NCHRP

REPORT 471

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Evaluation of Roadside Features to Accommodate Vans, Minivans, Pickup Trucks, and 4-Wheel Drive Vehicles

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Evaluation of Roadside Features to Accommodate Vans, Minivans, Pickup Trucks, and 4-Wheel Drive Vehicles

HAYES E. ROSS, JR.
ROGER P. BLIGH
Texas Transportation Institute
College Station, TX

AND

KING K. MAK
San Antonio, TX

SUBJECT AREAS
Safety and Human Performance

Research Sponsored by the American Association of State Highway and Transportation Officials
in Cooperation with the Federal Highway Administration

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

Note: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

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FOREWORD

By Staff
Transportation Research Board

This report presents the findings of a study of light truck characteristics and the light truck market, as well as the performance of widely used highway safety features when such features are impacted by light truck subclasses. Computer simulation, crash data, and crash testing studies were used to expand the knowledge base of light truck performance for impacts with roadside features. This report will be of particular interest to roadside safety practitioners, particularly those involved with roadside safety hardware.

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) required that the Secretary of Transportation

> issue a final rule regarding the implementation of revised guidelines and standards for acceptable roadside barriers and other safety 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 102-240, 12/18/91)

This ISTEA requirement created the need to (1) determine if vans, minivans, pickup trucks, and 4-wheel drive vehicles (light trucks) have impact behaviors different from the previously tested passenger vehicles; and (2) assess the adequacy of current design guidelines and standards for roadside barriers, safety appurtenances, and geometric features.

At the time this study was initiated, only limited research had been conducted on the safety performance of light trucks. The available research results suggested that (1) a higher fatality rate exists for some run-off-the-road crashes involving light trucks, (2) higher centers of gravity may result in a greater propensity to roll over during or after interaction with a roadside feature, and (3) this class of vehicles represents more than one-quarter of the fleet and may grow to represent one-third of the vehicle fleet.

The objectives of NCHRP Project 22-11 were to (1) evaluate the current information on the safety performance of roadside features for each subclass of light trucks; (2) assess the significance of gaps in safety performance information; and (3) recommend priorities for future research, testing, and development needed to ensure that roadside features accommodate light trucks.

A research team from the Civil Engineering Department and the Texas Transportation Institute, Texas A&M University System, was selected to undertake this research, which began in late 1994. The Phase I effort—to collect and synthesize information relative to the performance of roadside features with each subclass of light trucks and to identify the current and projected light truck sales and design characteristics—was accomplished using information from a variety of sources, including computerized databases, accident databases, trade magazines and journals, extensive parking lot surveys, and contacts with agencies and individuals having expertise/information in the subject area. The Phase II goal—to expand the knowledge base of light truck performance for impacts with roadside features—was accomplished through computer simulation studies, crash data studies, and crash testing studies. The research team found that (1) light truck sales are now approximately equal to automobile sales; (2) with few exceptions, widely used roadside safety hardware, or modified versions thereof, can be expected to perform in a satisfactory manner for most expected impacts by the light truck subclasses; (3) light trucks have a greater propensity to overturn than automobiles for encroachments on roadside geometric features; and (4) the ¾-ton pickup, a test vehicle recommended in *NCHRP Report 350*, is a good design vehicle to represent the heavier passenger vehicles in general and to represent the heavier light truck subclasses in particular. The researchers also recommended further study of the impact performance of the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier for light trucks.

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AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 22-11 by the Texas Transportation Institute (TTI), Texas A&M University System. Hayes E. Ross, Jr., Professor of Civil Engineering and Research Engineer, TTI, was the principal investigator. Other authors of this report are King K. Mak, private consultant and former Research Engineer, TTI, and Roger P. Bligh, Assistant Research Engineer, TTI.

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CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

1.1 RESEARCH PROBLEM STATEMENT

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) 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 safety appurtenances, including longitudinal barriers, end terminals, and crash cushions. Such revised standards shall accommodate vans, minivans, 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. (Intermodal Surface Transportation Efficiency Act of 1991, Pub. L. No. 102-240, § 1073, 105 Stat. 1914)

This ISTEA requirement created the need to (1) determine if vans, minivans, pickup trucks, and 4-wheel drive vehicles (hereafter referred to as light trucks) have impact behaviors different from the previously tested passenger vehicles, and (2) assess the adequacy of current design guidelines and standards for roadside barriers, safety appurtenances, and geometric features. In this report, roadside barriers, safety appurtenances, and geometric features will be referred to as roadside features. Roadside features shall include, but not be limited to, permanent and temporary traffic barriers, crash cushions, terminals, truck-mounted attenuators (TMAs), breakaway supports, cross-sectional elements, and terrain.

For several reasons there has only been limited research on the safety performance of light trucks. One reason is that until recently, crash testing for roadside features required only the use of automobiles. Another reason is the relatively recent emergence of many types of light trucks for use primarily as passenger vehicles. A final reason is that only in the last few years have accident data become available to permit the study of vehicles in this class. The research that has been undertaken suggests that (1) a higher fatality rate exists for some run-off-the-road accidents involving light trucks, (2) higher centers of gravity (CG) may result in a greater propensity for rollover during or after interaction with a roadside feature, and (3) this class of vehicles represents more than 25 percent of the vehicle fleet and may grow to represent one-third of it.

Research is needed to evaluate the safety performance of current roadside features for light trucks. Specifically, there is a need to determine which combinations of roadside features and subclasses of light trucks represent the greatest potential for safety problems. Further, there is a need to assess the adequacy of current standards and guidelines for the design, placement, and testing of roadside features related to light trucks.

1.2 OBJECTIVES

The objectives of this research were to (1) evaluate current information on the safety performance of roadside features for each subclass of light trucks; (2) assess the significance of gaps in safety performance information; (3) obtain additional technical data for the safety performance evaluation of vans, minivans, pickup trucks, and 4-wheel drive vehicles with roadside features through crash testing and other analysis methods; and (4) recommend priorities for future research, testing, and development needed to ensure that roadside features accommodate light trucks.

Also, in *NCHRP Report 350* (*6*), a 2000 kg pickup truck is designated as the standard 2000P test vehicle. It has been proposed as the surrogate for all light trucks. A final aim of Project 22-11 is to aid in determining whether the 2000P test vehicle is an appropriate or sufficient surrogate for evaluating the safety performance of roadside features with light trucks.

1.3 SCOPE

The study consisted of two phases. In the first phase the emphasis was on gathering data on the nature of the light truck population, light truck properties, and impact performance data of light trucks. Also in Phase I, preliminary evaluations were made of roadside hardware for light truck impacts and features were selected for further evaluation in Phase II. An interim report was written documenting the Phase I efforts (*1*).

Phase II consisted of in-depth evaluations of the safety performance of roadside features for light truck impacts. Adequacy of the *NCHRP Report 350* 2000P test vehicle (a ¾-ton pickup truck) as a representative light truck was also examined in Phase II.

1.4 RESEARCH APPROACH

The goals of Phase I were to (a) collect and synthesize information relative to the performance of roadside features with each subclass of light trucks, (b) collect and synthesize information relative to current and projected light truck sales and design characteristics, and (c) conduct preliminary analysis to compare the safety performance of safety features for the light truck subclasses. For goals (a) and (b), the researchers relied on information from a variety of sources, including computerized databases, various accident databases, trade magazines and journals, extensive parking lot surveys, and contacts with agencies and individuals having expertise/information within the subject area. Prior to addressing goal (c), the researchers developed a comparison scheme whereby performance of roadside safety features with light truck subclasses could be compared. The scheme involved use of existing experimental data, computer simulations, and accident data analysis. Initial application of the scheme was made to address goal (c). The goal of Phase II was to greatly expand knowledge about light truck performance in impacts with roadside safety features. To accomplish this goal, a three-pronged effort was undertaken: computer simulation studies, crash (i.e., accident) data studies, and crash testing studies.

Computer simulation studies examined the behavior of light truck subclasses during impacts with widely used longitudinal barriers (e.g., guardrails, median barriers, and bridge rails), and during encroachments on common roadside geometric features (e.g., fill sections and driveway sections). A similar study of automobiles, conducted at Texas Transportation Institute (TTI) under separate sponsorship (*2*), was included for comparison purposes. The BARRIER VII program (*3*) and a version of the Highway-Vehicle-Object-Simulation-Model (HVOSM) program (*4*) were used in the longitudinal barrier studies. Another version of the HVOSM program (*5*) was used in the roadside geometric features study. A large number of simulated impacts and encroachments were made, encompassing a wide range of speed and angle combinations, for each of the light truck and automobile subclasses.

The crash data study consisted of evaluating the frequency, severity, and rollover involvement of single-vehicle, ran-off-road type crashes for automobile and light truck subclasses. The crash databases used in the study included the Fatal Accident Reporting System (FARS), the National Automotive Sampling System (NASS) General Estimates System (GES), and the Highway Safety Information System (HSIS). All these databases contain police-level or enhanced police-level crash data.

The FARS and GES databases are collected and maintained by NHTSA. FARS is a census of all fatal traffic crashes, while the NASS GES is a nationally representative sample of traffic crashes. Both databases are based on state police-level traffic crash reports that are edited, supplemented with additional information, and transcribed into a standardized format. For purposes of this study, 5 years of FARS data (1991–1995) and 4 years of NASS GES data (1992–1995) were analyzed.

The HSIS databases are developed and maintained by the Highway Safety Research Center at the University of North Carolina, for FHWA. State police-level crash data files were merged with highway and traffic data files for several participating states. The analysis done for this study included data from four HSIS states: Illinois, Michigan, North Carolina, and Utah. These four states were selected because of available information on wheelbase (through decoding of the vehicle identification number) from which automobiles could be categorized into generic platforms. The latest available 5 years of crash data from the four states were used.

The purpose of these analyses was to compare the crash frequency, severity, and rollover involvement of various automobile platforms and light truck subclasses in collisions with roadside features. Therefore, the datasets were subsetted to include only single-vehicle crashes involving late-model vehicles striking roadside objects or appurtenances.

A limited full-scale crash testing program was also conducted. Factors considered in the selection of test details included (a) the degree to which various safety features had been evaluated in terms of *NCHRP Report 350* requirements, (b) the extent of use of the respective features nationwide, and (c) the probability of acceptability performance when impacted by the full range of light truck subclasses at the extremes of the expected impact conditions.

A test program was selected, consisting of two phases. Phase 1 consisted of four tests wherein the Standard G4(1S) Guardrail System (details given later in this report) was impacted by a range of light truck subclasses at a nominal speed of 100 km/h and a nominal impact angle of 20 degrees. Phase 2 consisted of three tests. In the first test, a 2000P test vehicle impacted a Standard G4(1S) Guardrail system at a nominal speed of 110 km/h and a nominal impact angle of 20 degrees. In the next test a 2000P test vehicle impacted a Modified G4(1S) Guardrail system at a nominal speed of 110 km/h and a nominal impact angle of 20 degrees. In the modified system a wood blockout is used instead of the steel blockout. In the third test a 4-wheel drive version of the 2000P test vehicle impacted a Modified G4(1S) Guardrail system at a nominal speed of 104 km/h and a nominal impact angle of 20 degrees.

CHAPTER 2

FINDINGS

2.1 LIGHT TRUCK DATA

Data on light truck sales and light truck dimensional and inertial properties were derived from various sources, including the following:

a. *Gasoline Truck Index*, *Diesel Truck Index*, and *Import Truck Index*. These documents provided the following parameters: front overhang, overall length, overall height, overall width, wheelbase, curb weight on front tires, curb weight on rear tires, tire and rim size, and track width.

b. *Automotive News*, *Ward's Automotive Yearbooks*, and the Oak Ridge National Laboratory series *Light-Duty Vehicle MPG and Market Shares Report*. These publications provided sales data.

c. NHTSA's Light Vehicle Inertial Parameter Database. This is the most comprehensive source for CG height and moments of inertia data. It contains measured vehicular inertial parameters for 356 tests performed with NHTSA's Inertial Parameter Measurement Device. These data were reported in a *Society of Automotive Engineers* (SAE) paper (*7*).

d. Other sources for inertial properties. Another report by NHTSA (*8*) contains inertial properties, including CG height, roll, and yaw moments of inertia for 51 vehicles, including 21 automobiles, 13 pickup trucks, 10 utility vehicles, and 7 vans. An SAE technical paper (*9*) presents measured inertial properties of sport utility vehicles, pickup trucks, and vans and describes analytical estimation techniques for moments of inertia applicable to light trucks. Several rollover studies have also reported some inertial properties for light trucks. A paper entitled, "Engineering Parameters Related to Rollover Frequency," by Jones and Penny (*235*) presents data for 11 models of pickups and 16 models of utility vehicles. Others include "Vehicle Dynamics and Rollover Propensity Research" by Garrott et al. (*236*) and "An Evaluation of Static Rollover Propensity Measures," by Chrstos (*237*). CG heights for a Chrysler minivan, a full-sized Ford pickup truck, and a GM sport/utility vehicle were published in a University of Michigan report entitled "Center of Gravity Height: A Round-Robin Measurement Program" by Winkler et al. (*238*). In addition, many test agencies have reported CG height and, in a few instances, moments of inertia for various light trucks, which were used as test vehicles in full-scale crash tests or in computer simulation studies. It should be noted that much of these data are for vehicles produced prior to 1990.

e. Parking lot surveys. Significant parking lot and dealer's lot data were gathered as part of this project, primarily dimensional properties such as overall length, wheelbase, front overhang, bumper height, and so on. The software program "VINAssist," version 1.06LE, was used to identify specifics of each vehicle surveyed (model year, type of cab [if applicable], 2- or 4-door, type of engine [diesel or gasoline], 2- or 4-wheel drive, etc.).

Note that these data were collected in the initial phase of the project, during the 1994–95 period. Subsequently, the project focused on filling voids in roadside safety features' performance data through computer simulation studies, crash data studies, and full-scale crash testing studies. As the project scope and budget permitted, some of the early data were updated.

2.1.1 Subclasses

In the initial phase of the project it was necessary to select a set of light truck subclasses in which the numerous light truck makes and models could be categorized. Light truck subclasses as defined by the Insurance Institute for Highway Safety and the Highway Loss Data Institute were adopted. They are listed below, followed by examples of each:

Small Utility Vehicles	(Suzuki Samurai, Geo Tracker, Isuzu Amigo)
Midsize Utility Vehicles	(Ford Explorer, Bronco; Chevrolet S10 Blazer, K1500 Blazer; Dodge Ramcharger; Jeep Cherokee; Isuzu Trooper; Nissan Pathfinder)
Large Utility Vehicles	(Chevrolet Suburban 1500, 2500)
Small Pickups	(Dodge Dakota; Chevrolet T10, S10; Ford Ranger)
Standard Pickups	(Chevrolet 1500, 2500, 3500; Dodge D150, D250, D350; Ford F150, F250, F350)

Passenger Vans	(These are commonly called minivans and examples are Chevrolet Astro Van; Plymouth Voyager; Ford Aerostar)
Large Vans	(These are commonly called full-size vans and examples are Dodge B150, B250, and B350; Ford E150, E250, and E350; Chevrolet Sportvan 20, Chevy Van 10, Chevy Van 20, Chevy Van 30)

Although the Insurance Institute for Highway Safety includes 1-ton vans in the “large van” subclass and 1-ton pickups in the “standard pickup” subclass, both were excluded from the study since they have relatively small sales/exposure and they are primarily used for commercial purposes rather than as passenger vehicles. Appendix A of the interim report (*1*) contains a listing of all makes and models within each of these subclasses for the 1990–94 model years.

2.1.2 Sales Data

Since 1980, sales of light trucks have been on a steady and rather dramatic increase. As shown in Figure 1, market shares of light trucks in relation to total passenger vehicle sales, both domestic and import, increased from approximately 20 percent in 1980 to almost 48 percent in 1998. Figures in parentheses are the total passenger vehicle units sold, which includes automobiles and light trucks. As an example, in 1998 a total of 15,508,625 passenger vehicles were sold, of which 47.5 percent were light trucks, or a total of approximately 7,369,000 units.

Figure 2 shows market shares of each of the light truck subclasses for the 1988–1998 period. Figures in parentheses are the total number of light truck units sold. For example, in 1998 a total of 7,369,136 light trucks were sold. Of this total, the breakdown of sales for each subclass is as follows:

Subclass	Market Share (%)	Total Units Sold
Passenger Van	16.58	1,221,800
Large Van	5.34	393,511
Small Pickup	14.45	1,064,840
Large Pickup	25.72	1,895,340
Small Utility	3.61	266,025
Midsize Utility	23.60	1,739,120
Large Utility	10.70	788,500
Totals	100.00	7,369,136

From Figure 2, it can be seen that:

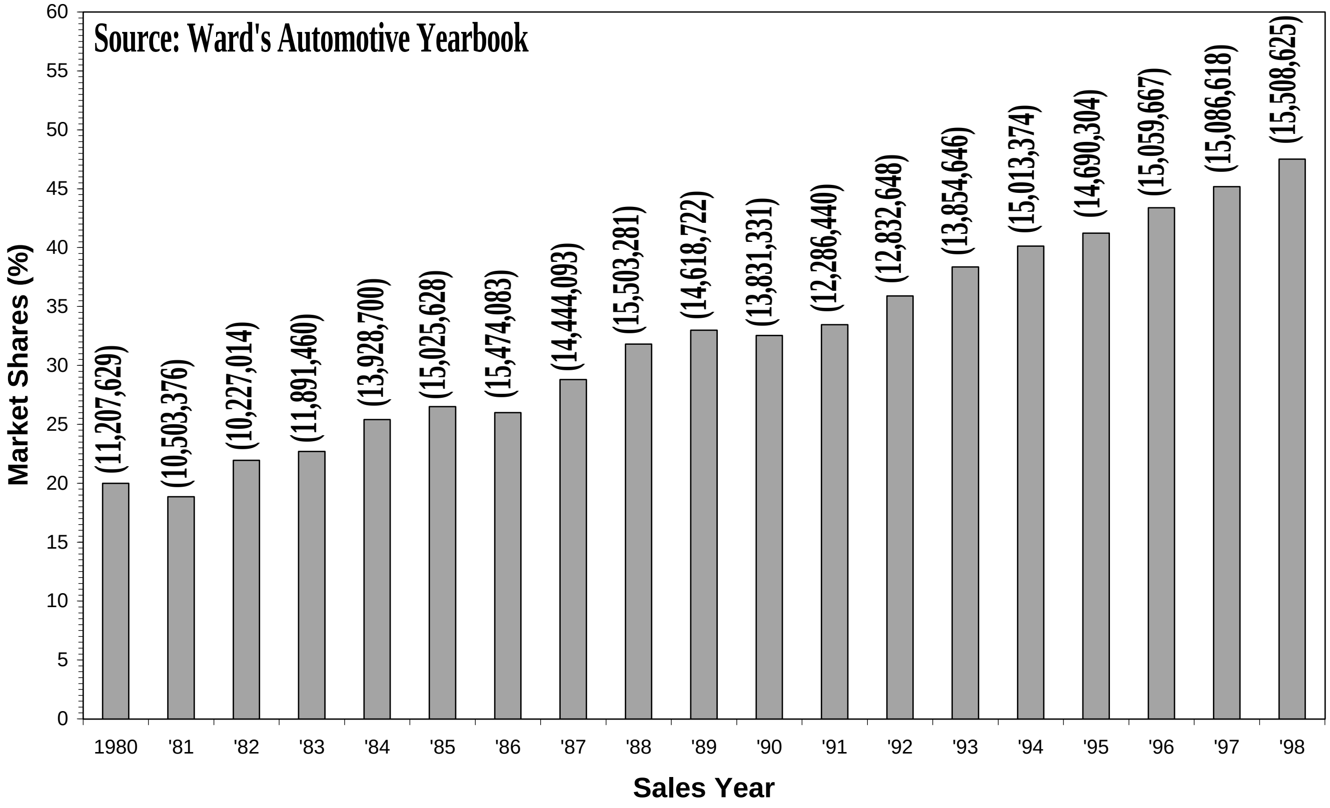


Figure 1. Light truck market shares (total passenger vehicle units sold given in parentheses).

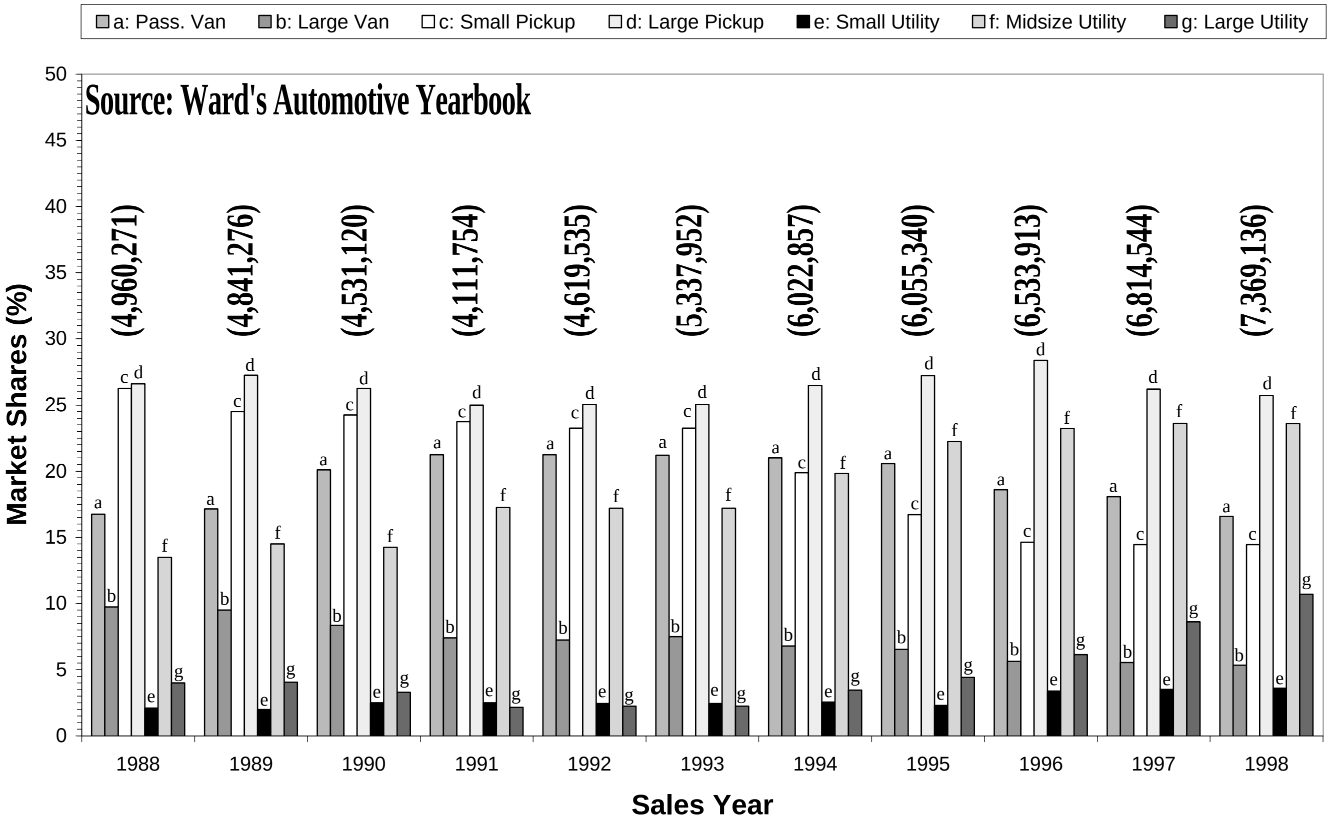


Figure 2. Market shares of light truck subclasses (total units of light trucks sold given in parentheses).

a. Large pickups (½-ton and ¾-ton pickups) continue to be the dominant subclass in terms of sales, with about 25 percent of the light truck market in 1998; most of these are ½-ton pickups.

b. Sales of the midsize utility subclass have been increasing steadily, and in 1998 market shares of the midsize utility subclass held a close second to the large pickup subclass.

c. Market shares of the passenger van subclass have been in slight decline since 1994, but the subclass retained third place in market shares in 1998.

d. Market shares of the small pickup subclass have declined somewhat since 1993, but the subclass retained fourth place in market shares in 1998.

e. Market shares of the large utility subclass have been increasing somewhat since 1993, and the subclass was fifth in sales in 1998.

f. Market shares of the large van subclass and the small utility subclass have remained fairly constant over the past few years.

2.1.3 Dimensional and Inertial Data

Figures 3 through 6 contain bumper height, front overhang, wheelbase, and undeflected tire diameter for the 1989–95 model years. These data were acquired through parking lot surveys and included 4-wheel drive vehicles. Vehicles with special “jacked-up” suspension systems were omitted. As previously stated, with the exception of bumper height, data on the same parameters were also collected from published sources and were correlated with parking lot data. Shown in Figures 7 through 9 are selected inertial data for light trucks, including curb weight, CG location above ground, and CG location aft of the front axle.

These data suggest that the ¾-ton pickup truck is reasonably representative of the light truck population, especially the heavier light trucks. In terms of some of the more sensitive parameters such as bumper height, front overhang, mass, and CG location above ground, there are some subclasses with parametric values that are believed to be “more critical” than those of the ¾-ton pickup and some with values less critical. More critical means that an impact will be more demanding on a safety feature (i.e., more difficult for the impact performance of the features to meet recommended criteria), with all other parameters being equal. Demands on a longitudinal barrier will generally increase as the bumper height increases, as the front overhang decreases, as the CG height increases, and as the mass increases.

Nominal values of the parameters for the 2,040 kg (4,500 lb) full-size automobile previously used as a design vehicle (*10*) are also shown on the figures. The light truck parameters are typically more critical than those of the 2,040 kg (4,500 lb) automobile (i.e., for the 2,040 kg [4,500 lb] automobile,

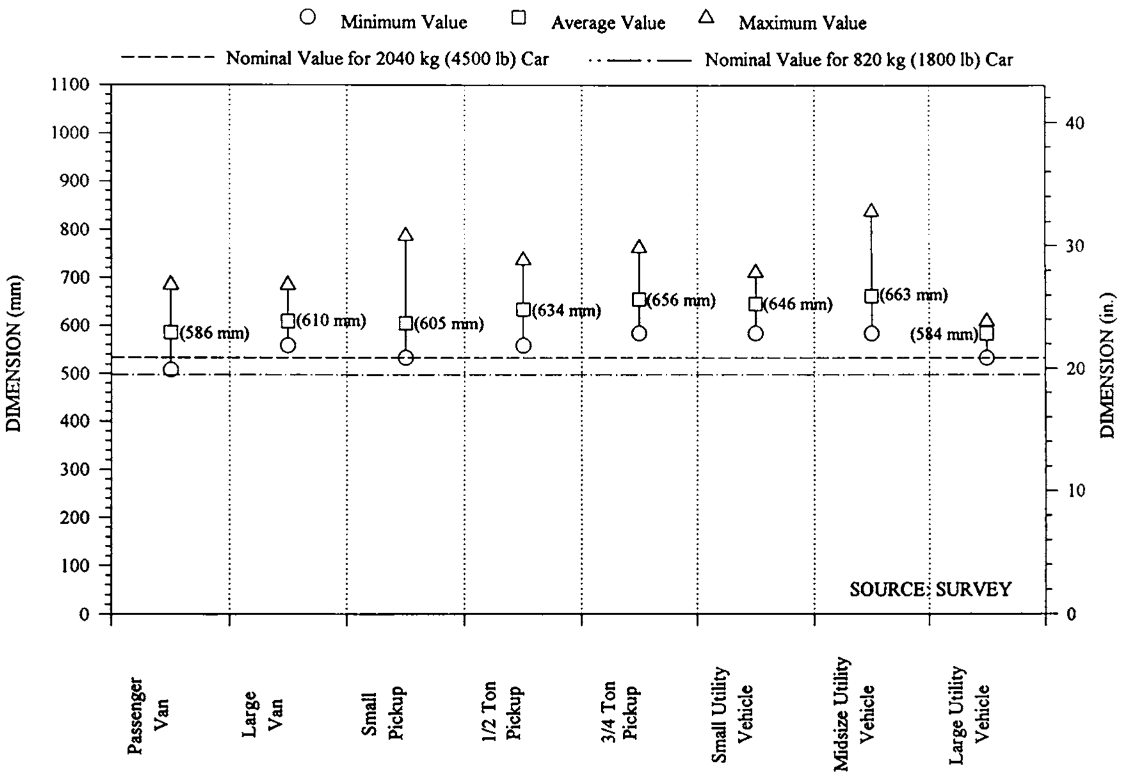


Figure 3. Bumper height (top of bumper), 1989–1995 models.

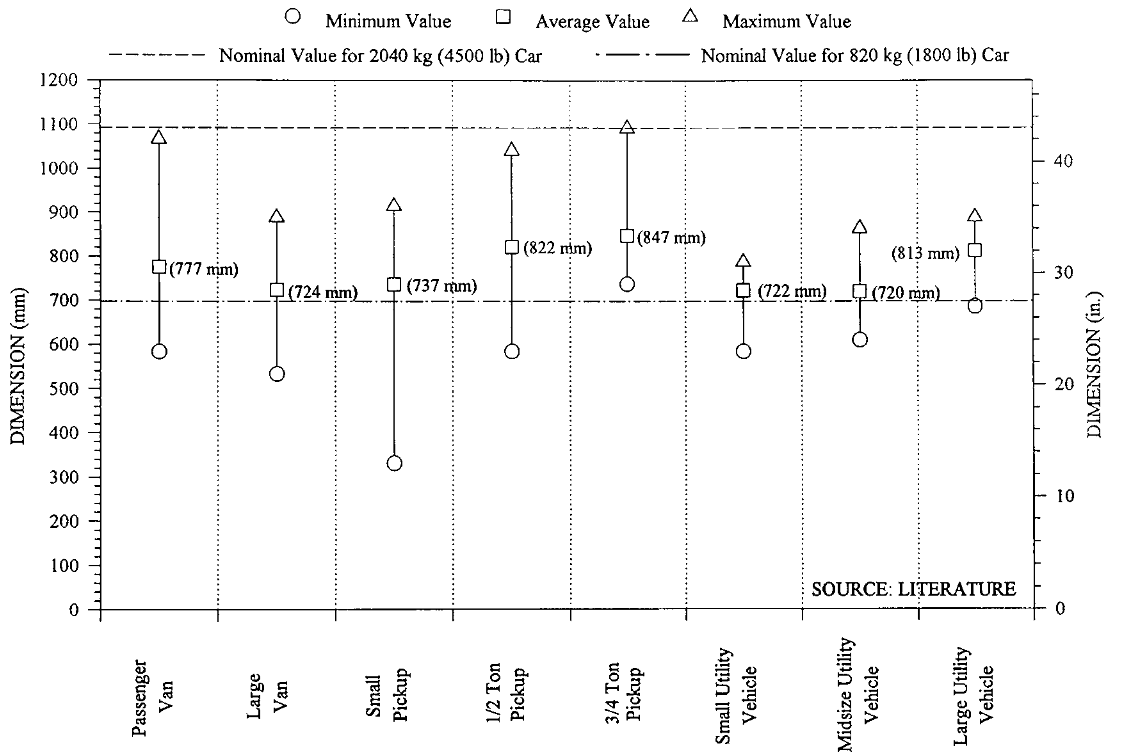


Figure 4. Front overhang, 1989–1995 models.

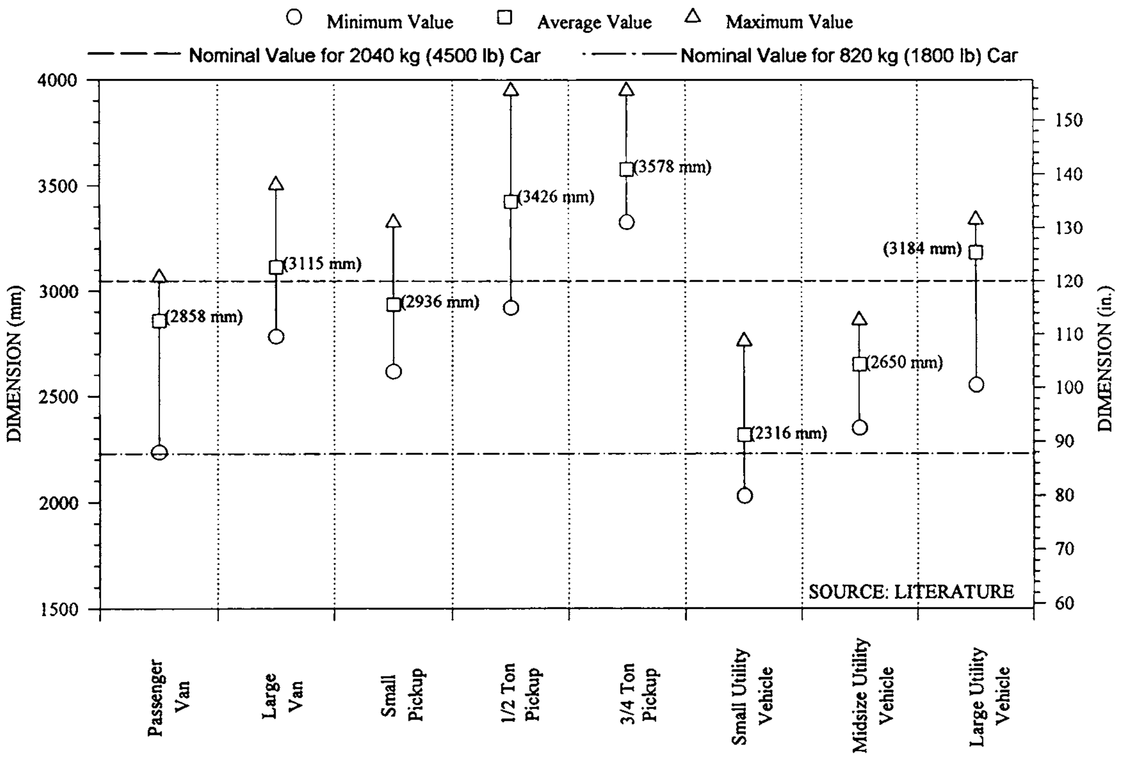


Figure 5. Wheelbase, 1989–1995 models.

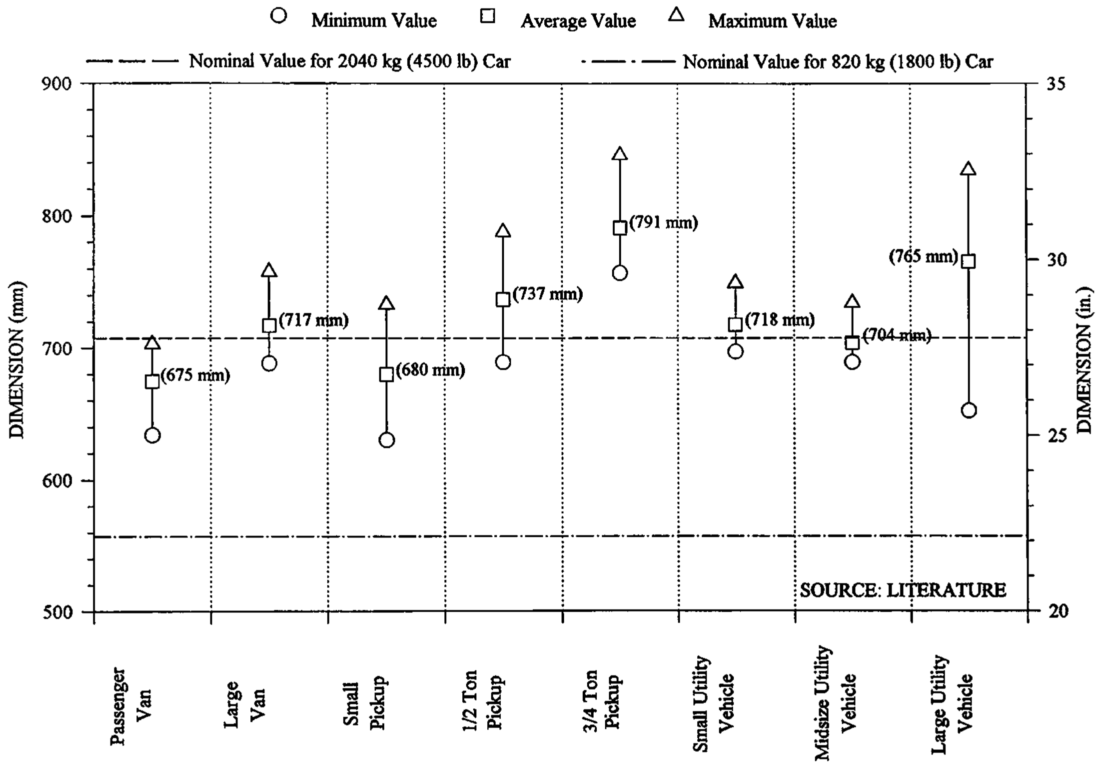


Figure 6. Tire outside diameter, 1989–1995 models.

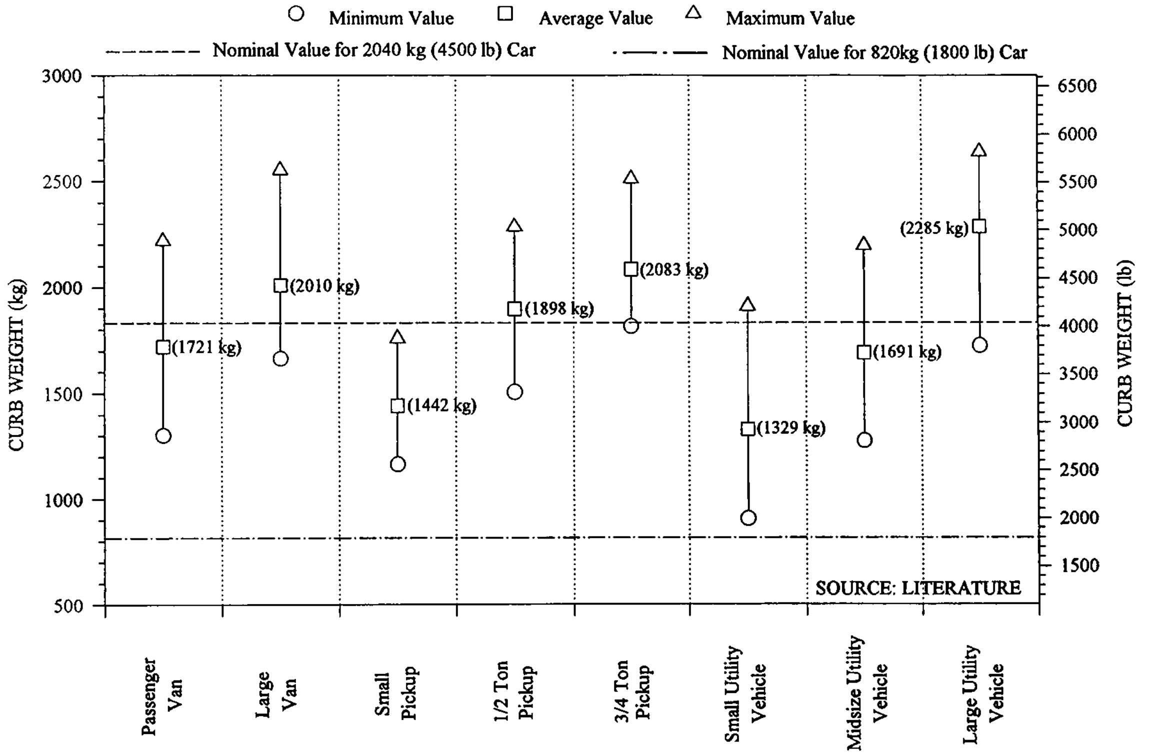


Figure 7. Curb weight, 1989–1995 models.

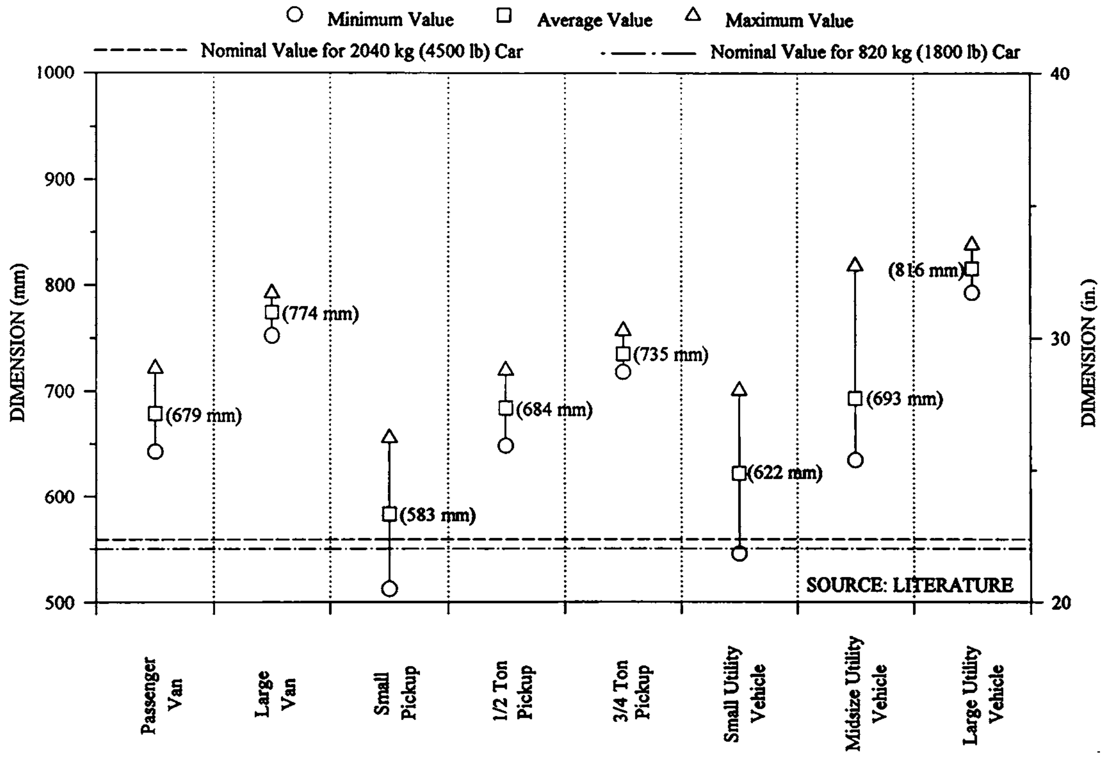


Figure 8. Center of gravity location above ground.

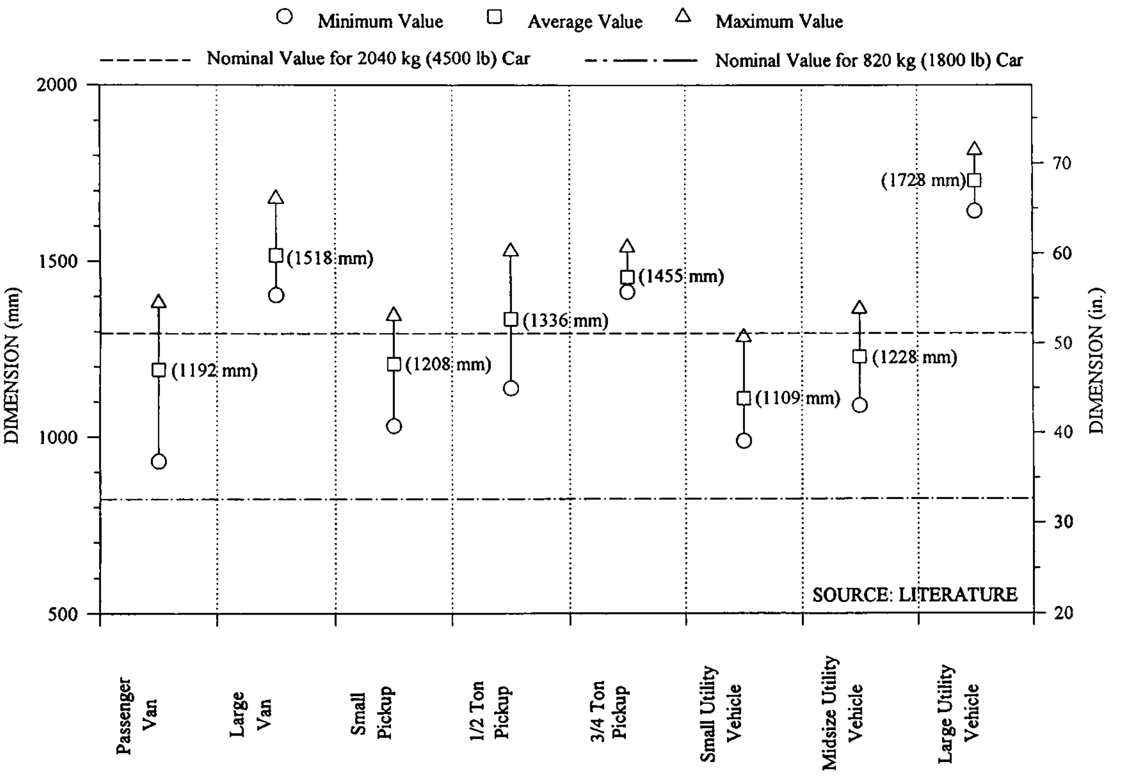


Figure 9. Center of gravity location from front axle.

bumper heights are lower, front overhang is larger, and center-of-mass height is lower).

As part of the crash test study discussed in Section 2.4, inertial properties of the light truck subclasses used in the crash tests were measured. These are reported in Appendix C. Further discussion of the suitability of the ¾-ton pickup as a representative light truck appears in subsequent parts of this report.

2.1.4 Projected Trends

The sales of light trucks (i.e., vans, minivans, pickup trucks, and 4-wheel drive vehicles) have been one of the few bright spots for the U.S. automotive industry in recent years. According to *Ward's Automotive Reports*, the sales of light trucks in 1963 numbered approximately one million vehicles and accounted for 13.9 percent of total new vehicle purchases. The percentage increased to 21.1 percent in 1981 and to a record 38.3 percent (5.3 million units) in 1993. Light trucks are no longer used principally by farmers and construction workers, but are becoming increasingly popular with families for use as passenger vehicles.

Because of the intensely competitive nature of the automobile industry and the unpredictable nature of factors that influence vehicle design, including fuel prices, it is extremely difficult to project or predict even short-term trends in the vehicle fleet. However, these uncertainties notwithstanding, the automotive industry is predicting continued increases in the market share of light trucks in new vehicle purchases. A report entitled "Delphi VII—Forecast and Analysis of the North American Automotive Industry," in 1994 (*11*) reported the following projections:

a. Development cycles for new vehicular platforms would continue to decrease, from 48 months in 1994 to 36 months in 2003. (This means that the highway community would probably have to deal with new design vehicles more frequently.)
b. Sales of automobiles and light trucks would continue to increase at a modest rate, and the ratio of light truck to total passenger vehicle sales would continue to increase slightly up to 2003. The study projected sales of light trucks to reach approximately 38 percent of total passenger vehicle sales by 2003. However, as shown in Figure 1, these projections were off target since 1998 sales showed approximately 48 percent of total passenger vehicle sales were light trucks.
c. Automobile sales by segment (i.e., size/model) would see modest growth in the upper/specialty segment.
d. Light truck sales by segment (i.e., size/model), would see no major changes in the light truck market overall segmentation.
e. By the year 2003 almost all light trucks would have driver's side airbags and 50 percent would have pas-

senger side airbags. (Adjustments in occupant risk criteria used in assessing crash test results may be warranted. For instance, higher occupant impact velocities [OIV] and ridedown accelerations [RA] may be acceptable.)

f. Automobile and light truck weight was projected to decrease by 7 to 8 percent by 2003.
g. There would be little change in frame designs for automobiles and light trucks by 2003.
h. Automobiles and most minivans would continue to have integral body/frame or uni-body construction, while the remainder of light truck subclasses would continue to have separate body/frame construction.

2.2 COMPUTER SIMULATION STUDY

2.2.1 Objective

The objective of the computer simulation study was to examine the safety performance of roadside features for various light truck subclasses and automobile platforms. Results of this phase of the project provided supplemental information from which potential problem areas and gaps in safety performance could be identified.

2.2.2 Roadside Features Evaluated

Three types of roadside features were addressed by the computer simulation study: rigid longitudinal barriers, flexible longitudinal barriers, and roadside geometric features. Details of the simulation study were as follows:

- Rigid longitudinal barriers—Rigid longitudinal barriers are those for which minimal deflections are expected during most impacts by passenger vehicles. The three most commonly used rigid barriers in the United States were studied. They are listed by name below followed by the *Roadside Design Guide* (*12*) designation in parentheses:
  –New Jersey Safety-Shape—(SGM11a),
  –Constant-Slope—(no AASHTO designation), and
  –Vertical-Wall—(no AASHTO designation).

  Details of these barriers are shown in Figures 10, 11, and 12.

- Flexible longitudinal barriers—Flexible longitudinal barriers are those for which measurable deflections are expected during most impacts by passenger vehicles. The most commonly used flexible barriers in the United States were studied. They are
  –G42W—Wood-Post W-Beam Guardrail (SGR04b),
  –G41S—Steel-Post W-Beam Guardrail (SGR04a),
  –G9—Thrie-Beam Guardrail (SGR09a),
  –G1—Cable Guardrail (SGR01a), and
  –G3—Box-Beam Guardrail (SGR03).

  Details of these barriers are shown in Figures 13 through 17.

- Roadside geometric features—The roadside geometric features investigated included fill embankment sections with varying depths, and driveway/median crossovers with varying foreslopes and driveway slopes. Figures 18 and 19 show details of the geometric features studied. Variables investigated for these geometric features are given in Section 2.2.5.

2.2.3 Simulation Programs

Three computer programs were used to simulate impact with the previously identified roadside safety features. Selection of the program depended on the application.

Rigid Longitudinal Barriers—Vehicular stability is a key factor in the evaluation of impacts with sloped-face rigid barriers, making the capability to model three-dimensional response a necessity for investigating this type of longitudinal barrier. A TTI-modified version of the HVOSM computer program (*4*) was selected for use in simulating impacts of light trucks and automobiles with rigid barriers. It was modified by TTI to include an improved sheet metal crush routine and the ability to model “hardpoints” within the vehicle’s structure.

Even with these improvements to the program, limitations still remain with regard to the tire and suspension models. During impacts with rigid barriers, the leading tire and associated suspension system is typically subjected to extremely high loads and loading rates, often resulting in large displacements and structural failure. Very little data are available on tire- and suspension-system damping properties for these high loading rates, and the models are not designed to simulate structural failures. However, when properly calibrated, the HVOSM program is a useful tool in the analysis of vehicle and barrier interaction. Reference should be made to the interim report (*1*) for a limited calibration study of HVOSM for rigid barrier impacts.

The DYNA-3D (*13*) computer program is emerging as a much-improved tool for simulating vehicular impacts with barriers, both rigid and flexible, and other roadside safety features. However, use of the program was not an option in Project 22-11 because of (a) its limited validation at the time the study was conducted, (b) the large number of computer simulation runs needed, and (c) the lack of detailed vehicular data needed. DYNA-3D requires large computer run times compared to HVOSM.

Flexible Barriers—Vehicle override or vaulting, wheel snagging, and overturn are all potential problems associated with light truck impacts with flexible barrier systems. Of all the candidate simulation programs available at the time of the simulation study, the Numerical Analysis of Roadside Design (NARD) program (*14*) was thought to be best suited for pre-

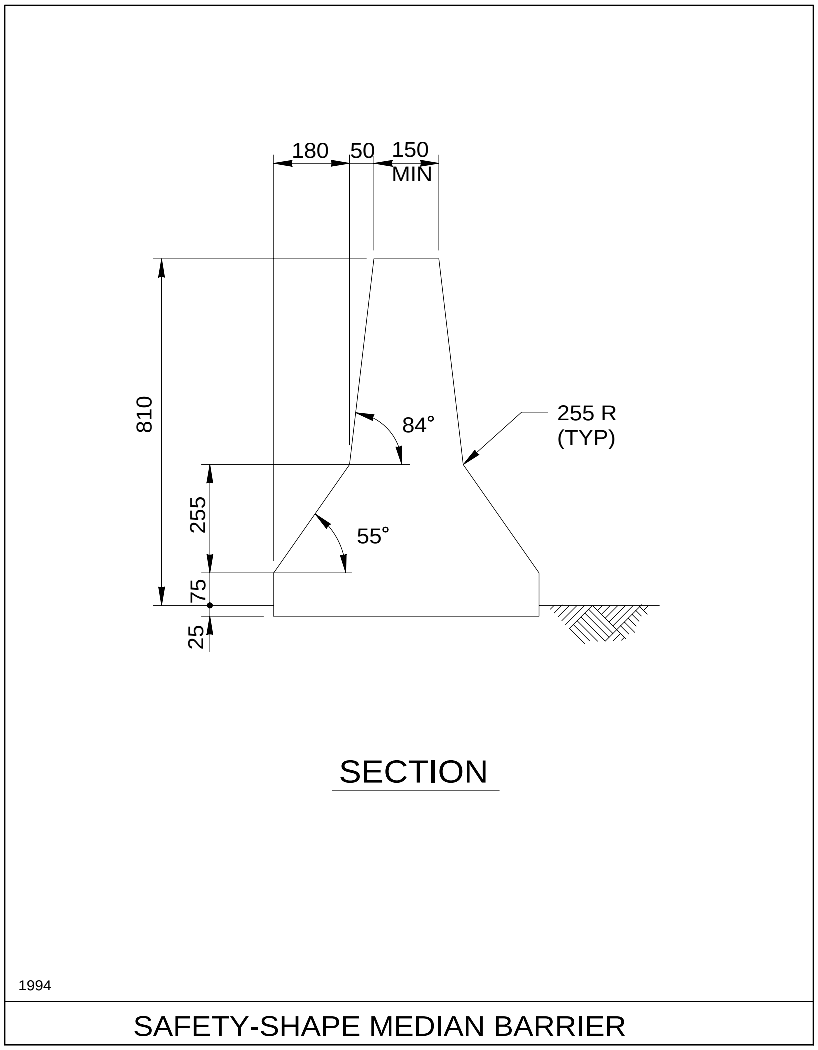


Figure 10. Safety-Shape Barrier—SGM11a (measurements are in millimeters).

dicting these types of three-dimensional responses. The DYNA-3D program was ruled out for reasons previously given for the rigid barrier simulations.

It was understood at the initiation of this task that one of the major obstacles in the implementation of the NARD program, even for commonly used flexible barriers, is the lack of validation and the presence of some code problems. In addition, many limitations exist in simulating impacts in which tire and suspension interaction play a predominant role. During impact with a post, the leading tire and its associated suspension system are typically subjected to extremely high loads and loading rates. Very little data are available on tire and suspension system damping properties for such high loading rates, and the model is not designed to simulate structural snagging or failures such as bent rims, jammed wheels, and so on. For these reasons, the validation and calibration effort was considered to be particularly important for the proposed study due to the relative instability of some of the light truck subclasses and the complex failure modes (e.g., bumper override, vehicle vaulting, and vehicle overturn) observed in full-scale tests.

Several flexible barrier models were developed for use with the NARD program, including the G1 Cable Guardrail, G2 Weak-Post W-Beam Guardrail, G3 Box-Beam, G41S Steel-Post W-Beam Guardrail, and G9 Thrie-Beam Guardrail. From the outset, numerous run-time errors plagued the analysis efforts. After devoting a substantial amount of time and effort to correcting these problems (which some believe to be inherent in the code) satisfactory results were not reached. A decision was made to redirect resources designated for simulation of flexible barriers to the use of BARRIER VII (*3*).

BARRIER VII was originally intended to be used to supplement NARD studies for impacts with non-rigid longitudinal barriers. The advantage in using BARRIER VII to aid

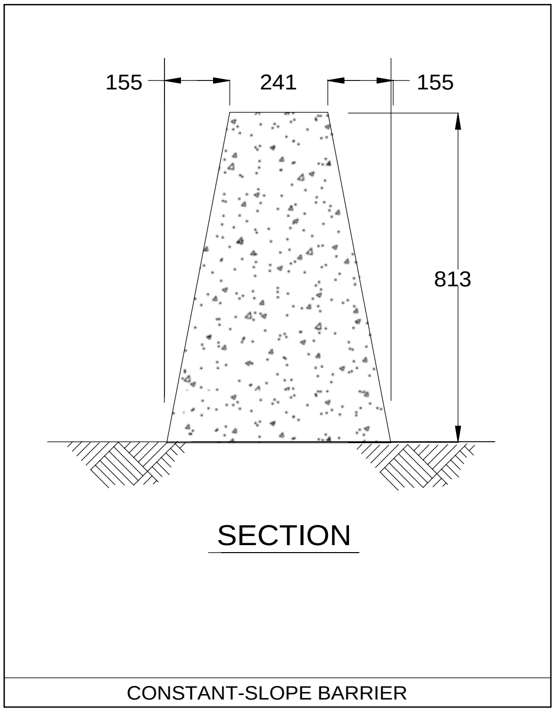


Figure 11. Constant-Slope Barrier (measurements are in millimeters).

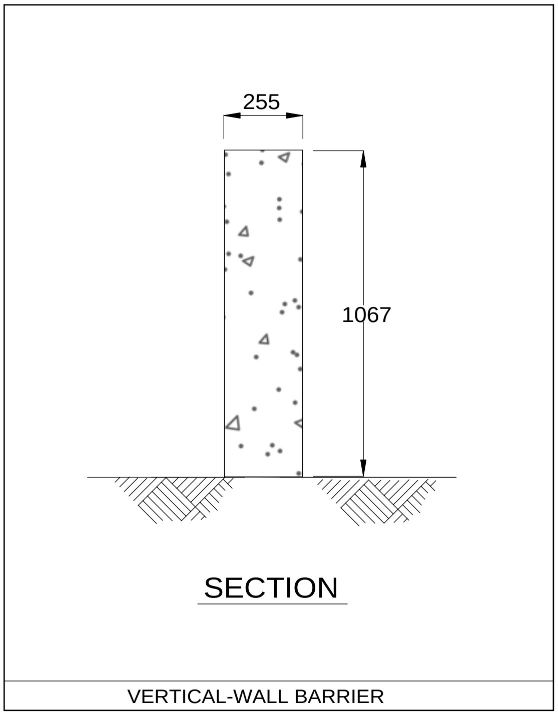


Figure 12. Vertical-Wall Barrier (measurements are in millimeters).

in this analysis lies in its relative simplicity. The two-dimensional nature of the code greatly simplifies the amount of vehicle input required. Thus, it is a rather simple process to vary parameters such as wheel location, front overhang distance, and so on, and determine their effect on snagging. Although its two-dimensional code limits the program's ability to simulate three-dimensional vehicle response, the sophisticated barrier model it possesses can provide insight into the wheel interaction problem, which appears to be a critical factor in the impact performance of light trucks.

It should be noted that as with other programs, BARRIER VII is not capable of simulating wheel snagging, but it can be used to estimate the degree of wheel snagging that will occur during impacts with beam and post barrier systems. This is accomplished by using the rotation point of the post, post deflection, and tire position at time of contact with the post. The program output also provides barrier deflection and barrier stresses, which can provide additional means of comparison among the subclasses of light trucks and automobiles.

Roadside Geometric Features—A number of computer programs have been developed for analyzing various vehicle-handling scenarios. Principal among these is the HVOSM program. HVOSM is very well validated and has proven to be reliable in predicting the onset of rollover on roadside slopes, embankments, and ditches. Among the various HVOSM versions, two were considered for use in simulating roadside geometric features such as slopes, ditches, and driveways, namely HVOSM-RD2 (*5*), and HVOSM-TTI (*15*). A desirable feature of the TTI version not present in the RD2 version is the ability of specified vehicular contact points (other than the tires) to interact with the terrain. This feature, which can be used to model bumper or sheet metal contact with the ground, has been shown to be an important factor affecting the stability of vehicles in simulations of roadside encroachments. A feature in the RD2 version not present in the TTI version is the ability to simulate 4-wheel independent suspension. Since many light trucks still utilize a solid rear axle, and given that only minor differences were observed between the two models in cases where no vehicle contact points interacted with the terrain, the TTI version was used because of the importance of vehicle/terrain interaction in predicting vehicular response.

The same vehicle model developed and calibrated for the rigid barrier analysis was transferred to the TTI version. The model was modified to permit bumper and sheet metal contact with the terrain.

2.2.4 Vehicles

It was necessary to select particular vehicular models from each of the respective light truck and automobile subclasses for use in the computer simulation study. Vehicles were

(Text continues on page 17)

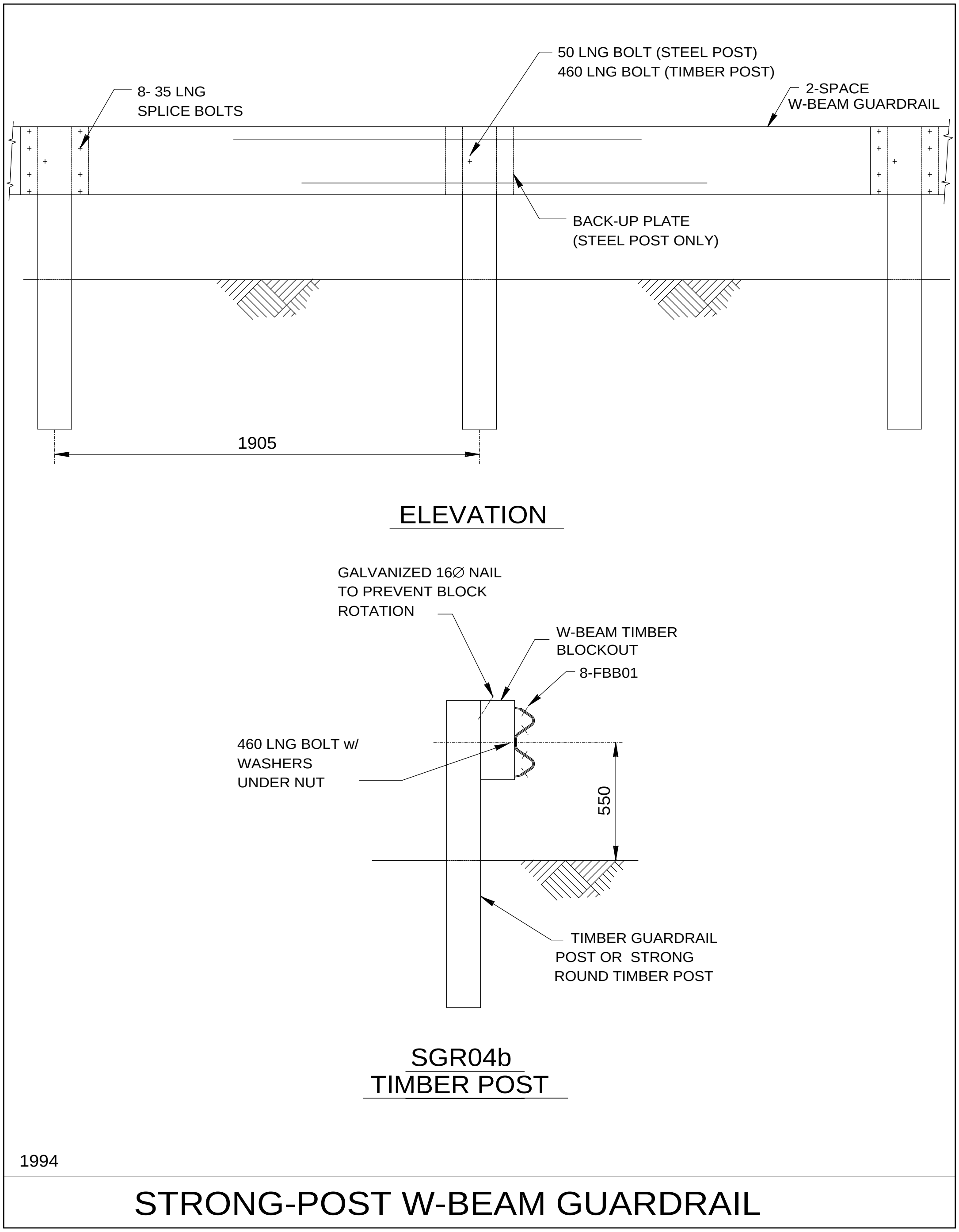


Figure 13. Wood-Post W-Beam Guardrail—SGR04b (measurements are in millimeters).

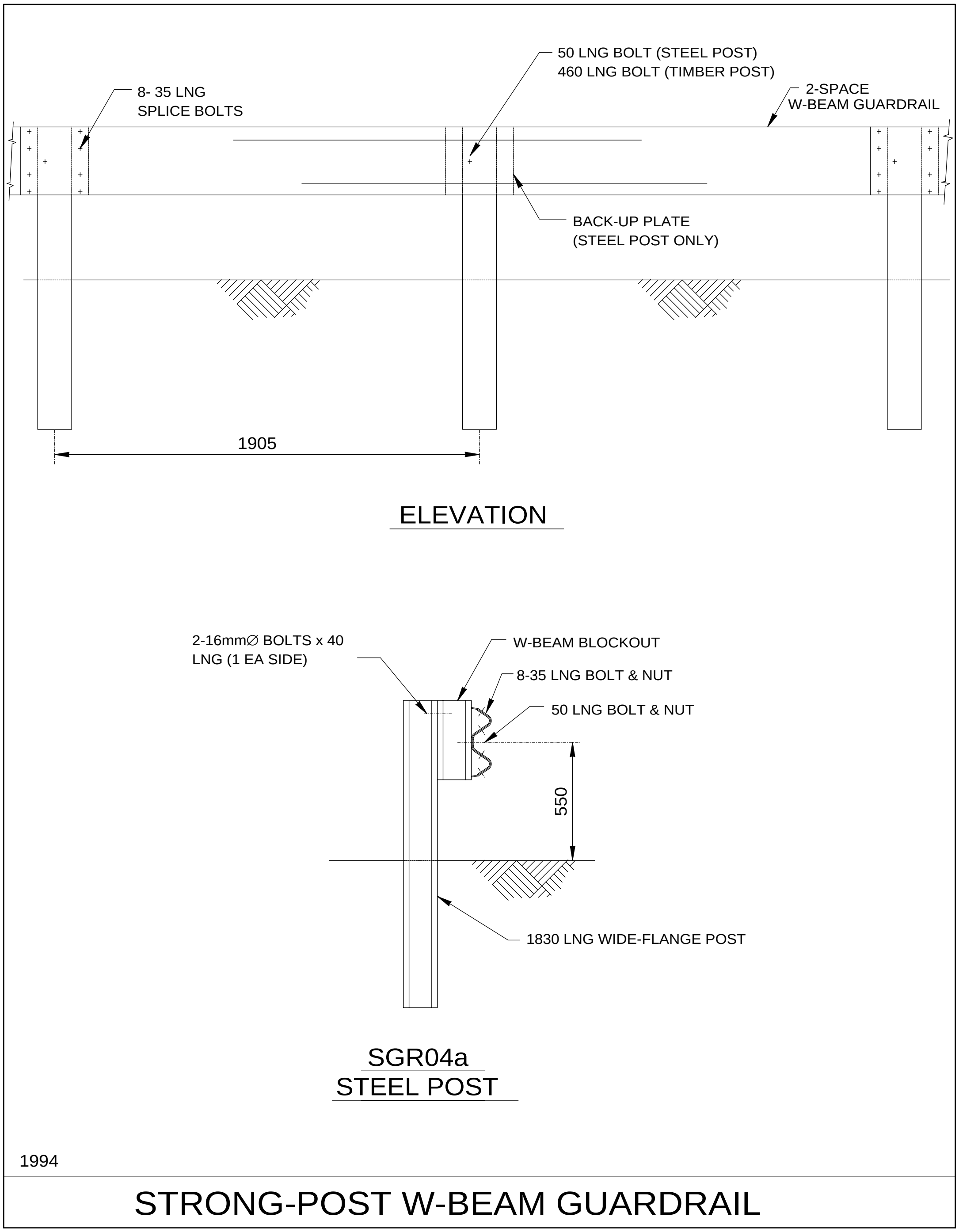


Figure 14. Steel-Post W-Beam Guardrail—SGR04a (measurements are in millimeters).

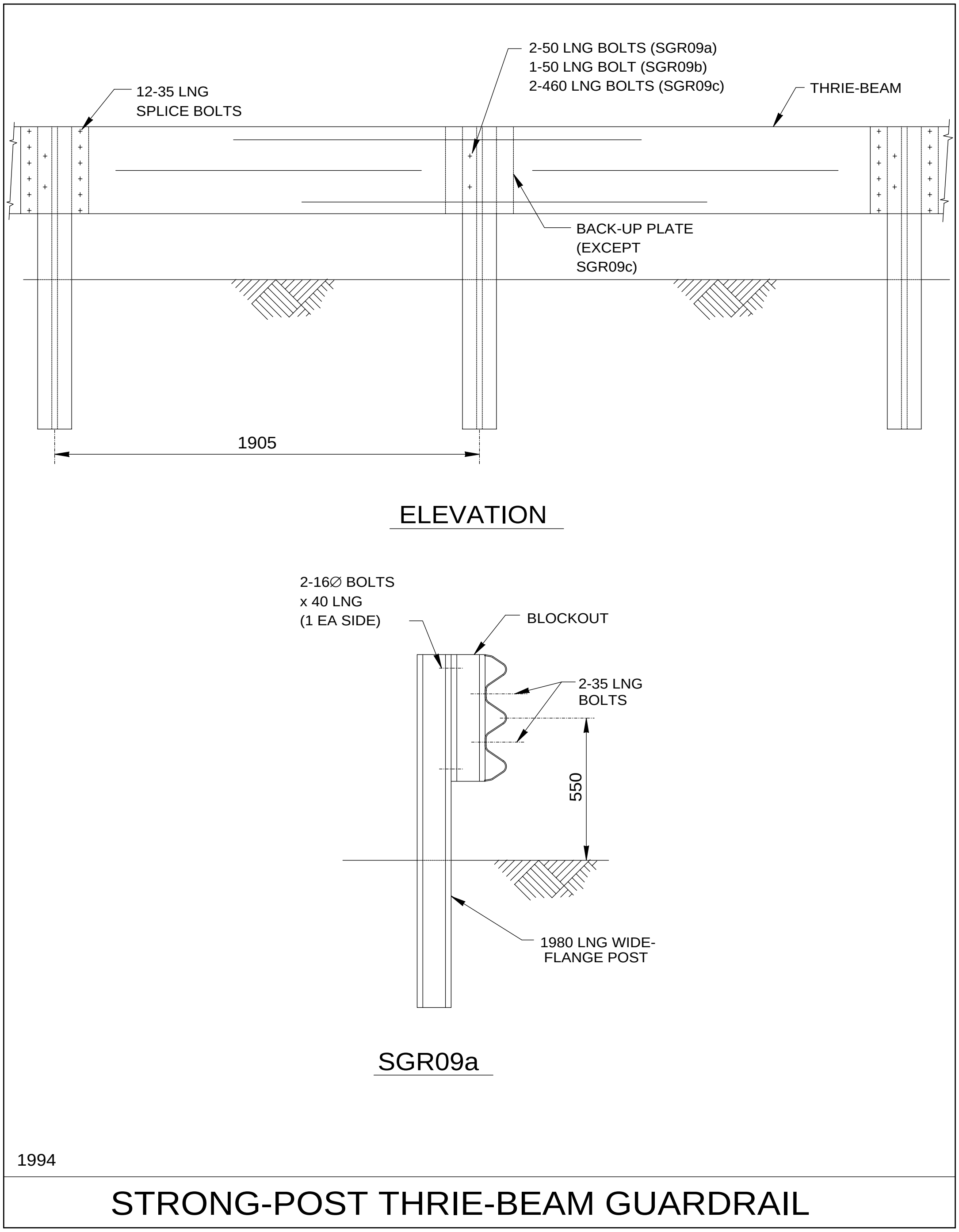


Figure 15. Thrie-Beam Guardrail—SGR09a (measurements are in millimeters).

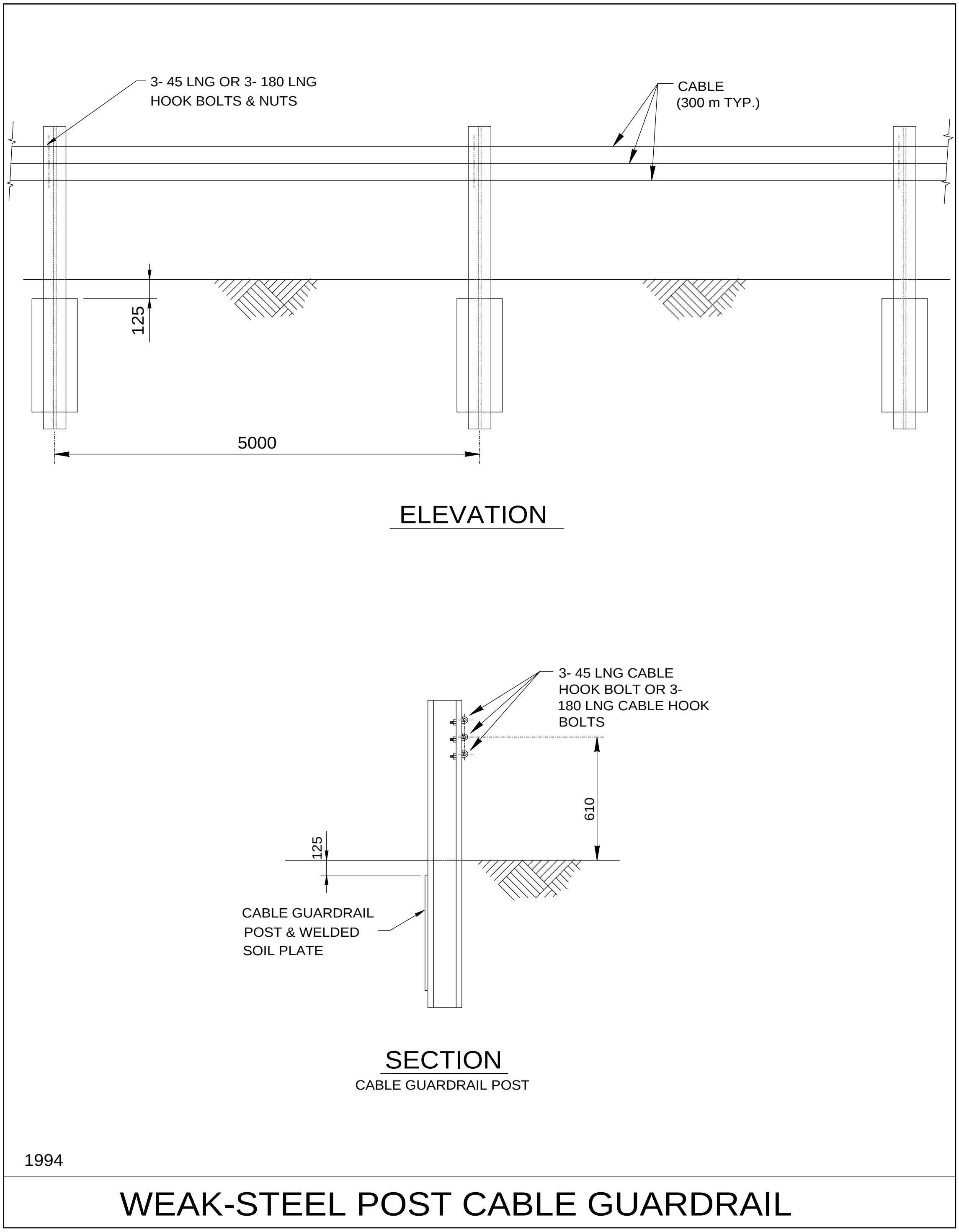


Figure 16. Cable Guardrail—SGR01a (measurements are in millimeters).

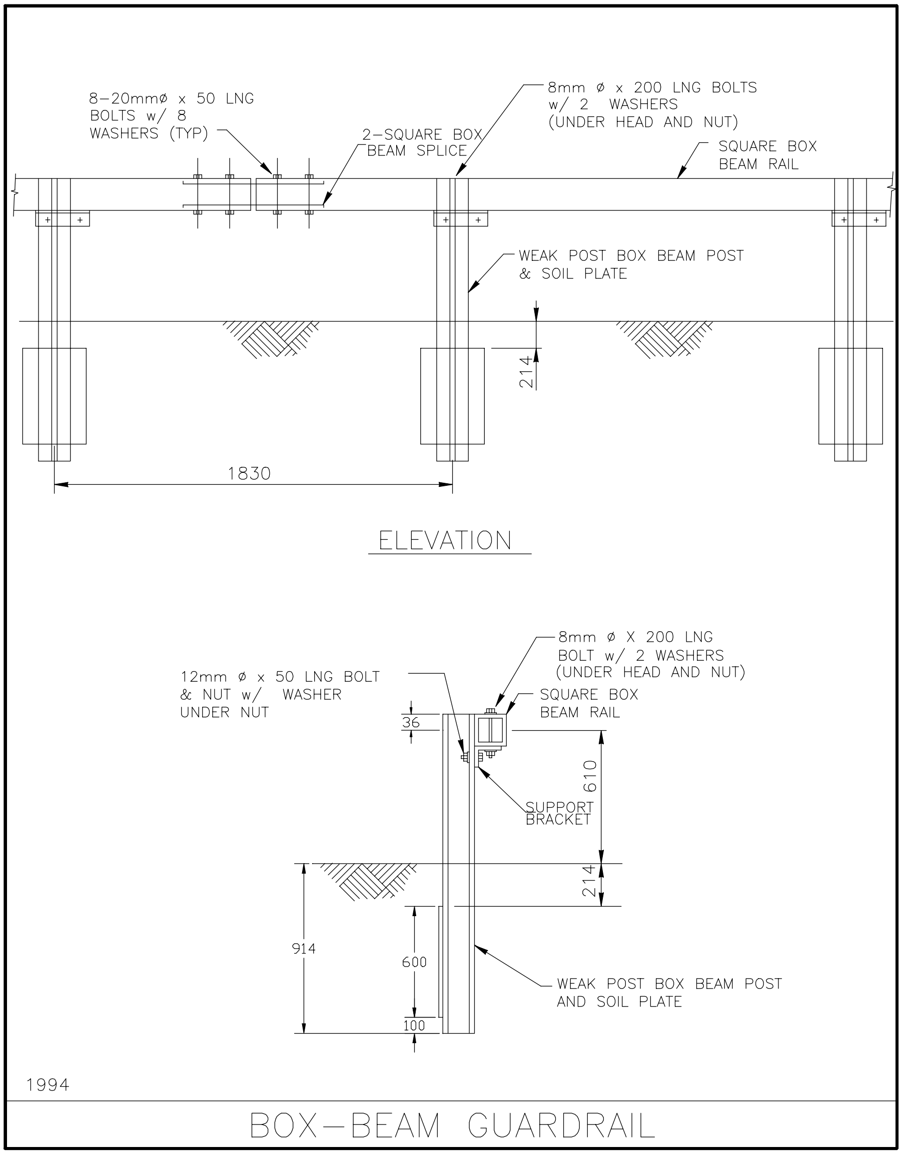


Figure 17. Box-Beam Guardrail—SGR03.

selected based on the availability and detail of data needed for the HVOSM and BARRIER VII programs, the age of the vehicle, and sales volume. Input data were derived from several sources: “Measured Vehicle Inertial Parameters—NHTSA’s Data Through 1992” (*7*), “Vehicle Dynamics Simulation and Metric Computation for Comparison with Accident Data” (*8*), “Light Truck Inertial Properties” (*9*), and “Tire Parameter Determination—Report No. DOT HS-802094” (*16*). These data were supplemented with data gathered in parking lot and dealer’s lot surveys. The parking lot data provided dimensional information. Adjustments were also necessary for CG locations, since the reported data were for the total vehicle, whereas HVOSM requires CG data for the sprung mass. See Section 2.2.6 for the actual values used.

Listed below are the actual light truck models used in the computer simulation program to represent the light truck subclasses.

Category	Vehicle Modeled	Comments
Small Utility	1990 Jeep	1989 Jeep Wrangler suspension data.
Midsize Utility	1983 Chevrolet S-10 Blazer	
Large Utility	1984 Chevrolet C-20 Suburban	
Small Pickup	1986 Ford Ranger	1985 Ford Ranger suspension data.
Large Pickup	1984 Chevrolet C-20	
Passenger Van	1990 Plymouth Voyager	1989 Plymouth Voyager suspension data.
Large Van	1987 Ford E-150 Econoline Van	

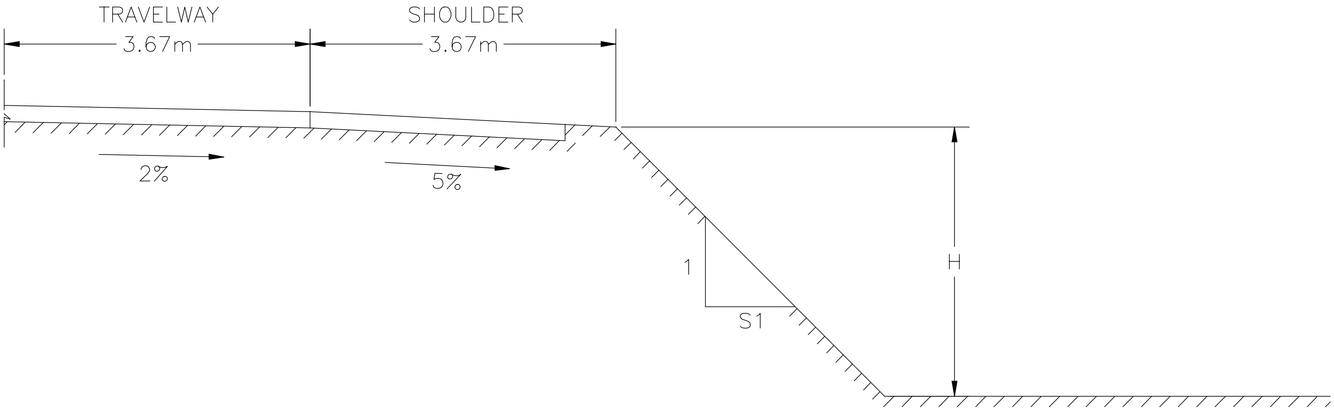


Figure 18. Fill-section geometry.

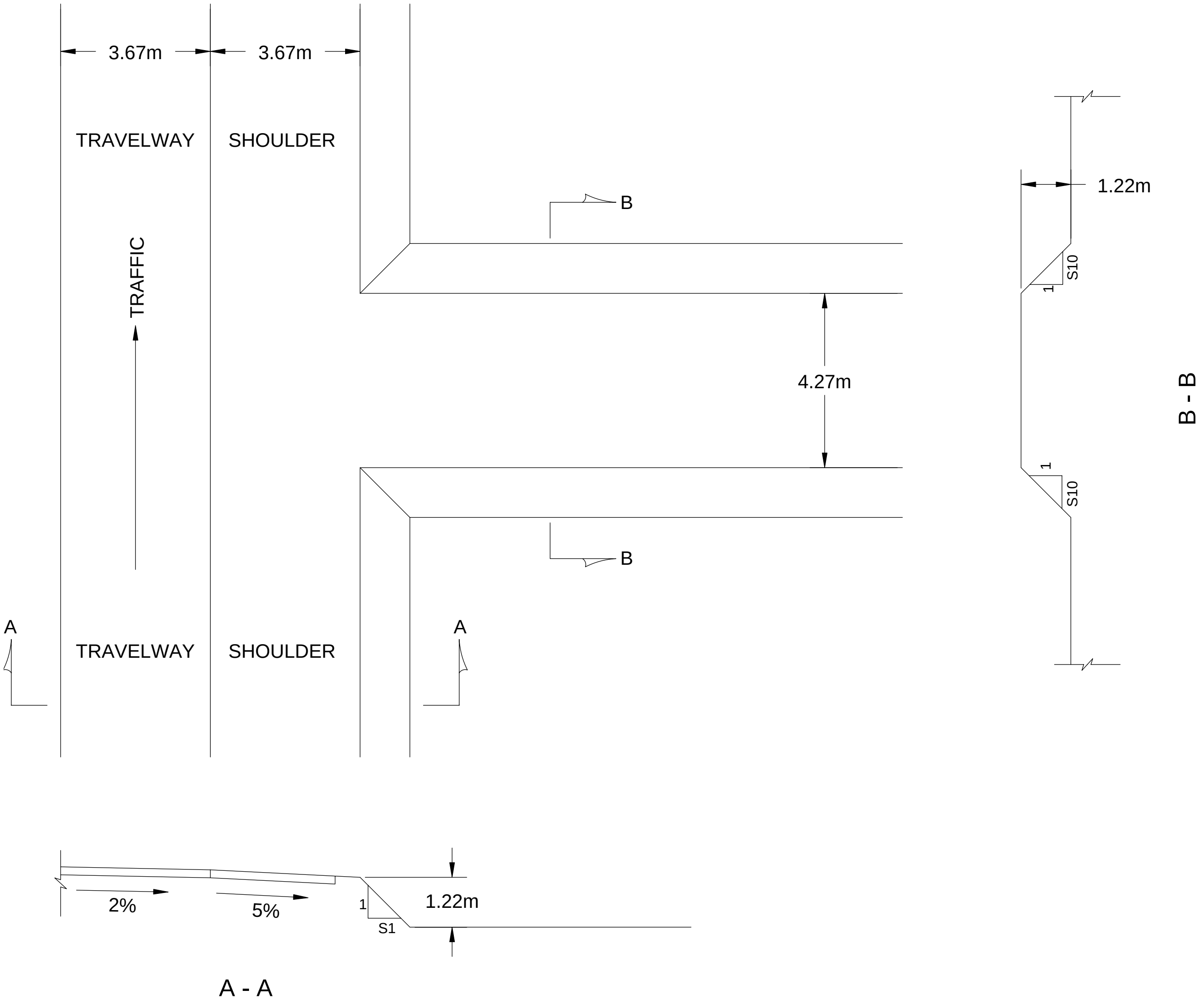


Figure 19. Driveway geometry.

The following categories were selected in the FHWA study (*2*) for the automobiles simulated.

Category	Wheelbase	
Small 1 (S1)	< 95 in.	< 2415 mm
Small 2 (S2)	95–99 in.	2415–2525 mm
Midsize 1 (M1)	100–104 in.	2526–2650 mm
Midsize 2 (M2)	105–109 in.	2651–2775 mm
Large 1 (L1)	110–114 in.	2776–2900 mm
Large 2 (L2)	> 114 in.	> 2900 mm

Actual automobile models used in the simulation program to represent these categories are listed below.

Category	Vehicle Modeled	Comments
Small 1	1995 Geo Metro	1987 Hyundai Excel suspension data.
Small 2	1995 Ford Escort	1989 Ford Escort suspension data.
Midsize 1	1995 Toyota Camry	1983 Toyota Camry suspension data.
Midsize 2	1995 Ford Taurus	1985 Oldsmobile Cierra suspension data.
Large 1	1995 Buick LeSabre	1980 Buick LeSabre suspension data.
Large 2	1995 Lincoln Towncar	1980 Buick LeSabre suspension data.

2.2.5 Matrix of Simulations

Rigid Longitudinal Barriers—Two types of impacts were simulated for the rigid longitudinal barriers: tracking and non-tracking. In a tracking impact the vehicle approaches the barrier with only a forward, translational velocity, and no yaw rate. In a non-tracking impact the vehicle approaches the barrier with forward and lateral components of translational velocity, at a given yaw rate. Non-tracking impacts occur when the vehicle "spins out" prior to impact. An effort was made to examine both tracking and non-tracking types of impacts because of their occurrence in the real world, and because there are indications that for certain conditions one type may be more critical than the other.

All combinations of the following were investigated in the tracking simulations:

- Vehicles—13 (as previously described) 7 light trucks and 6 automobiles.
- Barriers—3 (as previously described).
- Impact conditions
  –Approach speeds—3 (70 km/h, 85 km/h, and 100 km/h).
  –Approach angles—3 (15 degrees, 20 degrees, and 25 degrees).

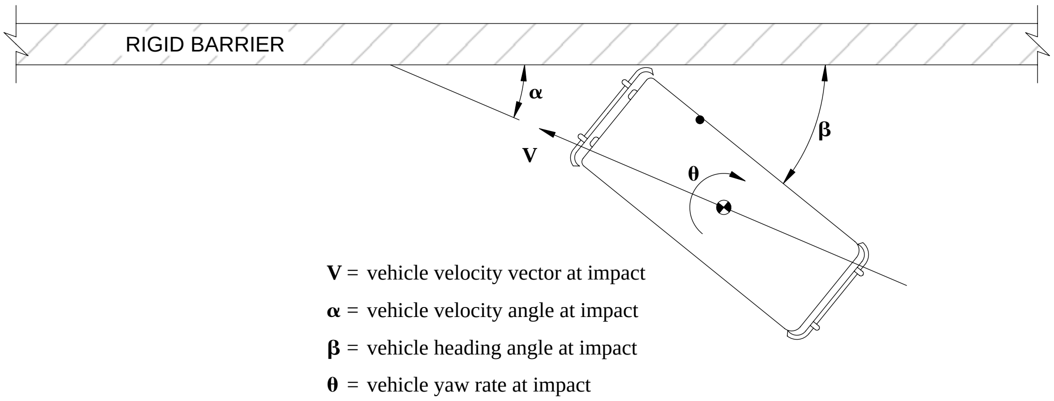
This produced a total of 351 simulated impacts.

All combinations of the following were investigated in the non-tracking simulations:

- Vehicles—13 (as previously described) 7 light trucks and 6 automobiles.
- Barriers—3 (as previously described).
- Impact conditions
  –Resultant approach speed—2 (70 km/h and 100 km/h).
  –Vehicle heading angle—2 (35 degrees and 45 degrees).
  –Vehicle velocity angle—2 (15 degrees and 25 degrees).
  –Vehicle yaw rate—1 (15 deg./sec).

This produced a total of 312 simulated impacts. See Figure 20 for a description of the above impact condition terms.

Flexible Longitudinal Barriers—All simulated impacts with the flexible longitudinal barriers were for tracking conditions. The BARRIER VII program used in these simulations is limited to two-dimensional motion and thus cannot simulate overturns that are of concern in non-tracking impacts.



V = vehicle velocity vector at impact
α = vehicle velocity angle at impact
β = vehicle heading angle at impact
θ = vehicle yaw rate at impact

Figure 20. Non-tracking impact parameters.

All combinations of the following were investigated:

- Vehicles—13 (as previously described) 7 light trucks and 6 automobiles.
- Barriers—5 (as previously described).
- Impact conditions
  - –Approach speeds—3 (70 km/h, 85 km/h, and 100 km/h).
  - –Approach angles—2 (20 degrees and 25 degrees).

This produced a total of 390 simulated impacts. The initial impact point for each simulation was midway between two support posts of the barrier being simulated. As discussed in Section 2.2.8.2, this was not, in general, the "critical impact point" as described in *NCHRP Report 350*.

Roadside Geometric Features—Fill sections and driveways were the two geometric features examined in the simulation study. Following is a description of the matrix of simulations for each.

For fill sections all combinations of the following were investigated:

- Vehicles—13 (as previously described) 7 light trucks and 6 automobiles.
- Fill Section
  - –Side Slope—3 (6 : 1, 4 : 1, and 3 : 1).
  - –Ditch Depth—3 (1.5 m, 3 m, and 6.1 m).
  - –Tire-Terrain Friction Coefficient—2 (0.3 and 0.5).
- Vehicular Encroachment
  - –Speeds—1 (100 km/h).
  - –Angles—1 (15 degrees).

The above combinations produced a total of 234 simulated encroachments.

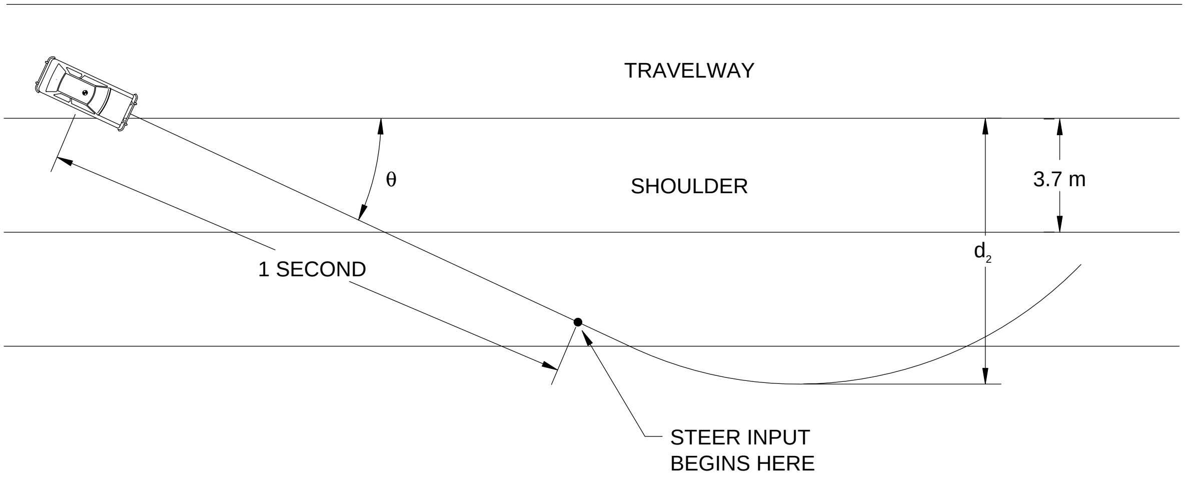
Reference should be made to Figure 18 for a description of the fill-section geometry. In each of the runs an effort was made to simulate what may be described as a typical driver's response upon realizing his/her vehicle is leaving the roadway, as illustrated in Figure 21. One second is typically assumed as the average perception-reaction time for a driver. At one second after leaving the travelway (when right front tire crosses the edge of the travelway) a panic steer input was made to simulate a driver attempting to return to the travelway. This placed the right front tire approximately 7.2 m from the travelway once steer back began, or about 3.5 m laterally from the shoulder break. Lateral distance from the travelway to the shoulder break was 3.7 m. The vehicle was assumed to be in a coasting, unpowered mode, and no braking was applied at any time.

Tire-terrain friction coefficients of 0.3 and 0.5 were assumed. These are believed to be representative of well-compacted terrain. A cornering vehicle will be more prone to overturn on saturated terrain subject to rutting or on terrain with irregularities or appurtenances such as eroded areas, vegetation such as small trees, shrubs, and so on. However, the HVOSM does not have the capability to simulate tire rutting and its effect on vehicular stability.

Assumed encroachment conditions and driver response parameters were chosen in an attempt to replicate typical real-world occurrences, but are not necessarily the most critical scenarios. For example, for any of the selected roadside geometric conditions, a lower speed and/or lower encroachment angle may have produced a more unstable situation for the vehicle.

For driveways, with the exceptions given below, all combinations of the following were investigated:

- Vehicles—13 (as previously described) 7 light trucks and 6 automobiles.
- Driveway



d_2 = maximum lateral movement of vehicle

Figure 21. Fill-section encroachment parameters.

- –Ditch Side Slope—3 (6 : 1, 8 : 1, and 10 : 1).
- –Driveway Side Slope—3 (6 : 1, 8 : 1, and 10 : 1).
- –Ditch Depth—1 (1.0 m).
- –Tire-Terrain Friction Coefficient—1 (0.5).
- Vehicular Encroachment
  - –Paths—2 (see Figure 22).
  - –Speeds—2 (80 km/h and 100 km/h).

For "Path 2" the "ditch side slope" does not influence the simulation. Only one encroachment speed was examined for the automobiles, namely 100 km/h. The above combinations produced a total of 240 simulated encroachments. The vehicle was assumed to be in a coasting, unpowered mode. No braking or steering was applied. Reference should be made to Figure 19 for a description of the driveway geometry.

2.2.6 Input Data

A total of 1,872 simulated impacts/encroachments were conducted. Each of the programs used in this effort requires numerous input parameters for both the vehicle and the feature being studied. Inclusion of all input data for each simulated impact/encroachment would have required hundreds of pages and was thus not feasible. Rather, as a compromise, it was concluded that limited sample input data in engineering format would be provided, followed by limited "card image" lists of input. In engineering format, all input parameters are identified along with their respective values. In card image format, all input values are presented, but the reader must be familiar with the sequence of input values to be able to relate them to the respective parameters. The sample data are given in Appendix A.

2.2.7 Evaluation Criteria

Evaluation factors were dependent on the computer program and the application.

Rigid Longitudinal Barriers—In rigid longitudinal barrier impact simulations the HVOSM program provided essentially the same information available from a crash test, with the exception of occupant compartment deformation. Thus, the results were evaluated in terms of occupant risk and post-impact trajectory parameters as given in *NCHRP Report 350*. Occupant risk is evaluated through OIV, RA, and vehicular stability (overturn not permitted).

Flexible Longitudinal Barriers—In flexible longitudinal barrier impact simulations the BARRIER VII program provided vehicular accelerations, barrier deformation, and information from which the potential for wheel snagging on guardrail posts could be assessed. OIV and RA were calculated according to *Report 350* recommendations. Figure 23 illustrates the manner in which wheel snagging was assessed.

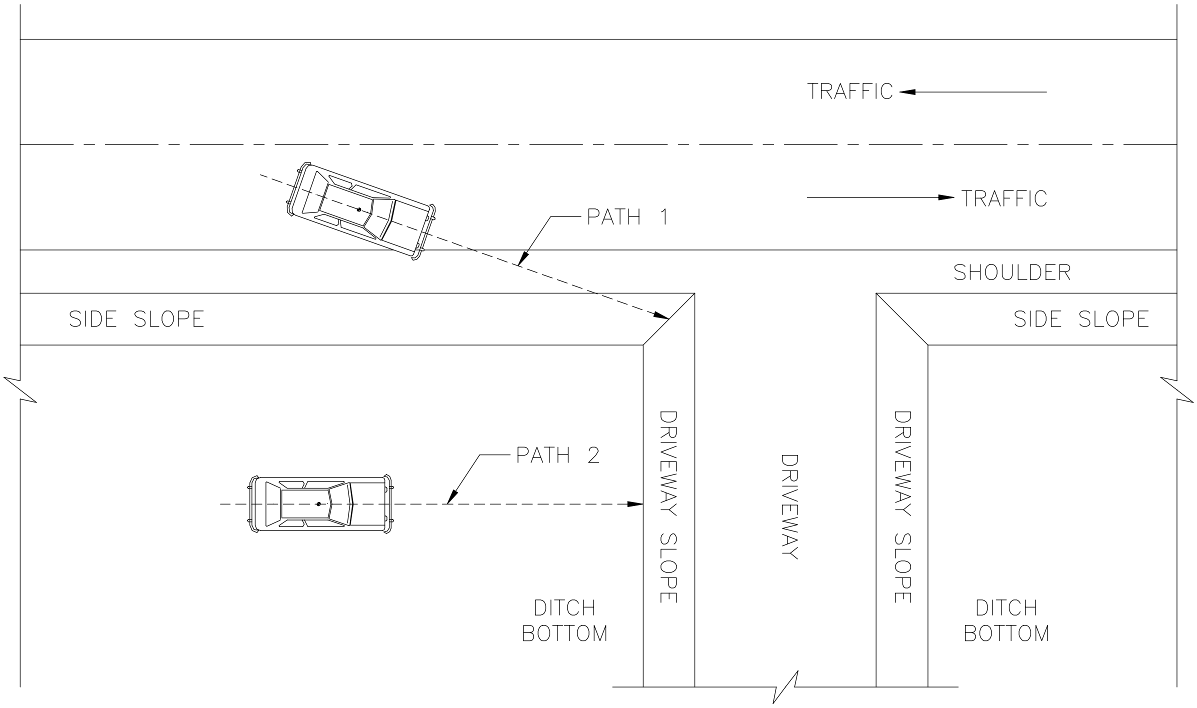


Figure 22. Encroachment paths for driveway simulations.

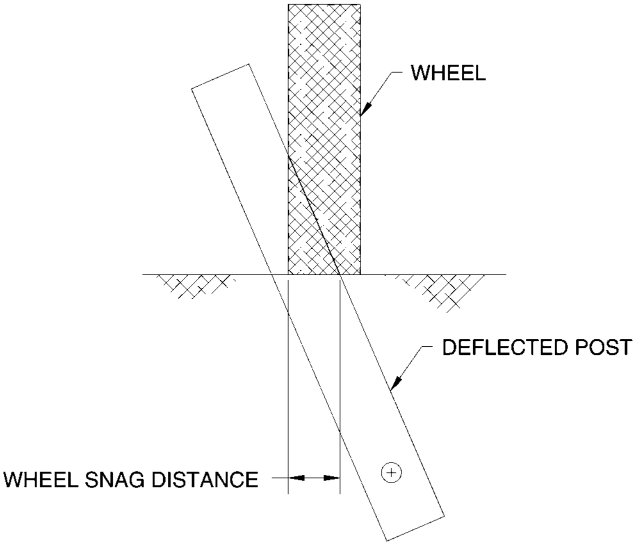


Figure 23. Measurement of wheel snag.

Note that wheel-post interaction is not accounted for in BARRIER VII, so snagging can only be implied.

For strong-post guardrail systems, including those systems shown in Figures 13, 14, and 15, the extent of wheel snagging has been found to correlate with impact performance (*17*). For these types of systems, it has been found that if the wheel snag distance exceeds the depth of the post, there is a good likelihood of adverse impact performance, manifest by excessive decelerations and/or unstable vehicular behavior. Following are nominal post depths for the three strong-post systems:

System	Post Depth (mm)
G42W	200
G41S	150
G9	150

Note that wheel snagging of any degree is not considered a major problem for the weak-post systems, including those systems shown in Figures 16 and 17. These posts are easily ridden down or pushed over by the wheel or vehicular contact.

Roadside Geometric Features—*Report 350* evaluation criteria do not in general apply for vehicular encroachment on a roadside geometric feature, since an impact does not usually occur and since the event occurs over a relatively long time period in comparison to an impact. Thus, in accordance with a previous study (*18*), the primary evaluation factors selected for these types of simulations were the vehicle's (a) maximum resultant accelerations, (b) maximum angular displacements, and (c) stability (whether or not it overturned).

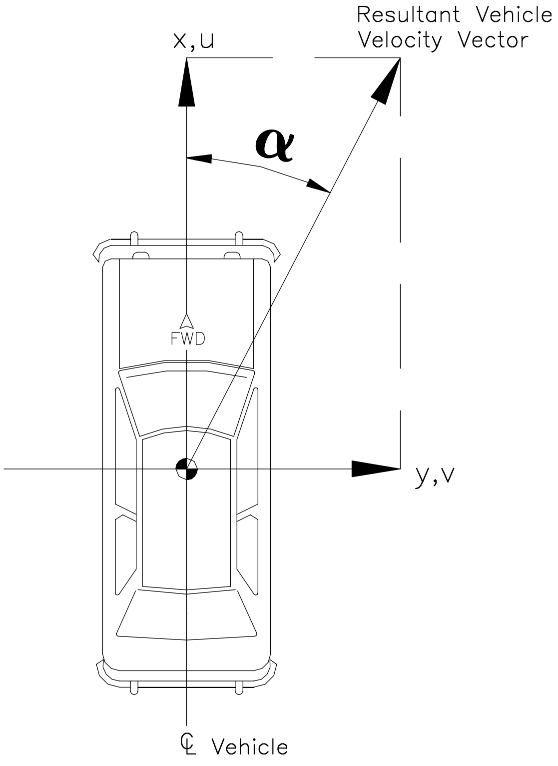
In addition, for the fill-section study, the vehicle's behavior was characterized as either stable, sideslipping, or spinning out. With reference to Figure 24, these terms are defined as follows:

- Stable—no sideslipping or spinning out.
- Sideslipping—when $\mathrm{TAN}^{-1} \frac{|v|}{u} > 20$ degrees.
- Spin out—when $u \leq 0$.

Also, in the fill-section study, the lateral extent of the vehicle's movement was determined and reported. This is a measure of the extent of lateral distance needed for the driver to begin to return to the travelway.

2.2.8 Results

The results of the large number of computer simulations are summarized in tabular form. The following abbreviations are used in the tables:



u = component of vehicle velocity in x direction.

v = component of vehicle velocity in y direction.

$$\text{Sideslip Angle} = \boldsymbol{\alpha} = \mathrm{TAN}^{-1}\frac{|v|}{u}$$

Figure 24. Sideslip and spin out parameters.

Light Trucks

SUV—small utility vehicle
MUV—midsize utility vehicle
LUV—large utility vehicle
SPU—small pickup
LPU—large pickup
PVN—passenger van
LVN—large van

Automobiles

Size	Wheelbase	
S1—small	<95 in.	<2415 mm
S2—small	95–99 in.	2415–2525 mm
M1—midsize	100–104 in.	2526–2650 mm
M2—midsize	105–109 in.	2651–2775 mm
L1—large	110–114 in.	2776–2900 mm
L2—large	>114 in.	>2900 mm

Reference should be made to Section 2.2.4 for a description of the specific vehicles used in the simulation programs for the vehicle types listed above.

2.2.8.1 Rigid Longitudinal Barriers

Results of simulated impacts with rigid longitudinal barriers were tabulated and are given in Appendix A. Tables 1 through 6 summarize key findings from the large volume of data generated from the simulated rigid barrier impacts. These tables identify those tracking and non-tracking impacts in which some type of failure is predicted for each of the three rigid barriers. A review of simulation results for each kind of barrier is listed below.

New Jersey Safety-Shape Barrier—Simulation results for the New Jersey Safety-Shape Barrier suggest the following:

1. Light trucks are much more unstable (i.e., more likely to overturn) than automobiles for tracking impacts with the New Jersey Safety-Shape Barrier.
2. Within the light truck subclasses, the SUV has the greatest instability for impacts with the New Jersey Safety-Shape Barrier, even at a relatively low speed of 70 km/h and an impact angle of 25 degrees. The LUV, SPU, and LVN vehicles also exhibit instability for some impact conditions.

TABLE 1 Predicted failure conditions—New Jersey Safety-Shape Barrier—tracking

Vehicle[1]		Impact Conditions		Failure Type
		Speed (km/h)	Angle (deg.)	
Light Trucks	SUV	100	25	ROLLOVER
	SUV	100	20	ROLLOVER
	SUV	100	15	ROLLOVER
	SUV	85	25	ROLLOVER
	SUV	85	20	ROLLOVER
	SUV	70	25	ROLLOVER
	MUV	100	25	ROLLOVER
	LUV	100	20	ROLLOVER
	LUV	100	15	ROLLOVER
	LUV	85	25	ROLLOVER
	SPU	100	25	ROLLOVER
	SPU	100	20	ROLLOVER
	SPU	85	25	ROLLOVER
	PVN	100	25	ROLLOVER
	LVN	100	25	ROLLOVER
	LVN	100	20	ROLLOVER
	LVN	85	25	ROLLOVER
Automobiles	No Failures Predicted			

[1] See Section 2.2.8 for vehicular descriptions.

TABLE 2 Predicted failure conditions—New Jersey Safety-Shape Barrier—non-tracking

Vehicle[1]		Impact Conditions			Failure Type
		Speed (km/h)	Vehicle Heading Angle (deg.)	Velocity Vector Angle (deg.)	
Light Trucks	SUV	100	35	25	ROLLOVER
	LUV	70	45	15	ROLLOVER
	SPU	100	35	25	ROLLOVER
	PVN	100	45	25	R.A. = -22.6g's in Y direction
Automobiles	S1	100	45	15	ROLLOVER
	S1	70	45	25	ROLLOVER
	S1	70	45	15	ROLLOVER
	S2	100	45	15	ROLLOVER
	S2	100	35	15	ROLLOVER
	S2	70	45	25	ROLLOVER
	S2	70	35	15	ROLLOVER

[1] See Section 2.2.8 for vehicular descriptions.

3. A number of tracking crash tests have been conducted with light truck subclasses impacting the New Jersey Safety-Shape Barrier (see Tables 28 and 31). Most of the tests were with the LPU, but tests with an SPU and a LUV were also conducted. Tests with a Chevrolet 2000P vehicle (LPU) at impact conditions of 100 km/h at impact angles of 20 degrees and 25 degrees, and at impact conditions of 89.0 km/h and 20 degrees, met *NCHRP Report 350* evaluation criteria. Similar results were predicted in the simulation study. Note that a Chevrolet pickup was used in the simulation study. Crash tests of a Ford 2000P vehicle (LPU) at impact conditions of 96.9 km/h and 21.5 degrees, and impact conditions of 104.2 km/h and 25.6 degrees, resulted in rollovers. Crash tests of a LUV at impact conditions of 97.5 km/h and 6.5 degrees, and 97.7 km/h and 14.5 degrees were successful. The simulation study predicted overturn for the LUV at 100 km/h at 15 degrees. However, a Chevrolet Suburban was used in the simulation study whereas a Ford Bronco was used in the crash tests.
4. There were no predicted automobile overturns with the New Jersey Safety-Shape Barrier for the tracking impact conditions studied.
5. Tracking crash tests have been conducted with both large and small automobiles impacting the New Jersey Safety-Shape Barrier, at speeds of approximately 100 km/h and impact angles of 20 and 25 degrees (*18*, *21*, *22*). Results of all tests met recommended performance criteria. Similar results were predicted in the simulation study.
6. Smaller automobiles tend to be more unstable than larger automobiles for non-tracking impacts with the New Jersey Safety-Shape Barrier.
7. Results of the crash data study (see Section 2.3 and Appendix B) tend to corroborate the simulation studies. With some exceptions, the crash data study found a greater propensity for overturn of light trucks impacting "concrete median barriers" than automobiles. It is conjectured that most of these were New Jersey Safety-Shape Barriers.

Constant-Slope Barrier—Simulation results for the Constant-Slope Barrier suggest the following:

1. Of the three rigid barriers studied, the Constant-Slope Barrier introduces greater instability to impacting vehicles, especially light trucks.
2. Light trucks are much more unstable than automobiles for tracking impacts with the Constant-Slope Barrier.
3. Within the light truck subclasses, the SUV and the SPU have the greatest propensity for overturning for tracking impacts with the Constant-Slope Barrier, even at a relatively low speed of 70 km/h and an impact angle of 15 degrees. The MUV, PVN, and the LVN also exhibited instability at certain impact conditions. The LUV and the LPU both were stable.

TABLE 3 Predicted failure conditions for the Constant-Slope Barrier—tracking

Vehicle[1]		Impact Conditions		Failure Type
		Speed (km/h)	Angle (deg.)	
Light Trucks	SUV	100	15	ROLLOVER
	SUV	85	25	ROLLOVER
	SUV	85	20	ROLLOVER
	SUV	85	15	ROLLOVER
	SUV	70	25	ROLLOVER
	SUV	70	20	ROLLOVER
	SUV	70	15	ROLLOVER
	MUV	100	25	R.A. = -20.7g's in Y direction
	MUV	100	15	ROLLOVER
	MUV	85	20	ROLLOVER
	MUV	85	15	ROLLOVER
	SPU	100	20	ROLLOVER
	SPU	100	15	ROLLOVER
	SPU	85	25	ROLLOVER
	SPU	85	20	ROLLOVER
	SPU	85	15	ROLLOVER
	SPU	70	25	ROLLOVER
	SPU	70	20	ROLLOVER
	SPU	70	15	ROLLOVER
	LPU	85	25	ROLLOVER
	PVN	100	25	ROLLOVER
	PVN	100	20	ROLLOVER
	PVN	100	15	ROLLOVER
	PVN	85	20	ROLLOVER
	LVN	100	25	ROLLOVER
	LVN	100	20	ROLLOVER
	LVN	100	15	ROLLOVER
	LVN	85	25	ROLLOVER
	LVN	85	20	ROLLOVER
Automobiles	S1	70	20	ROLLOVER
	S1	70	15	ROLLOVER

[1]See Section 2.2.8 for vehicular descriptions.

TABLE 4 Predicted failure conditions—Constant-Slope Barrier—non-tracking

Vehicle[1]		Impact Conditions			Failure Type
		Speed (km/h)	Vehicle Heading Angle (deg.)	Velocity Vector Angle (deg.)	
Light Trucks	MUV	100	45	25	ROLLOVER
	MUV	100	45	15	ROLLOVER
	LUV	70	45	15	ROLLOVER
	SPU	100	35	25	ROLLOVER
	PVN	100	45	25	O.I.V. = 19.5m/s in X direction
	PVN	100	45	15	O.I.V. = 13.9m/s in X direction
	PVN	70	45	25	O.I.V. = 15.2m/s in X direction
Automobiles	S1	100	45	15	ROLLOVER
	S2	100	45	15	ROLLOVER
	S2	70	45	15	ROLLOVER
	S2	70	35	15	ROLLOVER
	M1	100	45	25	ROLLOVER

[1] See Section 2.2.8 for vehicular descriptions.

4. Only one test of a light truck impacting the Constant-Slope Barrier has been conducted, and that was with an LPU (see Table 28). In a test at approximately 100 km/h and an impact angle of 25 degrees the results met *NCHRP Report 350* requirements. Results similar to those observed in the crash tests were predicted in the simulation study.
5. The only overturns predicted for automobiles in a tracking impact with the Constant-Slope Barrier were for the S1 vehicle at a low speed of 70 km/h.
6. Smaller automobiles tend to be more unstable than larger automobiles in non-tracking impacts with the Constant-Slope Barrier.
7. Tracking crash tests have been conducted with both large and small automobiles impacting the Constant-Slope Barrier, at speeds of approximately 100 km/h and impact angles of 15 degrees, 20 degrees, and 25 degrees (*23*). Results of all tests met recommended performance criteria. Similar results were predicted in the simulation study.

Vertical-Wall Barrier—Simulation results for the Vertical-Wall Barrier suggest the following:

1. Of the three barriers studied, the Vertical-Wall Barrier introduces much less instability to impacting vehicles. In fact, no overturns were predicted for any of the vehicles.

TABLE 5 Predicted failure conditions—Vertical-Wall Barrier—tracking

Vehicle[1]		Impact Conditions		Failure Type
		Speed (km/h)	Angle (deg.)	
Light Trucks	MUV	100	25	R.A. = -23.0g’s in Y direction
	SPU	85	25	R.A. = -20.0g’s on Y direction
	LPU	100	25	R.A. = -21.2g’s in Y direction

[1] See Section 2.2.8 for vehicular descriptions.

TABLE 6 Predicted failure conditions—Vertical-Wall Barrier—non-tracking

Vehicle[1]		Impact Conditions			Failure Type
		Speed (km/h)	Vehicle Heading Angle (deg.)	Velocity Vector Angle (deg.)	
Light Trucks	SUV	100	35	25	R.A. = -22.9g's in Y direction
	LUV	100	45	25	R.A. = -21.4g's in Y direction
	LUV	100	35	25	R.A. = -44.6g's in Y direction
	SPU	100	45	25	O.I.V. = 20.9m/s in X direction
	SPU	100	45	15	O.I.V. = 13.2m/s in X direction
	SPU	100	35	25	R.A. = -22.0g's in Y direction
	SPU	70	45	25	O.I.V. = 14.9m/s in X direction
	LPU	100	45	25	O.I.V. = 20.0m/s in X direction
	LPU	70	45	25	O.I.V. = 13.1m/s in X direction
	LVN	100	45	15	R.A. = -23.0g's in X direction
Automobiles	L2	100	45	25	O.I.V. = 16.6m/s in X direction
	L2	100	45	15	O.I.V. = 12.0m/s in X direction
	L2	70	45	25	O.I.V. = 13.0m/s in X direction

[1] See Section 2.2.8 for vehicular descriptions.

2. Non-tracking impacts with the Vertical-Wall Barrier can result in excessive OIVs and/or RAs, primarily for light trucks.
3. Crash tests of a Vertical-Wall Barrier have been conducted with an LPU at impact conditions of 96.1 km/h at 20.2 degrees, and 102.2 km/h at 25.1 degrees, and the results met *NCHRP Report 350* recommended evaluation criteria (see Table 28). Similar results were predicted in the simulation study.

There were no predicted overturns of the LPU (the 2000P vehicle) with the New Jersey Safety-Shape Barrier, whereas overturns were predicted for the LUV and the LVN for several impact conditions. Also, the LPU was stable for all but one impact condition with the Constant-Slope Barrier, whereas the LVN overturned for several impact conditions. This raises some concern as to the adequacy of the 2000P vehicle as a representative of the larger light truck subclasses, at least for impacts with the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier.

2.2.8.2 Flexible Longitudinal Barriers

Results of simulated impacts with flexible longitudinal barriers for the light trucks and results of simulated impacts with flexible longitudinal barriers for the automobiles were tabulated and are given in Appendix A.

Limits in the scope of the study precluded a determination of the critical impact point (CIP) for each of the 390 simulated impacts with flexible barriers. The CIP for a flexible barrier is the impact location along the barrier deemed to have the greatest potential for causing wheel/vehicular snagging on the barrier for the given impact conditions (mass, speed, and angle of impact of vehicle). Thus, the CIP is the location with the greatest potential for causing the highest vehicular decelerations, and vehicular instability. Determination of the CIP generally requires an iterative process wherein the BARRIER VII program is repeatedly used to converge on the CIP. Since the CIP was not determined, it was decided that in each simulation the barrier impact point would be midway between two support posts. Thus, the values shown for “wheel snag” and “maximum dynamic deflection” may be greater for an impact at the CIP, depending on the location of the CIP in relation to the simulated impact point. The selected impact point will also account for some of the seeming inconsistencies in the results. For example, similar amounts of wheel snag and/or dynamic deflection are observed for two different impact speeds, all other factors being the same. This would indicate that at the lower speed, the impact point was nearer the CIP than at the higher speed.

Tables 7 through 11 summarize key findings from the large volume of data generated in the simulated flexible barrier impacts. It must be remembered that BARRIER VII is a two-dimensional program and thus cannot predict vehicular overturn. Also, BARRIER VII cannot account for wheel-to-post interaction, although the degree of wheel snag on a post can be estimated. Thus the key evaluation parameters provided by the program include occupant risk factors (OIV and occupant RA), wheel snag distance, and barrier deflection. *NCHRP Report 350* recommended limits for the OIV and the RA are 12 m/s and 20 G, respectively. Tables 7 and 8 contain maximum values of these parameters for both light trucks and automobiles, for each of the barriers studied, for two of the more severe impact conditions, namely 100 km/h impacts at 25 degrees and at 20 degrees. Tables 9, 10, and 11 summarize conditions for which the wheel snag distance exceeded the depth of the post for the semi-rigid barrier systems (G42W, G41S, and G9). Wheel snag distances shown in the tables are measured as shown in Figure 23. The post depths are as follows:

System	Post Depth (mm)
G42W	200
G41S	150
G9	150

For example, Table 9 shows that the wheel snag distance for a 100 km/h impact at 25 degrees into a G42W guardrail is 372 mm with the LVN. This means that the back side of the wheel was predicted to be $372 - 200 = 172$ mm behind the back side of the post. Testing has shown those wheel snag distances that exceed the post width often cause undesirable, and in some instances, unacceptable vehicular behavior.

Vehicular parameters influencing wheel snag include front overhang distance, or the distance from the center of the front wheels to the front of the vehicle’s structure, and weight. Shown in Table 12 are the front overhang distance and weight for each of the vehicles simulated. Combinations of short front overhang and large weight contribute to increased snagging. For example, the LVN has a relatively short overhang and large weight, and as can be seen in the summarized tables, is predicted to have high snagging potential.

Note that wheel snagging in weak-post systems (G1 and G3) typically does not cause significant or adverse effects on

TABLE 7 Summary of maximum values for 100 km/h, 25 degree, flexible barrier simulated impacts

Barrier	Vehicle Type	Max. OIV (m/s)	Vehicle	Max. R.A. (G’s)	Vehicle	Max. Wheel Snag (mm)	Vehicle	Max. Dyn. Deflection (m)	Vehicle[1]
G42W	Light Trucks	6.4	SUV	11.0	SPU	372	LVN	0.9	LPU, LVN
	Automobiles	7.5	S1	8.8	M1	274	S2	0.7	M2, L1, L2
G41S	Light Trucks	6.9	SPU	9.3	SPU	404	LVN	0.9	LVN
	Automobiles	7.7	S1, S2	9.5	S1	278	S2	0.7	L1, L2
G9	Light Trucks	6.7	SPU	7.9	SPU	500	LVN	1.2	LPU, LVN
	Automobiles	7.5	S2	9.1	S1	328	M2	0.8	M2, L1, L2
G1	Light Trucks	4.2	SUV, SPU	5.7	SPU	N/A	N/A	2.8	LVN
	Automobiles	4.9	S1	8.2	S1	N/A	N/A	2.1	L2
G3	Light Trucks	4.6	SUV	11.3	SPU	N/A	N/A	1.8	LVN
	Automobiles	5.4	S1	8.0	S1	N/A	N/A	1.4	L2

[1] See Section 2.2.8 for vehicular descriptions.

TABLE 8 Summary of maximum values for 100 km/h, 20 degree, flexible barrier simulated impacts

Barrier	Vehicle Type	Max. OIV (m/s)	Vehicle	Max. R.A. (G's)	Vehicle	Max. Wheel Snag (mm)	Vehicle	Max. Dyn. Deflection (m)	Vehicle[1]
G42W	Light Trucks	5.8	SUV	9.3	SPU	257	LVN	0.7	LUV, LPU, LVN
	Automobiles	7.0	S1	8.3	S1	206	S2	0.6	M2
G41S	Light Trucks	5.8	SUV	9.7	SPU	244	LVN	0.7	LUV, LPU, LVN
	Automobiles	6.8	S1	9.0	L1	258	S2	05	S2, M1, M2, L1, L2
G9	Light Trucks	5.4	SUV, MUV	8.8	SUV	325	LVN	0.8	LPU, LVN
	Automobiles	6.4	S1	9.7	M1	273	S2	0.6	M2, L1, L2
G1	Light Trucks	4.0	SUV, MUV, SPU	5.0	SPU	N/A	N/A	2.0	LVN
	Automobiles	4.6	S1	7.2	S1	N/A	N/A	1.6	L2
G3	Light Trucks	4.4	SUV	11.3	SPU	N/A	N/A	1.3	LVN
	Automobiles	5.4	S1	7.4	S1	N/A	N/A	1.0	L2

[1]See Section 2.2.8 for vehicular descriptions.

vehicular response or occupant risk values. Thus, wheel snag distances for these barriers are not reported.

A review of results of simulated impacts with the flexible barriers studied suggests the following:

1. For the range of impact conditions examined, occupant risk values were not excessive for light trucks or automobiles for any of the five barriers studied. However, occupant risk values can be expected to be higher in actuality for some impact conditions due to the effects of wheel snagging on posts (which is not accounted for in BARRIER VII).

TABLE 9 Summary of conditions where wheel snag exceeded post depth—G42W

Vehicle Type	Impact Conditions		Wheel Snag[1] (mm)	Vehicle[2]
	Speed (km/h)	Angle (deg.)		
Light Trucks	100	25	217	SUV
	100	25	212	SPU
	100	25	219	LPU
	100	25	372	LVN
	100	20	207	LPU
	100	20	257	LVN
	85	25	212	LPU
	85	25	246	LVN
Automobiles	100	25	202	S1
	100	25	274	S2
	100	25	257	M2
	100	20	206	S2

[1] See Figure 14.
[2] See Section 2.2.8 for vehicular descriptions.

2. For given impact conditions, higher occupant risk values are generally associated with the smaller light trucks and automobiles. Differences between the values for the smaller light trucks and automobiles are relatively small.
3. For given impact conditions, larger wheel snag distances and barrier deflections are generally associated with the larger light trucks and automobiles. However, for given impact conditions, larger light trucks produce larger wheel snag distances and barrier deflections than do larger automobiles. This can be attributed to the relatively short overhang distances in combination with the vehicular weight of the larger light trucks.
4. For given impact conditions, more wheel snag will occur in the G41S and the G9 systems than in the G42W system. Note that the blockout depth for the G41S and the G9 systems is 150 mm, whereas it is 200 mm for the G42W system.
5. Several crash tests with light trucks have been conducted on the five barrier systems. Reference should be made to Table 29 for a summary of guardrail crash tests with light trucks. Results of these tests cannot be compared with the BARRIER VII output directly because of the previously discussed limitations of the program. Also, in each of the reported tests the barrier was impacted at the CIP, whereas in BARRIER VII the barrier was impacted midway between two guardrail posts (see further discussion

TABLE 10 Summary of conditions where wheel snag exceeded post depth—G41S

Vehicle Type	Impact Conditions		Wheel Snag[1] (mm)	Vehicle[2]
	Speed (km/h)	Angle (deg.)		
Light Trucks	100	25	234	SUV
	100	25	273	LUV
	100	25	186	SPU
	100	25	372	LPU
	100	25	404	LVN
	100	20	159	SUV
	100	20	166	LUV
	100	20	204	LPU
	100	20	244	LVN
	85	25	179	LUV
	85	25	231	LPU
	85	25	265	LVN
	85	20	154	LPU
	85	20	198	LVN
	70	25	154	LPU
	70	25	197	LVN
Automobiles	100	25	201	S1
	100	25	278	S2
	100	25	181	M1
	100	25	253	M2
	100	25	249	L1
	100	25	230	L2
	100	20	189	S1
	100	20	258	S2
	100	20	226	M2
	100	20	194	L1
	100	20	152	L2
	85	25	227	S2
	85	25	214	M2
	85	25	171	L1
	85	25	163	L2
	85	20	204	S2
	85	20	168	M2

[1] See Figure 14.
[2] See Section 2.2.8 for vehicular descriptions.

of this point in Section 2.2.3). A brief summary of these crash tests and the implied BARRIER VII predictions follows.

TABLE 11 Summary of conditions where wheel snag exceeded post depth—G9

Vehicle Type	Impact Conditions		Wheel Snag[1] (mm)	Vehicle[2]
	Speed (km/h)	Angle (deg.)		
Light Trucks	100	25	266	SUV
	100	25	342	LUV
	100	25	233	SPU
	100	25	458	LPU
	100	25	229	PVN
	100	25	500	LVN
	100	20	180	SUV
	100	20	236	LUV
	100	20	173	SPU
	100	20	288	LPU
	100	20	325	LVN
	85	25	177	SUV
	85	25	224	LUV
	85	25	169	SPU
	85	25	291	LPU
	85	25	357	LVN
	85	20	168	LVN
Automobiles	100	25	247	S1
	100	25	304	S2
	100	25	212	M1
	100	25	328	M2
	100	25	290	L2
	100	25	316	L2
	100	20	217	S1
	100	20	273	S2
	100	20	158	M1
	100	20	269	M2
	100	20	229	L1
	100	20	224	L2
	85	25	207	S1
	85	25	271	S2
	85	25	158	M1
	85	25	225	M2
	85	25	207	L1
	85	25	193	L2
	85	20	165	S2

[1] See Figure 14.
[2] See Section 2.2.8 for vehicular descriptions.

G42W—The following tests were conducted at approximately 100 km/h:

- LPU—Test no. 471470-2 was conducted at an impact angle of approximately 25 degrees. Results met *NCHRP Report 350* recommended evaluation criteria, although there was moderate snagging of the front wheel on a guardrail post. Moderate wheel snagging was predicted by BARRIER VII.
- LVN—Test no. GR-7 was conducted at an impact angle of approximately 20 degrees. Results of this test met *NCHRP Report 230* (*10*) recommended eval-

TABLE 12 Front overhang and mass of simulated vehicles

Vehicle[1]		Front Overhang (mm)	Mass (kg)
Light Trucks	SUV	664	1360
	MUV	787	1395
	LUV	864	2135
	SPU	709	1355
	LPU	686	2080
	PVN	848	1730
	LVN	762	2635
Automobiles	S1	762	815
	S2	787	1010
	M1	1067	1321
	M2	965	1450
	L1	1118	1560
	L2	1067	1830

[1] See Section 2.2.8 for vehicular descriptions.

uation criteria. There was moderate snagging. Moderate snagging was predicted by BARRIER VII.

G41S—Test no. 471470-27 was conducted at approximately 100 km/h at an impact angle of approximately 25 degrees:

- LPU—Major wheel snagging occurred, the vehicle overturned and thus the test failed. Major wheel snag was predicted by BARRIER VII.

Test no. 472480-5 was conducted at approximately 110 km/h at an impact angle of approximately 20 degrees (see Appendix C):

- LPU—Vehicle overturned and test failed. No simulated impacts were conducted at these impact conditions.

The following tests (Tests no. 472480-1, -2, -3, and -4) were conducted at approximately 100 km/h at an impact angle of approximately 20 degrees (see Appendix C of this report):

- SUV—The test results met *NCHRP Report 350* evaluation criteria with no wheel snagging. Minor wheel snag was predicted by BARRIER VII. The front overhang of the test vehicle was 610 mm whereas it was 664 mm in the simulated vehicle. This suggests the vehicular crush stiffness used in the simulated vehicle was too low.
- MUV—The test results met *NCHRP Report 350* evaluation criteria with moderate wheel snagging. No wheel snagging was predicted in BARRIER VII. The front overhang of the vehicle in the test was 730 mm, whereas the front overhang in the simulate vehicle was 787 mm. This will account for some of the differences in the wheel snagging.
- LPU—The test results met *NCHRP Report 350* evaluation criteria, although major wheel snagging occurred. Moderate to major wheel snagging was predicted in BARRIER VII.
- LVN—The test results met *NCHRP Report 350* evaluation criteria, although major wheel snagging occurred. Major wheel snagging was predicted by BARRIER VII.

Modified G41S—Several tests have been conducted with modified versions of the G41S, wherein wood blockouts and larger steel blockouts were used in lieu of the standard steel blockouts (*25*, *26*, *27*). These tests verified what BARRIER VII results implied—that is, stronger and deeper blockouts on the steel posts would reduce the wheel snag problem. Tests with the wood blockouts were successful, but simulations of these configurations with BARRIER VII were not made.

G9—The following tests (471470-31 and GR-15) were conducted at approximately 100 km/h at an impact angle of approximately 25 degrees:

- LPU—Vehicle overturned and test failed. Major wheel snagging occurred. Major wheel snagging was predicted by BARRIER VII.
- LVN—Test results met *NCHRP Report 230* evaluation criteria. Moderate to major wheel snagging occurred. Severe wheel snagging was predicted by BARRIER VII. The front overhang distance for the van in the test was not available, and a comparison with the simulated vehicle's overhang was thus not possible.

Several tests have been conducted with modified versions of the G9, wherein wood blockouts and larger steel blockouts were used in lieu of steel blockouts, and wood posts were used in lieu of steel posts (*28*, *2*9). These tests verified what BARRIER VII results implied—that is, that stronger and deeper blockouts on the steel posts would reduce the wheel snag problem. However, simulations of these configurations with BARRIER VII were not made.

G1—The following tests (471470-28 and GR-17) were conducted at approximately 100 km/h at an impact angle of approximately 25 degrees:

- LPU—The test results met *NCHRP Report 350* evaluation criteria. BARRIER VII predicted acceptable results.

- LVN—The test results met *NCHRP Report 230* evaluation criteria. BARRIER VII predicted acceptable results.

G3—The following tests (471470-33 and GR-11) were conducted at approximately 100 km/h:

- LPU—This test was conducted at an impact angle of approximately 25 degrees. Test results met *NCHRP Report 350* evaluation criteria. BARRIER VII predicted acceptable results.
- LVN—This test was conducted at an impact angle of approximately 20 degrees. Results met *NCHRP Report 230* evaluation criteria. BARRIER VII predicted acceptable results.

6. Crash tests were conducted on four of the five barrier systems with automobiles (*24*). These tests were conducted in accordance with *NCHRP Report 230* recommendations. Results of these tests cannot be compared with the BARRIER VII output directly because of the above-mentioned limitations of the program. A brief summary of the relevant crash tests and the implied BARRIER VII predictions follows. Note that each test involved a small automobile (820 kg) (S1), impacting at approximately 100 km/h at an impact angle of approximately 20 degrees:

G42W—The test results met *NCHRP Report 230* evaluation criteria. Moderate snagging occurred. Moderate snagging was predicted by BARRIER VII.

G41S—No test.

G9—The test results met *NCHRP Report 230* evaluation criteria. Minor wheel snagging occurred. Moderate snagging was predicted by BARRIER VII.

G1—The test results met *NCHRP Report 230* evaluation criteria. BARRIER VII predicted acceptable results.

G3—The test results met *NCHRP Report 230* evaluation criteria. BARRIER VII predicted acceptable results.

In comparing the predicted performance of the LPU (2000P vehicle) with the other light truck subclasses, it can be seen that the LPU caused barrier loading (as measured by barrier deflection) similar to that of the other large light truck subclasses, the LUV and the LVN. The LVN generally had greater values of wheel snag than the other subclasses. This was expected since the LVN had a considerably higher mass than the other subclasses. A key factor in evaluating barrier performance is vehicular stability subsequent to impact. The two-dimensional limitations of BARRIER VII precluded a determination of this factor in the simulation study. Therefore, results of the flexible barrier simulations and comparisons that could be made offer inconclusive evidence regarding the adequacy of the 2000P vehicle as a good representative light truck.

2.2.8.3 Roadside Geometric Features

Results of simulated encroachments on roadside geometric features were tabulated and are given in Appendix A. Note that the encroachment speed for all fill-section simulations was 100 km/h. Also note that the tire-terrain coefficient of friction for all the driveway runs was 0.5. Since all simulated encroachments on the driveway configurations were in the tracking mode (no steer or breaking input), the tire-terrain coefficient of friction is not a major influencing factor on the results.

Tables 13 through 17 were prepared in an attempt to summarize key findings of the large volume of data generated from the simulated encroachments on geometric features. Tables 13 and 14 relate to the simulated encroachments on embankments or fill sections. There were no predicted overturns for the light trucks or the automobiles in any of the simulated encroachments on fill sections, although there were a number of predicted instances of sideslipping (see definition of sideslip in Section 2.2.7). Tables 13 and 14 present the predicted maximum extent of lateral movement of light trucks and automobiles, respectively, for each parametric combination studied. For example, for a friction coefficient of 0.5, a foreslope of 4:1, and a ditch depth of 3 m, the PVN showed the maximum lateral movement for all light trucks at 16.1, and the L1, the smaller of the two large automobile categories, showed the maximum lateral movement for all automobiles at 14.7 m. Recall that in each run, a panic return-to-the-travelway steer input was made 1 s after the vehicle left the edge of the travelway.

A review of the results of simulated encroachments on fill sections suggests the following:

1. All light truck and automobile subclasses were stable (i.e., there were no overturns) for all encroachment and geometric parameters evaluated. Tire-terrain friction coefficients of 0.3 and 0.5 were assumed. These are believed to be representative of well-compacted terrain. A cornering vehicle will be more prone to overturn on saturated terrain subject to rutting or on terrain with irregularities or appurtenances such as eroded areas, and vegetation such as small trees, or shrubs. However, the HVOSM does not have the capability to simulate tire rutting and its effect on vehicular stability.

   Assumed encroachment conditions and driver response parameters were chosen in an attempt to replicate typical real-world occurrences, but are not necessarily the most critical scenarios. For example, for any of the selected roadside geometric conditions, a lower

TABLE 13 Predicted maximum lateral vehicle movement for fill sections—light truck

Friction Coefficient	Fill Slope Parameters[1]		Maximum Conditions	
	Foreslope S1:1	Depth H (m)	Vehicle Type[2]	Lateral Movement d_2[3] (m)
0.3	6:1	1.5	PVN	16.9
	4:1	1.5	LVN	18.0
	3:1	1.5	PVN	16.7
	6:1	3.0	SUV, LVN	21.9
	4:1	3.0	LVN	22.6
	3:1	3.0	SUV	22.8
	6:1	6.1	SPU	28.1
	4:1	6.1	PVN	30.8
	3:1	6.1	PVN	32.6
0.5	6:1	1.5	PVN	12.6
	4:1	1.5	LVN	14.2
	3:1	1.5	LVN	12.9
	6:1	3.0	PVN, LVN	14.1
	4:1	3.0	PVN	16.1
	3:1	3.0	PVN	17.8
	6:1	6.1	PVN, LVN	14.1
	4:1	6.1	LVN	19.0
	3:1	6.1	PVN	23.3

[1] See Figure 9.
[2] See Section 2.2.8 for vehicular descriptions.
[3] See Figure 12.

speed and/or lower encroachment angle may produce a more unstable situation for the vehicle.

2. For a given set of encroachment and geometric parameters, the maximum extent of lateral movement for light trucks is slightly greater than for automobiles.
3. For a given fill-section depth, the extent of lateral movement of the light truck and automobile subclasses is not necessarily proportional to the steepness of the foreslope. For example, for a friction coefficient of 0.3 and a ditch depth of 1.5 m, the maximum lateral movement is as follows:

Foreslope	Maximum Lateral Movement (m)	
	Light Trucks	Automobiles
6 : 1	16.9	16.4
4 : 1	18.0	16.3
3 : 1	16.7	16.9

These seemingly inconsistent results are due primarily to the lateral extent of the foreslope on which the vehicle is traversing, and to a lesser extent on vehicle type and encroachment conditions. For the 1.5 m depth, the lateral dimension is 9 m for the 6 : 1 slope, 6 m for the 4 : 1 slope, and 4.5 m for the 3 : 1 slope. Thus, the vehicle remains on the flatter slope for a longer period than on the steeper slope. Once the vehicle gets on the flat ditch bottom, greater steering can be achieved. Therefore, depending on the combination of parameters being investigated, the vehicle may be able to achieve overall greater steering on the steeper slope.

4. For light trucks, the PVN and the LVN generally had higher lateral movements than the other subclasses.
5. For automobiles, the smaller of the small automobile categories, S1, and the smaller of the large automobile categories, L1, generally had higher lateral movements than the other subclasses.

Tables 15, 16, and 17 present failure conditions predicted for the driveway simulations. Vehicular overturn was the only failure criterion selected. Although high resultant accelera-

TABLE 14 Predicted maximum lateral vehicle movement for fill sections—automobiles

Friction Coefficient	Fill Slope Parameters[1]		Maximum Conditions	
	Foreslope S1:1	Depth H (m)	Vehicle Type[2]	Lateral Movement d_2[3] (m)
0.3	6:1	1.5	L1	16.4
	4:1	1.5	L1	16.3
	3:1	1.5	S1	16.9
	6:1	3.0	S1	21.7
	4:1	3.0	S1	20.8
	3:1	3.0	S1, S2	21.7
	6:1	6.1	S1	25.0
	4:1	6.1	S1	30.5
	3:1	6.1	S1	30.8
0.5	6:1	1.5	L1	11.4
	4:1	1.5	L1	12.4
	3:1	1.5	S1	12.3
	6:1	3.0	S1	12.8
	4:1	3.0	L1	14.7
	3:1	3.0	S2	15.2
	6:1	6.1	S1	12.8
	4:1	6.1	S1	18.4
	3:1	6.1	L1, L2	21.2

[1] See Figure 9.
[2] See Section 2.2.8 for vehicular descriptions.
[3] See Figure 12.

tions were indicated in some of the simulated encroachments, there is no widely accepted failure criterion for vehicular accelerations during relatively "long period" events, as occur in a roadside encroachment. These high accelerations occur once the vehicle has become airborne and returns to the ground.

Recall that the two encroachment paths simulated are illustrated in Figure 13. Note that in Path 1, both rolling and pitching motions are induced as the vehicle crosses the transition between the sideslope and the driveway slope, whereas in Path 2 only pitching motion is induced.

Tables 15 and 16 are for the light truck subclasses encroaching at 80 km/h and 100 km/h, respectively, and Table 17 is for the automobile subclasses encroaching at 100 km/h (80 km/h encroachments by automobiles were not simulated). A review of these results suggest the following for driveway features:

1. Light trucks have a greater propensity to overturn than do automobiles.
2. Light trucks are unstable at speeds of 80 km/h and 100 km/h, but with increased instability at the higher speed.
3. At 80 km/h, the smaller light truck subclasses (SUV, MUV, SPU, PVN) have a greater propensity to overturn than do the larger light truck subclasses (LUV, LPU, and LVN).
4. At 100 km/h, all of the light truck subclasses have a high overturn propensity.
5. At 100 km/h, most of the automobile subclasses have a high overturn propensity. Subclasses M1 and M2 have slightly lower propensities to overturn than do the other subclasses.
6. Results suggest that ditch and driveway slopes of 10 : 1, or perhaps even flatter, are needed to minimize overturn potential for light trucks and automobiles encroaching at 100 km/h on driveway sections.

Specific tests of the above features have not been conducted. However, the HVOSM program has compared favorably with limited tests of roadside geometric features (*18, 30*).

TABLE 15 Predicted failure conditions for driveways—light truck—80 km/h

Vehicle[1]	Driveway Parameters[2]		Encroachment Path[3]	Failure Type
	Foreslope S2:1	Driveway Slope S1:1		
SUV	10:1	6:1	1	ROLLOVER
SUV	8:1	10:1	1	ROLLOVER
SUV	8:1	6:1	1	ROLLOVER
SUV	6:1	10:1	1	ROLLOVER
SUV	6:1	8:1	1	ROLLOVER
SUV	6:1	6:1	1	ROLLOVER
MUV	10:1	10:1	1	ROLLOVER
MUV	10:1	8:1	1	ROLLOVER
MUV	10:1	6:1	1	ROLLOVER
MUV	8:1	10:1	1	ROLLOVER
MUV	8:1	8:1	1	ROLLOVER
MUV	8:1	6:1	1	ROLLOVER
MUV	6:1	10:1	1	ROLLOVER
MUV	6:1	8:1	1	ROLLOVER
MUV	6:1	6:1	1	ROLLOVER
MUV	N/A	8:1	2	PITCHOVER
LUV	10:1	8:1	1	ROLLOVER
LUV	8:1	6:1	1	ROLLOVER
LUV	6:1	8:1	1	ROLLOVER
LUV	6:1	6:1	1	ROLLOVER
SPU	10:1	8:1	1	ROLLOVER
SPU	10:1	6:1	1	ROLLOVER
SPU	8:1	10:1	1	ROLLOVER
SPU	8:1	8:1	1	ROLLOVER
SPU	8:1	6:1	1	ROLLOVER
SPU	6:1	8:1	1	ROLLOVER
SPU	6:1	6:1	1	ROLLOVER
LPU	10:1	8:1	1	ROLLOVER
LPU	8:1	10:1	1	ROLLOVER
LPU	8:1	6:1	1	ROLLOVER
LPU	6:1	10:1	1	ROLLOVER
LPU	6:1	8:1	1	ROLLOVER
PVN	10:1	10:1	1	ROLLOVER
PVN	10:1	8:1	1	ROLLOVER
PVN	10:1	6:1	1	ROLLOVER
PVN	8:1	10:1	1	ROLLOVER
PVN	8:1	6:1	1	ROLLOVER
PVN	6:1	10:1	1	ROLLOVER
PVN	6:1	8:1	1	ROLLOVER
PVN	6:1	6:1	1	ROLLOVER
LVN	10:1	10:1	1	ROLLOVER
LVN	10:1	6:1	1	ROLLOVER
LVN	6:1	8:1	1	ROLLOVER
LVN	6:1	6:1	1	ROLLOVER

[1] See Section 2.2.8 for vehicular descriptions.
[2] See Figure 10.
[3] See Figure 13.

TABLE 16 Predicted failure conditions for driveways—light truck—100 km/h

Vehicle[1]	Driveway Parameters[2]		Encroachment Path[3]	Failure Type
	Foreslope S2:1	Driveway Slope S1:1		
SUV	10:1	10:1	1	ROLLOVER
SUV	10:1	8:1	1	ROLLOVER
SUV	10:1	6:1	1	ROLLOVER
SUV	8:1	10:1	1	ROLLOVER
SUV	8:1	8:1	1	ROLLOVER
SUV	8:1	6:1	1	ROLLOVER
SUV	6:1	10:1	1	ROLLOVER
SUV	6:1	8:1	1	ROLLOVER
SUV	6:1	6:1	1	ROLLOVER
MUV	10:1	10:1	1	ROLLOVER
MUV	10:1	8:1	1	ROLLOVER
MUV	10:1	6:1	1	ROLLOVER
MUV	8:1	10:1	1	ROLLOVER
MUV	8:1	8:1	1	ROLLOVER
MUV	8:1	6:1	1	ROLLOVER
MUV	6:1	10:1	1	ROLLOVER
MUV	6:1	8:1	1	ROLLOVER
MUV	6:1	6:1	1	ROLLOVER
MUV	N/A	8:1	2	ROLLOVER
LUV	10:1	10:1	1	ROLLOVER
LUV	10:1	8:1	1	ROLLOVER
LUV	10:1	6:1	1	ROLLOVER
LUV	8:1	10:1	1	ROLLOVER
LUV	8:1	8:1	1	ROLLOVER
LUV	8:1	6:1	1	ROLLOVER
LUV	6:1	10:1	1	ROLLOVER
LUV	6:1	8:1	1	ROLLOVER
LUV	6:1	6:1	1	ROLLOVER
SPU	10:1	10:1	1	ROLLOVER
SPU	10:1	8:1	1	ROLLOVER
SPU	10:1	6:1	1	ROLLOVER
SPU	8:1	10:1	1	ROLLOVER
SPU	8:1	8:1	1	ROLLOVER
SPU	8:1	6:1	1	ROLLOVER
SPU	6:1	10:1	1	ROLLOVER
SPU	6:1	8:1	1	ROLLOVER
SPU	6:1	6:1	1	ROLLOVER
LPU	10:1	6:1	1	ROLLOVER
LPU	8:1	8:1	1	ROLLOVER
LPU	8:1	6:1	1	ROLLOVER

TABLE 16 (*Continued)*

Vehicle[1]	Driveway Parameters[2]		Encroachment Path[3]	Failure Type
	Foreslope S2:1	Driveway Slope S1:1		
LPU	6:1	10:1	1	ROLLOVER
LPU	6:1	8:1	1	ROLLOVER
PVN	10:1	10:1	1	ROLLOVER
PVN	10:1	8:1	1	ROLLOVER
PVN	10:1	6:1	1	ROLLOVER
PVN	8:1	10:1	1	ROLLOVER
PVN	8:1	8:1	1	ROLLOVER
PVN	8:1	6:1	1	ROLLOVER
PVN	6:1	10:1	1	ROLLOVER
PVN	6:1	8:1	1	ROLLOVER
PVN	6:1	6:1	1	ROLLOVER
LVN	10:1	8:1	1	ROLLOVER
LVN	10:1	6:1	1	ROLLOVER
LVN	8:1	10:1	1	ROLLOVER
LVN	8:1	8:1	1	ROLLOVER
LVN	8:1	6:1	1	ROLLOVER
LVN	6:1	10:1	1	ROLLOVER
LVN	6:1	8:1	1	ROLLOVER
LVN	6:1	6:1	1	ROLLOVER

[1] See Section 2.2.8 for vehicular descriptions.
[2] See Figure 10.
[3] See Figure 13.

Results obtained in the study of actual crashes, as reported in Section 2.3 and Appendix B, show that light trucks are more likely to overturn than automobiles for encroachments involving roadside features, especially ditches and embankments. It is conjectured that many of these involve driveway-type features. As such, the simulation results are corroborated by the crash study. Also, the crash study results show that the sport utility vehicles have higher overturn rates than do the pickups and vans. To some extent, this corroborates simulation results of the roadside geometric features study for driveways.

In comparing the predicted performance of the LPU (2000P vehicle) with the other light truck subclasses for fill sections, it can be seen that the other subclasses required slightly more lateral distance for recovery than did the LPU. In comparing the predicted performance of the LPU with the other subclasses for driveway sections, it can be seen that the smaller subclasses generally had higher overturn rates than did the larger subclasses, including the LPU. In comparing the predicted performance of the LPU with the other large subclasses, it can be seen that the overturn rates were similar. Thus, the results of simulated encroachments on geometric features and these comparisons suggest that the 2000P is a reasonably good representative of the larger light truck subclasses.

2.3 CRASH DATA STUDY

2.3.1 Objective

The objective of the crash data study was to evaluate the safety performance of roadside features for various light truck and automobile subclasses using available crash databases.

The study approach consisted of evaluating the frequency, severity, and rollover involvement of single-vehicle, ran-off-road type crashes for light truck and automobile subclasses. The crash databases used in the study included: FARS, NASS GES, and HSIS. All these databases contain police-level or enhanced police-level crash data. Details of the analyses and results are presented in Appendix B. A summary and highlights of the analysis are provided in the following sections.

2.3.2 Analysis of FARS Data

Five years of FARS data, 1991–1995, were analyzed. The data were first screened for single-vehicle crashes involving late-model (1990–1996) automobiles and light trucks striking roadside objects and appurtenances. Since only fatal crashes were included in this database, evaluation of the impact performance was limited to crash frequency and

TABLE 17 Predicted failure conditions for driveways—automobiles—100 km/h

Vehicle[1]	Driveway Parameters[2]		Encroachment Path[3]	Failure Type
	Foreslope S2:1	Driveway Slope S1:1		
S1	10:1	10:1	1	PITCHOVER
S1	10:1	8:1	1	ROLLOVER
S1	10:1	6:1	1	ROLLOVER
S1	8:1	6:1	1	ROLLOVER
S1	6:1	10:1	1	ROLLOVER
S1	6:1	8:1	1	ROLLOVER
S1	6:1	6:1	1	ROLLOVER
S1	N/A	6:1	2	PITCHOVER
S2	10:1	6:1	1	ROLLOVER
S2	8:1	8:1	1	ROLLOVER
S2	8:1	6:1	1	ROLLOVER
S2	6:1	10:1	1	ROLLOVER
S2	6:1	8:1	1	ROLLOVER
S2	6:1	6:1	1	ROLLOVER
S2	N/A	8:1	2	PITCHOVER
M1	10:1	6:1	1	ROLLOVER
M1	8:1	6:1	1	ROLLOVER
M1	6:1	6:1	1	ROLLOVER
M1	N/A	10:1	2	PITCHOVER
M1	N/A	8:1	2	PITCHOVER
M2	10:1	10:1	1	ROLLOVER
M2	8:1	6:1	1	ROLLOVER
M2	6:1	10:1	1	ROLLOVER
M2	6:1	8:1	1	ROLLOVER
M2	6:1	6:1	1	ROLLOVER
L1	10:1	6:1	1	ROLLOVER
L1	8:1	10:1	1	ROLLOVER
L1	8:1	8:1	1	ROLLOVER
L1	8:1	6:1	1	ROLLOVER
L1	6:1	10:1	1	ROLLOVER
L1	6:1	8:1	1	ROLLOVER
L1	6:1	6:1	1	ROLLOVER
L1	N/A	10:1	2	ROLLOVER
L2	10:1	10:1	1	ROLLOVER
L2	10:1	6:1	1	ROLLOVER
L2	8:1	8:1	1	ROLLOVER
L2	8:1	6:1	1	ROLLOVER
L2	6:1	10:1	1	ROLLOVER
L2	6:1	8:1	1	ROLLOVER
L2	N/A	6:1	2	PITCHOVER

[1] See Section 2.2.8 for vehicular descriptions.
[2] See Figure 10.
[3] See Figure 13.

rollover involvement. Also, the FARS light truck categorization scheme differed slightly from that defined above. Specifically, the subclass of "compact utility vehicle" as used in FARS includes both small and midsize sport utility vehicles.

2.3.2.1 Crash Frequency

There were a total of 6,671 fatal, single-vehicle crashes involving late-model automobiles or light trucks striking roadside objects and appurtenances for the 5-year period. As shown in Table 18, automobiles as a group were significantly overrepresented in fatal crashes in relation to their market share (61.5 percent of sales versus 67.1 percent of fatal crashes) while light trucks were underrepresented. The 1993 new vehicle sales figures were used to approximate the distribution or market share of late-model (1990–1996) automobiles and light trucks during the years 1991–1995, which was believed to be a reasonable estimate. The year 1993 was the midpoint for the period of interest. Also, the vehicle population was limited to late-model vehicles so that the attrition rate was low enough not to be of concern.

For automobile platforms, the data indicate that the two small automobile platforms (S1 and S2) were significantly overrepresented in fatal crashes by ratios of over 1.5 to 1. The M1 platform was slightly overrepresented, but the difference was not statistically significant. The three larger automobile platforms were underrepresented in fatal crashes when compared to their market shares.

For light trucks, the minivan and large van subclasses were significantly underrepresented (3.3 percent of fatal crashes versus 8.2 percent of market share for minivans, and 1.2 percent of fatal crashes versus 2.9 percent of market share for large vans). The utility vehicle subclasses were also underrepresented, though to a lesser degree. On the other hand, the pickup truck subclasses were significantly overrepresented, particularly for the compact pickup truck subclass (11.3 percent of fatal crashes versus 7.7 percent of market share).

2.3.2.2 Rollover Involvement

Light trucks experienced higher rollover rates than automobiles (60.7 percent versus 47.1 percent) in fatal crashes, as shown in Table 19. Among the various automobile platforms, the rollover rates for the two small automobiles and the two midsize automobile platforms were essentially the same, while the two large automobile platforms had significantly

TABLE 18 Frequency and percent rollover of fatal, single-vehicle crashes by vehicle platform/subclass—FARS data

Vehicle Type	Platform/ Subclass	Crash Frequency		% by Sales*	Rollover Frequency	
		N	% Crashes		N	% Rollover
Automobile	Small I	354	5.3	2.8	170	48.0
	Small II	1,320	19.8	11.3	621	47.0
	Midsize I	1,593	23.9	21.3	778	48.8
	Midsize II	695	10.4	14.6	340	48.9
	Large I	331	5.0	7.8	134	40.5
	Large II	166	2.5	3.8	57	34.3
	Subtotal**	4,473	67.1	61.5	2,100	47.1
Light Truck	Compact Utility	381	5.7	8.7	244	64.0
	Large Utility	56	0.8	1.3	44	78.6
	Minivan	218	3.3	8.2	135	61.9
	Large Van	79	1.2	2.9	40	50.6
	Compact Pickup	755	11.3	7.7	449	59.5
	Standard Pickup	709	10.6	9.7	422	59.5
	Subtotal	2,198	32.9	38.5	1,334	60.7
Total		6,671	100.0	100.0	3,434	51.6

Notes. * Based on 1993 sales figures.
** Includes 14 crashes with unknown platform.

TABLE 19 Percent rollover by vehicle type and object struck—FARS data

Object Struck	Automobile		Light Trucks		Combined	
	N	% Rollover	N	% Rollover	N	% Rollover
Bridge Rail	88	37.5	55	60.0	143	46.2
Concrete Barrier	123	36.6	49	55.1	172	41.9
Guardrail	665	50.5	387	66.1	1,052	56.3
Culvert	358	56.7	198	67.2	556	60.4
Ditches	481	69.9	299	68.6	780	69.4
Embankment	703	70.6	420	68.8	1,123	69.9
Curb	446	41.7	121	53.7	567	44.3
Sign	229	51.1	146	57.5	375	53.6
Utility Pole	882	22.0	259	37.1	1,142	25.4
Bridge Pier/Abutment	115	13.0	52	21.2	167	15.6
Total	4,090	47.1	1,986	60.7	6,077	51.6

lower rollover rates. For the light truck subclasses, LUVs had the highest rollover rate (78.6 percent) followed by compact utility vehicles (64.0 percent). It was somewhat surprising that minivans have the next highest rollover rate (61.9 percent), which was slightly above that for both compact and standard pickup trucks. Large vans had the lowest rollover rate among the light truck subclasses at 50.6 percent.

Rollover rates categorized by vehicle type and roadside object struck are shown in Table 19. Fatal crashes involving ditches and embankments had the highest rollover rates among the various struck objects (69.4 percent for ditches and 69.9 percent for embankments), followed by culverts (60.4 percent). This was to be expected given the steep sideslopes typically associated with these features. On the other hand, impacts with rigid point fixed objects had the lowest rollover rates (e.g., 15.6 percent for bridge piers/abutments and 25.4 percent for utility poles). The lower incidence of rollover in fatal crashes involving rigid objects may be attributed to the likelihood that a large portion of the impact energy was dissipated in the impact with the rigid object. The rollover rates for impacts with non-rigid or low-profile fixed objects, such as sign supports and curbs, were considerably higher. In collisions with these objects, very little energy would be dissipated and, consequently, the vehicle would still be traveling at essentially the same speed after separating from the struck object. This lack of speed reduction, combined with the fact that the vehicle would be somewhat destabilized from the impact with the object, could lead to a higher propensity of rollover. As shown in Table 19, nearly half of all fatal crashes involving longitudinal barriers resulted in rollovers. Guardrails have the highest rollover rate (56.3 percent), followed by bridge rails (46.2 percent) and concrete barriers (41.9 percent). It should be noted, however, that impacts with guardrail terminals were not distinguished from impacts with the guardrail length-of-need. The higher incidence of rollover in impacts with guardrails could be partially attributed to impacts with guardrail terminals, which tend to be more severe and may constitute up to one-third of all guardrail impacts.

The percentages of rollovers associated with ditches and embankments were similar for automobiles and light trucks (70.3 percent versus 68.7 percent). Light trucks are more likely to roll over than automobiles in fatal crashes involving utility poles, longitudinal barriers (i.e., guardrails, bridge rails, and concrete barriers), culverts, curbs, and to a lesser extent, signs and bridge piers/abutments.

2.3.3 Analysis of NASS GES Data

Data from NASS GES were analyzed for the years 1992–1995. Again, the data were screened for single-vehicle crashes involving late-model automobiles or light trucks (1990–1996) striking roadside objects and appurtenances. Evaluation of the impact performance included analysis of the crash frequency, crash severity, and the occurrence of rollover.

The NASS GES database does not contain any weight or measurement variable (e.g., wheelbase) on the vehicle. Thus, it was not possible to categorize the automobiles into generic platforms as in the case of the FARS database. The light truck subclasses follow the categorization scheme used in NASS GES coding. The subclass of “compact utility vehicle” as used in NASS GES includes both SUVs and MUVs.

2.3.3.1 Crash Frequency

There were a total of 6,188 single-vehicle crashes involving late-model automobiles or light trucks striking roadside objects and appurtenances in the NASS GES database for the 4-year analysis period. Since the GES used a stratified random sampling scheme to select the crashes for inclusion in the database and the sampling scheme was biased toward more severe crashes, it was necessary to weight the crash frequencies in the analysis. The weighted crash frequency totaled 685,764. Both unweighted and weighted frequencies are presented in Table 20. However, the percentages given in this report were calculated based on the weighted frequencies.

As shown in Table 20, automobiles were overrepresented in crashes (74.3 percent) in relation to their market share (61.5 percent) while light trucks were underrepresented. Within the light truck subclasses, the minivan and large van were significantly underrepresented in crashes. The sport utility vehicle and pickup truck subclasses were also underrepresented, but only slightly. Again, 1993 new vehicle sales figures were used to approximate the distribution or market share of late-model (1990–1996) automobiles and light trucks during the years of 1992 to 1995, which was believed to be a reasonable estimate.

It should be noted that, among utility vehicles or pickup trucks, a significant percentage were of unknown size. For example, pickup trucks of unknown size accounted for 6.1 percent of the crashes compared with 7.2 percent for compact pickup trucks and 3.6 percent for standard pickup trucks. Given the large number of vehicles of unknown size, it was not appropriate in most instances to further break down the comparisons by size within the utility vehicle and pickup truck subclasses.

2.3.3.2 Rollover Involvement

As shown in Table 20, light trucks were more likely to roll over than automobiles (18.2 percent versus 10.2 percent). For light truck subclasses, pickup trucks have a slightly lower than average rollover rate of 17.4 percent. Sport utility vehicles had the highest overall rollover rate (22.8 percent), with compact sport utility vehicles having a slightly higher rollover rate than their larger counterparts.

Table 21 shows the rollover rate by object struck. When all vehicle types were considered, embankments had the highest rollover rate (29.8 percent), followed by culverts/ditches (26 percent). Rollover did not appear to be a problem in crashes involving impact attenuators, although the sample size was extremely small. Bridge structures (4.0 percent) and posts, poles, and supports (4.6 percent) also had low rollover rates, while the rollover rates for longitudinal barriers were slightly higher (6.2 percent for guardrails and 7.1 percent for concrete and other longitudinal barriers).

Light trucks were more likely to roll over than automobiles in impacts with all the roadside features listed in Table 21. The difference was particularly pronounced for curbs and guardrails. The light truck rollover rates for these features were 3.1 and 2.4 times higher than for automobiles, respectively.

2.3.3.3 Injury Severity

Table 21 also shows the percent total injury (i.e., all injury levels) and percent incapacitating and fatal injury (A+K as

TABLE 20 Frequency and percent rollover of single-vehicle crashes by vehicle platform/subclass—NASS GES data

Light Truck Subclass		Total Crashes			% by Sales*	Rollover Crashes		
		Unweighted	Weighted	% of Crashes		Unweighted	Weighted	% Rollover
Automobile		4,609	509,560	74.3	61.5	543	52,146	10.2
Utility Vehicle	Compact	245	25,961	3.8	8.7	66	6,189	23.8
	Large	46	4,659	0.7	1.3	10	892	19.1
	Unknown	75	9,017	1.3	N/A	23	1,965	21.8
	Subtotal	366	39,637	5.8	10.0	99	9,046	22.8
Minivan		154	16,917	2.5	8.2	26	2,362	14.0
Large Van		32	3,927	0.6	2.9	5	430	10.9
Pickup Truck	Compact	446	49,378	7.2	7.7	106	10,267	20.8
	Standard	222	24,679	3.6	9.7	40	3,766	15.3
	Unknown	359	41,666	6.1	N/A	62	6,128	14.7
	Subtotal	1,027	115,723	16.9	17.4	208	20,161	17.4
Combined Light Trucks		1,579	176,204	25.7	38.5	338	31,999	18.2
Total		6,188	685,764	100.0	100.0	881	84,145	12.3

Notes. * Based on 1993 sales figures.
N/A = Not applicable.

TABLE 21 Percent rollover and injury by vehicle type and object struck—NASS GES data

Object Struck	Automobiles			Light Trucks			Combined		
	% Rollover	% Total Injury	% (A+K) Injury	% Rollover	% Total Injury	% (A+K) Injury	% Rollover	% Total Injury	% (A+K) Injury
Impact Attenuator	0.0	23.1	4.6	0.0	38.0	0.0	0.0	24.7	4.1
Bridge Structure	3.8	40.4	6.9	4.3	37.8	3.3	4.0	39.6	5.9
Guardrail	4.7	31.5	5.3	11.2	39.1	11.4	6.2	33.3	6.7
Concrete/Other Barrier	6.5	41.3	4.3	10.2	44.4	3.8	7.1	41.8	4.2
Post, Pole or Support	4.0	42.3	6.5	6.0	33.8	5.8	4.6	39.8	6.3
Curb	6.3	28.4	4.3	19.8	38.7	6.8	8.9	30.3	4.7
Culvert or Ditch	23.2	39.4	9.9	32.8	45.2	12.0	26.0	41.1	10.5
Embankment	24.2	50.5	10.8	44.3	44.8	14.8	29.8	49.0	11.9
Total	10.2	38.6	6.9	18.2	39.4	8.9	12.3	38.8	7.4

classified by the Police Injury Code) by vehicle type and object struck. Embankments had the highest total (49.0 percent) and (A+K) injury (11.9 percent) rates, followed closely by culverts and ditches (41.1 percent total injury and 10.5 percent [A+K] injury). Guardrails had a lower total injury rate than concrete and other barriers (33.3 percent versus 41.8 percent), but a higher (A+K) injury rate (6.7 percent versus 4.2 percent). Impact attenuators had the lowest total and (A+K) injury rates at 24.7 percent and 4.1 percent, respectively. Since under-reporting was common for impact attenuators, the actual injury rates should be even lower. However, the sample size used in the current analysis was very small. Impacts with curbs also resulted in relatively low injury rates (30.3 percent overall injury and 4.7 percent [A+K] injury).

Automobiles had a higher percent injury and percent (A+K) injury than light trucks in crashes with bridge structures and posts, poles, and supports. For impacts with guardrails, light trucks had only a slightly higher overall percent injury than automobiles (39.1 percent versus 31.5 percent), but a significantly higher (A+K) injury rate (11.2 percent versus 5.3 percent). For impacts with concrete and other longitudinal barriers, the injury rates were similar between automobiles and light trucks. For impacts with curbs and culverts/ditches, light trucks had higher injury rates than automobiles. For impacts with embankments, light trucks had a slightly lower overall injury rate than automobiles (44.8 percent versus 50.5 percent), but significantly higher (A+K) injury rate (40.8 percent versus 24.2 percent).

2.3.4 Analysis of HSIS Data

The analysis included the latest available 5 years of crash data from four HSIS states: Illinois (1988–1990, and 1992); Michigan (1987–1991); North Carolina (1990–1994); and Utah (1990–1994). Note that only 4 years of crash data were used for Illinois due to problems with the 1991 data. These four states were selected because they have the necessary information on wheelbase (through decoding of the vehicle identification number) to categorize automobiles into generic platforms.

The data were first screened for single-vehicle crashes involving 1988 or later model automobiles and light trucks striking roadside objects and appurtenances. Evaluation of the impact performance included analysis of crash frequency, crash severity, and occurrence of rollover. The light truck subclasses follow the categorization scheme used in HSIS coding, which includes pickup trucks, sport utility vehicles, vans, and passenger vans. This coding scheme precluded any further breakdown of the pickup truck and sport/utility vehicle subclasses by size.

2.3.4.1 Crash Frequency

As shown in Table 22, there were a total of 58,020 single-vehicle, ran-off-road crashes involving 1988 or later model automobiles and light trucks striking roadside objects and appurtenances in the four HSIS states for the period studied (which varies from state to state). The breakdown of the crashes by state was as follows: 9,927 crashes for Illinois, 17,910 crashes for Michigan, 23,476 crashes for North Carolina, and 6,707 crashes for Utah.

Overall, automobiles were overrepresented in crashes (67.3 percent) in relation to their market share (61.5 percent) while light trucks were underrepresented with the exception of Utah. In Utah, automobiles were slightly underrepresented in crashes relative to market share (57.3 percent versus 61.5 percent) and light trucks slightly overrepresented. It should be pointed out that the market shares of automobiles and light trucks in each of these four states may be significantly different from the national sales figures, which would affect the comparisons.

TABLE 22 Frequency of single-vehicle crashes by vehicle platform/subclass—HSIS data

Vehicle Type	Platform/ Subclass	% by Sales*	Illinois		Michigan		North Carolina		Utah		Total	
			No.	%	No.	%	No.	%	No.	%	No.	%
Automobile	Small 1	2.7	1,308	13.2	1,783	10.0	2,834	12.1	776	11.6	6,701	11.5
	Small 2	11.3	1,630	16.4	2,589	14.5	4,736	20.2	1,203	17.9	10,158	17.5
	Midsize 1	21.3	2,776	28.0	4,282	23.9	6,011	25.6	1,186	17.7	14,255	24.6
	Midsize 2	14.6	756	7.6	1,622	9.0	1,480	6.3	421	6.3	4,279	7.4
	Large 1	7.8	359	3.6	775	4.3	565	2.4	165	2.4	1,864	3.2
	Large 2	3.8	370	3.7	663	3.7	648	2.7	92	1.4	1,773	3.1
	Subtotal	61.5	7,199	72.5	11,714	65.4	16,274	69.3	3,843	57.3	39,030	67.3
Light Truck	Pickup	17.5	1,495	15.1	3,516	19.6	4,828	20.6	1,529	22.8	11,368	19.6
	Sport/Utility	9.9	536	5.4	1,144	6.4	1,430	6.1	831	12.4	3,941	6.8
	Van	2.9	318	3.2	661	3.7	361	1.5	149	2.2	1,489	2.5
	Passenger	8.2	379	3.8	875	4.9	583	2.5	355	5.3	2,192	3.8
	Subtotal	38.5	2,728	27.5	6,196	34.6	7,202	30.7	2,864	42.7	18,990	32.7
Total		100.0	9,927	100.0	17,910	100.0	23,476	100.0	6,707	100.0	58,020	100.0

Note. * Based on 1993 sales figures.

For automobiles, the smallest automobile platform, S1, was significantly overrepresented in crashes, as shown in Table 22, with a ratio of percent involvement in crashes to percent market share of over 4 to 1. The S2 and M1 platforms were also overrepresented in crashes, while the three larger platforms were underrepresented. Though the percentages vary, these trends hold true for all four states analyzed. The one exception was the Utah data that indicate that the M1 platform was underrepresented. For light trucks, the pickup truck subclass was slightly overrepresented in crashes (19.6 percent of crashes versus 17.5 percent of market share), while the sport utility, van, and passenger van subclasses were all underrepresented. With a few exceptions, these trends hold true for all four states though the percentages vary among the states.

Subsequent analyses were conducted for each of the four states individually and no attempt was made to combine the data from the four states since there were considerable differences in how the data were coded and in the definitions used. Because of length restrictions, only the Illinois and North Carolina data are reported here. Additional data can be obtained by contacting the authors. The analyses covered two major areas: rollover involvement and injury severity. In some of the tables for the individual states, the sample sizes for some cells were too small for the results to be stable or meaningful. Thus, it was decided that results for cells with a sample size of less than 20 would not be shown. For cells with such small sample size, one more or one less crash could significantly change the results and lead to different conclusions.

2.3.4.2 Illinois Data

Rollover Involvement—Table 23 shows the number and percentage of rollovers for single-vehicle, ran-off-road crashes in Illinois. The Illinois crash data provide coding for three events in the impact sequence, which allowed for a more detailed analysis of the rollover occurrence. The first event was almost always coded as "ran-off-road," thus the second event was really the first harmful event and the third event was the event subsequent to the first harmful event. Rollovers in the second event were termed "primary" (i.e., the vehicle rolled over without striking another roadside feature). Rollovers in the third event were termed "secondary" (i.e., the errant vehicle struck another roadside feature prior to rolling over).

The Illinois data indicated that light trucks had a significantly higher rollover rate than automobiles (32.8 percent for light trucks versus 18.2 percent for automobiles). The trend was more pronounced for primary rollovers than for secondary rollovers. It was interesting to note that the ratio of primary to secondary rollovers was more than 3 to 1 (17 percent primary versus 5.2 percent secondary). This suggests that rollover as a result of impacting with another roadside feature was much less frequent than rollover as the first harmful event.

For automobiles, the rollover rate was higher than average for the two small automobile platforms and decreased with increasing vehicle platform size. Similar trends were observed for both primary and secondary rollovers. Among the light truck subclasses, the rollover rate for sport utility vehicles

TABLE 23 Percent rollover by vehicle platform/subclass—Illinois data

Vehicle Type	Platform/ Subclass	Rollover			Non-Rollover	Total	% Rollover		
		Primary	Secondary	Total			Primary	Secondary	Total
Automobile	Small 1	286	94	380	928	1,308	21.9	7.2	29.1
	Small 2	253	74	327	1,303	1,630	15.5	4.6	20.1
	Midsize 1	317	121	438	2,338	2,776	11.4	4.4	15.8
	Midsize 2	82	31	113	643	756	10.9	4.1	15.0
	Large 1	16	14	30	329	359	4.5	3.9	8.4
	Large 2	20	3	23	347	370	5.4	0.8	6.2
	Subtotal	974	337	1,311	5,888	7,199	13.5	4.7	18.2
Light Truck	Pickup	355	108	463	1,032	1,495	23.8	7.2	31.0
	Sport/ Utility	178	48	226	310	536	33.2	9.0	42.2
	Van	87	11	98	220	318	27.4	3.4	30.8
	Passenger Van	89	18	107	272	379	23.5	4.7	28.2
	Subtotal	709	185	894	1,834	2,728	26.0	6.8	32.8
Total		1,683	522	2,205	7,722	9,927	17.0	5.2	22.2

was higher than the average for all light trucks (42.2 percent versus 32.8 percent), while pickup trucks, vans, and passenger vans had slightly lower than average rollover rates.

Table 24 shows the secondary rollover rate by vehicle type and object struck. Except for a few roadside features, such as guardrails, highway signs, and utility poles, the sample sizes were relatively small. Thus, no attempt was made to further break down the vehicle types by the individual automobile platforms and light truck subclasses. As may be expected, ditches/embankments had the highest rollover rate (48.2 percent). Impact attenuators (0.0 percent), bridge structures (0.0 percent), traffic signals (0.4 percent), utility poles (2.7 percent), and light standards (2.9 percent) had the lowest rollover rates, followed by signs (4.7 percent) and trees (5.3 percent). In comparison, curbs/islands (11.1 percent), mailboxes (11.2 percent), and delineator posts (19.3 percent) had relatively high rollover rates. The rollover rates for various categories of longitudinal barriers were relatively low and consistent (5.1 percent for guardrails, 5.3 percent for concrete median barriers and 5.9 percent for bridge rails).

The data indicate that light trucks were more likely to roll over than automobiles in impacts with most roadside features. There were a few exceptions where the rollover rates were actually lower for light trucks (e.g., light standards, concrete median barriers, and trees) or substantively the same (e.g., impact attenuators, traffic signals, and bridge structures). The lower rollover rate for light trucks in impacts with concrete median barriers (2.5 percent for light trucks versus 5.8 percent for automobiles) was somewhat surprising since the rollover rates for light trucks were higher for other types of longitudinal barriers, including guardrails and bridge rails.

It was also interesting to note that light trucks had significantly higher rollover rates for impacts involving mailboxes (18.8 percent for light trucks versus 6.5 percent for automobiles), delineator posts (32.3 percent for light trucks versus 12.5 percent for automobiles), and curbs/islands (20.0 percent for light trucks versus 9.1 percent for automobiles). This suggests that light trucks, once destabilized, were more likely to roll over than automobiles.

Injury Severity—Table 25 shows the percent of total injury (i.e., all injury levels) and percent of incapacitating and fatal (A+K) injury crashes by vehicle platform/subclass and rollover (primary and secondary) involvement. As expected, the injury severity of rollover crashes was much higher than non-rollover crashes in terms of both total injury (64.0 percent versus 33.1 percent) and (A+K) injury (25.5 percent versus 10.9 percent). This trend holds true for both automobiles and light trucks.

For all crashes, the percent of total injury and the percent of (A+K) injury were similar for both automobiles and light trucks. Among automobiles, there was a general trend of

TABLE 24 Percent rollover (secondary) by object struck and vehicle type—Illinois data

Object Struck	Automobile		Light Truck		Total	
	No.	% Rollover	No.	% Rollover	No.	% Rollover
Guardrail	1,254	4.7	374	6.4	1,628	5.1
Conc. Median Barrier	223	5.8	40	2.5	263	5.3
Median Fence	22	9.1	3	-	25	12.0
Bridge Rail	171	4.1	99	9.1	270	5.9
Impact Attenuator	33	0.0	6	-	39	0.0
Highway Sign	515	3.7	203	7.4	718	4.7
Traffic Signal	183	0.0	69	1.4	252	0.4
Light Standard	332	3.0	87	2.3	419	2.9
Tree	544	5.3	214	5.1	758	5.3
Utility Pole	461	2.4	164	3.7	625	2.7
Mail Box	77	6.5	48	18.8	125	11.2
Delineator Post	83	12.5	31	32.3	114	19.3
Curb/Island	44	9.1	10	-	54	11.1
Bridge Structure	60	0.0	18	-	78	0.0
Culvert Headwall	3	-	4	-	7	-
Ditch/Embankment	100	42.0	66	57.6	166	48.2
Total	4,105	5.2	1,436	8.7	5,541	6.2

Note. Percentages for cells with sample sizes of less than 20 are not shown.

decreasing injury severity as the vehicle platforms increased in size. Among light trucks, sport utility vehicles had the highest percent total and (A+K) injury, followed by pickup trucks, while passenger vans and vans had lower injury rates.

For rollover crashes, the injury rates were higher for automobiles than for light trucks. It was interesting to note that the rollover crashes involving larger automobiles may have been actually more severe than those involving smaller automobiles. The L1 platform had the highest percent total injury (80.0 percent) and percent (A+K) injury (53.3 percent), followed by the M2 platform (71.7 percent total injury and 31.9 percent [A+K] injury). This finding may be due to the fact that the impact conditions (i.e., speed, angle, and orientation) necessary to cause rollover in larger automobiles are more severe than those required to produce rollover in smaller automobiles. Among light trucks, sport utility vehicles had the highest percent of total injury (64.6 percent) and percent of (A+K) injury (25.2 percent), followed by passenger vans. Pickup trucks actually had the lowest injury rates in rollover crashes.

2.3.4.3 North Carolina Data

Rollover Involvement—The number and percentage of rollover crashes by vehicle platform/subclass are shown in Table 26. The rollover rate for light trucks (30.0 percent) was significantly higher than that for automobiles (21.1 percent). For automobiles, there was a definite trend of higher rollover rates for the smaller automobile platforms except for the M2 platform, which had the lowest rollover rate (7.5 percent). The S1 and S2 platforms had higher rollover rates (30.3 percent and 22.3 percent, respectively) than the average of 21.1 percent for all automobiles. Among light trucks, sport utility vehicles had a higher rollover rate (39.2 percent) than the average for all light trucks (30.0 percent), while pickup trucks (28.0 percent), vans (25.8 percent), and passenger vans (27.4 percent) had lower than average rollover rates for light trucks, but higher rollover rates than the combined average for all passenger vehicles (23.8 percent).

Injury Severity—Table 26 also shows the percent total injury and percent (A+K) injury crashes by vehicle platform/subclass and rollover involvement. When all roadside crashes were considered, the percent of total injury was slightly higher for automobiles than for light trucks (45.9 percent versus 44.3 percent), but the percent (A+K) injury was lower (7.8 percent versus 9.0 percent). For automobiles, there was a general trend of decreasing total and (A+K) injury rates with increasing vehicle size. For light trucks, pickup trucks had the highest percent injury and percent (A+K) injury

TABLE 25 Percent injury and percent (A+K) injury by vehicle platform/subclass and rollover (primary and secondary) involvement—Illinois data

Vehicle Type	Platform/ Subclass	Rollover			Non-Rollover			Total		
		No.	% Injury	% (A+K) Injury	No.	% Injury	% (A+K) Injury	No.	% Injury	% (A+K) Injury
Automobile	Small 1	380	69.7	27.6	928	38.7	12.1	1,308	47.7	16.6
	Small 2	327	69.4	24.5	1,303	36.0	11.8	1,630	42.7	14.4
	Midsize 1	438	64.6	28.3	2,338	32.6	11.2	2,776	37.7	13.9
	Midsize 2	113	71.7	31.9	643	28.5	9.5	756	34.9	12.8
	Large 1	30	80.0	53.3	329	32.8	10.6	359	36.8	14.2
	Large 2	23	52.2	26.1	347	27.7	6.3	370	29.2	7.6
	Subtotal	1,311	68.0	28.0	5,888	33.6	11.0	7,199	39.9	14.1
Light Truck	Pickup	463	55.9	20.1	1,032	33.0	12.2	1,495	40.1	14.6
	Sport/Utility	226	64.6	25.2	310	33.9	7.7	536	46.8	15.1
	Van	98	50.0	20.4	220	25.0	10.5	318	32.7	13.5
	Passenger Van	107	60.8	23.4	272	27.9	8.1	379	37.2	12.4
	Subtotal	894	58.1	21.8	1,834	31.5	10.6	2,728	40.2	14.3
Total		2,205	64.0	25.5	7,722	33.1	10.9	9,927	40.0	14.1

(44.8 percent and 9.4 percent), followed closely by sport utility vehicles (44.8 percent and 8.8 percent). Similar trends were observed for non-rollover crashes.

As expected, the injury severity of rollover crashes was much higher than non-rollover crashes in terms of both total injury (64.0 percent versus 39.6 percent) and (A+K) injury (14.0 percent versus 6.3 percent). This trend held true for both automobiles and light trucks. Given a rollover crash, the severity was higher for automobiles than for light trucks in terms of total injury (67.6 percent versus 58.4 percent), but slightly lower for (A+K) injury (13.7 percent versus 14.4 percent). The North Carolina data also indicate that rollover crashes were more severe for larger automobiles than for smaller ones. The L2 platform had the highest percent total injury (72.7 percent) and percent (A+K) injury (21.2 percent), while the S1 platform had the lowest (65.6 percent total injury and 11.2 percent [A+K] injury). Among light trucks, all four subclasses had similar percentages of total injury. Passenger vans had the highest percent (A+K) injury (17.5 percent), followed by pickup trucks (15.3 percent), sport utility vehicles (12.1 percent) and vans (9.7 percent).

2.3.5 Summary of Findings

- Automobiles were significantly overrepresented in ran-off-road crashes involving roadside features in relation to their market share, while light trucks were underrepresented. Only the Utah data showed an opposite trend with automobiles slightly underrepresented in ran-off-road crashes and light trucks overrepresented.
- For automobiles, the two small automobile platforms were significantly overrepresented in ran-off-road crashes in relation to their market share. In comparison, the three larger automobile platforms were underrepresented. The Utah data again showed some variations from the other three states.
- For light trucks, pickup trucks were significantly overrepresented in ran-off-road crashes in relation to their market share while minivans, large vans, and sport utility vehicles were underrepresented.
- Light trucks were more likely to roll over than automobiles in ran-off-road crashes involving roadside features. The North Carolina data suggest that this trend was more pronounced for primary rollovers than for secondary rollovers.
- For automobiles, the rollover rates generally decreased with increasing vehicle size. In fatal ran-off-road crashes, the small and midsize platforms showed similar rollover rates while the two large automobile platforms showed significantly lower rollover rates.
- For light trucks, sport utility vehicles had the highest rollover rates, followed by pickup trucks, while vans generally had the lowest rollover rate.
- As may be expected, the rollover rates for ran-off-road crashes were highest for impacts with ditches and embankments. Impacts with rigid objects, such as bridge piers/structures, trees, utility poles, and signs tended to

TABLE 26 Percent injury and percent (A+K) injury by vehicle platform/subclass and rollover involvement—North Carolina data

Vehicle Type	Platform/ Subclass	Rollover			Non-Rollover			Total			
		No.	% Injury	% (A+K) Injury	No.	% Injury	% (A+K) Injury	No.	% Rollover	% Injury	% (A+K) Injury
Automobile	Small 1	858	65.6	11.2	1,976	45.4	6.9	2,834	30.3	51.5	8.2
	Small 2	1,057	67.9	13.2	3,679	41.6	5.8	4,736	22.3	47.5	7.5
	Midsize 1	1,106	67.7	15.2	4,905	38.5	6.2	6,011	18.4	43.8	7.8
	Midsize 2	259	69.5	15.8	1,221	36.7	6.1	1,480	7.5	42.4	7.8
	Large 1	84	71.4	15.5	481	37.6	6.9	565	14.9	42.7	8.1
	Large 2	66	72.7	21.2	582	35.6	5.3	648	10.2	39.4	6.9
	Subtotal	3,430	67.6	13.7	12,844	40.1	6.2	16,274	21.1	45.9	7.8
Light Truck	Pickup	1,350	58.9	15.3	3,478	39.3	7.1	4,828	28.0	44.8	9.4
	Sport/Utility	560	57.0	12.1	870	37.0	6.7	1,430	39.2	44.8	8.8
	Van	93	60.2	9.7	268	36.6	6.0	361	25.8	42.7	6.9
	Passenger Van	160	58.8	17.5	423	33.3	3.6	583	27.4	40.3	7.4
	Subtotal	2,163	58.4	14.4	5,039	38.3	6.7	7,202	30.0	44.3	9.0
Total		5,593	64.0	14.0	17,883	39.6	6.3	23,476	23.8	45.4	8.1

have low rollover rates. Impacts involving longitudinal barriers also had relatively low rollover rates.

- Light trucks were more likely to roll over than automobiles in ran-off-road crashes involving most roadside features, especially ditches and embankments. The higher rollover rates for light trucks with features such as mailboxes, delineator posts, and curbs/islands, suggests that light trucks, once destabilized, are more prone to rollovers than automobiles. The rollover rates for impacts with rigid objects, such as bridge piers/structures, trees, and utility poles tended to be similar for both automobiles and light trucks.
- Nearly half of the fatal ran-off-road crashes involving longitudinal barriers resulted in rollovers, with a lower percentage of rollover for rigid barriers (e.g., concrete barriers and most bridge rails) than for more flexible guardrails.
- The severity of rollover ran-off-road crashes was much higher than that of non-rollover ran-off-road crashes in terms of both total injury and (A+K) injury. This trend held true for both automobiles and light trucks.
- For all ran-off-road crashes, the percent of total injury and (A+K) injury were similar for both automobiles and light trucks. For automobiles, there was a general trend of decreasing percentages of total and (A+K) injury for ran-off-road crashes as the vehicle platforms increased in size. In the category of light trucks, sport utility vehicles and pickup trucks had higher injury rates than vans and passenger vans.
- Given a rollover crash, the injury rates were higher for automobiles than for light trucks. For automobiles, the rollover ran-off-road crashes involving larger automobiles may actually be more severe than those involving smaller automobiles. This may be due to the more severe impact conditions required to overturn larger automobiles. Among light trucks, sport utility vehicles and passenger vans had higher injury severity than pickup trucks and vans in rollover ran-off-road crashes.
- Ran-off-road crashes involving embankments and rigid fixed objects, such as bridge structures, trees, and utility poles had the highest injury rates. On the other hand, ran-off-road crashes involving non-rigid fixed objects, such as highway signs and mailboxes, had the lowest injury severity. Ran-off-road crashes involving longitudinal barriers had intermediate injury rates and severity was considerably higher for impacts with barrier ends.

2.4 CRASH TESTING STUDY

2.4.1 Objective

The objective of the crash testing study was to obtain additional performance data for light truck subclasses during impact with a widely used roadside safety feature.

2.4.2 Selection of Test Details

Factors considered in the selection of test details included (a) the degree to which various safety features have been evaluated in terms of *NCHRP Report 350* requirements, (b) the extent of use of the respective features nationwide, and (c) probability of acceptability performance when impacted by the full range of light truck subclasses at the extremes of the expected impact conditions. In this regard, the following points were considered:

1. Most of the widely used roadside and median barrier systems and many of the bridge rail systems have been tested according to *NCHRP Report 350* test level 3 requirements (which include testing with a ¾-ton pickup truck).
2. Most, if not all, of the proprietary crash cushions and barrier end treatments have been tested according to *NCHRP Report 350* test level 3 requirements.
3. A limited number of sign and luminaire support structures have been tested according to *NCHRP Report 350* test level 3 requirements. The critical test for most such structures involves an impact with an 820 kg automobile, and most of the widely used support structures have been tested (based on *NCHRP Report 230* requirements) according to *Report 350* test level 3 requirements for the 820 kg automobile. Support structures that have met *NCHRP Report 230* requirements are expected to meet *NCHRP Report 350* requirements. As a consequence, no major or unique problems are expected with the performance of these structures for the full range of light truck subclasses.
4. The G4(1S) W-Beam Guardrail system is believed to be the most widely used roadside hardware feature in the United States. Although the G4(1S) system has been tested according to *NCHRP Report 350* test level 3 requirements and found to be unacceptable, testing of the system at more representative impact conditions seemed warranted in view of its very wide use. Most impacts occur at speed-angle combinations less than 100 km/h—20 degrees. However, the percentile of impacts that exceed this threshold has increased as a result of increases in speed limits from 55 mph to 70 mph on most controlled access roadways. It is surmised that as impact speeds increase, associated impact angles decrease.

Based on these considerations a test program was selected, consisting of two phases. Phase 1 consisted of four tests wherein the Standard G4(1S) Guardrail system was impacted by a range of light truck subclasses at a nominal speed of 100 km/h and a nominal impact angle of 20 degrees. The purpose of these tests was to assess performance of the most widely used guardrail system to impacts by light truck subclasses at impact conditions more representative of real-world conditions than those required in Test 3-11 of *NCHRP Report 350* (100 km/h at 25 degrees). Vehicles from four of the seven subclasses listed in Section 2.2.8 were chosen for testing: SUV, MUV, LPU, and LVN. Limits in the project budget precluded testing a vehicle from all seven subclasses. However, it was concluded that the vehicle subclasses that were tested would subject the guardrail to demands equal to or greater than the subclasses not tested.

Phase 2 consisted of three tests. The primary objective was to further evaluate the G4(1S) system at a higher impact speed (110 km/h), and with a 4-wheel drive vehicle. A 20-degree impact angle was selected since this would permit a determination of the effects of increased speed on performance given that the previous four tests on the G4(1S) under NCHRP Project 22-11 were at 100 km/h and 20 degrees. Impact conditions of 110 km/h and 20 degrees produce an impact severity (IS) approximately equal to test 3-11 conditions of 100 km/h and 25 degrees as defined in *Report 350*. It has been suggested that the IS of test 3-11 should not change if the impact speed and angle of test 3-11 of *Report 350* are changed in a future update.

The Standard G4(1S) W-Beam Guardrail system was evaluated in the first five tests. Figure 14 gives details of the system. It consists of 1.8-m-long W150H14 steel posts with 356-mm-long W150H14 steel blockouts, spaced 1.9 m on center and 7.6-m-long 12-gauge W-beam rail elements. Distance from the ground to the center of the W-beam rail element was 550 mm. The W-beam rail elements were attached to the posts with 16-mm-diameter carriage bolts without washers. Backup plates, similar in cross section to the W-beam rail element and 305 mm in length, were used at non-splice posts.

For the last two tests, the Modified G4(1S) W-Beam Guardrail system was used. The Modified G4(1S) Guardrail system consisted of 1.8-m-long W150H14 steel posts with 150-mm H 200-mm H 360-mm-long routed wood blockouts, spaced 1.9 m on center and 7.6-m-long 12-gauge W-beam rail elements. A 100-mm-wide, 10-mm-deep channel was routed out and centered on the post side of the blockout to fit over the flange of the post and prevent rotation of the blockout. The offset depth of the wood blockout was 190 mm. Distance from the ground to the center of the W-beam rail element was 550 mm. The W-beam rail elements were attached to the posts with 16-mm-diameter oval shoulder bolts without washers. The bolt hole on the blockout was offset to match one of the two bolt holes on the post. No backup plates were used.

Figures 25 through 29 are photos of the five light truck types tested. Figures 30 and 31 are photos of the G4(1S) and the Modified G4(1S).

2.4.3 Findings

Table 27 summarizes key test parameters and test results. Findings of the tests of the G4(1S) Guardrail system and the

Figure 25. Vehicle/installation geometrics for test 472480-1.

Modified G4(1S) Guardrail system in terms of *NCHRP Report 350* evaluation criteria are summarized below. For the Standard G4(1S) Guardrail system:

1. The test at a nominal impact speed of 100 km/h and a nominal impact angle of 25 degrees with the 2000P standard test vehicle was unsuccessful. (Test conducted within a separate study. See "Crash Testing and Evaluation of Existing Guardrail Systems" [*20*]).
2. The tests at a nominal impact speed of 100 km/h and a nominal impact angle of 20 degrees with the following vehicles were successful:
   - 1992 Chevrolet Geo Tracker, 2-wheel drive,
   - 1992 Ford Explorer, 2-wheel drive,
   - 1993 Chevrolet G20 Van, 2-wheel drive, and
   - 1992 Chevrolet 2500 Pickup, 2-wheel drive (2000P test vehicle).
3. The test at a nominal impact speed of 110 km/h and a nominal impact angle of 20 degrees with the 2000P standard test vehicle was unsuccessful.

For the Modified G4(1S) Guardrail system:

1. The test at a nominal impact speed of 100 km/h and a nominal impact angle of 25 degrees with the 2000P standard test vehicle was successful. (Test conducted in a separate study. See "*NCHRP Report 350* Test 3-11 of the Thrie Beam Guardrail with Steel Post and Routed Wood Blockouts"[*27*].)
2. The test at a nominal impact speed of 110 km/h and a nominal impact angle of 20 degrees with the 2000P standard test vehicle was successful.
3. The test at a nominal impact speed of 104 km/h and a nominal impact angle of 20 degrees with a 4-wheel drive version of the 2000P standard test vehicle was unsuccessful.

The Standard G4(1S) Guardrail system had satisfactory performance for all the light truck subclasses tested for impact conditions of 100 km/h and an impact angle of 20 degrees. It can also be seen that the Modified G4(1S) Guardrail system met *NCHRP Report 350* requirements for test level 3, and for impact conditions of 110 km/h and an impact angle of 20 degrees with the 2000P test vehicle, whereas the Standard G4(1S) Guardrail system failed for the same conditions. It is thus concluded that the Modified G4(1S) will contain and safely redirect most light trucks, even at extreme impact conditions. However, under extreme impact conditions, the Modified G4(1S) Guardrail system may not contain the heavier 4-wheel drive light truck subclasses.

It was observed during the Phase 1 testing that the 2000P loaded and damaged the barrier in a way similar to that of the large van, and that the post-impact behavior of the 2000P was more unstable (i.e., there was more rolling and yawing motion) than any of the other light truck subclasses. This evidence further supports the selection of the 2000P vehicle as a good light truck design vehicle, or one that will exhibit the greatest demands on a roadside feature for given impact conditions. In other words, if a roadside feature performs acceptably during impact by the 2000P vehicle, indications are that it will perform acceptably for most other light truck subclasses, especially for the heavier light truck subclasses. Exceptions to this may be the heavier 4-wheel drive light trucks, with higher centers of mass.

Figure 26. Vehicle/installation geometrics for test 472480-2.

2.5 SUMMARY OF LITERATURE DATA

A literature study was conducted in Phase I of Project 22-11 to document existing data on the performance of light trucks with roadside safety features. Included in the study was a review of relevant crash test studies and computer simulation studies. Results were presented in the interim report (*1*). Since then much more information has been generated, primarily through crash testing in accordance with *NCHRP Report 350* recommendations.

2.5.1 Computer Simulation Studies

In addition to the simulation study within Project 22-11, and those reported in the interim report, a number of other simulation studies have been conducted, primarily with the DYNA-3D program (*13*). FHWA has sponsored most of these studies to promote and enhance the DYNA-3D program's use in designing and analyzing roadside safety features. It was not within the scope of this project to critically review and summarize these studies. However, an overview is presented here and interested readers are referred to the cited references.

The C2500 pickup truck has often been used in simulation studies because it was a design vehicle recommended in *NCHRP Report 350*. The pickup truck vehicle model developed at the National Crash Analysis Center was a model of a Chevy C1500 pickup truck that was later modified to a C2500 model. The C1500 pickup truck model was initially evaluated using a frontal impact crash test with a rigid wall as shown in Figure 32. Additionally, a redirectional impact into a rigid wall crash test was used to further evaluate the model; however, the redirectional impact was conducted using a C2500 truck (*32*, *217*).

Vehicle crush, deformation of various parts of the vehicle, and acceleration histories were used to evaluate the performance of the C1500 model. It was believed that the model was suitable for roadside safety applications. However, two fundamental changes were made shortly after the model was developed: it was modified to resemble a C2500 pickup truck, and the number of elements of the model were reduced significantly to at least one-fifth of its original number. The reason for the first change was to accommodate the actual truck type required for use per *NCHRP 350* requirements. The other change, reducing the number of elements from around 50,000 to around 10,000, was made to reduce computationally

Figure 27. Vehicle/installation geometrics for test 472480-3.

related expense involved in using such a large model. Subsequently, two lines of C2500 pickup truck models were maintained and updated, the detailed line (which currently stands at version 4) and the reduced line (which currently stands at version 8). The model was used in simulating:

A. Impacts with the MELT end terminal (*218*),
B. Impacts with the bullnose median barrier (*210*),
C. Impacts with the G4 Guardrail systems (*177*),
D. Impacts with breakaway sign supports (*176*),
E. Impacts with portable concrete barriers (*77*), and
F. Side impacts with rigid and breakaway luminaire poles (*42*).

Modifications were made to the C2500 pickup truck model to include rotating tires so events such as impacting a shaped concrete barrier would be accurately represented. Side impact simulations (*42*) required the use of a detailed model instead of the bullet (i.e., reduced) model since the deformation of the occupant compartment was extensive, as shown in Figure 33. Other light truck models being developed are the Dodge Caravan and the Ford Explorer models. Both models are expected to have a very detailed mesh.

2.5.2 Crash Testing Studies

Subsequent to Phase I and the interim report of Project 22-11, many more crash tests have been conducted, both within Project 22-11 (as given in Section 2.4) and external to the project. Many of these tests have been conducted at TTI, and many others have been conducted at other test agencies. Most of these tests were conducted in accordance with *NCHRP Report 350* recommendations. As such, numerous tests have been made with a wide variety of roadside safety features with a ¾-ton pickup truck, a *Report 350* standard test vehicle (referred to as the 2000P vehicle). An effort was made to update the data presented in the interim report by collecting and summarizing crash tests of roadside safety features with light trucks conducted within the United States since publication of the interim report.

The updated results are given in Tables 28 through 37. Each table is subdivided according to test article type such as bridge rails, guardrails, terminals, and so on. Information reported in the tables includes a test number and the reference document describing the test, a brief description of the test article and vehicle, and impact conditions, as well as an assessment of the test results. It should be noted that most of the tests reported in the tables are part of a testing program for a system, and that

Figure 28. Vehicle/installation geometrics for test 472480-4.

most of the programs also involved one or more tests with a small automobile, as recommended in *NCHRP Report 350*. Details of the test program and the system tested can be obtained from the cited references.

2.5.2.1 Bridge Rails

Table 28 summarizes light truck testing with bridge rails. In earlier bridge rail tests a pickup truck ballasted to a total mass of approximately 2450 kg was used, with approximate impact conditions of 100 km/h at 20 degrees, in accordance with AASHTO guide bridge rail specifications (*30*). Subsequently, bridge rail tests with pickup trucks have been conducted in accordance with *NCHRP Report 350* recommendations. For *Report 350* test level 3, a 2000 kg pickup impacts the railing at 100 km/h at 25 degrees. The IS (see definition in *NCHRP Report 350*) of the earlier tests was approximately 20 percent less than that for the *Report 350* test level 3. As a consequence, direct comparison of earlier bridge rail tests with current tests cannot be made. However, the earlier tests provide added insight into the safety performance of bridge rails with pickup trucks from which some general observations can be made.

The widely used New Jersey Safety-Shape (tests 405491-1 and 7069-14), the F-Shape (test 7069-4), the Vertical-Wall (tests 7069-6, 1862-8-89, and 405511-01), and the Constant-Slope (test 7147-15) Bridge Rails performed satisfactorily with pickup trucks when tested to Performance Level 2 (PL-2) of the AASHTO Guide Specification (*30*) or test level 3 of *NCHRP Report 350*. It follows that these same shapes, when used as median barriers, would perform in the same manner if rigidly anchored.

Although light truck testing of the rigid barriers has generally been successful, further investigation of the New Jersey Safety-Shape and the Constant-Slope Barriers for other light truck subclasses at other impact conditions may be warranted, as discussed in Section 2.2.8.

As shown in Table 28, many other bridge rail types have been successfully tested and some have been unsuccessful. Most of these are "state-specific" railings, rather than widely used railings.

2.5.2.2 Guardrails

Table 29 summarizes light truck testing with guardrails. All widely used guardrail systems have been tested accord-

Figure 29. Vehicle/installation geometrics for test 472480-7.

ing to *NCHRP Report 350* test level 3 recommendations. These include the G1, G2, G3, G4(1S), G4(2W), and G9 systems. With the exception of the G2, the G4(1S), and the G9 systems, all met *NCHRP Report 350* evaluation criteria.

The G2 Weak-Post W-Beam Guardrail was found to be deficient as a test level 3 barrier but was found to have satisfactory performance as a test level 2 barrier (test 471470-22). As summarized in Table 29, a recent test (test 473750-3) of a modified version of the G2 system was successful.

In an earlier series of tests conducted on the G4(1S) (tests 4798-6, -7, and -8), an increasing propensity for rollover with an increase in the center-of-mass height was demonstrated. In these tests, a smaller pickup was redirected in a very stable manner, while a full-size, $^{1}/_{2}$-ton pickup achieved a roll

Figure 30. G4(1S) guardrail installation before test 472480-1.

angle of 35 degrees, and a $^3/_4$-ton van overturned. The initial test of the G4(1S) Guardrail system with the 2000P vehicle for test level 3 (test 471470-27) resulted in a rollover, and was thus a failure. Modifications were made to the system, one of which proved acceptable for test level 3 (test 405421-01) and one of which did not (test 405421-2).

As shown in Table 29, other tests have been conducted with the Standard G4(1S) system and the Modified G4(1S) system at impact conditions other than test level 3 conditions. Reference should be made to Section 2.4 for discussion of these tests and their implications.

A test of the Standard G9 Thrie-Beam system for test level 3 of *Report 350* resulted in a failure (test 471470-31). Upon impact, the 2000P vehicle was redirected, but large pitch and roll rates were induced, resulting in a violent rollover. A modified version of the G9 system met test level 3 requirements (tests 471470-30 and 404211-10).

The concrete New Jersey Safety-Shape Barrier is now being used for roadside applications, and as such can be considered a “guardrail.” When anchored against movement during an impact, performance will be as described in Section 2.5.2.1. When freestanding, or unanchored, performance will be as described in Section 2.5.2.7.

2.5.2.3 *Transitions*

Table 30 summarizes light truck testing with transitions. Impact performance of guardrail-to-bridge rail transitions with light trucks has been mixed, with some successes and some failures. Failures have resulted primarily from excessive occupant compartment deformations and vehicular overturn. A high occurrence of floor-pan deformation in pickup truck tests that was not evident in previous testing with large

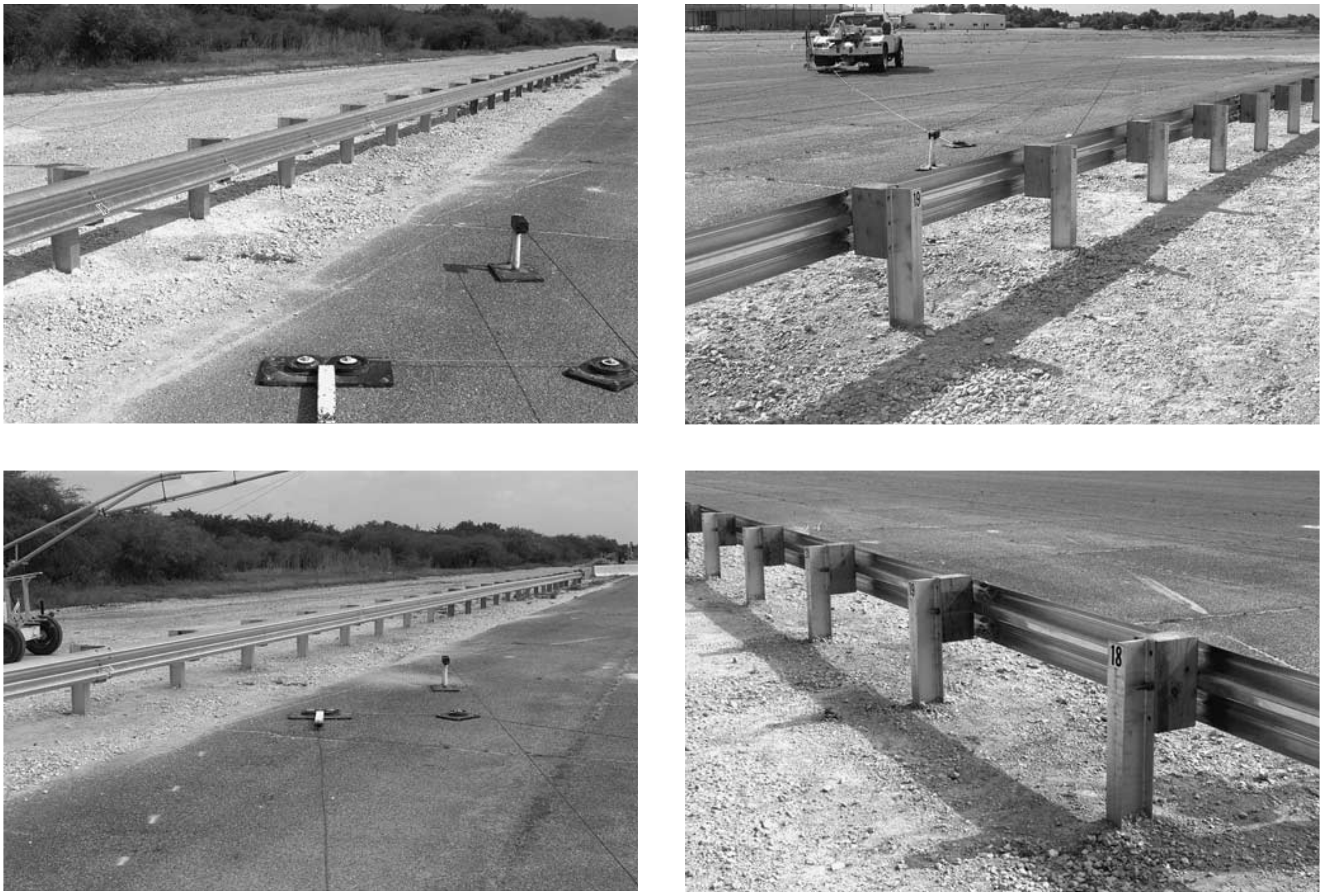


Figure 31. Modified G4(1S) before tests 472480-6 and 472480-7.

TABLE 27 Summary of Project 22-11 crash tests

			Impact Conditions			Occupant Risk Values		
Test Article	Test No.	Vehicle	Vehicle Mass (kg)	Speed (km/h)	Angle (deg.)	Impact Velocity (m/s)	Ridedown Acceleration (G's)	Comments
G4(1S)	472480-1	1992 Geo Tracker	982	99.7	19.7	6.4	9.1	Test was satisfactory. Vehicle smoothly redirected.
G4(1S)	472480-2	1992 Ford Explorer	1775	96.3	19.7	5.0	8.9	Test was satisfactory. Vehicle smoothly redirected. Moderate wheel snagging on post.
G4(1S)	472480-3	1993 Chevrolet G20 Van	1900	99.5	19.8	4.6	8.3	Test was satisfactory. Vehicle smoothly redirected. Major wheel snagging on post.
G4(1S)	472480-4	1992 Chevrolet 2500 Pickup	2000	97.5	19.7	4.8	8.2	Test was satisfactory. Vehicle smoothly redirected. Major wheel snagging on post.
G4(1S)	472480-5	1995 Chevrolet 2500 Pickup	2000	111.1	22.2	5.6	13.1	Test was a failure. Vehicle redirected but overturned.
Modified G4(1S)	472480-6	1995 Chevrolet 2500 Pickup	2000	110.9	21.2	6.0	10.1	Test was satisfactory. Vehicle smoothly redirected. Wheel snagging occurred and vehicle had moderate roll angle.
Modified G4(1S)	472480-7	1995 Chevrolet 4x4 2500 Pickup	2300	103.5	19.5	4.8	12.3	Test was a failure. Rail failed and vehicle rode on top of rail.

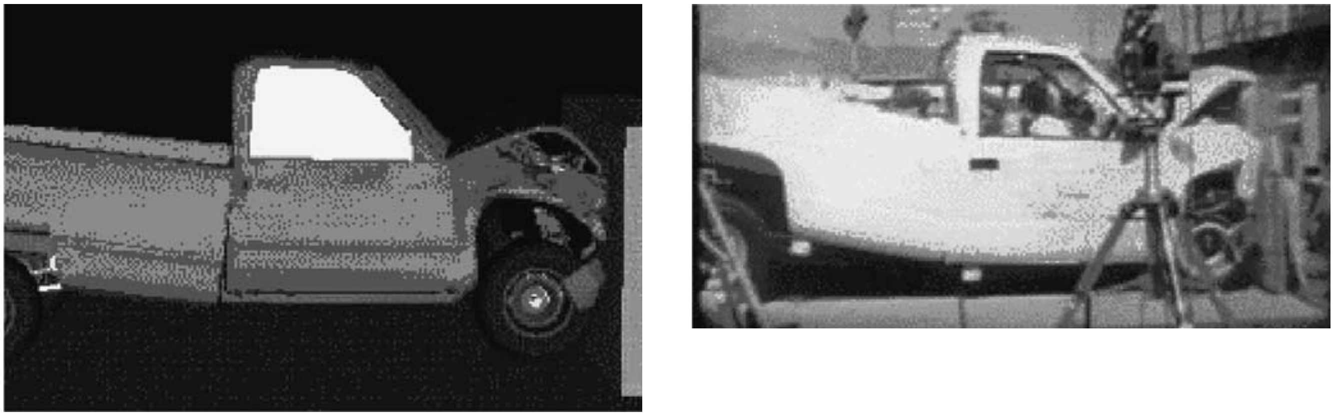


Figure 32. Top view of simulation and test for truck into rigid wall.

passenger sedans has been observed. This floor-pan deformation has occurred in instances when no evidence of wheel snagging on the end of the parapet was reported. This is attributed primarily to the reduced front overhang dimension of the pickup truck resulting in more vehicle-barrier interaction. It may also be due to other inherent characteristics of pickup trucks, such as crush stiffness, or wheel suspension properties. Further study of this occurrence could be addressed with state-of-the-art computer programs using finite element modeling (*13*).

Transition of a W-Beam or a Thrie-Beam Guardrail Barrier to a rigid bridge rail, such as a New Jersey Safety-Shape Barrier, is the more common transition type. It is also the more difficult in terms of meeting *NCHRP Report 350* requirements. Tests 414424-1, 7069-21, I6-1, 473390-6, 7069-20, 404211-4, 404211-12, ITNJ-1, -2, -3, -4, and MTSS-1 and -2 were evaluations of these types of transitions. It can be seen that some were successful and others were not. Interested readers may review references cited in Table 30 for details of the tests and the transition designs evaluated.

2.5.2.4 Median Barriers

Table 31 summarizes light truck testing with median barriers. As indicated, the number of median barriers tested with light trucks has been minimal. This is due primarily to the widespread use of the New Jersey Safety-Shape Median Barrier. Tests of New Jersey Safety-Shape Bridge Rails have application to median barriers, provided the geometry is equal and provided both have the same anchorage. The same is true for the Constant-Slope Barrier, which is being used both as a bridge rail and as a median barrier. Many previously used metal median barriers, such as steel cable barriers and W-beam median barriers, have been replaced by concrete barriers, or are no longer being installed in significant numbers.

It is interesting to note in Tables 28 and 31 that no rollovers occurred in any of the tests of the New Jersey Safety-Shape Barrier with Chevrolet pickups, whereas rollovers did occur with Ford pickups (tests 3825-15 and 270687-WDT1). This is attributed to differences in the suspension properties, frontal geometry, and crush characteristics of the two vehicles.

Figure 33. Pickup truck crush during side impact test and simulation.

TABLE 28 Summary of crash tests with light trucks—bridge rails

Test No. (Ref.)	Test Article		Vehicle Description				Impact Conditions		Assessment of Results
			Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
7069-18 (*19*)	Oregon Side-Mounted Thrie Beam		Chev. Custom 20 Pickup	3/4 ton	1982	2605 (5737)	74.2 (46.1)	20.9	passed
7069-23 (*19*)	BR27D (PL-1)	on Sidewalk	Chev. Custom 20 Pickup	3/4 ton	1984	2527 (5565)	72.9 (45.3)	20.2	passed
7069-31 (*19*)		on Deck	Chev. Custom 20 Pickup	3/4 ton	1985	2527 (5566)	73.4 (45.6)	18.8	passed
7069-6 (*19*)	32-in. Vertical Parapet		Chev. Custom 20 Pickup	3/4 ton	1982	2615 (5759)	96.1 (59.7)	20.2	passed
405491-1 (*19*)	32-in. N.J. Safety Shape		Chev. 2500 Pickup	3/4 ton	1991	2077 (4575)	101.2 (62.9)	25	passed
7069-14 (*19*)			Chev. Custom 20 Pickup	3/4 ton	1981	2599 (5724)	92.8 (57.7)	20.6	passed, 23 in. climb
7069-4 (*19*)	32-in. F-Shape		Chev. Scottsdale Pickup	3/4 ton	1981	2624 (5780)	105.2 (65.4)	20.4	passed, 21 deg. roll
7069-2 (*19*)	Illinois 2399-1 (PL-2)		Chev. Custom 20 Pickup	3/4 ton	1981	2632 (5797)	102.3 (63.6)	19.2	passed
7069-24 (*19*)	BR27C (PL-2)	on Sidewalk	GMC Sierra 2500 Pickup	3/4 ton	1984	2528 (5568)	100.7 (62.6)	19.4	passed
7069-33 (*19*)		on Deck	Chev. Custom 20 Pickup	3/4 ton	1985	2529 (5570)	89.0 (58.3)	19.6	passed
7069-36 (*19*)	Illinois Side Mount (PL-2)		Chev. Custom 20 Pickup	3/4 ton	1986	2526 (5565)	97.2 (60.4)	20.4	passed
1862-8-89 (*19*)	27-in. Vertical Wall, 8-in. Curb		Chev. C-20 Pickup	3/4 ton	1982	2607 (5742)	100.0 (62.1)	10	passed
7147-15 (*20*)	32-in. Constant Slope		Chev. Custom 20 Pickup	3/4 ton	1985	2076 (4573)	97.2 (60.4)	25.5	passed, 30 deg. roll
7199-4 (*34*)	Tennessee Concrete Beam and Post		GMC Sierra 2500 Pickup	3/4 ton	1984	2043 (4500)	99.6 (61.9)	25.6	passed
PU-1 (*35*)	Nevada Bridge Rail (27-in. safety shape with 12-in. aluminum rail)		Chev. C-10 Pickup	1/2 ton	1981	2453 (5408)	104.6 (65.0)	19.0	passed, 11 deg. roll
1952-5-90 (*36*)	Michigan Open Parapet Bridge Rail on 10-in. curb	with Al top rail	GMC C1500 Pickup	1/2 ton	1984	2613 (5760)	100.1 (62.2)	20	failed, severe snagging and intrusion
1952-7-91 (*36*)		without Al top rail	Chev. C-10 Pickup	1/2 ton	1982	2599 (5730)	98.5 (61.2)	20	failed, severe snagging and intrusion
1952-2-89 (*36*)	Michigan R4 Retrofit Bridge Rail		Ford F150 Pickup	1/2 ton	1983	2596 (5724)	97.5 (60.6)	20	passed, 20 deg. roll
472 (*37*)	CALTRANS Type 115 (side mount metal tube railing)		Dodge Ram Pickup		1985	2481 (5470)	103.3 (64.2)	21.0	passed, severe snagging
473 (*37*)	CALTRANS Thrie Beam Bridge Rail (side mount)		Chev. Pickup		1983	2452 (5400)	72.2 (44.9)	21.0	passed
7212-2 (*41*)	Glulam Timber Rail with Sawn Lumber Posts (PL-1)		GMC Pickup	3/4 ton	1984	2529 (5570)	74.2 (46.1)	19.1	passed
7212-5 (*41*)	Glulam Timber Rail with Sawn Lumber Posts and Curb (PL-1)		Chev. Custom 20 Pickup	3/4 ton	1984	2527 (5565)	74.0 (46.0)	20.3	passed
7212-7 (*41*)	Side Mount W-beam with Sawn Lumber Posts (PL-1)		Ford F250 Pickup	3/4 ton	1985	2527 (5567)	75.6 (47.0)	20.5	passed
472070-02 (*43*)	W-Beam retrofit for concrete baluster		Ford F250 Pickup	3/4 ton	1986	2528(5566)	75.3(46.7)	19.7	passed
7147-19 (*20*)	NETC Bridge Rail		Ford F250 Pickup	3/4 ton	1984	2528(5568)	92.2(57.3)	20.6	passed
7069-25 (*19*)	BR27C Bridge Rail with 8 inch curb		GMC Sierra 2500 Pickup	3/4 ton	1984	2528(5568)	100.8(62.6)	19.4	passed
7147-09 (*20*)	Washington D.C. Historic Bridge Rail		Chev. Custom Deluxe Pickup	3/4 ton	1986	2526(5565)	76.8(47.7)	20.6	passed
472610-02 (*44*)	Wyoming 830WYBRAIL Bridge Railing		Chev 2500 Pickup	3/4 ton	1989	2000(4404)	101.0(62.7)	24.9	passed
405511-01 (*45*)	1.07 m Vertical Wall Bridge Railing		Chev. 2500 Pickup	3/4 ton	1989	2076(4571)	102.2(63.5)	25.1	passed

(Table continues on next page)

TABLE 28 ***(Continued)***

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
472610-04 (*46*)	Wyoming 740WYBRAIL Bridge Railing	Chev. 2500 Pickup	3/4 ton	1989	2000(4404)	101.7(63.2)	25.2	passed
405890-1 (*47*)	Oregon Crooked River Bridge	Ford F250 Pickup	3/4 ton	1992	2000(4404)	99.3(61.7)	26.4	passed
472070-06 (*48*)	Vandal Protection Fence on NJSS	Ford F250 Pickup	3/4 ton	1991	2525(5560)	101.1(62.8)	20.2	passed
270687-HPA2 (*49*)	Navy Trestle Bridge Rail	Ford F250 Pickup	3/4 ton	1988	2449(5393)	40.2(24.9)	20.1	passed
418048-1 (*50*)	Texas T411 Aesthetic Bridge Rail	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	101.3(62.9)	24.9	failed, occ. comp. deformation
418048-2 (*51*)	Texas Type T6 Bridge Rail	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	99.9(62.0)	26.6	failed, vehicle rolled
418048-3 (*53*)		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	101.6(63.1)	25.4	failed, vehicle rolled on side
418049-8 (*59*)		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	101.0 (62.7)	26.0	passed
418040-12 (*60*)		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	99.5(61.8)	27.0	failed, vehicle rolled
404251-2 (*52*)	Massachusetts Bridge Rail	Chev. 2500 Pickup	3/4 ton	1993	2076(4571)	99.4 (61.7)	25.4	passed
418048-06 (*54*)	Texas T202 Bridge Rail	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	99.4(61.7)	25.3	passed
404311-2 (*55*)	Alaska Bridge Rail	Chev. 2500 Pickup	3/4 ton	1995	2000(4405)	100.7(62.5)	25.8	passed
404531-2 (*56*)	New York Two-Rail Bridge Rail	Chev. 2500 Pickup	3/4 ton	1994	2075(4569)	101.7(63.1)	25.4	passed
418049-7 (*57*)	Texas T4 Bridge Rail	Chev. 2500 Pickup	3/4 ton	1995	2000(4404)	101.4(62.9)	24.8	passed
404531-6 (*56*)	New York 4-Tube Bridge Rail	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.3(62.3)	25.1	passed
404251-5 (*58*)	Massachusetts S3-TL4 Bridge Rail	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.9(62.6)	25.0	passed
404201-8 (*61*)	Oregon Bridge Rail	Chev. 2500 Pickup	3/4 ton	1995	2000(4404)	100.7(62.5)	25.4	passed
C-1 (*38*)	Bridge Railing for Longitudinal Timber Decks	Dodge	3/4 ton	1984	2452	71.0	23.4	passed
CTBR-1 (*212*)	Curb-Type Bridge Railing for Longitudinal Timber Decks	Ford	3/4 ton	1984	2012	49.9	24.3	passed
FPAR-2 (*214*)	Foothills Parkway Bridge Rail	Chevy	3/4 ton	1984	2300	75.0	20.7	failed
FPAR-3 (*214*)		Ford	3/4 ton	1985	2452	73.5	22.7	passed
FSCR-3 (*226*)	Bridge Railing for Timber Deck	Ford	3/4 ton	1986	2045	92.5	21.8	passed
FSCR-4 (*226*)		Chevy	3/4 ton	1984	2087	98.0	24.9	passed
FSSB-1 (*38*)	Bridge Railing for Longitudinal Timber Decks	Dodge	3/4 ton	1984	2452	72.4	21.8	passed
FSSR-1 (*38*)		Chevy	3/4 ton	1984	2542	71.2	19.1	passed
GWMP-3 (*214*)	George Washington Memorial Parkway Bridge Rail	Chevy	3/4 ton	1985	2452	75.0	22.7	passed
I2-2 (*223*)	Iowa Retrofit Concrete Barrier Rail	Chevy	3/4 ton	1983	2518	100.3	20	passed
LVBR-1 (*40*)	Flexible Bridge Railing for Longitudinal Timber Decks	Chevy	3/4 ton	1984	2041	50.2	26.8	failed
LVBR-2 (*40*)		Chevy	3/4 ton	1985	2043	49.2	24.9	passed
LVBR-3 (*227*)	Semi-Rigid Top-Mounted W-Beam Bridge Railing	Ford	3/4 ton	1988	2001	51.2	25.2	passed

TABLE 28 ***(Continued)***

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
LVCS-4 (*39*)	Low-Volume Curb-Type Bridge Railings for Timber Decks	Ford	3/4 ton	1985	1999	23.2	15	passed
LVCT-1C (*39*)	Timber Curb-Type Rail 10-in. high (Trapezoidal)	Ford F250 Pickup	3/4 ton	1985	2000 (4406)	24 (15)	15	failed, tire climbed curb
MN-2 (*213*)	Minnesota Combination Bridge Rail	Ford	3/4 ton	1986	2005 (4416)	97.5 (60.6)	25.5	failed, interior deformation
MN-3 (*213*)		Ford	3/4 ton	1986	2015 (4438)	100.6 (62.5)	25.9	passed
MNPD-1 (*201*)	Traffic/Bicycle Bridge Rail	Ford	3/4 ton	1988	2001 (4407)	105.2 (65.3)	25.5	passed
MS30-3 (*220*)	Missouri 30 in. New Jersey Safety Shape Bridge Rail	Chevy	3/4 ton	1984	2477 (5456)	102.2 (63.5)	20	passed
NEOCR-1 (*219*)	Open Concrete Bridge Rail	Chevy	3/4 ton	1985	2404 (5295)	76.8 (47.7)	20	passed
NEOCR-2 (*219*)		Chevy	3/4 ton	1986	2445 (5385)	73.8 (45.8)	20	passed
NEOCR-5 (*215*)		Ford	3/4 ton	1986	2447 (5390)	96.2 (59.8)	21.7	passed
NEOCR-6 (*215*)		Dodge	3/4 ton	1985	2449 (5394)	98.2 (61.0)	20	passed
NTBR-1 (*214*)	Natchez Trace Parkway Bridge Rail	Chevy	3/4 ton	1984	2451 (5399)	72.7 (45.2)	22.4	passed
SBLR-2 (*214*)	Steel-Backed Log Rail	Chevy	3/4 ton	1986	2452 (5401)	74.2 (46.1)	20.9	passed
STCR-1 (*225*)	Bridge Railing on Transverse Glue-Laminated Bridge Decks	Chevy	3/4 ton	1990	1966 (4330)	66.6 (41.4)	25.6	passed
STTR-1 (*204*)	Bridge Rail for Transverse Glue-Laminated Timber Decks	Ford	3/4 ton	1990	1994 (4392)	93.7 (58.2)	25.5	passed
TRBR-2 (*204*)		Ford	3/4 ton	1988	1993 (4390)	99.2 (61.6)	27.4	passed
WRBP-1 (*225*)	Bridge Railing on Transverse Glue-Laminated Bridge Decks	Ford	3/4 ton	1994	2031 (4474)	69 (42.9)	26.2	passed

2.5.2.5 Guardrail End Treatments

As indicated in Table 32, several proprietary end treatments for the W-beam guardrail have been successfully tested in accordance with *NCHRP Report 350* test level 3 recommendations. These include the ET-2000, SRT, BRAKEMASTER, REGENT, QuadTrend, BEST, and FLEAT guardrail end treatments. Some of these designs have also been modified to meet *NCHRP Report 350* test level 2 recommendations. The WYBET terminal has been qualified for *NCHRP Report 350* test level 3 recommendations for steel box-beam guardrails. Other proprietary end treatments that qualified according to *NCHRP Report 350* test level 3 recommendations include the TRITON and QuadTrend terminals. The TRITON system has also been qualified for *NCHRP Report 350* test level 2 recommendations. A proprietary end treatment for the Low-Profile Barrier has also been qualified for *NCHRP Report 350* test level 2 recommendations.

The only nonproprietary end treatment that qualified to *NCHRP Report 350* test level 3 recommendations is the Minnesota ELT. Use of this device is limited to wood-post guardrail systems.

2.5.2.6 Crash Cushions and TMAs

As indicated in Table 33, several proprietary crash cushions have been successfully tested in accordance with *NCHRP Report 350* test level 3 recommendations. These include the ABSORB 350, NCIAS, QuadGuard Elite, TRACC (Trinity Roadside Protection System), REACT 350, Wide React, QuadGuard LMC, QuadGuard Wide, ADIEM, CAT, and Fitch Inertia Sand Barrels. Some of these designs have also been modified to meet *NCHRP Report 350* test level 2 recommendations.

Table 33 also summarizes tests of TMAs. TMAs meeting *NCHRP Report 350* recommendations include the ALPHA 100K TMA, Safe-Stop TMA, Connecticut TMA, and the RENCO TMA.

2.5.2.7 Work Zone Barriers

Table 34 summarizes tests with temporary or work zone barriers. Nonproprietary barriers meeting test level 3 of *NCHRP Report 350* include the Virginia Portable Concrete Barrier, Georgia Portable Concrete Barrier, and the F-Shape

(Text continues on page 74)

TABLE 29 Summary of crash tests with light trucks—guardrails

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
471470-28 (*20*)	G1 Cable System	Chev. 2500 Pickup	3/4 ton	1989	2075 (4570)	95.1 (59.1)	26.7	passed
471470-21 (*20*)	G2 Weak Post W-Beam	Chev. Custom 20 Pickup	3/4 ton	1985	2076 (4573)	99.8 (62.0)	24.4	failed, vehicle rolled onto side
471470-22 (*20*)		Chev. Custom 20 Pickup	3/4 ton	1985	2076 (4573)	71.0 (44.1)	26.1	passed
471470-33 (*20*)	G3 Box Beam	Chev. 2500 Pickup	3/4 ton	1989	2076 (4573)	95.2 (59.1)	25.5	passed
0482-1 (*62*)	G4(2W), 12'-6" post spacing	Chev. C-20 Pickup	3/4 ton	1985	2000 (4404)	69.5 (43.2)	24.5	failed, vehicle vaulted
471470-26 (*20*)	G4(2W)	Chev. 2500 Pickup	3/4 ton	1989	2074 (4568)	100.7 (62.6)	24.3	marginal, 39 deg. roll
4798-6 (*63*)	G4(1S)	Chev. S-10 Pickup	small 1/2 ton	1982	1480 (3260)	96.5 (60)	22	passed
4798-8 (*63*)		Ford F150 Pickup	1/2 ton	1979	1897 (4178)	91.6 (56.9)	23.5	marginal, 35 deg. roll
4798-7 (*63*)		Dodge B200 Van	3/4 ton	1979	1963 (4324)	95.3 (59.2)	24.0	failed, vehicle rolled
WE4-2 (*35*)		Chev. C-10 Pickup	1/2 ton	1981	2447 (5390)	106.0 (65.9)	18.8	passed
471470-27 (*20*)		Chev. 2500 Pickup	3/4 ton	1988	2075 (4570)	101.4 (63.0)	26.1	failed, vehicle rolled onto side
471470-31 (*20*)	G9 Thrie Beam	GMC 2500 Pickup	3/4 ton	1990	2076 (4573)	102.2 (63.5)	26.1	failed, vehicle rolled violently
471470-30 (*20*)	Modified Thrie Beam	GMC 2500 Pickup	3/4 ton	1989	2076 (4573)	100.2 (62.3)	25.1	passed
1862-15-92 (*33*)	G4(1S), 6:1 downslope	Chev. C-20 Pickup	3/4 ton	1982	2592 (5710)	96.1 (59.7)	20	passed
1862-3-89 (*33*)	G4(1S), 1,192-ft radius	Chev. C-20 Pickup	3/4 ton	1983	2593 (5712)	98.3 (61.1)	20	passed
1862-6-89 (*33*)	G4(1S), 1,192-ft radius, 10% superelevation, 2% shoulder upslope	Ford F100 Pickup	1/2 ton	1982	2600 (5727)	98.0 (60.9)	20	failed, vehicle rolled
1862-9-90 (*33*)	Modified G4(1S), 1,192-ft radius, 10% superelevation, 2% shoulder upslope (increased post embedment)	Dodge D150 Pickup	1/2 ton	1982	2607 (5743)	97.5 (60.6)	20	failed, vehicle vaulted and rolled
1862-10-90 (*33*)	Modified Thrie Beam, 1,192-ft radius, 10% superelev., 2% shoulder upslope	Ford F100 Pickup	1/2 ton	1982	2607 (5743)	98.1 (61.0)	20	marginal, 45 deg. roll
1862-16-91 (*33*)	G4(1S), 1,192-ft radius, 10% superelevation, edge of roadway	Ford F150 Pickup	1/2 ton	1984	2610 (5748)	99.1 (61.6)	20	failed, vehicle rolled
1862-1-88 (*33*)	G4(1S), 8-in. Type A curb and gutter	Chev. C-20 Pickup	3/4 ton	1982	2607 (5742)	98.6 (61.3)	20	failed, vehicle vaulted
1862-17-92 (*33*)	G4(1S), 6-in. Type A curb and gutter, 2% shoulder downslope	Ford F150 Pickup	1/2 ton	1984	2069 (4562)	74.2 (46.1)	25	failed, vehicle intrusion, came to rest on top of rail
405391-1 (*64*)	7 1/4-in. diam. Round Post W-beam with 5-in. blockout	Chev. C2500 Pickup	3/4 ton	1989	2000 (4404)	102.2 (63.5)	25.4	passed
414424-2 (*65*)	Curved 10 ga. Thrie Beam, 4.9-m (16-ft) Radius, 787-mm (31-in.) high	Chev. Custom 20 Pickup	3/4 ton	1985	2000 (4404)	101.4 (63.0)	25.6	failed, vehicle vaulted
414424-3 (*65*)	Curved 10 ga. Thrie Beam, 4.9-m (16-ft) Radius, 787-mm (31-in.) high	Ford F250 Pickup	3/4 ton	1988	2000 (4404)	101.4 (63.0)	24.6	failed, vehicle vaulted
405561-01 (*66*)	Cable guardrail	Chev. 2500 Pickup	3/4 ton	1989	2000 (4404)	100.6(62.5)	25.5	N/A, redirected
405421-01 (*27*)	G4(1S) with timber blockouts	Chev. 2500 Pickup	3/4 ton	1989	2076(4571)	101.5(63.0)	25.5	passed
405501-01 (*67*)	Merritt Parkway Steel-Backed Timber Rail	Chev. 2500 Pickup	3/4 ton	1989	2000(4404)	100.0(62.1)	25.2	passed
405561-02 (*66*)	Cable guardrail	Chev. 2500 Pickup	3/4 ton	1989	2000(4404)	97.7(60.7)	26.2	N/A, redirected

TABLE 29 ***(Continued)***

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
405501-03 (*67*)	Merritt Parkway Steel-Backed Timber w/curb	Chev. 2500 Pickup	3/4 ton	1989	2000(4404)	99.3(61.6)	25.2	passed
400001-MPT1 (*68*)	Mondo Plastic - plastic blockout	Chev. 2500 Pickup	3/4 ton	1992	2000(4404)	100.9(62.7)	25.3	passed
439637-01 (*69*)	TxDOT guardrail on steel posts	Chev. 2500 Pickup	3/4 ton	1992	2000(4404)	101.8(63.2)	24.8	passed
405421-2 (*26*)	Mod. G4(1S) w/ W150x17.0 blockouts	Chev. 2500 Pickup	3/4 ton	1993	2074 (4567)	99.68(61.8)	25.7	failed, vehicle penetrated rail and rolled
405421-3 (*29*)	Mod Thrie Beam w/430 mm long blockouts	Chev. 2500 Pickup	3/4 ton	1992	2077 (4573)	100.4 (62.3)	26.1	failed, vehicle redirected and rolled
472480-1 (*70*)	Standard G4(1S)	Geo Tracker		1992	1060 (2334)	99.7 (61.9)	19.7	passed
472480-2 (*70*)		Ford Explorer		1992	1775 (3909)	96.3 (59.8)	19.7	passed
472480-3 (*70*)		Chevrolet G20 Van	3/4 ton	1993	1900 (4185)	99.5 (61.8)	19.8	passed
472480-4 (*70*)		Chev. 2500 Pickup	3/4 ton	1992	2000 (4404)	97.5 (60.5)	19.7	passed
472480-5 (*70*)		Chev. 2500 Pickup	3/4 ton	1995	2000 (4040)	111.1 (69.0)	22.2	failed, vehicle overturned
414588-1 (*71*)	W-Beam Guardrail w/ recycled plastic posts	Chev. 2500 Pickup	3/4 ton	1993	2000 (4404)	100.6 (62.5)	26.5	failed, rail ruptured
404211-11 (*72*)	Wood Post Thrie Beam	Chev. 2500 Pickup	3/4 ton	1993	2075 (4569)	99.6 (61.8)	23.6	passed
404211-10 (*28*)	Thrie Beam w/6'9" steel post/wood blockout	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	98.3(61.0)	24.4	passed
472480-6 (*70*)	Modified G4(1S) W-beam Guardrail	Chev. 2500 Pickup	3/4 ton	1995	2000(4404)	110.9(68.8)	21.2	passed
472480-7 (*70*)		Chev. 2500-4x4 Pickup	3/4 ton	1995	2300(5065)	103.5(64.3)	19.5	failed, rail ruptured
473750-1 (*73*)	PennDOT Type 2 Guide Rail	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.2(62.2)	25.9	failed, rail ruptured
404201-1 (*74*)	Strong Post W-beam with curb	Chev. 2500 Pickup	3/4 ton	1995	2075(4569)	101.8(63.2)	25.2	passed
473750-2 (*75*)	PennDOT Type 2 Guide Rail (mod)	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.3(62.3)	25.3	failed, vehicle redirected
473750-3 (*76*)		Chev. 2500 Pickup	3/4 ton	1995	2000(4404)	102.4(63.6)	26.5	passed
GR-7 (*24*)	G4(2W)	Dodge B200 Van		1979	2112 (4650)	94.5 (58.7)	20.9	passed
GR-9 (*24*)	G2	Dodge B200 Van		1980	2107 (4640)	95.6 (59.4)	23.9	failed, rollover
GR-11 (*24*)	G3	Dodge B200 Van		1979	1989 (4380)	98.2 (61.0)	18.8	failed, exceeded occupant risk parameters
GR-15 (*24*)	G9	Dodge B200 Van		1980	1989 (4380)	96.6 (60)	25	passed
GR-17 (*24*)	G1	Dodge B200 Van		1979	1889 (4160)	93.5 (58.1)	24.2	passed
400001-SCW1 (*79*)	Stone Cast Wall	Chev. 2500 Pickup	3/4 ton	1995	2000 (4404)	101.6 (63.1)	35.2	passed
BSP-1 (*211*)	Buffalo Beam Guardrail	Chevy	3/4 ton	1984	2039 (4491)	99.8 (62.0)	24.5	passed
BSP-2 (*211*)		Ford	3/4 ton	1988	2015 (4438)	90.9 (56.5)	25.3	passed
BSP-4 (*211*)		Ford	3/4 ton	1986	2034 (4480)	107.2 (66.6)	26.5	failed
BSP-5 (*211*)	W-Beam Guardrail	Ford	3/4 ton	1988	2002 (4410)	102.0 (63.4)	26	passed

(Table continues on next page)

TABLE 29 ***(Continued)***

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
BSP-6 (*211*)	Buffalo Beam Guardrail	Ford	3/4 ton	1986	2005 (4416)	103.3 (64.2)	26.5	failed
BSP-7 (*211*)		Ford	3/4 ton	1990	1973 (4346)	100.4 (62.4)	25.4	passed
MIW-1 (*194*)	Michigan Type B (W-Beam)	GMC	3/4 ton	1994	2007 (4421)	99.8 (62.0)	25.8	failed, vehicle rolled
MIW-2 (*N/A*)	Michigan W-Beam Guardrail	GMC	3/4 ton	1994	2034 (4480)	99.0 (61.5)	25 target	failed, no containment
MOSW-1 (*190*)	Guardrail on Slope	Chevy	3/4 ton	1994	2024 (4458)	100.7 (62.5)	28.48	passed
NEC-1 (*197*)	Guardrail Over Curb	GMC	3/4 ton	1991	1979 (4359)	103.2 (64.1)	24.5	failed
NEC-2 (*N/A*)		GMC	3/4 ton	1994	2032 (4476)	100.3 (62.3)	25 target	passed
OLS-1 (*203*)	Ohio Long-Span Guardrail	Chevy	3/4 ton	1991	1999 (4403)	101.3 (62.9)	25.4	failed, severe penetration
OLS-2 (*203*)		Chevy	3/4 ton	1991	1997 (4399)	102.7 (63.8)	24.5	failed, vehicle rolled
OLS-3 (*195*)		Chevy	3/4 ton	1992	1994 (4392)	102.4 (63.6)	24.7	passed

TABLE 30 Summary of crash tests with light trucks—transitions

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
414424-1 (*65*)	Thrie Beam Transition to CSSB	Chev. C2500 Pickup	3/4 ton	1986	2000 (4404)	98.1 (60.9)	26.0	passed, floorpan deformed 3.75 in.
7069-28 (*19*)	Oregon Thrie Beam Transition (PL-1)	Chev. Custom 20 Pickup	3/4 ton	1985	2527 (5565)	76.7 (47.7)	19.0	passed
7069-21 (*19*)	Nested Thrie Beam Transition to Vertical Parapet (PL-2)	Chev. Custom 20 Pickup	3/4 ton	1984	2526 (5565)	98.8 (61.4)	18.3	passed, floorpan deformed 7 in.
475 (*37*)	CALTRANS Transition from W-beam to Side-Mount Thrie Beam Bridge Rail (PL-1)	Chev. Pickup		1983	2452 (5400)	71.0 (44.1)	18.0	passed
477 (*37*)	CALTRANS Transition from W-beam to Type 115 Bridge Rail (PL-1)	Chev. Custom Deluxe Pickup		1985	2452 (5400)	74.8 (46.5)	19.2	passed
408390-1 (*78*)	T201 Tubular Transition	Chev. 2500 Pickup	3/4 ton	1995	2000 (4404)	101.7 (63.2)	25.7	failed, vehicle rolled
404211-7 (*78*)	Nebraska Transition	Chev. 2500 Pickup	3/4 ton	1995	2075(4569)	99.6 (61.8)	24.6	passed
404211-9 (*80*)	Connecticut Transition	Chev. 2500 Pickup	3/4 ton	1995	2000 (4404)	100.8(62.6)	25.6	passed
473390-6 (*81*)	Minnesota F-Shape Transition	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	101.6(63.1)	25.3	N/A
473390-5 (*81*)	Minnesota J-Shape Transition	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	101.4(62.9)	25.5	failed
418040-13 (*82*)	Texas T201 Transition	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.7(62.5)	25.3	failed
418040-11 (*83*)	T501 Transition	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	101.0(62.7)	26.2	passed
418049-10 (*83*)		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.6(62.5)	25.0	passed
418049-9 (*83*)		Chev. 2500 Pickup	3/4 ton	1995	2000(4404)	99.8(61.9)	25.2	failed, ridedown too high
404311-5 (*84*)	Alaska Multi-State Thrie Beam Transition	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.6(62.5)	25.4	passed
404531-7 (*85*)	New York 4-Tube Transition	Chev 2500 Pickup	3/4 ton	1995	2000(4404)	98.6(61.2)	25.3	failed, too much compartment damage
473160-12 (*86*)	Wyoming TL-4 Transition	Chev. 2500 Pickup	3/4 ton	1995	2000(4404)	102.5(63.6)	24.1	passed
417929-4 (*87*)	W-Beam on Barrels Transition	Ford F250 Pickup	3/4 ton	1993	2000(4404)	101.(62.7)	20.0	passed
472070-3 (*88*)	W-Beam Retrofit Transition	Ford F250 Pickup	3/4 ton	1986	2076(4571)	73.1(45.4)	26.3	passed
405501-04 (*67*)	Merritt Parkway Steel-Backed Timber Rail	GMC 2500 Pickup	3/4 ton	1990	2000(4404)	101.9(63.3)	26.4	passed
405491-02 (*89*)	W-Beam Transition with timber blockout	GMC 2500 Pickup	3/4 ton	1989	2076(4571)	99.8(61.9)	25.3	failed, vehicle rolled
7069-20 (*19*)	Thrie-Beam Bridge Rail Transition	Chev. C-20 Pickup	3/4 ton	1981	2529 (5570)	100.9 (62.7)	19.0	failed, door ripped off
7212-3 (*41*)	West Virginia Bridge Rail Transition	GMC Pickup	3/4 ton	1984	2527(5567)	72.1 (44.8)	18.0	passed
473160-6 (*107*)	Wyoming Transitions	Chev. 2500 Pickup	3/4 ton	1995	2000(4404)	99.9(62.0)	25.8	failed, rolled onto side
473160-7 (*107*)	Wyoming Transitions	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	100.4(62.3)	25.3	passed, vehicle redirected
404211-4 (*108*)	Vertical Flared-Back Transition	Chev. 2500 Pickup	3/4 ton	1994	2074(4567)	101.0(62.7)	24.8	failed, vehicle rolled
404211-12 (*109*)	Vertical Wall Transition	Chev. 2500 Pickup	3/4 ton	1994	2077(4574)	101.3(62.9)	24.2	passed, vehicle redirected

(Table continues on next page)

TABLE 30 ***(Continued)***

Test No. (Ref.)	Test Article		Vehicle Description				Impact Conditions		Assessment of Results
			Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
01-7620-012(*91*)	QuadGuard Transition		GMC C2500 Pickup	3/4 ton	1988	1993(4388)	101.3(62.9)	20.0	passed
01-7620-014(*91*)			GMC C2500 Pickup	3/4 ton	1989	2001(4406)	101.9(62.3)	21.0	passed
170-008 (*92*)	TRITON BARRIER Transition	to W-beam	Chev. Pickup	3/4 ton	1988	1955 (4310)	71.8 (44.6)	26.0	passed, vehicle pocketed
170-012 (*92*)		to rigid CMB	Chev. Pickup	3/4 ton	1988	2001 (4411)	72.0 (44.7)	24.0	passed, 19 deg. roll
I6-1 (*221*)	Iowa W-Beam Approach to Concrete Safety Shape		Ford	3/4 ton	1983	2458 (5414)	98.9 (61.4)	20	passed
ITNJ-1 (*206*)	Transition to Concrete Safety Shape Barriers		Chevy	3/4 ton	1988	1994 (4392)	99.9 (62.0)	25	failed, vehicle rolled
ITNJ-2 (*206*)			Chevy	3/4 ton	1991	1977 (4354)	101.6 (63.1)	25.7	passed
ITNJ-3 (*206*)	Transition to Concrete Safety Shape Barriers		Chevy	3/4 ton	1990	1991 (4385)	102.0 (63.4)	26.9	failed, vehicle rolled
ITNJ-4 (*206*)			Chevy	3/4 ton	1988	2004 (4414)	102.3 (63.5)	24.6	passed
MST-1 (*193*)	Approach Guardrail Transition to Thrie Beam		GMC	3/4 ton	1992	1991 (4385)	101.4 (63.0)	27.5	failed, vehicle laid on side
MST-2 (*193*)			Chevy	3/4 ton	1993	2043 (4500)	99.5 (61.8)	27.9	failed, vehicle laid on side
MTSS-1 (*216*)	Transition to Single Slope Concrete Median Barrier		Chevy	3/4 ton	1985	2043 (4500)	104.0 (64.6)	24.2	failed, interior deformation
MTSS-2 (*216*)			Chevy	3/4 ton	1985	2034 (4480)	92.5 (57.5)	28.7	passed
MWT-2 (*192*)	Missouri W-Beam to Thrie Beam Transition		GMC	3/4 ton	1993	2022 (4453)	98.3 (61.1)	25.3	failed, vehicle laid on side
NEBT-1 (*205*)	Nebraska Thrie Beam Transition		Chevy	3/4 ton	1990	2004 (4414)	103.2 (64.1)	24.9	failed, interior deformation
SDC-1 (*198*)	Cable Guardrail to W-Beam		GMC	3/4 ton	1993	2013 (4433)	101.9 (63.3)	27.6	passed
SDC-2 (*198*)			GMC	3/4 ton	1994	2023 (4456)	101.8 (63.2)	25.2	passed
STCR-2 (*225*)	Transition on Transverse Glue-Laminated Bridge Decks		Chevy	3/4 ton	1990	2035 (4482)	69.9 (43.4)	25.8	passed
STTR-3 (*204*)	Transition for Transverse Glue-Laminated Timber Decks		Ford	3/4 ton	1988	1997 (4399)	101.0 (62.7)	25.6	passed
TRBR-3 (*204*)			Ford	3/4 ton	1987	2029 (4469)	104.9 (65.2)	26.4	passed
WRBP-2 (*225*)	Transition on Transverse Glue-Laminated Bridge Decks		Ford	3/4 ton	1993	2011 (4430)	71.6 (44.5)	26.3	passed

TABLE 31 Summary of crash tests with light trucks—median barriers

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
3825-12 (*90*)	Precast, Concrete Safety-Shaped Median Barrier (fixed to simulate rigid barrier)	Datsun Pickup	small 1/2 ton	1974	1105 (2434)	98.2 (61.0)	15.0	passed, > 32-in. climb, 8-deg. roll
3825-13 (*90*)		Ford F250 Pickup	3/4 ton	1977	2038 (4490)	92.2 (57.3)	6.5	passed, 26-in. climb, 1.5 deg. roll
3825-14 (*90*)		Ford F250 Pickup	3/4 ton	1977	2038 (4490)	93.5 (58.1)	14.0	passed, > 32-in. climb, 3-deg. roll
3825-15 (*90*)		Ford F250 Pickup	3/4 ton	1974	2061 (4540)	96.9 (60.2)	21.5	failed, rolled onto side
3825-16 (*90*)		Chev. Cheyenne 4-wd Pickup		1972	2161 (4760)	96.1 (59.7)	14.5	passed
3825-10 (*90*)		Ford Bronco		1966	1633 (3598)	97.5 (60.6)	6.5	passed
3825-11 (*90*)		Ford Bronco		1966	1633 (3598)	97.7 (60.7)	14.5	passed
481 (*93*)	CMB retrofitted with Concrete Glare Screen	Chev. Pickup		1985	2445 (5390)	89.0 (55.3)	20	passed, 37-in. climb, 13-deg. roll
270687-WDT1 (*94*)	Washington DOT Glare Screen on Concrete Median Barrier	Ford F-250 Pickup	3/4 ton	1989	2000(4404)	104.2(64.7)	25.6	marginal, vehicle rolled on side
404151-01 (*95*)	Canadian Precast Rubber Barrier	Chev. 2500 Pickup	3/4 ton	1991	2000(4404)	100.4(62.3)	25.3	failed, occ. comp. deformation
GR-14 (*24*)	MB3	Dodge B200 Van		1980	1839 (4050)	94.0 (58.4)	18.7	passed
QMB001 (*229*)	Quickchange Moveable Barrier	Chev. 2500	3/4 ton	1989	2032 (4480)	100.6 (62.5)	25	passed
RTS01 (*233*)	Concrete Reactive Tension Barrier	Chev. 2500	3/4 ton	1987	1998 (4405)	98.9 (61.5)	25	passed
RTS03 (*233*)		Chev. 2500	3/4 ton	1990	2008 (4427)	98.2 (61.0)	25	passed
RTS04 (*233*)	Steel Reactive Tension Barrier	Chev. 2500	3/4 ton	1984	1997 (4403)	99.2 (61.7)	25	passed

TABLE 32 Summary of crash tests with light trucks—end treatments

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
PU-3 (*35*)	ELT	Ford F150 Pickup	1/2 ton	1982	2595 (5722)	82.7 (51.4)	0.2	marginal, 43 deg. roll
220510-2 (*96*)	ET-2000	Chev. 2500 Pickup	3/4 ton	1989	2000 (4409)	101.8 (63.3)	20.3	passed, impact at post 3
220510-4 (*96*)		Chev. 2500 Pickup	3/4 ton	1989	2000 (4409)	102.2 (63.5)	14.8	passed, impact on nose
220510-5 (*96*)		Chev. Cheyenne Pickup	3/4 ton	1989	2000 (4409)	104.2 (64.8)	0.8	passed, impact on nose
220537-6 (*96*)		Chev. 2500 Pickup	3/4 ton	1989	2000 (4409)	101.6 (63.1)	20.5	passed, reverse direction
BN-12 (*97*)	Thrie Beam Bull-Nose Median Barrier Terminal	Ford F150 Pickup	1/2 ton	1984	2445 (5390)	88.4 (54.9)	-0.1	passed
1949A-03 (*98*)	Constant Slope Low Profile End Treatment	Chev. Custom Deluxe Pickup	3/4 ton	1984	2043(4500)	74.8(46.5)	0	stable
471470-35 (*20*)	Modified Metric MELT on G4(2W)	Chev. 2500 Pickup	3/4 ton	1991	2076(4571)	102.4(63.6)	0	passed, controlled stop
471470-36 (*20*)		GMC 2500 Pickup	3/4 ton	1989	2075(4569)	101.0(62.7)	21.5	failed, vehicle penetrated rail
405541-01 (*99*)	Modified MELT	Chev. 2500 Pickup	3/4 ton	1989	2077(4573)	97.4(60.5)	20.5	passed, vehicle redirected
405541-03 (*100*)	Modified MELT w/slotted end posts	Chev. 2500 Pickup	3/4 ton	1992	2076(4571)	101.8(63.2)	20.6	passed, vehicle redirected
405521-1 (*101*)	W-Beam Back-Slope w/ditch	Chev. 2500 Pickup	3/4 ton	1991	2076(4571)	98.1(57.1)	21/25	passed, vehicle redirected
405521-2 (*101*)	W-Beam Back-Slope w/inlet	Chev. 2500 Pickup	3/4 ton	1990	2076(4571)	97.0(60.2)	21.9	passed, vehicle redirected
471470-20 (*20*)	Mod. Mini-MELT Terminal for light post	Dodge Custom 250 Pickup	3/4 ton	1985	2078(4576)	101.8(63.2)	20.8	failed, vehicle rolled on side, righted
471470-21 (*20*)	W-Beam (G2) w/turned-down terminal	Chev. Custom 20 Pickup	3/4 ton	1985	2076(4571)	99.8(61.9)	24.4	passed
471470-22 (*20*)		Chev. Custom 20 Pickup	3/4 ton	1985	2076(4571)	71.0(44.1)	26.1	passed, vehicle contained and redirected
471470-32 (*20*)	Metric MELT on G4(2W)	GMC 2500 Pickup	3/4 ton	1989	2076(4571)	100.5(62.4)	20.6	failed, vehicle rolled
471470-34 (*20*)		Chev. 2500 Pickup	3/4 ton	1989	2076(4571)	100.7(62.5)	0	failed, vehicle rolled
473080-4 (*102*)	Vermont terminal	Chev. 2500 Pickup	3/4 ton	1991	2000(4404)	69.8(43.3)	20.5	passed, vehicle redirected
404211-1 (*103*)	Buried-in-backslope	GMC 2500 Pickup	3/4 ton	1995	2000(4404)	97.2(60.4)	25.2	passed, vehicle redirected
473160-2 (*104*)	WYBET-350	Chev. 2500 Pickup	3/4 ton	1992	2000(4404)	99.5(61.8)	20.2	passed, vehicle redirected
473160-3 (*104*)		GMC 2500 Pickup	3/4 ton	1993	2000(4404)	102.5(63.6)	0	passed, vehicle redirected
473160-5 (*104*)	WYBET-350-MB	Chev. 2500 Pickup	3/4 ton	1992	2000(4404)	100.1(62.2)	20.5	passed, vehicle redirected
520201-1 (*105*)	ET-2000	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	99.1(61.5)	0	passed, vehicle redirected
473390-1 (*110*)	Minnesota ELT	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	102.1(63.4	21.0	passed
473390-2 (*110*)		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	99.7(61.9)	0	passed
400001-XTI3(*111*)	ET-2000 w/breakaway steel posts	Chev. 2500 Cheyenne Pickup	3/4 ton	1994	2000(4404)	98.9(61.4)	0/9	passed, vehicle redirected
400001-XTI1(*111*)		Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	99.9(62.0)	20.1	passed, vehicle redirected

TABLE 32 ***(Continued)***

Test No. (Ref.)	Test Article		Vehicle Description				Impact Conditions		Assessment of Results
			Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
473390-4 (*81*)	Minnesota ELT		Ford F-250 Pickup	3/4 ton	1993	2000(4404)	102.0(63.3)	25.4	failed, vehicle rolled
473390-4 (*81*)			Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	98.9(61.4)	25.0	failed, comp. damage
473160-11(*104*)	WYBET-350		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	99.0(61.4)	14.4	passed, vehicle redirected
400001-XTI4(*112*)	ET-2000 w/breakaway steel posts		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	98.3(61.0)	20.0	passed, vehicle redirected
400001-LET1(*113*)	LET-LITE		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.3(62.3)	0.4	passed, vehicle stopped
404211-8 (*114*)	Cable Guardrail System		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	101.4(62.9)	24.8	passed, vehicle redirected
01-7606-005 (*115*)	BRAKEMASTER System Terminal		Chev. C2500 Pickup	3/4 ton	1989	1985(4372)	95.4(59.2)	20.5	passed
01-7606-004 (*115*)			Chev. C2500 Pickup	3/4 ton	1988	1998(4399)	99.4(61.7)	21.0	passed
01-7606-002 (*115*)			Chev. C2500 Pickup	3/4 ton	1988	2002(4408)	96.3(59.8)	14.1	passed
01-7606-003 (*115*)			Chev. C2500 Pickup	3/4 ton	1991	2044(4501)	100.3(62.3)	0	passed
01-7605-001(*116*)	TL-3 Triton Barrier Terminal		GMC C2500 Pickup	3/4 ton	1989	1993(4388)	98.9(61.4)	0	passed
01-7605-004(*116*)			GMC C2500 Pickup	3/4 ton	1988	1998(4399)	98.4(61.1)	15.0	passed
01-7605-005(*116*)			Chev. C2500 Pickup	3/4 ton	1990	1997(4397)	99.7(61.9)	20.0	passed
01-7624-001 (*117*)	QuadTrend 350 Transition Terminal		Chev. C2500 Pickup	3/4 ton	1988	2007(4419)	100.9(62.6)	20.0	passed
01-7624-005 (*117*)			Chev. C2500 Pickup	3/4 ton	1989	2003(4410)	96.3(59.8)	21.0	passed
01-7624-003 (*117*)			Chev. C2500 Pickup	3/4 ton	1988	2008(4422)	98.9(61.4)	0	passed
01-7624-004 (*117*)			Chev. C2500 Pickup	3/4 ton	1988	1994(4391)	97.6(60.6)	15.0	passed
01-7622-002 (*118*)	REGENT System Terminal		Chev. C2500 Pickup	3/4 ton	1988	1996(4395)	97.1(60.3)	20.0	passed
01-7622-012 (*118*)			Chev. C2500 Pickup	3/4 ton	1988	1999(4402)	98.3(60.0)	0.0	passed
01-7622-014 (*118*)			Chev. C2500 Pickup	3/4 ton	1989	1995(4393)	101.7(63.1)	20.0	passed
171-008 (*119*)	Triton Barrier End Treatment	End-on	Chevrolet Cheyene 2500 Pickup	3/4 ton	1988	1994 (3496)	71.1 (44.2)	1.5	passed, 34 deg. roll
171-011 (*119*)		Angle on nose	Chevrolet Cheyene 2500 Pickup	3/4 ton	1988	1967 (4337)	74.5 (46.3)	16.5	passed
171-012 (*119*)		Midlength of Terminal	Chevrolet Cheyene 2500 Pickup	3/4 ton	1987	1965 (4332)	74.0 (46.0)	21.0	passed, vehicle captured, 16 deg. roll
170-007 (*119*)		Angle on nose, 2 ft offset from rigid barrier	Chevrolet Pickup	3/4 ton	1988	1956 (4312)	67.9 (42.2)	25.0	passed, vehicle brought to stop

(Table continues on next page)

TABLE 32 ***(Continued)***

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
BEST-10 (*209*)	BEST Terminal	Chevy	3/4 ton	1990	2003 (4411)	102.1 (63.4)	14.3	passed
BEST-11 (*209*)		GMC	3/4 ton	1990	2000 (4405)	101.6 (63.1)	20.5	passed
BEST-2 (*209*)		Chevy	3/4 ton	1991	2000 (4405)	101.8 (63.2)	20.1	failed, no containment
BEST-3 (*209*)		Chevy	3/4 ton	1992	1996 (4396)	102.7 (63.8)	20.9	passed
BEST-5 (*209*)		Chevy	3/4 ton	1991	2000 (4405)	99.8 (62.0)	0.5	passed
BEST-6 (*209*)		Chevy	3/4 ton	1990	1997 (4399)	101.3 (62.9)	0.2	passed
BEST-9 (*209*)		Chevy	3/4 ton	1990	2005 (4416)	101.0 (62.7)	1.2	passed
FLEAT-3 (*200*)	FLEAT Energy Absorbing Terminal	Chevy	3/4 ton	1992	1996 (4396)	100.4 (62.4)	0	passed
FLEAT-4 (*196*)		Chevy	3/4 ton	1992	2034 (4480)	71.7 (44.5)	21.9	passed
MBN-1 (*202*)	Bullnose Median Barrier	Ford	3/4 ton	1989	1998 (4400)	101.4 (63.0)	0.1	failed
MBN-3 (*199*)	Bullnose Median Barrier	Chevy	3/4 ton	1990	1989 (4400)	100.2 (62.2)	-1.08	failed
MBN-4 (*199*)		Chevy	3/4 ton	1991	2010 (4427)	103.5 (64.3)	0.58	passed
MBN-5 (*191*)		Chevy	3/4 ton	1993	2039 (4491)	103.0 (64.0)	13.4	passed
MBN-6 (*191*)		GMC	3/4 ton	1992	2031 (4474)	101.5 (63.0)	20.4	failed, vehicle vaulted
MBN-7 (*191*)		Chevy	3/4 ton	1992	2036 (4485)	100.0 (62.1)	24.9	failed, vehicle laid on side
MBN-8 (*191*)		GMC	3/4 ton	1992	2033 (4478)	99.8 (62.0)	21.5	passed

TABLE 33 Summary of crash tests with light trucks—crash cushions and TMAs

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
(*120*)	Fitch Sand Barrels	Chev. C-20 Pickup	3/4 ton	1990	2043 (4500)	96.5 (60)	0	passed
PU-2 (*35*)	Energite Sand Barrels	Chev. C-10 Pickup	1/2 ton	1982	2452 (5400)	88.0 (54.7)	0.3	failed, vehicle ramped
PU-4 (*35*)		Ford F150 Pickup	1/2 ton	1982	2445 (5390)	89.6 (55.7)	0.9	failed, vehicle ramped
PU-5 (*35*)	VAT	Chev. C-15 Pickup	1/2 ton	1983	2458 (5420)	87.3 (54.3)	-1.9	passed
CAIS (*35*)	CIAS	Chev. C-10 Pickup	1/2 ton	1982	2443 (5387)	91.4 (56.8)	1.5	passed
GREAT-1 (*35*)	GREAT	Chev. C-10 Pickup	1/2 ton	1983	2450 (5400)	88.2 (54.8)	11.1	passed
105-02 (*35*)		Ford F250 Pickup	3/4 ton	1969	2527 (5573)	95.9 (59.6)	0	passed
178-005 (*121*)	EASI Cushion Wall	Chev. Custom 20 Pickup	3/4 ton	1980	1994 (4396)	73.8 (45.9)	18	passed
220517-08 (*122*)	ADIEM Impact Attenuator System	Ford F250 Pickup	3/4 ton	1989	2000(4404)	99.4(61.7)	20.2	passed, smooth redirection
270687-VAN13 (*123*)	REACT 350 Vanderbilt	Chev. 2500 Pickup	3/4 ton	1990	2000(4404)	70.7(43.9)	1.7	passed
270687-ENT4 (*124*)	Entwistle Dragnet	Ford F250 Pickup	3/4 ton	1989	2000(4404)	100.0(62.1)	0	passed
220538-09 (*125*)	ADIEM	Ford F250 Pickup	3/4 ton	1989	2000(4404)	100.3(62.3)	0.4	passed
220538-10 (*125*)		Ford 250 Pickup	3/4 ton	1990	2000(4404)	100.5(62.4)	20.5	passed
270687-RSS2 (*126*)	High-Speed REACT	Chev. 2500 Pickup	3/4 ton	1990	2000(4404)	113.8(70.7)	0	marginal, controlled stop
405651-02 (*127*)	Conn. Impact Attenuation System (CIAS)	Chev. 2500 Pickup	3/4 ton	1990	2000(4404)	100.7(62.5)	19.9	failed, occupant deformation
400001-RSS2 (*128*)	REACT 350 on asphalt	Chev. 2500 Pickup	3/4 ton	1990	2000(4404)	98.2(60.9)	21.4	passed, steep exit angle
400001-WDR1(*129*)	Wide REACT	Chev. 2500 Pickup	3/4 ton	1991	2000(4404)	96.5(59.9)	0	passed, vehicle redirected
404091-2 (*130*)	Trinity Roadside Protection System (RPS)	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	101.2(62.8)	19.5	passed, vehicle redirected
400001-BBE4 (*131*)	B&B Electromatics Traffic Gate (Drawbridge)	Chev. 2500 Pickup	3/4 ton	1991	2000(4404)	70.8(43.9)	90	failed, vehicle broke through cable
472380-02 (*132*)	Vanderbilt Narrow Impact Attenuation System	Chev. 2500 Pickup	3/4 ton	1988	2000(4404)	97.0(60.2)	0	passed
472380-04 (*133*)		Dodge 2500 Pickup	3/4 ton	1986	2000(4404)	97.2(60.4)	15.0	passed
472380-05 (*134*)		Ford F250 Pickup	3/4 ton	1988	2000(4404)	100.4(62.3)	19.3	failed, occ. & traj. marginal
472380-06 (*135*)		Chev. 2500 Pickup	3/4 ton	1988	2000(4404)	98.2(60.9)	21.4	failed, veh. ramped and rolled
472380-07 (*136*)		Ford F250 Pickup	3/4 ton	1989	2000(4404)	98.6(61.2)	19.8	failed, vehicle rolled
472380-08 (*137*)		GMC 2500 Pickup	3/4 ton	1989	2000(4404)	101.9(63.3)	20.7	passed, redirected
220517-07 (*138*)	ADIEM Impact Attenuator System	Chev. 2500 Pickup	3/4 ton	1989	2000(4404)	70.2(43.6)	0.3	passed
270687-FSB3 (*139*)	Fitch Inertia Sand Barrels	Chev. C-20 Pickup	3/4 ton	1990	2000(4404)	101.7(63.2)	15	passed, redirected behind
270687-FSB4 (*139*)		Chev. C-20 Pickup	3/4 ton	1990	2000(4404)	100.2(62.2)	20	passed, controlled stop
270687-VAS2 (*140*)	Chain Link Vehicle Arrestor System	Ford F250 Pickup	3/4 ton	1988	2000(4404)	102.2(63.5)	0	passed, controlled stop

(Table continues on next page)

TABLE 33 ***(Continued)***

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
270687-VAN09 (*141*)	Vanderbilt Narrow Impact Attenuation System	GMC 2500 Pickup	3/4 ton	1989	2000(4404)	102.5(63.6)	20.3	passed, redirected
270687-VAN10 (*142*)	REACT 350 Vanderbilt	Chev. 2500 Pickup	3/4 ton	1989	2000(4404)	74.2(46.1)	19.7	passed, redirected
405651-3 (*143*)	CIAS-Connecticut Impact Attn. System	Chev. 2500 Pickup	3/4 ton	1992	2077(4404)	99.5(61.8)	20.5	passed, redirected
405651-4 (*143*)		GMC 2500 Pickup	3/4 ton	1992	2075(4404)	99.9(62.0)	14.6	passed, redirected
404231-1 (*144*)	NCIAS	Chev. 2500 Pickup	3/4 ton	1992	2076(4571)	99.2(61.6)	14.7	passed, redirected
220550-1 (*145*)	ADIEM w/new plastic covers	Ford F-250	3/4 ton	1991	2000(4404)	72.3(44.9)	0	passed, vehicle stopped
404091-6 (*130*)	Trinity Roadside Protection System (RPS)	Chev. 2500 Pickup	3/4 ton	1992	2000(4404)	98.1(60.9)	14.0	passed, vehicle stopped
220549-1 (*146*)	Texas Barrel Cushion	Ford F250 Pickup	3/4 ton	1990	2000(4404)	100.7(62.5)	19.2	passed, smooth redirection
220549-2 (*146*)		Ford F250 Pickup	3/4 ton	1990	2000(4404)	99.7(61.9)	16.5	passed, controlled redirect, stop
404231-3 (*144*)	NCIAS	Chev. 2500 Pickup	3/4 ton	1994	2076(4571)	97.1(60.3)	20.2	passed, vehicle redirected
400001-BBE5 (*147*)	B&B Electromatics Traffic Barrier Gate	Ford F250 Pickup	3/4 ton	1993	2000(4404)	69.2(39.1)	90	failed, gate ruptured
400001-WDR7 (*148*)	Wide REACT	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	96.9(60.2)	22.5	passed, vehicle redirected
400001-WDR8 (*148*)		Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	97.8(60.7)	14.7	passed, vehicle redirected
404231-4 (*144*)	NCIAS	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	95.9(59.5)	20.7	failed, significant occ. comp. deformation
404091-11 (*130*)	Trinity Roadside Protection System (RPS)	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	99.9(62.0)	20.6	passed, vehicle contained and redirected
400001-BBE6 (*149*)	B&B Traffic Control Gate	Ford F250 Pickup	3/4 ton	1993	2000(4404)	68.1(42.3)	90	failed, veh. penetrated; cables pulled out of swages
404091-17 (*130*)	Trinity Roadside Protection System (RPS)	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	100.4(62.3)	0	passed, controlled stop
404091-18 (*130*)		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.9(62.6)	20.0	passed, vehicle redirected
400001-BBE7 (*150*)	B&B Traffic Control Gate	Ford F250 Pickup	3/4 ton	1992	2000(4404)	71.0(44.1)	90	passed, vehicle stopped
400001-SRR1 (*151*)	REACT 2-rows @ 24 inch	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.4(62.3)	0	passed, vehicle redirected
400001-SRR3 (*152*)		Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	101.2(62.8)	20.6	passed, veh. redirected
400001-SRR6 (*153*)		Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	100.4(62.3)	19.3	passed, veh. redirected
400001-SRR4 (*154*)	REACT 1-row @ 24 inch	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	97.9(60.8)	0	passed, veh. redirected

TABLE 33 ***(Continued)***

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
01-7620-002 (*155*)	TL-3 QuadGuard System Crash Cushion	Chev. C2500 Pickup	3/4 ton	1989	2001(4406)	100.0(62.1)	21	passed
01-7620-003 (*155*)		GMC C2500 Pickup	3/4 ton	1988	2001(4406)	98.6(61.2)	21	passed
01-7620-005 (*155*)		Chev. C2500 Pickup	3/4 ton	1988	2045(4503)	97.1(60.3)	15	passed
01-7620-006 (*155*)		Chev. C2500 Pickup	3/4 ton	1989	2042(4496)	98.6(61.2)	0	passed
01-7620-001 (*155*)		Chev. C2500 Pickup	3/4 ton	1990	1964(4324)	98.6(61.2)	21	passed
01-7620-011 (*156*)	TL-2 QuadGuard System Crash Cushion	Chev. C2500 Pickup	3/4 ton	1988	2045(4503)	68.3(42.4)	0	passed
01-7612-001 (*157*)	Wide QuadGuard System Crash Cushion	Chev. C2500 Pickup	3/4 ton	1989	2032(4476)	94.2(58.5)	21.0	passed
01-7612-003 (*157*)		Chev. C2500 Pickup	3/4 ton	1988	1959(4314)	98.7(61.3)	15.0	passed
01-7612-004 (*157*)		Chev. C2500 Pickup	3/4 ton	1988	1991(4384)	99.9(62.0)	0	passed
01-7612-006 (*157*)		Chev. C2500 Pickup	3/4 ton	1988	2016(4439)	98.4(61.1)	21.5	passed
01-7612-008 (*157*)		Chev. C2500 Pickup	3/4 ton	1990	1998(4399)	97.7(60.7)	21.0	passed
01-7602-005 (*158*)	QuadGuard LMC System Crash Cushion	Chev. C2500 Pickup	3/4 ton	1990	2007(4419)	98.4(61.1)	16.0	passed
01-7602-001 (*158*)		Chev. C20 Pickup	3/4 ton	1981	2013(4433)	95.4(59.2)	21.0	passed
01-7602-003 (*158*)		Chev. C2500 Pickup	3/4 ton	1989	2002(4408)	100.4(62.3)	0	passed
01-7620-016 (*159*)	TL-2 QuadGuard System Crash Cushion	Chev. C2500 Pickup	3/4 ton	1990	2016(4439)	66.7(41.4)	0	passed
01-7620-019 (*159*)		Chev. C2500 Pickup	3/4 ton	1989	2006(4417)	71.3(44.3)	20.0	passed
01-7611-002 (*160*)	QuadGuard Elite System Crash Cushion	GMC C2500 Pickup	3/4 ton	1989	2019(4446)	101.0(62.7)	0	passed
01-7629-001 (*161*)	WorkZoNet Dragnet Arrestor	Chev. C2500 Pickup	3/4 ton	1988	2009(4424)	93.9(58.3)	0	passed
01-7617-002 (*162*)	ALPHA 100K TMA	Chev. C2500 Pickup	3/4 ton	1992	1999(4402)	96.6(61.8)	0	passed
01-7618-001 (*163*)	Safe-Stop TMA	Chev. C2500 Pickup	3/4 ton	1989	2000(4403)	98.9(61.4)	0	passed
9910-12 (*164*)	Energy Absorption Alpha Model	Chev. Scottsdale Pickup	3/4 ton	1981	2043(4500)	72.6(45.1)	0	N/A
472910-01 (*165*)	Polyethylene Cylinder TMA	GMC 2500 Pickup	3/4 ton	1991	2000(4404)	99.6(61.8)	0	failed, high ridedown
472910-02 (*165*)		GMC 2500 Pickup	3/4 ton	1991	2000(4404)	102.4(63.6)	0	failed, occ. risk too high
472910-04 (*166*)	Vanderbilt TMA	GMC 2500 Pickup	3/4 ton	1990	2000(4404)	101.9(63.3)	0	marginal, ridedown marginal
400001-VTM1 (*167*)		Chev. 2500 Pickup	3/4 ton	1990	2000(4404)	98.1(60.9)	0	marginal
049F-03 (*168*)	Hexcel HEX-MOD4 TMA	Dodge Ram 250 SE Pickup	3/4 ton	1986	2000(4404)	97.4(60.5)	0	failed, occ. risk too high

(Table continues on next page)

TABLE 33 ***(Continued)***

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
405241-01 (*169*)	Connecticut Truck-Mounted Attenuator	Ford F250 Pickup	3/4 ton	1988	2000(4404)	70.9(44.0)	0	passed
405241-02 (*170*)		Chev. C2500 Pickup	3/4 ton	1989	2000(4404)	70.3(43.6)	0	passed
405241-03 (*171*)		Ford F250 Pickup	3/4 ton	1988	2000(4404)	69.6(43.2)	10.3	passed
400001-RNC2 (*172*)	RENCO Truck-Mounted Attenuator	Ford F250 Pickup	3/4 ton	1994	2000(4404)	100.3(62.3)	0	passed
400001-REN1 (*173*)		Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	69.4(43.1)	0	passed
350-3-31B (*228*)	CAT	Dodge Ram 250	3/4 ton	1989	1964 (4326)	100.6 (62.5)	0	passed
350-3-33C (*228*)		Dodge Ram 250	3/4 ton	1989	1964 (4326)	97.4 (60.5)	15	passed
350-3-37 (*228*)		Chev. C2500	3/4 ton	1989	1966 (4330)	99.8 (62.0)	20	passed
AET1B (*230*)	BSI - ABSORB 350 Crash Cushion	Chev. 2500	3/4 ton	1988	1976 (4357)	99.2 (61.6)	0	passed
AET03 (*230*)		Chev. 2500	3/4 ton	1998	1996 (4400)	97.2 (60.4)	15	passed
AET04 (*230*)		Chev. 2500	3/4 ton	1988	1930 (4255)	98.2 (61.0)	20	passed
AET05 (*230*)		Chev. 2500	3/4 ton	1989	1958 (4317)	67.2 (41.8)	0	passed
AET06 (*230*)		GMC Sierra	3/4 ton	1989	1985 (4376)	97 (60.3)	0	passed
AET07 (*231*)		GMC Sierra	3/4 ton	1983	1969 (4339)	95.6 (59.4)	20	passed
AET11 (*231*)		Chev. 2500	3/4 ton	1978	1975 (4354)	97.2 (60.4)	20	passed
AET15 (*232*)		Chev. 2500	3/4 ton	1976	1976 (4357)	71.2 (44.2)	20	passed

TABLE 34 Summary of crash tests with light trucks—work zone barriers

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
9901F-1 (*174*)	Portable, Low-Profile Concrete Barrier	GMC Sierra 2500	3/4 ton	1984	2043 (4500)	71.4 (44.4)	26.1	passed, 44 deg. roll
147-43 (*175*)	Triton Barrier	Chev. Cheyenne 2500	3/4 ton	1988	1971 (4345)	72.3 (44.9)	25.0	passed
9901F-01 (*178*)	Low Profile Barrier	GMC Sierra 2500	3/4 ton	1984	2043 (4500)	71.5 (44.4)	26.1	passed
270687-YEW7 (*179*)	Water-Cell Barrier	Chev. 2500 Pickup	3/4 ton	1990	2000 (4040)	100.5 (62.4)	25.7	passed
400001-RPC3 (*180*)	Rockingham PreCast Concrete Barrier	Chev. 2500 Pickup	3/4 ton	1990	2000 (4040)	101.8 (62.6)	25.7	passed
1959A-01 (*156*)	Limited Slip Concrete Barrier-pinned	Chev. C250 Pickup	3/4 ton	1985	2000(4404)	97.0(60.2)	25.7	failed, veh. rolled
1959A-02 (*181*)	Limited Slip Concrete Barrier-not pinned	Ford F-250 Pickup	3/4 ton	1986	2000(4404)	99.6(61.8)	26.1	failed, barrier fell off deck
1959A-03 (*181*)	Limited Slip Concrete Barrier-pinned	Ford F-250 Pickup	3/4 ton	1986	2000(4404)	97.5(60.5)	26.2	passed, max. roll 45.1 deg.
1959A-04 (*181*)	Limited Slip Concrete Barrier-grid slot	Ford F-250 Pickup	3/4 ton	1986	2000(4404)	97.9(61.9)	23.7	passed, rear of veh. rode on top
1959A-05 (*181*)		Chev. C-20 Pickup	3/4 ton	1985	2000(4404)	71.7(44.5)	25.0	failed, barrier fell off deck, veh. rolled on side, righted
270687-YEW3 (*182*)	Yodock Water-Cell Long. Barrier	Chev. 2500 Pickup	3/4 ton	1988	2000(4404)	74.2(46.1)	25	failed, veh. mounted barrier
270687-YEW4 (*182*)		Chev. 2500 Pickup	3/4 ton	1988	2000(4404)	71.5(44.4)	25.8	passed, veh. redirected
270687-YEW6 (*179*)		Chev. Pickup	3/4 ton	1990	2000(4404)	99.1(61.5)	25	failed, veh. penetrated barrier
402041-1 (*183*)	Virginia DOT Concrete Median Barrier	Chev. 2500 Pickup	3/4 ton	1994	2000(4404)	100.6(62.5)	24.5	passed, veh. redirected
473220-7 (*184*)	NYDOT Portable Concrete Median Barrier	Chev. 2500 Pickup	3/4 ton	1995	2000(4404)	98.0(60.8)	26.3	failed, I-beam connection failed
400001-ESI1 (*185*)	JJ Hooks Concrete Median Barrier	Chev. 2500 Pickup	3/4 ton	1993	2000(4404)	101.0(62.7)	25	passed, veh. redirected
404821-1 (*186*)	GA DOT Concrete Median Barrier	Chev. 2500 Pickup	3/4 ton	1996	2000(4404)	99.9(62.0)	25.6	passed, veh. redirected
01-7604-001 (*187*)	TL-3 Triton Longitudinal Barrier	Chev. C2500 Pickup	3/4 ton	1990	2005(4415)	97.6(60.6)	25.0	passed
01-7604-003 (*187*)		Chev. C2500	3/4 ton	1990	2017(4441)	96.3(59.8)	25.0	passed
I3-1 (*224*)	Iowa Temporary Concrete Barrier Rail Half-Section	Chevy	3/4 ton	1985	2443 (5381)	100.3 (62.3)	20	failed, no containment
I5-1 (*222*)	Iowa Steel Temporary Barrier Rail	Chevy	3/4 ton	1983	2495 (5495)	97.5 (60.6)	22.5	passed
ITMP-1 (*208*)	F-Shape Temporary Concrete Barrier	Chevy	3/4 ton	1985	2000 (4405)	103.1 (64.0)	27.6	failed, no containment
ITMP-2 (*208*)	F-Shape Temporary Concrete Barrier	Chevy	3/4 ton	1986	2005 (4416)	100.3 (62.7)	27.1	passed
KTS-1 (*207*)	Temporary Barrier for Offroad Applications	Chevy	3/4 ton	1990	1998 (4400)	99.6 (61.9)	26.9	passed
SGD1 (*234*)	Safe Guard Barrier	Chev. Custom Delux	3/4 ton	1972	2005 (4420)	101.6 (63.1)	25	passed

TABLE 35 Summary of crash tests with light trucks—roadside geometric features

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
4798-14 (*63*)	3:1 Slope, 15-ft Embankment Height	Ford F150 Pickup	1/2 ton	1979	2020 (4450)	80.5 (50)	15	23 deg. roll
4798-15 (*63*)		Dodge B200 Van	3/4 ton	1979	1870 (4120)	80.5 (50)	23	23 deg. roll

TABLE 36 Summary of crash tests with light trucks—support structures

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
453360-3 (*188*)	Skid-Mounted Sign Support	Chev. Custom 20 Pickup	3/4 ton	1984	2000(4404)	98.0(60.9)	0	passed

TABLE 37 Summary of crash tests with light trucks—other features

Test No. (Ref.)	Test Article	Vehicle Description				Impact Conditions		Assessment of Results
		Make and Model	Rating	Model Year	Gross Weight kg (lb)	Speed km/h (mph)	Angle (deg.)	
7046-5 (*189*)	Instrumented Wall	Chevrolet Custom 20	3/4 ton	1979	2456 (5409)	105.9 (65.8)	19.9	N/A
7046-6 (*189*)		Chevrolet Custom 20	3/4 ton	1979	2466 (5432)	75.3 (46.8)	19.0	N/A
7046-7 (*189*)		Chevrolet Suburban		1980	2452 (5400)	103.1 (64.1)	19.7	N/A
7046-8 (*189*)		Chevrolet Suburban	1/2 ton	1979	2428 (5350)	71.9 (44.7)	19.5	N/A

Temporary Barrier. Proprietary portable barriers meeting test level 3 of *NCHRP Report 350* include the Yodock Water-Cell Barrier, Rockingham PreCast Concrete Barrier, J-J Hooks Concrete Barrier, and the TL-3 Triton Barrier. The proprietary Low-Profile Barrier meets test level 2 of *NCHRP Report 350*, as do modified versions of some of the above-mentioned proprietary barriers.

2.5.2.8 Roadside Geometric Features

Testing of roadside geometric features with light trucks has been very limited, as can be seen in Table 35. In two full-scale embankment traversal tests, a $^{1}/_{2}$-ton pickup truck and $^{3}/_{4}$-ton van successfully negotiated a 3:1 side slope with an embankment height of 4.6 m (15 ft). In a similar test with a small automobile, the vehicle slid down the embankment and rolled over when the tires plowed into the ground. This would appear to indicate that, in terms of roadside encroachments, a small automobile is more critical than a high CG van. However, the rollover of the small automobile was not a function of the geometry of the side slope; it was attributed to soft soil conditions at the toe of the slope. The van, on the other hand, experienced a 23-degree roll angle before stabilizing, and would likely have been more sensitive to the actual geometry of the side slope. Reference may be made to Section 2.2 for computer simulations made of roadside geometric features with an array of light truck subclasses.

2.5.2.9 Support Structures

As shown in Table 36, only one crash test has been conducted with support structures, and that was with a temporary sign support. The primary concerns in structures of this type are the change in vehicular velocity and the OIV that occurs during impact. Small vehicles and their occupants are at greater risk during such impacts than are occupants of heavier vehicles. The critical test for a support structure is typically a slow speed impact with a small automobile, which is a recommended test in *NCHRP Report 350*. Since most breakaway or yielding sign and luminaire support structures have been qualified by this criterion, there is no apparent need to test these structures with light trucks.

2.5.2.10 Other Features

Table 37 summarizes tests of light trucks with an instrumented wall. The purpose of the tests was to measure impact forces for a variety of passenger vehicles, light trucks, and heavy trucks.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATION

3.1 ADEQUACY OF SAFETY FEATURES FOR LIGHT TRUCKS

The primary objective of this research was to assess the adequacy of highway safety features to accommodate impacts by the various light truck subclasses. Four basic procedures were undertaken to address this requirement: (1) computer simulation studies, (2) crash data studies, (3) full-scale crash test studies, and (4) a review of the literature.

Computer simulation studies were used to examine the behavior of light truck subclasses during impacts with widely used longitudinal barriers (e.g., guardrails, median barriers, and bridge rails), and during encroachments on common roadside geometric features (e.g., fill sections and driveway sections). A similar study of automobiles, conducted at TTI under separate sponsorship (*2*), was included for comparison purposes. A large number of simulated impacts and encroachments were made encompassing a wide range of speed and angle combinations for each of the light truck and automobile subclasses. This is the advantage of computer simulation studies: a very large combination of conditions can be examined economically. Results of this phase of the project provided supplemental information from which potential problem areas and gaps in safety performance could be identified. Simulation programs used in these studies have been validated to varying degrees. For example, the program used to simulate encroachments on roadside safety features has been shown to provide accurate results when compared with actual tests, whereas the program used to simulate rigid longitudinal barriers has been subjected to limited validation studies. Since inception of the simulation studies described herein, significant advancements have been made in the development and application of the DYNA-3D computer program, greatly improving the fidelity of simulations of vehicular impacts with safety features. It is expected that DYNA-3D will be used to expand and supplement the computer studies reported here.

The crash (accident) data study consisted of evaluating the frequency, severity, and rollover involvement of single-vehicle, ran-off-road type crashes for automobile and light truck subclasses. The crash databases used in the study include FARS, NASS GES, and HSIS. All these databases contain police-level or enhanced police-level crash data.

The purpose of the crash data analyses was to compare the crash frequency, severity, and rollover involvement of various automobile platforms and light truck subclasses in collisions with roadside features. Therefore, the datasets were subsetted to include only single-vehicle crashes involving late-model vehicles striking roadside objects or appurtenances.

A limited full-scale crash testing program was also conducted to provide additional insight on the behavior of widely used roadside safety features when impacted by light truck subclasses. Factors considered in the selection of test details included (a) the degree to which various safety features have been evaluated in terms of *NCHRP Report 350* requirements, (b) the extent of use of the respective features nationwide, and (c) the probability of acceptability performance when impacted by the full range of light truck subclasses at the extremes of the expected impact conditions.

A test program was selected, consisting of two phases. Phase 1 consisted of four tests wherein the Standard G4(1S) Guardrail system was impacted by a range of light truck subclasses at a nominal speed of 100 km/h and a nominal impact angle of 20 degrees. Phase 2 consisted of three tests. In the first test a 2000P test vehicle impacted a Standard G4(1S) Guardrail system at a nominal speed of 110 km/h and a nominal impact angle of 20 degrees. In the next test a 2000P test vehicle impacted a Modified G4(1S) Guardrail system at a nominal speed of 110 km/h and a nominal impact angle of 20 degrees. In the modified system a wood blockout is used instead of the steel blockout. In the third test a 4-wheel drive version of the 2000P test vehicle impacted a Modified G4(1S) Guardrail system at a nominal speed of 104 km/h and a nominal impact angle of 20 degrees.

The literature study consisted of the collection and synthesis of published data on the impact performance of roadside safety features when impacted by light trucks. Numerous crash test studies provided most of the data collected, with computer studies providing limited data. Most widely used roadside safety features have now been crash tested in accordance with *NCHRP Report 350* recommendations, and as such have been subjected to at least one test with a light truck, the 2000P (¾-ton pickup truck) test vehicle. As discussed in Section 3.2, the 2000P was found to be a reasonably good representative of the heavier light truck subclasses, and thus a roadside safety feature meeting *Report 350* recommendations can be expected to perform in an acceptable manner when impacted by most of the heavier light truck subclasses.

Each of these four procedures provided valuable insight on the problem under investigation. However, because of the inherent limitations of the computer simulation programs used in the study, and inherent limitations of the crash data study, more emphasis must be placed on results of crash tests.

The following sections contain a synthesis of the findings as related to specific highway safety features.

3.1.1 Bridge Rails

The concrete New Jersey Safety-Shape Barrier is believed to be the most commonly used bridge rail and median barrier in the United States. Results of this study indicate that "mixed" impact performance of the New Jersey Safety-Shape Barrier can be expected for light trucks. Crash test data and simulation data indicate acceptable impact performance for test level 3 conditions of *NCHRP Report 350* when Chevrolet pickups are used. Rollover has been observed in crash tests at certain impact conditions with Ford pickups.

Results of the simulation study indicate that light trucks are more likely to overturn than automobiles for impacts with the New Jersey Safety-Shape Barrier. Within the light truck subclasses, the SUV has the greatest propensity to overturn, even at relatively low speeds and impact angles. The LUV, the SPU, and the LVN also exhibit a propensity to overturn for certain impact conditions.

Results of the crash data study tend to corroborate the simulation studies. With some exceptions, the crash data study found a greater propensity for overturn of light trucks impacting "concrete median barriers" than automobiles. It is conjectured that most of these barriers were New Jersey Safety-Shape Barriers.

Use of the concrete Constant-Slope Barrier as a bridge rail and as a median barrier has increased in recent years. Crash testing of the Constant-Slope Barrier has been limited, with only one known test with a light truck. The Constant-Slope Barrier successfully passed *NCHRP Report 350* test level 3 requirements.

Results of the simulation study indicated that light trucks had a greater propensity for overturning in impacts with the Constant-Slope Barrier than in impacts with the New Jersey Safety-Shape Barrier.

A concrete Vertical-Wall Barrier is occasionally used as a bridge rail. Crash testing and simulation studies indicated that light truck impacts with the Vertical-Wall Barrier are very stable, much more so than the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier. Care must be taken, however, in selecting the Vertical-Wall Barrier's height. For a redirection impact, the occupant's upper torso and head can be projected through the vehicle's side window, and then can strike the face of the Vertical-Wall Barrier if its height is too great. A vehicle tends to roll away from the face of the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier during an impact, and thus the occupant will not normally contact the face of the barrier.

Although the simulation study pointed to much better performance of the Vertical-Wall Barrier, firm recommendations relative to the merits of the three widely used barriers (New Jersey Safety-Shape Barrier, Constant-Slope Barrier, and Vertical-Wall Barrier) cannot be made because of the previously mentioned limitations of the computer programs used in the simulation study. Further, there are insufficient data from the crash data study and the crash test studies to corroborate findings of the simulation study. Also, barrier cost-effectiveness continues to be an elusive factor in determining the more appropriate barrier. It is known that for shallow approach angles, vehicles will be redirected away from the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier with minimal or no damage, whereas there will always be damage for any approach angle into the Vertical-Wall Barrier. Please see Section 4.1, item 5, and Section 4.2, item 1, for further discussion of rigid barriers.

A number of "state-specific" bridge rails have been successfully tested according to test level 3 recommendations of *NCHRP Report 350*. Reference should be made to Section 2.5.2.1 for more details.

3.1.2 Guardrails

Widely used guardrail systems include the G4(1S), the G4(2W), and the G9. The G1, G2, and G3 systems are used to a lesser extent. All of these systems have been tested according to *NCHRP Report 350* test level 3 recommendations. With the exception of the G2, the G4(1S), and the G9 systems, all met *NCHRP Report 350* evaluation criteria. However, as described in Section 2.5.2.2, modified versions of the G2, G4(1S), and G9 systems have passed *NCHRP Report 350* test level 3 recommendations.

Crash testing conducted as part of Project 22-11 (see Section 2.4) verified acceptable impact performance of the G4(1S) system for a range of light truck subclasses at impact conditions of 100 km/h and a 20 degree impact angle. The G4(1S) Guardrail system is believed to be the most widely used roadside safety feature in the United States. The testing program also included a test of the Modified G4(1S) system at impact conditions of 110 km/h and an impact angle of 20 degrees with the *NCHRP Report 350* 2000P test vehicle (¾-ton pickup). The test was successful. In addition, a test was conducted with a 4-wheel drive ¾-ton pickup, with the Modified G4(1S) system at impact conditions of 104 km/h and an impact angle of 20 degrees. This test was not successful. It is thus concluded that the Modified G4(1S) will contain and safely redirect most light trucks, even at extreme impact conditions. However, under extreme impact conditions, the Modified G4(1S) Guardrail system may not contain the heavier 4-wheel drive light truck subclasses.

With some exceptions, results of the simulation study of flexible barriers tended to compare favorably with crash test studies (see Section 2.2.8.2). Limitations of the program used in the simulation study precluded detailed analysis of vehicular impacts with the barriers. The simulation study also indicated that the larger light truck subclasses were more critical in terms of barrier design than the lighter light truck subclasses. For given impact conditions, the larger subclasses induced higher loads on the barrier and were more prone to snagging problems between the front wheel and barrier posts.

The crash data study found that almost half of fatal accidents involving impacts with longitudinal barriers were rollovers (see Section 2.3). Of these, a higher percentage of the fatal rollovers were with flexible barriers than rigid (i.e., concrete) barriers.

The concrete New Jersey Safety-Shape Barrier is now being used for roadside applications, and as such can be considered a “guardrail.” Reference should be made to Section 3.1.1 for discussion of this barrier.

3.1.3 Median Barriers

Widely used median barriers include the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier. Of these, the New Jersey Safety-Shape Barrier is much more widely used. Metal barriers, including the Steel W-Beam Barrier and the Steel Box-Beam Barrier, are still in use, but many have been replaced by the New Jersey Safety-Shape Barrier or the Constant-Slope Barrier. Crash testing of the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier has been conducted according to *NCHRP Report 350* recommendations, and both have been found acceptable. Crash testing of the metal median barriers has not been conducted. The simulation studies of Section 2.2 examined the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier but did not address metal median barriers. Reference should be made to Section 3.1.1 for a discussion of the impact performance of the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier for light trucks.

3.1.4 Guardrail End Treatments

Up to the end of the 1980s, most guardrail end treatments were generic, nonproprietary designs. The breakaway cable terminal and the “Texas twist” were the most widely used systems. Since that time, several proprietary designs have been developed and qualified according to *NCHRP Report 350* recommendations and are now widely used. These include the ET-2000, SRT, BEST, SKT, FLEAT, and REGENT. The only nonproprietary end treatment qualified to *NCHRP Report 350* test level 3 recommendations is the Minnesota ELT. Use of this device is limited to wood-post guardrail systems.

Further crash testing, examination by computer simulation, or examination by crash data studies of guardrail end treatments were not within the scope of this study. Notwithstanding this, the authors are unaware of any data identifying in-service problems with these devices for the light truck subclasses. Reference should be made to Section 2.5.2.5 for further discussion of these designs and testing of them.

3.1.5 Crash Cushions and TMAs

All widely used crash cushions have been successfully tested in accordance with *NCHRP Report 350* test level 3 recommendations. With few exceptions, all are proprietary devices. These include the ABSORB 350, NCIAS, Quad-Guard Elite, TRACC, REACT 350, Wide React, QuadGuard LMC, QuadGuard Wide, ADIEM, CAT, and Fitch Inertia Sand Barrels. Some of these designs have also been modified to meet *NCHRP Report 350* test level 2 recommendations.

TMAs meeting *NCHRP Report 350* recommendations include the ALPHA 100K TMA, Safe-Stop TMA, Connecticut TMA, and the RENCO TMA.

Further crash testing, examination by computer simulation, or examination by crash data studies of crash cushions and TMAs were not within the scope of this study. Notwithstanding this, the authors are unaware of any data identifying in-service problems with these devices for the light truck subclasses. Reference should be made to Section 2.5.2.6 for further discussion of these designs and testing of them.

3.1.6 Work Zone Barriers

Nonproprietary barriers meeting test level 3 of *NCHRP Report 350* include the Virginia Portable Concrete Barrier, Georgia Portable Concrete Barrier, and the F-Shape Temporary Barrier. Proprietary portable barriers meeting test level 3 of *NCHRP Report 350* include the Yodock Water-Cell Barrier, Rockingham Precast Concrete Barrier, J-J Hooks Concrete Barrier, and the TL-3 Triton Barrier. The proprietary Low-Profile Barrier meets test level 2 of *NCHRP Report 350*, as do modified versions of some of the above-mentioned proprietary barriers.

Further crash testing, examination by computer simulation, or examination by crash data studies of work zone barriers were not within the scope of this study. Notwithstanding this, the authors are unaware of any data identifying in-service problems with these devices for the light truck subclasses. Reference should be made to Section 2.5.2.7 for further discussion of these designs and testing of them.

3.1.7 Roadside Geometric Features

Crash testing of roadside geometric features with light trucks has been very limited (see Section 2.5.2.8). However, computer simulation studies have shed light on the behavior of automobiles and light trucks encroaching on embankments and on driveway sections (see Section 2.2.8.3). The crash data study (see Section 2.3) has also shed light on the behavior of automobiles and light trucks encroaching on roadside geometric features. On the basis of results of these studies, it is concluded that (a) light trucks have a greater propensity to overturn than automobiles, (b) the propensity to overturn for light trucks increases with speed at a rate greater than automobiles, (c) for embankments, light trucks require a greater lateral distance off the road to recover and begin a return to the road (i.e., greater clear zone) than automobiles, and (d) driveway and cross median slopes of 10 to 1 or flatter are needed to minimize overturn potential for light trucks.

3.1.8 Sign and Luminaire Support Structures

The primary concern in structures of this type is the change in vehicular velocity and the OIV that occurs during impact. Small vehicles and their occupants are at greater risk during such impacts than are occupants of heavier vehicles. The critical test for a support structure is typically a slow speed impact with a small automobile, which is a recommended test in *NCHRP Report 350*. Since most breakaway or yielding sign and luminaire support structures have been qualified by this criteria, there is no apparent need to test these structures with light trucks. The small automobile required in the *Report 350* test has a mass of 820 kg. The smallest light truck has a mass greater than 820 kg.

Further crash testing, examination by computer simulation, or examination by crash data studies of support structures were not within the scope of this study. Notwithstanding this, the authors are unaware of any data identifying in-service problems with these devices for the light truck subclasses.

3.2 ADEQUACY OF 2000P TEST VEHICLE

The following is an excerpt from Appendix A of *NCHRP Report 350*:

> A pickup truck was selected to replace the full-size automobile widely used in the past (4500S vehicle in *Report 230*) for the following reasons:
>
> (1) Sales of light-duty trucks in general, and pickup trucks in particular, have increased to the point that they now constitute a significant portion of all passenger vehicles operating on U.S. highways.
> (2) Full-size automobiles with the mass of the 4500S test vehicle (2040 kg) are no longer sold in the U.S. with the exception of a few expensive luxury automobiles. The nominal mass of a full-size family sedan now being sold in the U.S. is about 1350 kg.
> (3) Although there are structural and profile differences, the recommended 2000 kg pickup will produce impact loading reasonably similar to the 4500S vehicle of *Report 230*. Limited full-scale crash tests with an instrumented wall (*17*) indicate that a pickup will produce a maximum impact force slightly less than that of an automobile of equal mass, whereas the effective height of the impact force will be slightly higher for the pickup, all other conditions being equal. Consequently, the 2000P test vehicle is expected to provide linkage with the numerous tests conducted with the 4500S vehicle.
>
> A ¾-ton pickup is recommended for the following reasons:
>
> (1) Section 1073 of the Intermodal Surface Transportation Efficiency Act of 1991 mandated the development of standards for roadside barriers and other safety appurtenances "... which provide an enhanced level of crashworthy performance to accommodate vans, minivans, pickup trucks, and 4-wheel drive vehicles ..." The ¾-ton pickup is believed to be representative of a large segment of the light-duty truck population. The light-duty truck population includes large numbers of conversion vans on ¾-ton chassis, Blazers, Broncos, and pickups with and without 4-wheel drive, pickups with campers, minivans, etc., whose mass and center of mass above ground approximate those of the ¾-ton pickup. However, the exact degree to which features designed to meet test and evaluation requirements recommended herein will satisfy the intent of Section 1073 is not known at this time. Impact performance of any given feature is known to be sensitive to small changes in test parameters, especially those associated with the test vehicle. It must also be noted that some 4-wheel drive vehicles, as well as some conventional-drive vehicles, are either manufactured or customized by their owners to have oversized tires, extended suspension systems, small track widths, etc. These design features can greatly diminish a vehicle's stability, i.e., its resistance to overturn. It is not economically feasible to design safety features to accommodate vehicles of this type.
> (2) Very little, if any, ballast will be needed to meet the recommended test inertial mass.
> (3) Use of a specific pickup type will enhance test standardization. (*6*, pp. 67–68)

Since publication of *NCHRP Report 350*, considerable insight has been gained as to the adequacy of the 2000P test vehicle as a surrogate or representative light truck design vehicle. However, before discussing these findings, it is important to understand the logic that has driven the development of test guidelines for the past 30 years. An effort has been made to select test vehicles and test conditions (e.g., speed and encroachment angle) that approach extremes of the spectrum for use in evaluating the impact performance of a feature. Typically a small and a large passenger vehicle have been used to evaluate most features, with large trucks occasionally being used for very high-performance features. It has been assumed that features exhibiting satisfactory performance for these vehicles at extreme impact conditions would in general exhibit satisfactory performance for the passenger vehicle population for most real-world impact conditions.

Among other reasons previously given, the 2000P vehicle was selected because its size and mass approached the upper limit of passenger vehicles, and light trucks in particular. It was not selected to be representative of all light truck subclasses.

The question then is this: will a feature designed for and satisfactorily tested with the 2000P vehicle perform satisfactorily for other light truck subclasses, especially the heavier light truck subclasses? Limited data have been gleaned from this study to address this question. These data were derived from studies of the dimensional and inertial properties of light trucks, computer simulation studies, crash (i.e., accident) data studies, and crash test studies and are summarized below.

Dimensional and Inertial Properties—Vehicular properties believed to be of key significance in terms of a features impact performance are mass, center-of-mass height, front overhang (i.e., distance from center of front wheel to forward-most part of vehicle), bumper height, wheel size, wheelbase, mass distribution (as measured by mass moments of inertia), wheel suspension properties, and crush stiffness. To the extent available, these properties were collected and comparisons were made between the various light truck subclasses (see Section 2.2). Within the limits of these data, the 2000P vehicle is considered a good representative of the larger light truck subclasses.

Computer Simulation Studies—as previously discussed, a large number of simulated impacts were made with widely used longitudinal barriers and roadside geometric features, for the various light truck subclasses. The following was noted:

A. There were no predicted overturns of the LPU (the 2000P vehicle) with the New Jersey Safety-Shape Barrier, whereas overturns were predicted for the LUV and the LVN for several impact conditions. Also, the LPU was stable for all but one impact condition with the Constant-Slope Barrier, whereas the LVN overturned for several impact conditions. This raises some concern as to the adequacy of the 2000P vehicle as a good representative of the larger light truck subclasses, at least for impacts with the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier.

B. In comparing predicted performance of the LPU with the other light truck subclasses for flexible barriers, the LPU caused barrier loading (as measured by barrier deflection) similar to that of the other large light truck subclasses, the LUV and the LVN. The LVN generally had greater values of wheel snag than the other subclasses. This was expected because the LVN had a considerably higher mass than the other subclasses. A key factor in evaluating barrier performance is vehicular stability subsequent to impact. The two-dimensional limitations of BARRIER VII precluded a determination of this factor in the simulation study. Therefore, results of the flexible barrier simulations and comparisons that could be made offer inconclusive evidence regarding the adequacy of the 2000P vehicle as a good representative light truck for impacts with flexible barriers.

C. With regard to roadside geometric features, comparisons of the predicted performance of the LPU with the other light truck subclasses for fill sections revealed that the other subclasses required slightly more lateral distance for recovery than the LPU. In comparisons of the predicted performance of the LPU with the other subclasses for driveway sections, the smaller subclasses generally had higher overturn rates than did the larger subclasses, including the LPU. In comparing the predicted performance of the LPU with the other large subclasses, the overturn rates were similar. Thus, the results of simulated encroachments on geometric features and these comparisons suggest that the 2000P is a reasonably good representative of the larger light truck subclasses.

Crash (i.e., Accident) Data Study—The study, as previously discussed, consisted of evaluating the frequency, severity, and rollover involvement of single-vehicle, ran-off-road type crashes for light truck and automobile subclasses. The crash databases used in the study were FARS, NASS GES, and HSIS. All these databases contain police-level or enhanced police-level crash data. On the basis of the crash data analysis, it was concluded that the current test vehicles specified in *NCHRP Report 350* (i.e., the 820-kg automobile [820C] and the 2000-kg, $^3/_4$-ton pickup truck [2000P]) appear to be good surrogates for the vehicle fleet on the basis of the "worst practical condition" philosophy. There were no indications of large gaps in impact performance that are not being adequately addressed by 820C and 2000P design test vehicles. The platforms/subclasses represented by the 820C and 2000P test vehicles were generally more critical than the other platforms/subclasses in terms of injury severity and rollover involvement.

Crash Testing Studies—As previously discussed, a two-phase crash test program was conducted as part of Project 22-11. Phase 1 consisted of four tests wherein the Standard G4(1S) Guardrail system was impacted by a range of light truck subclasses at a nominal speed of 100 km/h and a nominal impact angle of 20 degrees. The purpose of these tests was to assess the performance of the most widely used guardrail system to impacts by light truck subclasses at impact conditions more representative of real-world conditions than those required in test 3-11 of *NCHRP Report 350* (100 km/h at 25 degrees). Vehicles from four of the seven subclasses were chosen for testing: the SUV, the MUV, the LPU, and the LVN. Limits in the project budget precluded testing a vehicle from all seven subclasses. However, it was concluded that the vehicle subclasses that were tested would subject the guardrail to demands equal to or greater than the subclasses not tested.

Phase 2 consisted of three tests. The primary objective was to further evaluate the G4(1S) system at a higher impact speed (110 km/h), and with a 4-wheel drive vehicle. A 20 degree impact angle was selected since this would permit a determination of the effects of increased speed on performance, given that the previous four tests on the G4(1S) were at 100 km/h and 20 degrees. Impact conditions of 110 km/h and 20 degrees produced an IS as defined in *Report 350* approximately equal to test 3-11 conditions of 100 km/h and 25 degrees. The Standard G4(1S) W-Beam Guardrail system was evaluated in each of the four tests of Phase 1, and in the first test of Phase 2. The Modified G4(1S) W-Beam Guardrail system was evaluated in the last two tests of Phase 2. It was observed during the Phase 1 testing that the 2000P loaded and damaged the barrier in a way similar to that of the LVN, and the post-impact behavior of the 2000P was more unstable (i.e., there was more rolling and yawing motion) than any of the other light truck subclasses.

A limited number of other crash tests have been conducted with light truck subclasses other than the LPU. These have included LUV tests with precast concrete barriers (*90*), LUV tests with an instrumented wall (*189*), LVN tests with the G1, G3, G4(2W) and the G9 flexible barriers (*24*), and a LVN with the G4(1S) barrier (*63*). Comparable tests have been conducted with the LPU for the instrumented wall tests (*189*), the G9 flexible barrier (*20*), and the G4(1S) barrier (*20*). Results of these comparisons indicated that the 2000P vehicle created demands on the barrier equal to or greater than the LUV or the LVN.

For vehicles of similar mass, it is believed that the LPU is a more demanding vehicle than the LVN largely because of the differences in the front overhang. The larger front overhang in the LVN reduces the amount of wheel contact and potential snagging on support posts in longitudinal barrier impacts, inducing a greater degree of redirection in the vehicle prior to wheel contact. A greater amount of wheel-to-post contact and subsequent wheel snagging has resulted in a more unstable post-impact behavior for the LPU. For vehicles of similar mass, the reason the LPU is more critical than the LVN is not so obvious since both have similar front overhangs. In fact, according to the limited data that exist, the differences between the LPU and the LVN are not as pronounced as the differences between the LPU and the LVN. It is surmised that the differences that do exist are attributable primarily to the differences in the body makeup; the LVN has a solid shell, whereas the LPU has two somewhat independent shells (i.e., the bed and the cab), resulting in significantly different torsional stiffnesses. Other factors that can contribute to differences in behavior are frontal crush stiffness, center-of-mass height, wheelbase, and mass distribution as measured by mass moments of inertia.

This evidence supports the selection of the 2000P vehicle as a good light truck design vehicle, or one that will exhibit the greatest demands on a roadside feature for given impact conditions. In other words, if a roadside feature performs acceptably during impact by the 2000P vehicle, indications are that it will perform acceptably for most other light truck subclasses, especially for the heavier light truck subclasses. Exceptions to this may be the heavier 4-wheel drive light trucks, with higher centers of mass.

In summary, most of the data support the 2000P as a good design vehicle to represent the heavier passenger vehicles in general and to represent the heavier light truck subclasses in particular. The computer simulation study indicated that the 2000P might not be a good design vehicle for widely used rigid barriers, namely the concrete New Jersey Safety-Shape Barrier and the concrete Constant-Slope Barrier. Further investigation of this concern is warranted.

Although not within the scope of this project, further investigation of the small passenger design vehicle for impact performance evaluation of safety features may be warranted. According to the computer simulation study, small light truck subclasses are definitely more unstable (i.e., prone to overturn) than the small automobile subclasses for impacts with rigid barriers, and for encroachments on roadside geometric features. Selection of a small light truck design vehicle in lieu of a small automobile may be needed.

CHAPTER 4
CONCLUSIONS AND SUGGESTED RESEARCH

4.1 CONCLUSIONS

Prior to the publication of *NCHRP Report 350* in 1993, roadside safety features were designed to accommodate impacts or encroachments by automobiles only. In recognition of the increased use of light truck subclasses as passenger vehicles, *Report 350* required the use of a light truck (i.e., the 2000P test vehicle, a ¾-ton pickup truck), in addition to a small automobile, in the evaluation of a safety feature's impact performance. Since the publication of *NCHRP Report 350*, most of the widely used safety features have been crash tested in accordance with its recommendations. Most features not meeting *Report 350* recommendations have been modified and retested to meet its requirements.

The basic purpose of this study was to determine if widely used roadside safety features would safely accommodate most real-world impacts expected from the range of light truck subclasses. These features included bridge railings, roadside barriers (i.e., guardrails), median barriers, guardrail transitions and end treatments, crash cushions, breakaway support structures, and work zone barriers. Computer simulation studies, crash (i.e., accident) data studies, crash test studies, and literature studies were used to address the study objectives. It was found that with few exceptions these widely used features, or designs modified to meet *NCHRP Report 350*, would safely accommodate most impacts expected from the range of light truck subclasses in the vehicle mix, as detailed in the following conclusions.

1. Sales of light trucks are approaching 50 percent of the passenger vehicle market in the United States. Therefore, roadside safety features should be designed to perform in an acceptable manner when impacted by the range of light truck subclasses, for most expected impact conditions.
2. Within the light truck subclasses the LPU has the greatest sales, followed by the MUV, the PVN, the SPU, the LUV, the LVN, and the SUV.
3. During an impact, the larger light truck subclasses, such as the LPUs and the large sport utility vehicles, place greater demands on longitudinal barriers, crash cushions, and end treatments than automobiles of equal mass. This is attributed in large part to higher "stability factors" (e.g., ratio of center-of-mass height to tire track width), shorter front overhangs, and higher bumpers of the light trucks.
4. Most widely used longitudinal barriers, which include bridge rails, guardrails, and median barriers, have passed tests recommended in *NCHRP Report 350* for test level 3 (i.e., the "standard" test level). One of the *Report 350* recommended test level 3 tests for a longitudinal barrier is a ¾-ton pickup truck (classified as an LPU) impacting at 100 km/h at an impact angle of 25 degrees.
5. Widely used rigid longitudinal barriers (i.e., concrete barriers) will safely contain and redirect most expected impacts by the range of light truck subclasses. These include the concrete New Jersey Safety-Shape Barrier, the concrete Constant-Slope Barrier, and the concrete Vertical-Wall Barrier. However, the simulation study conducted as part of Project 22-11 indicates that further examination of the impact behavior of light trucks with the New Jersey Barrier and the Constant-Slope Barrier may be warranted (see Section 4.2).
6. Bridge rail and median barrier types that have passed *Report 350* test level 3 include the concrete New Jersey Safety-Shape Barrier, the concrete Constant-Slope Barrier, and the concrete Vertical-Wall Barrier.
7. Various "state-specific" bridge rails have passed *NCHRP Report 350* test level 3 recommendations.
8. Widely used flexible longitudinal barriers (i.e., metal barriers as opposed to rigid concrete barriers) will safely contain and redirect most expected impacts by the range of light truck subclasses. However, under extreme impact conditions, and for some of the larger 4-wheel drive vehicles, the widely used guardrail systems may not perform as desired.
9. Guardrail types that passed *NCHRP Report 350* test level 3 recommendations include the G1 Cable Barrier, G3 Box-Beam Barrier, and G4(2W) W-Beam Rail supported by wood posts with wood blockouts, and G9 Thrie-Beam Rail supported by wood posts with wood blockouts.
10. Guardrail types that did not pass *NCHRP Report 350* test level 3 recommendations were the G2 W-Beam on weak steel post barrier, the G4(1S) W-Beam on strong steel posts with steel blockouts, and the G9 Thrie-Beam

on strong steel posts with steel blockouts. However, modified versions of these guardrails did pass *NCHRP Report 350* test level 3 recommendations.

11. Although the widely used G4(1S) Guardrail system failed *NCHRP Report 350* test level 3 conditions, it safely contained and redirected an array of light truck subclasses at 100 km/h and 20 degrees, including the ¾-ton pickup. Impact conditions of 100 km/h at 20 degrees are believed to be more representative of in-service impacts than 100 km/h at 25 degrees.
12. A modified version of the G4(1S) (i.e., wood blockouts used instead of steel blockouts) successfully passed *NCHRP Report 350* test level 3 conditions. It also passed an impact with the ¾-ton pickup at 110 km/h and 20 degrees. It failed an impact with a 4-wheel drive, ¾-ton pickup at 104 km/h at 20 degrees.
13. Nearly half of fatal ran-off-road crashes involving longitudinal barriers resulted in rollovers, with a lower percentage of rollover for rigid barriers than for flexible barriers.
14. Light trucks are more prone to overturn after impact with a longitudinal barrier than automobiles are.
15. Widely used guardrail end treatments, crash cushions, and TMAs have passed tests recommended in *NCHRP Report 350*, which include at least one test with a ¾-ton pickup. The vast majority of these devices are proprietary. Further crash testing, examination by computer simulation, or examination by crash data studies of these devices were not within the scope of this study. Notwithstanding this, the authors are unaware of any data identifying in-service problems with the above-mentioned devices for the light truck subclasses.
16. Several nonproprietary precast concrete barriers for use in work zones have met test level 3 conditions of *NCHRP Report 350*, including the Virginia Portable Concrete Barrier, Georgia Portable Concrete Barrier, and the F-Shape Temporary Barrier. Proprietary portable barriers meeting test level 3 conditions of *NCHRP Report 350* include the Yodock Water-Cell Barrier, Rockingham Precast Concrete Barrier, J-J Hooks Concrete Barrier, and the TL-3 Triton Barrier. The proprietary Low-Profile Barrier meets test level 2 conditions of *NCHRP Report 350*, as do modified versions of some of the above-mentioned proprietary barriers. Further crash testing, examination by computer simulation, or examination by crash data studies of work zone barriers were not within the scope of this study. Notwithstanding this, the authors are unaware of any data identifying in-service problems with the above-mentioned devices for the light truck subclasses.
17. Occupants of small, low-mass vehicles are at greater risk during impacts with breakaway or yielding sign and luminaire supports than are occupants of heavier vehicles. The critical test for a support structure is typically a slow speed impact with a small automobile, which is a recommended test in *NCHRP Report 350*. Larger vehicular velocity changes and larger OIVs typically occur at the lower speed. Since most breakaway or yielding sign and luminaire support structures have been qualified by this criteria, there is no apparent need to test these structures with light trucks. The small automobile required in the *Report 350* test has a mass of 820 kg. The smallest light truck has a mass greater than 820 kg. The authors are unaware of any data identifying in-service problems with widely used sign and luminaire breakaway structures for the light truck subclasses.
18. Light trucks are more likely to overturn when encroaching on a roadside geometric feature than automobiles are. Roadside geometric features include embankments and ditches, and driveway and median crossover slopes.
19. For encroachments on an embankment, light trucks require greater lateral distances (i.e., clear zones) to recover than automobiles do.
20. Driveway and median crossover slopes of 10 to 1 or flatter are needed to minimize overturn potential of light trucks traveling at 100 km/h.
21. For ran-off-road crashes, the sport utility vehicles have the highest rollover rates within the light truck subclasses, followed by pickup trucks. Vans generally have the lowest rollover rate.
22. For all ran-off-road crashes, the percent of total injury and percent A+K injury were similar for automobiles and light trucks.
23. Given a rollover crash, the injury rates are higher for automobiles than for light trucks.
24. Most of the data gathered and analyzed support the ¾-ton pickup (a test vehicle recommended in *NCHRP Report 350*) as a good design vehicle to represent the heavier passenger vehicles in general and to represent the heavier light truck subclasses in particular. The computer simulation study indicated that the ¾-ton pickup may not be the more critical design vehicle for widely used rigid barriers, namely the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier (see Section 4.2).

4.2 SUGGESTED RESEARCH

1. The simulation study indicated areas of concern for the widely used New Jersey Safety-Shape barrier and the Constant-Slope Barrier. Rollover was predicted for a number of light truck subclasses at a range of impact conditions typical of real-world impact conditions. There were no predicted overturns of the LPU with the New Jersey Safety-Shape Barrier, whereas overturns were predicted for the LUV and the LVN for several impact conditions. Also, the LPU was stable for all but one impact condition with the Constant-Slope Barrier, whereas the LVN overturned for several

impact conditions. This raises some concern as to the adequacy of the LPU vehicle as a good representative of the larger light truck subclasses, at least for impacts with the New Jersey Safety-Shape Barrier and the Constant-Slope Barrier. Further study is needed to determine if potential problems exist. Since the beginning of Project 22-11, large advancements have been made with the finite element program LS-DYNA, and this program could be used to examine, with greater fidelity, rigid barrier impacts with selected light trucks. A limited crash test program may also be warranted to complement the LS-DYNA studies.

2. Further investigation of the small passenger design vehicle for impact performance evaluation of safety features may be warranted. According to the computer simulation study, small light truck subclasses are definitely more unstable (i.e., prone to overturn) than are the small automobile subclasses for impacts with rigid barriers, and for encroachments on roadside geometric features. Selection of a small light truck design vehicle in lieu of a small passenger automobile may be warranted.
3. Although the study pointed out problem areas in certain flexible guardrail barrier systems, most of these problems have been addressed in recent studies. Therefore, no recommendations are made relative to these systems.
4. Studies of roadside clear zone requirements should include light truck design vehicles. Light trucks tend to require greater clear zones than automobiles, all other conditions being equal.
5. Roadside features such as embankments and ditches, and driveway and median crossover slopes should be designed to accommodate light trucks. Light trucks tend to be more unstable on slopes and driveway sections than automobiles are.

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APPENDIXES A THROUGH C

UNPUBLISHED MATERIAL

Appendixes A through C as submitted by the research agency are not published herein. For a limited time, they are available for loan on request to NCHRP. Their titles are as follows:

Appendix A: Computer Simulation Study
Appendix B: Crash Data Study
Appendix C: Crash Testing Study

The **Transportation Research Board** is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's mission is to promote innovation and progress in transportation by stimulating and conducting research, facilitating the dissemination of information, and encouraging the implementation of research results. The Board's varied activities annually draw on approximately 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purpose of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation

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