis 192.
Use of Rumble Strips to Enhance Safety	Not yet awarded			Published as Synthesis 191.
Severity Indices for Roadside Features	Dan Turner & Jerome Hall	8/01/91	1/31/94	75% complete.
Performance and Operational Experience with Permanent and Temporary Crash Cushions	John Carney III	3/13/92	9/30/93	In publication process.
Highway Guardrail & Median Barrier Crashworthiness	Not yet awarded			Contract pending.

New NCHRP Research Projects in Highway Safety

Project Title	Principal Investigator/Contractor	Start	End	Status Notes
Driver Information Overload	Contractor not announced	1/03/94		Project about to start.
Recommended Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals	Contractor not announced	1/15/94		Project about to start.
Recovery-Area Distance Relationships for Highway Roadsides	Contractor not announced			Panel doesn't believe that allocation for project is sufficient.
Evaluation of Roadside Features to Accommodate Vans, Mini-vans, Pickup Trucks & 4-wheel Drive Vehicles	Contractor not announced	2/01/94		Final panel vote due 12/21/93.

1995 NCHRP Problem Titles Related to Roadside Safety Hardware

Title	Problem	Agency
Guidelines for the Selection, Installation and Maintenance of Highway Safety Features	C-05	RAC
The Development of Safe/Cost Effective Traffic Barrier Runout Length	C-20	TX
Develop Roadside Safety Devices for the Test Levels in NCHRP Report 350	C-35	FHWA
Effective and Essential VMS Messages	G-09	NJ
VMS Legibility and Awareness Enhancement	G-10	NJ
Improving the Nighttime Visibility of Guard Fence and Guardrail	G-19	TX
Guidelines and Safety Benefits of Glare Screens	G-41	SCOHTS