DESIGN GUIDELINES FOR THE USE OF CURBS AND CURB/GUARDRAIL COMBINATIONS ALONG HIGH-SPEED ROADWAYS

by

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ABSTRACT

The potential hazard of using curbs on high-speed roadways has been a concern for highway designers for almost half a century. Curbs extend 75-200 mm above the road surface for appreciable distances and are located very near the edge of the traveled way, thus, they constitute a continuous hazard for motorist. Curbs are sometimes used in combination with guardrails or other roadside safety barriers. Full-scale crash testing has demonstrated that inadequate design and placement of these systems can result in vehicles vaulting, underriding or rupturing a strong-post guardrail system though the mechanisms for these failures are not well understood. For these reasons, the use of curbs has generally been discouraged on high-speed roadways. Curbs are often essential, however, because of restricted right-of-way, drainage considerations, access control, delineation and other curb functions. Thus, there is a need for nationally recognized guidelines for the design and use of curbs.

The primary purpose of this study was to develop design guidelines for the use of curbs and curb-barrier combinations on roadways with operating speeds greater than 60 km/hr. The research presented herein identifies common types of curbs that can be used safely and effectively on high-speed roadways and also identifies the proper combination and placement of curbs and barriers that will allow the traffic barriers to safely contain and redirect an impacting vehicle.

Finite element models of curbs and curb-guardrail systems were developed, and the finite element program, LS-DYNA, was used to investigate the event of a vehicle traversing several curb types. Finite element analysis was also used in the analysis of a vehicle impacting a number of curb-guardrail combinations. The results obtained from these analyses were synthesized with the results of previous studies, which involved full-scale crash testing, computer simulation, and other methods. The combined information was then used to develop a set of guidelines for using curbs and curb-barrier combinations on high-speed roadways.

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I. INTRODUCTION

1.1 Background

There has long been concern over the use of curbs on high-speed roadways because of their potential to cause drivers to lose control and crash. Curbs extend 75-200 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 that may encroach on the roadside at any point within the length of the curb. AASHTO highway design policy discourages the use of curbs on high-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. In some cases, a barrier is placed in combination with a curb, and an inadequate design can result in vehicles vaulting or under-riding the barrier.

While the use of curbs is discouraged on high-speed roadways, they are often required because of restricted right-of-way, drainage considerations, access control, delineation, and other curb functions. Such installations are currently being put in place 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-and-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 (e.g., the Green Book). *(1)* The purpose of curbs is to provide drainage, delineate the edge of the pavement, support the pavement edge, provide the edge for a pedestrian walkway, and provide some redirective capacity for low speed impacts. On higher speed roadways, the subject of this study, the primary function of curbs is usually 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 1.1: 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 is 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 an 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 side slopes where a rollover would be even more likely. For these reasons, vertical face curbs are usually restricted to low speed facilities where the steering action of the curb is sufficient for redirection.

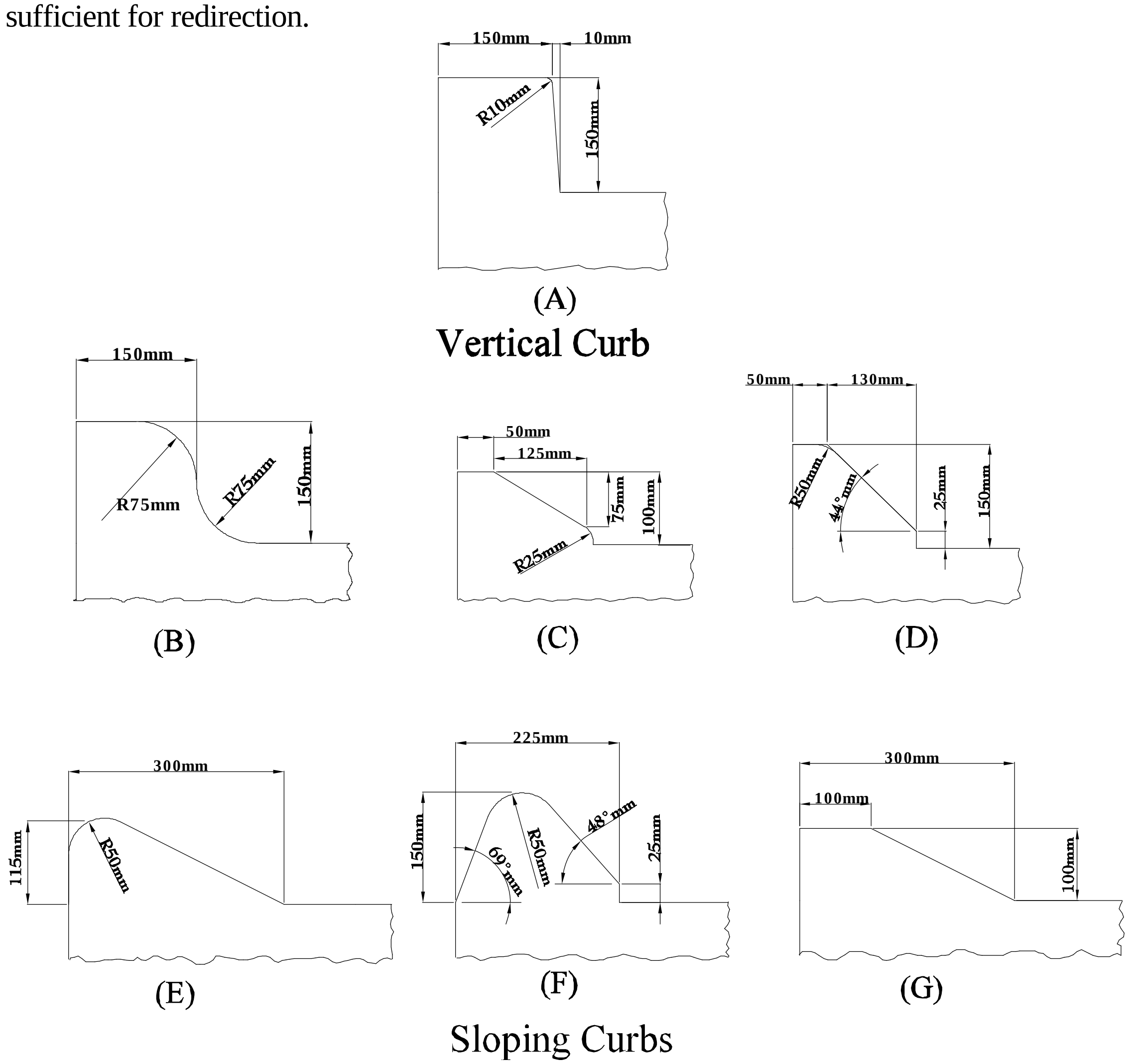

Figure 1.1: Typical AASHTO Highway Curbs *(1)*

Sloping curbs, as illustrated in Figure 1.1, 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 side slope 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 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 as shown in Figure 1.2. Figure 1.2 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/hr rural two-lane roadway in Maine. The curb is placed at this site to provide drainage away from the steep side slope behind the guardrail and thereby prevents 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.

Figure 1.2: Sloping curb installed flush with a strong-post w-beam guardrail on a 90 km/hr two-lane rural roadway in Maine.

The Green Book limits its guidance on the use of vertical face curbs and traffic barriers to the following statement (chapter 4, pp 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)(3)* 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 use of a curb no higher than 100 mm or stiffening of the guardrail to reduce its deflection by bolting a w-beam to the back of the posts or the addition of a rubrail usually proves satisfactory. 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." *(4)*

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." *(5)*

Most of the current understanding of vehicle behavior during impact with curbs was developed in full-scale tests performed nearly 40 years ago. *(5)* More recent testing of bridge railings and guardrail-to-bridge rail transitions have added to this knowledge somewhat. *(6)* 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 side 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 barriers, semi-rigid barriers and flexible barriers. The rigid barriers are often shaped, concrete barriers like the F-shape median barrier, the New Jersey barrier, the Ontario tall wall, etc. In essence, these types of barriers can also function as drainage devices so there are probably no common reasons why a curb would be used in conjunction with, a New Jersey barrier, for example.

Semi-rigid 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 crash tests. These barriers are used in nearly every state and account for the vast majority of the installed inventory of roadside hardware. *(7)* These types of barriers are also widely used in many states in conjunction with curbs, as illustrated in figure 1.2 and in figure 1.3. The use of curbs and strong-post W-beam guardrails is 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 three meters. Because these systems allow large lateral deflections, most vehicles would mount the curb while interacting with the barrier. For this reason the author believes 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. For example, 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 is to determine the lateral encroachment distance that it takes for a vehicle to stabilize after impacting a curb at highway speeds.

1.2 Purpose and Applicability

There is a need for nationally recognized guidelines for the design and use of curbs on various types of high-speed roadways. For example, it may be acceptable to use curbs specifically designed to reduce the risks outlined above. Minimal research has been done on sloping curbs, hence, there is very little information available pertaining to their effect on vehicle tripping or vaulting, especially considering today's mix of vehicle types and sizes. The National Cooperative Highway Research Program (NCHRP) has sponsored Worcester Polytechnic Institute to develop design guidelines for using curbs and curb-barrier combinations on roadways with operating speeds greater than 60 kph (37 mph) under Project Agreement NCHRP 22-17. The research presented in this dissertation is a large part of that study and will provide very useful information to the NCHRP 22-17 project.

1.3 Project Objectives

The objectives of this research are to identify the common types of curbs that could be used safely and effectively on high-speed roadways, to determine the proper combination and placement of curbs and barriers such that traffic barriers remain effective, and ultimately, to develop design guidelines based on site-specific criteria for installation of curbs and curb-barrier combinations on roadways with operating speeds greater than 60 km/hr.

The first phase of the project involves 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/hr (37 mi/hr). Computer simulation methods are 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 high-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 are then synthesized and guidelines for the use of curbs and curb-and-barrier systems are developed.

II. LITERATURE REVIEW

2.1 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.*(5)* This test series was followed in 1955 by another series of tests using the four best performing curbs from the first series.*(8)* The conclusion of the researchers was that barrier 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 United Kingdom. *(9)(10)(11)* These early crash tests formed the basis of the AASHTO policy described earlier 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, full-scale crash testing, and vehicle dynamics codes. Each of these methods are 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.

2.2 Analysis Methods Applied in the Study of Curb Safety

2.2.1 *Analytical Methods*

Most analytical work regarding vehicle impact into curbs have 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 2.1 can be developed. Figure 2.1 shows the characteristics of two particular experimental curbs, the Trief and Elsholz curbs.*(10)(11)*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.

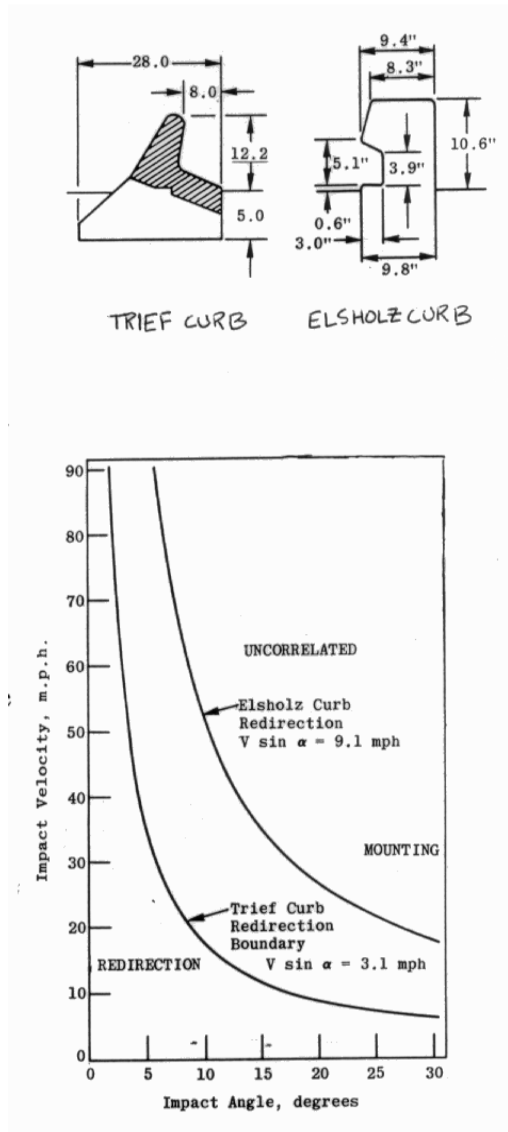

Figure 2.1: Curb performance characteristics of the Trief and Elsholz curbs *(10)*

The boundary between redirection and mounting can be described by the equation :

$$K = V \sin \alpha$$

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. Dunlap found that the characteristic lateral component of velocity for the Trief curb was 5 km/hr and for the Elsholz curb was 14.6 km/hr; thus, the Elsholz curb was more effective at redirecting vehicles than the Trief curb.*(12)*

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 vehicle that would be redirected by each type of curb can be estimated.*(12)* Dunlap used data from a specific roadway in Michigan for the speed distribution and the Hutchinson-Kennedy encroachment data for the impact angle distribution.*(13)* For the specific site in Michigan, Dunlap found that the Elsholz curb could be expected to redirect 70 percent of the impacting vehicles and the Trief curb could only be expected to redirect 27 percent. 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 2.1, 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 including pickup trucks, large sport utility vehicles, mini-vans, small sport utilities 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 1960's.

An analytical study on the safety of roadside curbs was conducted by Navin and Thomson at the University of British Columbia.*(14)* 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.

2.2.2 *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).*(15)* It was used 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.*(16)* The CALSVA program, developed by Cornell Aeronautical Laboratory, was only capable of simulating a limited range of impact scenarios due to 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).*(17)* 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 1980's by the National Highway Traffic Safety Administration (NHTSA) and Systems Technology, Incorporated (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 multi-purpose 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 Federal Highway Administration (FHWA) for use in the Interactive Highway Safety Design Model (IHSDM).*(18)* 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' speed and path choice 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).

2.2.3 *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.*(19)* 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.*(20)*

From 1981 to 1992 crash tests were conducted according to the test requirements specified in NCHRP Report 230.*(21)* 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/hr 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, sport utility vehicles, and pickup trucks emerged in their place. Since the first testing procedures specified in Highway Research Board Report 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/hr and an impact angle of 25 degrees, and
2) Test 3-10, which involves a 820C (e.g., Honda Civic or Ford Taurus) impacting the guardrail at a speed of 100 km/hr and an 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 roadways within the United Sates.

2.3 Effect of Curbs on Vehicle Stability

Olsen et al.*(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 2.1); nine full-scale tests were conducted on each curb type at speeds of 48, 72 and 97 km/hr and at 5, 12.5 and 20 degree encroachment angles. The computer program, Highway Vehicle Object Simulation Model (HVOSM), was used to simulate vehicle impact with three different curb types: AASHTO curb types B, D and G [1]. Twelve curb impacts were simulated on each curb type at impact speeds of 48, 72 and 97 km/hr and at 5, 12.5 and 20 degree encroachment angles. A 121-km/hr impact was also simulated at 5, 10 and 15 degrees encroachment angles.

Figure 2.2: Vehicle used in Olsen *et al* study *(22)*

The test vehicle used in their study was a 1963 Ford four-door sedan with heavy-duty suspension. The vehicle's mass was 1905 kg, and the center of gravity of the vehicle was 610 mm above ground. The test vehicle is shown in Figure 2.2. 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/hr at encroachment angles greater than 5 degrees. They also

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1 In their study the curbs were referred to as C, E and H curbs which was consistent with the nomenclature of the AASHTO "Blue Book". In the AASHTO "Green Book" these curbs are now referred to as B, D and G, respectively.*(13)* Nomenclature throughout this document will use the designations defined in the Green Book.

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 2.3.

Such vehicle trajectories may result in a vehicle snagging on the top of the rail 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, 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.

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

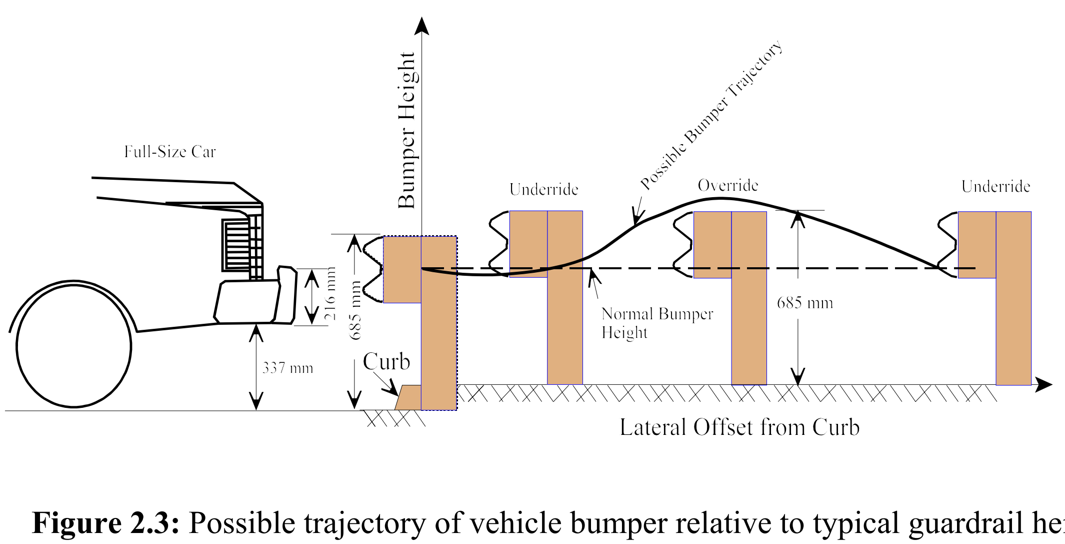


Figure 2.3: Possible trajectory of vehicle bumper relative to typical guardrail height

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/hr. The maximum rise height of the bumper, predicted from the simulations, was approximately 737 - 787 mm and occurred in the range of 2.44 - 3.0 m behind 150-mm curbs. The height of a typical w-beam guardrail is 686 mm, as shown in the sketch in Figure 2.3. 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/hr, 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 and cause snagging, as shown in Figure 2.3. During impact with the 150-mm 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's study is given in Table 2.1 and a summary of their HVOSM simulation results is given in Table 2.2.

Table 2.1. 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

Table 2.2. 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

Dunlap 1973 *(12)(23)*

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 1970's 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 barriers warrants more careful investigation.

Ross and Post *(24)*

Researchers at Texas Transportation Institute (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 impact with 150-mm and 200-mm curbs, modified curbs, and slopes. They 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 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. *(25)*

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 2.4, is the curb type most widely used by NDOR. The test matrix in the study included twenty-three full-scale tests: thirteen tests on the 100-mm lip curb, two tests on the 150-mm lip curb, and eight 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, they 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 to be significant. It was also concluded that the performance of w-beam guardrails could be adversely affected when installed behind curbs, and when curb-guardrail combinations are necessary, the curb should be placed behind the face of the guardrail to minimize the potential for vehicle ramping.

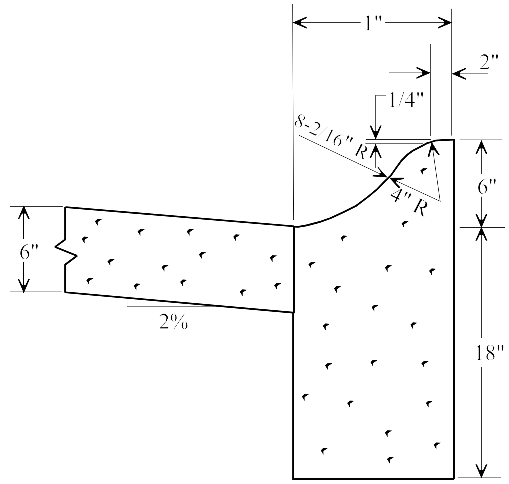


Figure 2.4: AASHTO Type I Curb

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 2043 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/hr 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 their study that there was only a slight potential for 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/hr. 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 Highway Vehicle Object Simulation Model (HVOSM) was also used to investigate alternate impact conditions. Simulation models of the twenty-three full-scale tests were developed, and the results were compared to the full-scale tests to validate their model. An additional 55 simulations were then performed. Thirty-one simulations were performed to supplement the original twenty-three impact scenarios, including five simulations with the 100-mm lip curb, sixteen simulations with the 150-mm lip curb and ten simulations with the 150-mm type I curb. Another twenty-four 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/hr 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 twenty-four 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/hr and encroachment angles of 5 and 20 degrees. The results of these simulations showed only minor differences in angular displacements of the vehicle, compared to the simulations with the curb placed on a negative grade (i.e., the test area was on a negative grade).

Non-tracking impacts of vehicles with the three curb types were also investigated using computer simulation; however, no test data was available for validating the results. Impact conditions used in the study included those contained in Appendix G of the NCHRP Report 350 and from accident data analysis studies. All simulations were performed with vehicle speed of 80.5 km/hr 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.

2.4 Effect of Curbs Installed in Conjunction with Guardrails

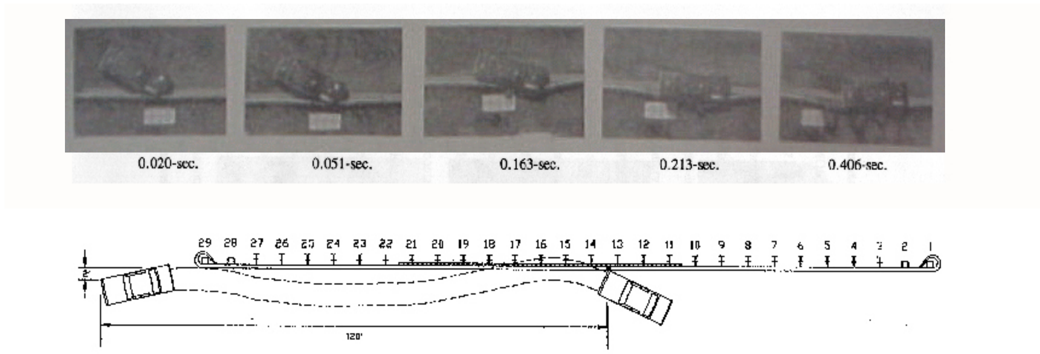
Holloway et al. *(26)*

A study was conducted by Holloway and other researchers at Midwest Roadside Safety Facility at the University of Nebraska-Lincoln that involved a full-scale crash test on Missouri's 150-mm vertical curb placed behind the face of a strong post w-beam guardrail (i.e.,G4(1S)). Missouri's 150-mm 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 edge 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/hr 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 2.5.

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 negative14 degrees (the roll angle was away from the system). The vehicle exited the rail at 706 milliseconds at a speed of 64 km/hr and an angle of 6.2-degrees. Vehicle decelerations and trajectory were well within the recommended limits of NCHRP Report 230. As a result of the test, they concluded that the system performed satisfactorily and the Missouri Department of Transportation should continue to use the guardrail-curb system where warranted.

***Bryden and Phillips** (27)*

Bryden and Phillips performed twelve full-scale crash tests for the New York Department of Transportation to evaluate the performance of a thrie-beam bridge-rail system. Two



Test Number	MO6C-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 10. Summary of Test Results, MO6C-1

Figure 2.5: Summary of Test Results for MwRSF Test M06C-1 *(26)*

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/hr at an impact angle of 26 degrees. The vehicle remained stable and was smoothly redirected in both tests.

FHWA Memorandum Feb 28, 1992 (28)

The results of a series of crash tests conducted by ENSCO was 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/hr 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 A 817-kg car impacted a G4(1S) guardrail system with a 150 mm high asphalt dike. The impact speed was 100 km/hr 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/hr 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/hr 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 asphalt dike was placed behind the front face of the w-beam. The impact speed was 100 km/hr 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 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/hr) according to NCHRP Report 230; thus the system did not meet all required safety criteria.

Polivka, et al. *(29)*

A study was conducted by researchers at the Midwest Roadside Safety Facility 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 in NCHRP Report 350 test Level 3, which involves a 2,000-kg pickup truck (1991 GMC 2500) impacting at a speed of 100 km/hr at an impact angle of 25 degrees.(2.12) Sequential photographs of the crash test are shown in Figure 2.6. The center of gravity of the test vehicle was 737 mm.

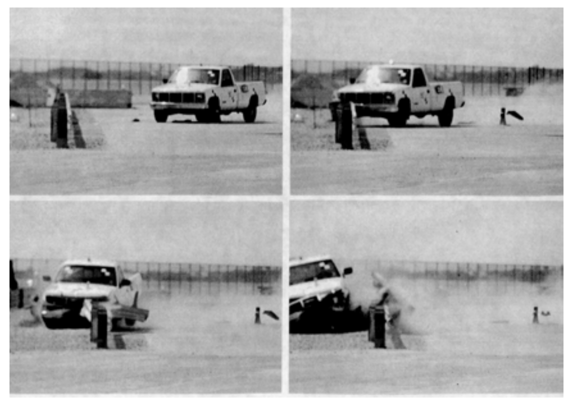


Figure 2.6: Sequential video frames from test NEC-1.*(29)*

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

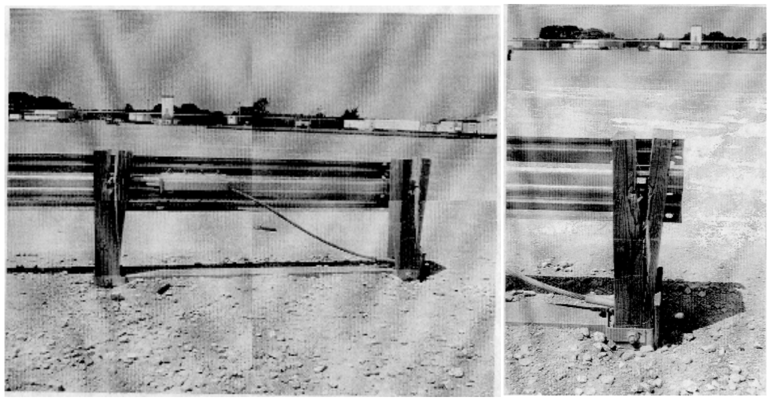


Figure 2.7: Guardrail terminal damage during test NEC-1. *(29)*

posts split during the collision, as shown in Figure 2.7, 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.

Polivka, et al. (30)

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 test Level 3. The test vehicle was a

2000-kg pickup truck (1994 GMC 2500) and the impact speed and angle were 100.3 km/hr and 28.6 degrees, respectively. The center of gravity of the test vehicle was 667 mm.

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 fist 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 2.8; 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 2.9 which was taken from Polivka *et al*.

Booth et al *(31)*

During the 1980's, the Federal Highway Administration (FHWA) sponsored the testing of numerous bridge railings, some of which included curbs. In particular, Texas Transportation Institute 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

Figure 2.8: 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. *(30)*

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.

Bullard and Menges*(32)*

This study was conducted by researchers at the Texas Transportation Institute (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 2.10.

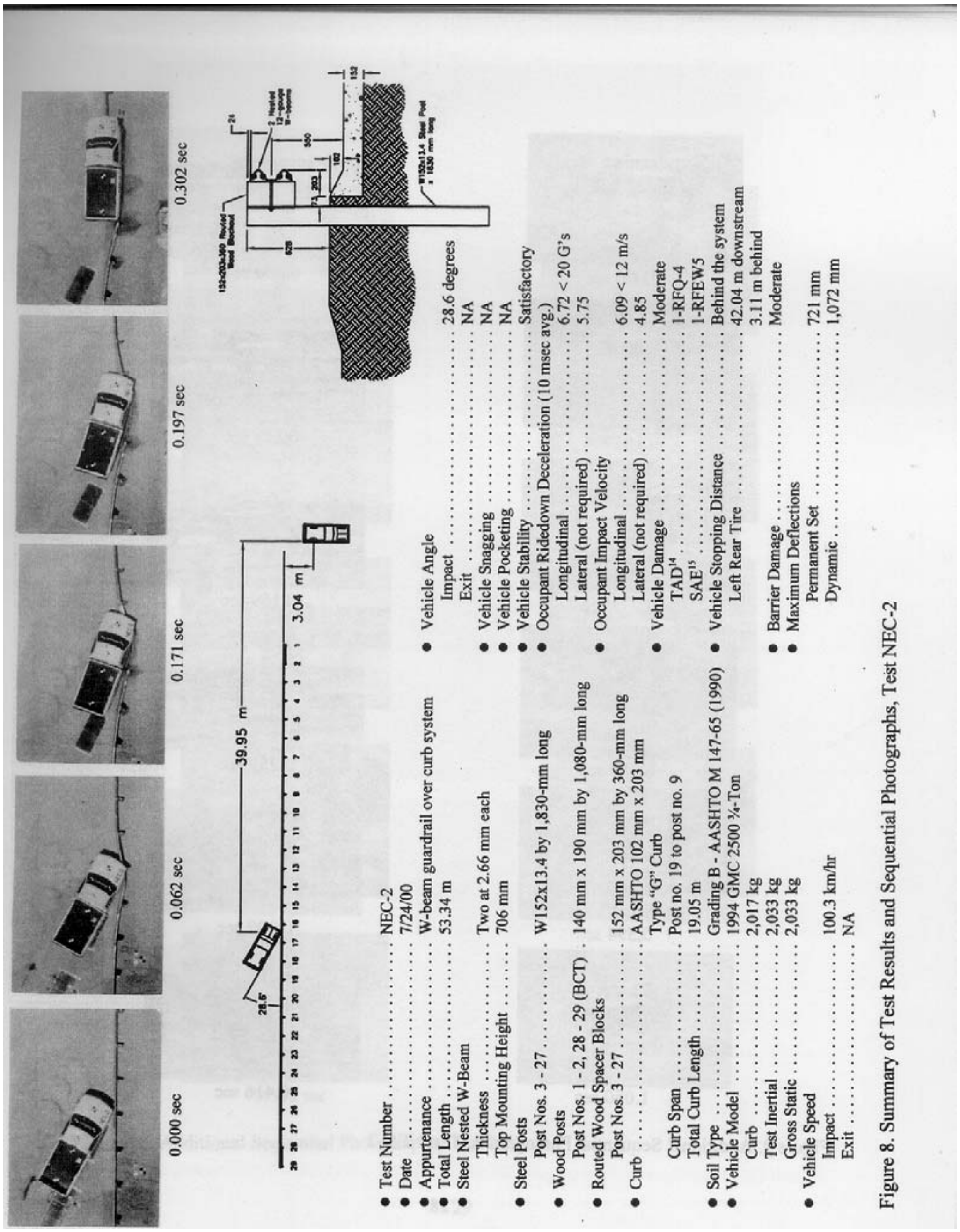


Figure 2.9: Summary of test results of Test NEC-2 from Polivka *et al. (30)*

TTI test 404201-1 was conducted at the Texas Transportation Institute on May 23, 2000 and involved a Chevrolet C2500 pickup impacting the curb-and-barrier system at 101.8 km/hr 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 2.11. 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.*(39)* 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 pre-existing splits passing through the bolt hole location in the posts, as shown in Figure 2.12. A summary of Test 404201-1 is shown in Figure 2.13.

2.5 EFFECTS OF CURB TRIP ON VEHICLE STABILITY

Cooperrider, et al. (33)

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 1980's) 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

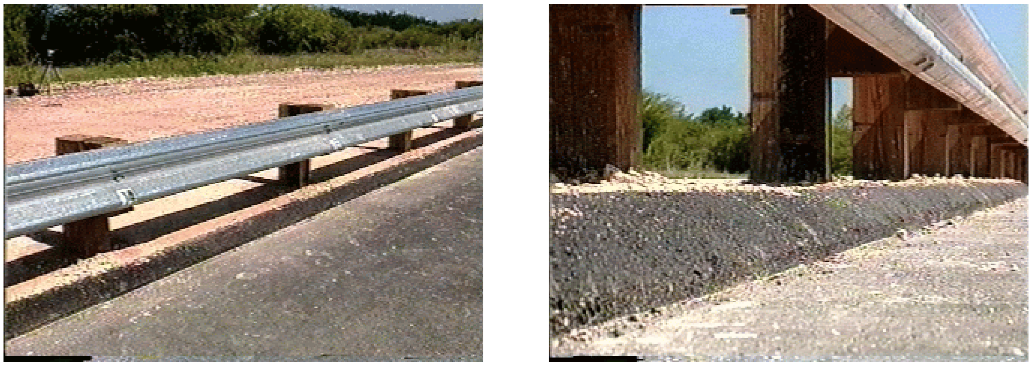


Figure 2.10: Guardrail/curb installation for TTI test 404201-1.*(32)*

Figure 2.11: Guardrail damage in test TTI 404201-1. *(32)*

Figure 2.12: Posts split vertically during TTI test 404201-1 along pre-existing splits in posts. *(32)*

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 below in Table 2.3.

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

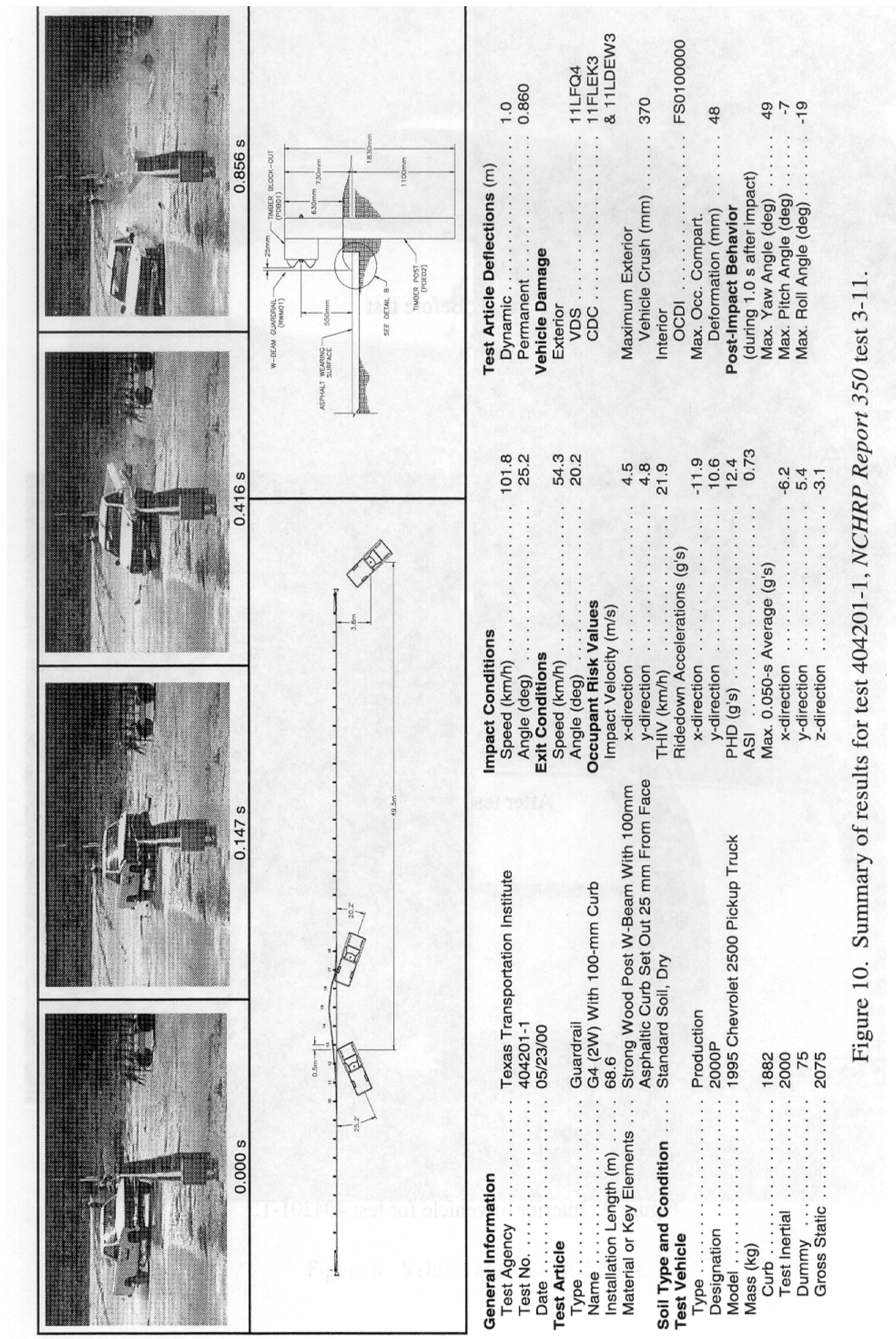


Figure 2.13: Summary of test results of TTI test 404201-1 from Bullard and Menges *(32)*

Table 2.3: Test Matrix for Cooperrider Study *(33)*

Test No.	Vehicle Model	Trip Method	Test Speed (km/hr)	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

maximum decelerations at the center of gravity was 12.4 g's, compared to maximum decelerations of 1.62 g's and 1.3 g's in the soil trip tests and dolly tests, respectively.

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

They found in their study 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 g's. 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.

DeLeys and Brinkman 1987 (34)

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 non-tracking departures from the roadway were investigated. A modified version of the Highway Vehicle Object Simulation Model (HVOSM) was used in this research that improved the programs application to rollover situations. The modifications to the program were made by McHenry Consultants, Inc. These modifications included further development of the tire model and the addition of a tire/deformable-soil interaction model to the program.

A literature review and accident data analysis[2] was performed in their study, and some of the principal findings from that review are listed below:

1. "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."
2. "In most (50% to 80%) of the rollover accidents, the vehicles were skidding out of control at a large yaw angle prior to overturning."
3. "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/hr."

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 was collected in these tests and was used for obtaining tire/ground coefficients of friction for typical roadside terrain surfaces, as well as, for validating the computer

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2 Accident data information came from the accident data recorded in the 1979 - 1981 National Accident Sampling System (NASS).

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 - 24 km/hr. The data from the tests indicated that the average coefficient of friction between the tires of the VW Rabbit and the sodded ground surface were typically about 0.5.

The modified version of HVOSM provided reasonable accuracy of the simulations of the tests on the various roadside terrains. They did 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.”*(34)*

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 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 2018 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 use of HVOSM for predicting the dynamic response of vehicles traversing various types and shapes of terrain, are listed below:

1. “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.”
2. “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 high tire load and large slip and camber angle conditions that prevail in most rollover events.”
3. “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, etc."

Allen et al. 1991 (35)

Researchers at Systems Technology, Inc. (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 and/or 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 Systems Technology, Inc. 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 side slopes. 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 Systems Technology, Inc. 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. "Communications services have also been added to VDANL so that it can provide commands for display image generators (Igs), 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 Federal Highway

Administration as part of the Interactive Highway Safety Design Model (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 if a truck-climbing lane was necessary for a proposed roadway alignment, and to determine if a loaded tractor-trailer would be able to maintain a specified speed traveling downgrade on the roadway without losing control.

2.6 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 - 48 km/hr. Curbs along high-speed roadways have been discouraged by AASHTO for many years due to the potential hazard caused by high-speed impact with curbs.*(1)* In the intermediate range of speed (between 60 - 80 km/hr), 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)(25)(26)(27)(28)(29)(30)(31)(32)* and computer simulation using the Highway Vehicle Object Simulation Model (HVOSM).*(22)(23)(24)* A summary of full-scale crash tests involving curb-guardrail combinations are presented in Table 2.4. Although it has been found that sloping curbs do not impede the redirection of a vehicle during tracking impact, they do affect the trajectory of a vehicle. Thus, the curb itself presents very little threat of harm when hit by a vehicle, but, 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, under-ride and snag on the barrier.*(22)(25)(29)(30)(31)* Another example, where a curb could have adverse effects on the performance of a device, is the placement of a curb in front of a breakaway pole. The breakaway feature at the base 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)(25)(38)* Design parameters defined by AASHTO for curb impacts are shown in Figure 2.14. It was reported that underride and vaulting of a standard strong-post guardrail was possible when the barrier was placed within some critical range behind the curb, usually within 0.76 m for underride and between 0.01 - 3.66 m for vaulting. This data was obtained through measuring vehicle trajectory during impact with curbs.

It has been assumed for many years by design engineers that if the curb is placed behind the face of the w-beam that the guardrail-curb system would perform adequately in safely containing and redirecting an impacting vehicle. Previous crash tests, involving large sedans and pickup trucks impacting various guardrail-curb combinations, have provided researchers with mixed results regarding the performance of such systems.*(25)(26)(28)(29)(30)(31)(32)*

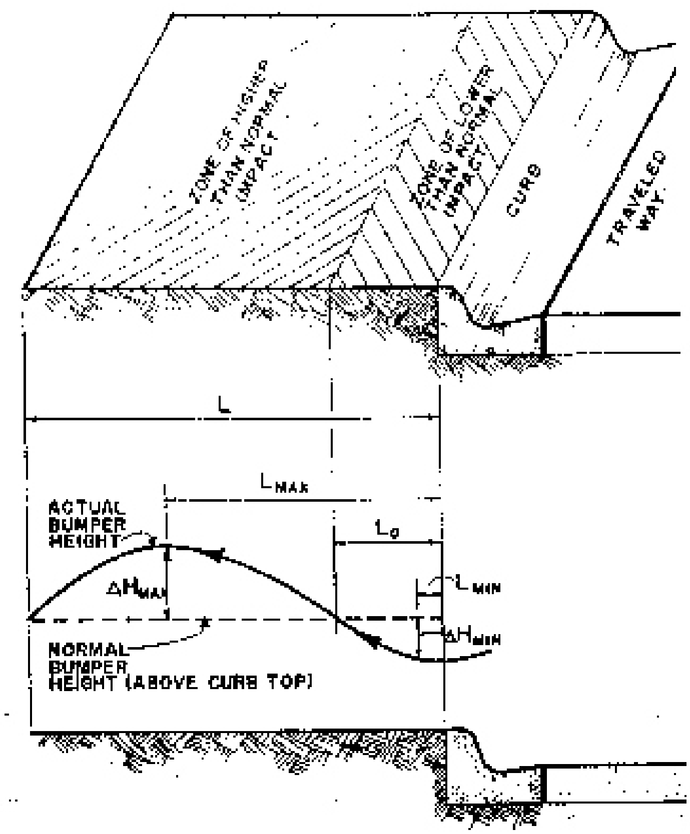
In full-scale crash tests performed by ENSCO, it was shown that vaulting is possible even when the curb is located flush with the face of a w-beam guardrail. If guardrail deflections during impact are sufficient to allow the wheel of the vehicle to contact and mount the curb, the vehicle may vault over the barrier.(26) 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 performed at Midwest Roadside Safety Facility (MwRSF), on the other hand, have demonstrated that similar curb/w-beam guardrail combinations do not degrade the performance of the barrier systems.*(24)(26)*

Some curb types are more likely to cause vaulting of a vehicle than others. The FHWA Memorandum in February 1992 reported that, in the case of curbs 150 mm high or higher, if a guardrail deflects enough for the wheels to mount the curb then the vehicle could vault over the guardrail.*(28)* 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 profile curbs would result in very little change in trajectory of the vehicle (50-mm maximum), regardless of the vehicle's speed and angle of impact.*(22)(25)*

A w-beam guardrail is sufficiently stiff enough 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.*(25)(28)* It has also been found that stiffening the guardrail system by installing a w-beam rail to the back side of the posts, or installing a rub-rail, will enhance the safety performance of a curb-guardrail system.(26) 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



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 2.14: Design Parameters for Curb Impacts as Defined by AASHTO *(38)*

guardrail system; however the system did meet all safety requirements of NCHRP Report 350.*(32)* 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.*(39)*

Table 2.4: 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
Holloway *et al.* *(26)*	MwRSF	M06C-1	1985 Ford LTD (2041 kg)	96.1 km/hr 25.1 degrees	152-mm vertical curb	G4(1S)	Passed	smoothly redirected
Bryden and Phillips *(27)*	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 *(28)*	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 airborn 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	
		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
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
Polivka *et al.* *(30)*	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
Bullard and Menges *(32)*	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

In test NEC-2, the G4(1S) guardrail with wood blockouts was modified and retested.*(30)* 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.*(25)(33)(34)* Vehicle tripping on curbs was addressed in Holloway *et al.* using HVOSM to simulate non-tracking impacts of large passenger sedans.*(25)* 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 non-tracking 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 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.*(34)* Full-scale tests were used to validate the computer models and, subsequently, over 200 simulation were conducted to investigate the rollover tendencies of vehicles traversing various side slopes, 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.*(33)* 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 was 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 due to impact with various vehicle tripping mechanisms such as curbs, soil, ditches, etc.*(35)(36)(37)* The results of the computer models developed in those studies were validated with full-scale tests. VDANL was chosen by the Federal Highway

Administration to be incorporated into the Interactive Highway Safety Design Model (IHSDM), which is used to assess new highway designs.

2.7 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 literature indicates, however, that 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 often include curbs along high-speed roadways for drainage reasons or to improve delineation, other methods should be sought to achieve those purposes.

From the literature study it was found that both the large and small cars crossing 150 mm high or smaller curbs in a tracking manner are not 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 loose 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 non-tracking 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 semi-controlled 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.

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.