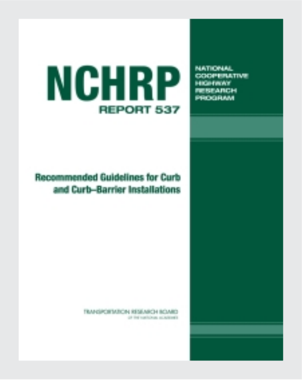

Recommended Guidelines for Curb and Curb-Barrier Installations

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 537

Recommended Guidelines for Curb and Curb–Barrier Installations

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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The work at BMI was done under the supervision of Hugh McGee and Forrest Council with the assistance of Christopher Daily, Kimberly Eccles, and Mona Killian, Research Engineers. The crash testing at E-TECH was done under the supervision of John F. LaTurner.

FOREWORD

By Charles W. Niessner
Staff Officer
Transportation Research Board

This report presents the findings of a research project to develop guidelines for the use of curbs and curb–guardrail combinations on high-speed roadways. The researchers make recommendations concerning the location of curbs with respect to the guardrail for various operating speeds. The report will be of particular interest to design engineers with responsibility for roadway design.

AASHTO highway design policy discourages the use of curbs on high-speed roadways because of their potential to cause drivers to lose control in a crash. Curbs can also cause a laterally skidding vehicle to roll over upon striking the curb, a situation referred to as tripping. In some cases, a barrier is placed in combination with a curb, and inadequate design can result in vehicles vaulting or underriding the barrier.

Although the use of curbs is discouraged on high-speed roadways, they are often required because of restricted right-of-way, drainage considerations, access control, and other curb functions. Highway agencies have typically tried to reduce problems caused by curbs by off-setting the curb from the travel way as far as possible and using different curb shapes. Off-setting the curb is not always possible because of the difficulty with right-of-way acquisition and, in some cases, the risk of detracting from features of historic parkways.

Under NCHRP Project 22-17, “Recommended Guidelines for Curbs and Curb–Barrier Combinations,” Worcester Polytechnic Institute undertook research to develop design guidelines for using curbs and curb–barrier combinations on roadways with operating speeds greater than 60km/h (40 mph).

The research team conducted an in-depth review of published literature to identify information pertinent to the design, safety, and function of curbs and curb–barrier combinations. Computer simulation methods were used in a parametric investigation involving vehicle impact with curbs and curb–barrier combinations. The computer simulations were used to determine which type of curbs are safe to use on higher-speed roadways and the proper placement of the barrier with respect to the curb. Full-scale crash tests were also conducted to validate the computer simulations. The results of the study were then synthesized and guidelines for the use of curbs and curb–barrier systems were developed.

The researchers developed recommendations for combinations of curb and strong-post guardrail, curb height, and lateral offset between the curb and guardrail for operating speeds greater than 60 km/hr (40 mph).

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CHAPTER 1

INTRODUCTION

BACKGROUND

There has long been concern over the use of curbs on roadways because of their potential to cause drivers to lose control and crash. Curbs extend 75 to 200 mm above the road surface for appreciable distances and are located very near the edge of the traveled way; thus, they present a possible hazard for motorists who may encroach on the roadside at any point within the length of the curb. This project focused on the use of curbs on higher-speed roadways, defined as roadways with design speeds of 60 to 100 km/h. AASHTO highway design policy discourages the use of curbs on higher-speed roadways because of their potential to cause drivers to lose control and crash. Curbs can also cause a laterally skidding vehicle to roll over upon striking the curb, a situation referred to as tripping. While the use of curbs is discouraged on higher-speed roadways, they are often required because of restricted right-of-way, drainage considerations, access control, delineation, and other curb functions.

In some cases, a barrier is placed in combination with a curb and an inadequate design can result in vehicles vaulting or underriding the barrier. Such installations are currently being constructed without a clear understanding of the effects that these combinations will have on the ability of the barrier to safely contain and redirect an errant vehicle. There have been a very limited number of full-scale crash tests on curb–barrier combinations and a large percentage of those tests involving the larger class of passenger vehicles such as the 2000-kg pickup truck were unsuccessful. Even the cases involving the 2000-kg pickup truck that satisfied the requirements of *NCHRP Report 350* resulted in excessive damage to the barrier system or extreme trajectories and instability of the vehicle.

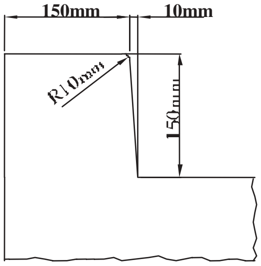
Policy on the design and use of cross-sectional highway features, including curbs, is contained in AASHTO's *Policy on Geometric Design of Highways and Streets* (i.e., the Green Book) *(1)*. The purposes of curbs are to provide drainage, delineate the edge of the pavement, support the pavement edge, provide the edge for a pedestrian walkway, and possibly provide some redirective capacity for low-speed impacts. On higher-speed roadways, the subject of this study, the primary function of curbs is to provide drainage, especially in the area of a bridge approach or other location where the risk of erosion is high.

The Green Book defines two basic types of curbs, as shown in Figure 1: vertical curbs and sloping curbs. Vertical curbs usually have a vertical or nearly vertical face. Such curbs usually serve several purposes, including discouraging vehicles from leaving the road, drainage, walkway edge support, and pavement edge delineation.

Vertical curbs have some ability to redirect errant vehicles since the impacting wheel is steered by the curb in a direction parallel to the traveled way. If the impact velocity and angle are modest, this steering action is all that may be required to prevent the vehicle from leaving the roadway. If the speed and encroachment angle are higher, then the steering action of the curb alone is not sufficient to redirect the vehicle. Since the vehicle center of gravity is much higher than the top of the curb, a high-speed impact with the curb will introduce a roll moment. This roll moment will in turn introduce instability into the vehicle trajectory and may even be large enough to cause the vehicle to roll over. Since curbs are often used primarily for drainage purposes, they are often found in conjunction with steep sideslopes where a rollover would be even more likely. For these reasons, vertical face curbs are usually restricted to low-speed facilities where vehicles are to be discouraged from leaving the roadway.

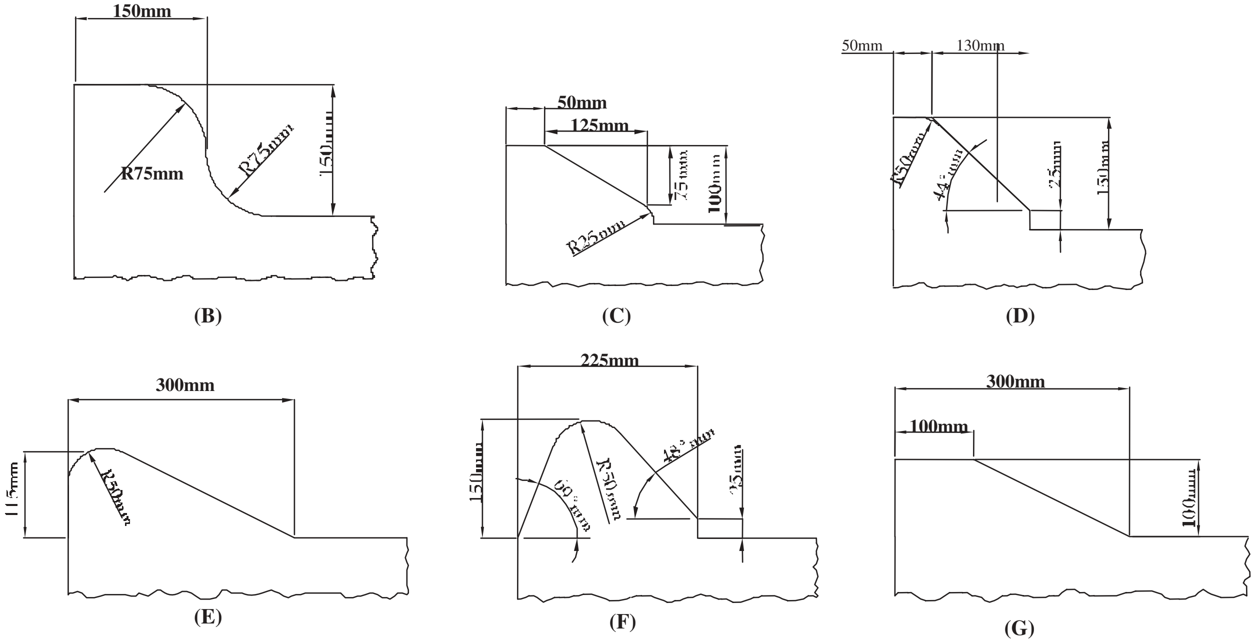
Sloping curbs, as illustrated in Figure 1, have a sloped face and are configured such that a vehicle can ride up and over the curb. These curbs are designed so that they do not significantly redirect a vehicle. They are usually used in situations where redirecting a possibly damaged and out-of-control vehicle back into the traffic stream is undesirable. Sloping curbs are often used primarily for drainage purposes but are also used on median islands and along shoulders of higher-speed roadways for delineation and other reasons. Sloping curbs provide drainage control while also allowing vehicles access to the roadside in emergency situations.

It is often necessary to use a curb for drainage or other reasons at a particular location that also warrants a traffic barrier. For example, approaches to bridge structures (e.g., overpasses) are often built on fills with steep slopes. An approach guardrail is required both to shield the end of the bridge railing and to shield errant motorists from the steep sideslope approaching the structure. If surface water were allowed to drain from the roadway down the steep slope next to the bridge, an erosion problem could develop. A curb is usually



(A)

Vertical Curb



(B) (C) (D)

(E) (F) (G)

Sloping Curbs

Figure 1. Typical AASHTO highway curbs (1).

required to channel the runoff into a catch basin or some other drainage structure. Both the curb and the traffic barrier are important functional features of the roadside in this situation.

Another similar situation occurs on roadways where a guardrail is needed to shield a steep roadside slope. Figure 2 shows a 100-mm high, sloped-face, asphalt curb installed just in front of the posts of a G4(1S) W-beam guardrail. The site is a 90 km/h rural two-lane roadway in Maine. The curb is placed at this site to provide drainage away from the steep sideslope behind the guardrail and thereby prevent erosion. The erosion would likely weaken the edge of the road, erode the soil from around the guardrail posts and cause slope stability problems. The curb is therefore necessary for proper drainage. Likewise, the guardrail is necessary for shielding errant motorists from the steep embankment. In such a situation there are few alternatives but to use a curb and traffic barrier combination.

The Green Book limits its guidance on the use of vertical face curbs and traffic barriers to the following statement (p. 327):

> When using curbs in conjunction with traffic barriers, such as on bridges, consideration should be given to the type and height of barrier. Curbs placed in front of traffic barriers can result in unpredictable impact trajectories. If a curb is used in conjunction with a traffic barrier, the height of a vertical curb should be limited to 100 mm or it should be of the sloping type, ideally, located flush with or behind the face of the barrier. Curbs should not be used with concrete median barriers. Improperly placed curbs may cause errant vehicles to vault the concrete median barrier or to strike it, causing the vehicle to overturn *(1).*

AASHTO's policy regarding the use of roadside barriers is contained in the *Roadside Design Guide (2).* The use of curbs in conjunction with traffic barriers is addressed in section 5.6.2.1 of the *Roadside Design Guide*:

> Crash tests have shown that use of any guardrail–curb combination where high-speed, high-angle impacts are likely should be discouraged. Where there are no feasible alternatives, the designer should consider using a curb no higher than 100 mm (4 in.) and consider stiffening the guardrail to reduce

Figure 2. Sloping curb installed flush with a strong-post W-beam guardrail on a 90 km/h two-lane rural roadway in Maine.

> potential deflection. Other measures that usually prove satisfactory are bolting a W-beam to the back of the posts, reducing post spacing, double nesting the rail, or adding a rubrail. On lower speed facilities, a vaulting potential still exists, but since the risk of such an occurrence is lessened, a design change may not be cost effective. A case-by-case analysis of each situation considering anticipated speeds and consequences of vehicular penetration should be used *(2)*.

The AASHTO policy quoted above is used by most states. For example, the Iowa Department of Transportation *Design Manual* states:

> It is not desirable to use guardrail alongside curbs. Every effort should be made to remove fixed objects or relocate them outside the clear zone, instead of using guardrail. If there is no other alternative to using guardrail, it may be used alongside a 4-inch sloped curb, normally with the installation line at the face of the curb. If 6-inch curbs are being used throughout the rest of the project, the curb should be transitioned to a 4-inch sloped curb throughout the guardrail installation *(3)*.

At first consideration, combining a curb and a traffic barrier might seem to be a reasonable strategy for redirecting errant vehicles. Curbs, as discussed above, possess some capacity to redirect vehicles, and traffic barriers are designed specifically for that purpose. Combining the two, therefore, might provide cumulative protection to motorists. Unfortunately, the curb's effect on the trajectory of the vehicle is complicated and can often involve transforming longitudinal kinetic energy into hard-to-control vertical and rotational kinetic energy. Researchers in an early California study called the tendency of the curb to launch the vehicle "dynamic jump" *(4)*.

Most of the current understanding of vehicle behavior during impact with curbs was developed in full-scale tests performed nearly 40 years ago *(4)*. More recent testing of bridge railings and guardrail-to-bridge rail transitions has added to this knowledge somewhat *(5)*. While the age, variability between tests, and adequacy of the traffic barriers make it difficult to generalize about the results of these tests, it has been generally accepted that when a curb is used in conjunction with a steel post-and-beam traffic barrier, the barrier must be stiffened in some manner to prevent large barrier deflections. In essence, if the barrier deflects too much, the curb can initiate a vertical component of vehicle motion that may launch the vehicle over the barrier. Common methods of stiffening the barrier include nesting two sections of W-beam, adding a W-beam on the back of the barrier, adding a rub rail, and reducing the post spacing. The basic objective is to keep the vehicle from contacting the curb by placing the curb behind the barrier face and limiting the deflection of the barrier.

There are three basic types of longitudinal traffic barriers: rigid, semirigid, and flexible. Rigid barriers are often shaped concrete barriers like the F-shape median barrier, the New Jersey barrier, the Ontario tall wall, and so forth. These types of barriers can also function as drainage devices, so there are probably no significant reasons why a curb would be necessary in conjunction with a concrete barrier.

Semirigid barriers include the widely used strong-post W-beam guardrails, which usually deflect laterally less than a meter in *NCHRP Report 350* Test Level Three (TL-3) crash tests *(2)*. These barriers are used in nearly every state and account for the vast majority of the installed inventory of roadside hardware *(6)*. These types of barriers are also widely used in many states in conjunction with curbs. The use of curbs and strong-post W-beam guardrails was a major issue in this research.

The flexible barriers include such systems as the weak-post three-cable guardrail, the weak-post W-beam guardrail, and the weak-post box-beam guardrail. These systems are designed to accommodate lateral deflections of as much as 3 m. Because these systems allow large lateral deflections, most vehicles would mount the curb while interacting with the barrier. For this reason, the authors believe that it is relatively unusual for states to use curbs in conjunction with weak-post guardrails. The issue of combining weak-post barriers and curbs relates to how far the barrier should be located behind the curb. If the barrier is located far enough behind the curb, the vehicle can stabilize prior to striking the barrier. An important issue in this research was the lateral encroachment distance necessary for a vehicle to stabilize after impacting a curb at highway speeds.

PROJECT OBJECTIVES

The primary goal of this research was to develop design guidelines for using curbs and curb–barrier combinations on roadways with operating speeds greater than 60 km/h. The guidelines took into account the following factors:

- Curb type, height, configuration, material, vertical reveal, and distance from edge of traveled way.
- Purposes of curb: aesthetics, hydraulics, delineation, access control, pedestrian refuge, protection of local environment, water quality, and historical preservation.
- For curb–barrier combinations, barrier type (i.e., flexible, rigid, and semirigid), height, configuration, distance from edge of traveled way, distance from curb, and end treatment.
- Roadside characteristics, including the surface behind curbs, such as grass, sidewalks, pavement, or sideslope.
- Environment.
- Area characteristics (e.g., suburban or rural).
- Climatic conditions (e.g., snow or heavy rains).
- Traffic characteristics, including speed, vehicle mix, and volume.
- Roadway alignment.
- Facility type (e.g., parkway, arterial, or freeway).
- Cross-section (e.g., median, number of lanes, shoulder, and roadside).

There were essentially two complementary objectives of this research: (1) determining the safety effectiveness of different types of curbs and (2) determining the proper combination and placement of curbs and barriers such that traffic barriers remain effective.

The first phase of the project involved an in-depth review of published literature in order to identify information pertinent to the design, safety, and function of curbs and curb–barrier combinations on roadways with operating speeds greater than 60 km/h (37 mph). Computer simulation methods were used in a parametric investigation involving vehicle impact with curbs and curb–barrier combinations to determine which types of curbs are safe to use on higher-speed roadways and to determine proper placement of a barrier with respect to curbing such that the barrier remains effective in safely containing and redirecting the impacting vehicle. The results of the study were then synthesized and guidelines for the use of curbs and curb-and-barrier systems were developed.

CHAPTER 2

LITERATURE REVIEW

INTRODUCTION

Assessing the safety effectiveness of curbs attracted a considerable amount of attention in the early decades of roadside safety research. Curbs were thought to be a low-cost method of keeping vehicles on the roadway for at least some impact conditions. In 1953 the California Division of Highways performed a series of 149 full-scale tests on 11 different types of curb geometries in order to assess the safety effectiveness of curbs *(4)*. This test series was followed in 1955 by another series of tests using the four best-performing curbs from the first series *(7)*. The conclusion of the researchers was that barrier curbs, i.e., vertical curbs, should be at least 10 inches high, have undercut faces, and have a relatively smooth surface texture. Other similar but less extensive studies were performed in Canada, Germany, and the United Kingdom *(8, 9, 10)*. These early crash tests formed the basis of the AASHTO policy described in Chapter 1. Although the vehicle fleet has changed considerably since the time of these early studies, the current version of the AASHTO Green Book contains substantially the same recommendations as the 1965 Green Book regarding the use of curbs.

The methods that have been employed for analyzing the safety effectiveness of curbs in earlier research included analytical methods, vehicle dynamics codes, and full-scale crash testing. Each of these methods is discussed in the following sections. Information from selected studies from previous research on curbs and curb–barrier combinations are also provided, followed by a summary of the literature review.

ANALYSIS METHODS APPLIED IN THE STUDY OF CURB SAFETY

Analytical Methods

Most analytical work regarding vehicle impact into curbs has been concerned with either redirectional capabilities of vertical face curbs or their potential to cause rollover. If the impact speed and angle are plotted on a graph and different symbols used to denote redirection and mounting, then a curve like Figure 3 can be developed. Figure 3 shows the characteristics of two particular experimental curbs, the Trief and Elsholz curbs *(9, 10)*. The line describes the boundary between redirective behavior and mounting behavior. Combinations of impact speed and angle falling to the left of the curve would result in redirection, and those falling to the right would result in mounting the curb.

The boundary between redirection and mounting can be described by $K = V \sin \alpha$ where V is the impact velocity and α is the impact angle. In essence, this expression indicates that a given curb will redirect the vehicle when the lateral component of the impact velocity is less than some characteristic value. In his 1973 study of barrier curbs, Dunlap found that the characteristic lateral component of velocity for the Trief curb was 5 km/h and for the Elsholz curb was 14.6 km/h; thus, the Elsholz curb was more effective at redirecting vehicles than the Trief curb *(11)*.

Dunlap attempted to extend this basic methodology by treating the impact speed and angle as a random probabilistic variable along with the vehicle type. If the distribution of encroachment angles and vehicle speeds for a particular roadway is known, the percent of vehicles that would be redirected by each type of curb can be estimated *(11)*. Dunlap used data from a specific roadway in Michigan for the speed distribution and the Hutchinson-Kennedy encroachment data for the impact angle distribution *(12)*. For the specific site in Michigan, Dunlap found that the Elsholz curb could be expected to redirect 70% of the impacting vehicles and the Trief curb could only be expected to redirect 27%.

Unfortunately, the curb characteristic lateral component of velocity is also a function of the characteristics of the vehicle that strike the curb and the type of curb. Some vehicles will have geometric, suspension, and handling characteristics more prone to mounting the curb than other vehicles. A curb's ability to redirect a vehicle depends not only upon the speed and angle of impact, but also upon the dimensions of the curb, the surface material of the curb, if it is wet or dry, and the radius of the impacting tire. The boundary line between mounting and redirection shown in Figure 3, therefore, is only valid for a single type of test vehicle impacting a specific type of curb. The dramatic changes in vehicle characteristics over the past decade seriously limit the validity of the findings of these early studies. The vehicles of today are lighter, have higher centers of gravity, and have lower profile tires. In addition, the passenger vehicle population has become much more diverse, now including pickup trucks, large and small sport utility vehicles (SUVs), and minivans,

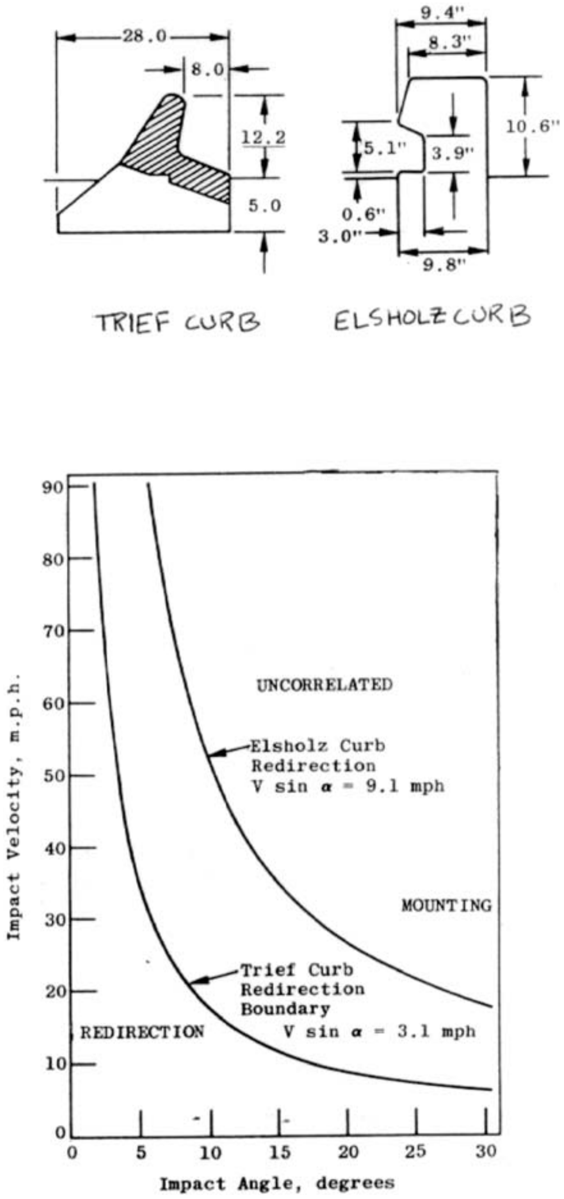


Figure 3. Performance characteristics of the Trief and Elsholz curbs (9).

as well as the traditional passenger car. Some of these vehicle types have proven to be less stable in collisions with traffic barriers than traditional passenger cars. While the testing done over the past 40 years provides some interesting insights, the results must be viewed carefully since the vehicle population of today is much different than it was during the 1960s.

An analytical study on the safety of roadside curbs was conducted by Navin and Thomson at the University of British Columbia in 1997 *(13)*. They developed the following empirical relationships to estimate the ability of a dry concrete curb to safely redirect a vehicle based on the findings produced in previous research:

$$h = r\left[\frac{V_r \sin\theta\left(\frac{\mu_N}{\mu_{CD}}\right)}{50}\right]^{\frac{1}{3.5}}$$

where

h is the height of the curb required to redirect the impacting vehicle,
r is the radius of the tire in millimeters,
V_r is the speed at redirection,
θ is the impact angle,
μ_N is the coefficient of friction of smooth rubber on test surface, and
μ_{CD} is the coefficient of friction of smooth rubber on dry concrete.

Note that the required height of the curb increases as the radius of the tires increases, the velocity of the vehicle increases, the angle of impact increases, or the friction coefficient increases.

Vehicle Dynamics Codes

The first computer simulation program used for the analysis of vehicle-curb impacts was the Cornell Aeronautical Laboratory Single Vehicle Accident program (CALSVA), developed in the 1960s *(14)*. It was used in the early 1970s by Wayne State University and the Highway Safety Research Institute (HSRI) at the University of Michigan to determine the redirection capability of various curb configurations *(15)*. The CALSVA program, developed by Cornell Aeronautical Laboratory, was only capable of simulating a limited range of impact scenarios because of the simplicity of the program; however, it did serve as a precursor to more advanced computer simulation codes.

The second generation version of CALSVA was the Highway Vehicle-Object Simulation Model (HVOSM) *(16)*. This program has been used extensively in conjunction with full-scale crash testing to study vehicle dynamics during impact with curbs. A comprehensive review of these studies will be presented in subsequent sections of this chapter.

The vehicle dynamics code VDANL (Vehicle Dynamics Analysis, Non Linear) was developed in the 1980s by the NHTSA and Systems Technology, Inc. (STI). It is a comprehensive vehicle dynamics simulation program that runs on a PC in a Windows environment. It was designed for the analysis of passenger cars, light trucks, articulated vehicles, and multipurpose vehicles, and it has been upgraded over the years to expand and improve its capabilities. It now permits analysis of driver-induced maneuvering up through limit performance conditions defined by tire saturation characteristics, as well as driver feedback control features.

VDANL was chosen by the FHWA for use in the Interactive Highway Safety Design Model (IHSDM) *(17)*. The IHSDM program is used to assess new roadway designs by using a driver performance model to simulate the vehicle/driver response when traversing the proposed roadway configuration. The Driver Performance Model in IHSDM estimates drivers' speeds and path choices along a roadway, and this information is provided as input to VDANL, which estimates vehicle kinematics such as lateral acceleration, friction demand, and rolling moment. The information from VDANL is used to identify conditions that could result in loss of vehicle control (i.e., skidding or rollover).

Full-Scale Crash Testing

Although advancements in computer simulation programs have made it possible to accurately reproduce and predict complex impact events, full-scale testing is still essential in evaluating the safety performance of curbs and other roadside appurtenances. To evaluate the performance of roadside safety barriers, impact conditions must meet the standard testing procedures accepted by the FHWA. The first procedures document was published by the Highway Research Board in 1962 *(18)*. The later revisions of the procedures were made by the National Cooperative Highway Research Program. The latest revisions of the testing procedures were published in *NCHRP Report 350* in 1993 *(19)*.

From 1981 to 1992 crash tests were conducted according to the test requirements specified in *NCHRP Report 230 (20)*. The test conditions required for evaluation of guardrail in *NCHRP Report 230* involved a 2000-kg sedan impacting the guardrail at a speed of 100 km/h and an angle of 25 degrees.

The most important change in *NCHRP Report 350* was that the large passenger sedan had virtually disappeared from the vehicle population, and new vehicle types, such as minivans, SUVs, and pickup trucks, had emerged in their place. Since the first testing procedures specified in *Highway Research Circular 482* up until *NCHRP Report 350*, the large car sedan (i.e., a 2040-kg car) had served as the crash test vehicle representing the fleet of large passenger vehicles. *NCHRP Report 350* replaced the large car with a 2000-kg pickup truck. The challenges that the pickup truck introduced to the crash testing procedures were due to its high, more forward center of gravity making it much more unstable during impacts than its predecessor, the large sedan.

The performance of a curb/guardrail combination are evaluated using test conditions specified in *NCHRP Report 350* for evaluating the crashworthiness of the length of need (LON) section of a guardrail. There are currently two tests that are required in *Report 350* to evaluate guardrail systems for use along high-speed roadways:

1. Test 3-11, which involves a 2000P pickup truck (e.g., Chevrolet 2500) impacting the guardrail at a speed of 100 km/h and an impact angle of 25 degrees, and
2. Test 3-10, which involves an 820C (e.g., Geo Metro) impacting the guardrail at a speed of 100 km/h and an impact angle of 20 degrees.

A guardrail system that meets the evaluation criteria for Tests 3-10 and 3-11 in *NCHRP Report 350* is generally considered acceptable for use on all TL-3 roadways within the United States.

EFFECT OF CURBS ON VEHICLE STABILITY

Dunlap, 1973 (*11, 21*)

The objective of Dunlap's research was to determine how far in front of the barrier the curb should be placed to achieve the best redirection performance from the curb–traffic barrier system. Dunlap examined all the test data available in the early 1970s and found that the results were difficult to generalize. While there were cases of vehicles vaulting over a guardrail or bridge railing when a curb was used in front of the guardrail, in many cases the guardrail itself had structural problems so it was difficult to assess the contribution of the curb to the failure. Dunlap performed computer simulations of a variety of curb and barrier combinations using HVOSM to determine the risk of overriding the barrier. Dunlap's analysis indicated that for the six curb and barrier combinations studied, vaulting was not expected to be a problem. This analysis, however, has several serious limitations not least of which is the validity for barrier impact analysis of the HVOSM computer program that was being used at the time. Dunlap's work does, however, illustrate two important points: (1) computer simulation is one possible method for assessing a variety of curb–barrier geometries and (2) the conventional wisdom that curbs should not be used in front of semirigid barriers warrants more careful investigation.

Olsen et al., 1974 (*22*)

Olsen and other researchers at Texas Transportation Institute (TTI) conducted a study to investigate how various types of curbs affect vehicle response, such as redirection, trajectory, path, roll, pitch, and accelerations. Their study involved full-scale tests and simulations of vehicles traversing various types of curbs. Eighteen full-scale tests were conducted on types B and D curbs (see Table 1); nine full-scale tests were conducted on each curb type at speeds of 48, 72, and 97 km/h and at 5-, 12.5-, and 20-degree encroachment angles. The HVOSM computer program was used to simulate vehicle impact with three different curb types: AASHTO curb types B, D, and G. Although in the study, the curbs were referred to as C, E, and H curbs (which is consistent with the nomenclature of the AASHTO Blue Book), the AASHTO Green Book now refers to these curbs as B, D, and G, respectively. Nomenclature

TABLE 1 Summary of full-scale test results from Olsen et al. (*22*)

Test number	Approach speed (mph)	Encroachment angle (degrees)	Maximum bumper height during vehicle trajectory (inches)
Curb Type D			
N-2[a]	30.4	5.1	24.1
N-3[a]	45.6	5.0	24.3
N-4	59.3	4.6	23.9
N-5	32	11.6	20.8
N-6	45.3	11.1	23.7
N-7	63.6	12.6	23.5
N-8	32.7	18.5	23.5
N-9	41.8	18.7	21.9
N-10	63.0	17.6	23.3
Curb Type B			
N-11[a]	34.2	4.9	26.2
N-12	44.7	5.1	24.8
N-13	34.2	11.2	23.8
N-14	43.5	12.8	23.1
N-15	32.1	17.4	22.1
N-16	43.0	18.4	23.5
N-17	66.5	5.1	24.3
N-18	62.2	12.3	21.4
N-19	61.5	18.6	23.0

[a] Vehicle redirected

throughout this document will use the Green Book designations. Twelve curb impacts were simulated on each curb type at impact speeds of 48, 72, and 97 km/h and at 5-, 12.5-, and 20-degree encroachment angles. Impacts at 121 km/h were also simulated at 5-, 10-, and 15-degree encroachment angles.

The test vehicle used in the study was a 1963 Ford four-door sedan with heavy-duty suspension. The vehicle's mass was 1,905 kg, and the center of gravity of the vehicle was 610 mm above ground. The test vehicle is shown in Figure 4.

Olsen et al. found that AASHTO types B, D, and G curbs, which are sloping curbs 150 mm or less in height, provide no redirection for a large passenger vehicle, such as a 1900-kg sedan, traveling at speeds greater than 72 km/h at encroachment angles greater than 5 degrees. They also found that type B and D curbs can produce, under certain speed and encroachment angles, vehicle ramping high enough to allow the bumper height to equal or exceed the height of a typical guardrail, as illustrated in Figure 5.

Such vehicle trajectories may result in a vehicle vaulting over the top of the rail or snagging on the tops of the posts and flipping over. Whether the vehicle penetrates behind the barrier or is redirected is, of course, influenced by other factors, including barrier configuration, lateral stiffness properties of the barrier, and impact conditions, as well as vehicle characteristics, such as bumper shape and vehicle kinematic properties. The trajectory of the vehicle after mounting a curb must allow the vehicle to contact the guardrail, or other roadside device, at the appropriate height.

Figure 4. Vehicle used in Olsen et al.'s study (22).

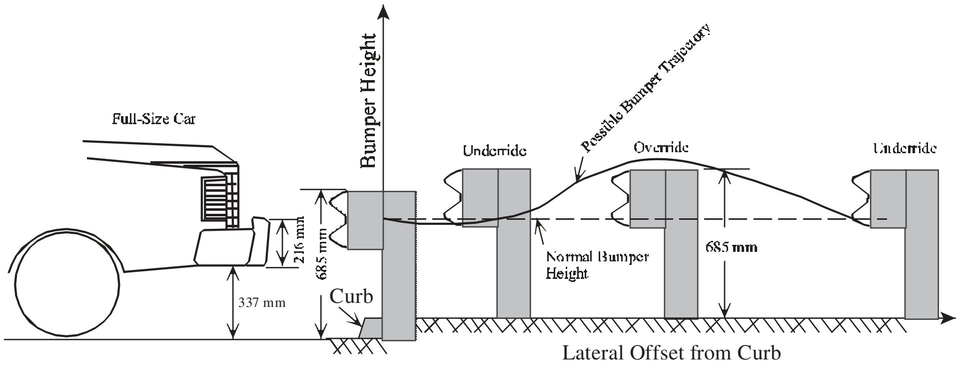


Figure 5. Possible trajectory of vehicle bumper relative to guardrail height.

Olsen et al. found that for 150-mm-high AASHTO B and D curbs an increase in either speed or impact angle resulted in greater lateral distances to the maximum rise point and higher vertical position of the vehicle at the maximum rise point. The encroachment angle had a more notable effect on the maximum rise point and position than did vehicle speed, when vehicle speed was greater than 100 km/h.

The maximum rise height of the bumper, predicted from the simulations, was approximately 737 to 787 mm and occurred in the range of 2.44 to 3.0 m behind 150-mm-high curbs. The height of a typical W-beam guardrail is 686 mm, as shown in the sketch in Figure 5. The maximum rise height during impact with the type G curb was only slightly affected by vehicle speed and encroachment angle. The maximum vertical rise of the vehicle impacting the type G curb was less than 50 mm. Furthermore, the maximum rise height did not increase an appreciable amount for speeds greater than 48 km/h, indicating that the maximum rise height during impact with the type G curb is relatively independent of vehicle speed and impact angle.

It was concluded that the maximum rise point was dependent on the combination of vehicle roll and pitch caused by striking the curb. When the wheel impacts the curb, the loads are distributed to the other three wheels, particularly the other front wheel. If the impacting wheel rises too quickly, then the vertical tire force will be sufficient to bottom out the suspension, introducing shock loads. In addition, excessive pitch and roll angles are produced when the fully compressed suspension unloads. The effect that curb geometry has on damping the roll angle during wheel impact obviously differs with the height and the steepness of the curb face. The pitch and roll angles produced by simulated collisions with type B and D curbs were as much as twice those produced by collisions with the type G curb.

Curbs that are 150-mm high and set in front of a 685-mm W-beam guardrail at a 0.61-m lateral offset may result in the vehicle impacting the guardrail at a point below the lower edge of the rail, possibly causing snagging, as shown in Figure 5. During impacts with the 150-mm-high curbs, the bumper would dip down slightly and then began to rise as the vehicle crossed the curb. If the angle of impact is such that the bumper is close to the guardrail before the wheel impacts the curb, then the dipping event would cause the bumper to impact the guardrail just below the W-beam rail. Note that the lower edge of the guardrail is 533 mm above the pavement surface due to the 150 mm elevation of the curb; whereas, the lower edge of the rail is only 381 mm above ground level in normal configuration. An initial dipping motion of the bumper was not evident during impact with the type G curb, and the bumper contacted the guardrail on the face of the W-beam in all impact cases.

The simulation study by Olsen et al. also demonstrated that the stiffness of the vehicle's suspension had little effect on vehicle trajectory. A summary of full-scale test results performed in Olsen et al.'s study is given in Table 1 and a summary of their HVOSM simulation results is given in Table 2. The HVOSM model had a disk wheel that was not detailed enough to accurately simulate wheel contact with a curb. The simulation results in *NCHRP Report 150* predicted that full-size cars would be redirected by a 13-in.-high Type X curb in 60-mph impacts up to 12.5 degrees. However, in 60-mph crash tests, the test vehicles crossed the curb. The disparity between the test results and the HVOSM predictions was more apparent in the high-speed tests, particularly between the predicted roll and bumper rise and those values measured from the test data.

Ross and Post, 1975 (*23*)

Researchers at TTI conducted a study to evaluate automobile behavior when traversing selected curb configurations and sloped medians and, also, to evaluate the potential for a vehicle to vault over roadside barriers placed in combination with curbs or sloped medians. HVOSM was used to simulate vehicle impacts with 150-mm-high and 200-mm-high curbs, modified curbs, and slopes. The researchers also compared the effects of standard curb shapes to various retrofit alternatives, such as installing wedge-shaped asphalt plugs in front of the curbs and replacement of the curbs with slopes.

It was concluded from the simulation results that traffic barriers should not be placed near curbs due to the probability of

TABLE 2 Summary of HVOSM simulation results from Olsen et al. (*22*)

Curb	Vehicle speed (mph)	Impact angle (deg)	Max roll angle (deg)	Max pitch angle (deg)	Max bumper height above curb (inches)	Lateral distance to max rise point (ft)	Bumper height above curb at 2-ft offset (inches)
Type B							
(6-in.)	30	20	+8.8	2.9	22	5	12
	45	20	-8.9	3.0	26	8	11
	60	12.5	-13	2.0	27	7	13
	60	20	-8	2.0	29	10	10
	75	10	-15.5	2.0	30	6	13
	75	15	-10.2	1.8	30	10	12
Type D							
(6-in.)	30	12.5	-9.5	2	21	4	13
	30	20	-8	2.5	21	6	11
	45	12.5	-11	2	23	5	12
	45	20	-8	2.2	25	8	11
	60	5	-11.2	2	23	3	17
	60	12.5	-12	2	25	6	13
	60	20	-9.5	2.5	31	10	11
	75	5	-12	1.5	23	4	16
	75	10	-13	2	25	6	13
	75	15	-11	2	31	9	12
Type G							
(4-in.)	30	12.5	-5	1	18	5	13
	30	20	-3	1	18	9	12
	45	5	-7	1	20	3	15
	45	20	-4	1	20	10	14
	60	5	-7	1	20	4	15
	60	12.5	-5	1	20	8	13
	60	20	-3	1	20	10	13

vehicles vaulting or underriding the barrier. They also showed that problems with barriers on raised curb-medians or curb–guardrail configurations could be reduced in certain situations by sloping the median or the roadside to the top of the curb.

Holloway et al., 1994 (*24*)

Three types of sloping curbs commonly used by the Nebraska Department of Roads (NDOR) were investigated for safety performance through a combination of full-scale testing and computer simulation using HVOSM. The curb types investigated included a 100-mm lip curb (1 : 3 slope on curb face), a 150-mm lip curb (1 : 3 slope on curb face) and a 150-mm AASHTO type I curb. The AASHTO type I curb, shown in Figure 6, is the curb type most widely used by NDOR. The test matrix in the study included 23 full-scale

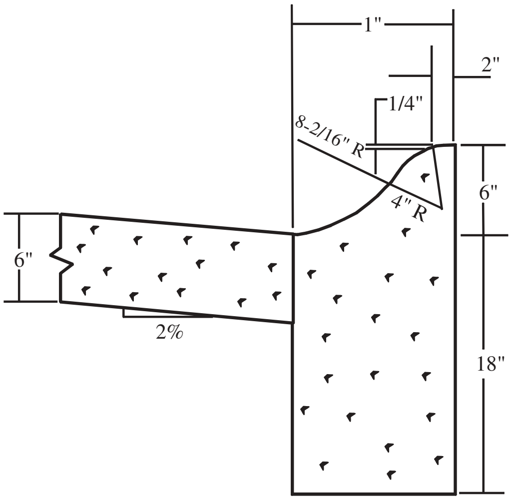


Figure 6. AASHTO Type I Curb.

tests: 13 tests on the 100-mm lip curb, 2 tests on the 150-mm lip curb, and 8 tests on the AASHTO type I curb.

The three curbs tested were found to have little potential for causing a vehicle to lose control during tracking impacts, and, thus, the researchers concluded that the curbs would not pose a significant hazard to vehicles impacting in a tracking mode. Although the 100-mm curb performed better than the 150-mm curbs in all impact conditions, the safety benefit was not considered significant. It was also concluded that the performance of W-beam guardrails could be adversely affected when installed behind curbs and that, when curb–guardrail combinations are necessary, the curb should be placed behind the face of the guardrail to minimize the potential for vehicle ramping.

The testing area was on a negative grade that may have had some effect on the vehicle kinematics during impact. Tests were conducted using two types of test vehicles: a small car with a mass of 817 kg (1984 Dodge Colt) and a large car with a mass of 2,043 kg (1986 Ford LTD). The center of gravity of the test vehicles were 533 mm and 572 mm for the 817-kg and 2043-kg vehicles, respectively.

The impact speeds used in the full-scale tests were 64.4, 72.4, 80.5, and 88.5 km/h at encroachment angles of 5, 12.5, and 20 degrees. Vehicle decelerations were very low, indicating that there is little risk of occupant injury as a direct result of curb impact. The yaw rate and yaw angle were also very low, indicating that there was minimal redirection of the vehicles as they impacted and mounted the curbs.

Thirteen full-scale tests were conducted on a 100-mm lip curb, and two full-scale tests were conducted on a 150-mm lip curb. For low-angle impacts on the 100-mm curbs with the 817-kg vehicle, the maximum roll and pitch angles increased as the impact velocity increased; values ranged from 5.6 to 9.0 degrees and 0.7 to 1.4 degrees for roll and pitch angles, respectively. For the moderate- and high-angle impact tests, the maximum roll angle increased as the impact speed increased, while the maximum pitch angle decreased with an increase in impact speed. The maximum roll angle in the tests was 9.3 degrees, and the maximum pitch angle was 2.6 degrees. Thus, the pitch and roll angles were considered to be relatively insignificant in terms of producing loss of vehicle control.

It was also concluded in the study that there was only a slight potential for an 817-kg vehicle to underride a standard 686-mm W-beam guardrail when the 100-mm lip curb is placed in combination with the guardrail. The greatest potential of the vehicle vaulting over the barrier would be when the barrier is located in a region 0.76 m to 2.74 m behind the curb.

Similarly, for low-angle impacts with the 2043-kg vehicle impacting the 100-mm lip curb, the roll and pitch angle increased as the impact speed increased. The maximum roll and pitch angles were 7.2 degrees and 1.1 degrees, respectively, for the low-angle impacts. The maximum roll and pitch angles for the high-angle impacts were 7.2 degrees and 2.0 degrees, respectively. There were only two tests conducted on the 150-mm lip curb. In these two tests, a 2043-kg vehicle impacted the curb at an encroachment angle of 20 degrees and at impact speeds of 72.4 and 86.9 km/h. The maximum roll and pitch angles were 7.8 degrees and 2.6 degrees, respectively. The tests indicated that there was a slight potential for the vehicle to underride a standard W-beam guardrail, if the guardrail was placed within 1.22 m of the curb; however, the tests also indicated that there was very little potential for the vehicle to vault over the barrier.

Tests conducted on the AASHTO type I curb resulted in maximum roll and pitch angles of 9.7 degrees and 3.1 degrees, respectively. Although the angular displacements of the vehicle during impact with this curb were somewhat higher than those produced in impacts with the lip curbs, the potential for loss of control of the vehicle was again considered very low. The driver of the vehicle in the study reported that the suspension system fully compressed and bottomed out against the suspension bumper stops during impact with the 150-mm curbs and a small jolt was felt. The trajectory of the vehicle during the tests indicated there was a potential for underride of a standard W-beam guardrail if the barrier is located within 1.22 m of the curb; however, there did not appear to be any significant risk of the vehicles vaulting over such a barrier.

The HVOSM was also used to investigate alternate impact conditions. Simulation models of the 23 full-scale tests were developed, and the results were compared to the full-scale tests to validate the model. An additional 55 simulations were then performed. Thirty-one simulations were performed to supplement the original 23 impact scenarios, including 5 simulations with the 100-mm lip curb, 16 simulations with the 150-mm lip curb, and 10 simulations with the 150-mm type I curb. Another 24 simulations were performed to evaluate the effects of curb impact with the curb placed on flat grade.

The simulations with the lip curbs were performed with vehicle velocities of 72.4 and 88.5 km/h at encroachment angles of 5 and 20 degrees. The results of the simulations with the 100-mm lip curb showed no potential for either underriding or vaulting a W-beam guardrail installed behind the curb. The results of the simulations with the 150-mm lip curb indicated that the small vehicle (817 kg) may underride a W-beam guardrail if the guardrail is placed within 1 m of the curb, and it is likely to vault over a guardrail placed 0.46 to 3.7 m behind the curb. The simulations with the large vehicle (2043 kg) indicated a slight potential for underriding a W-beam guardrail located within 1 m of the curb, and vaulting of the guardrail was likely if the barrier was placed in a region of 0.61 to 3 m behind the curb.

The simulations with the AASHTO type I curb indicated that impact with the curb could cause underride of a W-beam guardrail placed within 0.61 m of the curb. For small car impact, a potential for vaulting existed if the guardrail was placed 0.46 m to 3.0 m behind the curb. For large car impact, a potential for vaulting existed if the guardrail was placed 0.46 m to 3.7 m behind the curb.

The additional 24 simulations were performed on all three curb types to investigate the effects of impact with the curbs placed on flat grade. Impact conditions included vehicle speeds of 72.4 and 88.5 km/h and encroachment angles of 5 and 20 degrees. The results of these simulations showed only minor differences in angular displacements of the vehicle, compared with the simulations with the curb placed on a negative grade (i.e., the test area was on a negative grade).

Nontracking impacts of vehicles with the three curb types were also investigated using computer simulation; however, no test data were available for validating the results. Impact conditions used in the study were based on Appendix G of *NCHRP Report 350* and from accident data analysis studies. All simulations were performed with vehicle speed of 80.5 km/h and impact angle of 20 degrees. Three initial positions of the vehicle were investigated: (1) 150 degree yaw angle with 50 deg/sec yaw rate, (2) negative 30 degree yaw angle with a negative 25 deg/sec yaw rate, and (3) 180 degree yaw angle with 50 deg/sec yaw rate. They found that these curbs may be traversable over a wide range of vehicle orientations and impact conditions, and the curbs pose little threat of vehicle rollovers during impact.

EFFECT OF CURBS INSTALLED IN CONJUNCTION WITH GUARDRAILS

Buth et al., 1984 (*25*)

During the 1980s, the FHWA sponsored the testing of numerous bridge railings, some of which included curbs. In particular, TTI tested a New Hampshire bridge rail system with a curb protruding in front of the barrier face, and a Colorado Type 5 bridge rail system with a curb flush with the face of the barrier. In both tests, the front impact-side wheel was damaged during impact with the curb, and the wheel wedged between the curb and the bottom rail of the traffic barrier. The performance of both bridge railings was considered unsatisfactory, but it should also be noted that both railings had other poorly designed features that may have contributed to the poor performance.

Bryden and Phillips, 1985 (*26*)

Bryden and Phillips performed 12 full-scale crash tests for the New York Department of Transportation to evaluate the performance of a thrie-beam bridge-rail system. Two tests were conducted with a 150-mm curb placed flush with the face of the thrie-beam rail. The tests involved a 2043-kg Dodge station wagon impacting the system at approximately 100 km/h at an impact angle of 26 degrees. The vehicle remained stable and was smoothly redirected in both tests.

FHWA Memorandum, February 28, 1992 (*27*)

The results of a series of crash tests conducted by ENSCO, Inc., were reported in an FHWA Memorandum distributed on February 28, 1992. The tests involved various types and sizes of vehicles impacting W-beam guardrails with curbs placed behind the face of the W-beam rail element. In the cases involving curbs 150 mm high or higher, it was found that the vehicle would vault over the guardrail, if the guardrail deflected enough for the wheels to mount the curb. In crash tests in which the 100-mm AASHTO Type G curb was placed behind the face of the W-beam, the vehicle became airborne when guardrail deflection permitted the wheels to mount the curb; however, the vehicle did not vault the rail. The best alternative for reducing the safety hazards associated with guardrail-curb systems is to stiffen the guardrail. Stiffening the guardrail reduces guardrail deflection and reduces the potential of the vehicle contacting the curb. In tests where the guardrail was sufficiently stiff, the tires of the vehicle did not contact the curb, and the vehicle was redirected in a much more stable manner. Below is a summary of the ENSCO tests.

Test Number 1862-1-88

A 2452-kg pickup truck impacted a G4(1S) guardrail system with a 203-mm-high concrete curb (AASHTO type A) installed behind the face of the W-beam. The impact speed was 100 km/h and the impact angle was 20 degrees. There was significant deflection of the guardrail, and the wheels of the vehicle contacted the curb. The vehicle vaulted over the guardrail.

Test Number 1862-4-89

An 817-kg car impacted a G4(1S) guardrail system with a 150-mm-high asphalt dike. The impact speed was 100 km/h and the impact angle was 20 degrees. The wheels of the vehicle did not contact the curb during the crash event, and the vehicle was smoothly redirected.

Test Number 1862-5-89

A 2043-kg sedan impacted a G4(1S) guardrail system with a 150-mm-high asphalt dike. The impact speed was 100 km/h and the impact angle was 25 degrees. There was significant deflection of the guardrail, and the wheels of the vehicle contacted the curb. The vehicle vaulted over the guardrail.

Test Number 1862-12-90

A 2452-kg sedan impacted a G4(1S) guardrail system with a 100-mm-high concrete curb (AASHTO type G). The impact speed was 100 km/h and the impact angle was 25 degrees. The vehicle became airborne but did not vault the guardrail.

Test Number 1862-13-91

A 2043-kg sedan impacted a G4(1S) guardrail system stiffened with a W-beam bolted to the back of the steel posts. A 150-mm-high asphalt dike was placed behind the front face of the W-beam. The impact speed was 100 km/h and the impact angle was 25 degrees. The guardrail system was sufficiently stiff to prevent the wheels of the vehicle from impacting the curb. The vehicle was successfully redirected.

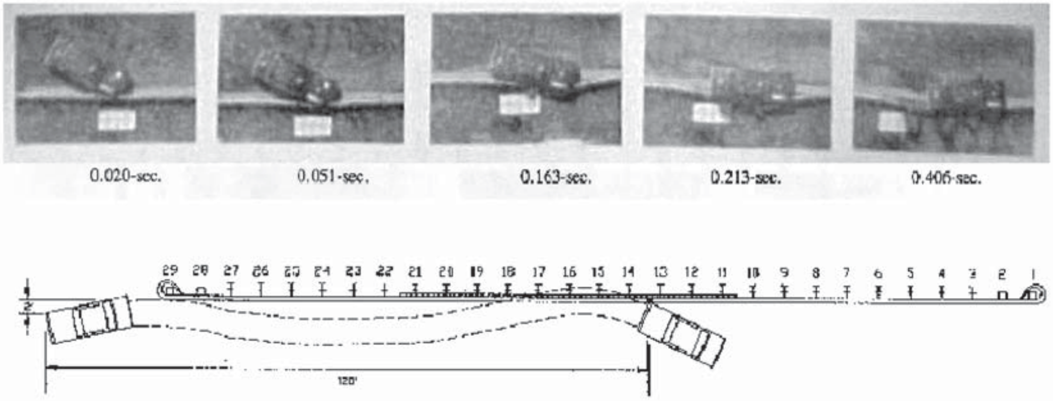
Test Number 1862-14-91

A 2043-kg sedan impacted a G4(1S) guardrail system stiffened with a C6x8.2 hot-rolled channel rub rail. A 150-mm-high asphalt dike was placed behind the face of the W-beam. Again the guardrail system was sufficiently stiff to prevent the wheels of the vehicle from impacting the curb and the vehicle was successfully redirected. The vehicle speed change at redirection, however, was greater than the allowable (24 km/h) according to *NCHRP Report 230;* thus the system did not meet all required safety criteria.

Holloway and Rossen, 1994 (*28*)

A study was conducted by Holloway and Rossen at Midwest Roadside Safety Facility at the University of Nebraska–Lincoln that involved a full-scale crash test on Missouri's 150-mm-high vertical curb placed behind the face of a strong-post W-beam guardrail (i.e., G4(1S)). Missouri's 150-mm-high vertical curb is very similar to the AASHTO type B curb, except that the Missouri vertical curb is on a flat grade and has very little rounding on the top and bottom edges of the curb. The impact conditions for the test was in accordance with *NCHRP Report 230* specifications; a 2043-kg test vehicle (1985 Ford LTD) impacted the system at 96 km/h at 25.1 degrees. The center of gravity of the test vehicle was 597 mm above ground. A summary of test M06C-1 is shown in Figure 7.

During the test, the right front tire contacted the curb 20 milliseconds after initial contact with the guardrail and mounted the curb soon after. The maximum roll angle was negative 14 degrees (the roll angle was away from the system). The vehicle exited the rail at 706 milliseconds at a speed of 64 km/h and an angle of 6.2-degrees. Vehicle decelerations and trajectory were well within the recommended limits of *NCHRP*



Test Number	M06C-1
Date	10/6/93
Installation	Single 12-Gauge W-Beam with 6 ft-3 in. Post Spacing over a 6 -in. Barrier Curb
Installation Length	175 ft
Post	
Size	W6x9
Length	6 ft
Guardrail	
Material	7 - 25 ft sections of 12 gauge W-beam
Curb Type	6-in. Barrier Curb
End Treatments	Breakaway Cable Terminals
Test Vehicle	1985 Ford LTD
Test Inertial Weight	4500 lbs
Gross Static Weight	4500 lbs

Impact Speed	59.7 mph
Impact Angle	25.1 deg
Impact Location	11.7 ft Upstream of Post No. 15
Exit Speed	40.0 mph
Exit Angle	6.2 deg
Normalized Occupant Impact Velocity	
Longitudinal	18.6 fps
Lateral	15.8 fps
Occupant Ridedown Deceleration	
Longitudinal	3.2 g's
Lateral	8.5 g's
Vehicle Damage	
TAD	1-RFQ-3, 1-RD-2
VDI	01RDES2
Maximum Permanent Set Deflection	30.1 in. @ Post No. 15
Maximum Dynamic Deflection	31.7 in. @ Post No. 15
Vehicle Rebound Distance	10.8 ft

Figure 7. Summary of results for MwRSF Test M06C-1 (28).

Report 230. As a result of the test, the researchers concluded that the system performed satisfactorily and the Missouri Department of Transportation should continue to use the guardrail-curb system where warranted.

Polivka et al., 1999 (*29*)

A study was conducted by researchers at the Midwest Roadside Safety Facility (MwRSF) at the University of Nebraska-Lincoln to evaluate the effects of an AASHTO type G curb (i.e., 102 mm high and 203 mm wide) placed flush behind the face of a G4(1S) guardrail system. Test NEC-1 was conducted with impact conditions recommended by *NCHRP Report 350* TL-3, which involves a 2000-kg pickup truck (1991 GMC 2500) impacting at a speed of 100 km/h at an impact angle of 25 degrees *(19)*. Sequential photographs of the crash test are shown in Figure 8. The center of gravity of the test vehicle was 737 mm.

The test installation was a standard 53.34-m-long G4(1S) guardrail system anchored on both the upstream and down stream ends of the system by an inline breakaway cable terminal with a strut between the two end posts.

The guardrail ruptured at a splice connection, thus the test was a failure. There was little vertical displacement of the vehicle as it crossed the curb in the full-scale test, and there seemed to be very little potential for underride or vaulting of the barrier. The anchor posts split during the collision, as shown in Figure 9, and there was a loss of tension in the W-beam, which resulted in pocketing and rupture of the W-beam rail at a splice connection. The splice failure was attributed to contact and snagging of the post blockout against the W-beam rail splice. The post twisted as it was pushed back in the soil, causing the bottom corner of the blockout to push up against the corner of the W-beam rail splice. This resulted in a tear in the W-beam at the lower downstream bolt location. It was suggested that the guardrail-curb combination could be significantly improved by increasing the capacity of the W-beam rail.

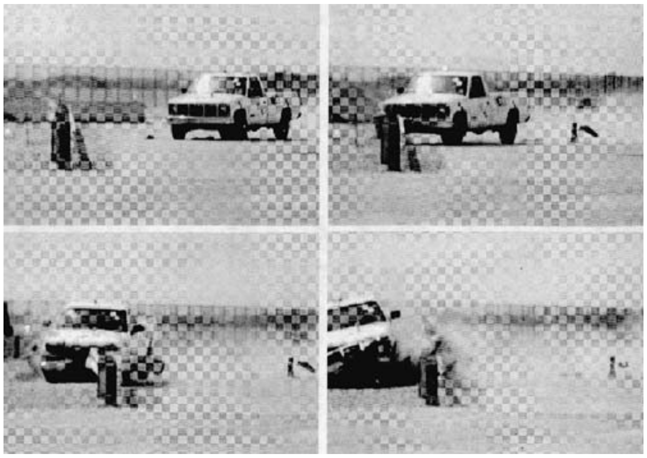


Figure 8. Sequential video frames from Test NEC-1 (29).

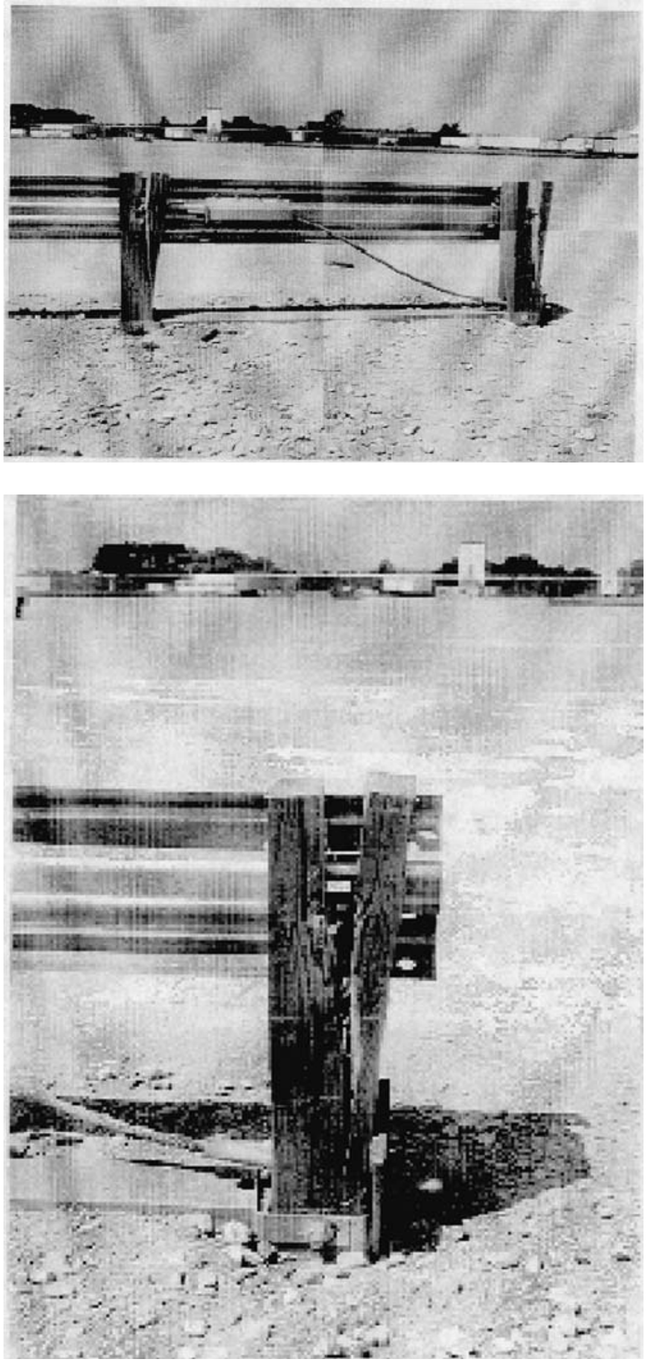


Figure 9. Guardrail terminal damage during Test NEC-1 (29).

Bullard and Menges, 2000 (*30*)

This study was conducted by researchers at the TTI and involved the evaluation of a 100-mm-high asphaltic curb, set out 25 mm from the face of the rail of a G4(2W) strong-post guardrail system, as shown in Figure 10.

TTI test 404201-1 was conducted at the TTI on May 23, 2000, and involved a Chevrolet C2500 pickup impacting

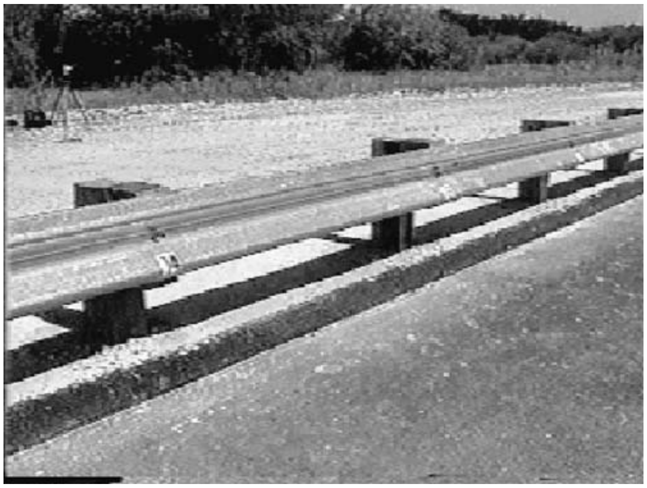


Figure 10. Guardrail–curb installation for TTI test 404201-1.

the curb-and-barrier system at 101.8 km/h at an angle of 25.2 degrees (i.e., *NCHRP Report 350* Test 3-11).

During the test, there was significant movement of the anchor system as the foundation of the anchor posts moved in excess of 70 mm. The test was successful; however, there was considerable damage to the guardrail system, as shown in Figure 11. The extent of damage to the system was much greater than that of previous crash tests on the G4(2W) guardrail system without a curb present *(31)*. From reviewing the film from the crash test and the test report, it is believed that the excessive damage to the system is due, in part, to the use of poor grade posts in the guardrail installation. Many of the posts split vertically during impact along preexisting splits passing through the bolt hole location in the posts, as shown in Figure 12. A summary of Test 404201-1 is shown in Figure 13.

Polivka et al., 2001 (*32*)

This study involved the second phase of the curb-and-barrier impact investigation conducted by MwRSF, in which the 102-mm AASHTO type G curb was installed in combination with a strong-post guardrail system. Test NEC-2 was conducted with impact conditions recommended in *NCHRP Report 350* TL-3. The test vehicle was a 2000-kg pickup truck (1994 GMC 2500) and the impact speed and angle were 100.3 km/h and 28.6 degrees, respectively. The center of gravity of the test vehicle was 667 mm.

Figure 11. Guardrail damage in TTI Test 404201-1.

The test installation was a modified G4(1S) guardrail with routed wood blockouts. In order to reduce the potential for rupture of the rail, two layers of 12-gauge W-beam were nested over a 26.67-m section of the guardrail. This modification was incorporated based on the results of test NEC-1, conducted in the first phase of the study, in which a splice rupture occurred during impact. The total length of the guardrail was 53.34 m, including an inline breakaway cable terminal located at both ends of the system.

The vehicle vaulted during impact and was airborne for much of the impact event. While the vehicle was airborne, it did get over the rail, as shown in Figure 14; however, the vehicle remained upright, came down on the front side of the guardrail, and satisfied all safety requirements of *NCHRP Report 350*. A summary of test NEC-2 is shown in Figure 15, which was taken from Polivka et al.

EFFECTS OF CURB TRIP ON VEHICLE STABILITY

DeLeys and Brinkman, 1987 (*33*)

Computer simulation was used in a study to determine the dynamic response of small and large passenger cars traversing various sideslope, fill-embankment, and ditch configurations. Both tracking and nontracking departures from the roadway were investigated. A modified version of HVOSM was used in this research that improved the program's application to rollover situations. The modifications to the program were made by McHenry Consultants, Inc. These modifications

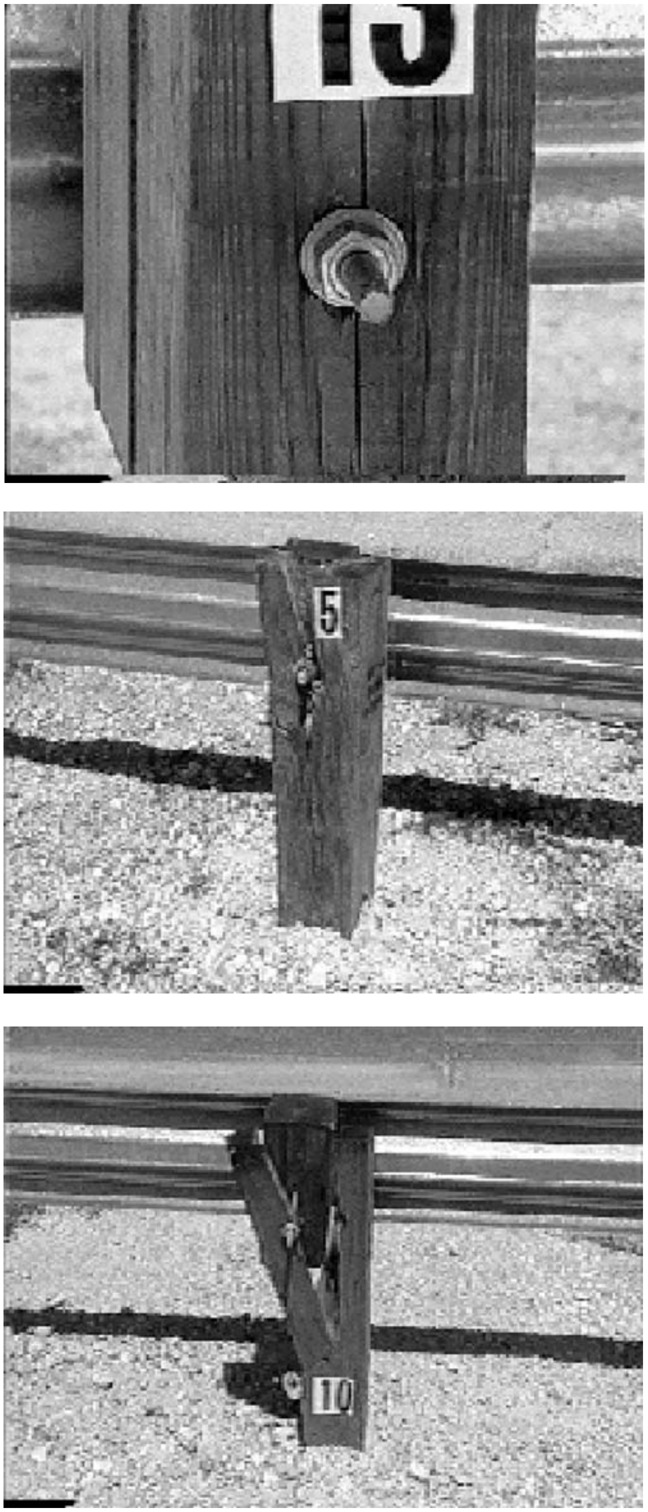


Figure 12. Posts split vertically during TTI Test 404201-1 along preexisting splits in posts.

included further development of the tire model and the addition of a tire/deformable-soil interaction model to the program. A literature review and analysis of accident data recorded in the 1979–81 National Accident Sampling System (NASS) was performed; some of the principal findings from that review are quoted below:

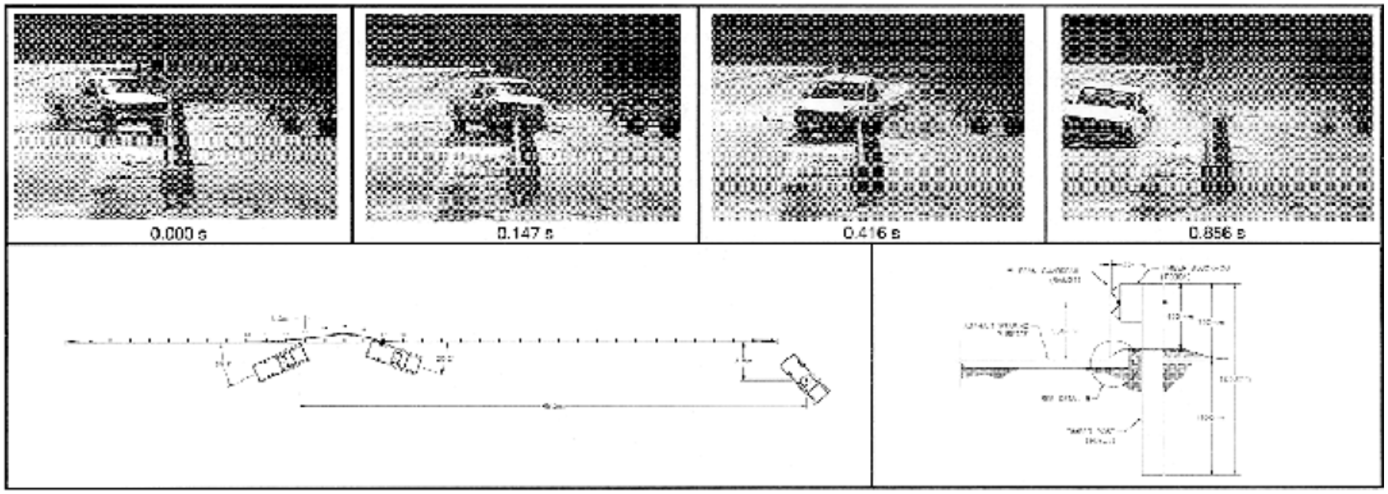
- Embankments, ditches, and culverts are the roadside terrain features cited as being most frequently involved in overturn accidents. However, detailed information on the geometry of the terrain and whether the rollover was caused by vaulting, or by the wheels hitting a small obstacle, or by the wheels digging into soft soil and tripping the vehicle is generally lacking in accident data files.
- In most (50% to 80%) of the rollover accidents, the vehicles were skidding out of control at a large yaw angle prior to overturning.
- About half of all accidental departures from the roadway occurred at path angles greater than 15 degrees, and the majority of the vehicles were estimated to have been traveling at speeds less than 64 to 80 km/h.

Full-scale tests were performed with an instrumented 1979 VW Rabbit automobile to provide data for evaluating the validity of the modified computer program. The tests included spinout of the car on level turf, dragging the car over a sod field, traversals of fill-embankments, and traversals of the front slope of a wide ditch. Motion-resistance force data were collected in these tests. They were used for obtaining tire/ground coefficients of friction for typical roadside terrain surfaces, as well as for validating the computer simulation models.

The drag tests were performed by attaching two steel cables to the center of the front and rear wheels on the right side of the vehicle. A load cell was installed on each cable to measure the forces as the vehicle was pulled sideways over the ground surface at speeds of 16 to 24 km/h. The data from the tests indicated that the average coefficient of friction between the tires of the VW Rabbit and the sodded ground surface was typically about 0.5.

The modified version of HVOSM provided reasonable accuracy of the simulations of the tests on the various roadside terrains. The authors do point out, however, that “the study did not thoroughly establish the extent to which the model accounts for all of the various real-world conditions that contribute to vehicle rollover” *(33)*.

Over 200 HVOSM simulations of vehicles traversing various sideslopes, fill-embankments, and ditch configurations were used to determine how much these roadside conditions affect the rollover tendencies of vehicles. In addition to the VW Rabbit model (1093-kg vehicle) that was developed and validated with the full-scale tests, two other vehicles were modeled: one was a relatively light vehicle and the other a much heavier vehicle. The lighter vehicle had a mass of



General Information	
Test Agency	Texas Transportation Institute
Test No.	404201-1
Date	05/23/00
Test Article	
Type	Guardrail
Name	G4 (2W) With 100-mm Curb
Installation Length (m)	68.6
Material or Key Elements	Strong Wood Post W-Beam With 100mm Asphaltic Curb Set Out 25 mm From Face
Soil Type and Condition	Standard Soil, Dry
Test Vehicle	
Type	Production
Designation	2000P
Model	1995 Chevrolet 2500 Pickup Truck
Mass (kg)	
Curb	1882
Test Inertial	2000
Dummy	75
Gross Static	2075

Impact Conditions	
Speed (km/h)	101.8
Angle (deg)	25.2
Exit Conditions	
Speed (km/h)	54.3
Angle (deg)	20.2
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	4.5
y-direction	4.8
THIV (km/h)	21.9
Ridedown Accelerations (g's)	
x-direction	-11.9
y-direction	10.6
PHD (g's)	12.4
ASI	0.70
Max. 0.050-s Average (g's)	
x-direction	-6.2
y-direction	5.4
z-direction	-3.1

Test Article Deflections (m)	
Dynamic	1.0
Permanent	0.860
Vehicle Damage	
Exterior	
VDS	11LFQ4
CDC	11FLEK3 & 11LDEW3
Maximum Exterior Vehicle Crush (mm)	370
Interior	
OCDI	FS0100000
Max. Occ. Compart. Deformation (mm)	48
Post-Impact Behavior (during 1.0 s after impact)	
Max. Yaw Angle (deg)	49
Max. Pitch Angle (deg)	-7
Max. Roll Angle (deg)	-19

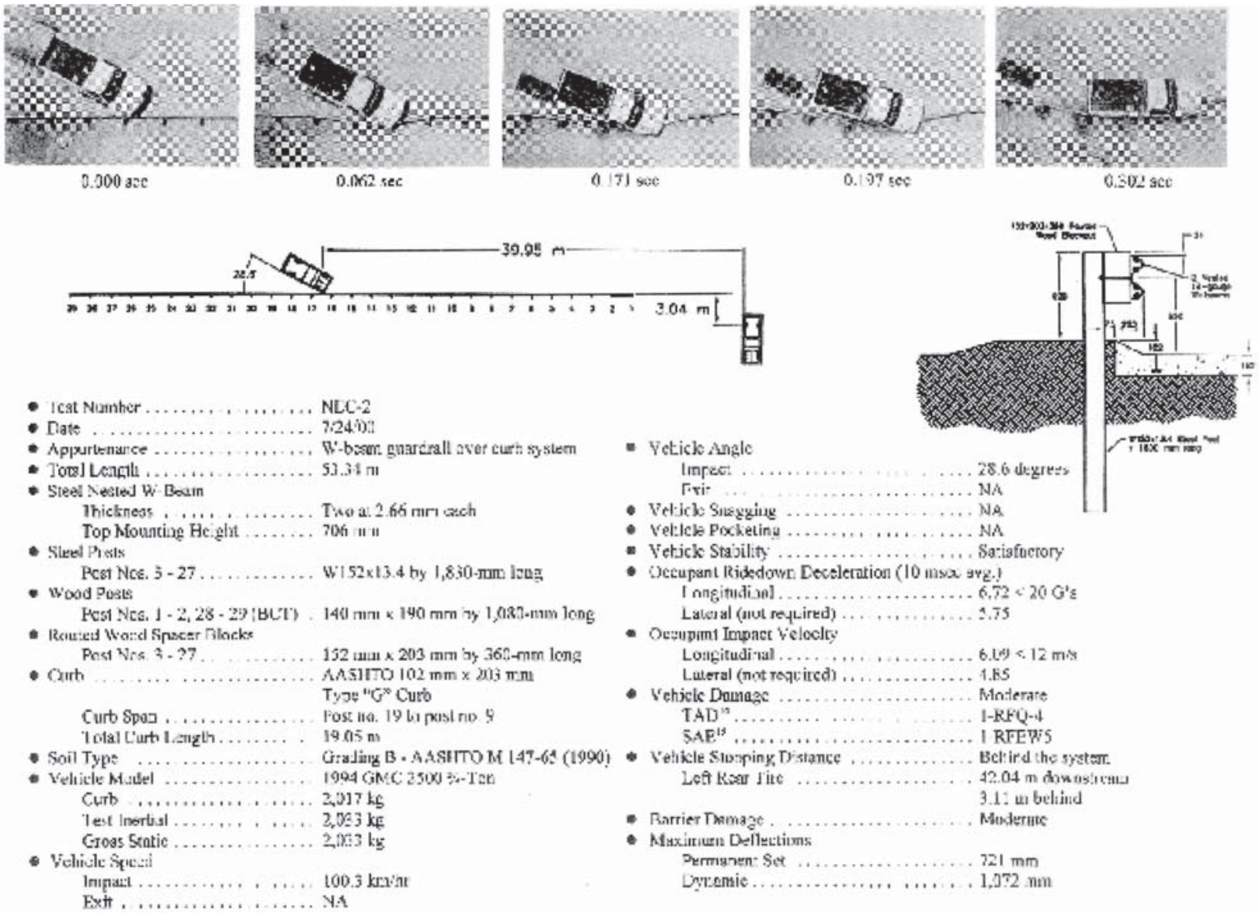
Figure 13. Summary of results of TTI Test 404201-1 from Bullard and Menges.

Figure 14. NCHRP Report 350 Test 3-11 impact with modified G4(1S) guardrail with nested 12-gauge W-beams and a 102-mm curb under the rail (32).

816 kg and was identical to the VW Rabbit model, except that the mass and moments of inertia were different. The heavier vehicle model had a mass of 2,018 kg, representing the larger class of passenger cars, and its physical characteristics were defined in HVOSM using available data typical for that vehicle type.

The conclusions that the authors made from the study, that pertain to the use of HVOSM for predicting the dynamic response of vehicles traversing various types and shapes of terrain, are presented below:

- The modified HVOSM has been demonstrated to be capable of predicting the response of vehicles operating on off-road terrains with reasonable accuracy. The development and incorporation of the deformable-soil model in HVOSM is considered an important improvement since it allows simulation for the effects of tire sinkage in soil which has been identified as one of the leading causes of rollover. However, evidence of the validity of the deformable-soil model is clearly still very limited.
- The relatively few simulations that resulted in vehicle rollover in this study point to the dynamic nature of the rollover phenomenon, which is sensitive to the complex interactions of many factors whose effects are not independent. Adequate vehicle parametric data for the severe operating regime associated with the rollover response are generally lacking. Among the most important of these are definitive data for tire properties under the



• Test Number	NEC-2
• Date	7/24/01
• Appurtenance	W-beam guardrail over curb system
• Total Length	53.34 m
• Steel Nested W-Beam	
Thickness	Two at 2.66 mm each
Top Mounting Height	706 mm
• Steel Posts	
Post Nos. 3 - 27	W152x13.4 by 1,830-mm long
• Wood Posts	
Post Nos. 1 - 2, 28 - 29 (BCT)	140 mm x 190 mm by 1,080-mm long
• Routed Wood Spacer Blocks	
Post Nos. 3 - 27	152 mm x 203 mm by 360-mm long
• Curb	AASHTO 102 mm x 203 mm Type "G" Curb
Curb Span	Post no. 19 to post no. 9
Total Curb Length	19.05 m
• Soil Type	Grading B - AASHTO M 147-65 (1990)
• Vehicle Model	1994 GMC 2500 ¾-Ton
Curb	2,017 kg
Test Inertial	2,033 kg
Gross Static	2,033 kg
• Vehicle Speed	
Impact	100.3 km/hr
Exit	NA
• Vehicle Angle	
Impact	28.6 degrees
Exit	NA
• Vehicle Snagging	NA
• Vehicle Pocketing	NA
• Vehicle Stability	Satisfactory
• Occupant Ridedown Deceleration (10 msec avg.)	
Longitudinal	6.72 < 20 G's
Lateral (not required)	5.75
• Occupant Impact Velocity	
Longitudinal	6.09 < 12 m/s
Lateral (not required)	4.85
• Vehicle Damage	Moderate
TAD[13]	1-RFQ-4
SAE[14]	1-RFEW5
• Vehicle Stopping Distance	Behind the system
Left Rear Tire	42.04 m downstream 3.11 m behind
• Barrier Damage	Moderate
• Maximum Deflections	
Permanent Set	721 mm
Dynamic	1,072 mm

Figure 15. Summary of results of Test NEC-2 from Polivka et al. (32).

high tire load and large slip and camber angle conditions that prevail in most rollover events.

- Ultimately, the vehicle rollover potential associated with roadside features is reflected by real-world accident experience. From the literature review performed as part of the study, it is apparent that the existing accident data base lacks the comprehensive and detailed information necessary to define the conditions that lead to rollover for different vehicle types. For example, data contained in accident data files, such as NASS and FARS, usually provide little or no information regarding the geometrics of the accident site (e.g., steepness of slopes, embankment height and roundings), whether the vehicles were tripped by a surface irregularity or as a result of tire ruts in soft soil, where rollovers were initiated with respect to the terrain feature (sideslope, backslope, toe of embankment, etc.), vehicle trajectory, and so forth

Cooperrider et al., 1990 (*34*)

Researchers at Failure Analysis Associates, Inc. (FaAA) performed a study to investigate the mechanics of vehicle rollovers. It was their perception that the experimental and analytical methods that were being used at that time (late 1980s) did not accurately represent real-world vehicle rollovers. Their investigation involved full-scale tests in which vehicles were tripped by three different trip mechanisms: sliding into a curb, sliding in soil, and being thrown from a dolly. They also developed a simple analytical technique to characterize the mechanics of these different trip modes based on a constant force method.

Eight full-scale tests were conducted using four different vehicle types to examine the rollover mechanics of vehicles tripped by a curb, rolled off a dolly, and tripped by tire-soil interaction. The test matrix and results from the study are presented in Table 3.

For the curb impact tests, a 152-mm-square section of steel box tubing, rigidly affixed to the roadway, was used to represent a curb. The vehicles were towed sideways and released just prior to contact with the curb. The friction between the tires and the road surface was reduced by applying soap film to the roadway. In order to more accurately represent the impact conditions of vehicles in real-world accidents, where an initial roll of the vehicle would be produced from the tire-ground interaction, a roll angle of 2.5 degrees was built into the test vehicles by extending the left suspension with wood blocks.

Two of the five curb impact tests resulted in rollover. The three vehicles that did not rollover sustained excessive damage to their wheels or axles during impact. Failure or partial failure of these components may result in a reduction of load applied to the vehicle, which reduces the potential for rollover. The tripping force must be applied for sufficient duration to cause rollover. For the vehicles that did roll over, the average maximum decelerations at the center of gravity was 12.4 Gs, compared with maximum decelerations of 1.62 Gs and 1.3 Gs in the soil trip tests and dolly tests, respectively.

The curb trip tests resulted in peak angular velocities of 260 deg/sec and 300 deg/sec. The peak angular velocities in the soil trip tests were similar with values of 230 deg/sec and 390 deg/sec. The peak angular velocity of the vehicle in the dolly test was 460 deg/sec, which was much higher than the

TABLE 3 Test matrix for Cooperrider et al. study (*34*)

Test no.	Vehicle model	Trip method	Test speed (km/h)	Results
1	1981 Dodge Challenger	Curb	48.1	no rollover
2	1981 Dodge Challenger	Curb	47.6	rollover
3	1979 Datsun B210	Curb	47.2	rollover
4	1972 Chevrolet C20 Van	Curb	47.6	no rollover
5	1981 Chevrolet Impala	Curb	48.6	no rollover
6	1981 Dodge Challenger	Dolly	48.6	rollover
7	1981 Dodge Challenger	Soil	54.2	rollover
8	1979 Datsun B210	Soil	43.5	rollover

curb-tripped and the soil-tripped vehicles. The higher roll rate of the dolly-rolled vehicle was attributed to the 48-degree initial roll angle of the dolly when it contacted the ground. This caused a greater moment arm from the point of impact to the center of gravity of the vehicle.

The analytical model developed in the study was based on the assumption that a constant tripping force acts on the vehicle during the rollover initiation phase. Although the model did not account for the effects of tire and suspension system compliance, the results compared well with the test data.

It was found that the kinematics of the tripped vehicle varied significantly, depending on the tripping mechanism (i.e., curb, soil and dolly). Curb impacts produced very high decelerations, usually in excess of 10 Gs. Some curb-tripped vehicles, however, did not rollover because critical structural components (e.g., the wheel assembly) failed during impact, providing an alternate path for the unbalanced forces. When components of a vehicle collapse or break during these types of impact, the duration force may not be sufficient to initiate a rollover.

Allen et al., 1991 (*35*)

Researchers at STI conducted a study to determine the directional and rollover stability of a wide range of vehicles using the computer simulation program VDANL. They showed that rollover stability and directional stability are related to center of gravity location and track width, as well as the other characteristics that influence these variables under hard maneuvering conditions. Vehicle dynamics and tire-ground interaction under such conditions are nonlinear and can be quite complex; therefore, computer simulation is essential in analyzing stability problems.

Forty-one vehicles were used in the study for parameter and field testing. Spinout occurs when rear tire adhesion limits are exceeded while the front tires still have side force capacity available. Computer simulation results were validated with the field test results, and it was found that in many cases the dynamic behavior of the vehicle was largely dependent upon the tire model and tire-ground interaction. Thus, detailed information about the tire properties and friction coefficients are necessary for valid model development.

One conclusion from their study was that load transfer distribution among the tires should be near to, or greater than, the vehicle weight distribution, although there are several other factors that influence limit performance maneuvering. As the center of gravity of a vehicle is raised or the track width is narrowed, wheel lift off becomes more likely and balancing load transfer distribution becomes a critical issue. The computer simulation program, VDANL, was validated for both stable and unstable vehicle maneuvering conditions and was considered to be a practical and effective means of analyzing vehicle stability problems.

Allen et al., 1997 (*36*)

Researchers at STI and JPC Engineering further improved the Slip Tire Model (STIREMOD) for use in the vehicle dynamics computer simulation program, VDANL. STIREMOD was expanded to include the full-range of operating conditions for both on- and off-road surfaces, including unlevel terrain, changing surface conditions, and tires plowing through soil. They discussed in some detail the input parameters for the model and the means for establishing typical model parameters. The model would be useful for the analysis of vehicle encroachments onto the road shoulders and sideslopes. The model could also be used for analyzing vehicle tire interaction with curbs, where the curb would be modeled as an abrupt change in surface shape and surface properties (e.g., asphalt pavement to a concrete curb).

Allen et al., 2000 (*37*)

Allen and other researchers at STI wrote a paper summarizing the development and application of the vehicle dynamics computer simulation model, VDANL. The subsystem models of VDANL are described (e.g., tires/wheels, brakes, steering, power train, roadway inputs, driver model, steering control, and speed control). Discontinuities in the roadway, such as potholes, speed bumps, and curbs, can be modeled in VDANL with additional inputs to the surface profile.

VDANL models the inertial component of the vehicle as a six-degree-of-freedom sprung mass connected by springs and dampers to the axles, which are supported by pneumatic tires. According to Allen et al., “Communications services have also been added to VDANL so that it can provide commands for display image generators, feel and motion systems, sound cuing, and miscellaneous controls and displays”*(37).* The program runs in real time on Pentium-class computers running Windows 95/98/NT network.

A specialized version of the software was developed for the FHWA as part of the IHSDM, which allows new roadway designs to be assessed using a driver model. Two case studies were presented in their study using VDANL–IHSDM to determine (1) if a truck-climbing lane was necessary for a proposed roadway alignment and (2) if a loaded tractor-trailer would be able to maintain a specified speed traveling downgrade on the roadway without losing control.

SYNTHESIS OF LITERATURE REVIEW

Both sloping and vertical curbs are regularly used in urban areas along low-speed roadways for drainage purposes, walkway edge support, pavement edge delineation, to discourage vehicles from leaving the roadway, and to provide limited redirection of encroaching vehicles. Vertical curbs have a vertical or nearly vertical face and are recommended for use only on low-speed roads. Sloping curbs have a sloping face and are configured such that a vehicle can ride up and over the curb, in order to reduce the likelihood of causing tire blowout or suspension damage. Sloping curbs are used primarily for drainage purposes, but are also used on median islands and along shoulders of high-speed roadways for delineation and other reasons.

Curbs along low-speed roadways are not likely to result in serious injuries and are commonly used in urban areas where speed limits are in the range of 40 to 48 km/h. Curbs along high-speed roadways have been discouraged by AASHTO for many years because of the potential hazard caused by high-speed impact with curbs *(1)*. In the intermediate range of speed (between 60 and 80 km/h), however, there are no standards for the use of curbs. Highway engineers must, therefore, determine if a curb is warranted based on individual roadway conditions and location. In urban areas, curbs are often considered acceptable; whereas in rural areas curbs are discouraged at intermediate speeds *(1)*.

There have been a limited number of studies performed to determine the effects of impact with curbs on the dynamic stability of vehicles and on the performance of barriers placed in combination with curbs. The studies have involved full-scale crash testing *(22, 24–30, 32)* and computer simulation using the HVOSM *(21–23)*. A summary of full-scale crash tests involving curb–guardrail combinations is presented in Table 4. Although it has been found that sloping curbs do not significantly redirect a vehicle during tracking impact, they do affect the vertical trajectory of the vehicle. Thus, while the curb itself presents very little threat of harm when hit by a vehicle, when a vehicle impacts and mounts a curb, the dynamics of the vehicle may cause the vehicle to impact a secondary object in such a manner that will cause the object to not function properly.

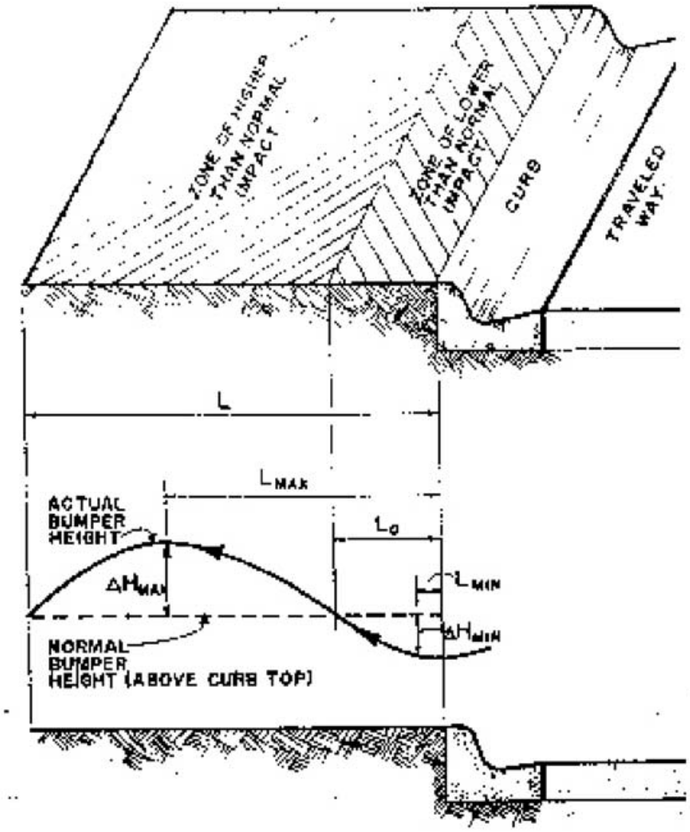
A curb located in front of a guardrail may cause an impacting vehicle to strike the guardrail at a point higher or lower than normal. Under certain impact conditions, the curb can cause the vehicle to ramp high enough to vault over the barrier, or, in some cases, underride and snag on the barrier *(22, 24, 25, 29, 32)*. Another example of possible adverse effects of a curb on the performance of a device is the placement of a curb in front of a breakaway pole. The breakaway features at the bases of the poles are designed to work when the pole is struck near the base. If a vehicle is airborne when it hits a breakaway pole, the impact point may be well above the base; thus the breakaway feature may not work as it is intended.

In some studies, the lateral displacement of the vehicle at maximum rise height has been considered an important factor for determining the potential for vehicle underriding or vaulting a barrier *(22, 24, 38)*. Design parameters defined by AASHTO for curb impacts are shown in Figure 16. It was reported that underride and vaulting of a standard strong-post guardrail were possible when the barrier was placed within some critical range behind the curb, usually within 0.76 m for underride and between 0.01 and 3.66 m for vaulting. These data were obtained through measuring vehicle trajectory during impact with curbs.

It was assumed for many years by design engineers that if the curb is placed behind the face of the W-beam that the curb-guardrail system would perform adequately in safely containing and redirecting an impacting vehicle. Previous crash

TABLE 4 Summary of full-scale crash tests of curb–guardrail combinations with curb located behind face of guardrail

Literature reference	Testing agency	Test no.	Vehicle type	Speed and angle	Curb type	Guardrail type	Result	Comment
Bryden and Phillips *(26)*	NYDOT		Dodge Station Wagon (2041 kg)	100 km/hr 26 degrees	152-mm vertical curb	Thrie-Beam Bridge Rail	Passed	smoothly redirected
FHWA Memorandum Feb 1992 *(27)*	ENSCO	1862-1-88	3/4-ton Pickup Truck (2449 kg)	100 km/hr 20 degrees	203-mm AASHTO A	G4(1S)	Failed	vehicle vaulted over rail
		1862-4-89	Small Car (820 kg)	100 km/hr 20 degrees	152-mm Asphalt Dike	G4(1S)	Passed	smoothly redirected
		1862-5-89	Large Car Sedan (2041 kg)	100 km/hr 25 degrees	152-mm Asphalt Dike	G4(1S)	Failed	vehicle vaulted over rail
		1862-12-90	Large Car Sedan (2449 kg)	100 km/hr 25 degrees	100-mm AASHTO G	G4(1S)	Passed	vehicle was airborne but did not vault
		1862-13-91	Large Car Sedan (2041 kg)	100 km/hr 25 degrees	152-mm Asphalt Dike	G4(1S) stiffened with W-beam	Passed	smoothly redirected
		1862-14-91	Large Car Sedan (2041 kg)	100 km/hr 25 degrees	152-mm Asphalt Dike	G4(1S) stiffened with rub rail	Failed	vehicle speed change at redirection was too high
Holloway & Rossen *(28)*	MwRSF	M06C-1	1985 Ford LTD (2041 kg)	96.1 km/hr 25.1 degrees	152-mm vertical curb	G4(1S)	Passed	smoothly redirected
Polivka et al. *(29)*	MwRSF	NEC-1	1991 GMC 3/4-ton Pickup (2,000 kg)	103.2 km/hr 24.5 degrees	102-mm AASHTO G	G4(1S)-mod with wood blockout	Failed	excessive anchor movement / guardrail ruptured
Bullard and Menges *(30)*	TTI	404201-1	1995 Chevrolet 3/4-ton Pickup (2000 kg)	101.8 km/hr 25.2 degrees	100-mm CDOT curb	G4(2W)	Passed	significant guardrail damage and anchor movement
Polivka et al. *(32)*	MwRSF	NEC-2	1994 GMC 3/4-ton Pickup (2,000 kg)	100.3 km/hr 28.6 degrees	102-mm AASHTO G	G4(1S)-mod with wood blockout nested W-beam	Passed	vehicle experienced extreme trajectory but did not vault over rail



L = Distance From Top of Curb to the Second Return to Normal Bumper Height
L_{max} = Distance Measured From Top of Curb to Occurrence of Highest Bumper Height Above Normal
L_o = Distance From Top of Curb to the First Return to Normal Bumper Height
L_{min} = Distance From Top of Curb to the Occurrence of Lowest Bumper Height Below Normal
ΔH_{min} = Maximum Bumper Height Below Normal Height
ΔH_{max} = Maximum Bumper Height Above Normal Height

Figure 16. Design parameters for curb impacts as defined by AASHTO (38).

tests, involving large sedans and pickup trucks impacting various curb-guardrail combinations, have provided researchers with mixed results regarding the performance of such systems *(24, 25, 27–30, 32)*.

In full-scale crash tests performed by ENSCO with full-size cars, it was shown that vaulting is possible even when the curb is located flush with the face of a W-beam guardrail. If guardrail deflections during impact are sufficient to allow the wheel of the vehicle to contact and mount the curb, the vehicle may vault over the barrier *(28)*. Even though the vehicle contacts the barrier prior to reaching the critical trajectory height that would signify override, the vehicle will continue to rise while it is in contact with the barrier and may result in vaulting during redirection. Crash tests with pickup trucks performed at Midwest Roadside Safety Facility, on the other hand, have demonstrated that similar curb/W-beam guardrail combinations do not degrade the performance of the barrier systems *(23, 28)*.

Some curb types are more likely to cause vaulting of a vehicle than others. The FHWA memorandum in February 1992 *(27)* reported that, in the case of curbs 150 mm high or higher, if a guardrail deflects enough for the wheels to mount the curb, the vehicle could vault over the guardrail. It was also reported in the FHWA memorandum that crash tests involving the AASHTO Type G curb (a 100-mm curb height with slanted face) placed behind the face of the W-beam resulted in the vehicle becoming airborne when guardrail deflection permitted the wheels to mount the curb; however, the vehicle did not vault the guardrail. A similar conclusion was found in other studies, which showed that vehicle impact with low curbs would result in very little change in the vertical trajectory of the vehicle (50-mm maximum), regardless of the vehicle's speed and angle of impact *(22, 24)*.

A W-beam guardrail is sufficiently stiff that the lateral deflections of the barrier are minimal during impact with a small car; thus for curb–guardrail combinations in which the curb is placed underneath a strong-post W-beam guardrail, there is little chance of vehicle contact with the curb *(24, 27)*. It has also been found that stiffening the guardrail system by installing a W-beam rail to the back of the posts or installing a rub-rail will enhance the safety performance of a curb–guardrail system *(28)*. The installation of a rub-rail may provide the most safety benefit, since it both stiffens the system to avoid vehicle-to-curb contact and shields the posts from potential wheel snag.

There have been three tests performed on curb–guardrail systems under *NCHRP Report 350* Test 3-11 impact conditions: MwRSF tests NEC-1, NEC-2 and TTI test 404201-1 *(29, 30, 32)*. These tests involved 100-mm-high curbs placed in combination with strong-post guardrails. Both test NEC-1 and test TTI 404201-1 resulted in significant tensile forces in the W-beam rail and excessive movement of the anchor system. In test NEC-1, the two upstream anchor posts for the G4(1S) guardrail with wood blockouts ruptured causing the vehicle to pocket *(29)*. This ultimately resulted in rupture of the W-beam rail element, and the vehicle penetrated the guardrail. The poor performance of this system was not directly attributed to the effects of the curb, but rather to a loss of tensile capacity of the guardrail during impact when the anchor system failed.

In TTI test 404201-1, the foundation of the anchor posts of the G4(2W) guardrail moved in excess of 70 mm at the ground line, and there was considerable damage to the guardrail system; however the system did meet all safety requirements of *NCHRP Report 350 (30)*. Also, the extent of damage to the system in test TTI 404201-1 was much greater than that of previous crash tests on the G4(2W) guardrail system without a curb present *(31)*.

In test NEC-2, the G4(1S) guardrail with wood blockouts was modified and retested *(32)*. The guardrail was modified by nesting 12-gauge W-beam rails along the length of the system. This test resulted in excessive vertical trajectory of the vehicle during impact, but the vehicle remained upright and successfully met all safety criteria of *NCHRP Report 350*.

Vehicle tripping on curbs was addressed in a very limited number of studies. The studies that were identified in the literature used a variety of techniques for analysis including analytical methods, computer simulation, full-scale crash testing, and accident data analysis *(24, 33, 34)*. Vehicle tripping on curbs was addressed in Holloway et al. using HVOSM to simulate nontracking impacts of large passenger sedans *(24)*. Based on the results of their simulations, they concluded that sloping curbs may not be a significant cause of vehicle rollovers; however, it should be noted that the models used in their study were not validated for nontracking impacts. It was not reported whether or not friction between the tires and ground surface was included in the simulations. Friction between the tires and ground will affect the initial roll angle and roll rate of the vehicle prior to impact, which may increase the vehicle's tendency to rollover.

DeLeys and Brinkman used crash data analysis and computer simulation to investigate rollover tendencies of vehicles traversing various kinds of roadside terrain. They concluded that the data bases lacked the comprehensive and detailed information necessary to define conditions that lead to rollover. A modified version of HVOSM with improved application for rollover situations was used in their study *(33)*. Full-scale tests were used to validate the computer models and, subsequently, over 200 simulations were conducted to investigate the rollover tendencies of vehicles traversing various sideslopes, fill embankments, and ditch configurations. They did not investigate vehicle-curb interaction; however, the models that were used in their study may have been applicable for such analysis.

Cooperrider et al. carried out a series of full-scale crash tests to determine the potential for rollover of various vehicle types tripped by a curb, sliding in soil, and rolled off a dolly *(34)*. A steel 152-mm-square tube section rigidly affixed to the roadway was used to represent a curb in their tests. In five of the eight tests that they conducted, the vehicles rolled over. In the cases where rollover did not occur, the wheel assembly failed during impact with the curb due to the high forces that were developed. The failure of the wheel assembly, consequently, removed the overturning force that was being applied to the vehicle. If the wheel assembly had not failed in those cases, it is possible that all the tests would have resulted in a rollover.

The vehicle dynamics code, VDANL, has been used to study vehicle rollover as a function of unstable maneuvering conditions and also to investigate vehicle rollover because of impact with various vehicle tripping mechanisms such as curbs, soil, ditches, and so forth *(35–37)*. The results of the computer models developed in those studies were validated with full-scale tests. VDANL was chosen by the FHWA to be incorporated into the IHSDM, which is used to assess new highway designs.

SUMMARY

While there has been some work performed on the safety effectiveness of curbs and the use of curbs in conjunction with traffic barriers, the literature review shows that there are many limitations, such as the age of the tests, the lack of sophistication in early computer models, and changing full-scale crash testing guidelines. The following are the major findings of the literature review:

- Curbs should not be used in combination with W-beam guardrail systems on high-speed roadways due to the potential safety hazard of vaulting or underriding the barrier. In cases where design engineers include curbs along high-speed roadways for drainage reasons or to improve delineation, other methods should be sought to achieve those purposes.

- Neither the large and small cars crossing 150-mm-high or smaller curbs in a tracking manner are likely to result in loss of vehicle control or cause serious injuries. The response of the 2000-kg pickup truck crossing curbs, however, was not known. The large passenger car used in the previous crash testing procedures was replaced in the current testing procedures (*NCHRP Report 350*) with the 2000-kg pickup truck. The dynamic response of this particular vehicle type crossing over curbs (not in conjunction with a roadside safety barrier) has never been evaluated with either full-scale tests or computer simulation.
- Most of the curb impacts that were found in the literature involved vehicles encroaching the curb in a tracking manner. It was concluded in every case that a vehicle encroaching onto a sloping curb in a tracking manner is not likely to cause the driver to lose control of the vehicle or cause the vehicle to become unstable unless a secondary impact occurs. Another aspect of collisions with curbs involves an out-of-control vehicle impacting the curb in a nontracking position. In these situations, vehicle tripping may be highly probable during impact.
- Errant vehicles leave the roadway in a variety of orientations; however, it is assumed that the majority of these vehicles encroach onto the roadside in a semicontrolled tracking manner. In such cases, the left or right front bumper would be the first point of contact with a roadside object in an impact event. The position of the bumper upon impact has, therefore, been a primary concern involving impacts with longitudinal traffic barriers, where it has been assumed that the position of the bumper during impact is a reasonable indicator of vehicle vaulting or underriding the barrier. Due to pitching of the moving vehicle, the bumper height at impact may be higher or lower than the static position of the bumper.
- Nontracking impacts with curbs may result in vehicle instability and rollover, especially impacts involving vehicles with high centers of gravity. From the literature study it seems that the most likely methods for analyzing nontracking impacts will be vehicle dynamics codes, such as VDANL. There has been a great deal of advancement in computation power and in code development over the past few years that has enabled computer simulation programs to become a very efficient means of analysis. Both tracking and nontracking impact on curbs may be investigated using vehicle dynamics codes, such as VDANL, and finite element analysis (FEA) using LS-DYNA.
- A small number of tests have been performed in which a curb was placed behind the face of guardrail barriers. The idea was to locate the curb such that minimal interaction between the vehicle and curb occurred. This worked well with lighter vehicles, such as the 820-kg small car, but did not prevent vehicle-curb interaction with the heavier vehicles, such as the 2000-kg pickup truck, unless the guardrail was retrofit in some manner to strengthen it and minimize guardrail deflection. To circumvent the problem, one option considered was to use a low-profile curb underneath the guardrail. This was expected to minimize the effects that the curb would have on vehicle trajectory when the wheels of the vehicle were able to contact the curb during impact; however, full-scale tests conducted by various organizations provided mixed results. In some cases the crash test was successful, while in others it was not. In cases where the test was a failure, it was not clear whether the failure was induced by vehicle-curb interaction or if it was simply caused by inadequate barrier performance.

CHAPTER 3

SUMMARY OF STATE SURVEYS ON CURBS AND CURB–BARRIER COMBINATIONS

INTRODUCTION

The objective of this research project was to develop design guidelines for using curbs and curb–barrier combinations on roadways with operating speeds greater than 60 km/h. Seven tasks were identified to accomplish this objective. The second of these tasks was to conduct a survey of transportation agencies to determine current practice, guidelines, and standards pertaining to the use of curb and curb–barrier combinations on higher-speed roadways. The survey was also intended to identify problems experienced by transportation agencies and solutions developed to counter those problems.

The research team composed a three-page survey (provided in Appendix A) and distributed it to all 50 states. The survey included 12 questions covering the types of curbs used, the guidelines for using them, the typical functional purposes of curbs, alternatives to using curbs, safety problems encountered, using curbs in combination with barriers, curb research, and voids for establishing guidelines. Twenty-seven states completed and returned the survey. Their responses are organized by topic. In lieu of the state's name, when reference is made to individual states, a numeric identifier is used.

TYPES OF CURBS USED BY THE STATES

According to AASHTO, curbs are used extensively on all types of urban highways but should be used cautiously on rural highways. There are two general classifications of curbs: vertical curbs and sloped curbs. Some raised aspect or vertical element is required to be considered a curb. Vertical curbs are relatively high and steep-faced. They used to be called barrier curbs, but this terminology is no longer used because these curbs are not redirective devices or traffic barriers. AASHTO Type A curb, shown in Figure 17, is a vertical curb that ranges in height from 150 to 225 mm. It is designed to inhibit or discourage vehicles from leaving the roadway. Vertical curbs should not be used on freeways and are considered undesirable on high-speed arterials. AASHTO recommends that vertical curbs not be used where design speeds exceed 65 km/h, except in predominantly urban or rapidly developing urban areas in the intermediate speed range.

Sloped curbs are designed to be low with flat sloping faces so that vehicles can cross them readily. AASHTO Type B, C, D, E, F, and G curbs, shown in Figure 18, are all typical sloped curbs. Types B, C, and D are considered to be mountable under emergencies. The vertical portion on the lower face of Types C, D, and F is constructed as an allowance for future resurfacing. All the sloped curbs shown in Figure 18 can be used as shoulder curbs to control drainage, improve delineation, and reduce erosion.

The survey respondents indicated the type or types of curbs they used for facilities with a design speed of 65 km/h or greater: AASHTO Type A vertical curb or Type B, C, D, E, F, or G sloped curbs. A summary of the results is presented in Table 5.

Five states indicated that they used Type A vertical curb although two of those states indicated that it was not used for speeds much greater than 65 km/h. Three other states employed a curb similar to Type A with a few minor modifications in the dimensions. Thirteen states employed a Type B sloped or similar curb. Type B was used by more of the responding states than any of the other curbs. Type C and Type D had a similar response, with seven states using each or a comparable version with slightly modified dimensions. Types E and G also had a similar response. Type F had the lowest response rate: only one state used a sloped curb that was similar to Type F. Additionally, seven states identified curbs used in their jurisdictions that could not be categorized with the AASHTO curbs. Seven distinct curbs were identified, shown in Figure 19.

Most of the states had guidelines or policies in place for when vertical or sloped curbs should be used. Only six states indicated that they did not have policies, two of which indicated that they followed AASHTO guidelines.

Eight states indicated that they limit the use of curb by facility type. State 8 did not use curbs on roadways with design speeds greater than 70 km/h with the exception of asphalt concrete dikes. State 13 also restricted their use to roadways with design speeds less than 70 km/h, but noted that exceptions exist, particularly in urban areas. State 25 limited their use to facilities with design speeds under 80 km/h. State 3 limited their use to non–access-controlled highways. State 7 and State 10 limited their use to urban streets. State 18 only

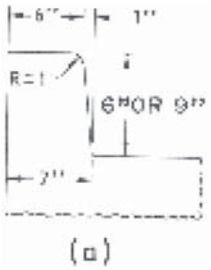


Figure 17. AASHTO vertical curb Type A (1″ = 25.4 mm).

used 76-mm asphalt or 100-mm lip curbs for design speeds greater than or equal to 80 km/h. State 19 responded that it did not restrict their use, but noted that the policy was that curbs are undesirable for use on roadways with design speeds greater than 80 km/h. State 24 also responded that it did not restrict their use, but its roadside design guide prohibits the use of nonsloped curb on new construction projects on highways with operating speeds greater than or equal to 80 km/h and along the mainline of Interstates, freeways, or high-speed parkways.

TYPICAL FUNCTION OF CURBS

AASHTO lists drainage control, pavement edge delineation, right-of-way reduction, aesthetics, delineation of pedestrian walkways, reduction of maintenance operations and assistance in orderly roadside development as purposes of curbs. States were asked to separately rank the functional purposes of vertical and sloped curbs used in their state. Most states identified drainage control as a primary or secondary purpose for vertical curb. Walkway support and pavement delineation were also highly rated as typical functional purposes of vertical curb. Only one state said the primary use of vertical curb was to protect vehicles from steep slopes. Respondents also identified other functional purposes of vertical curb not listed on the survey, including minimizing right-of-way impacts, access control, accommodating pedestrians, aesthetics, erosion control, delineating edge parking, and traffic channelization.

The primary functional purpose of sloped curb was most often listed as drainage. Twenty-four states listed it as the primary or secondary purpose. Pavement delineation was listed by 14 states as a primary or secondary functional purpose. One state listed walkway support as a primary functional purpose, and several others listed it as a secondary purpose. Protecting vehicles from slopes was listed as a secondary purpose by three states. Respondents also wrote in other functional purposes of sloped curb including erosion control, minimizing right-of-way impacts, access control, pedestrian needs, channelization, and delineation.

ALTERNATIVES TO USING CURBS

Eight survey respondents had found an alternative to using curbs for one or more of the functional purposes mentioned in the previous section. State 5 used sloping freeway curbs with catch basins to prevent embankment erosion in the gutter on

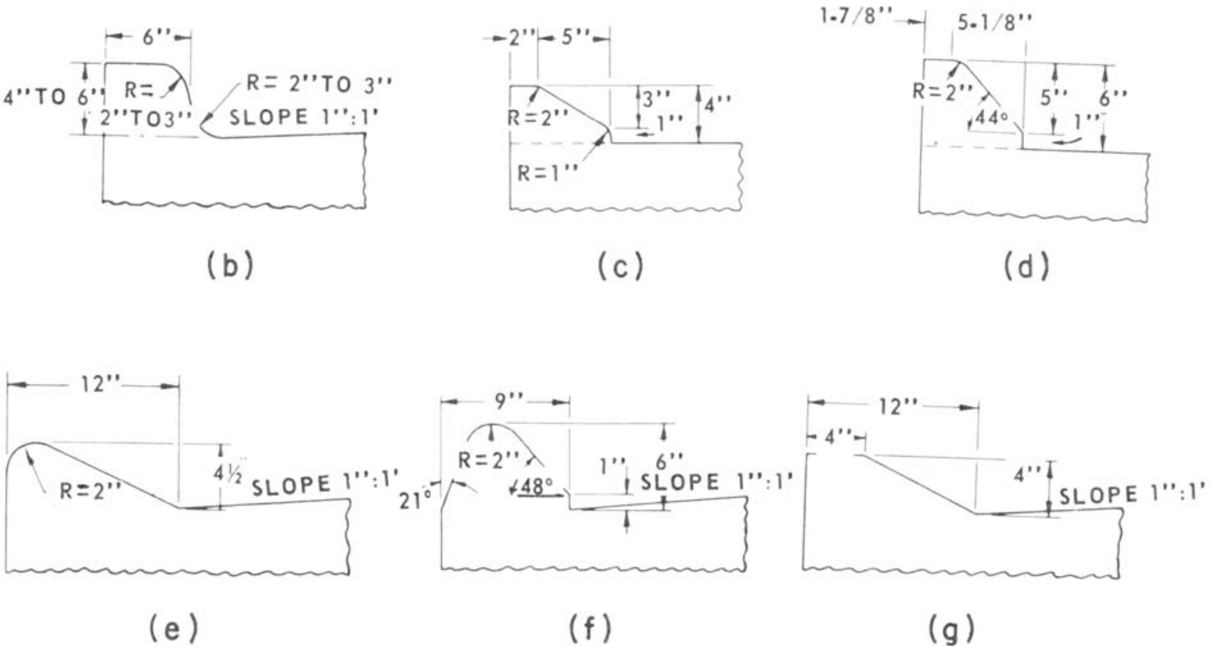
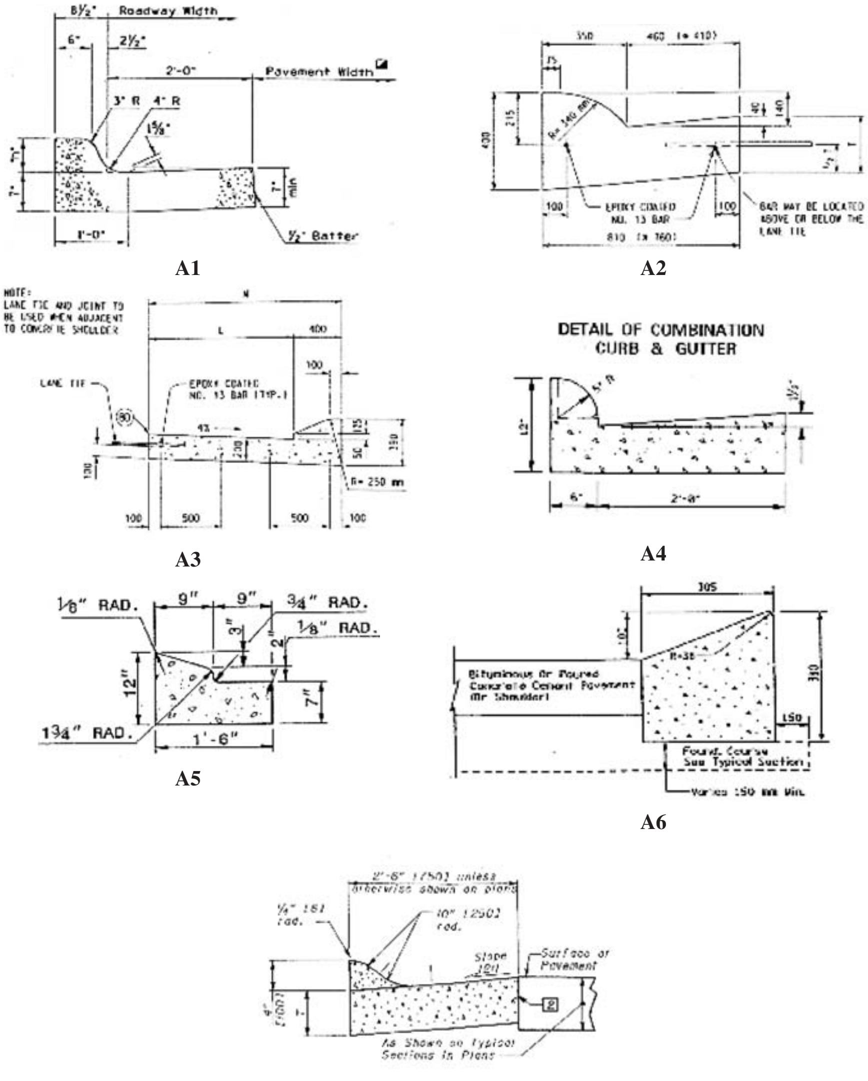


Figure 18. AASHTO sloped curbs (1″ = 25.4 mm).

TABLE 5 Vertical and sloped curb use among the states surveyed

AASHTO curb	Number of states using this curb	Number of states using a curb similar to this curb	Total
Type A Vertical	5	3	8
Type B Sloped	6	7	13
Type C Sloped	5	2	7
Type D Sloped	6	1	7
Type E Sloped	3	1	4
Type F Sloped	0	1	1
Type G Sloped	2	3	5



A1

A2

A3

A4

A5

A6

A7

Figure 19. Curbs used by various states that could not be classified as AASHTO curbs.

depressed freeway sections. State 4 used portable New Jersey shape concrete barrier along the edge of highways for drainage channelization. State 12 used pavement striping or flexible tubes in lieu of curbs for channelization. State 16 used open ditches for drainage but noted that it is not appropriate at most locations where curbs are specified. State 19 used drainage ditches or swales in place of curbs for drainage and berm guards or other safety barriers to protect vehicles from steep slopes. State 9 used concrete traffic separators in the median. State 25 used a unique curb and gutter adjacent to the travel lane on facilities of greater than 80 km/h. State 24 used a traversable curb that is more like a gutter or berm than a curb. The curb has no reveal and is 100 mm high and 305 mm wide with a 1:3 slope across the top. The curbs used by States 25 and 24 are included in Figure 19 as A5 and A6, respectively.

PREVIOUS CURB SAFETY PROBLEMS IDENTIFIED BY THE SURVEY

Only five states indicated that they had experienced safety problems when using curbs alone on higher-speed roadways. However, two states indicated that they did not use vertical curbs on facilities with posted speeds in excess of 70 km/h and one state indicated it only had ten miles of curbed high-speed highway in its system. Of the five states that experienced safety problems, only four states provided further information. State 25 had experienced cross-median fatalities with curbs along higher-speed roadways; median guardrail was installed to resolve this. State 9 indicated that it had had problems with vertical curb installed on a 90 km/h urban Interstate in the 1960s and was replacing the vertical curb with sloped curb or concrete barrier. State 19 had experienced problems with vaulting and rollover of vehicles in the tests performed for the Midwest State's Regional Pooled Research Program. State 27 also experienced problems with vaulting. This state reported that curbs are not typically used alone, but rather in combination with a guardrail and for protection from runoff or erosion of a steep slope.

CURB–BARRIER COMBINATIONS

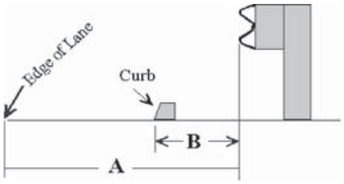


Figure 20. Schematic drawing used in the State Survey to identify curb and barrier placement along roadways.

The states were also asked about curb and barriers used in combination. The survey included the illustration in Figure 20. The survey respondents provided the type of curb used, the type of barrier used, the offset distance from the edge of the travel lane to the face of the guardrail or barrier (distance A in the illustration), and the offset from the face of the curb to the face of the guardrail or barrier (distance B in the illustration). Many states indicated that they tried not to use the two in combination. Three states said they did not use them in combination on higher-speed roads. Seven states responded that guardrail was used but did not specify the type of guardrail. The authors assume they are referring to a form of non-yielding, metal beam guardrail (i.e., not cable). The type of curb used differed greatly. Regarding offset distances, four states recommended the curb be placed offset from the barrier, though at distances that varied greatly; one state placed the curb under the barrier; and most states placed the curb face flush with the barrier face. The responses are summarized in Table 6.

The states were also asked if they had experienced any safety problems with curb–barrier combinations on higher-speed roads. Three states had experienced safety problems. State 6 had experienced vaulting with the 150-mm curb that was resolved by only using sloped curbs on higher-speed facilities. State 19 had also experienced vehicles vaulting. The respondent did not elaborate on how this problem was solved but did state that even with the curb face flush to the barrier, vehicle wheels can get caught between the curb and the guardrail. State 27 had experienced W-beam rail failure at the splice and switched to ten-gauge rail on all Interstates and ramps for roadside applications.

PREVIOUS CURB-RELATED RESEARCH CONDUCTED BY THE STATES

Survey respondents were asked if their states had conducted any research related to curbs or curb–barrier combinations. Seven states indicated that they had conducted or were currently participating in research on curbs or curb–barrier combinations. Three states had participated in the Pooled Fund Study by the Midwest Roadside Safety Facility entitled "Guardrail and Guardrail Terminals Installed over Curbs." One state had conducted crash tests of 100-mm and 150-mm curb beneath guardrail and determined that the 100-mm-high curb met the criteria of *NCHRP Report 350, Recommended Procedures for the Safety Performance Evaluation of Highway Features*. The 150-mm-high curb did not meet the criteria.

VOIDS FOR ESTABLISHING GUIDELINES

The states were asked to identify the most critical void for establishing guidelines for using curbs and curb–barrier com-

TABLE 6 Summary of curb–barrier installation practices among the states

ID	Curb type	Barrier type	Distance from edge of lane to barrier	Distance from face of curb to barrier face
1	A	Guardrail	0.6 m	0.15 m
3	A (similar)	Strong-post (steel)	2.4 m	0
4	Sloped	W-beam	0.6 m	0
6	C	W-beam	0.6 to 3.7 m	0
8	Asphalt dike	W-beam	0.6 to 3.0 m	0
9	Asphalt (100-mm max)	W-beam	1.8 to 3.0 m	0
10	A	Guardrail	2.4 m	0
11	Vertical and sloped	W-beam or T-beam	3.0 m	2.4-3.0 m
12	B or G	W-beam	Varies	0 or 0.23 m
13	B	W-beam	Varies	0-0.23 m
14	A	W-beam	0.3 m	0
15	G (similar)	W-beam	Varies	0.05 m or 0.25 m[a]
16	B and G	Strong-post, steel-plate	Varies	0
17	B	Guardrail	2.4 or 3.0 m	0
18	100-mm limit	W-beam	1.2 or 3.0 m	0 or 0.6 m behind post
18	100-mm curb	Raised median	1.2 or 3.0 m	0 or 0.6 m behind post
19	A or G	Steel-plate beam, concrete	Shoulder (1.8-3.0 m)	0 or behind guardrail
20	Sloped or vertical (100-mm max)	W-beam	Varies	0 or behind guardrail
21	A	F-shape concrete[b]	Shoulder (2.4 m)	Behind barrier or 3 m
22	C	Guardrail	0.3 m	0
23	Sloped	W-beam	Shoulder	0 or >0.46 m
24	Auxiliary type VI	Varies[c]	Varies	<0.3 m or >3.0 m
25	Shoulder berm gutter	Guardrail	Shoulder	Under guardrail
26	Sloped (50 mm)	Guardrail	Varies	0-.3 m
27	C	Strong-post (steel) blocked-out or 3-cable	Varies	0

[a] If curb/gutter is outside paved shoulder, 50 mm; when it contacts the lane, 250 mm.
[b] The transition is rolled down from barrier to curb.
[c] Varies, but not cable, concrete barriers, or attenuating devices.

binations that they would like to see addressed in this research project. Most indicated that they needed more guidance on the use of curbs and curb–barrier combinations at various speeds and functional classes, especially for high-speed facilities. They wanted to know the appropriate guardrail and curb to use for all speed and functional scenarios. Two states indicated they would also like guidance on the appropriate curb to be used with sidewalks. One state asked for guidelines for transitional sections (suburban to urban) of highway projects in developing areas. One state wanted to address the need for additional lane widths for each configuration. Two states identified the need for consideration of the practicalities of construction and maintenance in curb–barrier combinations. One of those two states had experienced problems with the combinations when milling, paving, or removing snow. The other state had experienced problems placing guardrail in pavement when installing guardrail in front of the curb.

Additionally, responding states also identified the following voids:

- Consideration of bumper height and vehicle center of gravity,
- Drainage alternatives,
- Usage of impact attenuators on medians,
- Curb–barrier combinations at bridge approaches with bridge rails,
- Safety impacts without a shoulder,
- Influence of asphalt concrete dikes and W-beam,
- Amount of allowable curb reveal to permit resurfacing without resetting the curb,
- Placement of sand barrels behind the curb, and
- Curb trajectory information.

ADDITIONAL INFORMATION

The state that originated the problem statement has a unique traversable curb (Type A6 in Figure 19) that it wanted to be included in the study. The curb has a nominal width of 300 mm with a 1 : 3 slope across the top and no vertical reveal. The curb is intended to permit pavement delineation and provide drainage control while minimizing the potential destabilization hazard to errant vehicles. To their knowledge, the curb had not been crash-tested.

One state was interested in design, maintenance, and construction issues concerning curb–barrier combinations. They had recently sent a questionnaire to all DOTs asking if the surveyed state installed curb in conjunction with strong-post guiderail. If so, the questionnaire inquired about installation, milling and overlay procedures, and whether the surveyed state had experienced any complications with the guiderail and curb combination while milling, installing, snow plowing, or overlaying.

Regarding curb–barrier combinations, one state recommended placing the face of the barrier at the back edge of the curb. They felt this would lessen the number of nuisance hits of the guardrail and lower damage to vehicles that may rub the curb slightly.

The state that identified bumper height and vehicle center of gravity as needing to be addressed indicated that the automobile industry should be included in any research since that industry has a large impact on the success or failure of roadside safety features.

SUMMARY

The survey of the states indicated that most states discouraged the use of curbs on roadways with design speeds over about 70 km/h. The most common type of sloped curb used by the states was the AASHTO Type B curb. Most states located guardrails such that the face of the curb and the face of the barrier were flush consistent with current AASHTO recommendations. There was a perceived need for better guidelines on the use of curbs on higher-speed roadways and on the use of curbs in conjunction with roadside barriers.

CHAPTER 4

RESEARCH APPROACH

INTRODUCTION

This chapter discusses the methods of analysis that were used in this study, including crash and geometric data analyses, computer simulation, and full-scale crash testing.

Existing crash and geometric databases were examined to determine if they could be used to characterize the extent and severity of safety problems associated with curb and curb–barrier combinations. The crash databases were also reviewed to determine if they could provide information regarding the nature of impacts involving curbs (e.g., impact speed, angle of impact) in order to develop input for full-scale crash testing and computer simulation studies.

Where validated computer models can be developed, computer simulation methods are the most versatile approach for investigating a wide range of possible impact scenarios (e.g., vehicle type, curb type, impact condition). Computer simulation can also be very useful for determining the precise effects that vehicle-curb interactions have on the stability of various vehicle types and the effects that curbs placed in combination with roadside safety barriers have on the performance of the barriers. Vehicle dynamics programs and Finite Element Analysis (FEA) are two such methods that were considered for use in this study. Vehicle dynamics programs have been used extensively in previous curb-safety-related studies, as indicated in the literature review (Chapter 2). FEA has been used in several studies involving vehicle impact with roadside safety hardware and has proven to be very effective. To the knowledge of the authors, however, FEA has not been used in any study involving curbs or curb–barrier combinations and, therefore, was not discussed in the literature review section of this report. Since FEA was an important analysis tool in this research, the effectiveness of the method applied in the study of roadside barrier crashworthiness is discussed in this chapter. A summary of previous studies using FEA to study vehicle impact with roadside safety barriers is presented and discussed later in this chapter.

Full-scale crash testing was another method used in this research. The advantage of full-scale crash tests is that they are actual physical impact events in which there is little ambiguity about the results. The disadvantage is that they are costly, and it is seldom feasible to perform very many tests. The testing results, therefore, usually do not address a very wide range of conditions. A full-scale testing program was used in this project to verify and confirm hypotheses developed from the computer simulation study, as well as to validate and strengthen the conclusions of this research.

ANALYSES OF CURB-RELATED SAFETY ISSUES USING CRASH AND INVENTORY DATA

Introduction

Since the inception of this study, an overall goal has been to use existing databases containing information on crashes, roadway inventory, and traffic to better characterize safety problems associated with curb and curb–barrier combinations on higher-speed roadways. Such information was used directly in the development of the design guidelines since it can provide real-world insight into the magnitude of the problem on various roadway types, the nature of the problem (e.g., how curb impacts are similar or dissimilar to other run-off-road collisions), and factors that might be influenced to reduce curb impact severity (e.g., to prevent rollover after a curb impact). In addition to this primary goal of input into design guidelines, a secondary but related goal of the crash-data analyses was to provide leads for the crash testing and simulation efforts that were later conducted.

The crash-data analyses took place in two phases. Phase I involved a detailed examination of existing databases to determine which ones might be suitable for use. Based on preliminary examination of data and discussions with the project panel, a final set of crash-data analyses were defined. These analyses were then carried out in Phase II, using the selected databases.

Examination of Databases

As detailed in an interim report, the national databases of interest included the following:

- Fatality Analysis Reporting System (FARS)
- National Automotive Sampling System—General Estimates System
- National Automotive Sampling System—Crashworthiness Data System
- FHWA's Highway Safety Information System (HSIS)

Preliminary examination of each of these databases was undertaken to determine whether it would be useful in the overall safety analysis and what types of analyses might be possible with it.

Fatality Analysis Reporting System (FARS)

This database is an annual census of all police-reported fatalities in the United States, with data coded and cleaned by a FARS coder in each state. Data from the 1994–99 period were used in this effort. FARS contains data on the presence of a "Curb" as both First Harmful Event (FHE) and Most Harmful Event (MHE), and data on "Rollover" separate from the event codes. FARS does not contain data on the full "Sequence of Events" in a crash (e.g., curb strike, then guardrail impact, then overturn). FARS does not contain any information on curb design parameters. Finally, since it is based on fatal crashes, FARS data could not be used to examine differences in injury severities with and without curbs; only the fatal crash failures are present.

National Automotive Sampling System— General Estimates System (NASS-GES)

The GES was established by NHTSA to allow national estimates of safety issues. It contains annual files for 1988 and later. Data from the 1995-99 period were used in this analysis. GES is based on an annual random sample of approximately 50,000 police crash reports of all severities (ranging from no-injury to fatality) pulled each year from 60 areas (400 police jurisdictions) across the nation. All cases are manually coded to approximately 90 common data elements. The coding is based on a review of the computerized codes on the original form and the narrative and sketch. GES assigns a weight for each case that allows one to develop national estimates; severity is the predominant weighting variable. As will be seen later, both weighted and unweighted data were used, depending on the nature of the specific analysis. While not containing a full sequence-of-events variable that would allow one to trace the entire crash sequence, GES does contain a number of variables that are of interest in this study, including a FHE and a MHE, both of which include striking a curb. The GES data do not contain any crash location information. Thus, they cannot be linked to any supplemental data, such as roadway inventories, operating speed inventories, or Average Annual Daily Traffic (AADT).

National Automotive Sampling System— Crashworthiness Data System (NASS-CDS)

The NASS Crashworthiness Data System contains detailed crash reconstruction data collected on site by expert investigators on approximately 5,000 crashes each year since 1979. Data for the 1997–99 period were used in this study. The crashes must involve a vehicle that is towed from the scene. Thus, none of the less-severe property-damage-only crashes (the successes with respect to roadside objects) are included. The sample, taken from police reports in the same jurisdictions as the NASS-GES sample, is an unequal probability sample that is heavily weighted toward more severe crashes. The data are the highest quality crash data available, since they are based on detailed follow-up investigations by trained investigators. In order to develop national estimates from the data (or estimates related to the overall crash severity distribution), the cases have to be weighted based on the probability of being selected.

CDS includes a virtually unlimited "Sequence of Events," with "Curb" as one of the objects that can be struck. Like the GES sample, there are no details of curbs or barriers, and only limited data on roadway geometrics; the data cannot be linked to supplemental roadway or traffic inventories. Unlike the GES data, the margin of error is rather large when one is exploring an issue with relatively few severe crashes per year (like curb-related crashes), since the sample for such crashes is quite small.

Enhanced CDS data were developed at TTI for NCHRP Project 17-11, "Determination of Safe/Cost Effective Roadside Slopes and Associated Clear Distances." NASS crash investigators collected additional data at selected CDS crash sites, and TTI reconstructed encroachment speed, angle, and tracking information where possible, including a confidence rating for the reconstructed data.

FHWA's HSIS

HSIS is the only national data file containing both crash and roadway inventory elements. It includes linkable files of police-reported crashes, roadway geometry inventories, and traffic volumes in eight states (five states in the 1985–97 period; three additional states in the 1990–97 period). The files contain data for crashes of all severities on all state-system roadways, i.e., it excludes municipal or county roads not controlled by the state. Since the current project focused on higher-speed major roadways that the states control, this restriction was unimportant. While six of the eight states have some form of both "Object Struck" and "Sequence of Events" or "First/Most Harmful Event," only Illinois and Michigan have a "Sequence of Events" variable in which curb impacts are separated from other objects and where "rollover" can be extracted as a separate event. Like the GES, both states also include information in the crash file related to crash/occupant injury severity and speed limit. Therefore, the data for these two states were chosen for use in this study. To capture the most recent years of data in the HSIS files, the 1996 and 1997 data for each state were used.

A further advantage of HSIS is the linkable roadway inventory data. For both Illinois and Michigan, the inventory file includes not only AADT and speed limit for each section of highway on the state system but also an indication of the presence of curb.

Finally, Michigan provides an additional file not present in any other HSIS state: a Guardrail Inventory File that contains information on the location and description of each section (run) of guardrail along each side of the highway (e.g., type, purpose, and distance from roadway). Because there can be multiple rails at any point on the roadway (e.g., rails on each side and in the median), the file is very complex and difficult to work with. Furthermore, it has not been actively maintained by the Michigan DOT since 1992. However, because this is the only known guardrail inventory file that can be linked with other roadway and traffic data to produce crash rates per passing vehicle, it was linked with the Michigan 1992 roadway inventory file and with Michigan 1993 and 1994 crashes in this study. Details of the complex merging effort and data decisions can be found in Appendix E.

Description of Data Analyses

Based on the goals of the project and the initial review of the available databases, the project panel defined a set of six crash-data analyses to be conducted. Table 7 provides a brief description of each analysis along with the database used. As noted earlier, the analyses fell into two major groups: those conducted to further define and examine the extent of the curb-related safety problem, and those primarily conducted to provide input into the simulation and crash-testing efforts.

Since an objective of the overall study effort was to relate curb design guidelines to some measure of roadway operating speed (and, ultimately, to design speed), the panel was interested in targeting operating speed in the crash-data analyses where possible. Unfortunately, operating speed is captured neither in crash data nor in normal roadway inventory data. However, in a supplemental analysis, 1998 non-crash speed data were obtained from Michigan DOT and were used with New York State DOT data to define surrogate operating speeds for different combinations of functional class and speed limit. These surrogate operating speeds were then attached to crashes and used in the Michigan severity modeling effort and in the Michigan and Illinois rollover analyses. These operating speeds could not be used in other analyses due either to the nature of the issue (e.g., extreme crashes are a function of individual vehicle speeds rather than average roadway speeds) or to the source of the data (e.g.,

TABLE 7 Description of data analyses conducted and databases used

Task title	Description	Data used
Extent of the U.S. Curb-Related Safety Problem	The extent of the national safety problem related to curbs was documented. Questions addressed included, "how large is both the fatal and nonfatal crash problem, and has there been any trend over the past 5 years?" and "are there differences in the nature of the curb-related fatal and nonfatal crashes as compared to noncurb single-vehicle crashes?"	1994-99 FARS 1995-99 NASS-GES
Examination of Curb-Related Rollover Risk and Nature Given a Crash	Given the severity of rollovers in general and the nature of the curb, this was a detailed, multifile examination of the risk and nature of rollover given a curb-related crash. To help ensure that the curb was directly related to the rollover, all three databases chosen include a "sequence of events" that allowed selection of only rollovers preceded by a curb impact.	1997-99 NASS-CDS 1996-97 Michigan 1996-97 Illinois
Crash, Injury, and Rollover Rates per Passing Vehicle for Guardrail Sections with and without Curbs	To examine differences in the crash rates and rollover rates for guardrails with and without curbs, Michigan data on guardrail inventory, roadway inventory, traffic and crashes on urban freeway and other urban multilane roads were used in both contingency table analysis and negative binomial models.	1992 Michigan Guardrail Inventory and Roadway Inventory 1993-94 Michigan crash data
Curb-Crash Severity Modeling	To further examine curb-crash severity, Michigan data for SV crashes in which a curb was the first object struck and SV crashes in which no curb was struck were used in the development of ordinal regression models to examine the effect of crash-related variables (e.g., rollover, speed limit, weather, vehicle type, operating speed) on crash severity.	1996-97 Michigan
Nature of Curb Impacts—Crash Reconstruction Data	To provide guidance to crash testing and simulation efforts, an attempt was made to extract the specific nature of curb-related impacts (e.g., angle of impact, speed, tracking/nontracking) from both basic NASS-CDS data and from enhanced CDS data obtained from the Texas Transportation Institute.	1997-99 NASS-CDS TTI Enhanced CDS data
Nature of Curb Impacts—Analysis Of "Extreme" Vs. "NonExtreme" Crashes	Extreme and nonextreme (i.e., severe and nonsevere) curb crashes were compared to define crash conditions that differ between the two categories. Such identified conditions might provide both further basic information on curb safety and additional factors for consideration in simulation and crash-testing efforts.	1995-99 NASS-GES 1996-97 Michigan 1996-97 Illinois

NASS-GES data do not contain functional class information). A more detailed description of the development of these assigned operating speeds is found in Appendix B.

It should also be noted that since the goal of this project was to define curb guidelines for higher-speed roads rather than city streets, and as directed by the project panel, a speed limit of 40 mph (65 km/h) was used as the lower boundary for most of the analyses conducted; all exceptions are noted.

COMPUTER SIMULATION METHODS

As discussed in Chapter 2, computer simulation has been used to assess the safety effectiveness of curbs since the late 1960s. Many of these analyses were performed using HVOSM, a rigid body vehicle dynamics code. Although early computer programs were limited in their abilities (due in large part to computational constraints), the results of those analyses have provided a great deal of information regarding the effect of curb impact on vehicle kinematics. Vehicle dynamics codes have come a long way since the 1960s and are now able to provide very accurate results regarding vehicle kinematics.

FEA is another computer simulation method that was useful in the study of curb and curb–barrier combinations. This method had not been used previously to study vehicle interaction with curbs, but it has been used extensively in recent years to study vehicle impacts with roadside hardware. Since the early 1990s FEA has rapidly become a fundamental part of the analysis and design of roadside safety hardware systems. In addition to being a reliable and relatively inexpensive means of analyzing and simulating impact events, it allows the analyst more control over the impact conditions and provides information about the mechanics of the impact event (stress, strain, energy, etc.) at specified time increments during impact. FEA is also capable of dealing with the highly nonlinear behavior associated with material properties, large deformations, and strain rate effects. The advantages and disadvantages of using vehicle dynamics programs and FEA are discussed in the following sections**.**

Vehicle Dynamics Codes

The HVOSM is a vehicle dynamics program that has been used extensively in conjunction with full-scale crash testing to study vehicle dynamics during impact with curbs *(14)*. Vehicle dynamics codes calculate the motions of the vehicle by modeling the vehicle as a series of rigid one-dimensional elements like springs, dampers, and masses. The tire and suspension models are the heart of a vehicle dynamics code since the only forces acting on the vehicle are presumed to arise from the tire interaction with the ground and inertia. The type of information that can be obtained from such analyses is related to the kinematics of the vehicle, such as vehicle trajectory, roll, pitch, and yaw. The trajectory of the vehicle has historically been used as a measure of the potential for override or underride of a barrier system. The HVOSM program has been modified and improved over the years and has been used for studying dynamic behavior of vehicles traversing various types of terrain. Development on HVOSM stopped, however, about 20 years ago as commercial vehicle dynamics codes supplanted it. HVOSM is now rarely used and vehicle suspension properties for modern passenger vehicles are not readily available for HVOSM.

VDANL is a comprehensive vehicle dynamics simulation program that runs on a PC in a Windows environment *(39)*. It was designed for the analysis of passenger cars, light trucks, articulated vehicles and multipurpose vehicles and has been upgraded over the years to expand and improve its capabilities. It now permits analysis of driver-induced maneuvering within limit conditions defined by tire saturation characteristics, as well as driver feedback control features. One of the significant advantages of using VDANL is that there is a large library of vehicle inertial and suspension properties available. Many of those properties have been validated by NHTSA using full-scale test track results. The one drawback of VDANL is that it is cannot simulate vehicle impact with an object and thus terrain must be smooth and continuous. This is because the program only simulates vehicle response due to interaction between the bottom of the tires and the ground. When a tire interacts with a curb that has a steep face, the contact will occur at a point higher up on the tire (i.e., not on the bottom of the tire), which cannot be accurately simulated with VDANL.

Nonlinear, Dynamic Finite Element Codes

For the simple event of vehicles traversing curbs, FEA provides little additional information about the kinematics of the vehicles than could be obtained through use of today's vehicle dynamics codes. FEA was, however, invaluable in the analysis of impacts with curb–barrier combinations. Vehicle dynamics codes only provide information regarding vehicle kinematics and cannot provide information about the vehicle interaction with the barrier. The performance of traffic barriers installed in conjunction with curbs cannot be directly analyzed using vehicle dynamics codes, because they are not designed to account for deformations of the vehicle or barrier. Since vehicle dynamics codes only address suspension and inertial forces, they are not appropriate for use when a vehicle strikes a barrier. A vehicle striking a barrier experiences forces arising from the interaction of the vehicle body and the barrier itself. These forces are highly nonlinear and usually involve large deformations, plastic behavior, and, often, failure of materials.

In FEA the entire substructure with its many parts and complicated shapes is divided into smaller units (finite elements) that are interconnected at discrete points (nodes). The stresses, strains, and motions of the model are computed at the element level and are then combined to obtain the solution of the whole body. The advantage of FEA is that the body of the vehicle is not rigid, and thus it can deform in a realistic manner during impact, whether it be the simple elastic deformations involved in transferring the load through the framework of the vehicle when crossing curbs or the large, plastic deformations involved in vehicle impacts with roadside safety barriers.

Vehicle dynamics codes have been used in previous studies to determine the potential for vaulting over or underriding barriers. In those studies, however, such potential was only speculated based on the vehicle's trajectory after crossing a curb; an actual impact event is much more complicated. FEA can provide detailed information about the impact event, including vehicle kinematics prior to and during interaction with the barrier, as well as damage sustained by both the vehicle and the barrier. FEA can also provide vehicle acceleration data that can be used for measuring injury risk factors of vehicle occupants.

For many years, full-scale crash testing was the primary method of determining the effectiveness of roadside safety hardware. More recently, there has been a great deal of advancement in computation power and in code development *(40)*. As a result the use of FEA for simulating collision events has become a reliable and widespread tool for investigating crashworthiness of roadside safety structures.

In 1998, the FHWA began the Centers of Excellence Program, in which it funds leading research organizations, including Worcester Polytechnic Institute (WPI), to investigate the impact performance of various roadside safety hardware. LS-DYNA was chosen by the FHWA to serve as the primary analysis tool to be used by the centers. LS-DYNA is a nonlinear, dynamic, explicit finite element code that is very efficient for the analysis of vehicular impact and is used extensively by the automotive industry to analyze vehicle crashworthiness *(41)*. It evolved from DYNA3D, public domain software developed in the mid- to late 1970s by John Hallquist at Lawrence Livermore National Laboratory. LS-DYNA's efficiency in simulating contact between various parts in a finite element model, along with its ability to effectively use underintegrated elements, has put LS-DYNA at the forefront of the nonlinear dynamic finite element software industry.

One advantage of FEA is that it is easy to vary parameters and assess exactly the structural and dynamic context of the collision. Parametric analyses are particularly straightforward, using simulation so that the variation of speeds and angles can be examined to find the critical impact conditions at which poor performance might occur. Simulation provides a method to explore a wide variety of curb–barrier combinations that would provide the broadest type of information for development of guidelines for the use of curb or curb–barrier combinations. The primary drawback of finite element simulations is that they must be validated to make sure that the predictions are realistic.

There are several public domain vehicle models available from the FHWA/NHTSA National Crash Analysis Center at George Washington University that have been validated for various impact conditions. A list of currently available vehicle models appears in Table 8.

Of the vehicle models listed in the table, the 1994 Chevrolet C-1500 reduced model has been used most widely by WPI researchers in particular and the Centers of Excellence community in general. While any of the models listed in Table 8 could have been used in this project, there is often considerable work needed to make a model useable in a particular impact scenario. The 1994 reduced model of the Chevrolet C-1500 was the easiest model to use since it had been widely used and debugged. The 1994 Chevrolet C-1500 (detailed model) and the 1993 Ford Taurus were also reasonably debugged but most of the other models had not been widely used outside of the NCAC and might have required significant debugging to be useful in this research.

The basic procedure used by the researchers at WPI in previous projects using FEA to examine roadside hardware has three steps: (1) build the finite element models, (2) validate them using crash tests found in the literature, and then (3) use the validated models to develop alternative designs. This procedure was followed in this project to ensure that the guidelines were based on models that had been validated against observable physical phenomena (e.g., crash tests).

Validation of Computer Models

Computer simulations were validated by comparing the simulated results to those obtained from full-scale crash tests. The accelerations at the center of gravity of the vehicle in the

TABLE 8 Public domain vehicle models available from the National Crash Analysis Center

Vehicle model type	
1998 Oldsmobile Cutlas Ciera	1996 Ford F-Series Truck
1994 Chevrolet C-1500 (detailed model)	1997 Geo Metro
1994 Chevrolet C-1500 (reduced model)	1993 Ford Taurus
1996 Plymouth Neon	Honda Accord
Chevrolet Lumina	Dodge Intrepid
Ford Crown Victoria	Ford Explorer

simulation and the full-scale test were compared using four quantitative techniques:

1. the Numerical Analysis of Roadside Design (NARD) validation parameters,
2. the analysis of variance (ANOVA) method,
3. the Geers parameters, and
4. the Test Risk Assessment Program (TRAP).

The NARD validation procedures are based on concepts of signal analysis and are used for comparing the acceleration-time histories of finite element simulations and full-scale tests *(42)*. The ANOVA method is a statistical test of the residual error between two signals *(43)*. Geers' method compares the magnitude, phase, and correlation of two signals to arrive at a quantitative measure of the similarity of two acceleration-time histories *(44)*. TRAP is a software program that was developed to evaluate actual full-scale crash tests and generate important evaluation parameters like the occupant impact velocities (OIVs), ride down accelerations, 50 msec average acceleration, and so forth. The program calculates standardized occupant risk factors from vehicle crash data in accordance with the NCHRP guidelines and the European Committee for Standardization (CEN) *(45)*. Using the same evaluation software for finite element simulations and full-scale tests further simplified the comparisons between actual physical tests and mathematical simulations.

Applicability of FEA to Roadside Barrier Impact Studies

Researchers at WPI had considerable experience using the LS-DYNA program for simulating vehicle impacts into roadside hardware *(46)*. As part of previous FHWA projects, Plaxico and Ray had developed finite element models of various roadside structures that were used to assess the impact performance of the systems. All the models were validated with the results of full-scale crash tests *(31)*. These models included the breakaway cable terminal; the MELT terminal; a weak-post guardrail system; and two strong-post guardrail systems, the G4(1W) and G4(2W) *(47–50)*. The G4(1W) and G4(2W) are both blocked-out strong-post W-beam guardrails; the G4(1W) uses 200 x 200mm wood posts; and the G4(2W) uses 150 x 200 mm wood posts. The G4(1W) is used in Iowa, and the G4(2W) is used in a number of other states.

A finite element model of the G4(2W) guardrail had been developed by researchers at WPI as part of a study sponsored by the Iowa Department of Transportation and the FHWA *(46)*. Simulations of Report 350 Test 3-11 impact conditions were performed with the model, and the results were compared to a full-scale crash test performed by TTI that established that the guardrail system successfully met the standards set in *NCHRP Report 350 (31)*. Figures 21 and 22 compare the FEA to the results of the full-scale crash test. This model was validated using the methods described previously. There was good agreement between the test and the simulation with respect to velocity histories, event timing, exit conditions, guardrail damage, and guardrail deflections, as well as the TRAP, NARD, Geers, and ANOVA evaluation parameters. A summary of major impact events, the time at which they occurred, and the corresponding velocity of the vehicle is presented in Table 9. Both the qualitative and quantitative comparisons of the finite element simulation to the physical crash test indicate that the simulation results reasonably replicate the guardrail performance in the test.

As an example of the use of FEA in this project, the validated model of the G4(2W) was used to simulate a Test Level 3 impact event involving the G4(2W) with a 150-mm-high AASHTO Type B mountable curb located just behind the face of the W-beam. The results are shown in Figure 23. The impact conditions were the same as those in TTI Test 471470-26. A rear view of both of the simulations (i.e., with and without a curb) is compared in Figure 24. From the results of the simulations it appears that the 150-mm-high AASHTO Type B curb placed behind the face of the G4(2W) guardrail system will likely cause serious instability when the vehicle exits the system. It is commonly observed in full-scale tests involving the 2000-kg pickup truck impacting various roadside barriers that when the rear tire contacts the barrier, the rotation of the tire tends to pitch the rear of the vehicle upwards, as shown in Figure 21. This phenomenon is further amplified when a curb is placed in combination with the guardrail. When the rear wheel hits the curb, an initial vertical displacement of the wheel prior to tire interaction with the barrier results, as demonstrated in Figures 23 and 24. The high pitch and exit angle of the vehicle during impact with the curb–guardrail combination make the post-impact behavior of the pickup very unpredictable. Rollover would be very likely given the exit conditions shown in Figure 23.

Typically, during impact with strong-post guardrail systems without a curb present, the front wheels of the pickup truck remain in contact with the ground over much of the event, which in effect reduces the lateral deflection of the system during impact and also decreases the redirection angle of the vehicle as it exits the system. In this finite element simulation of the curb–guardrail combination the vehicle was completely airborne during the time that it was in contact with the barrier, resulting in increased lateral deflection of the barrier and a much higher angle of redirection of the vehicle. The total deflection of the system in the simulations with and without a curb was 0.79 m and 0.71 m, respectively (i.e., the deflection in curb–barrier combination was 11.2% greater). The redirection angles of the vehicle in the simulations with and without a curb were 14 and 21 degrees, respectively. The redirection angle of the vehicle in the curb–guardrail simulation exceeded the allowable exit angle specified in *NCHRP Report 350*. According to criteria M of *Report 350,* the exit angle from the test article should be less than 60% of the test impact angle, measured at time of vehicle loss of contact with test device. The exit angle in the curb–guardrail simulation was 84% of the impact angle.

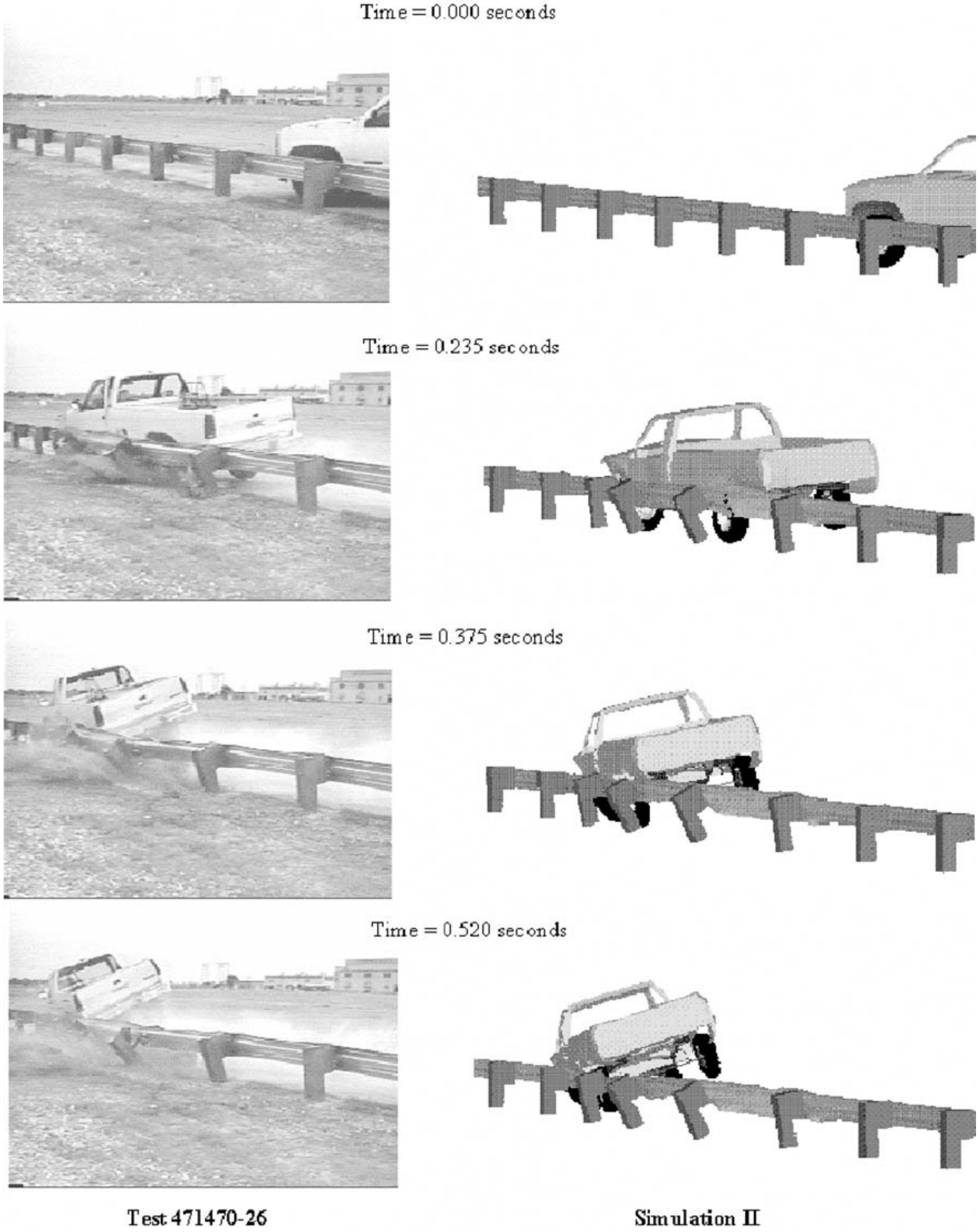


Figure 21. Sequential photographs for TTI Test 471470-26 (left) and G4(2W) finite element simulation (right).

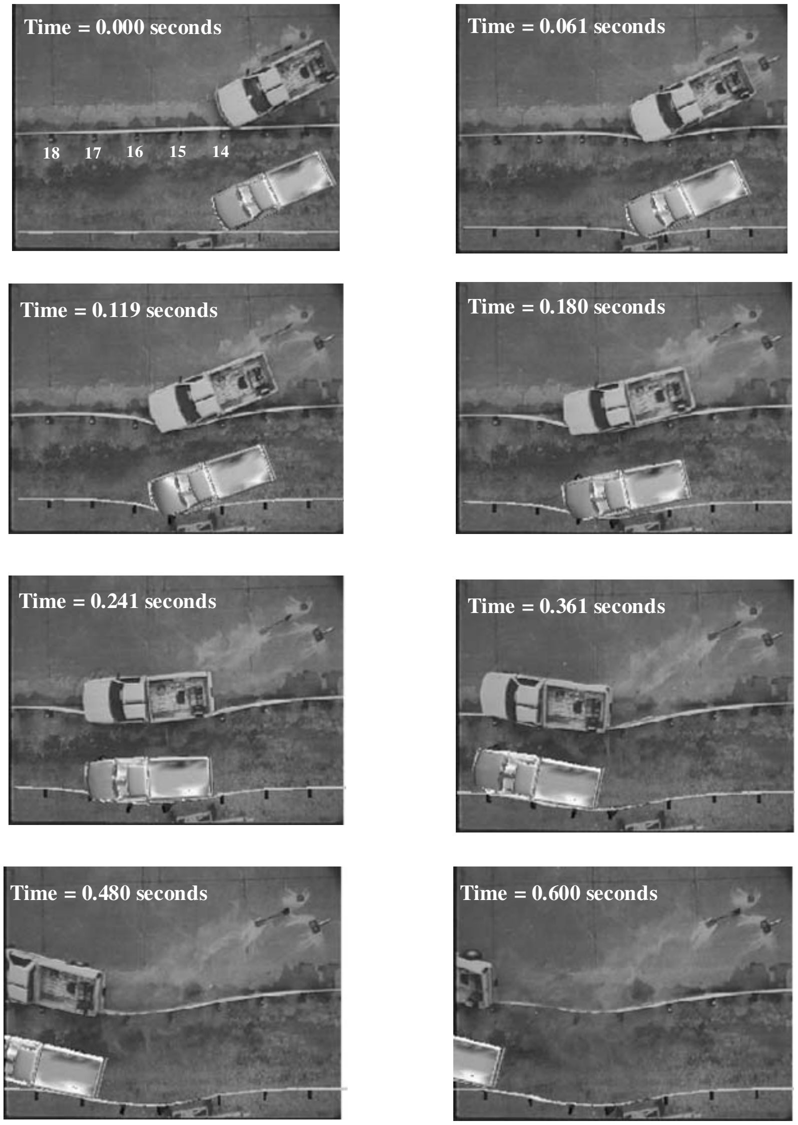


Figure 22. Sequential photographs for TTI Test 471470-26 (top) and G4(2W) finite element simulation (bottom), overhead view.

PARAMETRIC ANALYSES USING COMPUTER SIMULATIONS

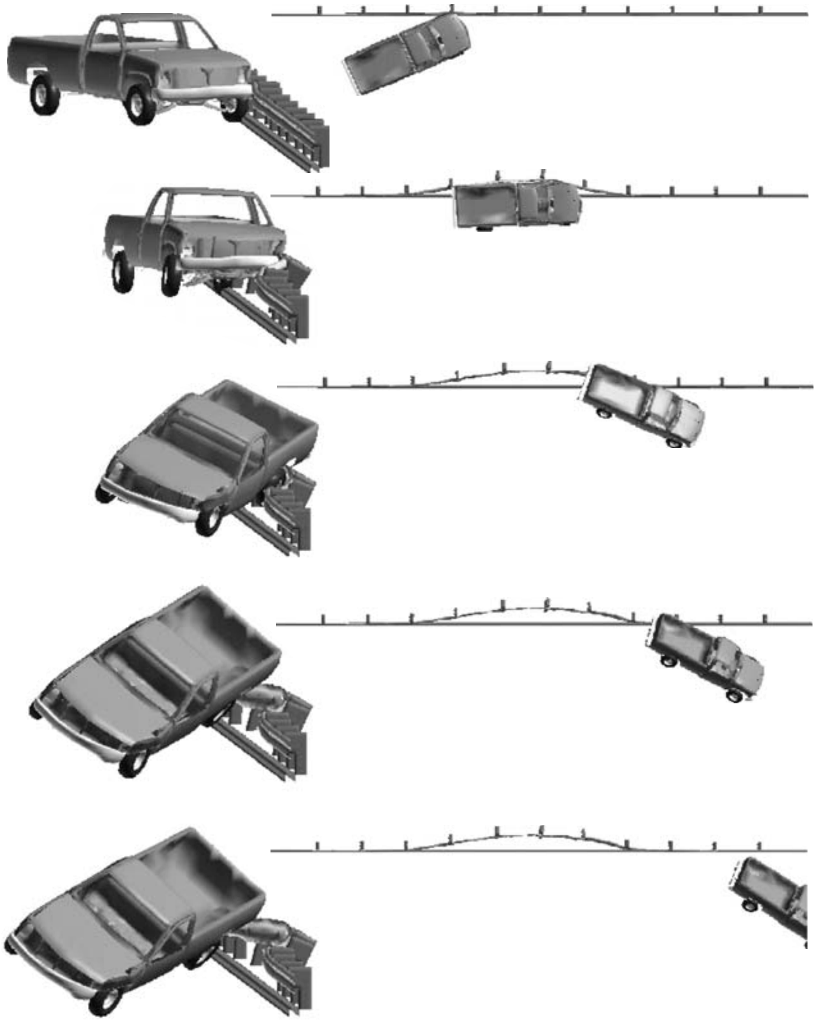
As demonstrated in the simulations, the potential for either barrier failure or vehicle vaulting can be assessed in much the same way that physical crash tests are evaluated. The advantage of finite element simulations is that once a model is developed and validated, the impact conditions, as well as the basic geometry of the installation, can be varied easily. Performing ten finite element simulations with the curb located at different distances from the face of the post, for example, would be straightforward and inexpensive and would allow the analyst to determine the effect of the curb offset on the performance of the barrier. Likewise, curbs with heights varying from 0 to 300 mm could be evaluated easily using finite element simulations. Another variable that could be investigated is vehicle speed. It is of interest to highway engineers to know the maximum impact speed that a system can withstand. Such information could be used for determining which system would be the most effective along a given stretch of roadway where site and operating conditions are known. Due to the fact that the project had limited funds, the project team and panel had to balance the number of simulations with the number of possible scenarios that could be investigated.

Analysis of Curb–Barrier Combinations

Analyses involving curb–barrier combinations were performed using the LS-DYNA finite element software. A matrix

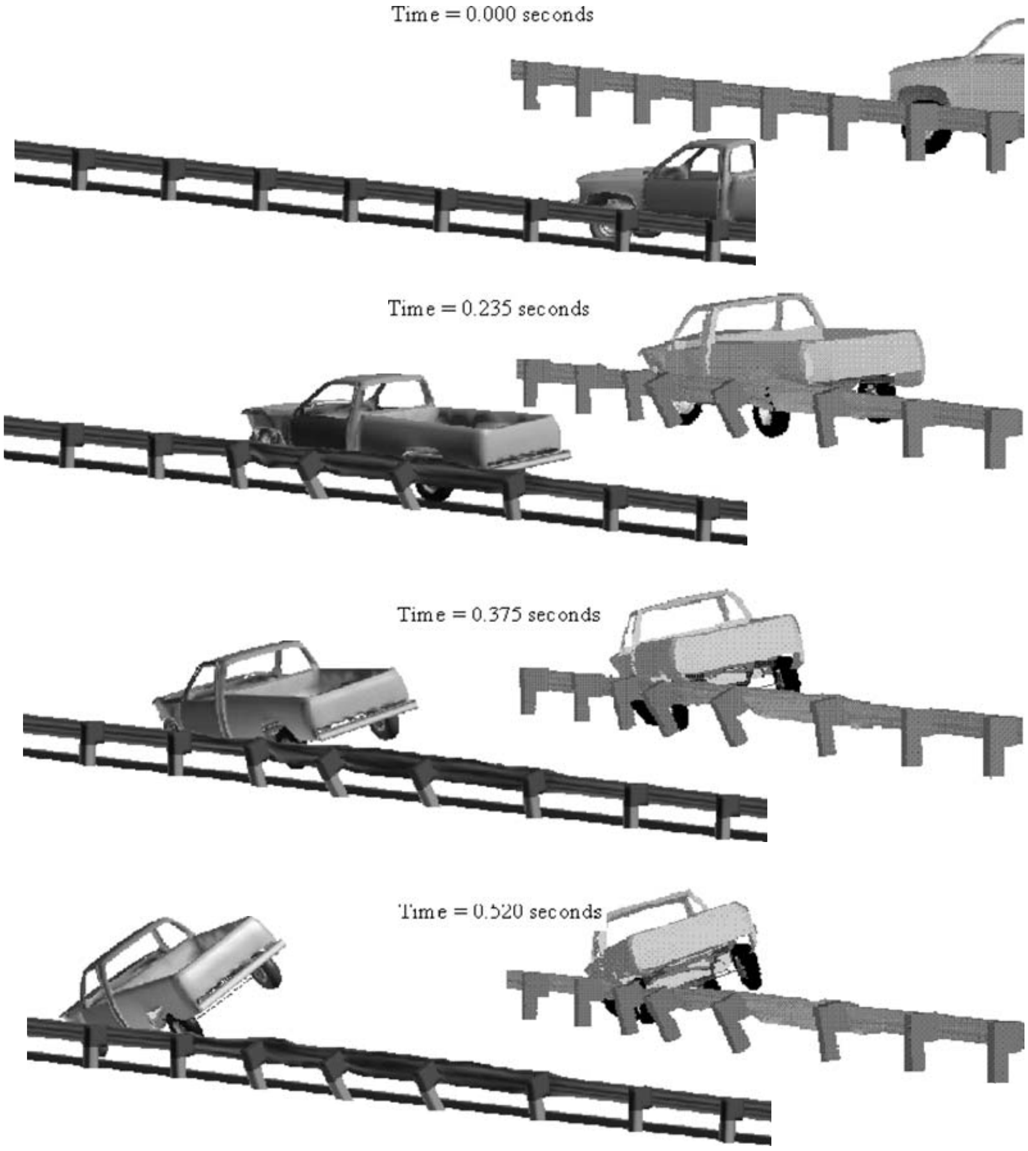
TABLE 9 Summary of major impact events of test 471470-26 and G4(2W) finite element simulation (*46*)

Summary of impact events	G4(2W)			
	Full-scale test		Finite element simulation	
	Time (sec)	Speed (km/h)	Time (sec)	Speed (km/h)
Initial Contact	0.000	100.8	0.000	100.8
Vehicle starts to yaw	0.056	100.8	0.044	100.6
Wheel impacts post 15	0.104	90.2	0.101	91.3
Wheel impacts post 16	0.193	74.8	0.190	75.7
Rear of vehicle contacts guardrail	0.203	73.2	0.207	73.0
Wheel Detaches	0.215	69.4	0.215	71.3
Vehicle parallel with guardrail	0.283	68.0	0.264	69.0
Vehicle exits guardrail	θ = 13.5E	64.0	θ = 14.3E	63.0



Front View **Overhead View**

Figure 23. Finite element simulation of a 2000P vehicle striking a G4(2W) with a 150-mm-high AASHTO Type B mountable curb.



G4(2W) with Curb

G4(2W) without Curb

Figure 24. Sequential photographs of finite element simulations comparing the impact performance of the G4(2W) with and without the AASHTO Type B curb.

of simulations was developed to provide information regarding the impact performance of the G4(1S) guardrail system in combination with various types of curbs at impact conditions specified by *NCHRP Report 350* Test 2-11 and Test 3-11. Both these tests involve the 2000-kg pickup truck impacting at 25 degrees. The impact speed for Test 2-11 is 70 km/h, which is in the intermediate speed range (i.e., 60 to 80 km/h), and the impact speed for Test 3-11 is 100 km/h, which represents the higher speed range (i.e., > 80 km/h). The performance of certain curb–barrier systems was also investigated at 85 km/h, which represented the upper limit of intermediate speed roadways (i.e., 60-80 km/h).

There are many barrier systems that could have been investigated in the study, such as the G4(2W), G9 (thrie-beam), G2 (weak-post W-beam), or G1 (weak-post cable), but it was decided to investigate combinations of curbs with the more widely used systems. The G4(2W) and the modified G4(1S) (i.e., steel posts with wood blockouts) are widely used systems and were good candidates for the research. Since both systems have successfully passed *NCHRP Report 350* TL-3 impact conditions, poor performance of these systems combined with a curb can be directly attributed to the presence of the curb and not necessarily to structural inadequacy of the barrier systems. Since there were a limited number of analyses that could feasibly be conducted, only the modified G4(1S) guardrail was used in the study so that the maximum number of curb types and impact conditions could be investigated. The G4(1S) is the most widely used strong-post guardrail in the United States, thus information regarding its performance with curbs should be the most beneficial to the states.

NCHRP Report 350 Test 2-11 and Test 3-11 impact conditions were chosen for the matrix of simulations because they involve the 2000-kg pickup, which is much more unstable than the 820-kg small car and also produces a more severe impact due to the larger mass of the pickup. The simulations were used to determine the most effective curb–barrier combinations for those impact conditions.

Analysis of Vehicle Impacts with Curbs

Analyses involving the simple impact of a vehicle and curb were also investigated using LS-DYNA. There are a number of variables that would have been interesting to investigate in this study, such as vehicle type (e.g., small car, pickup, SUV), curb type, impact speed, and angle of impact. Due to limitations in time and computational constraints, only a limited number of impact conditions were investigated. A matrix of simulations was developed to provide information regarding the vehicle's response when crossing a number of different curb types at various impact conditions. The information collected in this phase of the study served two purposes: (1) to quantify the effects of vehicle impact with curbs on the stability of the vehicle and (2) to provide information regarding the trajectory and path of the vehicle after impact with curbs.

Most of the curb impact studies that were identified in the literature involved vehicles encroaching the curb in a tracking manner. Another aspect of collisions with curbs involves an out-of-control vehicle impacting the curb in a nontracking position. In these situations, vehicle tripping may be highly probable during impact. Nontracking impacts with curbs may result in vehicle instability and rollover, especially impacts involving vehicles with high centers of gravity.

The side friction between the tires and ground for an out-of-control vehicle will cause the vehicle to roll, such that the vehicle has an initial roll-rate at the onset of impact with the curb. This factor is much more significant for vehicles with a high center of gravity, such as pick-up trucks and SUVs which make up a large percentage of the vehicle population currently on the road.

As documented in NHTSA's Rollover Status Report in *Traffic Safety Facts 1996 (51)*, rollover crashes, particularly single-vehicle (SV) accidents in light pickup trucks and SUVs, continue to take the lives of thousands of Americans each year. In 1996, almost 9,500 passenger vehicles (e.g., passenger cars, pickup trucks, vans, and SUVs were involved in fatal rollover crashes. Rollovers accounted for 36% of all fatal crashes involving SUVs and 24.5% of all fatal crashes involving pickup trucks, as illustrated in Figure 25. It is also

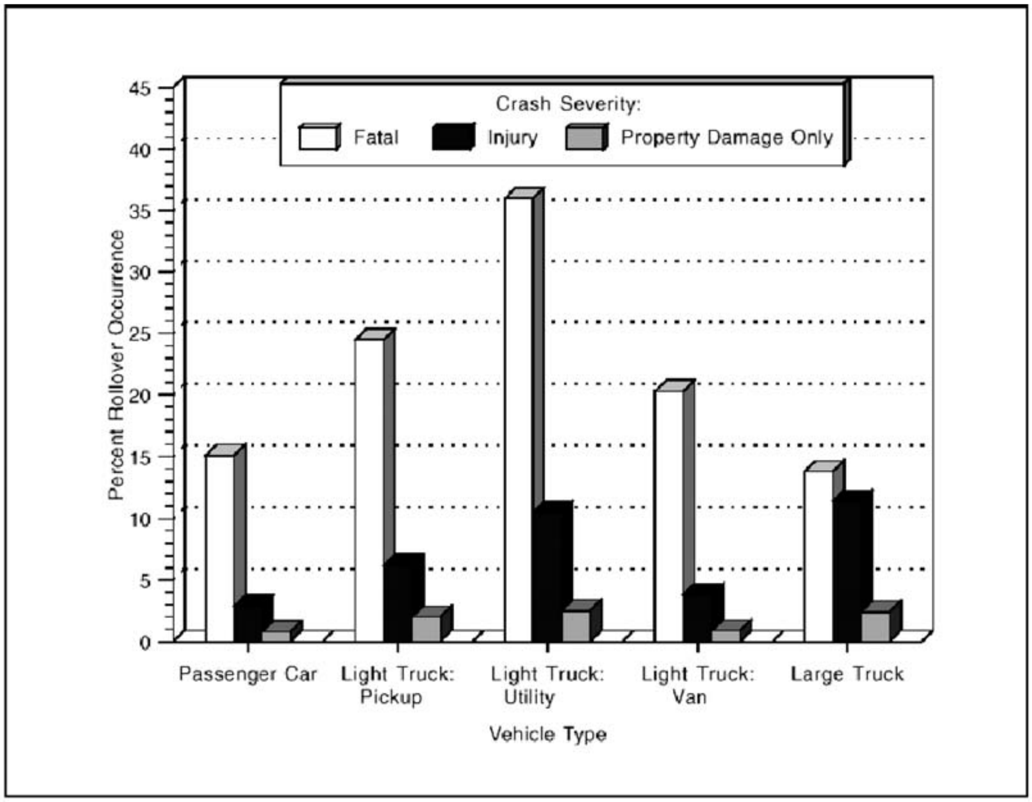


Figure 25. Rollover occurrence as a percent of all crashes, by vehicle type and crash severity (51).

notable that 5.3% of all accidents involving SUVs resulted in rollover.

The large percentage of SUVs and pickup trucks on today's highways along with their high rollover rate make nontracking impact with curbs a much more important factor now than in former years. There has been a great deal of advancement in computation power and in code development over the past few years that has enabled computer simulation programs to become a very efficient means of analysis. Although nontracking simulations were not included in this project, in theory both tracking and nontracking impacts with curbs could be investigated using a vehicle dynamics code, such as VDANL.

FULL-SCALE CRASH TESTING

Introduction

Full-scale crash testing is the method used by the FHWA to certify that a barrier system is crashworthy for use on federally funded highways. Although advancements in computer simulation programs have made it possible to accurately reproduce and predict complex impact events, full-scale testing is still essential in evaluating the safety performance of roadside appurtenances, including curbs and curb–barrier systems.

To evaluate the performance of roadside safety barriers, impact conditions must meet the standard testing procedures accepted by the FHWA. The current procedures are published in *NCHRP Report 350*. Prior to *Report 350*, the 2040-kg passenger sedan served as the crash test vehicle representing the large end of the passenger vehicle fleet. Because the large passenger sedan had virtually disappeared from the vehicle population by the late 1980s and new vehicle types, such as minivans, SUVs, and pickup trucks, had emerged in its place, *Report 350* replaced the large car with a 2000-kg pickup truck. The pickup truck introduced new challenges in crash testing due to its high center of gravity, which makes it much more unstable during impacts than the large car.

The 2000-kg pickup truck was chosen as a replacement for the 2040-kg passenger sedan for several reasons. First, both vehicles had similar mass and were therefore thought to represent a similar barrier loading. Second, the pickup truck was chosen as a surrogate for a much broader class of vehicles. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) required the FHWA to address the issue of the crashworthiness of the emerging SUV fleet; the FHWA responded by adopting the 2000-kg pickup truck in *Report 350* as a surrogate for the entire class of SUVs (e.g., pickup trucks, SUVs, minivans, and vans), now known as ISTEA vehicles. While some of the small SUV vehicles have worse stability characteristics, the pickup truck is one of the least stable vehicles in the vehicle fleet. It is characterized by a high center of gravity positioned far forward in the vehicle. There is little front overhang and the suspensions are relatively stiff. Testing with the pickup truck has presented some difficult challenges because of its inertial and stability characteristics. In the context of developing guidelines for curbs and curb–barrier combinations, it is important to remember that the pickup truck is not only an important test vehicle in its own right but also a surrogate for the broader class of ISTEA vehicles.

The performance of a curb–guardrail combination can be evaluated using test conditions specified in *NCHRP Report 350* for evaluating the crashworthiness of the length of need section of a longitudinal barrier. There are currently two tests required to evaluate guardrail systems for TL-3:

1. Test 3-11, in which a 2000P pickup truck (e.g., Chevrolet 2500) impacts the guardrail at a speed of 100 km/h and impact angle of 25 degrees, and
2. Test 3-10, in which an 820C (e.g., Honda Civic or Ford Festiva) impacts the guardrail at a speed of 100 km/h and impact angle of 20 degrees.

A guardrail system that meets all the strength and safety requirements specified in *NCHRP Report 350* is considered acceptable for use on all federal-aid roadways within the United States.

The literature review identified a limited number of full-scale tests involving vehicle impacts with curbs and curb–guardrail combinations. While full-scale crash testing was used in almost every study that involved vehicle-curb impact, all the tests that involved simple vehicle-to-curb impacts were performed using a large 2040-kg passenger sedan. The results of those earlier tests may have little significance regarding the effects of curb impact with the current fleet of vehicles, which ranges from very lightweight compact cars to large, unstable pickup trucks and SUVs.

In this project, a full-scale testing program was used to verify and confirm hypotheses developed from the computer simulations and to validate and strengthen the conclusions of the parametric studies. The few full-scale tests of curb–barrier combinations that were identified in the literature aided in the validation of the models so that the number of additional tests could be minimized.

Low-Speed Curb Traversal Tests

Full-scale live-drive tests were performed on three different types of curbs (AASHTO B curb, G curb, and vertical 6-in. curb) at varying speeds and angles (10, 15, 25, and 90 degrees). The test area was a gravel parking lot. The curbs were made using reinforced concrete cast in 1.2-m-long sections. Each set of curbs was attached to the ground with steel rods driven through holes in the curbs into the gravel. The area behind the curb was backfilled with gravel up to the top of the curb. The test setup is shown in Figures 26 and 27.

The vehicle path was marked on the ground using plastic strips. The driver aligned the vehicle with the strips to attain the desired approach angle, accelerated the vehicle to the desired speed, and then released the steering wheel just prior to striking the curb. After the rear wheels crossed the curb,

Figure 26. Full-scale curb test setup.

the driver reasserted control of the vehicle by steering and applying the brakes. Each test was performed multiple times to assess the repeatability of the event.

The relative displacements of all four wheels and the accelerations in the longitudinal, lateral, and vertical directions at two points on the vehicle were measured during each test.

Moderate-Speed Live-Driver Tracking Tests of AASHTO Mountable Curbs

Full-scale curb traversal tests were next performed at moderate speeds (i.e., approximately 56 km/h) with a live driver. The purpose of the tests was to evaluate the trajectory and

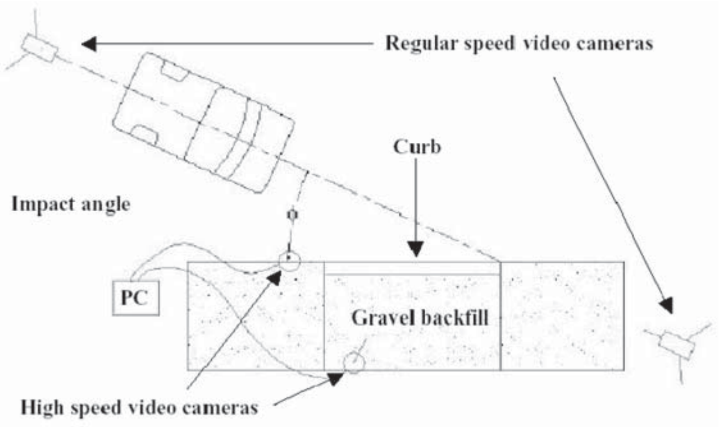


Figure 27. Full-scale curb test setup—overhead view.

kinematics of a typical 2000P vehicle traversing different types of AASHTO curbs at higher speeds. Due to the physical limitations of the testing site, only the low end of the speed range of interest (60 to 100 km/h) could be tested safely. During these tests, data were collected about the displacements and accelerations experienced by the vehicle.

The tests were performed using the 1995 Chevrolet C2500 Cheyenne pickup truck shown in Figure 26. The truck was modified by removing the bed and installing a roll bar, anti-rollover outriggers and ballast weights. The final mass of the vehicle, ready to be tested and refueled, was 2,165.90 kg; the final mass with fuel and driver was 2,248.00 kg.

The truck was driven toward a 12-m-long curb installation at angles of 15 and 25 degrees. Since the test vehicle was controlled by a driver, it was difficult to obtain precise, repeatable impact conditions. The driver was instructed to follow a painted line on the testing area and to hit the curbs at 35 mph (15.65 m/s). Due to the runway length available and the variability due to human and vehicle performance, the actual impact speed varied. After each test, the driver reported the impact speed. Brakes were applied by the driver only after the vehicle had crossed the curb.

Moderate-Speed Live-Driver Nontracking Tests of AASHTO Mountable Curbs

Nontracking full-scale curb traversal tests were also performed at moderate speeds (i.e., approximately 56 km/h) with a live driver. The purpose of these tests was to evaluate the vehicle trajectory and kinematics of a typical 2000P vehicle traversing different types of AASHTO curbs in nontracking mode in order to investigate the extent to which the curbs act as a tripping mechanism for vehicle rollover.

These tests were performed using the same 1995 Chevrolet C2500 Cheyenne pickup truck with the same modifications as for the tracking tests. The driver executed two different maneuvers resulting in a nontracking impact with the curb. These maneuvers were intended to reproduce two typical scenarios of vehicles running off the roadway, oversteering and understeering.

In scenario 1, oversteering, the vehicle was accelerated to a constant velocity of 35 mph (56 km/h) in a straight-line trajectory at a 55 ± 10(angle with respect to the curb line. At a marked point 6 m before the curb line, the driver turned the steering wheel approximately 45 degrees and immediately activated the emergency brake (i.e., rear brakes only) to break loose the rear end of the vehicle.

In scenario 2, understeering, the vehicle was accelerated to a constant velocity of 35 mph (56 km/h) in a straight-line trajectory at a 55 ± 10(angle with respect to the curb line. At a marked point 6 m before the curb line, the driver turned the steering wheel to approximately 60 degrees without applying the brakes.

For both scenarios, the truck impacted a 12-m-long installation of AASHTO curbs. The tests were conducted using curb types B, C, D, and NY.

Full-Scale Crash Tests of Curb–Guardrail Combinations

Several full-scale tests were conducted of 2500P trucks impacting curb–guardrail combinations. The test reports are included in Appendix I of this report. The impact conditions were similar to *NCHRP Report 350* Test 3-11. The following articles were tested:

- AASHTO Type B curb directly beneath modified G4(1S) guardrail,
- AASHTO Type B curb positioned 2.5 m in front of modified G4(1S) guardrail, and
- New York Type T100 curb positioned 4.5 m in front of modified G4(1S) guardrail.

The test vehicles were a 1998 GMC ¾-ton pickup (test inertial mass of 1,993 kg), 1994 Chevrolet ¾-ton pickup (test inertial mass of 2,002 kg), and a 1989 GMC ¾-ton pickup (test inertial mass of 2,014 kg). The guardrails tested were 53.34-m installations of AASHTO SGR04a guardrail with a SEW02a End Terminal and Re-Block recycled plastic blockouts made of 50% high-density polyethylene and 50% polypropylene. They were installed in dry NCHRP Report 350 Strong Soil. Figure 28 shows the test vehicle and configuration for the curb directly beneath the guardrail.

In each test, the vehicle impacted the curb at approximately 85 km/h and 25 degrees. The critical impact point was near the midpoint of the guardrail installation, 0.6 m upstream of Post 14 and 2.5 m upstream of a connection splice respectively.

SUMMARY

Real-world crash data were used to better characterize safety problems associated with curb and curb–barrier combinations on higher-speed roadways and to provide leads to the crash testing and simulation efforts conducted in this project. The analyses conducted with crash data included the following: assessment of the extent of the U.S. curb-related safety problem; examination of curb-related rollover risk and nature given a crash; comparison of crash, injury, and rollover rates per passing vehicle for guardrail sections with and without curbs; curb-crash severity modeling; and examination of the nature of curb impacts, using crash reconstruction data and comparing extreme and nonextreme crashes.

FEA was also used to study the effects of vehicle interaction with curbs and curb–guardrail combinations. The advantage of computer simulation is that once a model is developed,

Figure 28. Test vehicle and setup for Type B curb beneath guardrail.

the impact conditions and the basic geometry of the installation can be varied easily. The finite element program LS-DYNA was used in a parametric study to investigate the response of vehicles crossing various types of curbs. LS-DYNA was also used to investigate the effects of installing curbs in conjunction with guardrail, regarding the ability of the barrier to safely contain and redirect an impacting vehicle.

Full-scale crash tests were used to validate the computer models. Live-driver curb traversal tests were performed at low and moderate speeds in tracking and nontracking modes. Several full-scale tests of curb–guardrail combinations were also performed at higher speeds.

The results of these analyses are discussed in Chapter 5 of this report.

CHAPTER 5

ANALYSES AND RESULTS

INTRODUCTION

This chapter summarizes the analyses described in Chapter 4 and their results, as well as relevant analyses from prior studies. In most cases, significantly more detail was provided in one or more appendices or other publications. These results were used to develop the guidelines that were the primary product of this research project, described in Chapter 6.

PRIOR STUDIES

The analyses of vehicle impact with curbs and curb–barrier combinations conducted in this study were limited to one vehicle type, a 2000-kg pickup truck. Thus, guidelines based solely on the results of those analyses would only be applicable to that one type of vehicle. In order to develop a more general set of guidelines, additional information was needed about the response of a broader range of vehicle types. The literature provided an adequate amount of information on the response of various types of cars traversing curbs and also a limited amount of information from the results of full-scale crash tests regarding both cars and pickup trucks impacting curb–barrier combinations.

There are many factors that influence vehicle behavior when traversing curbs, such as abrupt steering caused by the interaction of the front wheels with the curb; loss of contact between the tires and ground; excessive vehicle accelerations; and excessive roll, pitch, and yaw rates of the vehicle during impact. Although each of these factors may lead to loss of control of the vehicle, all the data that have been collected from full-scale tests and computer simulations suggest that total loss of control was unlikely except in extreme cases. A more important issue, however, may be the effects that these factors precipitate when curbs are placed in combination with roadside hardware (e.g., guardrail, crash cushions, or breakaway poles). Even a slight increase in bumper height caused by traversing a curb may be sufficient to cause the vehicle to impact a roadside safety device at a point higher or lower than normal, which may lead to override or underride of barriers or adversely affect the breakaway mechanism of other roadside devices.

Two of the studies identified in the literature review addressed the issue of override and underride indirectly using both full-scale testing and computer simulation: Olsen et al. *(22)* and Holloway et al. *(24)*. In those studies the response of various types of cars traversing a number of different curb types was obtained and the information was used to assess vehicle stability and to estimate the potential for barrier override and underride. Roll and pitch displacement-time histories and relative bumper trajectory–time history of vehicles traversing curbs were collected in their studies. Various impact conditions and curb types were investigated in those studies, and all impact conditions were considered equally likely since data were not available to discern the most probable impact conditions of crashes. Only the maximum values of angular displacement and bumper height from the various studies were considered when synthesizing the data for use in this study. The maximum encroachment angle of both the Olsen et al. study and the Holloway et al. study was 20 degrees, whereas the maximum encroachment angle used in the current study was 25 degrees. Also, since the vehicle used in the Olsen et al. study was a 1965 Ford four-door sedan, those results may not be representative of the current vehicle fleet. The results and conclusions from the study by Olsen et al., however, were similar to those obtained in both the Holloway et al. study and the current study.

CRASH AND INVENTORY DATA ANALYSES

This section describes six analyses of crash and inventory data that were conducted in this study.

Extent of the U.S. Curb-Related Safety Problem

The goal of this effort was to define the extent of the national safety problem related to curbs using FARS and NASS-GES data. A more detailed description of this task can be found in Appendix C.

Table 10 presents FARS data for the 1994–99 period concerning how often “Curb” was noted as the FHE in fatal crashes on roads with speed limits of 40 mph (65 km/h) or greater for all crashes and SV fatal crashes. Table 11 presents NASS-GES national estimates for crashes of all severity on these higher-speed roads. These estimates are based on the GES weighting system, which was applied to the 50,000 cases collected each year. In both tables, the FHE differs from the

TABLE 10 Fatal crashes with curb as FHE and speed limit 40 mph (65 km/h) or greater

Year	Total fatal crashes (SL>=65 km/h)	Crashes with curb as FHE (SL>=65 km/h)	Percent of total fatal crashes (SL>=65 km/h)	Fatal single vehicle crashes (SL>=65 km/h)	Fatal SV crashes with curb as FHE (SL>=65 km/h)	Percent of fatal SV crashes (SL>=65 km/h)
1994	27191	291	1.1%	14520	271	1.9%
1995	28005	387	1.4%	15206	345	2.3%
1996	28464	396	1.4%	15293	359	2.3%
1997	28171	391	1.4%	14906	362	2.4%
1998	28453	325	1.1%	15227	308	2.0%
1999	28527	329	1.2%	15062	307	2.0%

MHE in that the FHE was not necessarily the fatality or injury-producing mechanism. Curb impacts are actually very seldom the MHE in fatal crashes.

As shown in Table 10, curbs on higher-speed roads were noted as the FHE in slightly over 1% of all fatal crashes on these roads each year; and, while varying somewhat, the frequency and percentage were relatively stable across the 6-year span. Curbs were noted as the FHE in approximately 2% of all SV fatal crashes on these roads.

Table 11 shows that in terms of total crashes (fatal and nonfatal), curbs were noted as the FHE in fewer than 1% of all GES crashes each year, a rate even lower than that for fatal crashes. As with fatal crashes, while varying slightly, the frequency and percentage were relatively stable across the 5-year span for crashes reported in the GES database. Curb impacts were the FHE in approximately 2.5% of the SV crashes.

These analyses were for roads with speed limits of 40 mph (65 km/h) or greater. If one included all speed limits, and thus urban streets where curbs are standard, the percentages for both fatal crashes and total crashes would increase, but not to a large extent. For example, in the 1999 FARS data, there are a total of 599 fatalities in which curb was the FHE on all roadways (regardless of speed limit). This represents approximately 1.6% of the total fatal crashes in 1999. Similarly, the 1999 weighted GES data for all speed limits indicate curb crashes represent approximately 1.0% of the crashes nationwide. Clearly, curbs are the initial objects struck in only a small portion of fatal or total crashes on the roadways of interest and on all roadways.

The remainder of the analyses in this task examined other factors related to these fatal and nonfatal crashes. All were restricted to the higher-speed roads (i.e., speed limits of 40 mph [65 km/h] or greater) and to the 1999 FARS and NASS-GES data. While only the highlights of the findings are included here, more detail is presented in Appendix C.

- Curb crashes were more urban than other crashes: 72.3% of the curb-related fatal crashes were on urban roads, with 26.7% of the total on urban Interstates or other freeways/expressways. For the GES national estimates, almost half (49.5%) of the total higher-speed curb-related crashes were in urban areas with populations greater than 100,000, and 71.9% were in areas with populations greater than 25,000. The location of these curb-related fatal and total crashes differed significantly from the location for all SV crashes on these higher-speed roads: 71.2% of fatal SV crashes occurred on rural roads, and 61% of total SV crashes occurred on roadways within areas of population less than 25,000. These findings probably reflect the fact that curbs were more often located in urban areas.
- The MHE in fatal curb crashes was often a rollover, but the MHE in total curb crashes was the curb impact itself.

TABLE 11 National estimates of crashes with curb as FHE and speed limit 40 mph (65 km/h) or greater, weighted data

Year	Total crashes nationwide (SL>=65 km/h)	Crashes with curb as FHE (SL>=65 km/h)	Percent of crashes with curb as FHE (SL>=65 km/h)	SV crashes nationwide (SL>=65 km/h)	SV crashes with curb as FHE (SL>=65 km/h)	Percent SV crashes with curb as FHE (SL>=65 km/h)
1995	2765377	23680	0.9%	855097	21784	2.5%
1996	2857985	23470	0.8%	899940	21761	2.4%
1997	2839031	20107	0.7%	876545	18981	2.2%
1998	2781930	23908	0.9%	844783	23002	2.7%
1999	2753457	21807	0.8%	835853	20843	2.5%

When curbs were noted as the FHE on these higher-speed roads, 38.9% of the 368 vehicles involved in fatal crashes were coded as having "Overturn" as the MHE. This was very similar to the 39.6% of all fatal SV crashes in which overturn was the MHE. Unfortunately, the data did not reveal whether the rollover was related to tripping on the curb or to an embankment or other object behind the curb. Only 18 (4.9%) of the 368 vehicles in fatal curb-related crashes, of which 15 were motorcycles, were coded as having the curb as the MHE. In contrast, for total crashes on these higher-speed roads, only 12.7% of the vehicles were coded as having "Overturn" as the MHE, and 50% were coded as having "Curb" as the MHE. The higher percentage of "Overturn" in the fatal data was the result of the nature of an overturn: once it occurs, it is likely to be fatal.

- The curb-related fatal crashes occurred predominately at nonjunction locations (80.5%). An additional 10.6% were at interchanges, with the majority of these being on ramps. The total crashes were also more likely to be at nonjunction locations, but not to the same extent (53%). Here, approximately 26% were at intersections, and an additional 11.6% of the total crashes were at interchanges, mostly on ramps.
- Pavement conditions (e.g., dry or wet) for fatal and total curb crashes were very similar to those for all SV fatal and total crashes: 90.3% of the curb-related fatal crashes occurred on dry pavement, 7.9% on wet pavement, and 1.2% in snow/slush/ice; 74.7% of the curb-related total crashes occurred on dry pavement and 21.8% on wet pavement.
- There were only subtle differences in the vehicle maneuvers prior to the crash (e.g., "going straight," "changing lanes," or "turning") for the curb and total SV crashes for both the fatal and GES samples.
- Vehicle types in curb-related fatal and total crashes did differ somewhat from vehicles in the comparable SV groups on these higher-speed roadways; they were more likely to be passenger cars (and motorcycles for the fatal subset), and somewhat less likely to be SUVs or pickup trucks. While these vehicle-related findings might be related to differential exposure (e.g., more passenger cars on urban roads where more curbs were located), they do not seem to indicate greatly increased curb-related problems for SUVs or pickups. Again, this conclusion is tenuous given the lack of exposure data in both the FARS and GES files.

In summary, curb-related fatal crashes on roadways with speed limits of 40 mph (65 km/h) and above represented a very small percentage of total fatal crashes (approximately 1%). Curb-related total crashes represented an even smaller percent of all crashes (less than 0.5%). Curbs were very seldom the MHE in fatal crashes (approximately 5%), but much more likely to be the MHE in total curb-related crashes (53%). This implies that curb impacts caused enough property damage to result in a reportable crash but that fatalities were more likely to result from a rollover. Finally, both fatal and total curb-related crashes differed from other SV fatal crashes on these higher-speed roadways in that they were much more likely to occur on urban roads and more likely to involve passenger cars rather than SUVs or pickups.

Curb-Related Rollover Risk and Nature Given a Crash

Rollover occurrence and risk is of particular interest when curbs are being studied, since the severity of impacts with this low-profile object would be expected to be related to whether a vehicle overturned rather than to energy exchange in the impact itself (unlike impacts with guardrails, for example). The FARS analysis described in the preceding section highlighted the fact that the MHE in most fatal curb-related crashes is a rollover. This set of analyses was conducted to further examine the incidence and nature of rollover in curb-related crashes.

In order to help ensure that the curb was directly related to the rollover under study, databases chosen for use had to have a sequence of events that would allow examination of only those rollovers preceded by a curb impact. NASS-CDS data and the HSIS data from both Michigan and Illinois included such a sequence variable and were thus used in the analyses. This subsection presents the results of the NASS cases and the Michigan and Illinois cases separately. A detailed description of this analysis can be found in Appendix D.

NASS-CDS Analysis and Results

NASS-CDS data for the 1997–99 period were used in the analysis. Using the investigator-supplied sequence of events, cases were chosen that involved at least one impact with a curb on roads with posted speed limits of 40 mph (65 km/h) or greater. The resulting sample was very small, particularly for cases involving rollover. In the 3 years, there were 101 SV crashes involving a curb, and 38 of these involved a rollover somewhere in the sequence. Of primary interest were those impacts in which a curb was the first event in the sequence (92 of the 101 curb-involved cases) and in which a rollover immediately followed the curb impact and thus was assumed to be related to it.

As noted earlier, the NASS-CDS data are from an unequal probability sample extracted from police reports from across the nation and overrepresent more severe crashes. The data can be presented in two forms, unweighted and weighted. The unweighted, or raw, data represent the actual number of cases in the sample. The weighted data represent the total number of such cases that would have occurred nationwide, given that the sample and the assigned weights are accurate, that is, given that the sample cases as a whole do in fact reflect the national incidence of all such crashes. The weight for each case is assigned by NASS. The weighted estimates are considered reliable when a large number of cases is being analyzed, but there are serious questions concerning the reliability of these estimates when relatively small samples are being studied, as is the circumstance here.

Table 12 shows NASS-CDS data for the frequency of overturn in SV crashes in which the curb impact was the first event in the crash sequence. In this sample, three cases have extremely high weights, and those cases largely determine figures in the "Weighted" column. For this reason, a truncated version of the weighted data is also presented; it gives estimates based on the sample excluding the three very high weight cases.

As shown in Table 12, the unweighted data indicate that in 17% of these SV crashes in which a curb was the first event, an overturn occurred immediately after the curb impact. In an additional 21% of these cases, an overturn occurred at some point in the crash sequence but could not be attributed to the curb impact. When the full NASS weights are applied to the same data, an overturn occurred immediately after the curb impact in 9% of the cases. An overturn occurred subsequently in the crash sequence but could not be attributed to the curb impact in an additional 6% of the weighted crashes. When the truncated weights are used, the overturn occurred in 13% of cases immediately after curb impact and in an additional 8% of the cases as a later event in the crash sequence.

The rollover cases were further examined to see if the investigator noted "Curb" as the "Tripping object" in the 16 cases in which the rollover immediately followed the curb impact, as one would expect. This was only true in ten cases, with three other cases having "Ground" as the tripping object and the remaining three being uncoded.

Thus, there is some lack of certainty concerning the percent of SV curb impacts resulting in an overturn. It would appear that such overturns occur in at least 7% of the curb impacts (based on the weighted data where the investigator noted "Curb" as the tripping object), and may be attributed to the curb impact in as many as 17% of the cases (based on the unweighted data, and assuming all overturns immediately following the curb impact were caused by the curb). The best estimate might be approximately 10%, based on the weighted and truncated-weight distributions.

These curb-related cases were also examined to see if information could be extracted concerning vehicle impact speed and whether the vehicle impacting the curb was tracking or nontracking. Unfortunately, the data did not provide such information.

Michigan and Illinois Analyses and Results

The HSIS databases for Illinois and Michigan used in this analysis included SV crashes that occurred in 1996 and 1997 on sections of roadways with curbs and posted speed limits at or above 40 mph (65 km/h). All such crashes were included in which a vehicle impacted a curb or another fixed object as the FHE or the first "substantial" harmful event. The latter subset included crashes in which the curb impact was not the first event, but was only preceded by nonobject events such as "uncoded or errors," "loss of control," or "ran off road left/right." For each case, it was also noted whether the vehicle that struck the curb or fixed object was involved in an overturn subsequent to the impact with the curb or fixed object. For comparison with the NASS-CDS data, the first analysis involved the overall rollover percentage for Michigan and for Illinois. The crashes were then categorized by land use (i.e., urban or rural) and roadway classification (i.e., Interstate or non-Interstate) for each state. Since assigned operating speed for the roadway where the crash occurred is a combination of land use and roadway class, distributions of rollover percentages were generated for four operating speed categories within each state. The assigned operating speeds were based on results from the analysis described in Appendix B.

Table 13 presents the rollover percentages for each state. In the Michigan data set, 5% of the SV curb crashes resulted in a subsequent overturn, while in Illinois, 8% subsequently overturned. While the percentage of overturns in curb crashes is the same as for other objects in Michigan, the percentage of overturns in curb crashes is higher than for other objects in Illinois (8% versus 2%). Both are in the same range as, but slightly lower than, the 10% best estimate from the CDS data.

TABLE 12 Frequency of overturn in NASS-CDS SV curb impacts in which the curb impact was the first event in the crash sequence

Incidence of overturn	Number of vehicles			Percent of vehicles		
	No weighting	Full weighting	"Truncated" weighting	No weighting	Full weighting	"Truncated" weighting
Did not overturn	57	30178	19530	61.96%	85.57%	79.33%
Overturn immediately following curb impact	16	3109	3109	17.39%	8.82%	12.63%
Overturn, not immediately following curb impact	19	1978	1978	20.65%	5.61%	8.04%
Total	92	35265	24617	100.00%	100.00%	100.00%

TABLE 13 Frequency of overturning vehicles in SV crashes in which either a curb or another fixed object was struck (Michigan and Illinois data, 1996–97)

State	FHE = curb impact			FHE = other fixed object impact		
	Did not overturn	Overturned	Percentage overturns	Did not overturn	Overturned	Percentage overturns
Michigan	1,487	83	5%	6,156	305	5%
Illinois	361	30	8%	1,969	36	2%
Total	1,848	113	6%	8,125	341	4%

Similar tables of rollover percentages for curb and other-fixed-object crashes were also produced for urban and rural Interstate and non-Interstate roadway classes. The samples of Illinois curb-related crashes were too small to be meaningful except for the urban non-Interstate category. The sample for the Michigan curb-related crashes in the rural Interstate category was also too small. In the other three categories (i.e., rural non-Interstate, urban Interstate, and urban non-Interstate), the Michigan data indicated that the curb-related rollover percentages were very similar to the rollover percentages for other objects. For the urban non-Interstate higher-speed roads, the Illinois data indicated a higher curb-related rollover percentage than was found for other objects that are struck first (7% versus 1%). When the data from the two states were combined, the curb-related rollover percentage was slightly higher on urban Interstates than on urban non-Interstates (8% versus 5%).

The final analysis involved curb-related crashes classified by roadway operating speed for their crash location (see Table 14). As can be seen from Tables 13 and 14, the Illinois curb-related rollover percentages were consistently higher than the corresponding Michigan percentages. This could have been related to curb design or placement standards or to differences in crash reporting between the two states. If non-injury crashes in Illinois were systematically reported less often than in Michigan, the rollover percentage for Illinois would be higher since rollover crashes, which are more likely to result in injuries, were most likely to be reported fully in both states. In both Illinois and Michigan, the proportion of curb crashes resulting in rollover appeared to increase as the assigned operating speed increased.

Summary

The early analyses of curb-related crashes on higher-speed roads indicated a relatively high frequency of "rollover" in FARS fatal curb-related crashes (40%), and a significant, though lower rollover percentage in the GES (all crashes) data (13%). Since neither of these databases included a sequence of events allowing a better link between the rollover and the curb or other-fixed-object impact, NASS-CDS, Michigan, and Illinois data were analyzed. The relatively small sample size of curb-related crashes on higher-speed roads and the issue of weighting led to difficulties in drawing firm conclusions from the 1997–99 NASS-CDS data. The Michigan and Illinois data provided somewhat larger samples. Even though conclusions were difficult with the CDS data, the "combined estimate" of 10% rollover was similar to, but slightly higher than, the rollover estimates from Michigan and Illinois. The Michigan data indicated that the curb-related rollover percentages were very similar to the rollover percentages for other objects for the three roadway categories where adequate samples were found (i.e., rural non-Interstate, urban Interstate, and urban non-Interstate roads). The Illinois data for urban non-Interstate roads, the only category with adequate sample size, indicated a higher curb-related rollover percentage than was found for other objects (7% versus 1%). Finally, because of the small sample

TABLE 14 Frequency of overturning vehicles in SV curb crashes categorized by roadway operating speed (Michigan and Illinois data, 1996–97)

Assigned operating speed	Michigan			Illinois		
	Did not overturn	Overturned	Percentage overturns	Did not overturn	Overturned	Percentage overturns
NA	50	4	7%	46	1	2%
40-49 mph	193	6	3%	59	6	9%
50-59 mph	633	28	4%	172	13	7%
60-69 mph	597	40	6%	75	8	10%
70-79 mph	30	5	14%	9	2	18%
Total	1503	83	5%	361	30	8%

sizes and poor quality of the raw data available for these cases, it was not possible to extract further information from the NASS-CDS data on vehicle tracking/nontracking prior to curb impact or vehicle impact speed, both of which would be presumably related to rollover risk.

In summary, rollover after impacts with curbs appears to be a relatively low-frequency occurrence in all crashes. However, it remains a problem worthy of design attention due to the severity of rollovers, as demonstrated by the higher rollover percentages in fatal curb-related crashes.

Crash, Injury, and Rollover Rates for Guardrail Sections with and without Curbs

Since rollover after striking a curb on higher-speed roads could be a significant cause of injury, different data sources were examined in an attempt to gather more information on rollover in the presence of curb and curb–guardrail combinations. The analyses described previously concerned the risk of rollover once a crash has occurred and therefore used crash data and a rollover subset within that data. The basic goal of the analysis described in this section was to examine curb–guardrail-related crash risk and rollover risk, which is similar to "crash rate" and "rollover rate," per passing vehicle for segments of highway with guardrails and segments with curb–guardrail combinations. These guardrail and curb–guardrail sections were not compared to roadway sections without a curb or guardrail since reporting of crashes on the latter section is a function of the nature of the roadside beyond the shoulder, which is not in any roadway inventory file. A more detailed description of this effort can be found in Appendix E.

To examine guardrail-related crash and rollover risk or rate per passing vehicle, a database was needed that allowed identification of specific segments of roadway with guardrails and with curb–guardrail combinations that could be linked with run-off-road crash and rollover counts, AADT, and other characteristics of the roadway, such as road classification, curvature, and speed limit. By definition, when one is attempting to compute "risk" or "rate," the analysis record needed is a segment of highway, not a crash, since one must also include segments of highway which have had no rollovers or crashes. The only database available for such an analysis, and probably one of very few such databases in the nation, was the Michigan HSIS database. While most states have roadway inventory files that include AADT and details of the cross-section of the roadway to the edge of the shoulder, few include any information on guardrails. Michigan had developed and maintained a separate guardrail inventory file up through 1992. Each record identifies a section of guardrail. The inventory provided details of location (i.e., side of the highway), beginning and ending milepoints, and details of the guardrail such as type, end treatment, and offset from the pavement edge. Since there was one record per guardrail section, there could be multiple records referring to the same milepost on the highway, as a result of guardrails being on each side of the road or even in the median as well as on each side of the road. In contrast, the Michigan Roadway Inventory File was organized by homogeneous segments of roadway, a new segment beginning when any change occurred in a major variable (e.g., divided/undivided, shoulder width/type, or lane width). When divided highways were present, there were separate inventory items for each direction of travel, but the record included both directions. The presence of curbs on the roadway was found under the "shoulder type" variable, and there were either two or four shoulders on each homogeneous segment, depending on whether the roadway was undivided or divided. Finally, the Michigan crash file had information on the crash milepost and the direction of travel of each of the vehicles, but did not specify the side of the divided roadway on which the crash occurred.

The complicated nature of the guardrail file resulted in a complex data screening and merging effort involving a series of decisions (e.g., how to properly link crashes that are not mileposted to different sides of the roadway). The product of the significant data-preparation effort was an analysis file containing 1993–94 crash counts and 1992 AADT and other roadway characteristic data (e.g., the presence of a curb) linked to directional segments of 1992 guardrail for three highway classes: urban freeways, urban multilane divided roads, and urban multilane undivided roads. Only these classes contained sufficient mileage of both guardrail-only sections and curb–guardrail combination sections, and even in these classes the total directional mileage was limited (e.g., only 15 total miles of curb–guardrail combination sections on urban freeways).

Two types of analysis were conducted: simple comparison of guardrail versus curb–guardrail crash rates per million vehicle-miles of passing vehicles within each of the three roadway classes, and regression modeling (i.e., Poisson and negative-binomial) in which AADT and other factors were better controlled for. Details of both analyses are presented in Appendix E.

The crash rates developed for total SV crashes, injury-producing SV crashes, and SV rollover crashes are shown in Table 2 in Appendix E for all three roadway classes. However, due to the small number of such crashes, only the rates related to urban freeways appeared to be somewhat meaningful; these are shown in Table 15.

For the urban freeways, it appeared that the total run-off-road rate was slightly lower on guardrail-only segments than on curb–guardrail segments (0.175 versus 0.195 crashes per million vehicle-miles passing). This may have been due to the presence of the curb as another object to strike on the roadside, or to other factors that were not accounted for in these analyses (e.g., speed limit). Perhaps of more importance, but with the same caveats, the injury crash rate in such crashes was also slightly higher where there was a curb present in addition to the guardrail. Finally, the rollover rate was

TABLE 15 Descriptors, crash frequencies, and crash rates per million vehicle-miles passing for guardrail-only and curb–guardrail segments on urban freeways in Michigan (1992 inventory data and 1993–94 crash data)

	Guardrail only	Curb–guardrail
Total Mileage	186.64	15.01
Average AADT	45,247	78,717
Total MVMT per Side	3064.1	442.1
Total SV Crash Freq.	537	87
Total SV Crash Rate	0.175	0.197
SV Injury Crash Freq.	139	29
SV Injury Crash Rate	0.045	0.066
SV Rollover Crash Frequency	31	5
SV Rollover Crash Rate	0.010	0.011

essentially the same for guardrail-only and curb–guardrail sections based on the simple rates.

However, the comparison of rates such as these can be misleading unless the rates are from highway segments with essentially the same AADT, because the relationship between crashes and AADT is not linear in nature. The second analysis, statistical modeling, was intended to account for this issue. Poisson and negative-binomial models were developed to predict both SV crash and SV injury crash frequency on urban freeways as a function of a number of predictor variables. Unfortunately, rollover crashes could not be analyzed separately due to the small sample size. Predictor variables analyzed included curb presence, segment length, AADT, horizontal curve presence, speed limit, and guardrail offset. Tables 3 and 4 in Appendix E provide the detailed results. Because the Poisson results were similar to the negative-binomial results, and since the latter is considered more appropriate, only the negative-binomial results are summarized here.

In almost all cases, the predictor variables in the model of both total SV and injury SV crashes exhibited logical behavior (e.g., crashes increased with AADT and segment length and decreased with increasing guardrail offset). Of most interest, the presence of a curb with the guardrail significantly increased both total and injury SV crashes when all other factors were held constant. The total SV crash model predicted 0.1525 crashes per mile on average, when the independent variables were held at their means. Crashes increased by 0.0640 per mile (42%) when a curb was present or when a curb was added to a guardrail. The injury crash model, which was considered to be a surrogate of rollover crashes, predicted 0.0416 injury crashes per mile, increasing by 0.0238 (57%) when a curb was added.

In summary, both the simple rate comparisons and the Poisson and negative-binomial models indicated that on urban freeways, segments with both guardrails and curbs were more likely to have both SV crashes and injury crashes than segments with only guardrails. While it was not possible to control for all potentially confounding variables, the fact that the models statistically control for exposure variables (e.g., segment length and AADT) and geometric/design variables (e.g., curves and speed limits) strengthens these findings. The injury-crash model was considered to be a limited surrogate for a model of rollover crashes. The presence of a curb appeared to increase the crash frequencies on these urban freeway segments.

Curb-Crash Severity Modeling

The analyses described in the preceding two sections were related to rollover, one of the most important factors predicting crash severity. The analysis in this task was designed to provide additional information on curb-crash severity in both rollover and nonrollover crashes. As noted previously, it is difficult to study either crash occurrence or severity of curb impacts since the vehicle almost always overrides the curb, and both the occurrence of a reported crash and the resulting severity are often defined by what is behind the curb. Unfortunately, there was no good inventory of the area behind the curb in even the best databases (e.g., the HSIS roadway inventory files).

The goal of this task was to compare the severity of all SV curb crashes with the severity of SV noncurb crashes (i.e., crashes with other roadside objects) to determine whether they differed under similar conditions. Since curb and noncurb crashes do not always occur under similar conditions, conditions were controlled through regression-type modeling. To ensure that the curb was related to the subsequent injury or rollover, a database was needed that included a sequence of events. To equalize the roadside behind the curb with the roadside for noncurb crashes to the extent possible, a subsample was needed of noncurb crashes that occurred in areas similar to the curb crashes (i.e., crashes occurring on a "curb-type" roadway, but without a curb present in the crash). These requirements led to the use of the 1996-97 Michigan HSIS database, which contained both crash and roadway inventory information. A more detailed description of this effort can be found in Appendix F.

The curb crashes included in the dataset were SV crashes involving a vehicle striking a curb as the first or first meaningful event in the sequence of events. Note that first meaningful included curb impacts as a second, third, or fourth event if all of the preceding events were nonobject/nonrollover events such as "loss of control" or "run off road." The noncurb crashes occurred on segments of roadway with a curb present on at least one side of the roadway (i.e., opposite shoulder or median) according to the roadway inventory data, but not where the crash occurred, based on the absence of curb in the sequence of events. Crashes in which curb impacts were noted as an event following an impact with another fixed object or a rollover were deleted from the data set. In all cases, the analyses were restricted to roadways with posted speed limits of 40 mph (65 km/h) or greater. "Overturn" was captured as an event, and by definition, followed the curb impact in the curb-crash set. Other variables captured for analysis included the speed limit, assigned operating speed, functional class, weather and light conditions, road surface, right shoulder type, highway area type, vehicle type, curve code, and terrain.

As detailed in Appendix F, when one is attempting to model differences in the full distribution of crash severity (for example, by use of the KABCO injury scale: K = killed; A = severe injury; B = moderate injury; C = minor injury; and O = no injury) as a function of other variables (such as curb/noncurb or speed limit), the most appropriate model is an ordinal regression model. Two common forms are the ordered logit and probit. In this case, the logit form proved to be most appropriate.

Models predicting severity were developed using the above set of variables. The primary model included speed limit and an urban/rural variable based on functional class as two of the independent predictors. A subsequent model used assigned roadway operating speed instead of these two variables, since assigned operating speed was a direct function of speed limit within functional class. Both of these models contained rollover as a predictor and thus allowed controlling for rollover in examining curb versus noncurb severity.

The speed limit–urban/rural model indicated that the effect of hitting a curb on injury severity was negative (i.e., it lowered injury severity), although this effect was only marginally significant (at the 8% level). The model, which controlled for many other variables, showed that injury severity was higher in the following cases:

- The vehicle rolled over;
- The crash occurred on an urban rather than rural roadway;
- The weather was clear or cloudy, not foggy, raining, snowing, sleeting/hailing, or severely windy;
- The road surface was dry, rather than wet, muddy, snowy, slushy, or with debris;
- The vehicles involved were trucks, buses, motorcycles, motor scooters and mopeds, rather than passenger cars, vans, or pickups;
- The crash occurred on level terrain;
- The crash occurred on a curve; or
- The posted speed limit was at the higher end of the 40–65 mph range.

The results of the second model in which assigned operating speed replaced speed limit and rural/urban variables indicated that many of the same predictors were significant. However, in this case, while assigned operating speed was a significant predictor, curb presence was no longer significant. This model implied that there was no difference in crash severity between the curb and noncurb crashes.

In conclusion, although the two models differed somewhat in their estimates of the effect of curbs on severity, both implied that in locations where curbs might be located, SV crashes involving curbs were clearly no more severe than crashes involving other roadside objects. Rollover was an important predictor of injury, perhaps the most important. When the rollover variable and all other variables except curb presence were held constant, curb impacts were slightly less severe, or at least no more severe, than crashes with other objects.

As noted earlier, there is no guarantee that the roadsides for these curb and noncurb crashes were similar, and if not, the severity difference found, or the lack thereof, may have been confounded by these unknown differences. However, given that this analysis was restricted to the most similar locations possible, those with a curb on at least one side of one roadway, the conclusion that curb crashes are at least no more severe, and probably less severe, than noncurb SV crashes appeared to be supported by the data.

Nature of Curb Impacts

One of the goals of the crash-data analysis effort was to develop or extract information from real-world crash data that might be useful in defining inputs to the simulation and crash-testing analyses. This was a two-part task.

Crash Reconstruction Data

The first part of this effort involved the analysis of NASS-CDS data to extract information on the specific nature of curb-related impacts in the real world (e.g., angle of impact, speed, tracking/nontracking). NASS-CDS was the only national database of crash reconstruction data where such detail was captured. Police data did not include such information. Two sources of CDS data were used: basic data downloaded from the NHTSA website and enhanced data obtained from TTI. Details of the data, analyses, and results are found in Appendix G.

Initially, NASS-CDS data for the 1997–99 period were downloaded from the NHTSA web site for analysis. The 11 separate files for each year (e.g., vehicle exterior file and event file) were combined into usable vehicle-based analysis files that allowed examination of the sequence of events for each vehicle in a crash and determination of when the curb was struck and what occurred after that impact. The NASS-CDS data contained up to 22 events (e.g., "hit curb") for each vehicle involved in a crash. However, detailed information such as impact speed and impact angle was only recorded for one event in each crash, the event that caused the largest change in velocity. Data on the direction of force and deformation extent were recorded for the events that caused the highest and second-highest changes in velocity.

Examination of the data after preparation indicated a major problem in the sample of curb-related cases: no impact angle or speed data were present, probably because CDS places higher priority on reconstruction of vehicle-to-vehicle impacts than fixed-object impacts. Of the 473 cases in which a curb impact was one of the events, including 32 cases in which the curb was the highest-change-in-velocity event, none included reconstructed impact speed and angle data. Examination of the "direction of force" variable also indicated that it could not be a measure of "angle of impact." This was verified in subsequent conversations with a NASS investigation supervisor, who indicated that the data might be used as an indicator of tracking/nontracking vehicles, although that also proved later to be somewhat questionable.

Because of these initial data problems, the researchers requested and received enhanced CDS data developed by Dr. Roger Bligh of TTI for NCHRP Project 17-11, "Determination of Safe/Cost Effective Roadside Slopes and Associated Clear Distances." In that project, TTI had NASS crash investigators capture additional data at selected CDS crash sites, and then reconstructed encroachment speed, angle, and tracking/nontracking information where possible. They also developed a confidence rating for the speed and angle reconstructions (i.e., 1 as low confidence and 10 as high confidence). TTI staff provided a set of 21 cases in which a curb had been struck for use in this study. All these cases were SV run-off-road (ROR) collisions; and all occurred on roadways with speed limits of 45, 50, or 55 mph (72, 80 or 89 km/h). Since the widest shoulder width was less than 6 ft, most of the curbs were apparently near the travel lane. For that reason, the encroachment data were expected to provide some indication of the speed and angle distributions for the curb impacts. In addition, whether the vehicle was tracking or not when it left the roadway was considered to be a good indicator of tracking during curb impact.

Table 16 presents the reconstructed encroachment speed data, based on a very small sample of 14 curb-related crashes; since the encroachment speed was "unknown" in 7 of the 21 crashes, only these 14 crashes were relevant. In addition to the raw frequencies for all cases and a subset of cases with higher confidence ratings (i.e., 5 or higher), percentages within speed categories are presented for the total unweighted data, the total unweighted subset of cases with higher confidence, the weighted full sample and the weighted high-confidence subset. The weights in the latter two cases are those provided in the CDS data for each NASS-CDS case.

As shown in the table, the encroachment speeds for this small sample of cases, which are estimates of the curb-impact speeds, ranged from 15 to 61 mph. Except for the Total Weighted group, which was almost totally influenced by one case with a weight of 10,939, the distributions were somewhat similar. Approximately 50% of the cases had encroachment speeds of between 35 and 45 mph. Similar tables related to reconstructed encroachment angle, combined speed and angle data, and tracking/nontracking status of the vehicle can be found in Appendix G.

Both samples of NASS-CDS data available for use in these analyses of speed, angle and tracking/nontracking were very small. Thus, the results must be viewed with caution. This is particularly true of some of the weighted results in the TTI data, which were significantly affected by two high-weight cases. Given these important caveats, based on the data available, the following observations can be made:

- Curb impact speeds ranged from 15 to 61 mph. Approximately 50% of the cases had encroachment speeds between 35 and 45 mph.
- Curb impact angles ranged from 6 to 31 degrees. In the majority of the unweighted cases (70%), the angles were 15 degrees or less, with 50% between 11 and 15 degrees. The distribution of impact angles in the weighted data was highly dependent on the inclusion of the high-weight cases, with 26 to 83% of the cases having angles less than 15 degrees and 20 to 80% between 11 and 15 degrees.
- According to the TTI (reconstructed) data, 77% of the vehicles in the unweighted sample and 97% of the vehicles in the weighted were tracking; while in the NASS-CDS data, 51% (unweighted) and 56% (weighted) were tracking based on direction of force.

Analysis of Extreme versus Nonextreme Crashes

The second part of this task involved analysis of the NASS-GES, Michigan, and Illinois data to determine if certain curb-related crash conditions might distinguish extreme crashes (those involving fatal or incapacitating injury) from nonextreme crashes (those involving property damage only [PDO]). Three analyses were conducted in this effort:

TABLE 16 Encroachment speed distributions from the TTI NASS-CDS sample

Speed (mph)	Unweighted data				Weighted data			
	All cases		High-confidence		All cases		High-confidence	
15-20	1	7.1%	0	0.0%	96	0.8%	0	0.0%
20.1-25	0	0.0%	0	0.0%	0	0.0%	0	0.0%
25.1-30	2	14.3%	1	9.1%	11205	92.3%	266	25.0%
30.1-35	1	7.1%	1	9.1%	24	0.2%	24	2.3%
35.1-40	4	28.6%	4	36.4%	361	3.0%	361	34.0%
40.1-45	3	21.4%	2	18.2%	272	2.2%	225	21.2%
45.1-50	0	0.0%	0	0.0%	0	0.0%	0	0.0%
50.1-55	1	7.1%	1	9.1%	82	0.7%	82	7.7%
55.1-61	2	14.3%	2	18.2%	106	0.9%	106	9.9%
Unknown	7		0		7		0	
Total	21	100.0%	11	100.0%	12153	100.0%	1064	100.0%

- A comparison of NASS-GES curb-related crashes resulting in severe injury with curb-related crashes resulting in no injury,
- A comparison of NASS-GES severe curb-related crashes with severe SV ROR crashes not involving a curb, and
- An analysis of Michigan and Illinois severe and nonsevere curb-related crashes.

Details of the analyses are given in Appendix H.

NASS-GES Severe and Nonsevere Curb-Related Crashes. The GES sample was drawn from the same police agencies as the NASS-CDS data described earlier, but the sample was much larger, approximately 50,000 cases per year. All 1995–99 GES crashes in which the curb was the FHE were divided into two groups: (1) all crashes involving fatal or incapacitating injury, approximately 10 to 15% of the sample, and (2) all PDO crashes, approximately 50% of the sample. The crashes in each group were categorized by roadway class and speed limit (i.e., Interstate highways, non-Interstate highways with speed limits of 40 to 50 mph, and non-Interstate highways with speed limits greater than 50 mph). The sample sizes for these categories are shown in Table 17.

The severe crashes were compared to the PDO crashes within the three roadway types for variables related to crashes (e.g., relationship to junction), vehicles (e.g., vehicle body type), and roadways (e.g., roadway profile).

These analyses were conducted using only unweighted GES data because severity was the predominant weighting variable used in weighting. However, to verify the unweighted results, a set of analyses was conducted of the severe curb and noncurb crashes using weighted data. These analyses indicated that the overwhelming majority of the variables analyzed had very similar distributions for the weighted and nonweighted data, for both the severe and PDO crashes. Generally, the distributions were within 2% of each other, and those outside this range exhibited differences of less than 5%. Therefore, using the nonweighted data appeared to be an appropriate method of comparison.

Some consistent findings were noted and are included in the summary at the end of this subsection.

NASS-GES Severe Curb-Related and Noncurb-Related SV Crashes. This second GES analysis compared extreme curb-related crashes to the larger group of extreme ROR crashes not involving a curb as the FHE. Again, the goal was to see if these high-injury curb and ROR crashes differed in ways that might provide guidance to the simulation, crash testing, and policy development efforts. The data set used was similar to the one described above. The curb-related group comprised SV crashes in which (1) a curb impact was the FHE, (2) the posted speed limit for the roadway was 40 mph (65 km/h) or greater, and (3) the most severe injury was either fatal or incapacitating. The noncurb group included SV crashes meeting the same criteria except the FHE was not a curb impact. These sets of crashes were first characterized as Interstates and non-Interstates, and the non-Interstate category was subdivided into multilane divided highways and multilane undivided highways to try to isolate groups more likely to have the same exposure to curb presence.

While a number of different categorizations of the data were used in these comparisons, the findings did not add a significant amount of information to that learned from the earlier analysis of severe versus nonsevere curb crashes. It was difficult to identify clear findings because the curb and noncurb crashes might well be occurring at different types of locations (i.e., the curb locations could be somewhat different from locations of crashes where no curb is involved). In addition, the freeway-related findings were based on very small samples of curb-related crashes. The more consistent patterns are included in a summary at the end of this subsection.

Michigan and Illinois Severe and Nonsevere Curb-Related Crashes. Analyses similar to those described above were conducted with the 1996–97 Michigan and Illinois HSIS data. Criteria similar to those described for the GES analyses were employed:

- A crash either involved at least one vehicle that struck a curb somewhere in the sequence of events or occurred on a segment of roadway equipped with curbs according to the roadway inventory data;
- Either the FHE was an impact with a curb or the second, third, or fourth harmful event was an impact with a curb and the preceding events were nonimpact events such as “uncoded or errors,” “loss of control,” “ran off road left,” or “ran off road right;”
- The posted speed limit was at least 40 mph; and
- The maximum injury in the crash was either a fatality or an incapacitating injury (K or A on the KABCO injury scale used by most police departments) for the severe impacts or PDO for the nonsevere impacts.

TABLE 17 Sample sizes for NASS-GES analysis of extreme crashes in which the curb was the FHE

Roadway class and speed limit	Fatal & severe injury crashes	PDO crashes
Interstate Highway (All Posted Speeds)	10	64
Non-Interstate Highway (Posted 40-50 mph)	105	428
Non-Interstate Highway (Posted over 50 mph)	17	113

These severe and nonsevere curb crashes were categorized further as Interstate and non-Interstate crashes. The sample sizes for severe and nonsevere curb crashes on Interstates and non-Interstates are presented in Table 18. Because of the extremely small sample size of Interstate crashes in Illinois, those were not analyzed.

Severe curb crashes differed from the nonsevere crashes on Michigan Interstates by occurring more often on ramps, in good weather, and involving alcohol use and motorcycles. Curbs were more often the MHE in the nonsevere Interstate crashes, with rollover and other impacts being the MHE in the severe crashes. The non-Interstate findings were somewhat similar. Curb impacts on these roads were more likely to be in urban areas, regardless of severity. Severe crashes differed from nonsevere crashes in both states by occurring more often in clear weather on dry roads. The Michigan data again indicated that the curb was less likely to be the MHE in the severe crashes and that more alcohol use and more motorcycles were involved in the severe crashes. Illinois data for the non-Interstates indicated that the severe crashes occurred slightly more often at night.

Comparison of Findings from the NASS-GES and State Analyses. The analyses described above examined a wide variety of crash-related factors that might differentiate among severe curb crashes, nonsevere curb crashes, and severe noncurb crashes. Both NASS-GES, a national database, and state-level data from Michigan and Illinois were examined. While there were some subtle differences among the results, there were some rather consistent findings related to curb design and placement:

- Overturn was an important variable in terms of severe injury causation. Curb designs or placement that decreases the probability of overturn are clearly important.
- Impact speed and angle were important; more severe curb-related crashes occurred at higher speeds, on grades, and on curved alignments.
- Both in comparison with other curb crashes (in GES and state data) and in comparison with other SV ROR crashes on freeways, severe curb crashes were more often related to ramps. This could simply be because curbs were more likely to be located on ramps than on other road segments of freeways. However, it does underline the need for forgiving curb designs on interchange ramps.
- Severe curb crashes on Interstates and higher-speed non-Interstates were more likely to be in urban areas. This could reflect such factors as high-speed roadside encroachments at which more barrier curbs are present and the higher severity of curb crashes on interchange ramps, more ramps being located in urban areas. Design and placement may therefore be even more critical on higher-speed roads in urban areas.
- Severe curb crashes were somewhat more likely to occur in clear weather on dry roads than less severe crashes were.
- There was little difference between the curb and non-curb groups with respect to violations cited or whether the crash was considered speed related. The pattern of which of the groups had higher proportions varied by roadway type. However, the Michigan data appeared to indicate more alcohol use in the severe crashes.
- There were no major differences between the frequency of rollovers in the severe curb-related and SV ROR crashes. The percentage of rollover was relatively high in both groups (18% and 70%, respectively). As expected, the mechanism for the rollover differed between the two groups, being the curb in the curb-related crashes.
- Curbs were problematic for motorcycles.

Summary of Crash and Inventory Data Analysis

This section has described the analysis efforts involving real-world crash data that were included in this project. The goals of these analyses were (1) to better characterize safety problems associated with curb and curb–barrier combinations on high-speed roadways, and (2) to provide leads to the crash testing and simulation efforts that were conducted in other parts of this project. All efforts were ultimately aimed at the development of the design guidelines.

The major findings concerning extent of the problem, curb-crash characteristics, and leads to simulation and crash testing efforts include the following:

- Curb-related crashes on roadways with speed limits of 40 mph (65 km/h) and above represented a very small percentage of either total fatal crashes (1%) or all crashes (0.5%). The importance of the curb problem stems from the potential for rollover following impact.

TABLE 18 Sample sizes of severe and nonsevere curb crashes in 1996 and 1997 Michigan and Illinois HSIS Data

	Michigan		Illinois	
	Severe (K+A)	Nonsevere (PDO)	Severe (K+A)	Nonsevere (PDO)
Interstate	17	185	2	26
Non-Interstate	63	1171	37	332
Total	80	1356	39	358

- Curbs were very seldom the MHE in fatal crashes (5%) but much more often the MHE in total curb-related crashes (53%). This implies that curb impacts can cause enough property damage to result in a reportable crash, but that a fatality is more likely to result from a rollover.
- SV curb-related crashes were clearly no more severe than crashes involving other roadside objects. Indeed, among crashes under similar conditions and controlling for rollover occurrence, curb impacts were slightly less severe than crashes with other objects.
- Severe curb crashes were often related to ramps.
- Severe curb crashes on Interstates and higher-speed non-Interstates were often in urban areas.
- It did not appear that environmental or driver factors played a major role in curb crashes. Severe curb crashes were likely to occur in clear weather on dry roads. There was little difference between the curb and noncurb groups with respect to violations cited or whether the crash was considered “speed related.” As might be expected from other research on alcohol use and crash severity, the data from Michigan did appear to hint at more alcohol use in the severe curb crashes than in the less severe crashes.
- Severe curb impacts involved passenger cars and motorcycles more often than SUVs or pickups.
- Rollover is a factor of interest in improving curb design and placement, since it clearly differentiated between a severe and nonsevere crash. Rollover after impacts with curbs appeared to be a relatively low-frequency occurrence, but it remains a problem worthy of design attention due to the severity of crashes involving rollovers, as demonstrated by the higher rollover percentages in fatal curb-related crashes.
- On urban freeways, segments with both guardrails and curbs were likely to have both more SV curb–guardrail crashes and more SV curb–guardrail *injury* crashes than segments with only guardrails. Assuming this relationship holds for other roadway classes, which it should for at least rural Interstates, it clearly supports attention to the design and placement of curbs in combination with guardrails.
- Even though a relatively large number of crash reconstructions are developed each year in the NASS-CDS system (i.e., 5,000 per year), there was very little information available on key issues, such as vehicle impact speed or angle for minor fixed objects like curbs; the need to weight such small samples resulted in interpretation problems.
- Based on an enhanced sample of 21 curb-related cases on higher-speed roads, it appeared that there was a wide range of impact speeds (i.e., 15 to 61 mph), with approximately 50% between 35 and 45 mph; that there was a wide range of impact angles (6 to 31 degrees) with a significant proportion falling between 11 and 15 degrees; and that 77% (unweighted) or 97% (weighted) of the vehicles in these crashes were tracking, depending on whether the unweighted or weighted data are used.

VEHICLE CURB TRAVERSAL SIMULATIONS AND TESTS

The kinematic behavior of a vehicle traversing a roadside curb is the primary focus of this section. The modified NCAC finite-element model of the C2500 pickup truck was used to investigate the vehicle’s response when crossing a number of different curb types at various impact conditions. The results of the simulations were verified through a series of live-driver curb traversal tests with a C2500.

Curb Traversal Simulations

The case of a vehicle impacting a curb in a tracking manner was investigated using LS-DYNA. This section is a brief overview of the methods and results of the FEAs; much more detail can be found in a dissertation by Plaxico *(52)*.

Parametric Study

A parametric study was conducted using different curb types, impact speeds, and impact angles, as shown in Table 19. The curb types included in the study were AASHTO Types A, B, C, D, and G and the 100-mm New York curb, which is referred to in the tables and figures as “New York” or “NY.” These curbs are illustrated in Figure 29. Two impact speeds were used: 70 km/h, which corresponds to the intermediate speed range of interest (i.e., 60 to 80 km/h), and 100 km/h,

TABLE 19 Simulation matrix of impact speed, angle of impact, and curb type for the 2000-kg pickup impacting in a tracking manner

Curb type	Impact speed = 70 km/h Angle of impact:			Impact speed = 100 km/h Angle of impact:		
	5°	15°	25°	5°	15°	25°
A	T	T	T			
B	T	T	T	T	T	T
C	T	T	T	T	T	T
D	T	T	T	T	T	T
G	T	T	T	T	T	T
New York	T	T	T	T	T	T

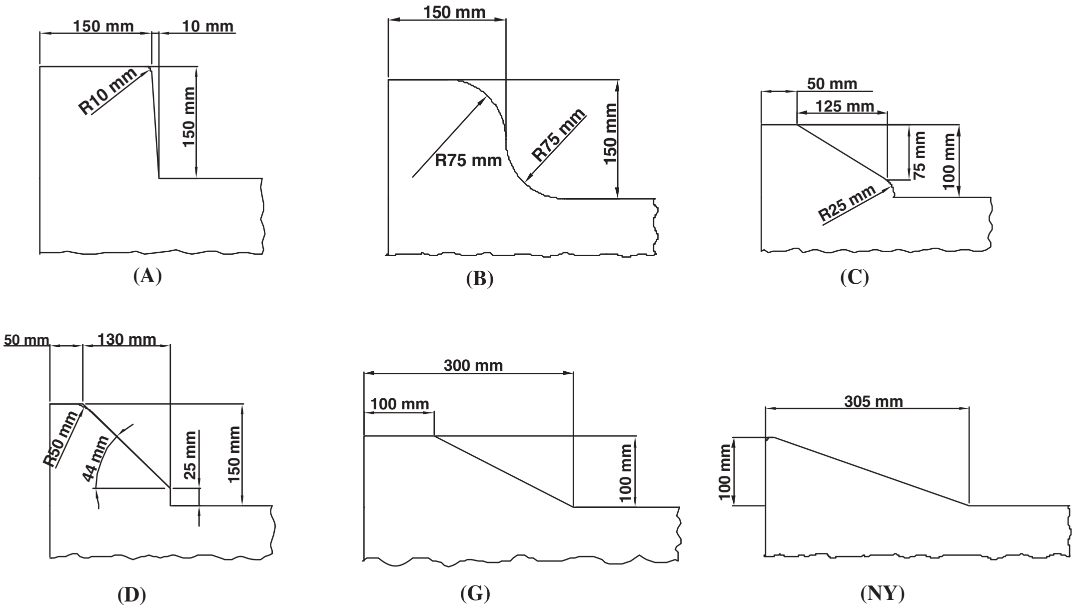


Figure 29. Curb types used in this study.

which corresponds to the high speed range (i.e., greater than 80 km/h). Three angles of impact were investigated: 5, 15, and 25 degrees. Impact angles of 5 and 15 degrees represented the more probable range, while the 25-degree impact was consistent with *NCHRP Report 350* impact conditions for longitudinal barriers. The vehicle used in the simulations was the 2000-kg C2500 pickup truck model developed by NCAC with modifications made by WPI.

Only one roadway cross-section, shown in Figure 30, was used in the parametric study. A typical two-lane cross-section in which a curb and a barrier may be installed together was chosen: a road surface with a 2% cross slope and 1.1-m wide gutter section with a 4.5% slope. Although a 4% backfill would have been typical, a level roadside (i.e., 0% slope) was used in this study since it was more conservative in terms of the potential for the vehicle to override a barrier. The roadway and curb were modeled using shell elements with rigid material properties, and the tire-ground interaction was simulated by using a surface-to-surface contact definition that included friction. The friction values used were based on results from physical tests in which a C2500 pickup truck was pulled at low speed over an asphalt surface and a concrete surface with its wheels locked and the force required to pull the truck was measured using a hydraulic scale.

Data collected from the simulations included bumper trajectories and vehicle paths; acceleration-time histories; yaw, pitch and roll-time histories; yaw, pitch, and roll angle rate-histories; sequential snapshots; and TRAP results (i.e., occupant risk values).

Results

Bumper trajectories and vehicle paths. Figure 31 shows the bumper height of the pickup truck during impact with the different curbs for each impact angle studied. From the results of the simulations, the following observations were made regarding the potential for barrier override.

Influence of lateral offset. For the 150-mm curbs (i.e., AASHTO types A, B, and D), there was a potential for barrier override if the barrier was positioned within 8 m behind the curb. For the 100-mm curbs (i.e., AASHTO types C and G and the NY curb), the potential for barrier override appeared

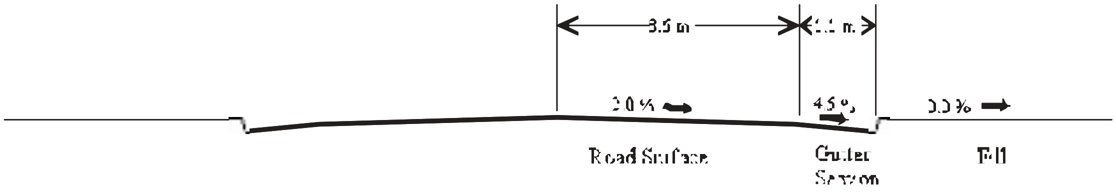


Figure 30. Roadway cross-section used in this study.

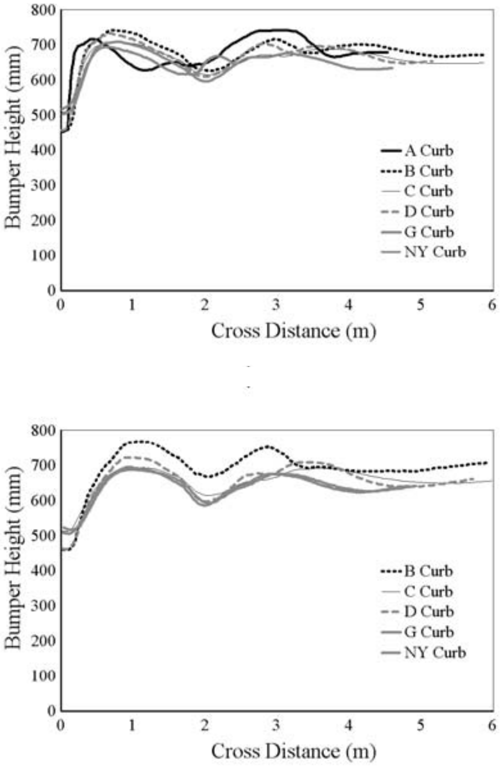


Figure 31a. Bumper height with respect to lateral distance behind curb and curb type for C2500 pickup crossing the curb at an angle of 5 degrees at 70 km/h (top) and 100 km/h (bottom).

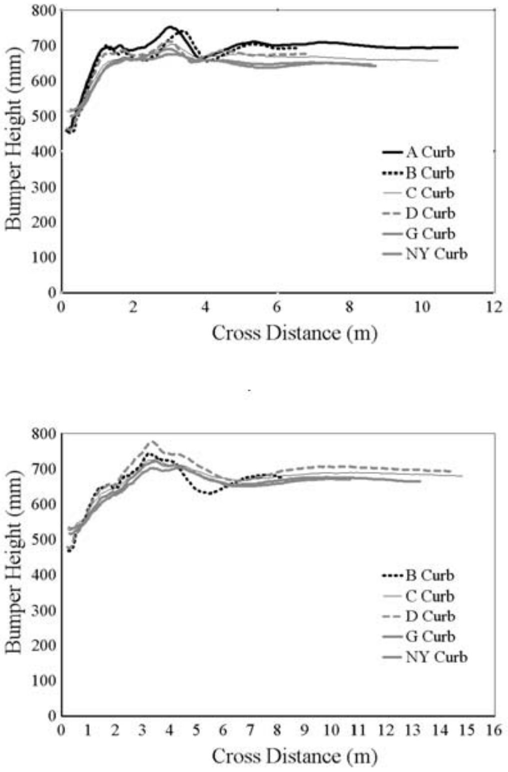


Figure 31b. Bumper height with respect to lateral distance behind curb and curb type for C2500 pickup crossing the curb at an angle of 15 degrees at 70 km/h (top) and 100 km/h (bottom).

to be less if the barrier was positioned between 2 m and 3 m or more than 8 m behind the curb. However, in the case of the 25-degree impacts, the trajectory of the front bumper continuously increased over a lateral distance of approximately 4 m behind the curbs.

Influence of impact conditions. The trajectory of the front bumper was nearly independent of vehicle speed but slightly dependent on impact angle (it increased with increase in impact angle; less so for the 150-mm curbs). For 100-mm curbs the potential for barrier override was minimal for impact angles of 5 and 15 degrees. For a given impact speed and angle, the mode of vehicle trajectory was similar for all curb types (for a given impact speed and angle, the maximum bumper trajectory occurs at approximately the same point, regardless of curb type).

Influence of curb type. The maximum value of bumper trajectory was dependent on curb height (i.e., increased with increase in curb height). It was also slightly dependent on slope of curb face, with some discrepancy in the results from the AASHTO curb type A analyses.

The accelerations and angle-displacement rates computed at the center of gravity of the vehicle model were extracted from the results of the FEAs and input into TRAP. From these data, occupant risk factors were computed based on OIVs and ridedown accelerations and were found to be minor, as expected. The primary purpose for using TRAP, however, was to obtain information that would aid in quantifying vehicle stability regarding the various curb types.

The stability of the vehicle during and after interaction with curbs may be adversely affected by wheel interaction with the curbs. For example, the front wheels of a vehicle may undergo abrupt steering during impact with a curb which may eventually lead to spin-out or overturn of the vehicle. TRAP provides information based on maximum accelerations, maximum angle displacements, and maximum displacements rates that may be useful in discerning vehicle instability. The results from TRAP for each analysis in the study matrix are presented in Table 20.

Acceleration-Time histories. An Acceleration Severity Index (ASI) value was computed from each analysis. These values were relatively low concerning occupant risk during impact, but they did give an indication of the overall acceleration response of the vehicle during vehicle-curb interaction, which may be regarded as some measure of difficulty for a driver to maintain control of the vehicle. For example, a higher ASI

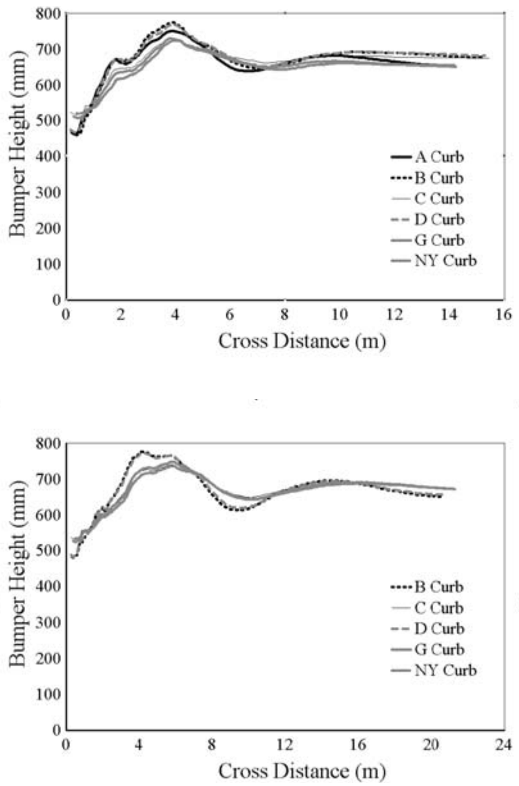


Figure 31c. Bumper height with respect to lateral distance behind curb and curb type for C2500 pickup crossing the curb at an angle of 25 degrees at 70 km/h (top) and 100 km/h (bottom).

value indicates that the vehicle experienced higher accelerations, which could affect the driver's ability to maintain control of the steering and braking of the vehicle during impact. Figures 32 and 33 show a comparison of the ASI for each analysis; note that curb types A, B, and D are 150-mm curbs and curb types C, G, and NY are 100-mm curbs.

Figures 32 and 33 point to the following conclusions about ASI values:

- They increased as impact velocity increased.
- They increased as impact angle increased.
- They increased as the curb height increased.
- They increased as the slope of the curb face increased.

Yaw, pitch, and roll. Figure 34 shows the maximum angular displacements and maximum angular displacement rates from each analysis case.

The following observations were made from the analyses:

- Roll angles were minimal in all cases (i.e., less than 8 degrees). They appeared to be unaffected by the slope of the curb face, especially at higher impact speeds, and almost unaffected by impact speed. The roll angle increased as curb height increased and decreased as impact angle increased.
- Roll rates were also independent of the slope of the curb face, and they were minimally affected by impact speed. The roll rate increased as curb height increased and as impact angle increased. The influence of impact angle on roll rates was much more pronounced for cases involving 150-mm curbs than for cases involving 100-mm curbs.
- Pitch angles were minimal in all cases (i.e., less than 3.5 degrees). They appeared to be independent of impact speed and slope of the curb. The pitch angles increased slightly as curb height increased.
- Pitch rates were independent of the impact speed and slope of the curb face. For the 150-mm curbs, pitch rates varied significantly with respect to impact angle; for the 100-mm curbs, the pitch rate was much less influenced by impact angle.
- Yaw angles were primarily affected by the steer angle of the front wheels after impact with the curb. As the front wheels steered out, usually to the right, during wheel-curb interaction, the yaw angle increased and was typically greatest at the end of the analysis. As the vehicle traversed the curb, the resulting yaw angle of the vehicle could lead to an impact with the barrier at a higher or lower impact angle than the original encroachment angle.
- Yaw angles were independent of curb height and impact speed but increased as the slope of the curb face increased. For the 150-mm curbs, the yaw angle ranged from 8 to 28 degrees and varied erratically with respect to the impact angle. For the Type C curb, the yaw angle ranged between 9 and 24 degrees; for the G curb, the angles were very low (3 to 10 degrees) except for the high-speed, high-angle impact for which the maximum yaw angle was 22 degrees; for the NY curb, the angles were also very low (i.e., 3 to 6 degrees, and negative 8 degrees in one case) except for the high-speed, high-angle impact for which the maximum yaw angle was 18 degrees.
- Yaw rates increased as the height of curb increased and as the slope of the curb face increased. For the 100-mm curbs, the yaw rate was independent of impact speed but increased slightly as the impact angle increased. For the A curb, there was no discernable effect of the impact angle on the yaw rate; for the B curb, the yaw rate varied significantly and erratically with respect to impact speed, while the impact angle had minimal influence except for the high-speed, high-angle impact; for the D Curb, the yaw rate increased as impact angle increased and increased slightly as impact speed increased.

Summary

The FEA program LS-DYNA was used in a parametric study to investigate the influence of several factors regarding

TABLE 20 Summary of results from TRAP for each analysis in the curb study matrix

Curb type		Impact conditions		Max. vertical acceleration (G's)			Max. vertical impulse (N*s)	ASI	Max. angle displacements (degrees)			Max. angle disp. rates (deg/s)		
		Speed (km/h)	Angle (deg)	60 Hz filter	10 ms average	50 ms average			Roll	Pitch	Yaw	Roll rate	Pitch rate	Yaw rate
150-mm curbs	**A**	**70**	**5**	6.31	3.21	1.05	1618	0.18	-6.4	3.0	22.6	68.2	36.2	35.2
			15	7 73	4 01	1 36	2170	0 20	6 5	3 1	27 4	77 0	50 3	40 9
			25	9 41	4 11	1 77	3519	0 22	5 4	2 4	12 0	82 3	69 0	38 0
	B	**70**	**5**	5 08	1 00	2 57	1785	0 11	6 9	2 4	20 2	46 1	28 3	47 2
			15	7 38	3 88	1 42	5238	0 19	6 6	3 3	25 2	67 5	54 4	47 2
			25	6 59	5 47	1 92	3453	0 25	5 4	2 8	26 9	116 0	34 1	44 3
		100	**5**	4 44	2 72	1 07	2523	0 19	7 6	2 3	21 4	62 4	27 8	34 6
			15	6 79	4 65	1 39	2517	0 22	5 0	2 6	20 0	80 7	39 9	37 2
			25	14 93	10 00	2 84	4284	0 29	4 2	2 4	23 1	97 5	71 6	57 1
	D	**70**	**5**	1 50	1 25	0 90	1506	0 10	7 4	2 2	11 1	45 8	17 9	22 7
			15	3 58	2 63	1 31	1990	0 14	5 4	2 6	8 4	63 4	34 4	32 7
			25	7 56	5 57	1 75	3349	0 21	5 2	2 7	28 1	100 7	38 8	39 7
		100	**5**	2 55	1 40	0 87	2115	0 14	7 1	1 8	7 8	45 3	13 4	26 9
			15	5 78	4 51	1 17	2443	0 19	5 3	2 8	24 6	72 9	37 7	37 6
			25	11 41	7 19	2 54	3772	0 26	4 2	2 4	23 8	95 8	57 5	51 1
100-mm curbs	**C**	**70**	**5**	1 30	0 97	0 63	1318	0 09	6 0	1 6	12 6	37 9	12 2	18 9
			15	2.86	1.73	0.95	1557	0.11	-4.2	2.1	11.4	36.4	22.9	21.7
			25	3.93	2.42	1.20	2411	0.16	-3.9	2.5	23.7	48.2	23.0	28.7
		100	**5**	1.50	1.03	0.70	1594	0.09	-5.7	1.4	9.1	36.8	12.1	17.9
			15	3.20	2.06	1.00	1990	0.15	-3.8	2.3	22.8	50.1	22.8	23.5
			25	5.86	4.54	1.25	2500	0.18	-3.4	2.0	23.7	61.1	28.0	27.8
	G	**70**	**5**	0.83	0.77	0.61	1097	0.07	-5.9	1.6	6.4	35.9	12.3	15.8
			15	2.17	1.41	0.85	1811	0.09	-4.0	2.2	4.1	36.1	17.9	17.5
			25	4.20	2.73	1.14	2319	0.14	-4.1	2.7	9.8	54.7	24.6	20.1
		100	**5**	0.99	0.89	0.74	1589	0.08	-5.4	1.3	3.3	37.7	12.1	13.1
			15	2.59	1.81	1.06	1973	0.12	-4.0	2.4	6.7	47.8	26.6	16.8
			25	7.81	5.87	1.81	2585	0.19	-3.6	2.2	21.7	66.2	26.9	29.0
	NY	**70**	**5**	0.43	0.34	0.26	796	0.05	-4.9	1.2	4.0	27.8	12.2	15.8
			15	1.30	0.84	0.63	1188	0.07	-3.8	2.1	3.0	32.3	14.5	12.5
			25	3.10	2.00	1.11	2017	0.14	-3.7	2.3	-7.8	35.0	25.1	16.2
		100	**5**	0.96	0.88	0.71	1477	0.08	-5.5	1.2	4.1	37.6	12.1	10.6
			15	1.72	1.43	0.97	1626	0.10	-3.7	2.0	5.9	29.2	19.0	13.3
			25	5.23	4.45	1.59	2313	0.17	-3.4	2.1	18.4	57.7	22.3	19.3

vehicle stability and trajectory when traversing curbs. The variables used in the study included curb height and shape, impact speed, and impact angle.

The results of the study indicated that the trajectory of the front bumper was only slightly affected by impact speed, impact angle, or the slope of the curb face. The most significant factor influencing trajectory was the height of the curb. Based on the range of impact conditions considered in this study, the trajectory of a 2000-kg pickup truck traversing curbs with a height of 100 or 150-mm was considered sufficient to override a standard strong-post guardrail placed at 0.5 to 8 m behind the curb.

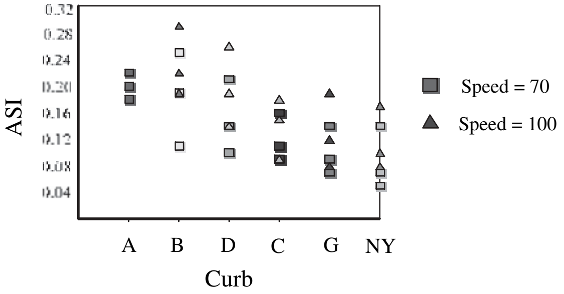


Figure 32. ASI of C2500 pickup truck by curb type and speed at impact, based on FEA.

Acceleration and angular rate data collected at the center of gravity of the vehicle model during analysis were used as inputs to TRAP. The results indicate that ASI values were proportional to impact speed, impact angle, curb height, and the slope of the curb face. This suggests that a driver was much less likely to lose control while traversing a lower curb with a more mild, sloping face (e.g., the New York curb) than while traversing a taller, steep-faced curb such as the AASHTO Type A or B.

The analysis showed that vehicle impacts with roadside curbs could often result in the driver losing control of the vehicle. There were many factors that influenced vehicle behavior during curb traversal, such as abrupt steering caused by the interaction of the front wheels with the curb, loss of contact between the tires and the ground, excessive vehicle accelerations, and excessive roll, pitch, and yaw during impact. While each of these factors may lead to loss of control of the vehicle, total loss of control is unlikely except in extreme cases. A more important issue may be the effects that these factors precipitate when curbs are placed in combination with roadside hardware (e.g., guardrail, crash cushions, or breakaway poles). Vehicle behavior in impacts with curb–guardrail combinations are discussed later in this section.

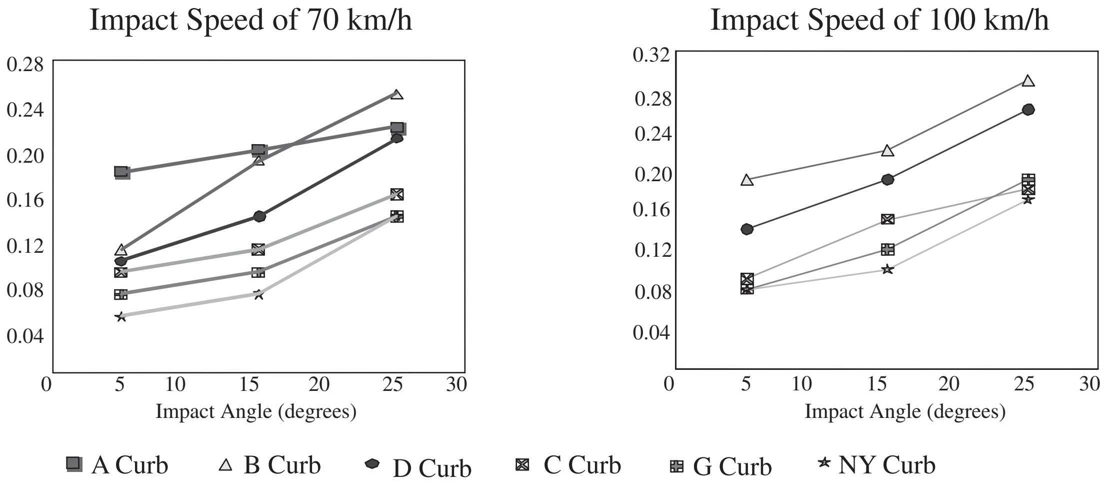


Figure 33. ASI of C2500 pickup truck by impact angle and each curb type at impact speeds of 70 km/h and 100 km/h, based on FEA.

Live-Driver Curb Traversal Tests

As described in Chapter 4, low-speed curb-traversal tests were conducted using a live driver and a C2500 pickup truck. These tests were primarily used to validate the finite-element model of the roadway and curb.

Tests were performed on the Type B curb, Type G curb, and 6-in. vertical curb at impact angles of 10, 15, 25, and 90 degrees. Tables 21 through 23 summarize the results.

The sequence of events that occurred in these tests is illustrated in Figure 35, which is a series of snapshots of the 25-degree test with the B curb. The vehicle impacted the curb at approximately 25 km/h, striking it first with the right front wheel. The front right suspension was compressed by the impact, and the linkage provided by the stabilizer bar caused the left suspension to slightly compress as well. While the front wheels started to rebound, the vehicle began to roll, extending the back right suspension and compressing the left suspension. The front left suspension then started to compress again, while the right one maintained a steady elongation because it encountered the descending slope of the backfill while the cabin rolled back. When the right back wheel impacted the curb, the right back suspension experienced a sudden compression. The impact force and rolling moment were transferred to the chassis, thus extending the two rear suspensions. During this phase, the relative rolling of the bed with respect to the pickup truck cabin was apparent. The lateral force caused by the impact of the back right wheel against the curb caused the vehicle to yaw towards the backfill behind the curb. In one of the tests, the high-speed video showed that the left back wheel left the ground right after the rebound. The pitching moment due to the back right wheel impact compressed the front suspension.

As described in Chapter 4, live-driver curb traversal tests were also conducted at moderate speeds, with the vehicle approaching the curb in both tracking and nontracking modes.

A number of tracking tests were first performed at 35 mph with the B, C, D, and NY curbs. The driver was able to achieve reasonably repeatable impact conditions and did not report any uncontrollable behavior of the vehicle, although at times he reported feeling strong shocks to the steering wheel. The vehicle traversed all the curbs without impacting any components other than the tires. Minor damage occurred to the tread of the tire impacting the curb, including plugs torn from the tire. Tables 24 to 27 summarize the results of these tests.

Nontracking tests were then conducted at 35 mph on the same curbs. Two nontracking scenarios were used: (1) oversteering and (2) understeering. During these tests, extreme trajectories and roll angles were often recorded in the impacts, and the anti-rollover outrigger was engaged twice, preventing the physical rollover of the vehicle. The vehicle was not damaged during the testing of the NY and C curbs; but, during the testing of the B and D curbs, damage to the wheels and the steering system was reported. In particular, bending of the rims was noticed each time they came into direct contact with the concrete curbs. Tire blow-out (i.e., tire failure by debedding and subsequent sudden air loss) was recorded in four cases. After one test with the D curb, the neutral position of the steering wheel was 180 degrees off-center, apparently a result of damage to one or more parts of the steering system. The B and D curbs also suffered severe damage, including gouges, scrapes, and broken concrete from the impact of the rims and rim flanges.

Tables 28 through 31 summarize the results of the nontracking tests.

CURB–GUARDRAIL SIMULATIONS AND TESTS

Finite-element simulations and full-scale crash tests were also used to investigate the response of a $^{3}/_{4}$-ton pickup truck

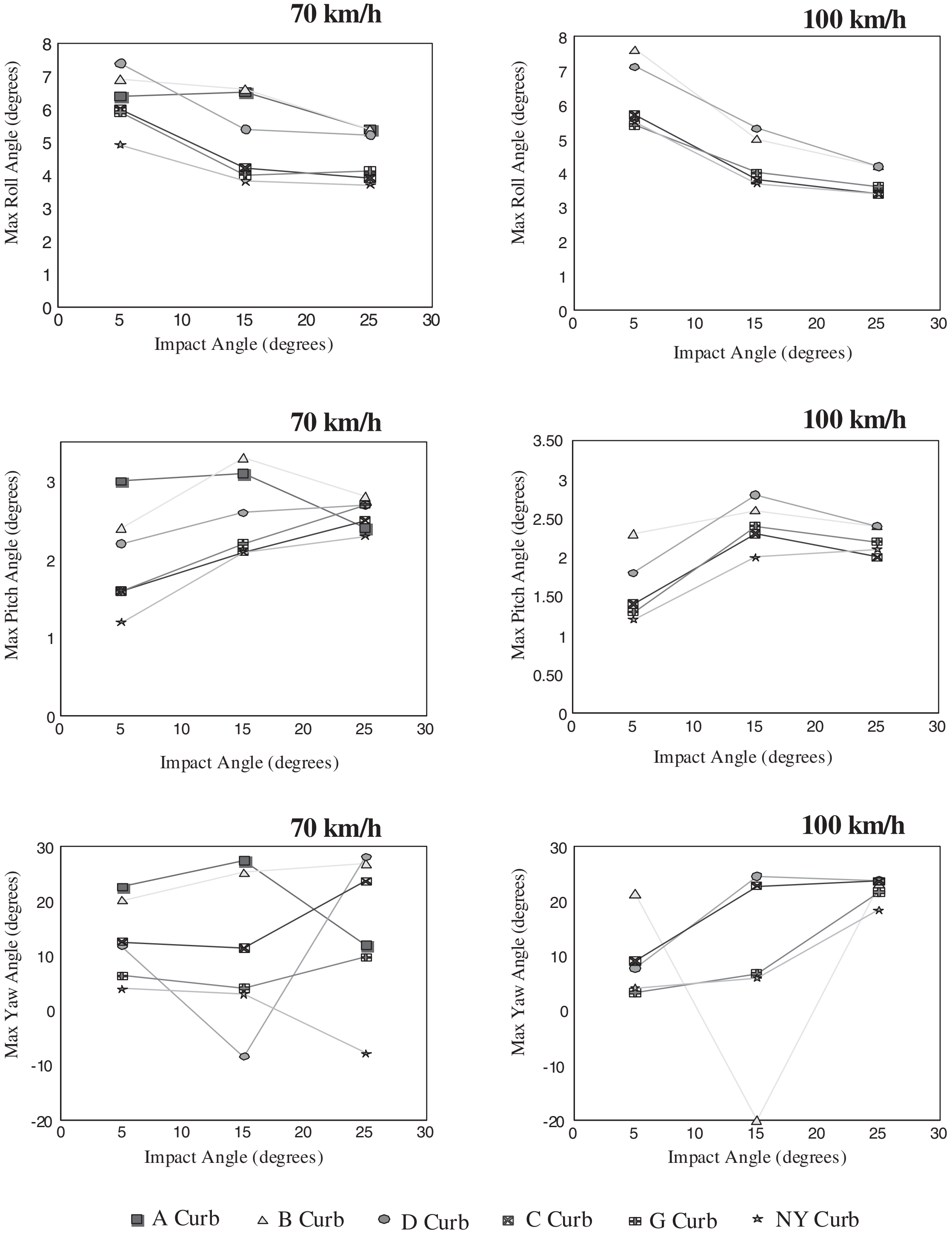


Figure 34. Maximum roll, pitch, and yaw angle displacements of C2500 pickup truck by curb type and speed at impact.

TABLE 21 Type B curb low-speed, live-driver test summary

	Impact angle			
	10°	15°	25°	90°
Maximum compression (mm):				
Front right wheel	73	86	102	110
Front left wheel	58	59	54	115
Back right wheel	39	50	38	97
Back left wheel	48	43	76	93
Maximum extension (mm):				
Front right wheel	59	39	32	95
Front left wheel	43	30	52	69
Back right wheel	81	84	85	118
Back left wheel	50	61	46	99
Maximum vertical acceleration (g):				
C.G. of truck	0.9	1.0	1.1	2.0
Bed of truck	2.5	2.5	3.7	6.2

TABLE 22 Type G curb low-speed, live-driver test summary

	Impact angle			
	10°	15°	25°	90°
Maximum compression (mm):				
Front right wheel	73	67	55	111
Front left wheel	103	103	115	106
Back right wheel	62	65	75	82
Back left wheel	50	59	60	74
Maximum extension (mm):				
Front right wheel	57	54	47	54
Front left wheel	75	64	58	69
Back right wheel	85	82	81	115
Back left wheel	46	65	51	103
Maximum vertical acceleration (g):				
C.G. of truck	1.2	1.4	1.8	1.3
Bed of truck	3.5	3.9	3.9	4.6

TABLE 23 Vertical 6-inch curb low-speed, live-driver test summary

	Impact angle			
	10°	15°	25°	90°
Maximum compression (mm):				
Front right wheel	102	119	132	131
Front left wheel	53	85	87	128
Back right wheel	88	90	115	104
Back left wheel	60	57	88	113
Maximum extension (mm):				
Front right wheel	89	75	64	90
Front left wheel	62	70	41	87
Back right wheel	48	85	125	189
Back left wheel	175	244	256	114
Maximum vertical acceleration (g):				
C.G. of truck	1.1	1.6	2.0	2.5
Bed of truck	3.8	5.4	7.4	6.8

impacting curb–barrier systems in which the barrier was a modified G4(1S) guardrail with wood blockouts.

Curb–Guardrail Simulations

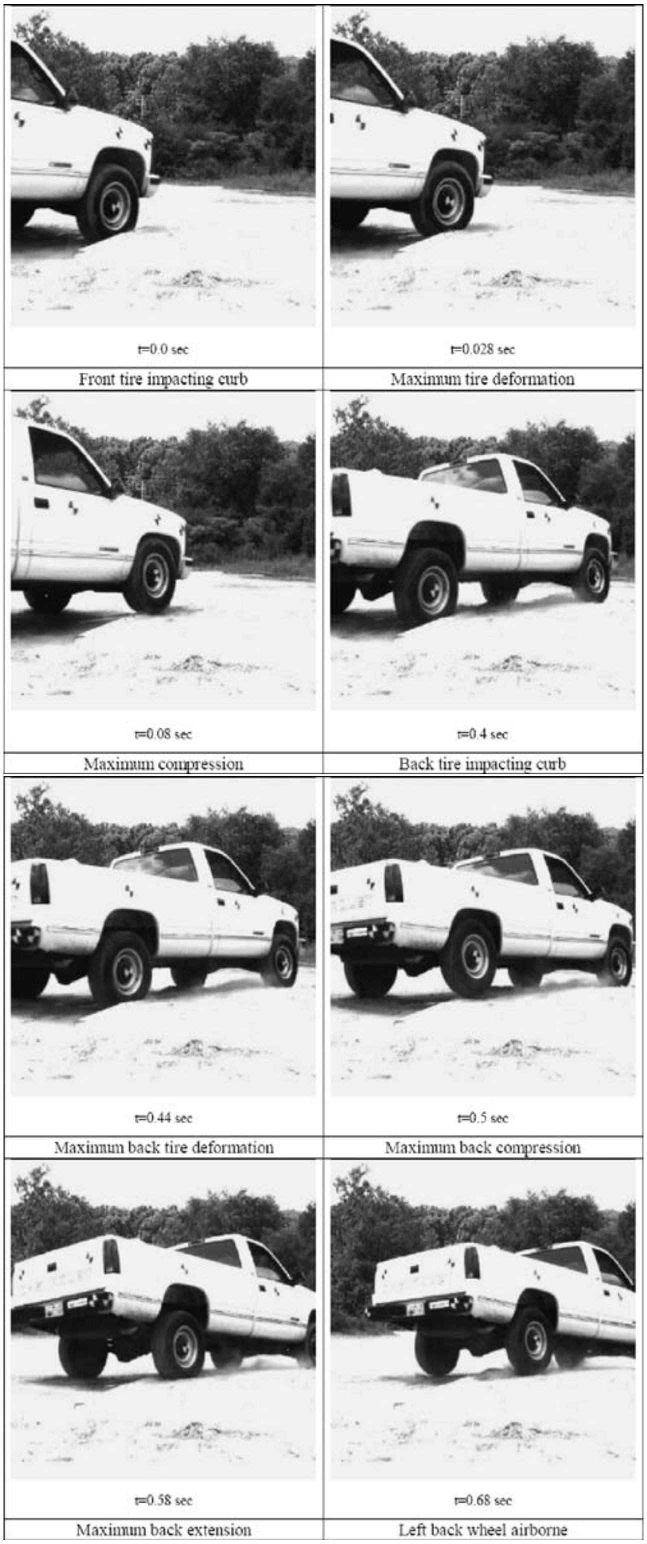
LS-DYNA was used to analyze various curb–guardrail systems subjected to impact by the modified C2500 pickup truck model under three different impact conditions:

- 100 km/h and 25 degrees (i.e., *NCHRP Report 350* Test 3-11),
- 85 km/h and 25 degrees, and
- 70 km/h and 25 degrees (i.e., *NCHRP Report 350* Test 2-11).

The study included the modified G4(1S) guardrail installed in combination with five curb types: AASHTO Types B, C, D, and G, and the 100-mm New York curb.

Parametric Study

A parametric study was again performed, this time varying the impact speed, curb type, and offset from the guardrail. The impact angle was 25 degrees in all simulations.



t=0.0 sec
Front tire impacting curb

t=0.028 sec
Maximum tire deformation

t=0.08 sec
Maximum compression

t=0.4 sec
Back tire impacting curb

t=0.44 sec
Maximum back tire deformation

t=0.5 sec
Maximum back compression

t=0.58 sec
Maximum back extension

t=0.68 sec
Left back wheel airborne

Figure 35. Sequential views of low-speed Type B curb impact at 25 degrees.

TABLE 24 Type B curb moderate-speed, live-driver test summary

	Impact angle	
	15°	25°
Maximum compression (mm):		
Front right wheel	137	100
Front left wheel	136	113
Back right wheel	93	91
Back left wheel	133	103
Maximum extension (mm):		
Front right wheel	111	93
Front left wheel	99	120
Back right wheel	75	64
Back left wheel	96	98
Maximum acceleration at C.G. (g):		
x	+1.7	1.3
y	-1.5	-1.4
z	+4.0	+2.8
Stability	Good	Adequate

TABLE 25 Type C curb moderate-speed, live-driver test summary

	Impact angle	
	15°	25°
Maximum compression (mm):		
Front right wheel	80	85
Front left wheel	123	57
Back right wheel	58	54
Back left wheel	65	113
Maximum extension (mm):		
Front right wheel	108	49
Front left wheel	82	105
Back right wheel	53	73
Back left wheel	52	94
Maximum acceleration at C.G. (g):		
x	-1.4	+1.3
y	+0.9	-1.2
z	-2.0	+2.9
Stability	Excellent	Excellent

TABLE 26 Type D curb moderate-speed, live-driver test summary

	Impact angle	
	15°	25°
Maximum compression (mm):		
Front right wheel	130	109
Front left wheel	101	111
Back right wheel	92	95
Back left wheel	105	136
Maximum extension (mm):		
Front right wheel	95	91
Front left wheel	131	141
Back right wheel	79	83
Back left wheel	104	102
Maximum acceleration at C.G. (g):		
x	-1.5	+1.8
y	+2.8	+1.9
z	+2.1	+4.3
Stability	Excellent	Adequate

TABLE 27 NY curb moderate-speed, live-driver test summary

	Impact angle	
	15°	25°
Maximum compression (mm):		
Front right wheel	126	67
Front left wheel	96	112
Back right wheel	81	79
Back left wheel	96	99
Maximum extension (mm):		
Front right wheel	101	81
Front left wheel	126	89
Back right wheel	93	57
Back left wheel	64	104
Maximum acceleration at C.G. (g):		
x	+1.7	+1.3
y	+1.6	+1.2
z	+2.0	-1.9
Stability	Excellent	Excellent

TABLE 28 Type B curb moderate-speed, nontracking test summary

Average values for all tests	Over-steering	Under-steering
Maximum compression (mm):		
Front right wheel	131	76
Front left wheel	47	98
Back right wheel	68	98
Back left wheel	67	23
Maximum extension (mm):		
Front right wheel	87	110
Front left wheel	73	101
Back right wheel	70	30
Back left wheel	86	11
Maximum acceleration at C.G. (g):		
x	+2.7	+1.8
y	+5.5	+4.0
z	±4.0	+3.7
Stability	Adequate to Poor	Adequate

TABLE 29 Type C curb moderate-speed, nontracking test summary

Average values for all tests	Over-steering	Under-steering
Maximum compression (mm):		
Front right wheel	108	54
Front left wheel	102	100
Back right wheel	77	74
Back left wheel	62	141
Maximum extension (mm):		
Front right wheel	82	97
Front left wheel	92	92
Back right wheel	82	46
Back left wheel	87	75
Maximum acceleration at C.G. (g):		
x	+3.4	+1.6
y	+2.2	+2.0
z	+2.5	+2.0
Stability	Poor	Good

TABLE 30 Type D curb moderate-speed, nontracking test summary

Average values for all tests	Over-steering	Under-steering
Maximum compression (mm):		
Front right wheel	63	195
Front left wheel	10	77
Back right wheel	54	91
Back left wheel	58	87
Maximum extension (mm):		
Front right wheel	71	123
Front left wheel	93	86
Back right wheel	40	52
Back left wheel	56	99
Maximum acceleration at C.G. (g):		
x	+3.5	+3.1
y	+3.5	+2.3
z	+1.7	+1.4
Stability	Poor	Good

TABLE 31 NY curb moderate-speed, nontracking test summary

Average values for all tests	Over-steering	Under-steering
Maximum compression (mm):		
Front right wheel	90	47
Front left wheel	84	77
Back right wheel	70	74
Back left wheel	57	131
Maximum extension (mm):		
Front right wheel	51	83
Front left wheel	105	83
Back right wheel	68	60
Back left wheel	78	61
Maximum acceleration at C.G. (g):		
x	+1.5	+1.5
y	+2.2	+1.9
z	+1.3	+2.5
Stability	Good	Excellent

The AASHTO curbs used in this study were the types most commonly used. Although according to the survey discussed in Chapter 3 many states did not use AASHTO curbs, most of them used curbs that were at least similar to one of these four types (i.e., B, C, D, and G) or Type A. The Type A curb was excluded from the curb–guardrail study because the results of the curb traversal study involving this curb were inconclusive.

Three curb placement scenarios were investigated. One scenario involved each of the curbs placed behind the face of the barrier with the front of the curb flush with the front of the W-beam where possible. This scenario was consistent with the recommendations of the FHWA memorandum of Feb 28, 1992, and was expected to provide useful information to the states about the performance of these currently advocated curb–barrier combinations *(27)*. Two other curb-placement scenarios were investigated to determine the effects of curbs placed in combination with guardrails where the offset distance from curb to barrier is greater than zero. Since offset curb–barrier combinations are more common along low- to moderate-speed roadways (i.e., less than 80 km/h), analyses of such combinations were primarily conducted for NCHRP Test Level 2 conditions (i.e., 70 km/h), although a select number of impacts with certain combinations were investigated at higher speeds. The placement of the curbs in those analyses was based on the results of the curb traversal study discussed previously, with consideration given to the clear zone distances that were required for typical roadways.

The backfill and the roadway terrain in the computer model simulations had zero slope. For design speeds of 70 to 80 km/h, the *Roadside Design Guide* states that the clear zone distance should range from 3.5 m for roadways with an average daily traffic (ADT) volume of less than 750 vehicles to 6.5 m for roadways with an ADT of greater than 6,000 vehicles *(2)*. For design speeds of 100 km/h the clear zone distance ranges from 5 to 8.5 m, depending on ADT. Based on the bumper trajectory plots obtained from the curb traversal study, a vehicle impact speed of 70 km/h and angle of 25 degrees will result in the height of the front bumper continuously increasing from the time of wheel contact with the curb to a lateral offset distance of approximately 4 m behind the curb. The bumper will be higher than the top of the guardrail until the vehicle reaches a lateral distance of 5 m behind the curb. Since the middle value of the clear zone distance is approximately 5 m, offset distances of 5 m or greater were not investigated since the guardrail would not have been warranted outside the clear zone area. In those cases, offset distances of 2.5 and 4.5 m were investigated under impact conditions consistent with *NCHRP Report 350* Test 2-11.

For the case of the pickup traversing a curb at 100 km/h and 25 degrees, the bumper trajectory plots from the curb traversal study indicated that the bumper height continuously increased after wheel impact with the curb until the vehicle reached a lateral distance of approximately 6 m behind the curb. The bumper remained higher than the guardrail for a lateral distance of approximately 8 m in this case, with the maximum height occurring between 4 and 6 m. Computer-simulated impacts with curb–barrier systems at an offset distance of 4 m were investigated under impact conditions consistent with *NCHRP Report 350* Test 3-11. The performance of certain curb–barrier systems was also investigated at 85 km/h, which represented the upper speed range for intermediate-speed roadways (i.e., 60 to 80 km/h).

Table 32 is a matrix of the simulations performed.

The backfill area behind the curbs was modeled with rigid elements using a dynamic coefficient of friction of 0.82 between the tires of the vehicle and the ground surface. It should be noted that the interaction between the tires and ground in these analyses may not accurately represent cases where the backfill is composed primarily of soft soil.

Data collected from the simulations included sequential snapshots of the impact event; acceleration-time histories; yaw, pitch, and roll time histories; W-beam tensile force-time histories; and TRAP results (i.e., occupant risk). Much more detail on the analyses and results can be found in Plaxico's dissertation *(52)*.

Results

At the beginning of each simulation, the vehicle was aligned to impact post 14 of the guardrail system. This point is 2.4 m upstream of a splice connection. The exact impact point can vary when a barrier is offset from a curb, depending on the yaw angle of the vehicle after impact with the curb.

It is important to note that vehicle impact into roadside barriers is highly nonlinear, which means that small variations in the system may lead to very different results. Such

TABLE 32 Simulations of impact tests with a curb and G4(1S) guardrail system

	Curb type	Offset distance from barrier to curb		
		0 m	2.5 m	4 m
Simulation Test 2-11: Impact speed 70 km/h, Angle of 25 degrees	B	✓	✓	✓
	C	✓	✓	✓
	D	✓	✓	✓
	G	✓	✓	✓
	NY	✓	✓	✓
Simulation Test 3-11: Impact speed 100 km/h, Angle of 25 degrees	B	✓		✓
	C	✓		✓
	D	✓		
	G	✓	✓	✓
	NY	✓		✓
Simulation:	B	✓	✓	✓
Impact speed 85 km/h, Angle of 25 degrees	C	✓	✓	✓

variations may include impact conditions, impact location on the barrier, vehicle suspension properties, soil conditions, barrier connections, and barrier component properties, to name only a few. Because of the nature of these factors, the results of the FEAs should only be viewed as a tool for assessing the performance of the system; they only represent a possible outcome for the conditions specified. For example, in many cases the trajectory of the vehicle during interaction with the barrier causes the tires to impact higher than normal against the W-beam rail. With the wheels in this position, the connection of the W-beam to the post becomes a critical factor. If the connection between the W-beam and post does not fail quickly enough during impact, the posts may pull the W-beam down to a point that allows the wheels of the vehicle to ride up the rail and launch the vehicle, as was the case involving the simulation of the modified C2500R impacting an AASHTO C curb at 100 km/h and 25 degrees with the guardrail positioned at 0-m offset from the curb, as shown in Figure 36.

A similar event also occurred in a recent crash test performed at the Midwest Roadside Safety Facility in Lincoln, Nebraska, which was documented in a test report by Polivka et al. *(29).* That test involved a modified G4(1S) guardrail with a 102-mm curb placed underneath the rail behind the face of the W-beam under impact conditions corresponding to *NCHRP Report 350* Test 3-11. A section of the guardrail in the impact region incorporated two layers of W-beam (i.e., nested W-beams) to reduce the potential for rupture. Consequently, this resulted in four layers of W-beam at the splice connections, which required a much higher force to pull the head of the bolt through W-beam slots in the connection of the rail to the posts. As a result of the stronger connection, the W-beam rail was pulled down and the vehicle launched into the air. Although the vehicle experienced extreme trajectory during the impact, the vehicle remained upright and came down on the front side of the guardrail and satisfied all requirements of *NCHRP Report 350*. The repeatability of such an event is questionable due to the instability of the vehicle during impact with the system; slight changes in either the system or impact conditions may lead to drastically different results.

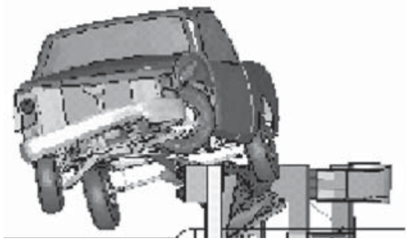


Figure 36. FEA simulation of C2500 pickup impacting guardrail with C curb under rail.

Vehicle Kinematics. Sequential snapshots of the impact event provided a qualitative means of evaluating the general behavior of vehicle interaction with the guardrail as well as the important safety issues regarding vehicle kinematics, such as barrier override, barrier underride, vehicle overturn, and vehicle redirection. Table 33 summarizes the results of these evaluations. The conclusions reached are given in the following paragraphs.

For impacts at 70 km/h and 25 degrees, all five curb types were analyzed. The following results were notable:

- In cases involving the barrier positioned at 0-m offset from the curb, it appeared that the vehicle remained very stable throughout the impact event and barrier damage appeared to be minimal, regardless of curb type. Although the scenario with the 150-mm AASHTO type D curb resulted in the bumper getting above the rail during redirection, the potential for override of the barrier appeared minimal.
- In cases involving the barrier positioned at 2.5-m offset from curb types B, C, D, and G, the sequential views of the impact events suggested that the vehicle would experience moderate roll angle during impact and a relatively high yaw rate, the front of vehicle redirecting out of the system before the rear of the vehicle contacted the rail. Also, while for cases involving 150-mm curb types the bumper of the vehicle climbed above the rail, there was little possibility of override in these cases. The impact scenario involving the 100-mm New York curb resulted in very stable redirection, although the yaw rate appeared somewhat high in this case as well.
- In cases involving the barrier positioned at 4.0-m offset from the curbs, the vehicle remained very stable throughout the impact event and barrier damage appeared to be minimal, regardless of the type of curb used in conjunction with the guardrail. However, the vehicle appeared to experience a high yaw rate during redirection, which could increase risk of occupant injury.

For impacts at 85 km/h and 25 degrees, only two curb types, the type B and C curbs, were used in these curb–barrier scenarios. These cases were analyzed in order to assess the performance of the curb–barrier systems at speeds corresponding to the upper bound of the moderate-speed range (i.e., 60 to 80 km/h) and the lower bound of the high-speed range (i.e., >80 km/h). The following results were observed:

- In the cases involving the barrier positioned at 0.0-m offset from the curbs, the sequential views of the impact suggested that the vehicle would remain relatively stable during impact. There was a slight pitch of the vehicle when the rear wheels contacted the 150-mm Type B curb.
- In the cases with the barrier positioned at 2.5-m offset from the curb, the analyses terminated prematurely due to numerical problems in the calculations that were related to contact between the W-beam rail and truck

TABLE 33 Curb–guardrail FEA for vehicle override, underride, rollover, and redirection

Offset distance	Impact speed	Curb type	Over-ride	Under-ride	Roll-over	Redirection comments
0.0 m	**70 km/h**	**B**	-	-	-	Stable redirection
		C	-	-	-	Stable redirection
		D	-	-	-	Slight bumper trajectory, stable redirection
		G	Analysis Not Conducted			
		NY	-	-	-	Stable redirection
	85 km/h	**B**	-	-	-	Slight pitch
		C	-	-	-	Stable redirection
	100 km/h	**B**	-	-	Possible	Excessive pitch
		C	Likely	-	Likely	Excessive trajectory
		D	-	-	Possible	Excessive pitch
		G	-	-	Possible	Excessive pitch
		NY	-	-	-	Moderate pitch, stable redirection
2.5 m	**70 km/h**	**B**	-	-	-	Moderate roll angle, high yaw rate, bumper above rail
		C	-	-	-	Moderate roll angle, high yaw rate, slight bumper trajectory
		D	-	-	-	Moderate roll angle, high yaw rate, bumper above rail, tie rod breaks
		G	-	-	-	Moderate roll angle, high yaw rate, bumper above rail
		NY	-	-	-	Stable redirection, high yaw rate
	85 km/h	**B**	Likely	-	-	Excessive roll angle, bumper above rail
			Analysis terminated prematurely as bumper started over rail.			
		C	Likely	-	-	Excessive roll angle, bumper above rail
			Analysis terminated prematurely as bumper started over rail.			
	100 km/h	**G**	Likely	-	Likely	Bumper over rail, truck rollover
4.0 m	**70 km/h**	**B**	-	-	-	Analysis terminated during redirection
		C	-	-	-	Stable redirection
		D	-	-	-	Stable redirection
		G	-	-	-	
		NY	Analysis Not Conducted			
	85 km/h	**B**	-	-	-	Stable redirection, high yaw rate
		C	-	-	-	Stable redirection, high yaw rate
	100 km/h	**B**	Likely	-	-	Override
		C	Likely	-	-	Override
		D	Analysis Not Conducted			
		G	Likely	-	-	Override
		NY	Possible	-	-	Excessive trajectory
			Analysis terminated prematurely during redirection			

fender. The analyses did continue long enough, however, to conclude that there was a potential for excessive roll of the vehicle during impact and that the bumper was likely to get over the W-beam rail. Furthermore, the momentum of the truck combined with the excessive trajectory of the bumper was sufficient to cause barrier override.
- In the cases involving the barrier positioned at 4.0-m offset from the curb, the sequential views of the impact events suggested that the vehicle would remain stable but was likely to experience a high yaw rate during redirection.

For impacts at 100 km/h and 25 degrees, all five curb types were analyzed with the barrier offset 0.0 m and 4.0 m from the curb. Only the Type G curb was analyzed for a barrier offset 2.5 m from the curb. The following results were observed:

- The sequential views of the simulated impact events involving the barrier positioned at 0.0-m offset from the curbs indicated that rollover of the vehicle was possible for each curb–barrier scenario involving the types B, C, D, and G curbs due to excessive pitch of the vehicle during redirection. Although the vehicle did not roll over in the simulations, the amount of damage to the front impact-side wheel during impact and the position of the front wheels during redirection became a critical factor regarding vehicle stability when the pitch angle of the vehicle was excessive during redirection. In the simulations, the wheels remained undamaged and in straight alignment during redirection. There was one case of barrier override involving the Type C curb. In this analysis, a wheel snag against a guardrail blockout early in the impact event caused the tie rod to break. The front wheel on the impact side of the vehicle then rotated 90 degrees toward the guardrail. The W-beam rail was pushed down and the vehicle launched over the guardrail.
- The impact scenario involving the 100-mm New York curb at a 0.0-m offset from the barrier resulted in minimal trajectory of the vehicle with only moderate pitch and a relatively stable redirection.
- In the case involving the barrier positioned at 2.5-m offset from the Type G curb, the trajectory of the truck was excessive during impact and, although the trajectory of the front bumper and the momentum of the vehicle appeared sufficient to cause the vehicle to override the barrier, the guardrail redirected the vehicle away from the system. The vehicle then proceeded to roll over onto its side.
- In the cases involving the barrier positioned at 4.0-m offset from the curb, the sequential views of the impact events suggested that barrier override was likely regardless of curb type. Note: the analysis involving the 100-mm New York curb resulted in premature termination due to numerical problems in the calculations that were related to contact between the front tire and the W-beam, but at the time the analysis was stopped the trajectory and roll angle of the truck was excessive enough to suspect barrier override, the likelihood of rollover, or both.

Vehicle Angular Displacement. The roll, pitch, and yaw angle displacement-time history data were collected at the center of gravity of the vehicle during the impact event. Table 34 summarizes the vehicle's angular position at the time of impact with the guardrail, the maximum roll and pitch angle of the vehicle during the impact event, and the yaw angle of the vehicle as it exited the guardrail. The following observations are based on these data:

- When the barrier was offset 2.5 m from the curb and the truck impacted the system at 70 or 85 km/h, the initial roll and pitch angle of the vehicle at the time of impact with the guardrail were typically both positive (i.e., away from the guardrail) with the exception of the NY curb. This resulted in the front bumper on the impact side of the vehicle being higher than normal at the time of impact and, according to a qualitative analysis of the sequential views of the impact, the bumper was above the rail during impact for each of these cases. The maximum roll angle of the vehicle during impact was relatively higher in those cases as well.
- In the cases involving the barrier offset a distance of 4.0 m from the curb and impact speeds of 70 and 85 km/h, the opposite was typically true, with both the initial roll and pitch angle of the vehicle being negative at the time of impact with the guardrail. In those cases the position of the front bumper on the impact side was relatively lower and, according to the sequential views, the bumper stayed below the top of the rail throughout the impact event. For the scenarios involving impact speeds of 100 km/h, the initial roll angle was typically either zero or positive, while the initial pitch angle was typically negative. In those cases the trajectory and momentum of the vehicle dominated and the primary result was vehicle override.
- In all cases involving the barrier offset at distances of 2.5 m or 4.0 m from the curb, the curb caused the wheels of the truck to steer toward the guardrail while the vehicle traversed the curb, resulting in the vehicle impacting the guardrail at a steeper than normal angle. Consequently, for any given curb–barrier case, the impact angle became steeper as the offset distance increased. A steeper impact angle may increase the severity of the impact by increasing the potential for failure of the barrier and by increasing occupant risk factors.

Tensile Force in the Guardrail. The maximum values of tensile force in the W-beam cross-section at two critical locations (i.e., in the impact region of the guardrail and at the upstream anchor) as computed in the FEAs are summarized in Table 35. The cases involving the modified C2500R pickup

TABLE 34 Angular displacement-time history data collected at the center of gravity of the vehicle in the curb–guardrail FEAs

Offset distance	Impact speed	Curb type	Impact angle with guardrail (degrees)			Max. angular displacement in impact (degrees)		
			Roll	Pitch	Yaw	Roll	Pitch	Yaw
0.0 m	**70 km/h**	**B**	0.0	0.0	-25.0	-1.9	-6.4	21.0
		C	0.0	0.0	-25.0	-7.0	-3.7	21.0
		D	0.0	0.0	-25.0	2.2	3.5	20.2
		G	Analysis not conducted					
		NY	0.0	0.0	-25.0	-4.3	-2.1	21.3
	85 km/h	**B**	0.0	0.0	-25.0	5.4	-7.6	19.3
		C	0.0	0.0	-25.0	8.2	-3.3	18.5
	100 km/h	**B**	0.0	0.0	-25.0	-18	-14.2	22.4
		C	0.0	0.0	-25.0	31.3	6.0	29.5
		D	0.0	0.0	-25.0	-12.5	-14.3	24.2
		G	0.0	0.0	-25.0	-11.4	-21.6	23.0
		NY	0.0	0.0	-25.0	-10.9	-9.1	23.5
2.5 m	**70 km/h**	**B**	0.27	0.44	-25.8	-11.9	-3.2	13.7
		C	Data not recorded due to input error					
		D	0.89	1.13	-26.8	-11.4	-5.2	18.9
		G	3.48	0.16	-26.2	-14.1	-6.3	19.9
		NY	2.87	-0.17	-26.0	-8.4	-5.2	15.8
	85 km/h	**B**	1.22	1.33	-25.7	-	-	-
		C	2.92	0.55	-26.3	-	-	-
4.0 m	**70 km/h**	**B**	-1.95	-1.14	-28.8	5.1	-2.8	NA
		C	-3.39	-2.48	-28.0	-7.6	-2.7	17.7
		D	-1.80	-1.55	-29.7	5.6	-2.9	19.2
		G	0.49	-0.85	-26.8	4.4	-3.4	14.6
		NY	Analysis not conducted					
	85 km/h	**B**	-1.63	-0.81	-27.8	-10.8	-2.0	18.9
		C	-0.82	-1.78	-28.1	-6.3	-3.2	17.0
	100 km/h	**B**	0.0	-0.49	-28.7	-19.6	-6.2	NA
		C	-0.06	-1.42	-27.6	-6.7	-3.5	NA
		G	2.21	-0.93	-27.5	-45.1	3.5	NA
		NY	1.84	-0.95	-27.5	-15.2	-3.1	NA

model impacting the guardrail at 100 km/h and 25 degrees with an offset distance of 0.0 m from curb to barrier are compared to the results of the modified C2500R pickup model impacting the guardrail under the same impact conditions without a curb present. In cases in which the rail forces were significantly higher when the curb was present than when it was not, there may be a potential for rupture. For the simulation of the guardrail without a curb present under *NCHRP Report 350* Test 3-11 conditions, the maximum force in the guardrail occurred in the impact region and was 209 kN and the maximum anchor force was approximately 179 kN. The following conclusions were reached:

- The results from the analyses of vehicle impact with the guardrail under Test 2-11 conditions involving each of the different curb types indicated that rupture of the guardrail was not likely to occur regardless of the offset location of the barrier with respect to the curb.
- The results from the analyses of vehicle impact at 85 km/h at 25 degrees indicated that rupture of the guardrail was not likely to occur for offset distances of 0 m or 4 m. When the guardrail was placed 2.5 m behind the curb, the tension in the rail reaches magnitudes that may be critical; however, there was also bumper override in those cases.
- The analyses of vehicle impact with the guardrail under Test 3-11 conditions involving each of the different curb types located at 0-m offset (i.e., under the W-beam rail) resulted in significantly higher forces in the rail and anchor then when the curb was not present. In all cases, however, there appeared to be potential for excessive anchor movement and rail rupture during impact. The maximum rail forces under Test 3-11 conditions for curb–barrier offset distances greater than 0.0 m are not shown in the table because the predominate outcome in all those cases was barrier override.

TABLE 35 Maximum tensile force values in the W-beam rail within the impact region and at the upstream anchor, based on FEA

Offset distance	Impact speed	Curb type	Maximum tensile force in W-beam rail					
			Impact region		Upstream anchor		Downstream location	
			(kN)	Force/209	(kN)	Force/179	(kN)	Force/147
0.0 m	**70 km/h**	**B**	127	0.61	-	-	71.2	0.48
		C	127	0.61	124	0.69	87.8	0.60
		D	128	0.61	127	0.71	82.9	0.56
		G	Analysis not conducted					
		NY	135	0.65	131	0.73	76.0	0.52
	85 km/h	**B**	165	0.79	141	0.79	117	0.80
		C	170	0.81	142	0.79	122	0.83
	100 km/h	**B**	232	1.11	-	-	182	1.24
		C	226	1.08	202	1.13	175	1.19
		D	243	1.16	210	1.17	183	1.24
		G	223	1.07	-	-	174	1.18
		NY	231	1.11	198	1.11	178	1.21
2.5 m	**70 km/h**	**B**	95.0	0.45	88.7	0.50	68.6	0.47
		C	Data not recorded due to input error					
		D	128	0.61	120	0.67	82.1	0.56
		G	123	0.59	118	0.66	77.8	0.53
		NY	132	0.63	119	0.66	77.7	0.53
	85 km/h	**B**	185	0.89	-	-	91.0	0.62
		C	205	0.98	177	0.99	102	0.69
4.0 m	**70 km/h**	**B**	101	0.48	89.4	0.50	66.1	0.45
		C	114	0.55	113	0.63	76.5	0.52
		D	97.5	0.47	-	-	65.1	0.44
		G	130	0.62	116	0.65	78.8	0.54
		NY	Analysis not conducted					
	85 km/h	**B**	171	0.82	143	0.80	103	0.70
		C	171	0.82	148	0.83	120	0.82

- For cases involving the guardrail positioned at 0.0-m offset from the curb, the maximum tension in the W-beam rail ranged from 107% to 111% and the maximum force at the upstream anchor was as high as 117% of the values computed in the analysis of the guardrail without a curb present.

TRAP Results. Table 36 summarizes the TRAP results, including the OIV, occupant ridedown acceleration (ORA), and maximum 50-m/s moving average acceleration for each curb–guardrail scenario. The OIV in all cases was below the maximum limit of 12 m/s, as required in *NCHRP Report 350*. For the curb–barrier scenarios in which the barrier was offset at 2.5 m or 4.0 m from the curb, the data analysis began at first tire contact with the curb. In some of these cases, occupant impact occurred prior to vehicle impact with the barrier (e.g., Type D curb, 70 km/h impact speed, 2.5-m offset), which resulted in very low values of OIV.

The longitudinal ORA values were below the maximum limit of 20 Gs required in *NCHRP Report 350* for the cases of 0.0-m offset distance from curb to barrier at all three impact speeds. Seven of the cases for which the offset distance was greater than zero resulted in longitudinal ORA values exceeding 20 Gs:

- 150-mm B curb, impact speed of 85 km/h and offset distance of 4.0 m;
- 150-mm B curb, impact speed of 100 km/h and offset distance of 4.0 m;
- 100-mm C curb, impact speed of 85 km/h and offset distance of 2.5 m;
- 100-mm C curb, impact speed of 100 km/h and offset distance of 4.0 m;
- 100-mm G curb, impact speed of 70 km/h and offset distance of 2.5 m;
- 100-mm G curb, impact speed of 70 km/h and offset distance of 4.0 m; and
- 100-mm G curb, impact speed of 100 km/h and offset distance of 4.0 m.

TABLE 36 Occupant risk factors computed using TRAP and the results from the FEAs of the curb–barrier impact study

Curb type		Impact conditions		OIV		ORA		Max. 50-m/s moving average		
		Speed (km/h)	Offset distance (m)	x-dir (m/s)	y-dir (m/s)	x-dir (Gs)	y-dir (Gs)	x-dir (Gs)	y-dir (Gs)	z-dir (Gs)
150-mm curbs	B	70	0.0	4.1	-3.6	-6.0	4.7	-4.6	3.3	2.0
			2.5	3.5	-2.5	-15.1	19.4	4.6	-10.0	7.4
			4.0	2.0	-4.5	13.6	-19.2	-6.3	8.3	-6.7
		85	0.0	4.2	-4.1	8.1	10.6	-4.2	5.7	4.2
			2.5	-	-	-	-	-	-	-
			4.0	0.1	-2.6	31.1	29.0	-14.7	10.1	-9.0
		100	0.0	5.5	-5.0	-11.0	14.9	-5.4	7.6	3.3
			4.0	3.6	0.3	-40.0	-49.9	-13.1	9.6	-14.6
	D	70	0.0	4.3	-4.1	-6.6	6.7	-4.6	3.7	-2.0
			2.5	-0.1	1.6	-12.7	17.3	-5.6	5.8	-7.7
			4.0	0.3	-1.6	13.3	14.4	-3.9	7.2	5.1
		100	0.0	5.9	-4.8	-14.0	15.9	-5.4	7.1	3.5
100-mm curbs	C	70	0.0	4.2	-4.2	-6.3	7.5	-4.0	3.8	-1.7
			2.5	-	-	-	-	-	-	-
			4.0	1.6	1.4	14.4	13.8	6.9	6.3	6.8
		85	0.0	4.1	-4.3	-12.9	12.6	-4.1	5.5	2.3
			2.5	6.1	-3.6	-25.2	-22.0	-9.2	8.5	-12.5
			4.0	0.7	-1.7	-20.0	16.9	-6.9	5.8	6.7
		100	0.0	5.7	-5.0	8.7	7.4	-5.3	6.0	-3.9
			4.0	5.0	-3.8	-40.0	-49.9	-6.5	5.8	-4.2
	G	70	0.0	-	-	-	-	-	-	-
			2.5	6.0	-2.4	-26.6	17.2	-6.6	5.2	-8.2
			4.0	1.1	-2.6	21.2	-16.8	-8.5	5.6	6.9
		100	0.0	4.8	-5.3	-11.6	14.8	-5.0	7.0	2.5
			4.0	6.3	-4.9	26.2	-29.2	13.4	-9.6	-11.5
	NY	70	0.0	4.7	-4.2	-5.1	5.7	-4.7	4.1	1.5
			2.5	5.8	-4.5	-11.0	10.9	-4.4	6.4	-5.1
			4.0	-	-	-	-	-	-	-
		100	0.0	5.0	-5.2	-8.2	13.1	-5.0	5.7	2.4
			4.0	5.3	-5.6	-17.0	21.1	-10.4	9.3	6.7

Summary

The results of the pickup truck model impacting the curb–barrier combination at 0-m offset distance (i.e., curbs under the face of the barrier) at speeds of 70 km/h and 85 km/h indicate that the vehicle would remain stable throughout the impact event and that barrier damage would be minimal regardless of the type of curb used. The bumper of the pickup was above the rail during redirection in one case involving the 150-mm AASHTO Type D curb, but the potential for override of the barrier was considered minimal.

At the higher impact speed of 100 km/h the analyses provided mixed conclusions. In one case involving the 100-mm high Type C curb, the vehicle vaulted over the guardrail, whereas vaulting was not a serious issue in the other cases. The difference in this particular case was attributed to a wheel snag against a blockout early in the impact event; this affected the way the vehicle interacted with the barrier throughout the remainder of the event. Wheel snag is common in impacts with strong-post W-beam guardrails, and similar results are possible for cases involving any of the curb types. It was also concluded that vehicle stability may be an issue during redirection due to the high pitch angles of the vehicle when exiting the system. Furthermore, the tensile forces in the W-beam were high during impact, indicating potential for rail rupture at the splice connections, especially for cases involving the 150-mm curbs. The most promising combination involved the 100-mm New York curb, which resulted in safe redirection of the vehicle, although the tensile forces in the rail were somewhat high.

The results of the FEAs regarding higher-speed impact indicated that the roll angle and pitch angle of the vehicle after traversing curbs had a significant influence on the kinematics of the vehicle during impact with the guardrail for cases involving offset distances of 2.5 m and 4.0 m. The potential for override was increased when the roll angle of the vehicle was positive (i.e., roll away from the barrier) at the time of impact with the guardrail. When the roll angle of the vehicle was negative (i.e., roll toward the barrier) at the time of impact with the guardrail, rollover became a likely outcome.

At impact speeds of 70 km/h into curb–guardrail systems at offset distances of 2.5 m and 4.0 m, there was very little probability of barrier override; but ORAs during redirection were relatively high. In one case involving the 100-mm Type G curb, the longitudinal ORAs exceeded the maximum value of 20 Gs allowed in *NCHRP Report 350*. At the intermediate speed of 85 km/h the results from the finite element simulations indicated the potential for a pickup truck to override a standard strong-post W-beam guardrail located at 2.5-m offset distance from both 150-mm and 100-mm curbs. At an offset distance of 4 m from curb to barrier, the guardrail redirected the vehicle at an impact speed of 85 km/h. The ORAs of the vehicle during redirection were considered high, and the Type B curb resulted in excessive ORAs (i.e., greater than 20 Gs).

Table 37 provides a summary of the results of the curb–barrier impact study regarding success or failure of the system in each case, based on the information obtained from the analyses. Analyses were not conducted for all combinations of impact speed, curb type, and offset distance because of limited funds.

Full-Scale Crash Tests of Curb–Guardrail Combinations

As discussed in Chapter 4, full-scale crash tests were conducted of selected curb–guardrail combination scenarios to complement the FEA results. A series of full-scale crash tests, each conforming to the recommendations in *NCHRP Report 350* Test 11 for longitudinal barriers, was performed to validate the design chart described in Chapter 6. The barriers for all tests were the AASHTO Standard G4(1S) or SGR04a guardrails, modified by the use of recycled plastic blockouts instead of wood blockouts. The impacting vehicle for each test was a 2000P vehicle (i.e., ¾-ton pickup truck). Testing

TABLE 37 Summary of curb–barrier impact study regarding success (✓) or failure (×) of the system based on the results of the FEAs

Impact speed	Curb type	Offset distance from barrier to curb		
		0 m	2.5 m	4 m
70 km/h	B	✓	✗ - high long. ORA - high lateral ORA	✓ - high lateral ORA
	C	✓	✓ ORA	✓
	D	✓	✓ - high lateral ORA	✓
	G	N/A	✗ -excess lateral ORA - high lateral ORA	✗ -excess lateral ORA - high lateral ORA
	NY	✓	✓	N/A (assumed ✓)
85 km/h	B	✓	✗ - override	✗ -excess lateral ORA - high lateral ORA
	C	✓	✗ -excess lateral ORA - override - high lateral ORA	✓ - high long. ORA - high lateral ORA
100 km/h	B	✓ - high pitch angle - high rail forces	N/A	✗ - override -excess long. ORA - high lateral ORA - high roll angle
	C	✗ - override - rollover -excess lateral ORA - high trans. ORA	N/A (assumed ✗)	✗ -excess lateral ORA - override - high lateral ORA - high roll angle
	D	✓ - high pitch angle - high rail forces	N/A	N/A
	G	✓ - high pitch angle - high rail forces	✗ - rollover - override -excess lateral ORA - high lateral ORA	✗ - override -excess lateral ORA - high lateral ORA - high roll angle
	NY	✓ - high rail forces	N/A	✓ - high trajectory - high roll angle - high long. ORA - high lateral ORA

long. = longitudinal.
N/A = not analyzed.
trans. = [PI to supply]

examined two types of curbs, three nominal impact speeds and three curb–barrier offset distances. Inadvertently a fourth variable was introduced in the test matrix, barrier height relative to the curb approach. The test matrix was subsequently expanded to compensate for this added variable. The test matrix is shown in Table 38.

Test Results

Figures 37 through 43 summarize the full-scale crash tests. Each figure shows the theoretical OIVs and ridedown accelerations in the longitudinal and lateral directions, theoretical head impact velocity (THIV), post-impact head deceleration (PHD), ASI, and maximum roll, pitch, and yaw angles.

Test 52-2556-001, conducted by E-TECH Testing Services, Inc., is summarized in Figure 37. In this test, vehicle contact with the test article occurred 2.5 m upstream of the connection splice at the 15th post in the installation. The bumper was forced back crushing the front right fender and wheel well. The entire front right corner of the vehicle came to bear against the W-beam guardrail. The blockouts supported the W-beam and began loading the posts laterally. The W-beam flattened out forming a ribbon that engaged the vehicle. As the W-beam deflected laterally it developed tension that forced the vehicle to yaw counterclockwise. Maximum dynamic deformation of the guardrail was 0.5 m, and the permanent deformation was 0.4 m. The tire and rim forced posts 15 and 16 to deform. The vehicle engaged two W-beam rails before losing contact with the installation. The exit trajectory of the vehicle center of gravity was 14 degrees relative to the installation centerline when the vehicle lost contact with the barrier. The exit velocity of the vehicle was 41.3 km/h. The emergency braking system was applied after loss of contact and the vehicle skidded to a stop 34 m downstream and 11 m left of its position at impact. The furthest piece of debris, a 6.4-kg blockout, ended up 4 m downstream and 7 m to the rear of its position at impact; the pickup sustained major dents in the bumper, right front fender, and passenger door, and the grill and right front headlight were broken. There was no windshield contact or damage and negligible deformation of the vehicle interior.

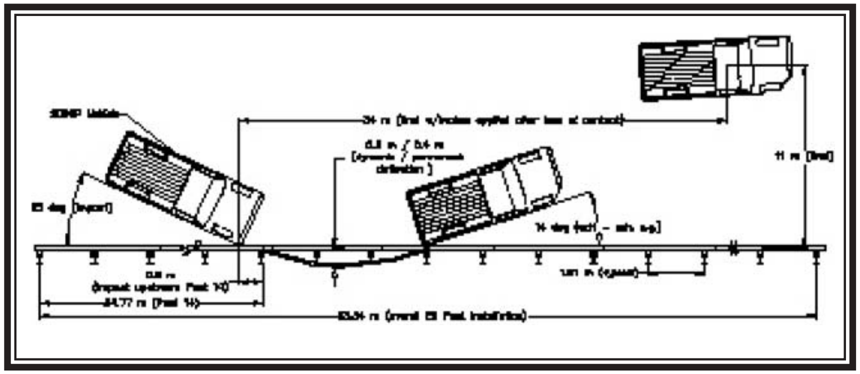
E-TECH Test 52-2556-002 is summarized in Figure 38. In this test, vehicle contact with the test article occurred 2.6 m upstream of the connection splice at the 14th post in the installation. The vehicle traversed the curb, forcing the tires to lose contact with the ground. The right corner of the bumper came into contact with the top ridge of the W-beam guardrail. The blockouts supported the W-beam and began loading the posts laterally. The front end of the vehicle rose up over the guardrail and the guardrail flattened and came to bear against the right front wheel. All four wheels became airborne, and, as the W-beam deflected laterally, it developed tension that forced the vehicle to yaw counterclockwise and roll. The vehicle vaulted over the guardrail, rolled over, came back down on the downstream section of guardrail, and then righted itself on all four wheels. Maximum dynamic deformation of the guardrail was 0.6 m, and the permanent deformation was 0.4 m. The tire and rim forced posts 15 and 16 to deform in the initial impact, and the vehicle engaged two W-beam rails before losing contact. The vehicle subsequently damaged six downstream posts and one section of rail. The vehicle rolled to a stop 21 m downstream and approximately 6 m behind its position at impact. The furthest piece of debris, a 6.4-kg blockout, ended up 0.5 m downstream and 1.5 m to the rear of its position at impact. The vehicle sustained major dents in the bumper, right front fender, roof, hood, and passenger door, and the windshields, mirror, grill and right front headlight were broken. There was a maximum 330 mm deformation of the vehicle interior at the right windshield pillar.

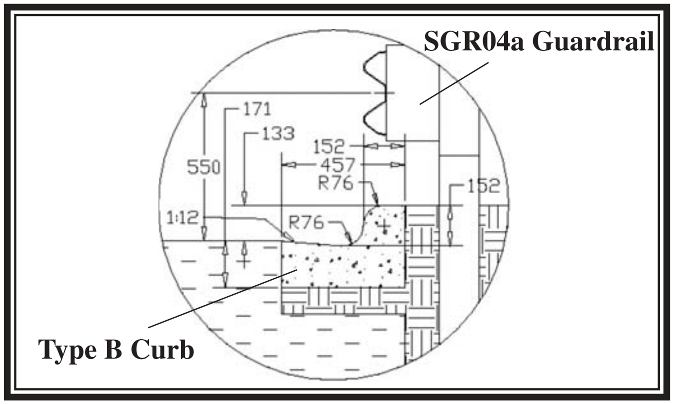
E-TECH Test 52-2556-003 is summarized in Figure 39. In this test, vehicle contact with the test article occurred 2.2 m upstream of the connection splice, just upstream of the 14th post in the installation. The vehicle traversed the curb, forcing the tires to lose contact with the ground. The bottom of the right corner of the bumper came into contact with the top edge of the W-beam guardrail. The blockouts supported the W-beam and began loading the posts laterally. The front overhang of the vehicle rose up over the guardrail and the guardrail came to bear against the right front wheel. All four wheels became airborne, and the front end of the vehicle passed over the guardrail. The rear end of the vehicle slid along the top of the downstream section of guardrail, and then the vehicle came to rest with the back tires on the guardrail and the front wheels on the ground behind the guardrail. Maximum dynamic deformation of the guardrail was 0.4 m, and the permanent deformation was 0.3 m. The right front wheel forced posts 15 and 16 to deform in the initial impact,

TABLE 38 Full-scale crash test matrix

E-TECH test no.	Nominal speed (km/h)	Curb type	Curb offset (m)	Guardrail height (mm) relative to approach
52-2556-001	85	B	0.0	550
52-2556-002	85	B	2.5	550
52-2556-003	80	NY	2.5	550
52-2556-004	80	NY	4.5	550
52-2556-005	80	NY	4.5	650
52-2556-006	70	NY	2.5	650
52-2556-007	85	NY	2.5	650

t = 0.000 sec t = 0.144 sec t = 0.288 sec t = 0.432 sec t = 0.576 sec t = final

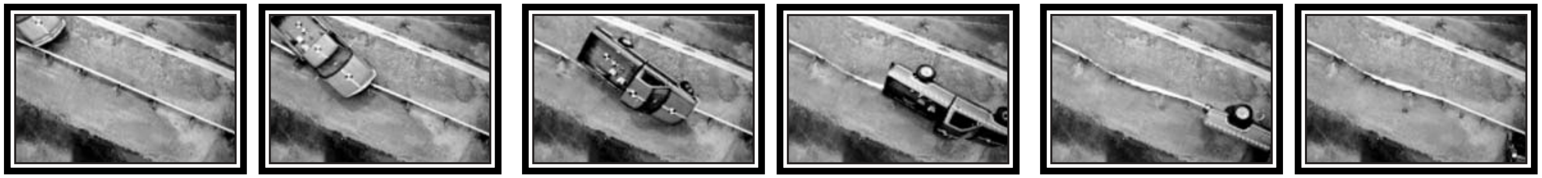




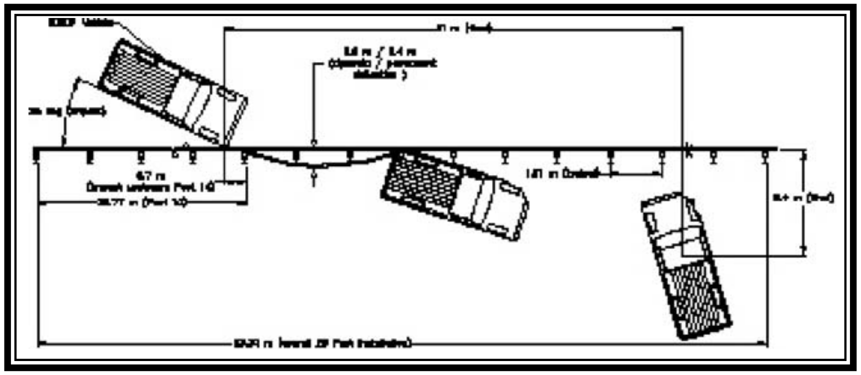
General Information	
Test Agency	**E-TECH Testing Services, Inc.**
Test Designation	**NCHRP 350 Test 3-11 (modified)**
Test No.	**52-2556-001**
Date	**6/5/03**
Test Article	
Curb Type	**AASHTO Type B**
Barrier Length	**53.34 m (overall)**
Height (mm - relative to approach)	**550**
Setback (m - relative to curb)	**0**
Material and key elements	**AASHTO SGR04a Guardrail with SEW02a End Terminal equipped Re-Block recycled plastic blockouts of 50% HDPE / 50% PP**
Foundation Type and Condition	**NCHRP 350 Strong Soil, dry**
Test Vehicle	
Type	**Production Model**
Designation	**2000P**
Model	**1998 GMC 3/4 Ton Pickup**
Mass (kg)	
Curb	**1975**
Test inertial	**1993**
Impact Conditions	
Speed (km/h)	**85.6**
Angle (deg)	**25**
Impact Severity (kJ)	**100.6**

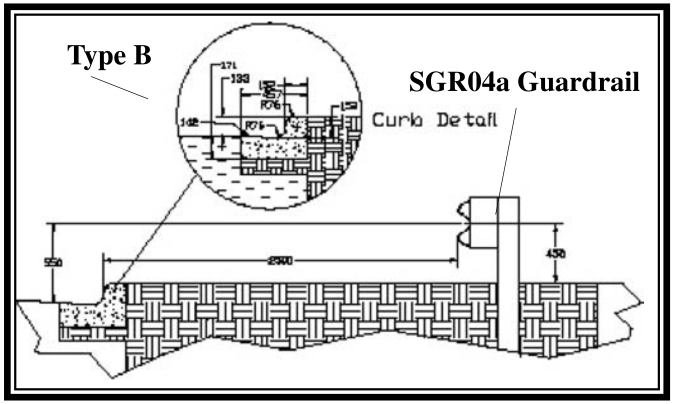
Exit conditions	
Speed (km/h)	**41.3**
Angle (deg - veh. c.g.)	**14**
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	**4.9**
y-direction	**-4.7**
Ridedown Acceleration (g's)	
x-direction	**-8.1**
y-direction	**-6.3**
European Committee for Normalization (CEN) Values	
THIV (km/h)	**24.1**
PHD (g's)	**8.8**
ASI	**0.7**
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	**6.5**
Maximum Pitch Angle	**-10.2**
Maximum Yaw Angle	**-52.0**
Test Article Deflections (m)	
Dynamic	**0.5**
Permanent	**0.4**
Vehicle Damage (Primary Impact)	
Exterior	
VDS	**RFQ-3**
CDC	**01RFWE2**
Interior	
VCDI	**AS0000000**
Maximum Deformation (mm)	**Negligible**

Figure 37. Summary of curb–guardrail crash test 52-2556-001, B curb below guardrail.



t = 0.000 sec t = 0.144 sec t = 0.288 sec t = 0.432 sec t = 0.576 sec t = final





General Information	
Test Agency	E-TECH Testing Services, Inc.
Test Designation	NCHRP 350 Test 3-11 (modified)
Test No.	52-2556-002
Date	6/18/03
Test Article	
Curb Type	AASHTO Type B
Barrier Length	53.34 m (overall)
Height (mm - relative to approach)	550
Setback (m - relative to curb)	2.5
Material and key elements	AASHTO SGR04a Guardrail with SEW02a End Terminal equipped Re-Block recycled plastic blockouts of 50% HDPE / 50% PP
Foundation Type and Condition	NCHRP 350 Strong Soil, dry
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1994 Chevrolet 3/4 Ton Pickup
Mass (kg)	
Curb	1919
Test inertial	2002
Impact Conditions	
Speed (km/h)	86.6
Angle (deg)	25
Impact Severity (kJ)	103.5

Exit conditions	
Speed (km/h)	N/A
Angle (deg - veh. c.g.)	N/A
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	5.5
y-direction	-3.2
Ridedown Acceleration (g's)	
x-direction	-10.8
y-direction	11.4
European Committee for Normalization (CEN) Values	
THIV (km/h)	22.4
PHD (g's)	14.7
ASI	0.8
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	472.1
Maximum Pitch Angle	26.9
Maximum Yaw Angle	20.3
Test Article Deflections (m)	
Dynamic	0.6
Permanent	0.4
Vehicle Damage (Primary Impact)	
Exterior	
VDS	R&T-5/RFQ-4
CDC	01RFE03
Interior	
VCDI	RF0000010
Maximum Deformation (mm)	330

Figure 38. Summary of curb–guardrail crash test 52-2556-002, B curb offset 2.5 m from guardrail.

t = 0.000 sec

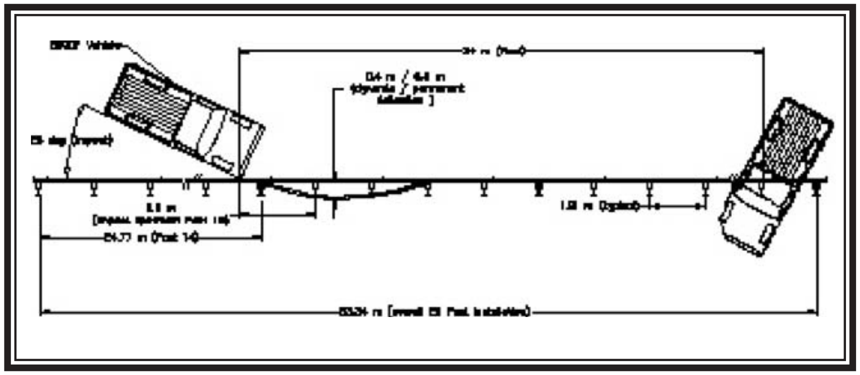
t = 0.096 sec

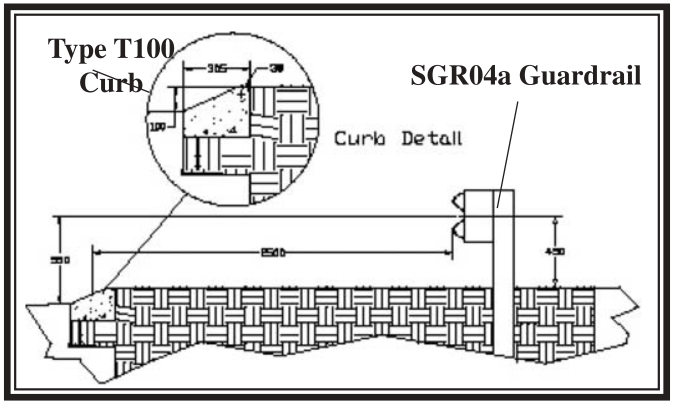
t = 0.192 sec

t = 0.288sec

t = 0.384 sec

t = final





General Information	
Test Agency	E-TECH Testing Services, Inc.
Test Designation	NCHRP 350 Test 3-11 (modified)
Test No.	52-2556-003
Date	7/21/2003
Test Article	
Curb Type	New York T100
Barrier Length	53.34 m (overall)
Height (mm - relative to approach)	550
Setback (m - relative to curb)	2.5
Material and key elements	AASHTO SGR04a Guardrail with SEW02a End Terminal equipped Re-Block recycled plastic blockouts of 50% HDPE / 50% PP
Foundation Type and Condition	NCHRP 350 Strong Soil, dry
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1994 GMC 3/4 Ton Pickup
Mass (kg)	
Curb	1940
Test inertial	1994
Impact Conditions	
Speed (km/h)	80.0
Angle (deg)	25
Impact Severity (kJ)	87.8

Exit conditions	
Speed (km/h)	N/A
Angle (deg - veh. c.g.)	N/A
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	5.6
y-direction	-3.0
Ridedown Acceleration (g's)	
x-direction	-6.1
y-direction	-4.3
European Committee for Normalization (CEN) Values	
THIV (km/h)	22.0
PHD (g's)	6.6
ASI	0.6
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	-41.9
Maximum Pitch Angle	-32.5
Maximum Yaw Angle	95.5
Test Article Deflections (m)	
Dynamic	0.4
Permanent	0.3
Vehicle Damage (Primary Impact)	
Exterior	
VDS	RFQ-3
CDC	01RFWW1
Interior	
VCDI	AS0000000
Maximum Deformation (mm)	74

Figure 39. Summary of curb–guardrail crash test at 80 km/h 52-2556-003, NY curb offset 2.5 m from guardrail, guardrail height 550 mm.

and the vehicle engaged two W-beam rails. The vehicle subsequently damaged two downstream posts and one section of rail. The vehicle slid to a stop 24 m downstream of its position at impact, straddling the rail. The vehicle sustained minor dents in the bumper and right front fender, a major dent in the bed on the driver side, major damage to the front right wheel and suspension, and a bent frame. There was no windshield contact or damage, and a maximum 74-mm deformation of the vehicle interior at the toe pan area on the passenger side.

E-TECH Test 52-2556-004 is summarized in Figure 40. In this test, the vehicle contacted the curb and the suspension compressed at first and then extended during the traverse. The body of the vehicle was noticeably elevated, but the tires remained in contact with the ground. The vehicle bumper contacted the guardrail just upstream of the connection splice at Post 15. The right corner of the bottom surface of the bumper came into contact with the top edge of the W-beam guardrail. The blockouts supported the W-beam and began loading the posts laterally. The front overhang of the vehicle rose up over the guardrail and the guardrail came to bear against the right front wheel. All four wheels became airborne, and the vehicle pitched up and passed over the guardrail with relatively minor change in direction. The vehicle landed behind the guardrail and remained upright. The vehicle slid to a stop 36 m downstream and 3.8 m to the right of its position at impact. Maximum dynamic deformation of the guardrail was 0.4 m, and the permanent deformation was 0.3 m. The pickup sustained minor dents in the bumper and right front fender and major damage to the front right wheel and suspension, and the frame was bent. There was no windshield contact or damage, and negligible deformation of the vehicle interior.

E-TECH Test 52-2556-005 is summarized in Figure 41. In this test, the vehicle bumper contacted the guardrail 0.6 m upstream of the connection splice at Post 15. The right corner of the bumper came into contact with the W-beam guardrail. The blockouts supported the W-beam and began loading the posts laterally. The W-beam flattened out, forming a ribbon that engaged the vehicle. As the W-beam deflected laterally, it developed tension that forced the vehicle to yaw counterclockwise. Maximum dynamic deformation of the guardrail was 0.6 m and the permanent deformation was 0.5 m. Posts 15 through 17 were deformed. The vehicle traversed four W-beam rails before losing contact with the installation. The vehicle exit angle was 12 degrees relative to the installation centerline when it lost contact with the barrier. The exit velocity of the vehicle was 43.3 km/h. The emergency braking system was applied after loss of contact, and the vehicle skidded to a stop 27 m downstream and 2 m left of its position at impact. The pickup sustained minor dents in the bumper and right front fender and major damage to the front right wheel and suspension, and the frame was bent. There was no windshield contact or damage, and negligible deformation of the vehicle interior.

E-TECH Test 52-2556-006 is summarized in Figure 42. In this test, the vehicle bumper contacted the guardrail 1.9 m upstream of the connection splice at Post 15. The right corner of the bumper came into contact with the W-beam guardrail. The blockouts supported the W-beam and began loading the posts laterally. The W-beam flattened out, forming a ribbon that engaged the vehicle. As the W-beam deflected laterally it developed tension that forced the vehicle to yaw counterclockwise. Maximum dynamic deformation of the guardrail was 0.5 m, and the permanent deformation was 0.3 m. In the initial impact, the right front wheel forced posts 15 and 16 to deform and the vehicle engaged two W-beam rails. The vehicle slid to a stop 22 m downstream of its position at impact and came to rest against the downstream section of guardrail. The pickup sustained minor dents in the bumper and right front fender, a major dent in the bed on the driver's side, major damage to the front right wheel and suspension, and the frame was bent. There was no windshield contact or damage, and negligible deformation of the vehicle interior.

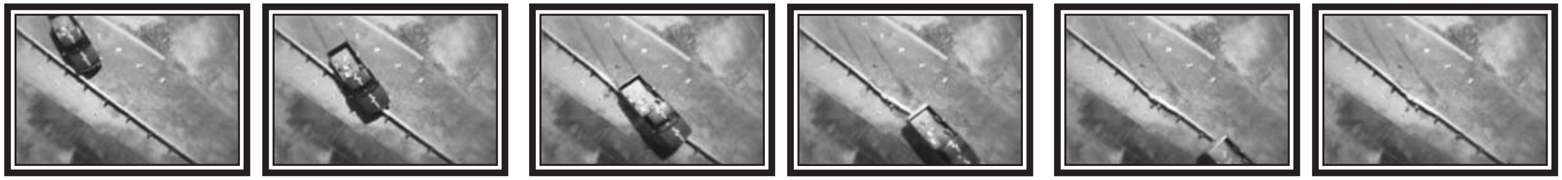
E-TECH Test 52-2556-007 is summarized in Figure 43. In this test, the vehicle bumper contacted the guardrail 2.5 m upstream of the connection splice at Post 15. The right corner of the bumper came into contact with the W-beam guardrail. The blockouts supported the W-beam and began loading the posts laterally. The W-beam flattened out, forming a ribbon that engaged the vehicle. As the W-beam deflected laterally it developed tension that forced the vehicle to yaw counterclockwise. Maximum dynamic deformation of the guardrail was 0.7 m, and the permanent deformation was 0.4 m. In the initial impact, the right front wheel forced posts 15 and 16 to deform and the vehicle engaged two W-beam rails. The vehicle slid to a stop 30 m downstream of its position at impact and came to rest against the downstream section of guardrail. The pickup sustained minor dents in the bumper and right front fender, a major dent in the bed on the driver's side, and major damage to the front right wheel and suspension; the frame was bent. There was no windshield contact or damage, and negligible deformation of the vehicle interior.

In all the tests, the damage to the guardrail was categorized as substantial since one or more replacement posts and W-beam sections would be needed for repair. Most other components of the installations were judged reusable.

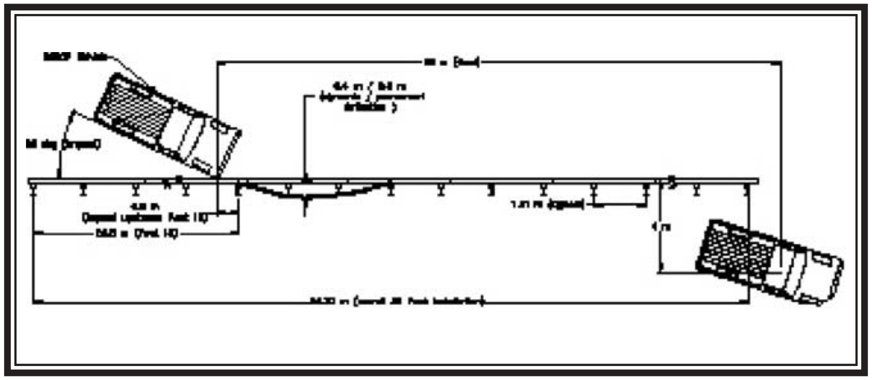
Summary of Crash Test Results

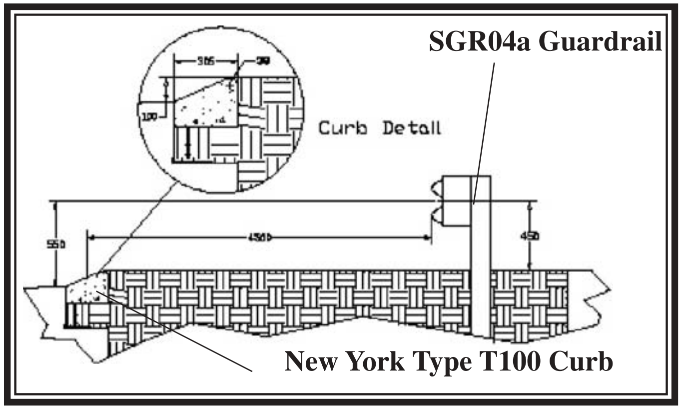
The results of the seven full-scale crash tests were evaluated using the structural adequacy, occupant risk, and vehicle trajectory evaluation criteria for longitudinal barrier Test 11 from *NCHRP Report 350*, as shown in Table 39. Note that the evaluations of the test results were based on the nominal impact speeds. The relevant evaluation criteria were as follows:

- Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the



t = 0.144 sec t = 0.288 sec t = 0.432 sec t = 0.576 sec t = final

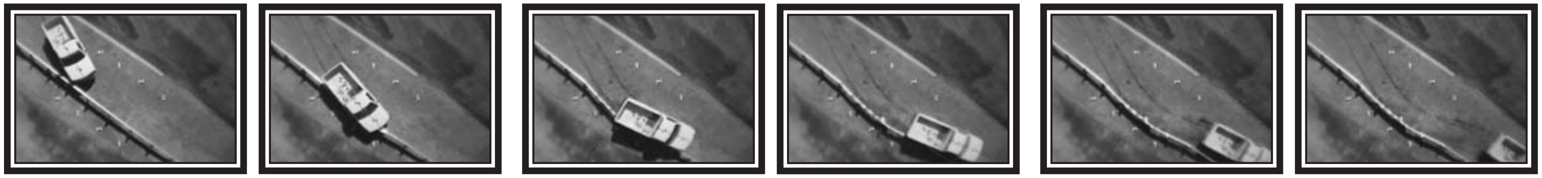




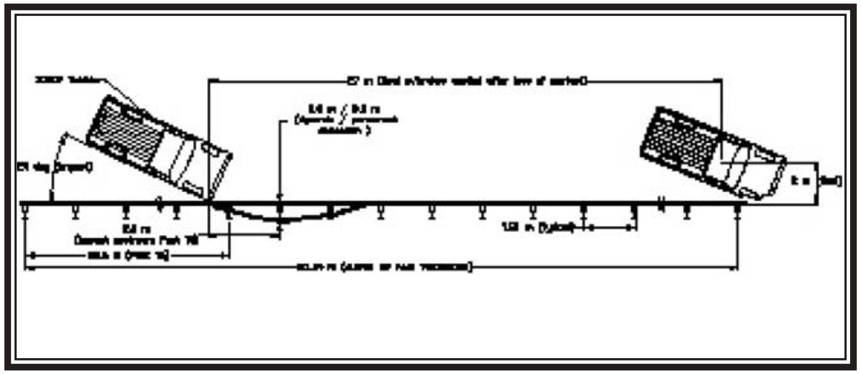
General Information	
Test Agency	E-TECH Testing Services, Inc.
Test Designation	NCHRP 350 Test 3-11 (modified)
Test No.	52-2556-004
Date	8/14/2003
Test Article	
Curb Type	New York T100
Barrier Length	53.34 m (overall)
Height (mm - relative to approach)	550
Setback (m - relative to curb)	4.5
Material and key elements	AASHTO SGR04a Guardrail with
	SEW02a End Terminal equipped
	Re-Block recycled plastic blockouts
	of 50% HDPE / 50% PP
Foundation Type and Condition	NCHRP 350 Strong Soil, dry
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1989 GMC
	3/4 Ton Pickup
Mass (kg)	
Curb	1947
Test inertial	2014
Impact Conditions	
Speed (km/h)	81.3
Angle (deg)	23
Impact Severity (kJ)	78.4

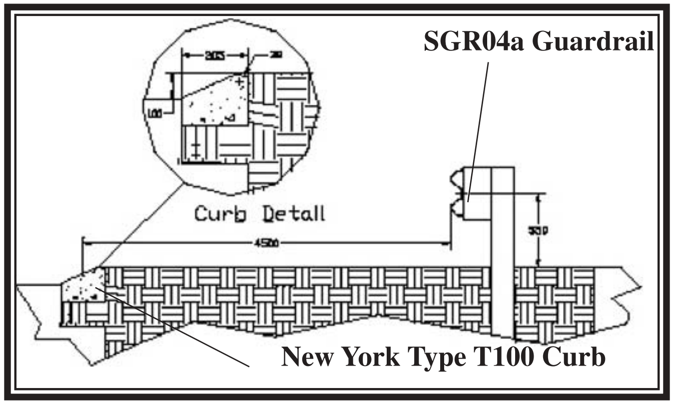
Exit conditions	
Speed (km/h)	N/A
Angle (deg - veh. c.g.)	N/A
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	4.7
y-direction	-3.6
Ridedown Acceleration (g's)	
x-direction	-4.1
y-direction	-4.9
European Committee for Normalization (CEN) Values	
THIV (km/h)	20.8
PHD (g's)	5.2
ASI	0.6
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	31.9
Maximum Pitch Angle	11.4
Maximum Yaw Angle	-12.9
Test Article Deflections (m)	
Dynamic	0.4
Permanent	0.3
Vehicle Damage (Primary Impact)	
Exterior	
VDS	RFQ-3
CDC	01RFEW3
Interior	
VCDI	AS0000000
Maximum Deformation (mm)	Negligible

Figure 40. Summary of curb–guardrail crash test 52-2556-004, NY curb offset 4.5 m from guardrail, guardrail height 550 mm.



t = 0.000 sec t = 0.192 sec t = 0.384 sec t = 0.576 sec t = 0.768 sec t = final

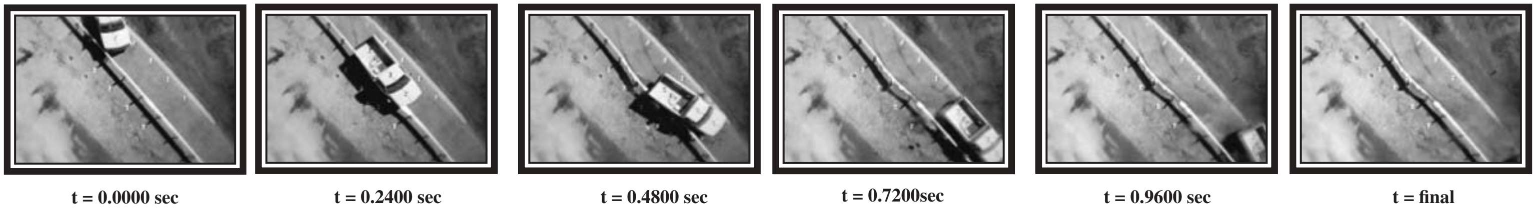


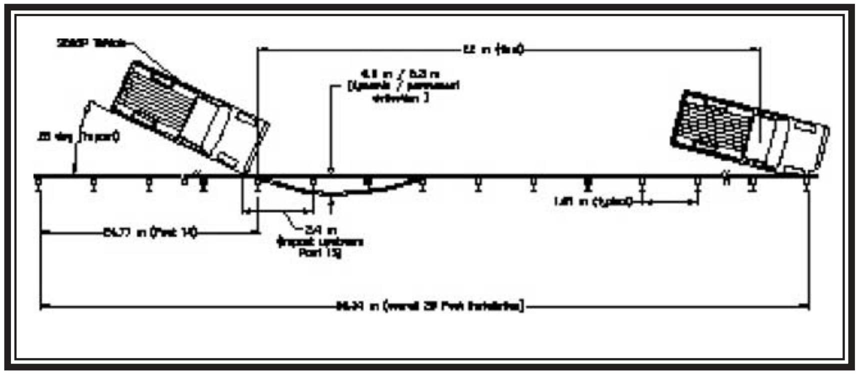


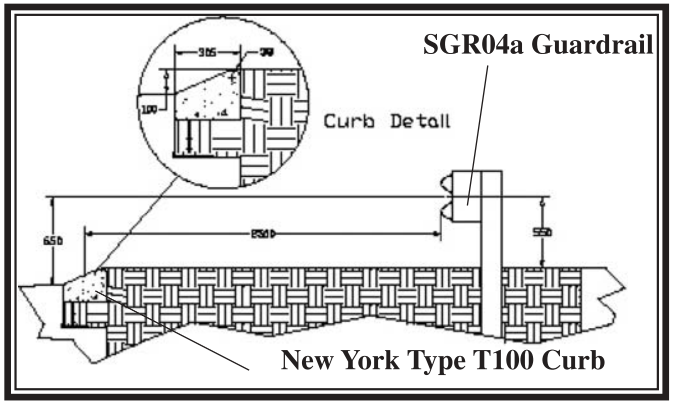
General Information	
Test Agency	**E-TECH Testing Services, Inc.**
Test Designation	**NCHRP 350 Test 3-11 (modified)**
Test No.	**52-2556-005**
Date	**9/5/2003**
Test Article	
Curb Type	**New York T100**
Barrier Length	**53.34 m (overall)**
Height (mm - relative to approach)	**550**
Setback (m - relative to curb)	**4.5**
Material and key elements	**AASHTO SGR04a Guardrail with** **SEW02a End Terminal equipped** **Re-Block recycled plastic blockouts** **of 50% HDPE / 50% PP**
Foundation Type and Condition	**NCHRP 350 Strong Soil, dry**
Test Vehicle	
Type	**Production Model**
Designation	**2000P**
Model	**1994 Chevrolet** **C2500 Pickup**
Mass (kg)	
Curb	**1904**
Test inertial	**1999**
Impact Conditions	
Speed (km/h)	**80.5**
Angle (deg)	**24**
Impact Severity (kJ)	**82.7**

Exit conditions	
Speed (km/h)	**43.3**
Angle (deg - veh. c.g.)	**12**
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	**4.2**
y-direction	**-3.8**
Ridedown Acceleration (g's)	
x-direction	**-7.6**
y-direction	**-5.8**
European Committee for Normalization (CEN) Values	
THIV (km/h)	**19.4**
PHD (g's)	**9.1**
ASI	**0.5**
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	**-8.9**
Maximum Pitch Angle	**-4.9**
Maximum Yaw Angle	**-37.2**
Test Article Deflections (m)	
Dynamic	**0.6**
Permanent	**0.5**
Vehicle Damage (Primary Impact)	
Exterior	
VDS	**RFQ-3**
CDC	**01RFEW3**
Interior	
VCDI	**AS0000000**
Maximum Deformation (mm)	**Negligible**

Figure 41. Summary of curb–guardrail crash test 52-2556-005, NY curb offset 4.5 m from guardrail, guardrail height 650 mm.


t = 0.0000 sec   t = 0.2400 sec   t = 0.4800 sec   t = 0.7200sec   t = 0.9600 sec   t = final



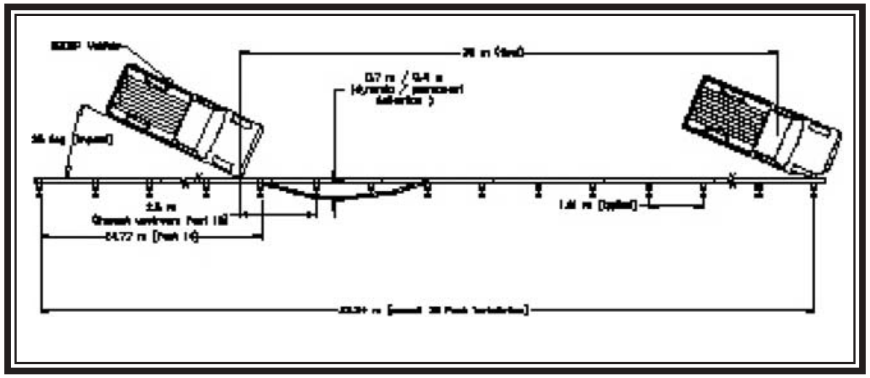


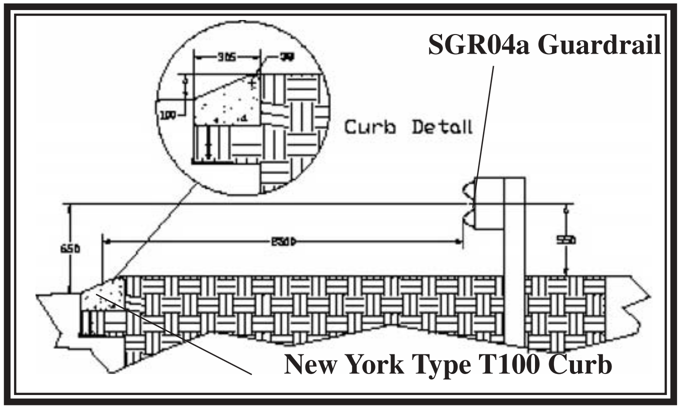
General Information	
Test Agency	**E-TECH Testing Services, Inc.**
Test Designation	**NCHRP 350 Test 2-11**
Test No.	**52-2556-006**
Date	**10/7/2003**
Test Article	
Curb Type	**New York T100**
Barrier Length	**53.34 m (overall)**
Height (mm - relative to approach)	**650**
Setback (m - relative to curb)	**2.5**
Material and key elements	**AASHTO SGR04a Guardrail with**
	SEW02a End Terminal equipped
	Re-Block recycled plastic blockouts
	of 50% HDPE / 50% PP
Foundation Type and Condition	**NCHRP 350 Strong Soil, dry**
Test Vehicle	
Type	**Production Model**
Designation	**2000P**
Model	**1990 Chevrolet**
	C2500 Pickup
Mass (kg)	
Curb	**1862**
Test inertial	**2007**
Impact Conditions	
Speed (km/h)	**69.6**
Angle (deg)	**25**
Impact Severity (kJ)	**67.0**

Exit conditions	
Speed (km/h)	**36.5**
Angle (deg - veh. c.g.)	**12**
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	**4.2**
y-direction	**-4.2**
Ridedown Acceleration (g's)	
x-direction	**-5.3**
y-direction	**-5.0**
European Committee for Normalization (CEN) Values	
THIV (km/h)	**19.6**
PHD (g's)	**7.3**
ASI	**0.5**
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	**6.9**
Maximum Pitch Angle	**-7.2**
Maximum Yaw Angle	**-39.2**
Test Article Deflections (m)	
Dynamic	**0.5**
Permanent	**0.3**
Vehicle Damage (Primary Impact)	
Exterior	
VDS	**RFQ-3**
CDC	**01RFEW3**
Interior	
VCDI	**AS0000000**
Maximum Deformation (mm)	**Negligible**

Figure 42. Summary of curb–guardrail crash test 52-2556-006, nominal speed 70 km/h, NY curb offset 2.5 m from guardrail.


t = 0.0000 sec t = 0.144 sec t = 0.288sec t = 0.432sec t = 0.576 sec t = final





General Information	
Test Agency	E-TECH Testing Services, Inc.
Test Designation	NCHRP 350 Test 3-11 (modified)
Test No.	52-2556-007
Date	12/4/03
Test Article	
Curb Type	New York T100
Barrier Length	53.34 m (overall)
Height (mm - relative to approach)	650
Setback (m - relative to curb)	2.5
Material and key elements	AASHTO SGR04a Guardrail with
	SEW02a End Terminal equipped
	Re-Block recycled plastic blockouts
	of 50% HDPE / 50% PP
Foundation Type and Condition	NCHRP 350 Strong Soil, drained
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1994 GMC
	C2500 Pickup
Mass (kg)	
Curb	1870
Test inertial	2001
Impact Conditions	
Speed (km/h)	85.6
Angle (deg)	25
Impact Severity (kJ)	101.0

Exit conditions	
Speed (km/h)	41.8
Angle (deg - veh. c.g.)	15
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	5.0
y-direction	-4.3
Ridedown Acceleration (g's)	
x-direction	-10.0
y-direction	-17.8
European Committee for Normalization (CEN) Values	
THIV (km/h)	20.7
PHD (g's)	17.8
ASI	0.8
Post-Impact Vehicular Behavior (deg - rate gyro)	
Maximum Roll Angle	17.0
Maximum Pitch Angle	-17.3
Maximum Yaw Angle	-40.2
Test Article Deflections (m)	
Dynamic	0.7
Permanent	0.4
Vehicle Damage (Primary Impact)	
Exterior	
VDS	RFQ-3
CDC	01RFEW3
Interior	
VCDI	AS0000000
Maximum Deformation (mm)	Negligible

Figure 43. Summary of curb–guardrail crash test 52-2556-007, nominal speed 85 km/h, NY curb offset 2.5 m from guardrail.

installation although controlled lateral deflection of the test article is acceptable.
- Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.
- The vehicle should remain upright during and after collision, although moderate rolling, pitching, and yawing are acceptable.
- After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.
- The OIV in the longitudinal direction should not exceed 12 m/s and the ORAs in the longitudinal direction should not exceed 20 Gs.
- The exit angle from the test article preferably should be less than 60% of the test impact angle, measured at time of vehicle loss of contact with test device.

In the tests shown in Table 39 that passed the *NCHRP Report 350* criteria, the vehicles were contained and redirected. The vehicles in the failed tests either completely or nearly completely vaulted the installation. In the successful tests, the vehicle's post-collision trajectory was acceptable and the recommended maximum longitudinal OIV and maximum ridedown acceleration were not exceeded. The vehicle trajectory in the failed tests was completely or very nearly completely behind the guardrail, which is unacceptable. In Test 52-2556-003, which is noted as "marginal pass," the vehicle came to rest on the rail with the cab on the backside of the rail.

In none of the tests was there any debris larger than a 6.4-kg plastic blockout to present a potential hazard to other traffic, pedestrians, or personnel in a work zone. The vehicle occupant compartment deformation evident after each passing test was also negligible. There was no windshield contact and no intrusion into the occupant compartment for the passing tests, and the test vehicles remained upright during and after the collision with moderate rolling, pitching, and yawing. In tests 52-2556-003 and 004, the occupant risk criteria were satisfied in a similar fashion. In failed test 52-2556-002, however, the vehicle rolled over and a downstream post likely penetrated the windshield; the maximum cab deformation was 330 mm.

SUMMARY

Several types of analyses were used in developing the guidelines discussed in Chapter 6: review of prior studies, analyses of actual crash and geometric data, FEA simulations, and full-scale curb traversal and crash tests. The results of these analyses provided insights into the nature and severity of crashes with curbs and curb–guardrail combinations, the behavior of pickup trucks in such crashes, and the effects of various curb and impact conditions.

TABLE 39 Summary of full-scale crash test results

E-TECH test no.	Nominal speed (km/h)	Curb type	Curb offset (m)	Guardrail height (mm) relative to approach	NCHRP 350 Test 11 evaluation
52-2556-001	85	B	0.0	550	Pass
52-2556-002	85	B	2.5	550	Fail
52-2556-003	80	NY	2.5	550	Marginal Pass
52-2556-004	80	NY	4.5	550	Fail
52-2556-005	80	NY	4.5	650	Pass
52-2556-006	70	NY	2.5	650	Pass
52-2556-007	85	NY	2.5	650	Pass

CHAPTER **6**

DESIGN GUIDELINES FOR THE USE OF CURBS WITH GUARDRAILS

DEVELOPMENT AND VALIDATION OF DESIGN GUIDELINES

Guidelines for the use of curbs and guardrails were developed by reviewing the results of crash tests in the open roadside safety literature, curb–guardrail FEAs, bumper position time-histories in curb-traversal FEAs and live-driver curb-traversal tests, and full-scale crash tests of selected curb–guardrail combinations. These analyses are discussed in Chapter 5.

Six types of curbs were considered in the analyses: AASHTO Types A, B, C, D, and G, and New York's T100 curb, referred to as NY in the figures. These curbs are shown in Figure 29. The barrier system considered in these analyses was the G4(1S), a strong-post W-beam guardrail with steel posts.

Figure 44 summarizes the results of the analyses of curb–guardrail combinations. Solid-filled shapes in the figure indicate failed tests or simulations and open shapes indicate successful tests or simulations; the shading in the figure marks the different types of curbs used. Tests or simulations were considered successful if they passed the criteria established in *NCHRP Report 350* (i.e., the occupant risk criteria were satisfied and no rollover, vaulting, or underride was observed). Circles indicate tests described in the literature, squares represent full-scale crash tests performed as a part of this project, and triangles represent simulations performed in this project. The points are located near but not necessarily at the nominal test condition. For example, there are five points near the 100 km/h 0-m offset point; all five tests were performed at these nominal conditions and are shown in a grouping simply because there are too many points to locate at the exact positions. The letters next to the shapes (e.g., C and NY) refer to the curb type.

The offset distance in Figure 44 refers to the distance between the face of the curb and the face of the guardrail, illustrated in Figure 45. As shown in Figure 44, a successful crash test is likely when the curb is positioned under the face of the guardrail for all speeds up to an operating speed of 100 km/h. The majority of full-scale crash tests in the literature were performed with these impact conditions. Two of the four tests found in the literature that were performed at 100 km/h resulted in failures, but these failures are believed to be the result of problems with the guardrails in those particular tests rather than a problem with the interaction between the curb and guardrail. Further information on these failed tests can be found in the literature review (Chapter 2). FEA simulations, indicated with a triangle in Figure 44, indicated that guardrail performance was not generally degraded by the presence of a curb under the face of the guardrail (i.e., at 0-m offset) for all operating speeds of 100 km/h or less.

There were no full-scale tests found in the literature for offsets greater than zero, so the design chart was developed primarily using information from FEA simulations of curb–guardrail impacts. In addition, simulations and live-driver tests of curb traversals (i.e., with no guardrail behind the curb) were used to assess the bumper height time history in order to determine when the bumper would be positioned correctly with respect to a guardrail. As shown in Figure 44, there is a region between 0 and 2.5 m in front of the guardrail where the FEA results were unacceptable. The single exception to this was the G curb at 2.5 m in front of the guardrail at 70 km/h. For the general case of vehicles leaving the roadway with a broad range of speeds and angles, the bumper is likely to be too high for acceptable guardrail performance in the region up to a lateral distance of 2.5 m for typical 685-mm tall guardrail systems. Guardrails should not be located any closer than 2.5 m from the curb line to minimize the chance of a vehicle vaulting over the barrier due to the bumper and suspension system being too high.

FEA simulations did indicate, however, that once the suspension and bumper had time to recover from the effects of the curb traversal, placing a guardrail may be acceptable. The necessary offset depends on the operating speed. For example, guardrails can be placed at a lateral offset of 2.5 m or greater from 150-mm tall sloping curbs as long as the operating speed is 70 km/h or less. The reason for the restriction on the operating speed is that higher speeds create more suspension system disturbance and therefore require more time and distance for the bumper to return to the correct position. Guardrails can be placed at offsets of 4.0 m or greater from curbs that are not more than 100-mm tall as long as the operating speed is less than 85 km/h. Smaller curb heights cause less suspension system disturbances so these smaller curbs can be used at higher speeds.

DESIGN GUIDELINES

The recommendations that were developed can be summarized as follows.

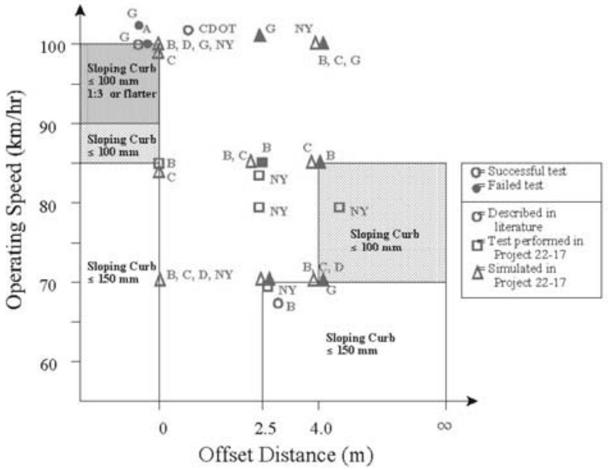


Figure 44. Summary of crash tests for curb–guardrail combinations.

Roads with Operating Speeds of 60 to 70 km/h

Any combination of a sloping-faced curb that is 150 mm or shorter and a strong-post guardrail can be used at a lateral offset of 0 m (i.e., the curb is flush with the face of the guardrail) on roads with operating speeds of 85 km/h.

Guardrails installed behind curbs should not be located closer than 2.5 m for any operating speed in excess of 60 km/h. The vehicle bumper may rise above the critical height of the guardrail for many road departure angles and speeds in this region, making vaulting the barrier likely. A lateral distance of at least 2.5 m is needed to allow the vehicle suspension to return to its predeparture state. Once the suspension and bumper have returned to their normal position, impacts with the barrier should proceed successfully. For roadways with operating speeds of 70 km/h or less, guardrails may be used with 150-mm high or shorter sloping-face curbs as long as the face of the guardrail is located at least 2.5 m behind the curb. Vehicles traveling at speeds greater than 70 km/h may vault over the guardrail for some departure angles.

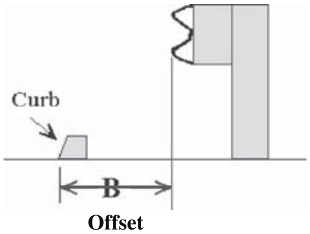


Figure 45. Curb and barrier placement along roadways.

Roads with Operating Speeds of 71 to 85 km/h

Any combination of a sloping-face curb that is 150 mm or shorter and a strong-post guardrail can be used at a lateral offset of 0 m (i.e., the curb is flush with the face of the guardrail) up to an operating speed of 85 km/h.

In cases where guardrails are installed behind curbs, a lateral distance of at least 4 m is needed to allow the vehicle suspension to return to its predeparture state at these operating speeds. Once the suspension and bumper have returned to their normal position, impacts with the barrier should proceed successfully. Guardrails may be used with 100-mm high or shorter sloping-face curbs as long as the face of the guardrail is located at least 4 m behind the curb. Vehicles traveling at speeds greater than 85 km/h may vault over the guardrail for some departure angles.

Roads with Operating Speeds Greater than 85 km/h

Above operating speeds of 85 km/h, guardrails should only be used with 100-mm high or shorter sloping-faced curbs, and the curbs should be placed at 0 m offset (i.e., the curb is flush with the face of the guardrail). Above operating speeds of 90 km/h, the sloping face of the curb must be no more than 1:3 and must be no more than 100 mm high.

Guardrails should not be located behind a curb on roads with operating speeds greater than 85 km/h.

Design Chart

The recommended guidelines for the use of curb–guardrail combinations are shown in Figure 46. The chart shows regions

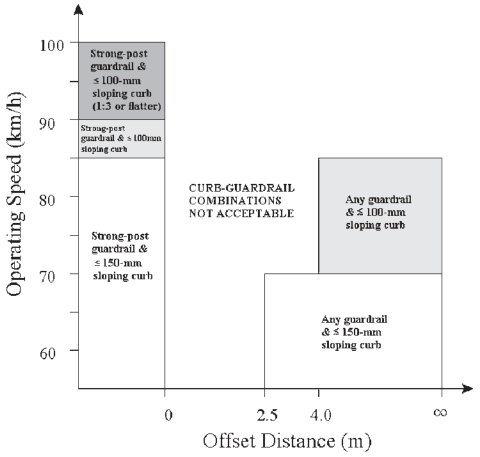


Figure 46. Design chart for curb–guardrail combinations by operating speed and offset distance.

where it is acceptable to use a curb–guardrail combination as a function of the lateral offset from the guardrail and the operating speed of the roadway; the shading in the figure marks the different types of curbs.

VALIDATION OF DESIGN GUIDELINES

The foregoing design guidelines and chart were developed almost entirely with FEAs so it was necessary to validate the results with some full-scale crash tests. A series of full-scale crash tests were performed in this project to validate the design chart, as discussed in Chapter 5. The tests are indicated on Figure 44 with square shapes. The purpose of these tests was to validate the design chart by confirming that test failures and successes were observed in appropriate regions of the chart.

E-TECH Test 52-2556-001 was an 85 km/h, 25-degree impact of the guardrail with a 150-mm high B curb located under the face of the rail. The test was a success and is plotted in the acceptable region of the design chart. Test 52-2556-002 was an 85 km/h, 25-degree impact of the guardrail located 2.5 m behind a 150-mm high B curb. Unfortunately, there was an installation error: the guardrail was 100 mm too short. The vehicle vaulted over the guardrail, so the test failed. The test conditions are plotted in the unacceptable section of the chart, although the incorrect rail height casts some uncertainty on this result. Test 52-2556-005 was a success, using a NY curb 4.5 m in front of the guardrail and impact conditions of 80 km/h and 25 degrees. This test is plotted in the acceptable region of the chart since the NY curb is a 100-mm high curb.

The objective of Test 52-2556-006 was to validate the corner of the 2.5-m offset, 150-mm high curb block. The guardrail was placed 2.5 m behind a 100-mm high NY curb, and the test was run at 70 km/h and 25 degrees. The test was a success and the impact conditions plotted in the acceptable region of the design chart, validating that portion of the chart. The last test, 52-2556-007, involved the same installation (i.e., a 100-mm high NY curb 2.5 m in front of the guardrail), but at a higher speed of 85 km/h. The FEAs and the design chart suggested that this test should be a failure, since it plots in the failing portion of the design chart. The crash test results, however, indicated it was a success. As mentioned earlier, the NY curb is characterized by a very low tripping risk index, so it seems likely that some very flat-faced, low-height curbs can be used 2.5 m in front of a guardrail even on some higher speed roadways. In general, however, guardrails should be placed at least 4 m behind the curb on roads with operating speeds between 71 and 85 km/h unless testing or analysis of a specific curb indicates that it will perform satisfactorily.

Except when the guardrail was installed with the incorrect height, the design chart correctly predicts the results of all the full-scale tests. This indicates that the design guidelines and chart are valid based on a comparison of five full-scale crash tests performed at a variety of locations on the design chart.

TRIPPING RISK INDEX

Development of the Tripping Risk Index

The information obtained from the full-scale testing and the finite-element parametric analysis performed in this project was also used to develop a tripping risk index (TRI) for mountable curbs. This index indicates the probability of a rollover based on events observed during the impact. The complexity of the problem under analysis makes the identification of the causes and effects difficult and probably impractical. It is possible that two full-scale tests under the same nominal impact conditions could lead to dramatically different results (i.e., the vehicle may or may not overturn).

Several events were identified that can be correlated to vehicle rollover during a curb impact: failure of one or two tires, rim-curb snagging, and rollover or outrigger engagement. A TRI value for each test or simulation was generated by assigning risk points to each adverse event recorded during the curb traversal. Points were also added based on the stability ranking, a subjective value recorded by the driver that indicated the stability of the vehicle during the impact. Table 40 shows the points assigned to each event and parameter.

The TRI for each test or simulation was then calculated as

$$TRI = \left(\frac{\sum RiskPts}{33} \times 100 \right) \times \frac{3600}{V^2}, \tag{1}$$

where

33 is the maximum number of risk points possible,
3600 is a normalization factor in kilometers per hour squared, and
V is the impact velocity in km/h.

Note that the TRI can never be equal to zero since there is always the possibility that a curb may act as a tripping mechanism due to some parameters or event not explicitly included in the TRI definition. The TRI is weighted by the inverse of the squared impact velocity (proportional to initial kinetic energy) to allow comparison of heterogeneous tests conducted at different speeds.

TABLE 40 Risk points for definition of the TRI

Event/parameter	Risk pts
Single tire failure	3
Double tire failure	5
Rim-curb snag	6
Rollover	10
Stability Ranking:	
Excellent	3
Good	6
Fair	9
Poor	12

Table 41 shows the TRI values for the studied impact scenarios. The TRI for each curb type is the arithmetic average of the TRI values for all the tests and simulations conducted on that particular curb type.

Relationship of TRI to Design Variables

The data in Table 41 suggest a correlation between the TRI and two geometric curb design variables: curb height and curb slope. To find an analytical approximate relation between the TRI and these two geometric variables, the method of least squares was used.

A linear relation was first assumed of the form

$$TRI = a_1 \cdot H + a_2 \cdot S, \tag{2}$$

where a_1 and a_2 are regression coefficients, H is the curb height, and S the gross curb slope, computed as the curb height divided by slope base. For each tested curb type,

$$TRI_i = [H_i \quad S_i] \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \qquad [TRI_{nx1}] = [A_{nx2}] \cdot [a_{2x1}] \tag{3}$$

The problem is overdetermined, but it was solved using the least squares method:

$$[a] = \left([A]^T \cdot [A]\right)^{-1} \cdot [A]^T \cdot [TRI] \qquad \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 0.0432 \\ 50.793 \end{bmatrix} \tag{4}$$

This linear model has a coefficient of determination, R^2, of 0.793.

Figure 47 shows the TRI plane as a function of curb height and slope; it was plotted by substituting the correlation coefficients of Equation 4 into Equation 2. Curbs that are in the lower one-third of the chart are considered the safest. The tripping risk increases as the curb slope and height increase. The black stars represent the curbs studied in this research.

The linear model was not able to correctly compute the TRI under all circumstances. For a very low curb with a nearly vertical face, the computed TRI indicated an unrealistic possibility that the curb might trip the vehicle. This is contrary to intuition; if the height of the curb approaches zero, there is no curb to trip the vehicle. Since the linear model was not always appropriate, a nonlinear model was sought to better describe the TRI as a function of the two geometric parameters.

A relation of the form $TRI = H^{a_1} \cdot S^{a_2}$, (5)

was assumed and linearized by taking the natural logarithms of both sides. With a simple transformation of the variables,

$$TRI' = \ln(TRI), \quad H' = \ln(H), \quad S' = \ln(S) \tag{6}$$

a linear expression was obtained:

$$TRI' = H' \cdot a_1 + S' \cdot a_2 \tag{7}$$

The problem was then solved in transformed space following the procedure presented for the linear model. Solving Equation 5 after the applicable substitution yields

$$\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 0.8333 \\ 0.7976 \end{bmatrix}, \rightarrow TRI = H^{0.8333} \cdot S^{0.7976} \tag{8}$$

The coefficient of determination for this nonlinear model, computed in the transformed space, is 0.9912. Figure 48 is a perspective view of the surface described by Equation 8.

Equation 8 was also used to develop the design diagram shown in Figure 49, identifying three areas of tripping risk. These areas were determined by tracing the isolevel lines of Equation 8, using a TRI of 20 for the first boundary and TRI of 45 for the second boundary. The diagram shows three rollover tripping risk regions: low risk, moderate risk, and high risk. The boundaries of the three regions are not defined uniquely since there is a certain degree of arbitrariness in TRI threshold values. The threshold values of 20 and 45 were selected after analysis of the data available.

Figure 49 can be used as a design tool. For example, if a certain road needs a curb height of 120 mm for hydrological reasons and the curb must be placed within the clear zone for the roadway, the diagram suggests that the curb slope be less than 0.3 for a low risk of tripping errant vehicles.

Conclusions

This section has presented an approximate method to numerically evaluate the tripping risk offered by different types of curbs. The method was used to rank the different curbs studied in this research as shown in Table 42.

Correlation between the TRI and two geometric curb design variables allowed the development of an approximate analytical relationship of the TRI as a function of the curb height and curb slope, defined in Equation 8. This relationship fits the data both visually and statistically with a coefficient of determination of 0.99, which is exceptionally good for experimental data.

Equation 8 was then used to develop the design diagram shown in Figure 49, which identifies three regions of low, moderate, and high risk of vehicle tripping offered by a curb characterized by its height and front face slope. Based on the tripping risk areas identified in Figure 49, the following can be concluded:

- Curbs with an experimental or estimated (i.e., by Equation 8) TRI above 45 should not be used on higher-speed roadways.

TABLE 41 TRI values by curb type

Test name	Impact speed	Tire damage no. failed	Rim-curb snag	Rollover	Stability rating	Risk points	Percentile risk points	Tripping risk index
Curb Type B								
V1-01_B	60.0	0	1	1		16	76.19	76.19
V1-02_B	60.0	1	1	0		9	42.86	42.86
V1-03_B	60.0	2	0	1	4	27	81.82	81.82
V2-01_B	80.0	0	1	1	4	28	84.85	47.73
V2-02_B	80.0	1	1	1	4	31	93.94	52.84
V2-03_B	80.0	2	0	1	4	27	81.82	46.02
603XB0135A	56.3	0	1	1	4	28	84.85	96.30
603XB0135B	56.3	1	1	0	3	18	54.55	61.91
603XB0235A	56.3	0	0	0	3	9	27.27	30.95
603XB0235B	56.3	0	0	0	3	9	27.27	30.95
Tripping Risk Index for the Curb Type (Average of the tripping risk of each test):								**56.76**
Curb Type C								
V1-01_C	60.0	0	0	1	4	22	66.67	66.67
V1-02_C	60.0	1	0	1	4	25	75.76	75.76
V1-03_C	60.0	0	0	1	4	22	66.67	66.67
V2-01_C	80.0	1	0	1	4	25	75.76	42.61
V2-02_C	80.0	1	0	0	2	9	27.27	15.34
V2-03_C	80.0	2	0	1	4	27	81.82	46.02
530XC0135A	56.3	0	0	1	4	22	66.67	75.66
530XC0135B	56.3	0	0	0	3	9	27.27	30.95
530XC0235A	56.3	0	0	0	2	6	18.18	20.64
530XC0235B	56.3	0	0	0	2	6	18.18	20.64
Tripping Risk Index for the Curb Type (Average of the tripping risk of each test):								**46.10**
Curb Type D								
602XD0125A	40.2	0	0	0	1	3	9.09	20.22
602XD0130A	48.3	0	1	0	4	18	54.55	84.26
602XD0130B	48.3	0	1	0	4	18	54.55	84.26
603XD0135A	56.3	1	1	0	3	18	54.55	61.91
603XD0135B	56.3	0	1	0	4	18	54.55	61.91
603XD0135C	56.3	2	1	1	4	33	100.00	113.50
603XD0235A	56.3	0	0	0	2	6	18.18	20.64
603XD0235B	56.3	0	0	0	2	6	18.18	20.64
Tripping Risk Index for the Curb Type (Average of the tripping risk of each test):								**58.41**
Curb Type G								
V1-01_G	60.0	2	0	1	4	27	81.82	81.82
V1-02_G	60.0	1	0	0	2	9	27.27	27.27
V1-03_G	60.0	0	0	0	3	9	27.27	27.27
V2-01_G	80.0	1	0	1	4	25	75.76	42.61
V2-02_G	80.0	2	0	0	2	11	33.33	18.75
V2-03_G	80.0	1	0	1	4	25	75.76	42.61
Tripping Risk Index for the Curb Type (Average of the tripping risk of each test):								**40.06**
Curb Type NY								
V1-01_NY	60.0	0	0	0	1	3	9.09	9.09
V1-02_NY	60.0	0	0	0	1	3	9.09	9.09
V1-03_NY	60.0	0	0	0	1	3	9.09	9.09
V2-01_NY	80.0	0	0	0	1	3	9.09	5.11
V2-02_NY	80.0	0	0	0	1	3	9.09	5.11
V2-03_NY	80.0	0	0	0	2	6	18.18	10.23
527XN0120A	32.2	0	0	0	1	3	9.09	31.60
529XN0135A	56.3	0	0	0	2	6	18.18	20.64
530XN0135B	56.3	0	0	0	2	6	18.18	20.64
530XN0235A	56.3	0	0	0	1	3	9.09	10.32
530XN0235B	56.3	0	0	0	1	3	9.09	10.32
Tripping Risk Index for the Curb Type (Average of the tripping risk of each test):								**12.84**

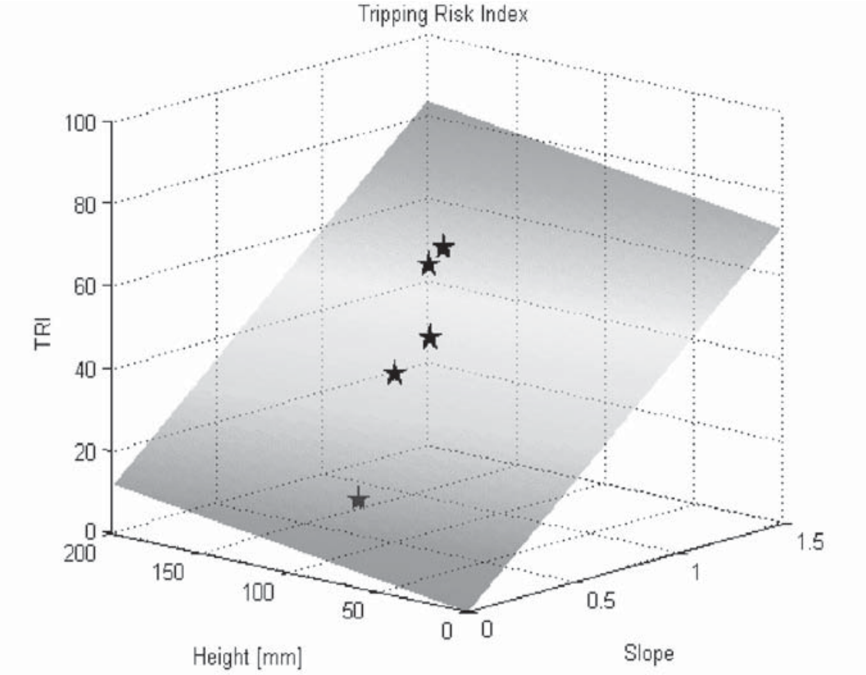


Figure 47. TRI as a linear function of curb height and slope.

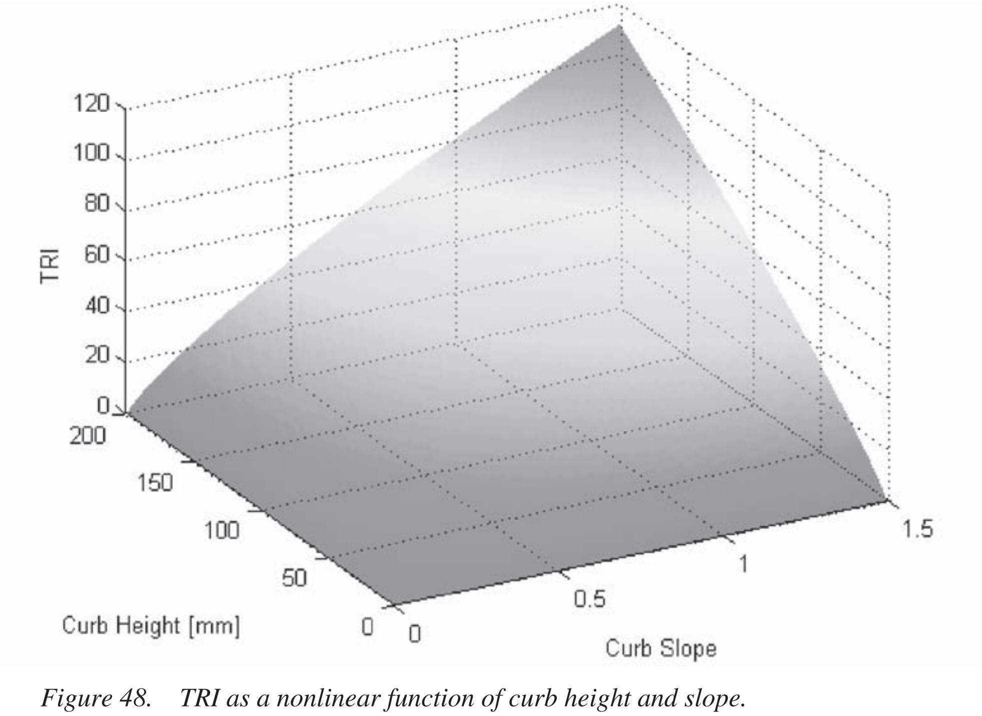


Figure 48. TRI as a nonlinear function of curb height and slope.

- Curbs that are located in the moderate risk area of the diagram should be avoided on higher-speed roadways. Their use may be acceptable where nontracking impacts are not probable (e.g., tangent section, warm climate, wide shoulder, or fenced roads) and on roads with 85th percentile speeds below 110 km/h.
- The use of low-tripping-risk curbs is recommended for roads with 85th percentile speeds above 110 km/h, where winter weather conditions (e.g., icing, snow, or mist) are expected and on poorly paved or drained roads. Low-tripping-risk curbs should always be used at access ramps and curves.

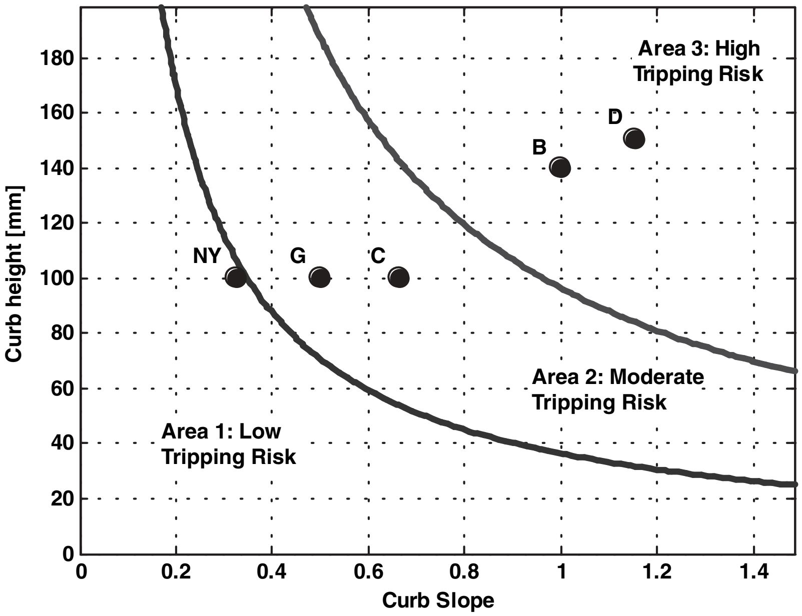


Figure 49. Curb geometric design diagram with respect to the tripping risk in nontracking impacts.

TABLE 42 Curb safety in nontracking impact scenarios

Safety rank	Curb type	TRI
1	NYDOT NY	12.48
2	AASHTO G	40.06
3	AASHTO C	46.10
4	AASHTO B	56.76
5	AASHTO D	58.41

CHAPTER 7

SUMMARY AND CONCLUSIONS

INTRODUCTION

The results of the studies identified in the literature and the parametric analyses conducted in this research were synthesized in order to develop a general set of guidelines for the design and installation of curbs and curb–barrier systems along roadways with operating speeds greater than 60 km/h. The guidelines are based on the results of both computer simulation and full-scale crash tests. The study involved the analysis of vehicles traversing several commonly used curb types under a variety of impact conditions, as well as the analysis of vehicle impact into various curb–guardrail combinations. The research presented herein identified common types of curbs that could be used safely and effectively on high-speed roadways and also identified the proper combination and placement of curbs and barriers that would allow the traffic barriers to be effective, i.e., safely contain and redirect an impacting vehicle.

SUMMARY OF PREVIOUS RESEARCH STUDIES

An in-depth review of published literature was conducted to identify information pertinent to the design, safety, and function of curbs and curb–barrier combinations. The studies found in the literature used a variety of vehicle types including small cars, large cars, and pickup trucks. It was found that both the large and small cars crossing curbs less than 150 mm high in a tracking manner are not likely to cause the driver to lose control of the vehicle or cause the vehicle to become unstable unless a secondary impact occurs. The dynamic response of a pickup truck crossing over curbs, however, had not been evaluated in previous studies with either full-scale tests or computer simulation and was thus unknown.

Although errant vehicles leave the roadway in a variety of orientations, it is assumed that the majority of these vehicles encroach onto the roadside in a semicontrolled tracking manner. In such cases, the left or right front bumper would be the first point of contact with a roadside object in an impact event. The position of the bumper upon impact has, therefore, been a primary concern involving impacts with longitudinal traffic barriers, where it has been assumed that the position of the bumper during impact is a reasonable indicator of vehicle vaulting, or underriding the barrier.

The result of much of this early testing and analysis was a general agreement that curbs in front of the guardrail could cause vaulting. If curbs were required for drainage purposes, the only alternative was to place the curb behind the face of the barrier. This arrangement shields the curb from the impact while allowing the curb to channel runoff. The idea was to locate the curb such that minimal interaction between the vehicle and curb occurred. This worked well with lighter vehicles such as the 820-kg small car, but did not prevent vehicle-curb interaction for the larger cars that have a mass of over 2,000 kg unless the guardrail was retrofitted in some manner to strengthen it and minimize guardrail deflection.

To circumvent the problem, one option that was considered was to use a low-profile curb underneath the guardrail to minimize the effects that the curb would have on vehicle trajectory if the wheels of the vehicle managed to make contact with the curb during impact. Tests were conducted by various organizations in which a low-profile curb was placed behind the face of the guardrail. This design proved successful in tests with the larger cars while tests involving pickup trucks resulted in success in some cases and failure in others. In cases where the test was a failure, it was not clear whether the failure was induced by vehicle-curb interaction or simply caused by inadequate barrier performance. It was apparent, however, that curb–barrier systems pose a much greater hazard to pickup trucks in high-speed impacts than they do to cars and also that much more information regarding pickup impact into curb–barrier systems was needed.

SUMMARY OF CURRENT RESEARCH

FEA was used in this research to conduct a parametric investigation involving a 2000-kg pickup truck impacting various curbs and curb–barrier combinations to determine which types of curbs are safe to use on higher-speed roadways and proper placement of a barrier with respect to curbing such that the barrier remains effective in safely containing and redirecting the impacting vehicle. The curb types used in the study included the 150-mm AASHTO Types A, B, and D; the 100-mm AASHTO Types C and G; and the 100-mm New York curb. The roadside safety barrier used in the study was the modified G4(1S) guardrail with wood blockouts, one of the most widely used guardrails in the United States.

Each component of the guardrail model was validated both quantitatively and qualitatively with laboratory tests, with the exception of the anchor system for which no test data were available. The modified NCAC C2500R (reduced element) pickup truck model (i.e., model with modifications made to the suspension system by WPI) was used to simulate the impact of a 2000-kg pickup truck. The NCAC C2500R model had been widely used in previous studies to analyze vehicle impact into roadside barriers and therefore the model had been generally debugged.

The accuracy of the model's results was quantified prior to being used in this study. The model was first used to simulate a 2000-kg pickup impacting the modified G4(1S) guardrail at 100 km/h at an angle of 25 degrees. The results were validated by comparing them to a full-scale crash test documented in the literature, and it was concluded that the model provided realistic behavior of both the guardrail and vehicle in such an impact event.

The validated model was then used in a parametric analysis to investigate the effects of various curb types in tracking impacts with a 2000-kg pickup truck on the stability and trajectory of the vehicle during simple curb traversals. The parametric analysis involved six curb types (AASHTO Types A, B, C, D and G and the 100-mm New York curb), two impact speeds (70 and 100 km/h) and three impact angles (5, 15, and 25 degrees).

The model was also used in a parametric study to investigate the crashworthiness of curb–barrier combinations in tracking impacts with the 2000-kg pickup truck. The parametric analysis involved the modified NCAC C2500R pickup truck model impacting the modified G4(1S) guardrail model (1) at impact speeds of 70, 85, and 100 km/h; (2) at an impact angle of 25 degrees; (3) and at offset distances from curb to barrier of 0, 2.5, and 4 m. The results of the curb traversal study indicated that the stability of the pickup truck was not compromised in tracking impacts, but the trajectory of the front bumper was sufficient to imply a risk of barrier override when a standard strong-post guardrail is placed anywhere from 0.5 m to 7.0 m behind 150-mm high curbs or 0.6 m to 7.0 m behind 100-mm high curbs.

The results of the pickup truck model impacting various curb–guardrail combinations confirmed that the presence of curbs was potentially hazardous. The results of the parametric study were used to identify certain combinations that were more likely to result in acceptable barrier performance and those more likely to result in unacceptable barrier performance, and guidelines defining proper curb type and barrier placement were presented. It should be noted that even cases identified as being successful resulted in poorer performance of the guardrail and a higher risk of injury for the occupants of the vehicle than was the case when the curb was not present. These guidelines were validated by full-scale crash tests of curb–guardrail combinations.

CONCLUSIONS

The result of the foregoing analyses and testing was the development of recommended guidelines for the use of curbs. The results of the study of tracking vehicles traversing curbs where guardrails are not present indicated that the front bumper trajectory is only slightly affected by the impact speed, impact angle, and slope of the curb face. The most significant factor influencing the trajectory and vehicle stability in these tracking impacts is the height of the curb.

Vehicles also often interact with curbs in a nontracking configuration. A tripping risk index (TRI) was developed to quantify the performance of curbs in nontracking situations. The index was developed using full-scale live-driver curb traversal tests and finite-element simulations of a 2000-kg pickup truck traversing a variety of curbs in nontracking impacts. TRI values above 45 were considered to indicate that vehicles were at high risk of tripping whereas TRI values less than 20 presented a very low risk. TRI values between 20 and 45 were considered moderate. The best curb evaluated in this study was the New York curb which resulted in a TRI of just over 12. The AASHTO Types C and G curbs presented moderate risk on high-speed roads and the AASHTO Types B and D presented high risk for high-speed roads. When curbs must be used on high-speed roads, the shortest possible curb height and flattest slope should be used to minimize the risk of tripping the vehicle in a nontracking collision.

Guidelines for use of curbs in conjunction with guardrails were also developed.

Any combination of a sloping-faced curb that is 150-mm or shorter and a strong-post guardrail can be used where the curb is flush with the face of the guardrail up to an operating speed of 85 km/h.

Guardrails installed behind curbs should not be located closer than 2.5 m for any operating speed in excess of 60 km/h. The vehicle bumper may rise above the critical height of the guardrail for many road departure angles and speeds in this region, making vaulting the barrier likely. A lateral distance of at least 2.5 m is needed to allow the vehicle suspension to return to its predeparture state. Once the suspension and bumper have returned to their normal position, impacts with the barrier should proceed successfully.

For roadways with operating speeds of 70 km/h or less, guardrails may be used with 150-mm high or shorter sloping-face curbs as long as the face of the guardrail is located at least 2.5 m behind the curb. Vehicles traveling at speeds greater than 70 km/h may vault over the guardrail for some departure angles.

In cases where guardrails are installed behind curbs on roads with operating speeds between 71 and 85 km/h, a lateral distance of at least 4 m is needed to allow the vehicle suspension to return to its predeparture position. Once the suspension and bumper have returned to their normal position, impacts with the barrier should proceed successfully. Guardrails may be used with 100-mm high or shorter sloping-face curbs as long as the face of the guardrail is located at least 4 m behind the curb. Vehicles traveling at speeds greater than 85 km/h may vault over the guardrail for some departure angles.

Above operating speeds of 85 km/h, guardrails should only be used with 100-mm high or shorter sloping-faced curbs, and they should be placed with the curb flush with the face of the guardrail. Above operating speeds of 90 km/h, the sloping face of the curb must be 1 : 3 or flatter and must be 100-mm high or shorter.

These recommended guidelines should help practitioners select appropriate curb and guardrail combinations at sites where both curbs and guardrails are necessary. Curbs should only be used on higher speed roadways when concerns about drainage make them essential to the proper maintenance of the highway.

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APPENDIXES A THROUGH I

UNPUBLISHED MATERIAL

Appendixes A through I 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	**State Survey Questionnaire**
APPENDIX B	**Analysis of Operating Speeds in Michigan and New York for Use in Other Analyses**
APPENDIX C	**Extent of the U.S. Crash Problem Related to Curbs: An Analysis of FARS and NASS-GES Data**
APPENDIX D	**Examination of Curb-Related Rollover Given a Crash: NASS-CDS and Michigan and Illinois HSIS Data**
APPENDIX E	**Analysis of Crash, Injury, and Rollover Rates per Passing Vehicle for Guardrail Sections with and without Curbs**
APPENDIX F	**Curb Crash Severity Modeling**
APPENDIX G	**Nature of Curb Impacts—Crash Reconstruction Data**
APPENDIX H	**Nature of Curb Impacts—Analysis of Extreme versus Nonextreme Crashes**
APPENDIX I	**Crash Test Reports**

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety 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
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation