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16. Abstract

Guidelines for testing and evaluating the impact performance of roadside safety features are periodically updated to stay current with improvements in technology and changes in the vehicle fleet and impact conditions. *NCHRP Report 350*, which contains current recommendations for testing and evaluating roadside safety devices, was published in 1993. Research to develop an update to *NCHRP Report 350* (Update) has recently been completed under NCHRP Project 22-14(02).

Changes being proposed as part of the new guidelines include new design test vehicles, revised test matrices, and revised impact conditions. These changes will likely necessitate the re-evaluation of the impact performance of some existing roadside features. Under this project, researchers performed an initial assessment regarding the ability of Texas roadside safety hardware to comply with the Update. The impact performance assessment was based on crash test results, engineering analyses, and engineering judgment. Categories of roadside appurtenances evaluated include guard fence, median barriers, bridge rails, precast work zone barriers, breakaway sign supports, and work zone traffic control devices. Proprietary devices such as crash cushions and guardrail end treatments were not considered.

The results of the performance assessment were used to prioritize additional testing and evaluation required to bring Texas roadside safety features into compliance with the new impact performance guidelines. This prioritization of hardware will help ensure efficient use of resources and provide a relatively seamless transition to the Update.

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INITIAL ASSESSMENT OF COMPLIANCE OF TEXAS ROADSIDE SAFETY HARDWARE WITH PROPOSED UPDATE TO NCHRP REPORT 350

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CHAPTER 1.

INTRODUCTION

BACKGROUND

For four decades, the United States has been committed to highway safety. Guidelines for testing roadside appurtenances originated in 1962 with a one-page document – *Highway Research Circular 482* entitled "Proposed Full-Scale Testing Procedures for Guardrails" *(1)*. This document included four specifications on test article installation, one test vehicle, six test conditions and three evaluation criteria. In 1974, National Cooperative Highway Research Program (NCHRP) *Report 153*, "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances" was published *(2)*. This 16-page document provided the first complete test matrix for evaluating safety features. Data collection methods, evaluation criteria, and limited guidance on reporting formats were included. These procedures gained wide acceptance following their publication, but it was recognized at that time that periodic updating would be needed.

Published in 1978, Transportation Research Circular 191, "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances" *(3)* provided limited interim changes to *NCHRP Report 153* to address minor changes requiring modified treatment of particular problem areas. An extensive revision and update to these procedures was made in 1981 with the publication of *NCHRP Report 230*, "Recommended Procedures for the Safety Performance Evaluation of Highway Features" *(4)*. This 42-page document contained different service levels for evaluating longitudinal barriers whose test matrices included vehicles ranging from small passenger cars to intercity buses.

In 1993, *NCHRP Report 350*, "Recommended Procedures for the Safety Performance Evaluation of Highway Features" was published *(5)*. This 132-page document represented a comprehensive update to crash test and evaluation procedures. It incorporated significant changes and additions to procedures for safety-performance evaluation, and updates reflecting the changing character of the highway network and the vehicles using it. Changes included the introduction of multiple test levels, inclusion of matrices for other roadside features that had not previously been addressed, adoption of a new design test vehicle, and more and different test conditions, etc.

Some of the notable differences between *NCHRP Report 350* and *NCHRP Report 230*, as excerpted from *Report 350*, were as follows:

- It provides a wider range of test procedures to permit safety performance evaluations for a wider range of barriers, terminals, crash cushions, breakaway support structures and utility poles, truck-mounted attenuators, and work zone traffic control devices.

- It uses a 4409-lb, 3/4-ton pickup truck as the standard design test vehicle in place of the 4500-lb passenger sedan to represent the growing population of light trucks in the vehicle fleet.

- It defines other test vehicles such as an 18,000-lb single-unit cargo truck and 80,000-lb tractor-trailer vehicles to provide the basis for optional testing to meet higher performance levels.

- It includes a broader range of tests for each category of safety feature to provide a uniform basis for establishing warrants for the application of roadside safety hardware that consider the levels of use of the roadway facility. Six basic test levels are defined for the various classes of roadside safety features.

- The report includes guidelines for the selection of the critical impact point for crash tests on redirecting-type safety hardware.

The Federal Highway Administration (FHWA) formally adopted the new performance evaluation guidelines for highway safety features set forth in *NCHRP Report 350* as a "Guide or Reference" document in the Federal Register, Volume 58, Number 135, dated July 16, 1993, which added paragraph (a)(13) to 23 CFR 625.5. FHWA subsequently mandated that, starting in September 1998, only highway safety appurtenances that have successfully met the performance evaluation guidelines set forth in *NCHRP Report 350* may be used on new construction projects on the National Highway System (NHS).

Through various pooled fund studies and other research projects, FHWA, Texas Department of Transportation (TxDOT), and state DOTs tested the most widely used safety appurtenances. Additionally, manufacturers worked toward recertification of their proprietary products. Ultimately, numerous changes and modifications to existing hardware were required to comply with *NCHRP Report 350*. Many of these changes were attributed to the change from the 4500-lb passenger sedan to the 4400-lb (2000P) pickup truck. The pickup truck represented an sport-utility vehicle (SUV) class of vehicle that had a higher center-of-gravity and was inherently less stable than the large passenger sedan used under *NCHRP Report 230*. In addition, the pickup truck had a shorter front overhang, often resulting in snagging of the front wheel and subsequent displacement of the wheel and tire into the floor/toe pan. As a result of snagging and wheel displacement, excessive intrusion into the occupant compartment was frequently observed. Work zone hardware, such as portable sign stands and barricades were tested, many for the first time. These devices often failed due to intrusion into the small 1800-lb (820C) passenger vehicle through the roof and windshield. Examples of changes in hardware as a result of the adoption of *NCHRP Report 350* include:

- The most common guardrail system in the U.S., the G4(1S) steel post W-beam guardrail, failed when the pickup truck rolled over as it exited the system. A change in offset blocks was required to bring the steel post guardrail system into compliance. The change made was the replacement of the steel blockout with a routed 6 inch x 8 inch wood or FHWA-accepted surrogate plastic blockout. The new system is referred to as the modified G4(1S).

- The G2 weak post W-beam guardrail failed due to override of the system by the pickup truck. To comply with Test Level 3 (TL-3) of *NCHRP Report 350*, the rail-to-post-connection was modified; the rail splices were moved to midspan between posts, and the rail height was increased.

- Guardrail-to-bridge rail transition designs were raised in height and stiffened considerably to address problems with vehicle instability and occupant compartment deformation in the 2000P (pickup truck) associated with many existing designs.

- Some bridge rails, such as the Texas T6 tubular bridge rail system, failed to comply with TL-3 impact conditions due to vehicle rollover of the 2000P vehicle and have been relegated to use on lower speed roadways as TL-2 systems.

- Other bridge rails, such as the Texas T202 concrete beam and post bridge rail and Texas T77 steel rail on concrete parapet, failed due to excessive occupant compartment deformation in the 2000P vehicle. Modifications, such as increased post offset distance and improved splice connections, enabled these systems to comply with *NCHRP Report 350*.

- Nationwide, many portable concrete barriers (particularly some of the pin-and-loop connection variety) failed to meet impact performance requirements of *NCHRP Report 350* due to connection failure and/or vehicle overturn with the 2000P vehicle. The Texas grid slot portable concrete barrier experienced large deflections, thus rendering it unsuitable for use in restricted work zones. Connections between barrier segments were redesigned (e.g., tightened and strengthened) to prevent failure, control dynamic deflections, and improve vehicle stability.

- Wooden Type III barricades and other commonly used work zone traffic control devices failed due to occupant compartment intrusion through the windshield when tested with the small 1800-lb passenger vehicle. Alternative designs fabricated from perforated steel tubing and hollow profile plastic were successfully developed and tested.

- Other work zone traffic control devices, such as portable sign stands, channelizing drums, and delineators, were tested by manufacturers for the very first time. Many types of sign substrates were evaluated for use, such as aluminum, wood, and plastic sign panels.

After an extended period of analyses, testing, and evaluation, hardware standards were updated to accommodate the pickup truck design test vehicle and other changes in *NCHRP Report 350*. On February 14, 2000, Dwight Horne, FHWA Director of Highway Safety Infrastructure issued a memorandum summarizing and describing all nonproprietary longitudinal roadside and median barriers that met *NCHRP Report 350* requirements at one or more test levels or were considered to be equivalent to barriers that had been tested.

However, the highway environment is continually changing and evolving and, consequently, the guidelines for testing and evaluating the impact performance of roadside safety features must be periodically updated to stay current with advancements in technology and changes in the vehicle fleet and impact conditions. In recognition of this inevitability, the forward of *NCHRP Report 350* states the following:

> "The evolution of the knowledge of roadside safety and performance evaluations is reflected in this document. Inevitably, parts of this document will need to be revised in the future, but it is the consensus opinion of the project panel and the many reviewers of these procedures that this document will effectively meet the needs for uniform safety performance evaluation procedures into the 21st century."

In 1997, Texas Transportation Institute (TTI) researchers first evaluated the needs and relevancy of updating *NCHRP Report 350* under NCHRP Project 22-14(01) "Improvement of the Procedures for the Safety Performance Evaluation of Roadside Features." The objectives were: 1) evaluate the relevancy and efficacy of the crash testing procedures; 2) assess the needs for updating *NCHRP Report 350*; and 3) provide recommended strategies for their implementation. Researchers produced many white papers outlining the various testing and evaluation areas of the document and discussing the state of the practice and observations made during the testing that followed the adoption of *NCHRP Report 350*.

Research to update *NCHRP Report 350* and take the next step in the continued advancement and evolution of roadside safety testing and evaluation was recently completed under NCHRP Project 22-14(02) *(6)*. The results of this research effort, which was conducted at the University of Nebraska, will be a new document that will be published by the American Association of State Highway and Transportation Officials (AASHTO) and will supersede *NCHRP Report 350*. Changes being proposed for incorporation into the new guidelines include new design test vehicles, revised test matrices, and revised impact conditions.

OBJECTIVES/SCOPE OF RESEARCH

TxDOT and other state DOTs make considerable use of various non-proprietary roadside safety hardware systems. Although some barrier crash testing has been conducted during the development of the updated criteria, many barrier systems and other roadside safety features have yet to be evaluated under the proposed guidelines. Therefore, evaluation of the remaining widely used roadside safety features following the safety-performance evaluation guidelines included in the update to *NCHRP Report 350* is needed.

The purpose of this research project is to examine the potential effects and impact of the update to *NCHRP Report 350* on current TxDOT hardware and assist TxDOT in developing a prioritization scheme for testing and evaluation of roadside safety features in accordance with the new impact performance guidelines. Categories of roadside appurtenances that were considered under the project include guard fence, median barriers, bridge rails, transitions from approach guard fence to bridge rails, crash cushions and attenuators, breakaway supports, work zone or temporary barriers, and work zone traffic control devices. Proprietary devices in these categories were not considered. The manufacturers of these devices will be required to assess the impact performance of their devices and ultimately demonstrate compliance of their devices with the new test and evaluation guidelines.

Researchers used crash test results, engineering analyses, and engineering judgment to assist with the hardware evaluation and prioritization under this project. A limited number of full-scale crash tests were performed under NCHRP Project 22-14(02) to help understand and evaluate the consequences of adopting the recommended changes on current hardware. Two additional crash tests of non-proprietary small sign support systems commonly used by TxDOT were conducted as part of this project and are reported herein. The use of computer simulation to assess the performance of hardware in accordance with the proposed update to *NCHRP Report 350* (Update) was severely limited due to the lack of validated finite element vehicle models representative of the new design test vehicles proposed under the Update.

CHAPTER 2.

OVERVIEW OF PROPOSED UPDATE TO NCHRP REPORT 350

Periodic changes in crash testing and evaluation methodologies are necessary to keep pace with the changing vehicle fleet and operating conditions, and to address issues and data gleaned from ran-off-road crash data. The recommended guidelines developed under NCHRP Project 22-14(02) reflect input received from researchers, hardware manufacturers, user agencies, and other professionals in the field of roadside safety design. They provide a basis on which the impact performance of roadside safety features can be assessed and compared. The crash-testing guidelines present matrices for vehicular tests that are defined in terms of vehicle type, impact conditions (i.e., speed and angle), and impact location. They further prescribe how to evaluate performance of a safety feature in terms of occupant risk, structural adequacy, exposure to workers and pedestrians that may be in the debris path resulting from the impact, and post-impact behavior of the vehicle.

The underlying philosophy behind the development of the new guidelines continues to be one of "worst practical conditions." When selecting test parameters such as test vehicle type and weight, impact speed and angle, and point of impact, effort was made to specify the worst, or most critical, conditions with consideration given to available technology, relevancy in terms of the incremental increase in the level of safety provided, and associated costs of new features compared to existing features. For example, the weights of the selected small passenger car and pickup truck test vehicles represent the 2nd and 94th percentiles, respectively, of passenger vehicles based on sales data. The selected impact speed and angle combination represents the 92.5th percentile as determined from the reconstruction of real-world crashes. When the combined effects of all testing parameters are considered, the tests prescribed in the update to *NCHRP Report 350* (Update) are believed to reasonably represent the extremes of impact conditions expected to be encountered in real-world crashes.

Major revisions proposed for incorporation into the new guidelines include new design test vehicles, revised test matrices and impact conditions, changes to the evaluation criteria, inclusion of tests for additional features, and increased emphasis on in-service performance evaluation. Some key observations and proposed changes include:

- Evaluation of vehicle sales data indicates that vehicles in the fleet have become larger and heavier since the publication of *NCHRP Report 350*. The efforts of automobile manufacturers to add additional comfort and safety amenities to their vehicles have added weight to even the smallest of passenger vehicles. This added weight can change the performance characteristics of these vehicles and place more demand on barrier systems. The center-of-gravity (C.G.) heights also continue to increase, which may further aggravate stability problems associated with some existing barriers. Continued increases in energy and fuel prices may ultimately reverse this trend. However, any reversal will likely be gradual in nature, and these heavier vehicles will remain part of the vehicle fleet for many years to come.

- It has been recommended to change the large design test vehicle from a standard cab, ¾-ton pickup truck with a C.G. height of approximately 27-inches to a ½-ton, four-door, crew-cab pickup truck with a minimum C.G. height of 28-inches It is still the intent to have this design test vehicle represent the light truck segment of the vehicle fleet. The weight of the test vehicle will increase approximately 13 percent from 4400 lb to 5000 lb, which represents the 94th percentile heaviest passenger vehicle in terms of sales (i.e., only 6 percent of new passenger-type vehicles sold weigh more than the specified test weight). The increase in weight will place more structural demand (i.e., increased impact forces) on existing appurtenances, and the increase in C.G. height may aggravate stability issues associated with some barrier systems.

- The weight of the small car test vehicle will increase 35 percent from 1800 lb to 2425 lb. This change reflects the fact that 1800-lb vehicles are virtually nonexistent in terms of new car sales. The weight specified for the newly recommended small passenger car represents the 2nd percentile lightest passenger vehicle in terms of sales (i.e., only 2 percent of new vehicles sold weigh less than the specified test weight).

- It has been recommended that the impact angle for all redirection tests be adjusted to 25 degrees. This change means an increase from the current 20 degree impact angle for small car tests and for pickup truck redirection tests on terminals and crash cushions. Considering both the increase in weight and impact angle, the impact severities of the small car redirection test (Test 3-10) and the pickup truck redirection tests on terminals and crash cushions (e.g., Test 3-35) increase by 106 percent and 73 percent, respectively. The revised small car redirection test will not pose a problem in terms of structural adequacy compared to the pickup truck test. However, the effect of the increase in angle and impact severity on vehicle stability and occupant risk may need to be evaluated for some devices. The substantial increase in impact severity for the pickup truck redirection tests on terminals and crash cushions will likely necessitate the modification or redesign of some of these devices.

- With the increase in weight to 5000 lb, the impact severity of the TL-3 pickup truck redirection test (Test 3-11) has an impact severity that is 16 percent greater than the current TL-4 single-unit truck test (Test 4-12). Consequently, it has been proposed to modify the conditions of the single-unit truck (SUT) impact in the Update to make it a more discerning test. The weight of the SUT will increase 25 percent from 17,640 lb to 22,050 lb, and the impact speed will increase 12 percent from 50 mph to 56 mph. The resulting increase in impact severity is 57 percent. This change may affect the status of some barriers currently classified as TL-4 barriers under *NCHRP Report 350*.

- The test matrix proposed in the *NCHRP Report 350* update for evaluation of breakaway support structures recommends three tests. The impact speed for the low-speed test (Test 60) has decreased from 21.7 mph to 18.6 mph. When combined with the increased weight of the new 2425-lb passenger car, the reduction in speed provides the same kinetic impact energy currently used in *NCHRP Report 350* to evaluate activation of breakaway supports. In addition to the traditional small car tests, evaluation of the impact performance of breakaway structures during high-speed impacts now also includes a test with a 5000-lb pickup truck at a speed of 62.2 mph. This test is intended to evaluate the geometric compatibility of the pickup with the support structure in terms of the potential for penetration of structural components or excessive intrusion into the occupant compartment.

- Evaluation Criterion D of *NCHRP Report 350* states that “Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.” To reduce the level of subjectivity associated with evaluating this criterion, the FHWA established a 6-inch threshold for occupant compartment deformation or intrusion. While the Update adopts a similar quantitative approach, it significantly relaxes the failure thresholds previously established by FHWA. Up to 9 inches of deformation or intrusion is permitted in the wheel/foot well and toe pan areas, as well as the front side door area above the seat. As much as 12 inches of deformation or intrusion is permissible in the floor pan and transmission tunnel areas, the side front panel, and the front side door area below the seat. Consequently, some devices that failed to comply with *NCHRP Report 350* due to excessive occupant compartment deformation may be acceptable under the Update.

- Side impact tests (off-tracking type impacts with the side of the vehicle impacting the device) will be included as optional tests and will not be a requirement of the new impact performance guidelines.

CHAPTER 3.

ASSESSMENT OF ROADSIDE SAFETY HARDWARE USED IN TEXAS

For economic reasons, many roadside safety features are optimized for the prescribed design impact conditions and have little or no factor of safety for accommodating more severe impacts. The changes in design vehicles and impact conditions proposed in the update to *NCHRP Report 350* (Update) will place more structural demand on barrier systems and may aggravate stability problems associated with some existing barriers.

A limited number of full-scale crash tests have been conducted under NCHRP Project 22-14(02) to help understand and evaluate the consequences of adopting the recommended changes on current hardware. Table 3-1 presents a summary of these tests. It should be noted that several of the tests listed in Table 3-1 involve a 5000-lb, ¾-ton, standard cab pickup. This vehicle was initially selected as the new design vehicle for the Update. The heavy design test vehicle was later changed to a 5000-lb, ½-ton, 4-door pickup to be more representative of large SUVs in terms of C.G. height and body structure. Several barrier systems that had previously been tested with the ¾-ton, standard cab pickup were retested with the ½-ton, 4-door pickup.

In the subsequent sections of this chapter, the results of these and other tests performed to date in accordance with the Update are used in combination with engineering analysis and engineering judgment to provide an initial assessment of the ability of TxDOT roadside safety hardware to comply with the Update. This initial evaluation is intended to help TxDOT prioritize future research and testing needs to achieve compliance of these devices with the Update, and to provide information that will assist TxDOT personnel in understanding of the implications of adopting the Update as it progresses through the AASHTO review and publication process. For ease of reference, the review is divided by category of roadside safety hardware (e.g., guardrail, median barrier, bridge rails, etc.).

GENERAL PERFORMANCE CONSIDERATIONS

The criteria used to assess the impact performance of Texas roadside safety hardware in regard to the Update are those recommended for evaluation of full-scale crash tests under both *NCHRP Report 350* and the Update. The assessment of a given device may include various qualitative and quantitative factors depending on the nature of the device and the availability of data.

Experience testing under *NCHRP Report 350* has identified three primary concerns or modes of failure: structural adequacy, vehicle stability, and occupant compartment deformation. Discussion of these three evaluation criteria will be helpful prior to assessing individual roadside safety devices.

Table 3-1. Summary of Crash Tests Conducted under NCHRP Project 22-14(02).

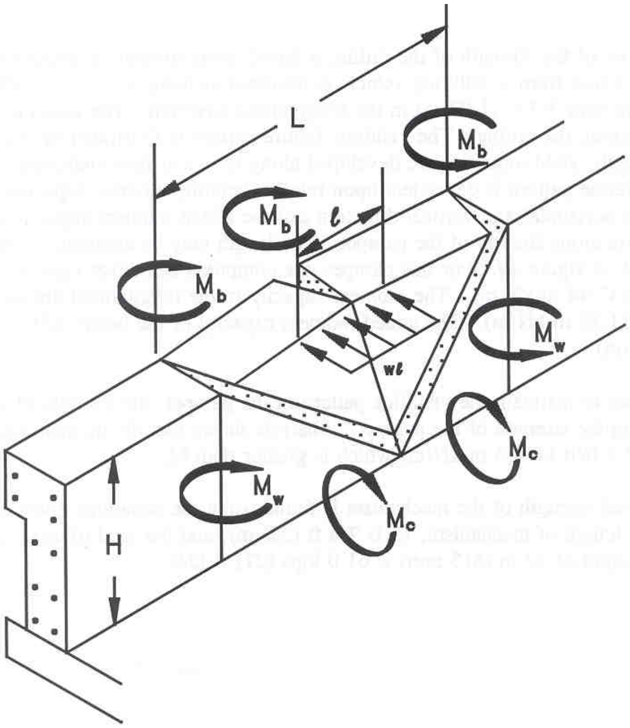
Ref. Test No.*	Agency Test No.	Test Designation	Test Article	Vehicle Make and Model	Vehicle Mass (lb)	Impact Speed (mph)	Impact Angle (deg)	Pass/Fail
1	2214WB-1	3-11	Modified G4(1S) Guardrail	2002 GMC 2500 ¾-ton Pickup	5000	61.1	25.6	Fail[1]
2	2214WB-2	3-11	Modified G4(1S) Guardrail	2002 Dodge Ram 1500 Quad Cab Pickup	5000	62.4	26.0	Pass
3	2214MG-1	3-11	Midwest Guardrail System (MGS)	2002 GMC 2500 ¾-ton Pickup	5000	62.6	25.2	Pass
4	2214MG-2	3-11	MGS	2002 Dodge Ram 1500 Quad Cab Pickup	5000	62.8	25.5	Pass
5	2214MG-3	3-10	MGS (Max. Height)	2002 Kia Rio	2588	60.8	25.4	Pass
6	2214TB-1	3-11	Free-Standing Temporary F-Shape Barrier	2002 GMC 2500 ¾-ton Pickup	5000	61.8	25.7	Pass
7	2214TB-2	3-11	Free-Standing Temporary F-Shape Barrier	2002 Dodge Ram 1500 Quad Cab Pickup	5000	61.9	25.4	Pass
8	2214NJ-1	3-10	32-in. Permanent New Jersey Safety Shape Barrier	2002 Kia Rio	2579	60.8	26.1	Pass
9	2214T-1	3-21	Guardrail to Concrete Barrier Transition	2002 Chevrolet C1500HD Crew Cab Pickup	5083	60.3	24.8	Pass
10	2214TT-1	3-34	Sequential Kinking Terminal (SKT)-MGS (Tangent)	2002 Kia Rio	2597	64.4	14.5	Pass
11	2214NJ-2	4-12	32-in. Permanent New Jersey Safety Shape Barrier	1989 Ford F-800	22,045	56.5	16.2	Fail[2]

* For reference purposes within this report
[1] Rail ruptured
[2] Truck rolled over rail

Structural Adequacy

In regard to longitudinal barrier impacts, structural adequacy is evaluated with respect to a barrier’s ability to contain the impacting vehicle and either redirect it or capture it and bring it to a controlled stop. The vehicle is not permitted to penetrate, underride, or override the barrier although controlled lateral deflection is acceptable.

Structural adequacy of a barrier is often equated to its ultimate strength or capacity to resist lateral impact forces. Engineering analyses based on yield line theory or plastic design procedures can be used to compute the load capacity of rigid or semi-rigid barriers (e.g. bridge rails and concrete median barriers). Figure 3-1 illustrates such a yield line failure analysis procedure for a vertical concrete parapet. Structural adequacy can then be assessed by comparing the capacity of a barrier to a design force corresponding to a desired test or performance level.



$$L = \frac{\ell}{2} + \sqrt{\left(\frac{\ell}{2}\right)^2 + \frac{8H(M_b + M_w H)}{M_c}}$$

$$(w\ell)_{ult} = \frac{8M_b}{L - \frac{\ell}{2}} + \frac{8M_w H}{L - \frac{\ell}{2}} + \frac{M_c L^2}{H\left(L - \frac{\ell}{2}\right)}$$

Figure 3-1. Yield Line Failure Analysis for Concrete Parapet *(9)*.

Data from two instrumented wall studies *(7,8)* were used to derive barrier design loads for various test or performance levels included in the AASHTO *LRFD Bridge Design Specifications*: Section 13 – Railings. The test levels correspond to those contained in *NCHRP Report 350*. In these research studies, instrumented concrete walls were designed to measure the magnitude and location of vehicle impact forces. In this first study *(7)*, eight full-scale crash tests were conducted using various sizes of passenger cars and buses. The wall consisted of four 10-ft long panels laterally supported by four load cells. Each of the 42-inch tall x 24-inch thick panels was also instrumented with an accelerometer to account for inertia effects. Surfaces in contact with the supporting foundation and adjacent panels were Teflon coated to minimize friction. In the second such study *(8)*, a new wall with a height of 90 inches was constructed using similar design details; crash tests with a variety of trucks (up to and including an 80,000-lb tractor with tank-type trailer) were conducted. Speeds in these tests ranged from 50 mph to 60 mph, and the impact angles ranged from 15 degrees to 25 degrees.

The design load calculated for both TL-3 and TL-4 is 54 kips. Note that this design force derived from an impact with a nearly rigid instrumented wall barrier and, therefore, is considered to represent the upper bound of forces that would be expected on actual barriers. The design loads established for TL-5 and TL-6, which include consideration of 80,000-lb tractor trailers, are 124 kips and 175 kips, respectively.

During the course of the instrumented wall work, the researchers derived relationships that use a measured lateral impact force resulting from a vehicle-barrier collision to estimate the impact force associated with a collision involving a different vehicle and/or impact conditions. The relationship is given as:

$$F_2 = F_1\left(\frac{V_2}{V_1}\right)^2\left(\frac{\sin\theta_2}{\sin\theta_2}\right)\left(\frac{L_1}{L_2}\right)\left(\sqrt{\frac{K_2}{K_1}}\right)\left(\sqrt{\frac{W_2}{W_1}}\right)$$

Where:

F = impact force,
V = impact velocity,
θ = impact angle
L = longitudinal distance from front of vehicle to center of gravity
K = barrier contact area or stiffness
W = vehicle weight

Using 54 kips as the design impact force for *NCHRP Report 350* test 3-11, the impact force corresponding to the revised Update test 3-11 with the ½-ton, 4-door pickup truck can be estimated. The impact speed and angle used in Update test 3-11 are the same as those prescribed under *NCHRP Report 350* and, therefore, will not influence the impact force. Assuming the contact area associated with impacts by both pickup trucks is essentially the same for a given longitudinal barrier system, the change in impact force becomes a function of vehicle weight and vehicle length. Using measured vehicle lengths of test vehicles (from the front bumper to the center of gravity) and the nominal vehicle weights specified for the respective pickup trucks, the impact force associated with Update test 3-11 can be estimated as follows:

$$F_2 = F_1 \left(\frac{L_1}{L_2} \right) \left(\sqrt{\frac{W_2}{W_1}} \right)$$

$$F_2 = 54 \left(\frac{90in}{100in} \right) \left(\sqrt{\frac{5000lb}{4409lb}} \right) = 52kips$$

The estimated impact force of 52 kips for Update test 3-11 represents a 4 percent <u>decrease</u> from the 54 kip design load used for *NCHRP Report 350* test 3-11. This result is somewhat unexpected considering the 13 percent increase in vehicle weight and impact severity associated with this test. It leads to the conclusion that the structural adequacy of TL-3 barriers that comply with *NCHRP Report 350* guidelines should be sufficient to comply with the same test level under the Update.

A similar analysis can be conducted for Test Level 4. As previously discussed, the Update recommends increasing the weight of the TL-4 single unit truck from 17,640 lb to 22,050 lb, and increasing impact speed from 50 mph to 56 mph. The impact angle will remain unchanged and, therefore, will not influence the impact force. Since the dimensions of the SUT have not changed, the vehicle length and the contact area associated with an impact into a given longitudinal barrier system will not be factors.

Using 54 kips as the design impact force for *NCHRP Report 350* test 4-12, and nominal vehicle weights and impact speeds specified for the respective TL-4 tests, the impact force associated with Update test 4-12 can be estimated as follows:

$$F_2 = F_1 \left(\frac{V_2}{V_1} \right)^2 \left(\sqrt{\frac{W_2}{W_1}} \right)$$

$$F_2 = 54 \left(\frac{56mph}{50mph} \right)^2 \left(\sqrt{\frac{22{,}050lb}{17{,}640lb}} \right) = 76\,kips$$

The estimated impact force of 76 kips for Update test 4-12 represents a 41 percent increase from the 54 kip design load used for *NCHRP Report 350* test 4-12. Consequently, some barriers that meet the *NCHRP Report 350* guidelines as a TL-4 barrier may not have adequate strength to comply with the same test level under the proposed Update.

Another aspect of the structural adequacy criteria is that the test vehicle should not override the barrier. Adequate barrier height is required to prevent heavy trucks with high centers of gravity from rolling over a barrier. Full-scale crash testing has shown that 32-inch tall barriers are capable of meeting TL-4 impact conditions under *NCHRP Report 350*. However, when Update Test 4-12 was conducted on a 32-inch tall New Jersey safety-shape concrete barrier (see Test 11 in Table 3-1), the single-unit truck (SUT) rolled over the top of the barrier.

After the unsatisfactory outcome of this test, it was proposed to reduce the center-of-gravity (C.G.) height of the ballast of the SUT from 67 inches to 63 inches. This effectively decreases the overturning moment by decreasing the moment arm between the C.G. of the truck and the reactive force applied by the barrier. Additional testing is required to determine if this decrease in C.G. height is sufficient to permit 32-inch tall barriers to contain the SUT or if taller barriers will be needed to comply with the Update.

Vehicle Stability

For all tests involving passenger vehicles, a key requirement for the safety of vehicle occupants is for the impacting vehicle to remain upright during and after the collision. Criterion F of *NCHRP Report 350* states that moderate roll, pitching, and yawing are acceptable. The commentary in Section A5.2 further explains that "Violent roll or rollover, pitching, or spinout of the vehicle reveal unstable and unpredictable dynamic interaction, behavior that is unacceptable." However, the term "moderate" used in Criterion F is not defined, thereby leaving evaluation of this criterion somewhat subjective.

The Update retains language that the impacting vehicle should remain upright during and after an impact. However, to provide a further indication of vehicle stability, and to make evaluation of Criterion F more quantitative, the maximum roll and pitch angles are not to exceed a threshold of 75 degrees.

Since the adoption of a ¾-ton pickup truck as the design test vehicle for structural adequacy tests, vehicle instability and rollover has been a common failure mode associated with longitudinal barrier impacts including guardrails, bridge rails, and transitions. Compared to passenger cars, pickup trucks have a higher center of gravity, a shorter front overhang, and greater bumper height (see Table 3-2). All of these factors combine to make the pickup truck a more critical vehicle than a passenger car in regard to impact performance with roadside safety features. The propensity for wheel snagging, occupant compartment deformation, and vehicle instability (i.e., rollover) are greater for the pickup truck than passenger cars.

National Highway Traffic Safety Administration (NHTSA) officials believe that the static stability factor (SSF) is one of the most reliable indicators of rollover risk in single vehicle crashes. A statistical study using data from six states showed that there is a strong correlation between a vehicle's SSF and its likelihood of being involved in a rollover. A higher SSF indicates a more stable vehicle with less propensity for rollover. As expected, the pickup trucks have a higher SSF than the passenger sedan (see Table 3-2). More interesting is that although the new 2270P has a slightly greater C.G. height than the 2000P, its SSF is actually greater than the 2000P. This is an indicator that the 2270P may be more stable in barrier impacts than the 2000P. Further, the longer front overhang of the 2270P makes it less critical than the 2000P in terms of snagging severity and snagging-induced instability. TTI researchers also believe the improved stability of the 2270P can be attributed to increased torsional rigidity provided by its different frame design and longer crew cab body.

Table 3-2. Comparison of Critical Test Vehicle Dimensions.

Vehicle Property	Vehicle Type		
	4500S[1]	2000P[2]	2270P[3]
C.G. Height (in.)	22	27	28
Front Overhang (in.)	43	32	39
Bumper Height[4] (in.)	12-21	16-25	14-27
Wheelbase (in.)	120	132	140
Track Width (in.)	62	64	68
Static Stability Factor[5]	1.41	1.19	1.21

[1] 4500-lb passenger sedan; *NCHRP Report 230* design vehicle
[2] 4409-lb, ¾-ton, standard cab pickup truck; *NCHRP Report 350* design vehicle
[3] 5000-lb, ½-ton, 4-door, quad-cab pickup truck; Update design vehicle
[4] Range: bottom edge – upper edge
[5] SSF = T/2h, where T = track width and h = C.G. height

Although the data are very limited at this point, these observations regarding the relative stability of the two pickup truck design vehicles are supported by crash test data. Test 6 and Test 7 in Table 3-1 are nominally identical tests of a precast, F-shape, pin-and-loop, concrete median barrier. The only difference is the type of pickup. Test 6 was conducted with a 5000-lb, ¾-ton, standard cab, GMC 2500 pickup; Test 7 involved a 5000-lb, ½-ton, 4-door, Dodge Ram 1500 quad-cab pickup. While both vehicles were contained and redirected, the ¾-ton, standard cab pickup exhibited much greater roll and was noticeably less stable than the ½-ton, quad-cab pickup.

Thus, devices that have stably contained and redirected the 2000P pickup under *NCHRP Report 350* guidelines would not be expected to have stability concerns with the new 2270P pickup in the Update. In fact, it is possible that some devices that failed to comply with *NCHRP Report 350* due to instability and rollover of the pickup truck might satisfy the Update.

Occupant Compartment Deformation

Another common mode of failure for bridge rails and guardrail-to-bridge rail transitions tested in accordance with the guidelines of *NCHRP Report 350* is excessive occupant compartment deformation. This type of failure is most often associated with severe snagging of the front, impact-side wheel at a joint, splice, or transition that results in the wheel being pushed into the fire wall and toe pan area of the occupant compartment. While such behavior was rarely observed when testing with large passenger sedans under *NCHRP Report 230*, the short front overhang of the pickup truck exposed the wheel and made snagging contact between the wheel and structural components of barriers a common occurrence.

As mentioned previously, Evaluation Criterion D of *NCHRP Report 350* states that "Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted." Because the extent of deformation that can cause serious injury was not defined, this criterion was subjective in nature. Testing houses routinely had internal and external discussions regarding the magnitude and location of deformation that should constitute a pass or fail. To reduce the level of subjectivity associated with evaluating this criterion, the FHWA established a 6 inch threshold for occupant compartment deformation or intrusion. This threshold subsequently became the standard by which testing houses evaluated occupant compartment deformation.

While the Update adopts a similar quantitative approach, it significantly relaxes the failure thresholds previously established by FHWA. The limiting extent of deformation varies by area of the vehicle damaged:

- roof ≤ 3.9 inches,
- windshield ≤ 3.0 inches,
- side windows – no shattering resulting from direct contact with structural member of test article,
- wheel/foot well/toe pan ≤ 8.9 inches,
- side front panel (forward of A-pillar) ≤ 11.8 inches,
- front side door area (above seat) ≤ 8.9 inches,
- front side door (below seat) ≤ 11.8 inches,
- floor pan and transmission tunnel area ≤ 11.8 inches.

In addition to establishing maximum acceptable deformation thresholds to establish pass/fail criteria, a damage rating scale was introduced to further indicate vehicle damage and barrier performance. The damage scale has the following ratings and associated ranges of intrusion/deformation:

Rating	Extent of Intrusion
Good	<5.9 inches
Acceptable	2.9 inches – 8.9 inches
Marginal	8.9 inches – 11.8 inches
Poor	>11.8 inches

The Update also makes a clear distinction between: "(a) penetration, in which a component of the test article actually penetrates into the occupant compartment; and (b) intrusion or deformation, in which the occupant compartment is deformed and reduced in size, but no actual penetration is observed." Penetration by any element of the test article into the occupant compartment of the vehicle is not allowed.

The change in deformation thresholds notwithstanding, design characteristics of the 2270P will decrease its propensity for severe snagging and excessive occupant compartment deformation. Improved vehicle design and vehicle crashworthiness (e.g., introduction of crumple zones and other energy management strategies) will reduce occupant compartment deformation in a variety of crash scenarios. Furthermore, the longer front overhang of the 2270P makes it less critical than the 2000P in terms of snagging severity and snagging-induced occupant compartment deformation.

Consequently, researchers believe that as a result of the relaxed deformation thresholds, improved vehicle design, and the longer front overhang of the 2270P pickup, occupant compartment deformation will cease to be a factor in the evaluation of roadside safety devices. Devices that have contained and redirected the 2000P pickup under *NCHRP Report 350* guidelines without excessive occupant compartment deformation (i.e., ≤ 6 inches) would not be expected to have occupant compartment intrusion or deformation concerns with the new 2270P pickup proposed under the Update. In fact, it is possible that some devices that failed to comply with *NCHRP Report 350* due to excessive occupant compartment deformation inside the pickup truck might satisfy the Update.

METAL BEAM GUARD FENCE

In the mid 1990s, TTI researchers conducted full-scale crash tests of all commonly used guardrail systems in accordance with *NCHRP Report 350* Test 3-11 under a pooled fund study administered by FHWA *(10)*. It was under this testing program that performance issues associated with light trucks impacting the standard strong steel-post W-beam guardrail system, G4(1S), were first identified. Snagging of the pickup truck's wheels on the steel support posts was aggravated by the collapse of the W6x9 steel offset blocks, and precipitated rollover of the truck as it exited the barrier. Subsequent testing demonstrated that a modified G4(1S) system that incorporates 8 inch deep wood or structural plastic offset blocks between the W-beam rail element and W6x9 steel posts in lieu of the original W6x9 steel offset block was able to accommodate the ¾-ton, 2-door, pickup truck design vehicle (denoted 2000P) and comply with *NCHRP Report 350* guidelines *(11,12,13)*.

The strong wood-post W-beam guardrail system, G4(2W), which utilizes 6 inch x 8 inch wood posts and offset blocks, contained and redirected the 2000P pickup *(10)*. However, instability of the pickup truck resulted in the test being classified as marginally acceptable.

Both of these strong-post W-beam guardrail systems are national standards and form the basis for TxDOT's current guard fence designs. A cross section of a typical TxDOT guard fence is shown in Figure 3-2. The guard fence is constructed with 12 gauge, W-beam rail mounted at a height of 21 inches to the center on 6-ft long W6x9 steel, 7-inch diameter wood, or 6 inch x 8 inch wood posts spaced at 6 ft-3 inches. The 8 inch deep offset blocks inserted between the rail and posts may be fabricated from wood or an approved alternative.

These strong-post W-beam guardrail systems are at or near their performance limits under *NCHRP Report 350* impact conditions. The increase in the weight of the proposed ½-ton, 4-door, pickup truck (designated 2270P) increases the impact severity of the structural adequacy test (Test 3-11) for longitudinal barriers by 13 percent. Under NCHRP Project 22-14(02), a series of crash tests were conducted to assess the impact performance of strong-post W-beam guardrail when subjected to the revised impact conditions.

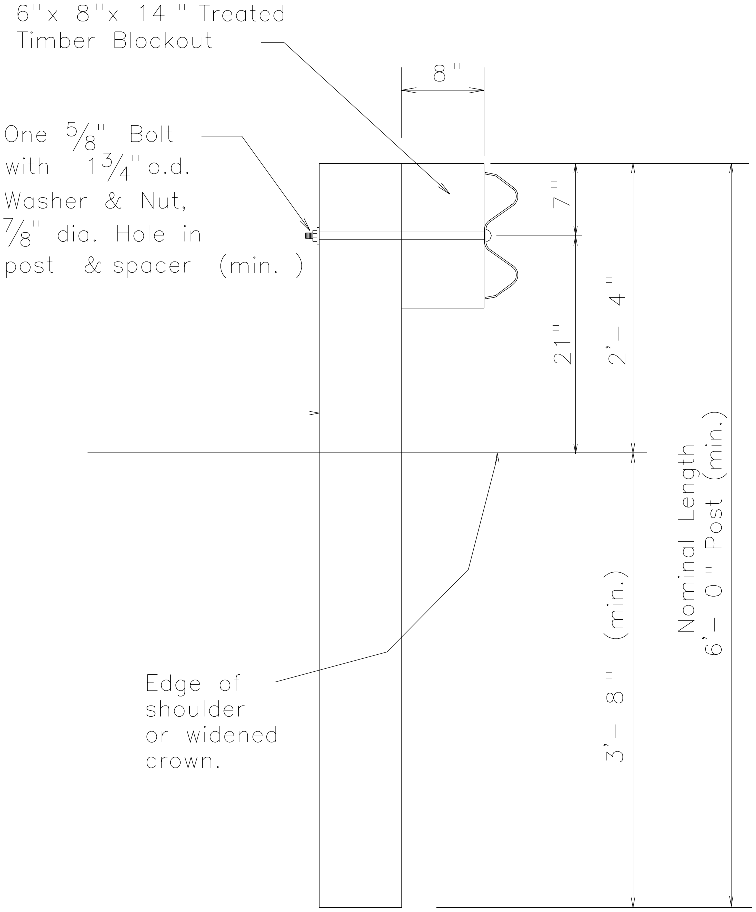


Figure 3-2. Typical Cross Section of Metal Beam Guard Fence.

As indicated in Test 1 of Table 3-1, a standard 27-inch tall, modified G4(1S) steel post W-beam guardrail failed due to rail rupture when impacted by a 5000-lb, ¾-ton pickup truck. In a subsequent test of the same system with the 5000-lb, ½-ton, 4-door pickup truck proposed as the design test vehicle for the Update, the guardrail successfully contained and redirected the vehicle. However, the rail was torn through approximately half of its cross section, indicating that the modified G4(1S) guardrail is at its performance limits with no factor of safety.

The same sequence of tests with the two different pickup trucks was conducted on a modified guardrail design known as the Midwest Guardrail System (MGS) *(14)*. This modified guardrail increases the W-beam rail height from 27 inches to 31 inches, increases the depth of the offset blocks between the rail and posts from 8 inches to 12 inches, and moves the rail splice locations from the posts to mid-span between posts. In both tests, the pickup truck was successfully contained and redirected. The MGS guardrail was also successfully tested under modified Test 3-10 impact conditions with the proposed 2425-lb small car at a speed of 62 mph and a modified angle of 25 degrees.

Two proprietary strong-post W-beam guardrail designs have also recently been tested with the proposed 5000-lb, ½-ton, 4-door pickup truck and 2425-lb small car with acceptable results. A system manufactured by Trinity Industries, known as the T-31 *(15)*, has a rail height of 31 inches and relocates the rail splices to midspan between posts. It incorporates a proprietary Steel Yielding Line Post (SYLP) and countersunk mounting bolt that enables the guardrail to function acceptably without offset blocks. The Gregory Mini-Spacer (GMS) guardrail system *(16)*, a product of Gregory Highway Products, utilizes a proprietary connection system that enables it to function satisfactorily without offset blocks. The GMS guardrail has a 31 inch mounting height, uses conventional W6x9 steel posts, and positions rail splices at the posts.

In summary, full-scale crash testing has shown the impact performance of the standard TxDOT metal beam guard fence design to be marginally acceptable with no factor of safety beyond the recommended impact conditions of the Update. No further testing of this system is deemed necessary. Should TxDOT desire to use a guardrail system with improved capacity for accommodating light trucks, there are three higher containment strong-post W-beam guardrail systems that comply with the Update guidelines available for use. The generic MGS will be more expensive and require more space than the modified G4(1S) due to the larger offset blocks. The cost of the proprietary T-31 and GMS guardrails should be comparable to conventional strong-post W-beam systems, and these systems will require less lateral space due to the absence of offset blocks.

MEDIAN BARRIERS

High-tension cable median barrier systems have rapidly gained popularity in Texas as a cost-effective alternative for shielding motorists from crossover crashes. Their relatively low cost makes cable median barrier systems appealing for treating long stretches of highway. Additionally, the flexibility of these systems results in lower decelerations to an impacting vehicle, which lowers the probability of injury to occupants. However, sufficient space must be available to accommodate the greater design deflections associated with these systems.

Presently, there are five high-tension cable barriers in the market place, at least four of which have had application on Texas highways. All of these systems are proprietary and, thus, will not be discussed in detail herein. However, it is fully expected that these systems will be capable of successfully containing and redirecting the new 5000-lb, ½-ton, 4-door pickup truck specified in the Update. The 13 percent increase in impact severity associated with Update test 3-11 will likely increase dynamic deflections of these systems. If desired, the modest increase in deflection can be offset through the use of reduced post spacing or other means.

Concrete median barriers that meet *NCHRP Report 350* include the New Jersey, F-shape, single slope, and vertical wall *(17,18)*. While the New Jersey profile has a long history of widespread use, it has been falling out of favor in recent years based on the realization that it can impart significant climb and instability to impacting vehicles. A vertical wall barrier eliminates issues of vehicle instability but will impart slightly higher decelerations and cause more vehicle damage than the other barrier types. The F-shape and single slope barriers have comparable impact performance and fall between the New Jersey safety shape and vertical wall parapet in terms of vehicle climb and decelerations.

The two types of concrete median barrier currently used by TxDOT are the F-shape concrete safety barrier (CSB(1)-04) and the single slope concrete barrier (SSCD(2)-00A). These concrete barriers are frequently used in narrow medians along high-speed, high-volume roadways due to their negligible deflection, low life-cycle cost, and maintenance-free characteristics. The rigid nature of these concrete barriers results in essentially no dynamic deflection. Thus, vehicle deceleration rates and probability of injury are greater for concrete barriers than for more flexible systems. Although the installation cost is relatively high, concrete barriers require little maintenance or repair after an impact. This reduces the risk to maintenance personnel on high-volume, high-speed roadways.

Basic dimensions of the F-shape concrete safety barrier are presented in Figure 3-3. The barrier is 32 inches tall and has a top width of 9.5 inches to accommodate lighting and signage when necessary. Reinforcement consists of #5 stirrups at 12 inches and eight #5 longitudinal bars spaced symmetrically about the vertical centerline of the barrier. Complete fabrication details for the F-shape concrete barrier can be found in TxDOT standard detail sheet CSB(1)-04.

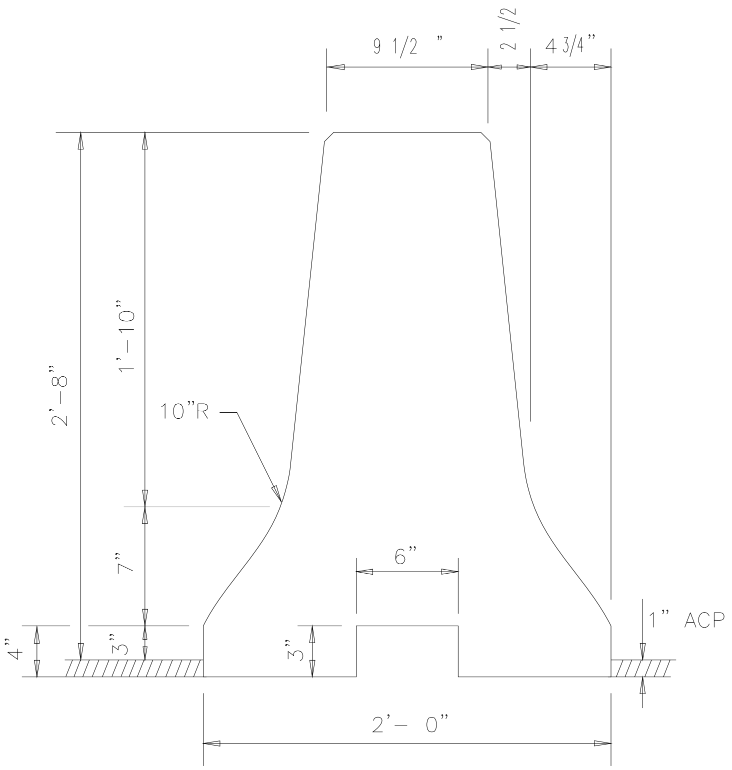


Figure 3-3. Typical Cross Section of F-Shape Concrete Safety Barrier.

A cross section of the single slope concrete barrier is shown in Figure 3-4. The barrier is 42 inches tall and has a top width and bottom width of 8 inches and 24 inches, respectively. The taller height and constant slope profile permit this barrier to accommodate multiple pavement overlays without affecting its impact performance with passenger vehicles. Reinforcement consists of #4 stirrups spaced at 12 inches and 10 #5 longitudinal bars spaced symmetrically about the vertical centerline of the barrier. The reader is referred to TxDOT standard detail sheet SSCB(2)-00A for complete fabrication details for the single slope concrete barrier.

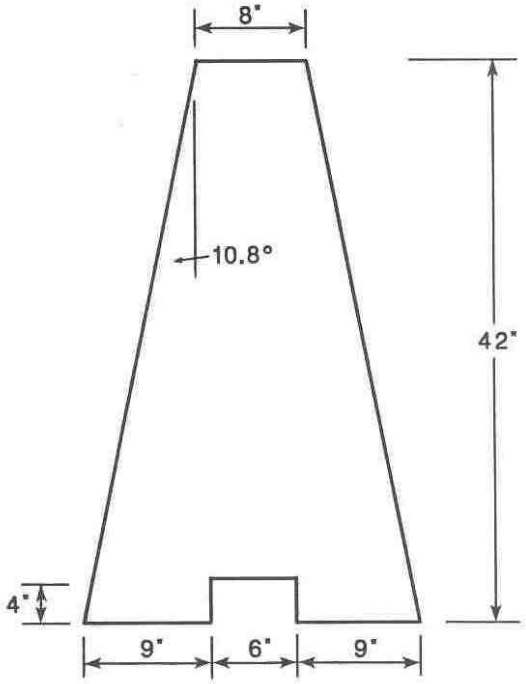


Figure 3-4. Cross Section of Single Slope Concrete Barrier.

Given the estimated impact force associated with Update test 3-11 with the new pickup truck is comparable to the design impact force used for *NCHRP Report 350* test 3-11, both the F-shape concrete safety barrier and single slope concrete barrier should easily meet structural adequacy requirements for the revised TL-3 impact conditions.

The only possible problem that might exist with either concrete median barrier is in regard to the stability of the new 5000-lb, ½-ton, 4-door, quad-cab pickup. However, as discussed earlier in this chapter, the new pickup truck design vehicle has a greater static stability factor than the ¾-ton, 2-door, standard cab pickup; limited full-scale crash testing conducted under NCHRP Project 22-14(02) with both vehicle types indicates that the ½-ton, 4-door quad-cab pickup is more stable than the ¾-ton, 2-door standard cab pickup.

Crash test data further support the argument that instability of the pickup truck should not be an issue with the F-shape concrete safety barrier or single slope concrete barrier. Under

NCHRP Project 22-14(02), two tests (Test 6 and Test 7 in Table 3-1) were conducted on a precast, F-shape, pin-and-loop, concrete median barrier. Test 6 was conducted with a 5000-lb, ¾-ton, standard cab, GMC 2500 pickup; Test 7 involved a 5000-lb, ½-ton, 4-door, Dodge Ram 1500 quad-cab pickup. In both tests, the vehicles were successfully contained and redirected. In another test, a 5000-lb, ¾-ton, standard cab pickup was successfully contained and redirected after impacting a precast, Texas F-shape concrete maintenance barrier with X-bolt connection and 10-ft long segments.

Testing has shown that a precast barrier system will impart more motion and instability to an impacting vehicle than a rigid, permanent barrier with the same profile. This effect is due to the deflection of the precast barrier system, which increases the effective impact angle between the pickup and the precast barrier segments downstream from the initial point of contact. Therefore, given that two different versions of a precast, F-shape barrier successfully contained and redirected the more critical 5000-lb, ¾-ton, standard cab pickup, it can be concluded that the permanent F-shape concrete safety barrier will successfully contain and redirect a 5000-lb, ½-ton, 4-door, quad-cab pickup in an upright and even more stable manner. Further, the single slope concrete barrier, which previous testing has shown to have comparable dynamic vehicle behavior to the F-shape profile, should also demonstrate satisfactory impact performance for Update test 3-11.

Although the focus of the discussion has been the pickup truck redirection test, consideration must also be given to the small car redirection test. As previously discussed, Update test 3-10 has been revised to include a heavier 2425-lb passenger car (denoted 1100C) impacting at a higher 25 degree impact angle. This test is compared to *NCHRP Report 350* test 3-10, which involves an 1800-lb vehicle impacting the barrier at an angle of 20 degrees. Considering both the increase in weight and impact angle, the impact severity of the revised small car redirection test (Update Test 3-10) has increased by 106 percent. Since the impact severity of the pickup truck redirection test is still twice that of the small car redirection test, the revised small car redirection test will not pose a problem in terms of structural adequacy. However, the effect of the increase in angle and impact severity on vehicle stability and occupant risk was a concern, particularly for shaped rigid barriers such as the New Jersey profile.

Update test 3-10 was conducted on a permanent New Jersey profile barrier under NCHRP Project 22-14(02) to investigate this impact performance concern (see Test 8 of Table 3-1). In this test, a 2002 Kia Rio was successfully contained and redirected in an upright and stable manner, and occupant risk measures were within acceptable limits. The New Jersey profile is known to impart more vehicle climb than the more stable F-shape and single-slope profiles. Therefore, the success of this test can be used to conclude that the impact performance of both the F-shape concrete safety barrier and single slope traffic railing will be satisfactory for Update test 3-10.

In summary, TxDOT's concrete median barriers should comply with the revised impact performance guidelines proposed under the update to *NCHRP Report 350*. Further testing and evaluation does not appear necessary at this time and, consequently, is given a low priority.

PORTABLE AND PRECAST CONCRETE MEDIAN BARRIER

Portable and precast concrete median barriers are often used in work-zones to shield motorists from hazards in the work area (e.g., pavement edge drops, excavations, equipment, etc.), provide positive protection for workers, and separate two-way traffic. Due to the temporary and frequently changing nature of work zones, these barriers are designed to be easily transported, placed, and relocated. Unlike permanent concrete barriers, these free standing temporary barriers can undergo large displacements when subjected to a vehicular impact. Thus, vehicle deceleration rates will typically be less for portable and precast concrete median barriers than for rigid, permanent concrete barriers. On the other hand, the deflection of the free-standing barrier systems imparts more motion and instability to an impacting vehicle than a rigid, permanent barrier with the same profile due to an increase in the effective impact angle between the vehicle and precast barrier segments downstream from the initial point of contact.

Portable and precast barriers used by TxDOT include three variations of an F-shape concrete safety barrier and the low-profile concrete barrier. Two connection options are available for the F-shape barrier: an X-bolt connection (joint connection type X on standard drawing CSB(2)-04) and a J-J Hooks connection (joint connection type J on standard drawing CSB(2)-04). The J-J Hooks connection is proprietary and will not be discussed herein.

Precast F-Shape Concrete Median Barrier with Type X Connection

The cross-bolted (or Type X) connection utilizes two threaded rods/bolts to form the connection. The bolts are placed in different horizontal planes in the barrier at a prescribed angle with respect to the longitudinal axis of the barrier. The bolts pass through guide pipes cast into the ends of the barrier segments. The bolts exit one barrier segment and enter the adjacent barrier segment at the vertical center line of the barrier section. In plan view, the two connection rods/bolts form an "X" across the joint between adjacent barrier segments. Triangular wedges are cast into the barrier to permit the exposed ends of the cross bolts to be recessed and, thus, prevent vehicle snagging. The guide pipes through which the cross bolts pass are oversized to provide connection tolerance for barrier fabrication, installation, and placement of the barrier on horizontal and vertical curves. The tight moment connection provided by the cross-bolted design minimizes barrier deflections while maintaining constructability.

The precast segments used with the Type X connection are 30 ft in length and have a standard F-shape profile. The segments are 32 inches in height, 24 inches wide at the base, and 9½ inches wide at the top. Horizontal barrier reinforcement consists of eight #5 bars spaced liberally within the vertical reinforcement. Vertical barrier reinforcement consists of #5 bars spaced 12 inches on center. Within 5 ft of the barrier ends, the spacing of the vertical bars is reduced to 6 inches. A U-shaped bar is tied to the bottom of the vertical bars to provide closed stirrups in this region. A photograph of the F-shape concrete safety barrier with Type X connections is shown in Figure 3-5. For complete fabrication details of this precast barrier system, the reader is referred to TxDOT standard detail sheets CSB(1)-04 and CSB(2)-04.

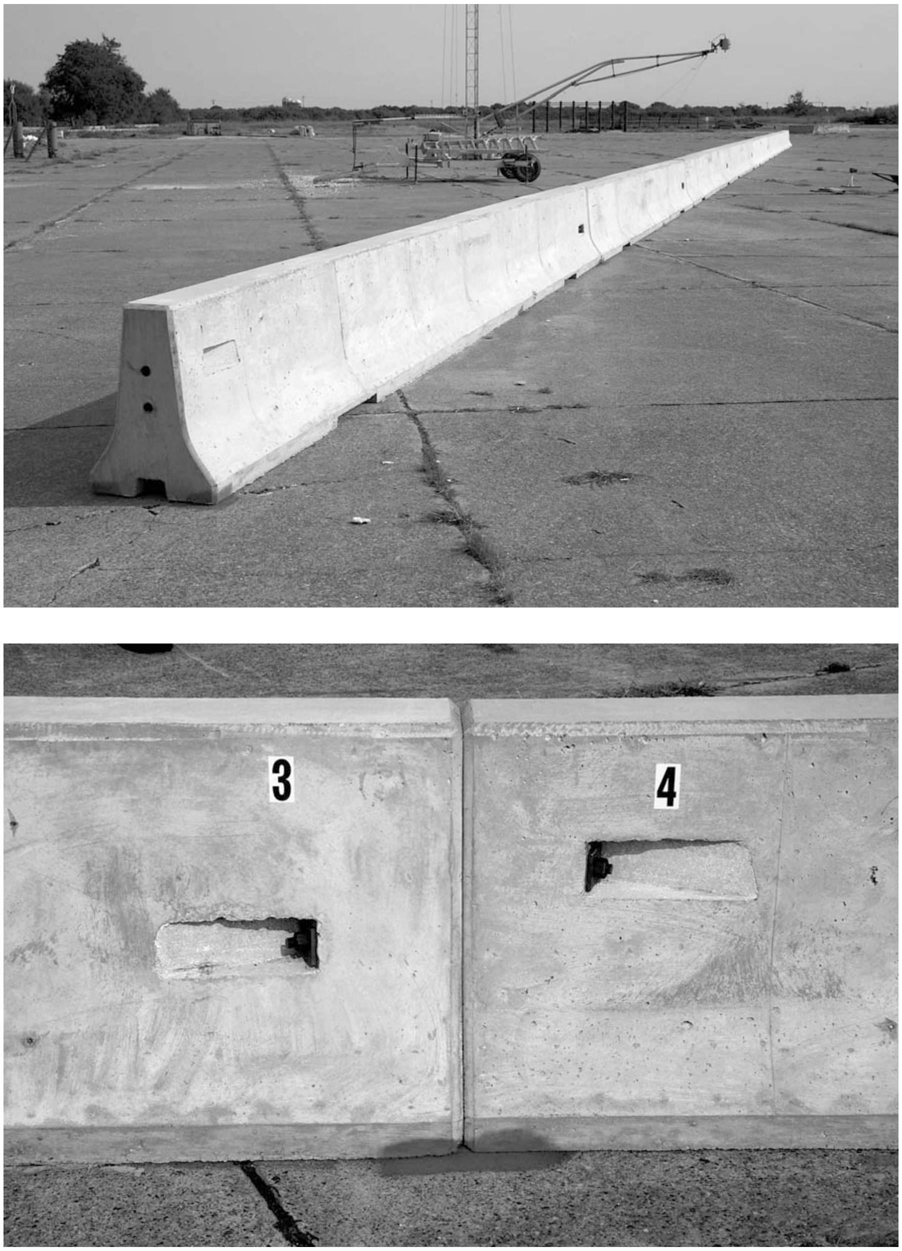


Figure 3-5. F-Shape Concrete Safety Barrier with X-Bolt Connection.

The F-shape concrete median barrier with Type X connection and 30-ft long precast segments was successfully tested under *NCHRP Report 350* guidelines *(19)*. A ¾-ton Chevrolet 2500 pickup with a test inertia weight of 4531 lb impacted the barrier at a speed of 62.3 mph and an angle of 25.7 degrees. The vehicle was successfully contained and redirected in a stable and upright manner. Occupant risk measures were below desirable levels, and the maximum roll angle was 23.3 degrees. The maximum occupant compartment deformation measured in the vehicle was 2.6 inches. Maximum dynamic deflection of the barrier was only 19.0 inches, which is the lowest deflection of any free-standing, unanchored concrete barrier system accepted under *NCHRP Report 350* guidelines.

A variation of this barrier system was developed for use by maintenance personnel in maintenance operations. The barrier has the same F-shape profile and dimensions, and uses the same Type X connection as the standard precast F-shape concrete safety barrier. However, the segment length is reduced to 10 ft to make it more easily transported and erected by TxDOT maintenance forces using readily available equipment such as a front-end loader with a fork attachment. This system can be used for many routine and emergency maintenance and construction operations that require quick response times. Further details of this barrier can be found in TxDOT standard drawing CSB(8)-04.

This F-shape maintenance barrier with Type X connections and 10-ft long segments successfully contained and redirected a 5000-lb, ¾-ton, 2-door, standard cab pickup truck with a 27-inch high C.G. *(20)*. Occupant risk measures were below desirable levels. The maximum roll angle of the vehicle was 30 degrees, and the maximum occupant compartment deformation was 1.8 inches in the firewall area. Maximum dynamic movement of the barrier segments was only 27 inches. Even though tested with an impact severity corresponding to the Update, this is still the lowest deflection of any free-standing, portable concrete barrier approved to *NCHRP Report 350* requirements other than the X-bolt barrier with 30-ft segments.

Recall from previous discussions that 5000-lb, ¾-ton, standard cab pickup truck is more critical than the 5000-lb, ½-ton, 4-door, quad-cab pickup truck currently proposed in the Update in terms of both structural adequacy and stability. Thus, the F-shape maintenance barrier with Type X connections and 10-ft long segments is considered to have met the requirements of *NCHRP Report 350* Update. Further, since the F-shape barrier with Type X connections and 30-ft long segments offers improved vehicle stability compared to the maintenance version of the barrier, the successful test of the F-shape maintenance barrier with the 5000-lb, ¾-ton, pickup can be used to infer compliance of the F-shape barrier with 30-ft long segments with the update.

Although Update test 3-10 has not been conducted on a portable, F-shape concrete median barrier, it is not believed to pose an impact performance problem for the Texas F-shape barriers with Type X connections. As mentioned previously, Update test 3-10 was conducted on a permanent New Jersey profile barrier under NCHRP Project 22-14(02) (Test 8 of Table 3-1). In this test, a 2002 Kia Rio was successfully contained and redirected in an upright and stable manner, and occupant risk measures were within acceptable limits. The New Jersey profile is known to impart more vehicle climb than the more stable F-shape profile, and the deflections of the F-shape barriers with Type X connections for impacts with the small car under Update test 3-10 impact conditions will be small. Therefore, both F-shape barriers with Type X connections should meet the impact performance requirements for Update test 3-10.

In summary, TxDOT's precast, F-shape barriers with Type X connections should comply with the revised impact performance guidelines proposed under the update to *NCHRP Report 350*. Further testing and evaluation does not appear necessary at this time and, consequently, is given a low priority.

Low Profile Barrier

The low-profile barrier system is a 20-inch high pre-cast concrete barrier system that incorporates a negative slope on the impact face. The low-profile barrier was originally developed for use in low speed work zones where the use of a traditional 32-inch high concrete barrier system would significantly limit visibility. Visibility is particularly important in urban areas where it is often necessary to have frequent openings in the barrier system that allow cross-traffic vehicles to enter the main traffic stream and vehicles in the main traffic stream to exit.

The low-profile barrier system consists of two different types of barrier segments: the primary low-profile segment and the end-treatment segment. The primary low-profile barrier segment is produced in 20 ft lengths. Figure 3-6 shows a sketch of the low-profile barrier segment cross-section. The low-profile end-treatment is a 20 ft long segment that tapers from a height of 20 inches at the high end to a height of 4 inches at the low end. Complete fabrication details for the low-profile barrier segment are presented in TxDOT standard detail sheet LPCB(1)-92, and complete fabrication details for the low-profile end-treatment are presented in TxDOT standard detail sheet LPCB(2)-92.

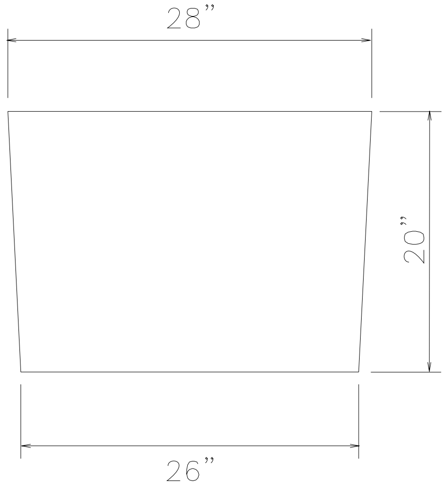


Figure 3-6. Cross-Section of Low-Profile Barrier Segment.

The low-profile barrier system has been successfully tested and approved for Test Level 2 of *NCHRP Report 350 (21)*. In addition, field experience with the low-profile barrier systems suggests that the low-profile barrier system is a valuable addition to the work zone barrier arsenal.

In addition to the low-profile barrier system meeting the qualifications for *NCHRP Report 350* TL-2 impact conditions, further testing conducted at TTI has shown that the low-profile barrier segment can also successfully redirect a 4500-lb full-size passenger vehicle impacting with a speed of 60 mph and an angle of 25 degrees. These impact conditions correspond to the full-service impact criteria presented in *NCHRP Report 230*. The impact severity, IS, associated with this more severe impact is 96,647 ft-lb. This impact severity is considerably higher (71 percent) than the impact severity associated with the revised TL-2 criteria recommended in the update to *NCHRP Report 350* (Update), which can be calculated to be 56,508 ft-lb. Therefore, researchers believe that the low-profile barrier system can easily meet the structural requirements for the revised TL-2 testing criteria.

The only possible problem that might exist with the low-profile barrier in regard to the new TL-2 testing criteria involves the stability of the new 5000-lb, ½-ton, 4-door, quad-cab pickup. Based on unreported testing conducted at TTI , it is known that when impacted at speeds greater than or equal to 50 mph, the low-profile barrier has a tendency to cause the *NCHRP Report 350* ¾-ton pickup to gently roll onto its side and slide down the roadway until coming to a stop. Because there is a 13 percent increase in the IS associated with the revised pickup impact, there is a slight chance that the pickup will become unstable under the new impact criteria. However, the impact severity associated with this 50 mph impact is 47 percent greater than the impact severity associated with the revised TL-2 impact conditions of the Update. Further, even though the new pickup truck design vehicle proposed in the Update has a vertical center-of-gravity approximately 1 inch greater than the ¾-ton, standard cab pickup of *NCHRP Report 350*, it has a greater static stability factor than the ¾-ton, 2-door pickup. Limited full-scale crash testing conducted under NCHRP Project 22-14(02) with both vehicle types indicates that the ½-ton, 4-door pickup is inherently more stable than the ¾-ton, 2-door pickup.

For these reasons, it is the opinion of the researchers that the low-profile barrier system should be able to successfully redirect the new pickup under TL-2 impact conditions. However, this assertion may ultimately have to be demonstrated through computer simulation or full-scale crash testing.

Based on the above discussion, the researchers have assigned a low priority to the retesting of the low-profile barrier system based on safety considerations alone. However, in light of the extensive popularity of this barrier system and its widespread use across the state, researchers believe that the testing priority of the low-profile barrier should be classified as medium.

TRANSITIONS

Transition sections are commonly used to connect a flexible approach guardrail to a more rigid bridge rail. The purpose of the transition is to gradually change the stiffness so that a vehicle impacting the flexible approach rail does not pocket or snag severely on the end of the stiffer bridge rail. The change in stiffness is generally accomplished through a combination of increased post strength, reduced post spacing, and/or increased rail strength.

Many of the guardrail-to-bridge rail transition designs tested and approved under *NCHRP Report 230* were unable to accommodate the ¾-ton pickup truck adopted as the design test vehicle for structural adequacy tests in *NCHRP Report 350*. The most common failure modes observed in full-scale crash tests of transitions with the pickup truck were excessive occupant compartment deformation and vehicle instability (i.e., rollover). It was found that the transition systems needed to be further stiffened to limit vehicle snagging to tolerable levels and avoid vehicle overturn.

It was further determined that the clear opening beneath the transition rail element had to be reduced through the addition of a rub rail or curb to prevent the wheel of the pickup from intruding underneath the transition rail and snagging on the stiff transition posts or end of the bridge rail parapet. As an example, a full-scale crash test was conducted to determine if the Type II curb detail can be eliminated from TxDOT's Test Level 3 nested thrie beam transition system without adversely affecting impact performance *(22)*. Test Designation 3-21 was performed in accordance with the guidelines and procedures set forth in *NCHRP Report 350*. This test consisted of a 4409-lb, ¾-ton pickup truck impacting the transition at a speed of 62.2 mph and an angle of 25 degrees. The test vehicle rolled over while exiting the test installation and, as a result, the nested thrie beam transition system without curb failed to meet the impact performance criteria of *NCHRP Report 350*. Therefore, the Type II curb had to be retained as part of the overall transition system.

TxDOT uses two different transition designs: a TL-3 system that is used on high-speed roadways (i.e., speeds $\geq$ 50 mph), and a TL-2 system that is used on roadways with speeds of 45 mph or less. These systems are evaluated below.

TL-3 Transition

A schematic of TxDOT's TL-3 transition is shown in Figure 3-7. This guardrail-to-concrete bridge rail transition consists of a nested thrie beam rail supported on 7-ft long steel or wood posts spaced at 18.75 inch. A 4-inch tall curb runs along the length of the nested thrie beam section. The front face of the curb is aligned with the traffic face of the wood blockout that offsets the thrie beam from the support posts. A thrie beam terminal connector is used to attach the downstream end of the transition to the concrete bridge rail parapet. On the upstream end, a 6 ft-3 inch, 10 gauge, thrie beam-to-W-beam transition element is used to transition the thrie beam to the W-beam rail element of the approach guardrail. Additional details of the TL-3 transition are presented in TxDOT standard detail sheet MBGF (TR)-02.

This transition system was originally designed and tested at the Midwest Roadside Safety Facility (MwRSF) at the University of Nebraska under sponsorship of the Midwest State's Regional Pooled Fund Program (TRP-03-69-98) *(23)*. Both steel post and wood post versions of the transition were successfully tested with a ¾-ton pickup truck following *NCHRP Report 350* test 3-21 impact conditions.

Under NCHRP Project 22-14(02), Update test 3-21 was conducted on the steel post version of this guardrail-to-concrete bridge rail transition to evaluate its impact performance with the 5000-lb, ½-ton, 4-door pickup and assess its compliance with the Update. In this test (Test 9 in Table 3-1), a 2002 Chevrolet C1500HD crew cab pickup weighing 5084 lb impacted the transition at its critical impact point at a speed of 60.3 mph and an angle of 24.8 degrees. The pickup was successfully contained and redirected in an upright manner. Consequently, the TxDOT TL-3 transition system complies with the update, and no further testing is necessary.

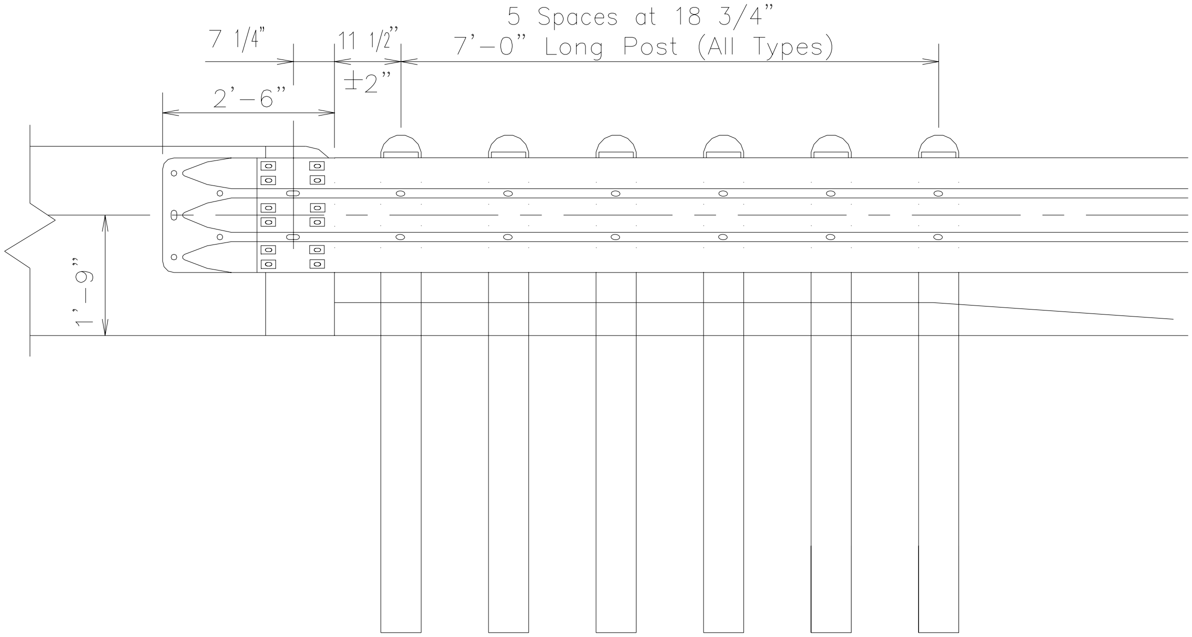


Figure 3-7. Elevation of Texas TL-3 Guardrail-to-Concrete Bridge Rail Transition.

TL-2 Transition

Most transition systems have been crash tested under TL-3 of *NCHRP Report 350*, which is the basic test level required to receive approval of the system for use on high-speed roadways. Since there are no national transition designs that have been developed for lower speed conditions, most states typically apply the same transition standard to all roadways regardless of speed and traffic volume. However, the new transition designs developed to comply with *NCHRP Report 350* represented a significant increase in installation cost and complexity over designs previously acceptable under *NCHRP Report 230*. Thus, it can be cost prohibitive to require use of the high-speed, TL-3 guardrail-to-concrete bridge rail transition systems on low-speed roadways.

For these reasons, TxDOT developed a cost-effective TL-2 transition for use on low-speed roadways. The TL-2 transition, shown in Figure 3-8, is entirely comprised of standard hardware components and is significantly less expensive and complex to install than the high-speed, TL-3 transition system. This transition consists of 12.5 ft of nested W-beam beam rail supported on 6-ft long steel or wood posts spaced at 37.5 inches. The 27-inch mounting height greatly simplifies the ability to connect the transition to some existing bridge rails. A W-beam terminal connector is used to attach the downstream end of the transition to the concrete bridge rail parapet. Additional details of the TL-3 transition are presented in TxDOT standard detail sheet MBGF (TL2)-05.

Figure 3-8. Photo of Texas TL-2 Guardrail-to-Concrete Bridge Rail Transition.

Test Designation 2-21 was performed in accordance with the guidelines and procedures set forth in *NCHRP Report 350 (22).* This test consisted of a 4409-lb, ¾-ton pickup truck impacting the critical impact point of the transition at a speed of 43.5 mph and an angle of 25 degrees. The test vehicle was successfully contained and redirected in a stable manner, and the TL-2 transition system met all applicable *NCHRP Report 350* evaluation criteria. The maximum dynamic deflection of the transition rail was only 2.6 inches. The maximum roll angle of the pickup truck was 13.4 degrees, and the maximum occupant compartment deformation was only 0.4 inches.

As discussed previously, the researchers believe the propensity for wheel snagging, excessive occupant compartment deformation, and vehicle instability (i.e., rollover) are greater for the ¾-ton pickup truck of *NCHRP Report 350* than the ½-ton, 4-door pickup truck designated in the Update. Although the 13 percent increase in vehicle weight and impact severity may slightly increase dynamic deflections, the small vehicle roll angle and occupant compartment deformation resulting from *NCHRP Report 350* test 3-21 indicate that the transition system can safely accommodate the increase without imparting excessive occupant compartment deformation (OCD) or vehicle instability. Indeed, even if the OCD were to modestly increase, it would unquestionably be below the 9 to 12 inch threshold established in the Update.

With these factors in mind, it is the opinion of the researchers that the TL-2 transition will comply with Update test 3-21. Further testing and evaluation does not appear necessary at this time and, consequently, is given a low priority.

BRIDGE RAILS

Bridge rails are longitudinal barriers designed to keep vehicles from encroaching off bridge structures and encountering underlying hazards. Bridge rails are typically rigid in nature due to the lack of space on bridge structures to accommodate barrier deflection. Common types of bridge rails include continuous concrete barriers, metal rails mounted on concrete parapets, and both concrete and metal beam and post systems.

The most common failure mode observed in bridge rail testing is excessive occupant compartment deformation arising from the wheel or other structural hard points on the impacting vehicle snagging on structural components of the bridge rail system. The clear openings between rail members and the setback distance of the traffic face of the rails from their support posts must be properly designed to minimize snagging on the support posts. Rail discontinuities such as joints and splices should facilitate smooth redirection without causing severe snagging. Severe snagging can result in high decelerations, vehicle instability, and/or unacceptable occupant compartment deformation, all of which can increase the probability of injury to occupants of an impacting vehicle.

Shaped rigid barriers, such as the New Jersey profile concrete barrier, should be designed with due consideration to vehicle stability. When a New Jersey-profile concrete barrier was crash tested with a ¾-ton, standard cab pickup truck at 62 mph and 25 degrees under *NCHRP Report 350* test 3-11, the barrier imparted significant climb, pitch, and roll to the pickup *(17)*.

Barrier profile is not the only source of vehicle instability. Inadequate rail height can also lead to vehicle instability and rollover. Although the 27 inch tall T203 bridge rail meets *NCHRP Report 350* requirements for a TL-3 barrier, any decrease in height due to pavement overlay will degrade impact performance and increase the propensity of vehicle instability and overturn.

TxDOT standards include various bridge rails that have been successfully tested or otherwise judged to meet the impact performance requirements of *NCHRP Report 350*. These crashworthy rail systems meet *NCHRP Report 350* test levels ranging from TL-2 to TL-6. This variety of rail types provides the bridge design engineer the flexibility to select a railing for a specific bridge site that is safe, cost-effective, and aesthetic.

Table 3-3 provides a summary of TxDOT's basic bridge traffic railing types by height and test level. As previously discussed, the estimated design impact force associated with Update test 3-11 with the new ½-ton, 4-door, pickup truck is comparable to the design impact force used for *NCHRP Report 350* test 3-11. Therefore, any railing system that complies with TL-2 or TL-3 of *NCHRP Report 350* should easily meet structural adequacy requirements for the same test level under the Update.

The same cannot be said about railings that comply with Test Level 4 of *NCHRP Report 350*. As previously discussed, the Update recommends increasing the weight of the TL-4 single unit truck from 18,000 lb to 22,050 lb, and increasing the impact speed of test 4-12 from 50 mph to 56 mph. Based on these conditions, the estimated design impact force for Update test 4-12 is 76 kips. This is a 41 percent increase from the 54 kip design load used for *NCHRP Report 350* test 4-12. Consequently, bridge rails that currently meet *NCHRP Report 350* guidelines as a TL-4 barrier may not have adequate strength to comply with the same test level under the Update.

Table 3-3. Summary of TxDOT Bridge Rails.

Std Name	Description	Height (in.)	Test Level
T101	Steel Post with W-Beam Backed by Steel Tubes	27	TL-3
T203	Concrete Beam and Post Parapet w/5 Ft Openings	27	TL-3
T221	Vertical Concrete Parapet	32	TL-4
T401	Concrete Parapet w/Steel Post and Rail	33	TL-3/TL-4*
T402	Concrete Parapet w/Steel Post and Rail	42	TL-4
T411	Concrete Traffic Rail w/windows (Texas Classic)	32	TL-2
T501	Concrete Safety Shape	32	TL-4
T6	Steel Post w/Tubular W-Beam	27	TL-2
T77	Steel Post w/Two Elliptical Pipes on Concrete Parapet	33	TL-3/TL-4*
HT	Heavy Truck Traffic Rail	50	TL-5
SSTR	Single Slope Traffic Rail	36	TL-4
TT	Tank Truck Traffic Rail	90	TL-6

* Analyses and tests of similar rails indicate that the geometry and strength of this rail is sufficient for TL-4, but this has not been verified through full-scale crash testing.

Although TL-3 has been selected by TxDOT as the minimum or basic requirement for bridge rails on high-speed roads in Texas, some of the railings in TxDOT's bridge rail standards have *NCHRP Report 350* TL-4 capacity (see Table 3-3). Table 3-4 presents a summary of the calculated design capacity of selected TxDOT bridge rails. These are railings whose structural adequacy for TL-4 of *NCHRP Report 350* has been demonstrated through testing and/or engineering analysis. When compared against the estimated design load of 68 kips associated with Update test 4-12, it can be seen that some of the current TL-4 railing systems may not have sufficient strength to accommodate the revised TL-4 impact conditions.

Table 3-4. Calculated Load Capacities of TxDOT Bridge Rails.

Bridge Rail System	Ultimate Load Capacity[1] (kips)
T77	62
T221	61
T401	72
T411	66
T501	79

[1] Capacity at a height of 32 inches based on yield line theory

However, it should be noted that strength analyses of barriers using yield line theory has been shown to be conservative. In other words, barrier systems often exhibit greater strength than indicated by engineering analyses. This difference is likely due in large part to inertia effects and dynamic rate effects that are not accounted for in the static analysis procedure. Furthermore, actual material strengths for the steel and concrete used in the construction of these rails are typically greater than the minimum specified strengths commonly used in the analyses. Thus, the actual capacities of the bridge rails listed in Table 3-4 may be greater than shown.

Furthermore, depending on the height of a given bridge rail, the impact load applied to the barrier by the SUT might be less than the 68 kip design load. This difference is due to the tendency of the SUT to roll into or on top of a barrier, thereby reducing the resultant lateral impact load applied to the barrier. As an example, TL-3 and TL-4 of *NCHRP Report 350* have the same design impact load of 54 kips. Testing of a 32-inch New Jersey profile bridge rail with an SUT following test 4-12 impact conditions resulted in successful containment and redirection with no discernable barrier damage, while a pickup truck test (test 3-11) into the same barrier system resulted in significant barrier damage *(23)*. This difference was attributed in large part to the roll motion of the single unit truck, which dissipated some of the truck's energy.

In addition to strength, adequate barrier height is required to prevent heavy trucks with high centers of gravity from rolling over a barrier. The T221, T401, T501, and T77 rails have heights of 32 inches to 33 inches. Full-scale crash testing has shown that 32-inch tall barriers are capable of meeting TL-4 impact conditions under *NCHRP Report 350*. However, when Update Test 4-12 was conducted on a 32-inch tall New Jersey safety-shape concrete barrier (see Test 11 in Table 3-1), the single-unit truck (SUT) rolled over the top of the barrier.

Based on the unsuccessful outcome of this test, it was proposed to reduce the center-of-gravity (C.G.) height of the ballast of the SUT from 67 inches to 63 inches. This effectively decreases the overturning moment applied to the SUT by decreasing the moment arm between the C.G. of the truck and the reactive force applied by the barrier. Additional testing is required to determine if this decrease in C.G. height is sufficient to permit 32-inch tall barriers to contain the SUT or if taller barriers will be needed to comply with the Update.

In conclusion, some modifications may be required to bring selected TxDOT bridge rails into compliance with the revised TL-4 impact conditions. Full-scale crash testing will be required to verify the impact performance of these designs. Further, deck designs associated with the modified rails may need to be strengthened to accommodate the additional moment generated by the increased impact loads. However, since TxDOT does not at this time require TL-4 railings on its bridges, and the proposed impact conditions may still be subject to change, such testing has been assigned a medium priority.

Returning to the discussion of impact performance with the new 5000-lb, ½-ton, 4-door, quad-cab pickup truck, the other issues that need to be addressed in addition to structural adequacy are vehicle stability and occupant compartment deformation. With reference to Table 3-3, it can be seen that three TxDOT bridge rails have a height of 27 inches. The T101 and T203, shown in Figure 3-9 and Figure 3-10, respectively, have been accepted as TL-3 barriers. The T6 tubular W-beam rail, shown in Figure 3-11, failed to meet TL-3 performance requirements due to rollover of the pickup truck in test 3-11 *(24)* and was subsequently approved as a TL-2 barrier for use on lower-speed roadways.

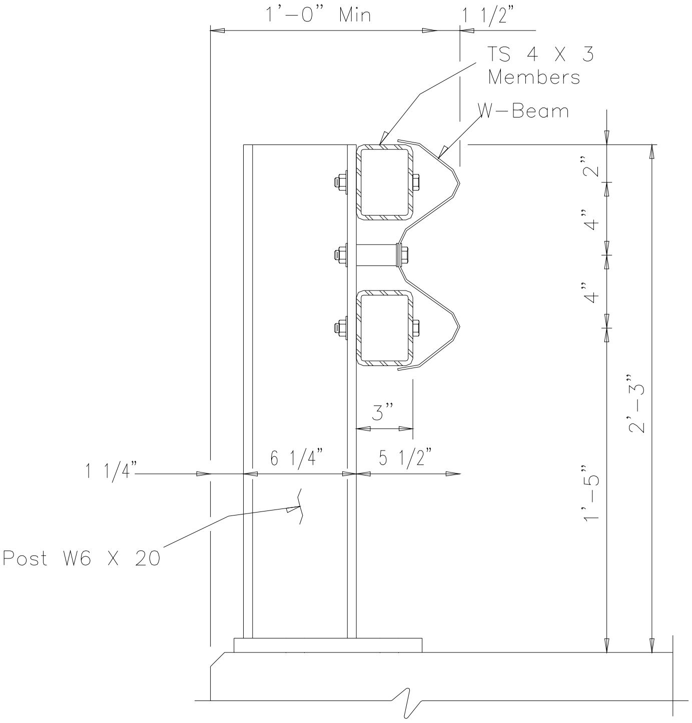


Figure 3-9. Cross Section of T101 Bridge Rail.

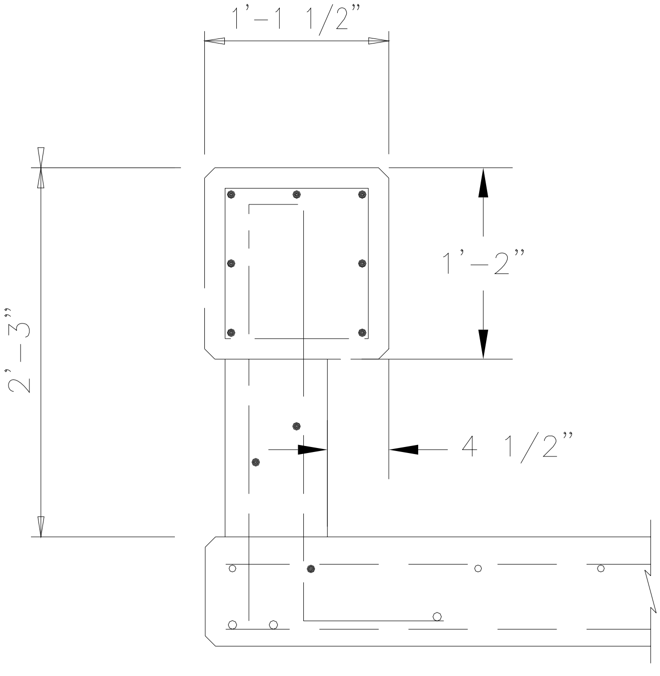


Figure 3-10. Cross Section of T203 Bridge Rail.

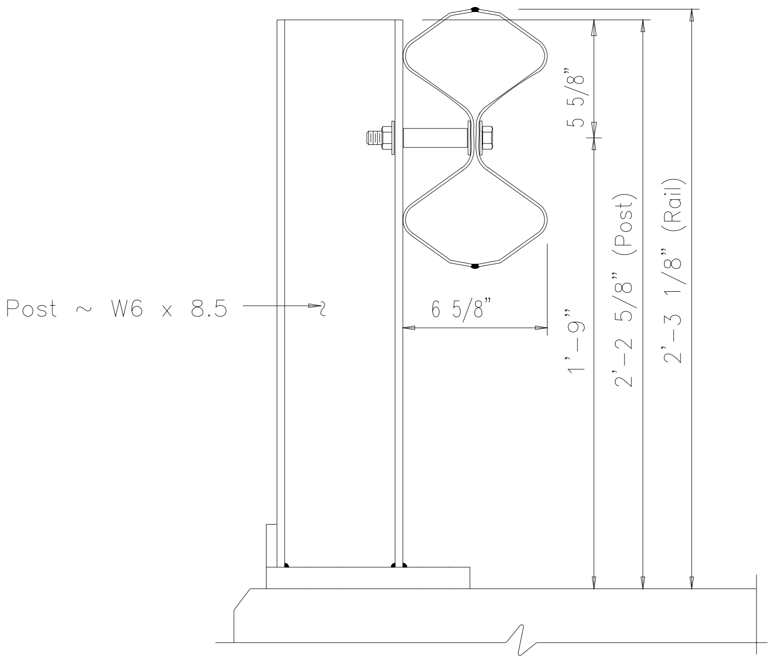


Figure 3-11. Cross Section of T6 Bridge Rail.

Crash testing of the T203 indicates that 27 inches is at or near the minimum height required to contain and redirect the ¾-ton, standard cab pickup under *NCHRP Report 350* test 3-11 impact conditions *(25,26)*. The increased impact severity of Update test 3-11 raises concern regarding the ability of the T203 to stably redirect the new ½-ton, 4-door quad-cab pickup. However, as discussed earlier, researchers believe the new pickup truck design vehicle is inherently more stable than the ¾-ton, 2-door, standard cab pickup of *NCHRP Report 350*. The ½-ton pickup has a greater static stability factor than the ¾-ton pickup, and limited full-scale crash testing conducted under NCHRP Project 22-14(02) with both vehicle types indicates that the ½-ton, 4-door quad-cab pickup is more stable than the ¾-ton, 2-door standard cab pickup.

It is possible that the small car may experience increased snagging on the concrete posts of the T203 under Update test 3-10 due to higher impact angle. However, any additional occupant compartment deformation (OCD) that might result from this snagging is unlikely to exceed the OCD thresholds of the Update. For these reasons, it is the opinion of the researchers that the T203 bridge rail should be able to successfully redirect the new pickup under TL-3 impact conditions. However, this assertion may ultimately have to be demonstrated through full-scale crash testing.

It is worthwhile noting that in addition to having satisfactory impact performance with passenger cars of various sizes, the 27-inch tall T101 bridge rail has also successfully contained and redirected a 20,000-lb school bus impacting at a speed of 55 mph and an angle of 15 degrees

(27). However, even though it has been accepted as an *NCHRP Report 350* TL-3 barrier by FHWA, the impact performance of the T101 with the ¾-ton pickup truck has never been evaluated. Some concern exists that wheel snagging on the W6x20 posts could lead to vehicle instability or excessive occupant compartment deformation.

Excessive occupant compartment deformation is not likely to be an issue for the T101 in regard to Update test 3-11 or Update test 3-10 due to the liberal threshold values established for occupant compartment deformation. The vehicle stability concern regarding the T101 rail requires evaluation through full-scale crash testing. Even though the new ½-ton, 4-door pickup is believed to be more stable than the ¾-ton, 2-door pickup, there is no testing with the ¾-ton pickup upon which a comparative analysis can be based.

The 27-inch tall T6 bridge rail is designed specifically for use on bridge length culverts or structures with thin decks. The breakaway post feature incorporated into this design helps minimize damage to the deck during an impact, thereby reducing repair costs and making attachment to thin decks practical. As mentioned above, the T6 rail failed to comply with TL-3 impact conditions due to rollover of the ¾-ton pickup in test 3-11. The new ½-ton pickup is not expected to mitigate this stability problem. However, the T6 should be capable of meeting the Update requirements for TL-2. Hence, testing of the T6 rail is given a low priority.

Taller bridge railings such as the T221 vertical wall parapet, T401 steel rail on concrete parapet, T501 New Jersey safety shape, T77 aesthetic rail, and single slope traffic rail (SSTR) should be capable of redirecting the new ½-ton, 4-door pickup under Update test 3-11 in a stable and upright manner.

Evaluation of the T501 safety shape and single slope traffic rail, shown in Figure 3-12 and Figure 3-13, respectively, follow the same arguments presented for the F-shape concrete median barrier and single slope concrete barrier. The reader is referred to the section entitled "Median Barriers" for further discussion pertaining to these barriers.

Vehicle stability is certainly not an issue for vertical concrete parapets such as the 32 inch tall T221 rail (shown in Figure 3-14). However, occupant risk could be a concern for Update test 3-10 with the new small car at an increased angle of 25 degrees. As mentioned previously, Update test 3-10 was conducted on a permanent New Jersey profile barrier under NCHRP Project 22-14(02) (see Test 8 of Table 3-1). In this test, a 2002 Kia Rio was successfully contained and redirected in an upright and stable manner, and occupant risk measures were within acceptable limits. While the vertical parapet is known to impart higher decelerations than the New Jersey profile barrier, the increase is not expected to be significant enough to exceed occupant risk thresholds. Testing of a vertical parapet should perhaps be conducted prior to publication of the Update to enlighten reviewers of any possible barrier design implications associated with the revised small car test conditions. For this reason, this testing has been assigned a medium priority.

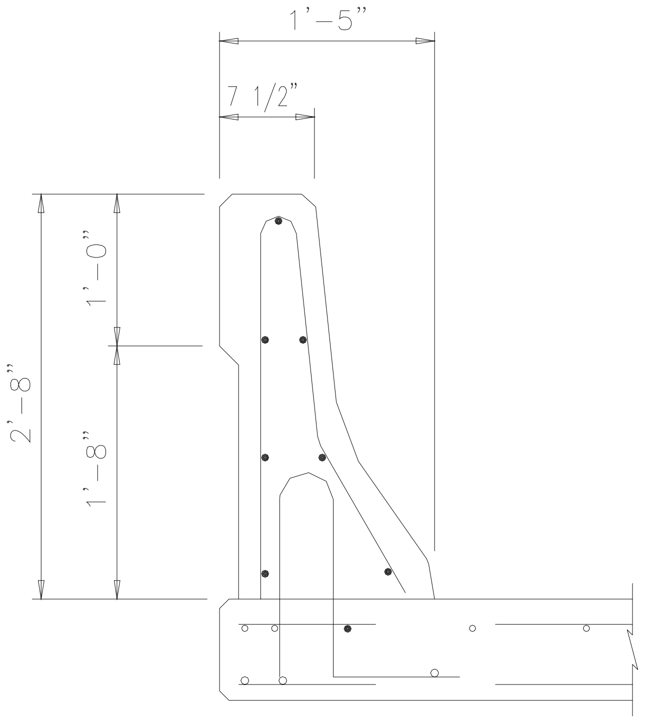


Figure 3-12. Cross Section of T501 Bridge Rail.

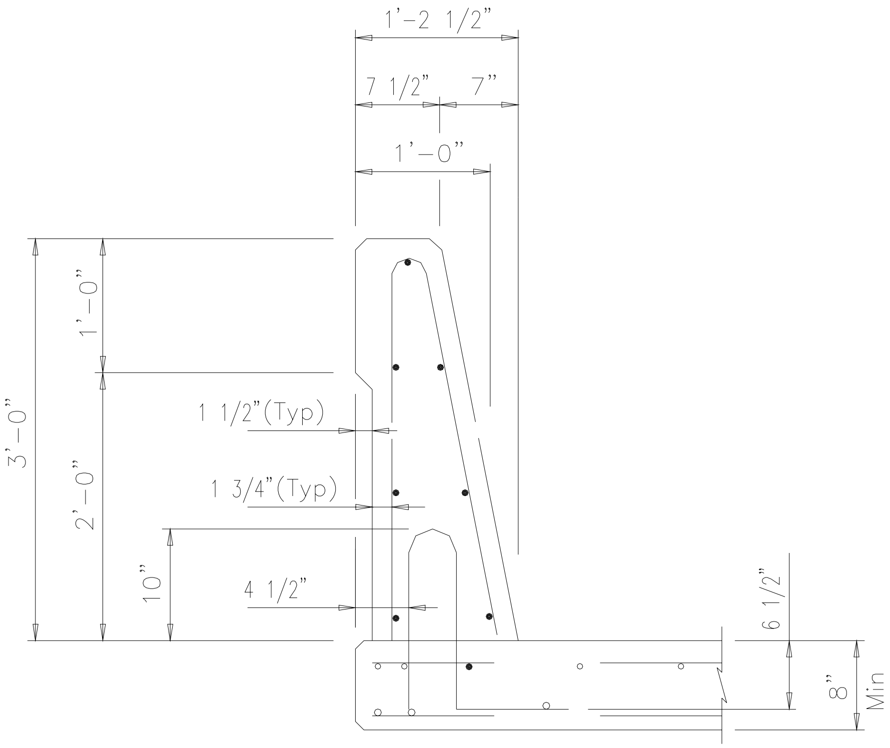


Figure 3-13. Cross Section of Single Slope Traffic Rail.

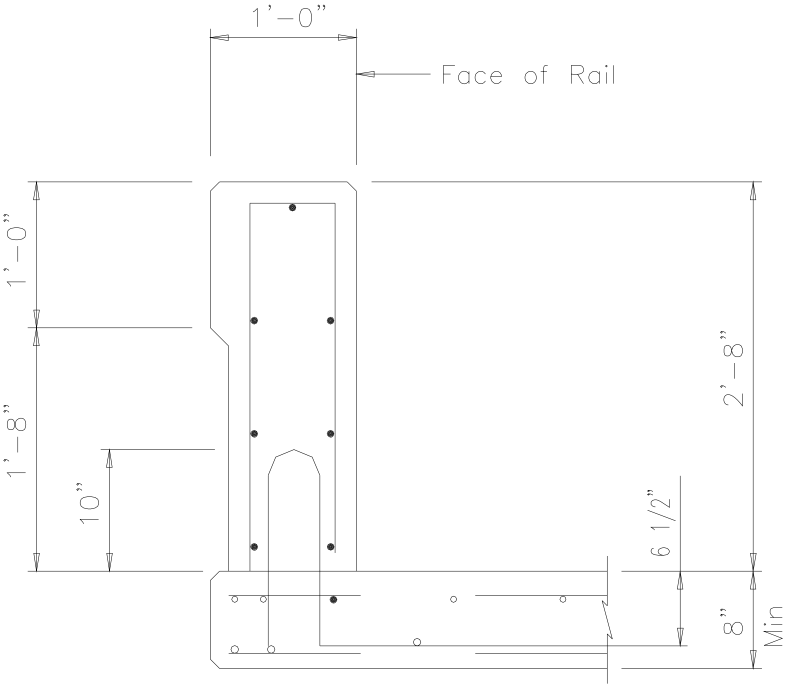


Figure 3-14. Cross Section of T221 Bridge Rail.

The T401 and T77 bridge rails, shown in Figure 3-15 and Figure 3-16, respectively, consist of a steel rail attached to a concrete parapet. The T401 has a single steel rail member mounted atop an 18-inch tall concrete parapet, while the T77 has two steel rail members mounted on a shorter, 9 inch concrete parapet. The concern associated with these rail systems relates to the potential for vehicle snagging on the posts and at the rail joints/splices. An initial design of the T77 rail was unsatisfactory due to excessive occupant compartment deformation generated from the front wheel gouging into the lower steel rail element at a splice *(28)*.

As discussed previously, design characteristics of the new ½-ton, 4-door pickup should decrease its propensity for severe snagging and excessive occupant compartment deformation compared to the ¾-ton pickup of *NCHRP Report 350*. Improved vehicle design and vehicle crashworthiness (e.g., introduction of crumple zones and other energy management strategies) will tend to reduce occupant compartment deformation, and the longer front overhang of the ½-ton, 4-door pickup makes it less critical than the 2000P in terms of wheel snagging severity and snagging-induced occupant compartment deformation. Additionally, the deformation thresholds have been significantly relaxed compared to those developed by FHWA for use in evaluating tests conducted under *NCHRP Report 350* guidelines. Therefore, both the T401 and T77 rails should satisfy the impact performance requirements of Update test 3-11. In fact, it is possible that the T411 Texas Classic rail, which failed to meet *NCHRP Report 350* requirements due to excessive occupant compartment deformation of the pickup in test 3-11 *(29)*, could comply with the requirements of Update test 3-11.

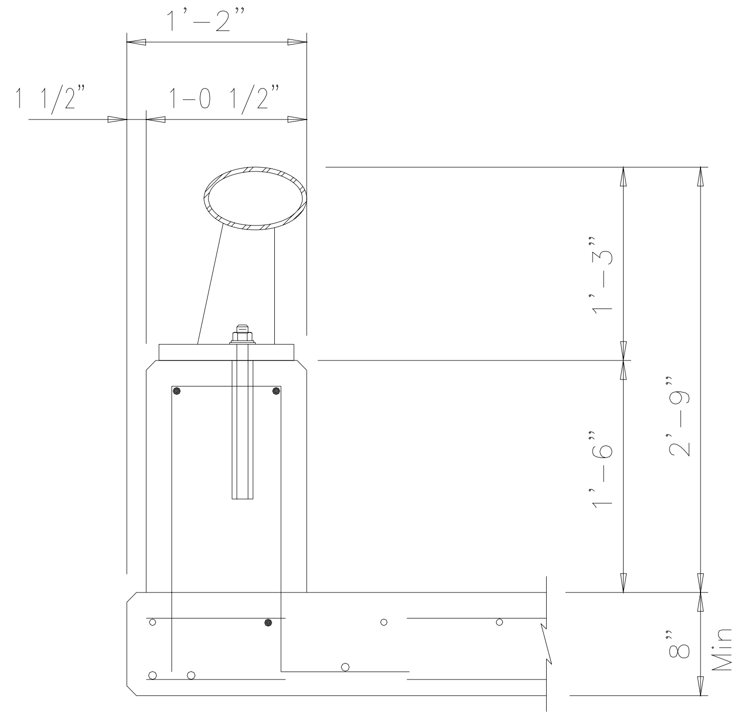


Figure 3-15. Cross Section of T401 Bridge Rail.

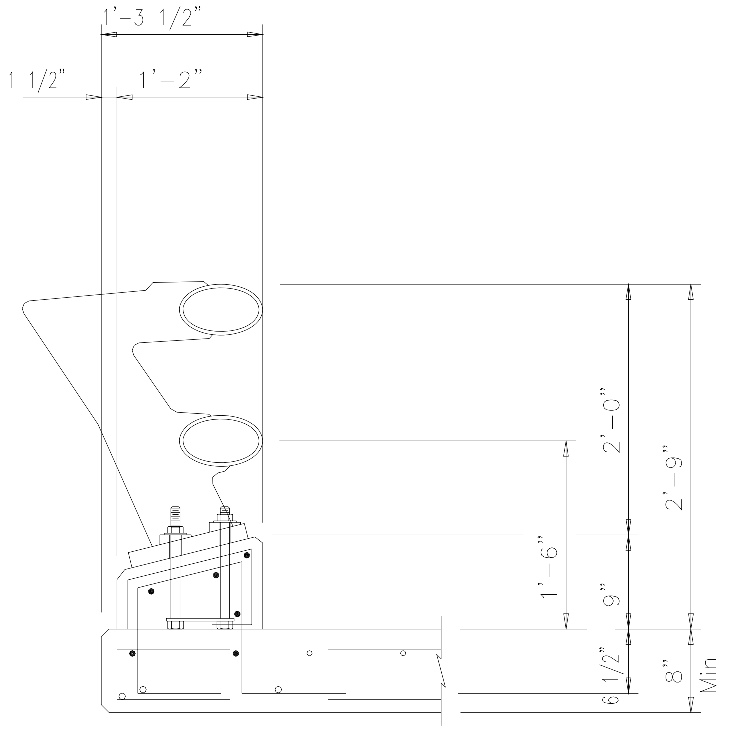


Figure 3-16. Cross Section of T77 Bridge Rail.

It is possible that the small car may experience increased snagging under Update test 3-10 due to the higher impact angle. However, any additional occupant compartment deformation that might result from this snagging is unlikely to exceed the OCD thresholds of the Update. Based on the reasons discussed above, further testing of the T401 and T77 bridge rails has been assigned a low priority.

WORK-ZONE TRAFFIC CONTROL DEVICES

Proper traffic control and delineation is critical to achieving safety in work zones. However, if not properly designed, the work zone traffic control devices themselves may pose a safety hazard to vehicle occupants or work crews when impacted by errant vehicles. Thus, FHWA and the *Manual on Uniform Traffic Control Devices* (MUTCD) require that the crashworthiness of work zone traffic control devices be demonstrated before they are implemented.

Before the publication of *NCHRP Report 350*, test matrices for work zone devices were not well defined. As a result, little crash testing was conducted and the impact performance of many commonly used devices was largely unknown. After the publication of *NCHRP Report 350* and its subsequent adoption by FHWA, TxDOT was one of the first agencies to assess the impact performance of various work zone traffic control devices.

The overall objective of the TxDOT research was to provide generic, cost effective work zone traffic control devices that meet *NCHRP Report 350* guidelines. The research was conducted in two phases. In the first phase, researchers evaluated the impact performance of existing work zone devices. The second phase involved the development, crash testing, and evaluation of improved designs to address the deficiencies identified in Phase I. Numerous full-scale crash tests were conducted on various work-zone devices including channelizing drums, vertical panels, two-piece cones, temporary and portable sign supports, and barricades. The research and testing culminated in the development of TxDOT's *Compliant Work Zone Traffic Control Device List*. The *Compliant Work Zone Traffic Control Device List* contains lists of systems and components approved for use on Texas highways. The document continues to be updated as a result of ongoing research and testing and is available through TxDOT's Traffic Operations Division.

The *NCHRP Report 350* test matrix for work zone traffic control devices consists of two tests with an 1808-lb passenger car: a low-speed test and a high speed test. For TL-3, the relevant test designations are 3-70 and 3-71, which have design impact speeds of 22 mph and 62 mph, respectively. *NCHRP Report 350* allows the omission of the low-speed test (test designation 3-70) when it can be clearly determined that the high-speed test (test designation 3-71) is more critical. This is often the case for work zone traffic control devices with a relatively small mass due to the increased propensity for occupant compartment intrusion at higher speeds.

In the update to *NCHRP Report 350* (Update), the 1800-lb passenger car has been replaced by a heavier 2425-lb passenger car (denoted 1100C). The impact speed for the low-speed test (test 3-70) has been decreased from 22 mph to 18.6 mph. The purpose of the speed reduction in Update test 3-70 was to maintain the same kinetic energy as *NCHRP Report 350* test 3-70. The impact speed for the high-speed test (Test 3-71) remains unchanged.

The *NCHRP Report 350* performance evaluation criteria for work zone traffic control devices consist of several factors. Of primary concern regarding the impact behavior of a work zone traffic control device is the integrity of the occupant compartment. To minimize the potential for injury during impact, penetration of the test article or parts of the test article into the occupant compartment is not permitted. Evaluation Criterion D of *NCHRP Report 350* further states that "Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted."

The Update adopts similar language but additionally establishes deformation thresholds to make assessment of Criterion D more quantitative and objective. Key to the evaluation of work zone traffic control devices is a roof deformation limit of 3.9 inches and a windshield deformation limit of 3 inches. Further, no tearing of the interior plastic liner of the laminated windshield glass is permitted. The language of Evaluation Criterion E regarding test article debris remains unchanged. It states that "Detached elements, fragments, or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle." The criterion is primarily for the protection of personnel in a work zone. If the driver of an errant vehicle can maintain control and not have their vision obstructed after impact with a work zone traffic control device, then the driver may be able to perform subsequent avoidance maneuvers to avoid hitting work zone personnel.

Because the key parameters of the two small passenger cars such as bumper height, hood height, front overhang, and "wrap-around" distance are comparable, the researchers believe that work zone traffic control devices that have successfully complied with test 3-70 and 3-71 of *NCHRP Report 350* should also comply with test 3-70 and 3-71 of the Update. The "wrap-around" distance is the distance from the ground, up around the front of the hood, and rearward across the hood to the base of the windshield. It is a strong indicator of whether or not a flexible or yielding temporary sign support will contact the windshield of the impacting vehicle.

In addition to the traditional small car tests, the test matrix for evaluation of the impact performance of work zone traffic control devices recommended in the Update also includes a high-speed test with the 5000-lb, ½-ton, 4-door pickup truck. This test is intended to evaluate the geometric compatibility of the pickup with the device in terms of penetration of structural components into or excessive intrusion of the occupant compartment.

TxDOT's *Compliant Work Zone Traffic Control Device List* and standard drawing sheets contain numerous types of work zone traffic control devices ranging from two-piece cones, channelizing drums, vertical panels, delineators, barricades, and temporary sign supports. The list is far too expansive to cite and discuss each device individually. It should suffice to say that there are no impact performance concerns of any of these devices with the pickup truck other than temporary sign supports.

Temporary sign supports are typically portable, free-standing systems that have sign panels mounted at various heights. They can be broadly divided into two categories by mounting height. Low-mounting height systems have mounting heights that typically range from 1 ft to 18 inches from the ground to the bottom of the sign. High-mounting heights are defined as those with a mounting height between 5 ft and 7 ft. TxDOT requires a 7 ft mounting height for their high-mounting height supports.

Temporary sign support systems present a design challenge for small cars due to their propensity to rotate into the windshield and/or roof of the impacting vehicle. Most of the acceptable alternatives for low-mounting height applications are proprietary sign stands that must be used in combination with a roll-up type fabric or vinyl sign panel to reduce the mass of the support and thereby limit the extent of windshield damage and roof deformation. Generally speaking, low-mounting height sign stands should not pose a safety concern for the new pickup truck design vehicle. As an example, the wrap-around distance of a Dodge Ram 1500 quad-cab pickup is approximately 100 inches. A typical 4-ft x 4-ft sign panel mounted in a diamond configuration at a height of 1 ft to the bottom of the sign has an overall height of 80 inches. Therefore, should the sign support yield and wrap around the front of the impacting pickup truck, it will not be able to contact the windshield. Even if the mounting height of the sign panel were increased to 2 ft, performance with the pickup truck should be satisfactory.

Taller (i.e., high-mounting height) portable sign stands pose more of a concern. These systems are typically fabricated with larger support members to accommodate service loads. If the supports do not readily fracture or release upon impact, they may deform around the front of the impacting vehicle and carry either the sign panel and/or top of supports into the windshield and/or roof. During small car impacts with the sign support oriented 90 degrees to the travel path of the vehicle (an FHWA requirement), the rigid substrate on some systems have penetrated the windshield and/or roof sheet metal.

TxDOT currently permits use of two different high-mounting height sign supports: one with wooden supports and the other with supports fabricated from perforated square steel tubing. Both systems have an option for using one or two supports. A single 4 inch x 4 inch wood upright can accommodate a 3 ft x 3 ft plywood sign panel *(24)*, while dual 4 inch x 4 inch uprights can readily support a 4 ft x 4 ft plywood sign panel *(31,32)*. The dual wooden sign support system with a rigid 4 ft x 4 ft plywood sign substrate mounted at 5 ft, shown in Figure 3-17, was successfully tested under *NCHRP Report 350* with an 1800-lb passenger car. Additionally, it was successfully crash tested with a 4409-lb, ¾-ton, standard cab pickup truck at a speed of 62.2 mph. Upon impact, the wooden uprights fractured at bumper height and near the tops of the wooden skids. The sign panel and fractured supports then rotated over the vehicle.

A 5-ft mounting height is generally believed to be more critical than a 7 ft mounting height from an impact performance standpoint, because the lower center of mass decreases the point of rotation of the supports and increases rotational velocity. These factors combine to increase the likelihood and severity of secondary impacts of the supports and sign panel with the windshield and roof of the impacting vehicle. Since the dual wooden sign support system met required evaluation criteria in the pickup truck test with the sign panel mounted at 5 ft, the researchers consider the same sign support system to be acceptable for a 7 ft mounting height as well.

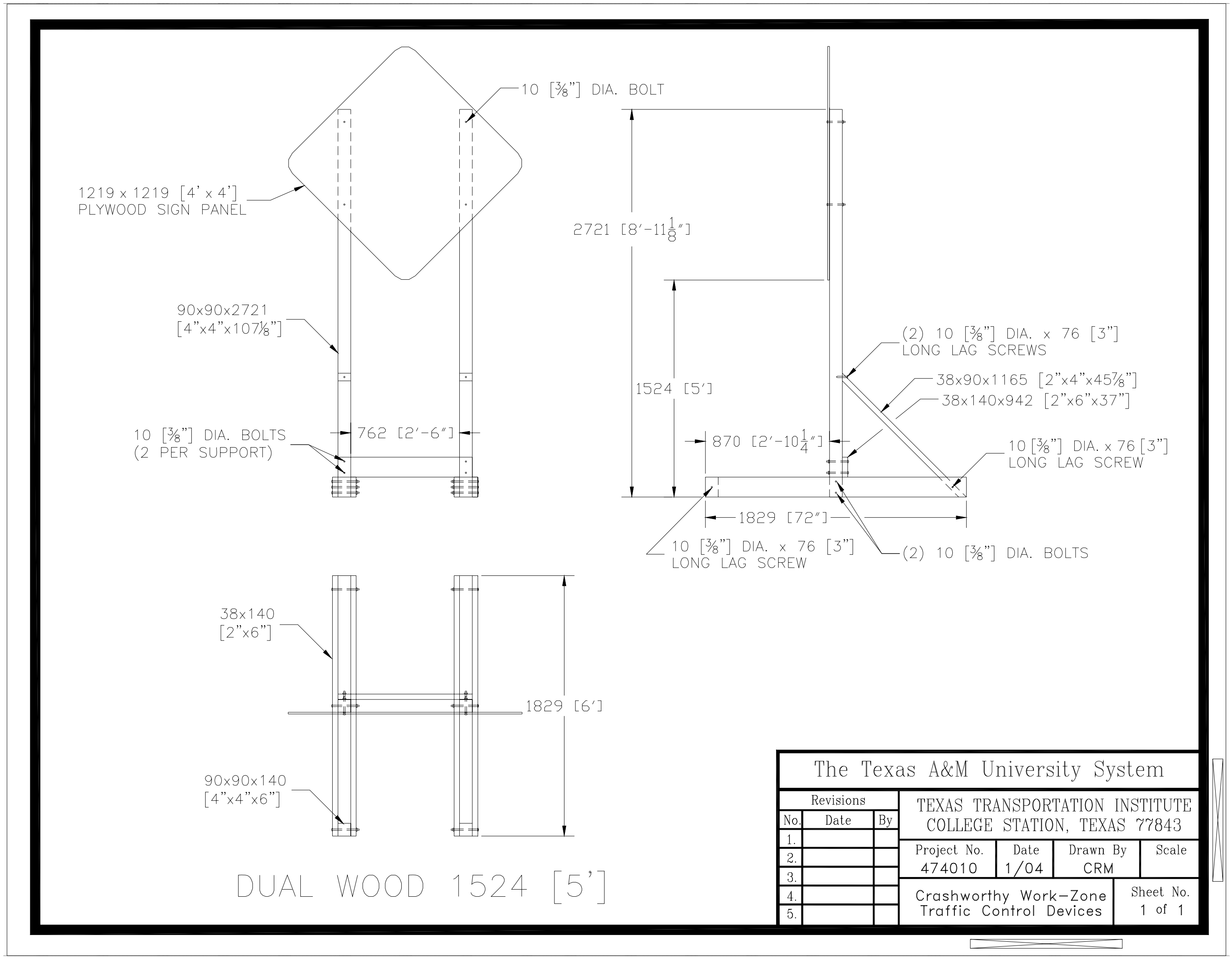


Figure 3-17. High-Mounting Height Sign Support with Wood Uprights.

The other high-mounting height sign support system used in Texas has a frame fabricated from perforated steel tube. In this design, a 48 inch long vertical sleeve fabricated from 2 inch square, 12-gauge perforated steel tubing is welded to the center of a 5 ft long skid fabricated from the same material. A 1-3/4-inch square x 11 ft long, 12-gauge perforated steel upright is inserted into the sleeve until it rests on a bolt passing through the bottom of the sleeve. Figure 3-18 presents a photograph of the system is presented. The system was successfully tested with a small car at zero and 90 degrees with a 4 ft x 4 ft x 3/8 inch corrugated plastic sign panel attached to the vertical supports in a diamond configuration at a mounting height of 7 ft above ground *(33)*.

The impact performance of this system with the new pickup truck under Update test 3-72 cannot be readily determined without a full-scale crash test. Because this system is widely used throughout the state due to its relatively light weight and portability, crash testing with the ½-ton, 4-door pickup truck to assess its compliance with the Update has been assigned a medium priority.

CRASH CUSHIONS AND GUARDRAIL END TREATMENTS

Crash cushions are used to shield motorists from gore areas and other discrete hazards such as bridge piers and overhead sign structures. When impacted head-on, a crash cushion attenuates the energy of a vehicle through various means such as momentum transfer, material deformation, and friction.

Crashworthy end treatments are required to safely terminate guardrail ends. The energy-absorbing end treatments used by Texas DOT are designed to dissipate the energy of a vehicle impacting head on through controlled deformation of the W-beam rail element. Weakened or breakaway posts are used in the end treatment section to help prevent vehicle climbing or vaulting during head-on impacts. End treatments must also provide anchorage to the guardrail system so that it can function properly to contain and redirect vehicles impacting along its length.

All of the crash cushions and guardrail end treatments currently used by TxDOT are proprietary in nature and, therefore, will not be discussed herein. The manufacturers of these devices will be required to assess the impact performance of their devices and ultimately demonstrate compliance of their devices with the new test and evaluation guidelines. However, the researchers do note that the dramatic increase in impact severity of the pickup truck redirection tests and other changes in the test matrices for terminals and crash cushions will likely necessitate the modification of some of these systems.

Figure 3-18. High-Mounting Height Sign Support with Perforated Steel Tube Uprights.

CHAPTER 4.

FULL-SCALE CRASH TESTING OF SMALL SIGN SUPPORTS

The two types of generic, permanent small sign support systems used in Texas are a wedge anchor system and a triangular slip base system. TxDOT standards also permit use of a fiber-reinforced plastic (FRP) support system. However, since the FRP system is proprietary, it will not be considered herein.

Of primary concern when evaluating the impact performance of small sign supports is the potential for windshield penetration and occupant compartment intrusion resulting from secondary contact between the impact vehicle and the structural components of the sign support system. Engineering analysis and/or computer simulation can be used to help predict whether or not secondary contact between a support system and an impacting vehicle will occur, and the probable location of the contact. However, the only way to reliably determine the extent of windshield damage and roof deformation resulting from such secondary contact is through full-scale crash testing.

NCHRP Report 350 requires only two tests with an 1800 lb car to evaluate breakaway support structures: one low-speed test at 21.7 mph and one high-speed test at 62.2 mph. The proposed test matrix in the update to *NCHRP Report 350* (Update) recommends three tests for evaluation of breakaway support structures.

The low-speed test (Test 60) utilizes a 2420-lb passenger car (denoted 1100C) impacting the support structure at a speed of 18.6 mph. This test evaluates the kinetic energy required to activate the breakaway, fracture, or yielding mechanism of the support. Of concern for this test are the potential for excessive velocity change and penetration of structural components into the occupant compartment of the impacting vehicle.

Two tests are recommended to evaluate the behavior of the breakaway support during high-speed impacts; test 61 with the 1100C vehicle and test 62 with a 5000-lb pickup truck (denoted 2270P), both impacting the support structure at a speed of 62.2 mph. These two tests evaluate the potential for penetration of structural components into the vehicle windshield, excessive occupant compartment intrusion, and vehicle instability, as well as occupant risk.

TxDOT decided to allocate some of the project’s resources to conduct full-scale crash testing of their two generic small sign support systems. The small car tests recommended in the Update are not expected to exhibit significantly different performance from the small car tests currently recommended under *NCHRP Report 350*. The biggest area of uncertainty in regard to the impact performance of small sign supports with respect to the Update is their geometric interaction with the pickup. For this reason, researchers decided to conduct Update test 3-62 on both the wedge anchor system and the triangular slip base system.

There are two variations of the Texas triangular slip base sign support system. One version uses a 10 British Wire Gauge (BWG) galvanized steel tube as the vertical support and can accommodate sign panels up to 16 square ft in area. The other version uses a schedule 80 pipe support and is acceptable for use with sign panels with areas up to 32 square ft. In absence of other factors, the heavier sign support system (i.e., the schedule 80 pipe support and larger sign panel) is typically considered to be the most critical in terms of occupant impact velocity. However, there was concern that the thin wall 10 BWG support could exhibit local buckling and collapse when impacted by the taller pickup trucks, possibly hindering the activation of the slip base mechanism. Therefore, since occupant impact velocity is not a major concern for the heavy pickup truck compared to the 1800-lb passenger cars used in previous testing of the Texas triangular slip base system, researchers decided to test the slip base with a 10 BWG support post.

All crash test, data analysis, and evaluation and reporting procedures followed under this project were in accordance with guidelines presented in the *NCHRP Report 350* Update. Appendix A presents brief descriptions of these procedures.

WEDGE ANCHOR SYSTEM (CRASH TEST 455266-1)

The test performed on the wedge anchor sign support system was *NCHRP Report 350* Update Test 3-62. The test involves the new 5000-lb, ½-ton, 4-door, quad-cab pickup truck (denoted 2270P) impacting the support structure at a target speed of 62.2 mph and target impact angle of 0 degree. This test assesses the geometric compatibility of the pickup truck with the sign support system. More specifically, the test evaluates the potential for structural components of the sign support to penetrate the vehicle windshield or cause excessive deformation of the occupant compartment. Vehicle stability and occupant risk are also evaluated.

Test Article Design and Construction

The wedge anchor sign support system was installed in *NCHRP Report 350* standard soil per TxDOT standard detail sheet SMD(TWT)-02. A 2.875-inch outside diameter (O.D.) galvanized steel tubular socket was cast inside a 12 inch diameter x 2 ft-6 inch deep non-reinforced concrete footing. The flattened edge of the 27-inch long socket was aligned parallel to the sign blank or perpendicular to the direction of impact.

A 13 BWG galvanized steel tube having an outside diameter of 2.375 inch and a nominal wall thickness of 0.095 inches was inserted into the socket to a depth of 12 inches. An 8.5-inch long, 11-gauge galvanized steel wedge was driven between the socket and support post to a depth of 5.5 inches to secure the post in position.

A 3-ft x 3-ft x 5/8-inch thick plywood sign panel was attached to the 2.375 inch O.D. vertical support using two mounting clamps spaced 6 inches from the top and bottom edges of the sign panel. The mounting height from the ground to the bottom of the sign blank was 7 ft.

Figure 4-1 shows a schematic of the wedge anchor sign support test installation. Photographs of the completed test installation are presented in Figure 4-2.

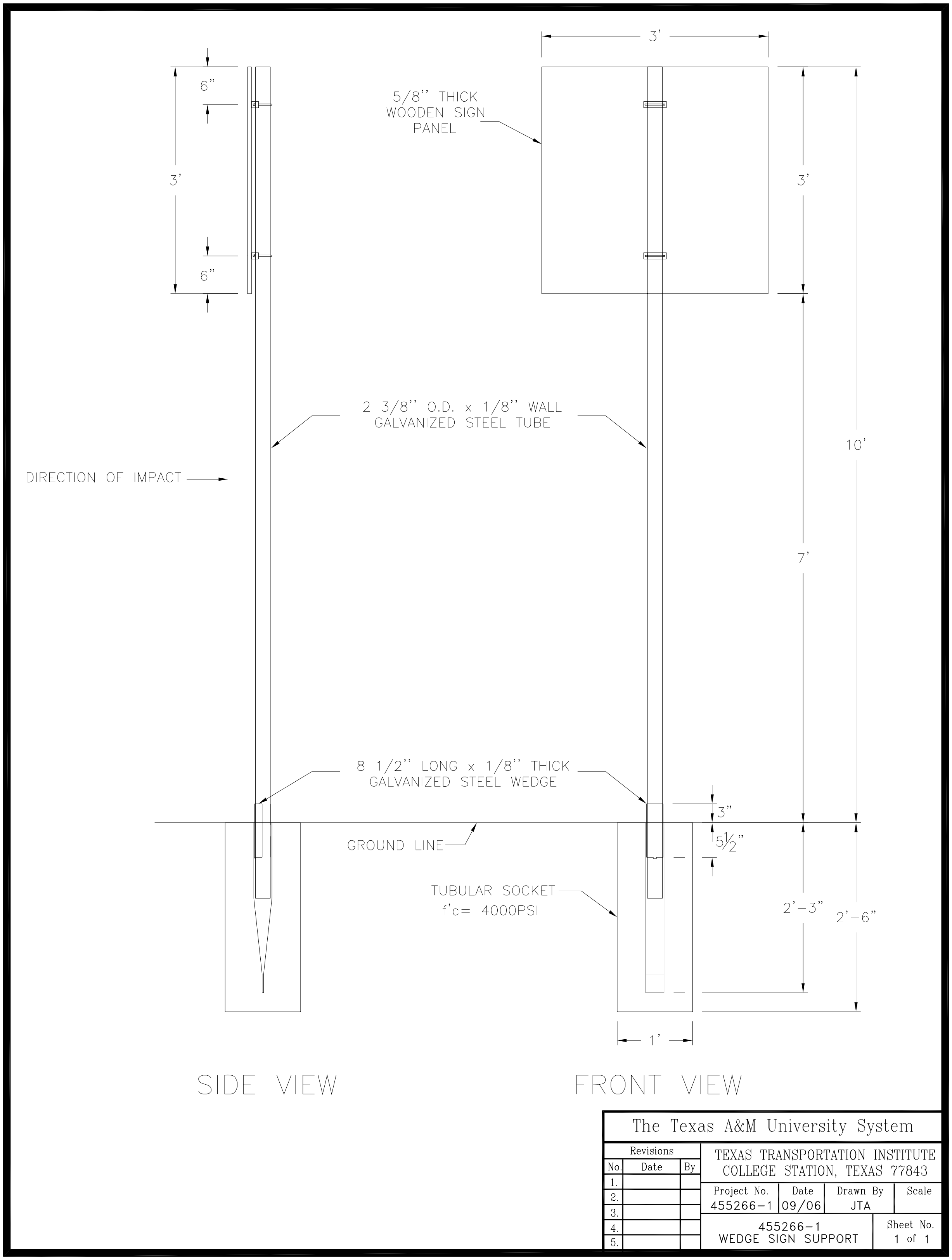


Figure 4-1. Details of the Wedge Anchor Sign Support System.

Figure 4-2. Test Article/Installation before Test 455266-1.

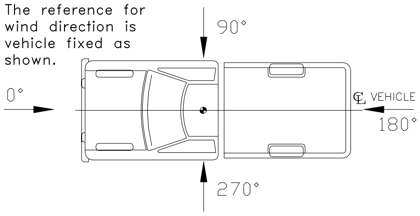
No rainfall was recorded during the 10 days prior to the test. Moisture content of the *NCHRP Report 350* standard soil in which the test article was installed was 6.5 percent on the day of the test.

Test Vehicle

A 2003 Dodge Ram 1500 quad-cab pickup truck, shown in Figures 4-3 and 4-4, was used for the crash test. Test inertia weight of the vehicle was 5013 lb, and its gross static weight was 5013 lb. The height to the lower edge of the vehicle bumper was 14.4 inches, and the height to the upper edge of the bumper was 26.9 inches. Figure B1-1 in Appendix B gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using the cable reverse tow and guidance system, and it was released to be free-wheeling and unrestrained just prior to impact.

Weather Conditions

The test was performed on the morning of August 31, 2006. Weather conditions at the time of testing were as follows: wind speed: 6-10 mph; wind direction: 145 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); temperature: 89^{o}F; relative humidity: 43 percent.



Test Description

The 2003 Dodge Ram 1500 quad-cab pickup truck, traveling at an impact speed of 63.2 mph and impact angle of 0.6 degrees, impacted the support 21.7 inches above the ground. Upon impact, the support began to deform, and at 0.005 s, the support contacted the hood. The support began to pull out of the socket at 0.008 s, and the support had completely pulled out of the socket by 0.021 s. At 0.045 s, the vehicle bumper lost contact with the support, and the vehicle was traveling at a speed of 62.8 mph. At 0.050 s, the support rolled off the hood onto the left front quarter panel. The sign panel separated from the support at 0.057 s, and the released sign panel contacted the roof at 0.097 s. The vehicle lost contact with the sign panel at 0.123 s while traveling at a speed of 62.4 mph. At 0.159 s, the support lost contact with the left front quarter panel, and the vehicle was traveling at a speed of 61.3 mph. Brakes on the vehicle were applied at 1.012 s at a location 161 ft downstream of impact, and the vehicle subsequently came to rest 275 ft downstream of impact. Figure B2-1 in Appendix B shows sequential photographs of the test period.

Figure 4-3. Vehicle/Installation Geometrics for Test 455266-1.

Figure 4-4. Vehicle before Test 455266-1.

Test Article Damage

Figures 4-5 and 4-6 show the damage to the support. No movement of the concrete footing was noted. The wedge fell down inside the socket after release of the support post. The sign panel came to rest 8 ft downstream of the socket. The mounting brackets were intact indicating that the sign panel slid off the support. The support came to rest 185 ft downstream and 32 ft to the left of centerline of the vehicle path. The support was bent at a 15 degree angle 11.4 inches from the bottom of the support, and at a 100 degree angle 18.9 inches from the bottom of the support.

Test Vehicle Damage

The vehicle sustained minimal damage, as shown in Figure 4-7. The front bumper, hood, left front quarter panel, roof, and stop light on the cab were deformed. The dent in the roof caused by the sign panel measured 9.8 inches wide × 21.2 inches long × 0.3 inch deep; and the dent in the left front quarter panel measured 3.9 inches wide × 7.9 inches long × 0.2 inch deep. No occupant compartment deformation occurred. Photographs of the interior of the vehicle are shown in Figure 4-8. Exterior crush measurements and occupant compartment measurements are noted in Tables B1-1 and B1-2 of Appendix B.

Occupant Risk Values

Data from the accelerometer, located at the vehicle center of gravity, were digitized for evaluation of occupant risk. In the longitudinal direction, the occupant impact velocity was 3.9 ft/s at 0.808 s; the highest 0.010-s occupant ridedown acceleration was -0.3 g's from 0.944 to 0.954 s; and the maximum 0.050-s average acceleration was -0.6 g's between 0.001 and 0.051 s. In the lateral direction, the occupant impact velocity was 0.3 ft/s at 0.808 s; the highest 0.010-s occupant ridedown acceleration was -0.3 g's from 0.932 to 0.942 s; and the maximum 0.050-s average was -0.3 g's between 0.067 and 0.117 s.

Theoretical Head Impact Velocity (THIV) was 2.7 mph or 3.9 ft/s at 0.808 s. Post-Impact Head Deceleration (PHD) was 0.3 g's between 0.944 and 0.954 s; and the Acceleration Severity Index (ASI) was 0.06 between 0.150 and 0.200 s. Figure 4-9 presents these data and other pertinent information from the test. Figure B3-1 in Appendix B presents vehicle angular displacements and Figures B4-1 through B4-6 show accelerations versus time traces.

Figure 4-5. After Impact Trajectory Path for Test 455266-1.

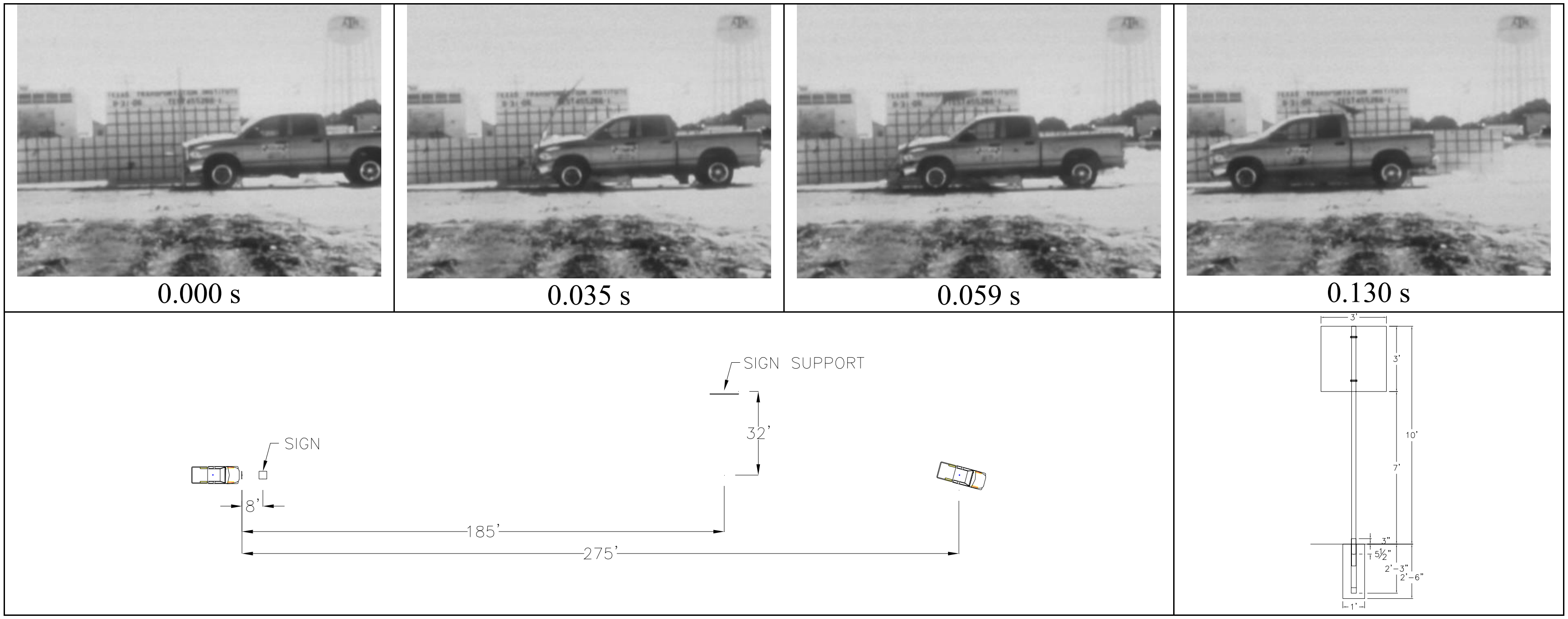
Figure 4-6. Installation after Test 455266-1.

Figure 4-7. Vehicle after Test 455266-1.

Before Test

After Test

Figure 4-8. Interior of Vehicle for Test 455266-1.


0.000 s

0.035 s

0.059 s

0.130 s

General Information	
Test Agency	Texas Transportation Institute
Test No.	455266-1
Date	08-31-2006
Test Article	
Type	Sign Support
Name	Wedge Sign Support
Installation Height (ft)	7.0
Material or Key Elements	2 inch ID × 132 inch Support with 3 ft × 3 ft × 5/8 inch Sign Panel
Soil Type and Condition	Standard Soil, Dry
Test Vehicle	
Type	Production
Designation	2270P
Model	2003 Dodge 1500 Quad-Cab Pickup
Mass (lb)	
Curb	4735
Test Inertial	5013
Dummy	No dummy
Gross Static	5013

Impact Conditions	
Speed (mph)	63.2
Angle (deg)	00.6
Exit Conditions	
Speed (mph)	61.3
Angle (deg)	N/A
Occupant Risk Values	
Impact Velocity (ft/s)	
Longitudinal	3.9
Lateral	0.3
THIV (mph)	2.7
Ridedown Accelerations (g's)	
Longitudinal	-0.3
Lateral	-0.3
PHD (g's)	0.3
ASI	0.06
Max. 0.050-s Average (g's)	
Longitudinal	-0.6
Lateral	-0.3
Vertical	-0.5

Test Article Debris Scatter (ft)	
Longitudinal	185.0
Lateral	32.0
Vehicle Damage	
Exterior	
VDS	12FL0
CDC	12FLEN1
Maximum Exterior Vehicle Crush (inches)	7
Interior	
OCDI	LF0000000
Maximum Occupant Compartment Deformation (inches)	0
Post-Impact Behavior	
(during 1.0 sec after impact)	
Max. Yaw Angle (deg)	-1
Max. Pitch Angle (deg)	1
Max. Roll Angle (deg)	-1

Figure 4-9. Summary of Results for *NCHRP Report 350* Update Test 3-62 on the Wedge Anchor Sign Support.

Assessment of Test Results

An assessment of the test based on the applicable *NCHRP Report 350* Update safety evaluation criteria is presented below.

Structural Adequacy

B. *The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.*

Results: The sign support yielded to the vehicle by pulling out of the ground. (PASS)

Occupant Risk

D. *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.*

Deformation of, or intrusions into, the occupant compartment should not exceed limits specified. (roof ≤3.9 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤8.9 inches; forward of A-pillar ≤11.8 inches; front side door area above seat ≤8.9 inches; front side door below seat ≤11.8 inches; floor pan/transmission tunnel area ≤11.8 inches)

Rating	*Extent of Intrusion*
Good	*<5.9 inches*
Acceptable	*5.9 inches – 8.9 inches*
Marginal	*8.9 inches – 11.8 inches*
Poor	*>11.8 inches*

Results: The detached support and sign panel did not penetrate, nor show potential for penetrating the occupant compartment, nor was it judged to present undue hazard to others in the area. (PASS)
No occupant compartment deformation occurred. (GOOD)

F. *The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.*

Results: The 2270P vehicle remained upright during and after the collision event. Maximum roll angle was -1 degree, and maximum pitch angle was 1 degree. (PASS)

H. *Occupant impact velocities should satisfy the following:*

Longitudinal and Lateral Occupant Impact Velocity

Preferred	*Maximum*
9.8 ft/s	*16.4 ft/s*

Results: Longitudinal occupant impact velocity was 3.9 ft/s, and lateral occupant impact velocity was 0.3 ft/s. (PASS)

I. *Occupant ridedown accelerations should satisfy the following:*

Longitudinal and Lateral Occupant Ridedown Accelerations

Preferred	*Maximum*
15.0 G's	*20.0 G's*

Results: Longitudinal ridedown acceleration was -0.3 G's, and lateral ridedown acceleration was -0.3 G's. (PASS)

Vehicle Trajectory

N. *Vehicle trajectory behind the test article is acceptable.*

Result: The vehicle came to rest 275 ft behind the sign support installation. (PASS)

The following supplemental evaluation factors and terminology, as presented in the FHWA memo entitled "ACTION: Identifying Acceptable Highway Safety Features," were used for visual assessment of test results. *(13)* Factors underlined below pertain to the results of the crash test reported herein.

Passenger Compartment Intrusion

1. *Windshield Intrusion*
    - *[✓ a. No windshield contact]*
    - *b. Windshield contact, no damage*
    - *c. Windshield contact, no intrusion*
    - *d. Device embedded in windshield, no significant intrusion*
    - *e. Complete intrusion into passenger compartment*
    - *f. Partial intrusion into passenger compartment*
2. *Body Panel Intrusion* *yes or [✓ no]*

Loss of Vehicle Control

1. *Physical loss of control*
2. *Loss of windshield visibility*
3. *Perceived threat to other vehicles*
4. *[✓ Debris on pavement]*

Physical Threat to Workers or Other Vehicles

1. *Harmful debris that could injure workers or others in the area*
2. *Harmful debris that could injure occupants in other vehicles*

If yes, Size: 3 ft × 3 ft × 5/8 inch sign panel *Speed: high or [✓ low]*

Mass: 44 lb *Trajectory: ht:* over cab

Vehicle and Device Condition

1. *Vehicle Damage*
    - *a. None*
    - *[✓ b. Minor scrapes, scratches or dents]*
    - *c. Significant cosmetic dents*
    - *d. Major dents to grill and body panels*
    - *e. Major structural damage*

2. *Windshield Damage*
    - *a. None*
    - *b. Minor chip or crack*
    - *c. Broken, no interference with visibility*
    - *d. Broken or shattered, visibility restricted but remained intact*
    - *e. Shattered, remained intact but partially dislodged*
    - *f. Large portion removed*
    - *g. Completely removed*
3. *Device Damage*
    - *a. None*
    - *b. Superficial*
    - *c. Substantial, but can be straightened*
    - *d. Substantial, replacement parts needed for repair*
    - *e. Cannot be repaired*

Summary of Test Results

The wedge anchor sign support system demonstrated satisfactory impact performance. The sign support activated by yielding to the impacting vehicle and then pulling out of its socket. The test vehicle sustained only minor damage, and there was no deformation of or intrusion into the occupant compartment. The computed occupant risk indices were below the preferred values set forth in the *NCHRP Report 350* Update. The 2270P vehicle remained upright and stable during and after the collision event with only 1 degree of pitch and roll. The vehicle came to a controlled stop 275 ft behind the point of impact.

Discussion

In anticipation of minor vehicle damage, the test plan called for use of the same pickup truck for both crash tests (i.e., wedge anchor system and triangular slip base system). To reduce the probability of vehicle damage from the first test influencing the outcome of the second test, researchers planned to impact the two sign support systems at the vehicle quarter points rather than the centerline. Review of the high-speed video from the first test indicated that the trajectory of the support post was influenced by the hood geometry of the pickup. The hood of the Dodge Ram has a distinct drop in elevation at its quarter point that guided the support post toward the side of the vehicle and away from the windshield. Had the impact point been aligned with the center of the truck, the yielding support and sign panel may have contacted the windshield. Therefore, it was decided to impact a second wedge anchor system to obtain a more definitive evaluation of its impact performance.

This evaluation was accomplished by impacting both a wedge anchor system and triangular slip base system in the second test. To minimize interaction between the two supports systems, they were spaced 15 ft apart along the path of the vehicle with the slip base in the first position and the wedge anchor in the second position. It was theorized that the slip base would activate and rotate over the vehicle prior to the wedge anchor system contacting and yielding around the front of the vehicle. The two support systems were laterally offset 6 inches in opposite directions from the vehicle centerline to minimize the influence of vehicle damage induced in the first impact with the slip base on the outcome of the second impact with the wedge anchor.

TRIANGULAR SLIP BASE AND WEDGE ANCHOR SYSTEMS (TEST 455266-2)

NCHRP Report 350 Update Test 3-62 was conducted to evaluate the impact performance of both a triangular slip base system and wedge anchor system when impacted by the new 5000-lb, ½-ton, 4-door, quad-cab pickup truck (denoted 2270P). This test involves the 2270P impacting the support structure at a target speed of 62.2 mph and target impact angle of 0 degree. The test evaluates the potential for structural components of the sign support to penetrate the vehicle windshield or cause excessive deformation of the occupant compartment. Vehicle stability and occupant risk are also evaluated.

Test Article Design and Construction

Two sign supports were installed for this test. A triangular slip base sign support system was installed in the first impact position and was offset 6 inches to the right of the vehicle centerline. A wedge anchor sign support system was erected in the second impact position, 15 ft downstream from the slip base, and offset 6 inches to the left of the vehicle centerline.

The wedge anchor system was installed in a manner identical to that described for the first test (i.e., Test 455266-1). The slip base assembly was installed in *NCHRP Report 350* standard soil following details of TxDOT standard drawing SMD(SLIP-1)-02.

A 10 BWG galvanized steel tube with an outside diameter of 2.875-inch and a nominal wall thickness of 0.134 inches was used as the vertical support for the slip base system. A T-shaped bracket was attached to the vertical support to provide bracing for the sign panel. The T-bracket consisted of a 3.25-inch O.D. stub welded to a 2.375-inch O.D. horizontal steel tube. The stub of the T-bracket fit over the end of the 2.875-inch O.D. support and was secured using two 3/8-inch diameter ASTM A307 bolts.

A 4 ft x 5 ft x 0.1-inch thick aluminum sign blank was attached to the 2.375-inch O.D. horizontal member and 2.875-inch O.D. vertical support using a total of three mounting clamps located 6 inches from the bottom and each edge of the sign panel. The mounting height to the bottom of the sign blank was 7 ft.

The upper slip base casting consists of an integral collar and triangular base plate. The upper slip base casting slides onto the end of the steel pipe support. The lower slip base assembly consists of a 3-inch diameter x 3-ft long galvanized schedule 40 pipe stub welded to a 5/8-inch thick steel triangular base plate having the same geometry as the upper plate. The pipe stub was embedded in a 12-inch diameter x 3.5-ft deep unreinforced concrete footing such that the top face of the lower triangular slip plate was approximately 2 inches above the ground.

The upper slip base unit is bolted to the lower slip base unit using three 5/8-inch x 2.5-inch long A325 or equivalent high-strength bolts that were tightened to a prescribed torque of 38 ft-lb. The slip base was oriented such that the direction of impact was perpendicular to one of the flat faces of the triangular plate. High-strength washers were used under both the head and nut of each bolt, and an additional washer was used to offset the two slip plates. The bolts are held in place by a keeper plate which is fabricated from 30 gauge galvanized sheet steel. Set screws in the collar of the upper slip base casting were then tightened to a prescribed torque of 60 ft-lb to secure the vertical support within the casting and keep it from rotating.

Figure 4-10 shows schematic of the triangular slip base sign support installation. Photographs of the completed test installation are presented in Figure 4-11.

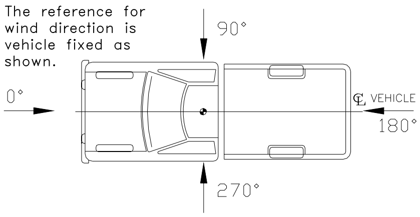
No rainfall was recorded during the 10 days prior to the test. Moisture content of the *NCHRP Report 350* standard soil in which the test article was installed was 6.5 percent on the day of the test.

Test Vehicle

A 2003 Dodge Ram 1500 quad-cab pickup truck, shown in Figures 4-12 and 4-13, was used for the crash test. Test inertia weight of the vehicle was 5013 lb, and its gross static weight was 5013 lb. The height to the lower edge of the vehicle bumper was 14.4 inches, and the height to the upper edge of the bumper was 26.9 inches. Figure C1-1 in Appendix C gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using the cable reverse tow and guidance system, and it was released to be free-wheeling and unrestrained just prior to impact.

Weather Conditions

The test was performed on the afternoon of August 31, 2006. Weather conditions at the time of testing were as follows: wind speed: 6-10 mph; wind direction: 145 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); temperature: 96^{o}F; relative humidity: 28 percent.



Test Description

The 2003 Dodge Ram 1500 quad-cab pickup truck, traveling at an impact speed of 63.7 mph, impacted the triangular slip base sign support at an angle of 0.4 degrees. Upon impact, the support deformed slightly approximately 18.5 inches above ground. At 0.009 s, the slip base began to activate and release the sign support. The upper support lost contact with the base at 0.017 s. At 0.066 s, the vehicle lost contact with the support, and the vehicle was traveling at a speed of 60.6 mph. The sign panel and support contacted the roof of the vehicle at 0.116 s, and the slip base casting separated from the support at 0.135 s.

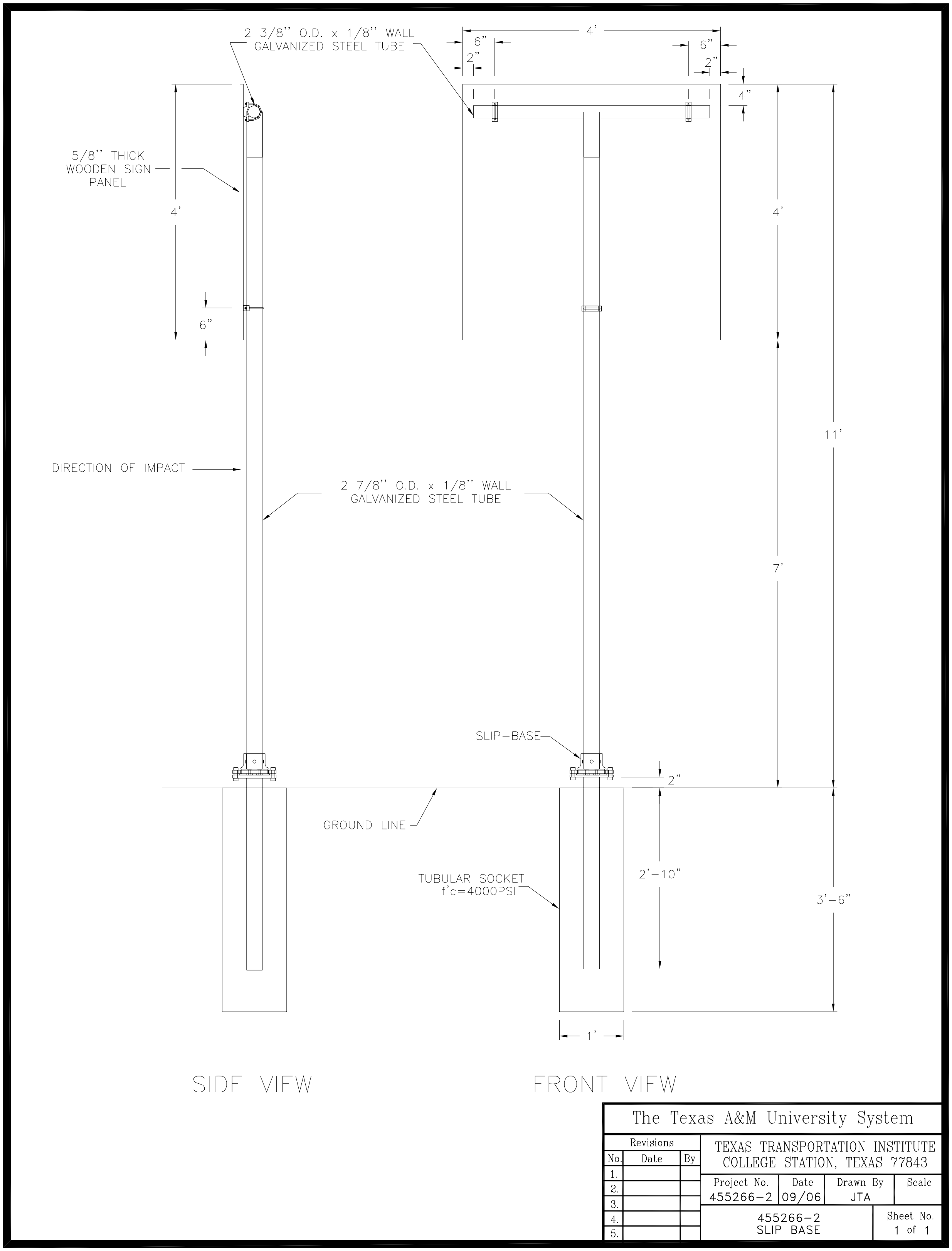


Figure 4-10. Details of the Triangular Slip Base Sign Support.

Figure 4-11. Test Article/Installation before Test 455266-2.

Figure 4-12. Vehicle/Installation Geometrics for Test 455266-2.

Figure 4-13. Vehicle before Test 455266-2.

At 0.168 s, the vehicle, while traveling at a speed of 58.9 mph, contacted the wedge anchor sign support. The support began to deform at ground level at 0.173 s, and the support began to pull upwards out of the socket at 0.202 s. The sign panel separated from the support, and the support had pulled out of the socket by 0.212 s. At 0.267 s, the vehicle lost contact with the wedge anchor support post, and the vehicle was traveling at a speed of 58.8 mph. Brakes on the vehicle were applied 110 ft downstream of the point of impact, and the vehicle subsequently came to rest 287 ft downstream of impact and 2 ft to the right of centerline of the initial path of the vehicle. Figure C2-1 in Appendix C shows sequential photographs of the test period.

Test Article Damage

Triangular Slip Base System

The soil around the concrete footing was slightly disturbed. The upper slip base casting separated from the support post and came to rest near the concrete footing, along with the keeper plate and slip bolts. The plywood sign panel separated from the support post and came to rest 79 ft downstream and 16 ft to the right of centerline of the path of the vehicle. The support post came to rest 173 ft downstream and 5 ft to the right of centerline of the path of the vehicle. Photographs of the damaged triangular slip base sign support system are shown in Figures 4-14 and 4-15.

Wedge Anchor System

The wedge anchor sign support pulled out of its socket. The plywood sign panel separated from the support and came to rest 54 ft downstream and 3 ft to the left of centerline of the path of the vehicle. The support post came to rest 141 ft downstream and 5 ft to the left of centerline. The support was kinked at an angle of 45 degrees a distance of 12 inches from the bottom of the support post and an angle of 15 degrees a distance of 27.5 inches from the bottom. The top 4 ft of the support post had some permanent curvature and flattening. Photographs of the damaged wedge anchor sign support system are shown in Figures 4-14 and 4-15.

Test Vehicle Damage

Review of the high-speed video indicated that most of the damage to the test vehicle was attributed to impact with the triangular slip base sign support system. The vehicle front bumper, hood, grill, radiator support, and roof were damaged. A small cut or tear was observed on each side of the roof due to contact with the sign panel mounting bolts of the triangular slip base system; one cut measured 4.3 inches x 0.8 inches, and the other measured 2.6 inches x 0.6 inches. Contact with the triangular slip base sign panel and support post caused the roof to deform downward 3 inches over a roughly circular area measuring approximately 52 inches in diameter. Maximum exterior crush to the front of the vehicle was 9.8 inches just to the right of centerline, which was the point of contact with the triangular slip base support post. Figure 4-16 presents photographs of the vehicle. Maximum occupant compartment deformation was 3.0 inches in the roof area on the passenger side. Photographs of the interior of the vehicle are shown in Figure 4-17. Exterior crush measurements and occupant compartment measurements are noted in Tables C1-1 and C1-2 of Appendix C.

Figure 4-14. After Impact Trajectory Path for Test 455266-2.

Figure 4-15. Installation after Test 455266-2.

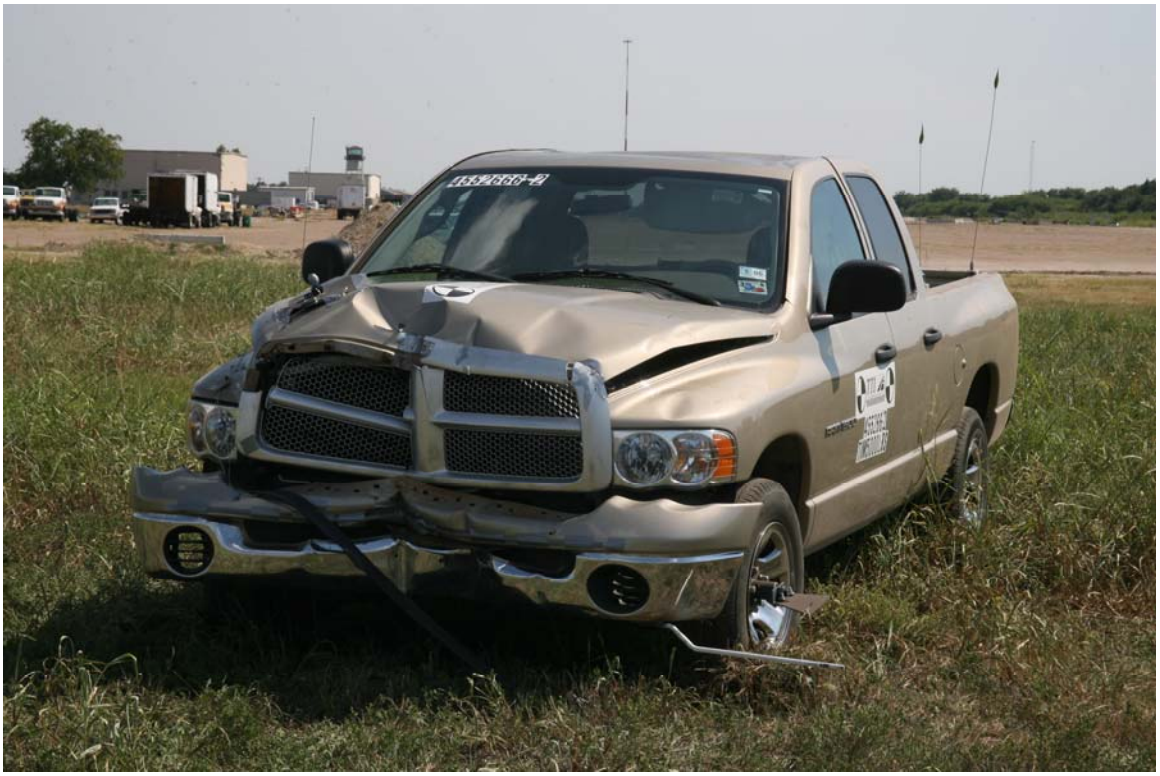


Figure 4-16. Vehicle after Test 455266-2.

Figure 4-17. Interior of Vehicle after Test 455266-2.

Occupant Risk Values

Data from the accelerometer, located at the vehicle center of gravity, were digitized for evaluation of occupant risk. In the longitudinal direction, the occupant impact velocity was 5.2 ft/s at 0.553 s; the highest 0.010-s occupant ridedown acceleration was -0.7 g's from 0.692 to 0.702 s; and the maximum 0.050-s average acceleration was -1.1 g's between 0.162 and 0.212 s. In the lateral direction, the occupant impact velocity was 0.3 ft/s at 0.553 s; the highest 0.010-s occupant ridedown acceleration was 0.7 g's from 0.690 to 0.700 s; and the maximum 0.050-s average was -0.4 g's between 0.276 and 0.326 s.

Theoretical Head Impact Velocity was 3.7 mph or 5.2 ft/s at 0.554 s; Post-Impact Head Decelerations was 1.0 g's between 0.690 and 0.700 s; and Acceleration Severity Index was 0.19 between 0.153 and 0.203 s. Figure 4-18 presents these data and other pertinent information from the test. Figure C3-1 in Appendix C presents vehicle angular displacements and Figures C4-1 through C4-6 show accelerations versus time traces.

Assessment of Test Results

An assessment of the test based on the applicable *NCHRP Report 350* Update safety evaluation criteria is presented below.

Structural Adequacy

B. *The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.*

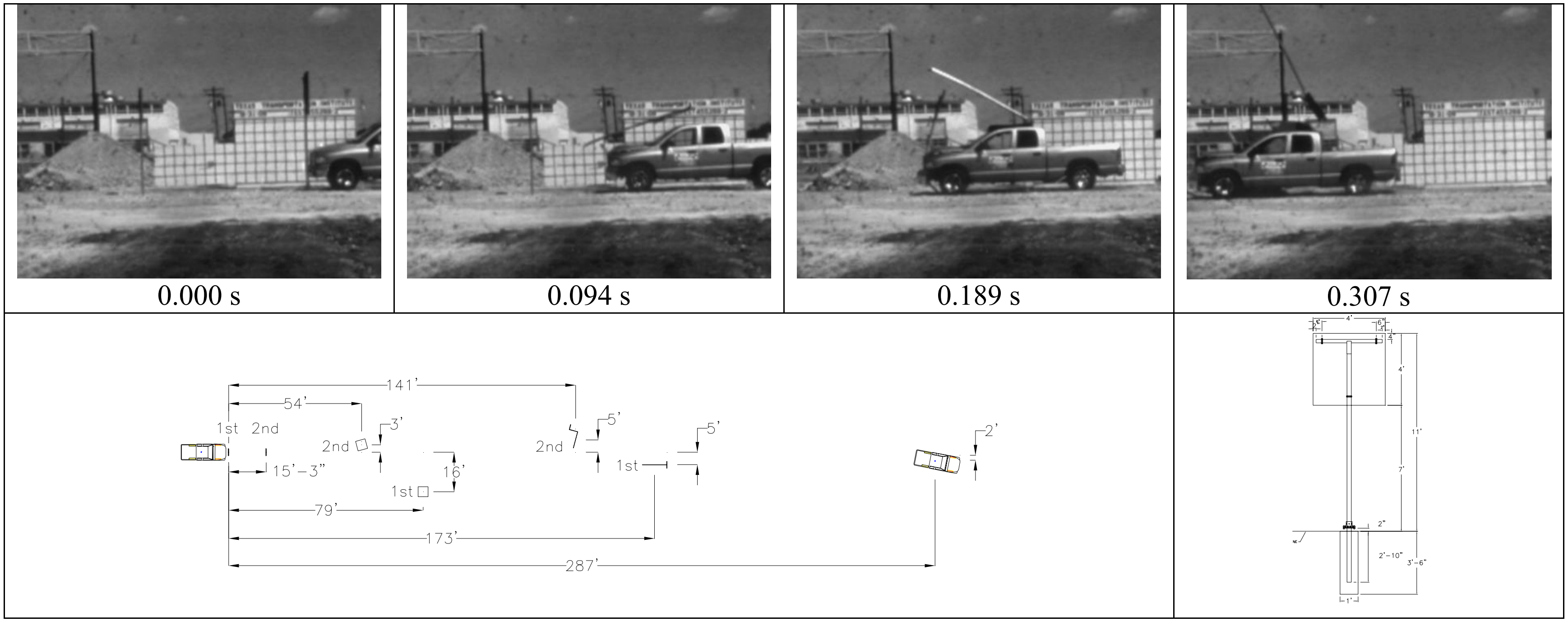
Results: Both sign supports yielded to the 2270P vehicle. The triangular slip base support slipped away at its base, and the wedge anchor support pulled out of its socket. (PASS)

Occupant Risk

D. *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.*

Deformation of, or intrusions into, the occupant compartment should not exceed limits specified. (roof ≤3.9 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤8.9 inches; forward of A-pillar ≤11.8 inches; front side door area above seat ≤8.9 inches; front side door below seat ≤11.8 inches; floor pan/transmission tunnel area ≤11.8 inches)

Rating	*Extent of Intrusion*
Good	*<5.9 inches*
Acceptable	*2.9 inches – 8.9 inches*
Marginal	*8.9 inches – 11.8 inches*
Poor	*>11.8 inches*


0.000 s

0.094 s

0.189 s

0.307 s

General Information	
Test Agency	Texas Transportation Institute
Test No.	455266-2
Date	08-31-2006
Test Article	
Type	Sign Support
Name	Slip Base and Wedge Sign Supports
Installation Length (ft (m))	7.0
Material or Key Elements	Slip Base: 2-5/8 inch Schedule 10 pipe with 4 ft × 4 ft × 5/8 inch Sign Panel Wedge: 2 inch ID × 132 inch Support with 3 ft × 3ft × 5/8 inch Sign Panel
Soil Type and Condition	Standard Soil, Dry
Test Vehicle	
Type	Production
Designation	2270P
Model	2003 Dodge 1500 Quad-Cab Pickup
Mass (lb)	
Curb	4735
Test Inertial	5013
Dummy	No dummy
Gross Static	5013

Impact Conditions	
Speed (mph)	62.7
Angle (deg)	0.4
Exit Conditions	
Speed (mph)	58.8
Angle (deg)	N/A
Occupant Risk Values	
Impact Velocity (ft/s)	
Longitudinal	5.2
Lateral	0.3
THIV (mph)	3.7
Ridedown Accelerations (g's)	
Longitudinal	-0.7
Lateral	0.7
PHD (g's)	1.0
ASI	0.19
Max. 0.050-s Average (g's)	
Longitudinal	-1.1
Lateral	-0.4
Vertical	-1.9

Test Article Debris Scatter (ft)	
Longitudinal	173.0
Lateral	16.0
Vehicle Damage	
Exterior	
VDS	12FC2
CDC	12FCEN2
Maximum Exterior Vehicle Crush (inches)	250
Interior	
OCDI	RF0200000
Maximum Occupant Compartment Deformation (inches)	3.0
Post-Impact Behavior	
(during 1.0 sec after impact)	
Max. Yaw Angle (deg)	-1
Max. Pitch Angle (deg)	1
Max. Roll Angle (deg)	4

Figure 4-18. Summary of Results for *NCHRP Report 350* Update Test 3-62 on the Slip Base and Wedge Sign Supports.

Results: No components from either sign support penetrated nor showed potential for penetrating the occupant compartment, nor did they present undue hazard to others in the area. (PASS)

There was no deformation of or intrusion into the occupant compartment resulting from impact with the wedge anchor sign support. (PASS)

Maximum occupant compartment deformation resulting from impact with the triangular slip base system was 3 inches in the roof area on the passenger side. (PASS)

F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.

Results: The 2270P vehicle remained upright during and after the collision event. Maximum roll angle was 4 degrees, and maximum pitch angle was 1 degree. (PASS)

I. Occupant impact velocities should satisfy the following:

Longitudinal and Lateral Occupant Impact Velocity

Preferred	*Maximum*
9.8 ft/s	*16.4 ft/s*

Results: Longitudinal occupant impact velocity was 5.2 ft/s, and lateral occupant impact velocity was 0.3 ft/s. (PASS)

I. Occupant ridedown accelerations should satisfy the following:

Longitudinal and Lateral Occupant Ridedown Accelerations

Preferred	*Maximum*
15.0 G's	*20.0 G's*

Results: Longitudinal occupant ridedown acceleration was -0.7 G's, and lateral occupant ridedown acceleration was 0.7 G's. (PASS)

Vehicle Trajectory

N. Vehicle trajectory behind the test article is acceptable.

Result: The vehicle came to rest 287 ft behind the test article. (PASS)

The following supplemental evaluation factors and terminology, as presented in the FHWA memo entitled "ACTION: Identifying Acceptable Highway Safety Features," were used for visual assessment of test results. *(13)* Factors underlined below pertain to the results of the crash test reported herein.

Passenger Compartment Intrusion

1. *Windshield Intrusion*
    - *[✓ a. No windshield contact]*
    - *b. Windshield contact, no damage*
    - *c. Windshield contact, no intrusion*
    - *d. Device embedded in windshield, no significant intrusion*
    - *e. Complete intrusion into passenger compartment*
    - *f. Partial intrusion into passenger compartment*
2. *Body Panel Intrusion* *[✓ yes] or no*

Loss of Vehicle Control

1. *Physical loss of control*
2. *Loss of windshield visibility*
3. *Perceived threat to other vehicles*
4. *[✓ Debris on pavement]*

Physical Threat to Workers or Other Vehicles

1. *Harmful debris that could injure workers or others in the area*
2. *Harmful debris that could injure occupants in other vehicles*

If yes, Size: 4 ft × 4 ft × 5/8 inch sign panel
Mass: 85 lb
Speed: high or [✓ low]
Trajectory: ht: over cab

Vehicle and Device Condition

1. *Vehicle Damage*
    - *a. None*
    - *b. Minor scrapes, scratches or dents*
    - *c. Significant cosmetic dents*
    - *[✓ d. Major dents to grill and body panels]*
    - *e. Major structural damage*
2. *Windshield Damage*
    - *[✓ a. None]*
    - *b. Minor chip or crack*
    - *c. Broken, no interference with visibility*
    - *d. Broken or shattered, visibility restricted but remained intact*
    - *e. Shattered, remained intact but partially dislodged*
    - *f. Large portion removed*
    - *g. Completely removed*
3. *Device Damage*
    - *a. None*
    - *b. Superficial*
    - *c. Substantial, but can be straightened*
    - *d. Substantial, replacement parts needed for repair*
    - *[✓ e. Cannot be repaired]*

Summary of Test Results

Triangular Slip Base System

The triangular slip base sign support system demonstrated satisfactory impact performance when evaluated in accordance with *NCHRP Report 350* Update criteria. The slip base mechanism activated as designed. The detached supports and sign panels did not penetrate, nor show potential for penetrating the occupant compartment, nor to present undue hazard to others in the area. Maximum occupant compartment deformation was 3.0 inches in the roof area on the passenger side resulting from secondary contact with the sign support and sign panel. The computed occupant risk indices were below the preferred values set forth in the *NCHRP Report 350* Update. The 2270P vehicle remained upright and stable during and after the collision event and came to a controlled stop behind the point of impact.

Wedge Anchor System

The wedge anchor sign support system demonstrated satisfactory impact performance. The sign support activated by yielding to the impacting vehicle and then pulling out of its socket. Even with the more central impact on the bumper and hood, there was no secondary contact between the sign support structure and windshield. The height of the hood helped propel the yielding support post forward and prevented it from deflecting rearward enough to engage the windshield. The test vehicle sustained only minor damage, and there was no deformation of or intrusion into the occupant compartment resulting from the impact with the wedge anchor system. The computed occupant risk indices were below the preferred values set forth in the *NCHRP Report 350* Update. The 2270P vehicle remained upright and stable during and after the collision event and came to a controlled stop behind the point of impact.

Discussion

Given that the triangular slip base with a 10 BWG support post was found to comply with the Update, what can be inferred regarding the impact performance of the slip base with a schedule 80 pipe support? It could be argued that the heavier mass of the schedule 80 support and its larger sign panel will produce greater occupant compartment deformation than that measured in the crash test of the lighter weight slip base system with 10 BWG support. However, the heavier mass also increases the inertial resistance of the schedule 80 support system, which can reduce the rotational velocity imparted to the support during impact. Decreased rotational velocity will tend to shift the point of contact on the roof further rearward and decrease the deformation resulting from that contact. Furthermore, the larger sign panels typically associated with the schedule 80 support are likely to span the width of the roof and engage the door headers. The door headers are much stiffer than the central portion of the roof, and engaging them will tend to reduce the overall deformation resulting from contact with the sign panel. For these reasons, the researchers believe that the triangular slip base with a schedule 80 support post will comply with the Update, and further testing of the system can be assigned a low priority.

CHAPTER 5.

PRIORITIZATION OF TESTING NEEDS

In the preceding chapters of this report, researchers used crash test results, engineering analyses, and engineering judgment to provide an assessment of the ability of TxDOT roadside safety hardware to comply with the update to *NCHRP Report 350* (Update). The criteria upon which the impact performance assessments were based include structural adequacy, vehicle stability, occupant compartment deformation, and occupant risk.

Table 5-1 presents a list of TxDOT-utilized roadside safety hardware evaluated under the project. The devices are grouped by applicable roadside safety category for ease of reference. The categories of roadside appurtenances include guard fence, median barriers, portable and precast barriers, transitions from approach guard fence to bridge rails, bridge rails, work zone traffic control devices, and breakaway small sign supports. All of the crash cushions and guardrail end treatments currently used by TxDOT are proprietary in nature and, therefore, these categories are not included. Similarly, proprietary devices in other categories were not considered either. The manufacturers of these devices will be required to assess the impact performance of their devices and ultimately demonstrate compliance of their devices with the new test and evaluation guidelines.

Each device included in Table 5-1 is identified by a standard drawing (when applicable) and a system description. Each device is assigned a performance assessment based on its ability to comply with the Update. The performance assessment takes one of two forms. For devices that have been crash tested in accordance with the impact performance guidelines of the Update, the performance is rated as either “Pass,” “Marginal,” or “Fail,” depending on the results and outcome of the test(s). Devices that are presently untested or only partially tested to the Update are rated based on their probability or likelihood of complying with the requirements of the Update – “Very High,” “High,” “Medium,” “Low,” or “Unlikely.” For example, if a device receives a performance assessment of “Very High,” it implies that the device has not been fully tested under the Update, but it has been judged to have a very high probability of complying with the new impact performance guidelines. If a device is assigned a performance assessment of “Pass,” it means that the device has been successfully tested under the Update.

It should be noted that the performance assessment is based on the applicable test level for which the device has been accepted under *NCHRP Report 350*. For example, if a barrier has been tested or otherwise accepted as a TL-2 system, the performance assessment pertains to the ability of the barrier to meet the requirements for the same test level (i.e., TL-2) under the Update. If the evaluation of the device indicated that it may be able to achieve a higher test level under the Update, it may be so noted in the comment field for that device.

Table 5-1. Performance Assessment and Prioritization of Texas Roadside Safety Hardware.

Standard Drawing	System Description	Performance Assessment	Prioritization	Comments
Guard Fence				
MBGF-03-A	Metal Beam Guard Fence	Marginal	N.A.	Rail element torn through half its cross-section; no factor of safety.
Median Barriers				
CSB(1)-04	F-Shape Concrete Safety Barrier	Very High	Low	Update test 3-11 conducted on precast F-shape; Update test 3-10 conducted on permanent New Jersey profile barrier.
SSCD(2)-00A	Single Slope Concrete Barrier	Very High	Low	
Portable and Precast Concrete Median Barrier				
CSB(1)-04 and CSB(2)-04	F-shape with Type X Connection (30-ft segments)	Very High	Low	Successful test 3-11 with more critical F-shape barrier with 10 ft segments more critical 5000 lb, ¾-ton pickup.
CSB(8)-04	F-shape with Type X Connection (10 ft segments)	Pass	N.A.	Successful Update test 3-11 with more critical ¾-ton pickup.
LPCB(2)-92	Low Profile Barrier	High	Medium	Requires Update test 3-11.
Guardrail-to-Bridge Rail Transitions				
MBGF(TR)-02	TL-3 Transition	Pass	N.A.	Successful Update test 3-21 on steel post system.
MBGF(TL2)-05	TL-2 Transition	High	Low	Requires Update test 2-21.

Table 5-1. Performance Assessment and Prioritization of Texas Roadside Safety Hardware (Continued).

Standard Drawing	System Description	Performance Assessment	Prioritization	Comments
Bridge Rails				
T101	W-Beam and Steel Tubes on Steel Posts	Medium	High	Requires Update tests 3-10 and 3-11.
T203	Concrete Rail on Concrete Posts	Medium	Medium	Requires Update tests 3-10 and 3-11.
T221	Vertical Concrete Parapet	High	Medium	Requires Update test 3-11.
T401	Elliptical Steel Rail on Concrete Parapet	High	Low	
T411	Texas Classic	Very High	Low	May meet TL-3 requirements due to more liberal occupant compartment deformation thresholds and improved vehicle design.
T501	New Jersey Safety Shape	Very High	Low	Successful Update test 3-10.
T6	Tubular W-beam	High	Low	Requires Update test 2-11.
T77	Two Elliptical Rails on Concrete Parapet	High	Low	
SSTR	Single Slope Traffic Rail	Very High	Low	

Table 5-1. Performance Assessment and Prioritization of Texas Roadside Safety Hardware (Continued).

Standard Drawing	System Description	Performance Assessment	Prioritization	Comments
Work Zone Traffic Control Devices				
	Low-Mounting Height Temporary Sign Supports	Very High	Low	Low mounting height should preclude contact with windshield of pickup truck in Update test 3-72. Performance in Update test 3-71 should be similar to *NCHRP Report 350* test 3-71.
	Tall-Mounting Height Temporary Sign Support (Wood 4x4 Supports)	Pass	N.A.	Dual wood support system successfully passed Update test 3-72 with ¾-ton pickup at more critical 5 ft mounting height.
	Tall-Mounting Height Temporary Sign Support (Perforated Steel Tube Supports)	Medium	Medium	Requires Update test 3-72.
	Type III Barricades	Very High	Low	Low height should preclude contact on windshield of pickup truck on Update test 3-72.
Small Sign Supports				
SMD(TWT)-02	Wedge Anchor System	Pass	N.A.	No windshield contact on Update test 3-62.
SMD(SLIP-1)-02	Triangular Slip Base (10 BWG Support)	Pass	N.A.	3 inches of roof deformation resulting from secondary contact of sign panel with roof in Update test 3-62.
SMD(SLIP-1)-02	Triangular Slip Base (Schedule 80 Pipe Support)	High	Medium	Requires Update test 3-62.

Researchers also assigned each device listed in Table 5-1 a prioritization for any additional crash testing and evaluation deemed necessary to bring the device into compliance with the new impact performance guidelines. The prioritization of each device is rated as "High," "Medium," "Low," or "Not Applicable (N.A.)." The prioritization is based on the degree of testing to the Update (if any), the performance assessment, usage and/or perceived importance of the device to TxDOT operations, and other applicable factors. Devices that have been successfully tested and found to comply with the requirements of the Update are assigned "N.A.," indicating that no further testing or evaluation is required.

Generally speaking, devices with higher risk of failure under the new guidelines are given higher priority in programming further crash testing and performance evaluation. Should the device ultimately fail to comply with the Update requirements, additional time and resources will be required to modify or upgrade the device to permit its continued use after adoption of the Update. Thus, addressing these devices will provide higher overall safety benefits.

Conversely, devices with low risk of failure (i.e., very high probability of complying with the update) are generally assigned a lower priority for further investigation. In these cases it is likely that the additional testing will merely confirm compliance of the device with the Update, and not as much benefit will be derived from the expended resources.

The "Comments" field of Table 5-1 is used to make relevant notes regarding the impact performance assessment and prioritization of a device, including successfully conducted tests and additional tests required to comply with the Update.

DISCUSSION

Devices that have been successfully tested and found to comply with the update include: metal beam guard fence, precast concrete F-shape barrier with Type X connection and 10-ft long segments, TL-3 nested thrie beam transition, wedge anchor small sign support system, triangular slip base sign support system with 10 BWG supports, and a tall-mounting height temporary sign support with wooden 4 inch x 4 inch supports. These devices should not require any further testing or evaluation unless possible future changes to the test matrices and impact conditions of the Update so dictate.

The only device assigned a high priority for further testing and evaluation under the update is the T101 bridge rail. This additional testing and evaluation is based primarily on the absence of pickup truck testing on this system.

Devices with a medium priority include: low profile barrier, T203 concrete beam and post bridge rail, T221 vertical concrete bridge rail, triangular slip base sign support system with schedule 80 pipe supports, and a tall-mounting height temporary sign support with perforated steel tube supports. These devices should be programmed for further testing and evaluation under the Update as resources permit.

Devices assigned a low priority for further testing and evaluation under the update include: F-shape concrete median barrier; single slope concrete median barrier; precast concrete F-shape barrier with Type X connection and 30-ft long segments; 27-inch tall, TL-2 nested W-beam transition; various bridge rails (T401, T411, T501, T6, T77, and SSTR); low-mounting height temporary sign supports; and Type III barricades. Future testing of some of these devices should be considered after the higher priorities have been addressed.

It may be of interest to note that as development of the *NCHRP Report 350* Update progressed under NCHRP Project 22-14(02), it appeared that the new design test vehicle for structural adequacy tests would be a 5000-lb, ¾-ton, standard cab pickup. The logic in this selection is that it was the same body style pickup used under *NCHRP Report 350* with a test inertial weight adjusted to reflect the upsizing trend indicated in sales of new passenger vehicles. Previous research had concluded that the ¾-ton, standard cab pickup was a reasonable surrogate for light truck vehicles, and there was a tremendous amount of experience and investment in designing for and testing with this truck.

The implications of specifying the heavier, 5000-lb, ¾-ton pickup truck as the new design test vehicle were not completely understood, but it was known that it would be more critical than the existing 4409-lb, ¾-ton pickup used under *NCHRP Report 350*. The 13% increase in weight and impact severity would place more demand on the structural adequacy of barrier systems, and would aggravate problems with vehicle stability and occupant compartment deformation. As an example, it was demonstrated in a full-scale crash test that standard guardrail designs would not accommodate the new vehicle under TL-3 impact conditions.

It was not until well into the Update development, and after the time during which this project was being programmed, that the design test vehicle changed to a 5000-lb, ½-ton, 4-door pickup truck. The rationale for this change is that this body style pickup has characteristics that more closely resemble large SUVs than the ¾-ton, standard cab pickup. Subsequent crash testing and analyses conducted under NCHRP Project 22-14(02), this project, and others indicate that the 5000-lb, ½-ton, 4-door, pickup truck will impart impact loads that are comparable to those of the 4409-lb, ¾-ton, standard cab pickup. Further, the ½-ton, 4-door, pickup truck will be more stable and have less propensity for occupant compartment intrusion than the ¾-ton pickup.

When these vehicle factors are combined with much more liberal thresholds for occupant compartment deformation, the need for revising existing hardware to comply with the Update does not appear to be as extensive as once anticipated. This fact is reflected in the performance assessments ratings assigned to Texas roadside safety hardware in Table 5-1. The researchers do note that the dramatic increase in impact severity of the pickup truck redirection tests and other changes in the test matrices for terminals and crash cushions will likely necessitate the modification of some of these systems. However, due to the proprietary nature of the devices in these roadside safety hardware categories, an assessment of their performance has not been addressed under this project.

CHAPTER 6.

SUMMARY AND CONCLUSIONS

NCHRP Report 350 "Recommended Procedures for the Safety Performance Evaluation of Highway Features" contains the current guidelines for evaluating the safety performance of roadside features, such as longitudinal barriers, terminals, crash cushions, and breakaway structures. This document was published in 1993 and was formally adopted as the national standard by FHWA later that year with an implementation date for late 1998.

A recommended update to *NCHRP Report 350* (Update) has been developed under NCHRP Project 22-14(02), "Improvement of Procedures for the Safety-Performance Evaluation of Roadside Features." This document contains revised criteria for safety-performance evaluation of virtually all roadside safety features. Changes to the design test vehicles and impact conditions will place greater impact performance demands on many current roadside safety features.

TxDOT makes considerable use of non-proprietary roadside safety systems. Although some barrier testing has been conducted under NCHRP Project 22-14(02) during the development of the Update criteria, many barrier systems and other roadside safety features have yet to be evaluated under the proposed guidelines. Therefore, evaluation of the remaining widely used roadside safety features following the impact performance requirements of the Update is needed.

Under this research project, researchers conducted a performance assessment of Texas roadside safety devices to help evaluate the impact of adopting the update to *NCHRP Report 350* on current hardware. Crash test results, engineering analyses, and engineering judgment were used to assist with the hardware evaluation. Categories of roadside features that were considered under the project include guard fence, median barriers, bridge rails, transitions from approach guard fence to bridge rails, breakaway sign supports, precast work zone barriers, and work zone traffic control devices. Proprietary devices were not considered. The manufacturers of these devices will be required to assess the impact performance of their devices and ultimately demonstrate compliance of their devices with the new test and evaluation guidelines.

Results of the performance assessment were used to develop a prioritization scheme for further testing and evaluation required to bring Texas roadside safety features into compliance with the new impact performance guidelines. The prioritization of hardware should assist TxDOT with an efficient use of resources and help provide a relatively seamless transition to the Update.

Two generic small sign support systems commonly used by TxDOT were tested under this project using the ½-ton, 4-door, quad cab pickup. The Update proposes the use of the pickup truck in the evaluation of breakaway support structures to assess the potential for occupant compartment intrusion. Evaluation summaries for the tests are shown in Table 6-1 and Table 6-2. As indicated in these tables, both the wedge anchor system and a triangular slip base system satisfied the evaluation criteria for Update test 3-62. All occupant risk criteria were below recommended values. The detached supports and sign panels did not penetrate, nor show potential for penetrating the occupant compartment, nor to present undue hazard to others in the area. The pickup remained upright and stable both during and after the collision event. The wedge anchor sign support did not contact the windshield, damage, or cause any occupant compartment deformation. In the test of the triangular slip base, secondary contact of the sign panel and support post resulted in occupant compartment deformation of 3 inches in the roof, which is less than the roof deformation limit of 3.9 inches.

Table 6-1. Performance Evaluation Summary for *NCHRP Report 350* Update Test 3-62 on the Wedge Anchor Sign Support.

Test Agency: Texas Transportation Institute　　Test No.: 455266-1　　Test Date: 08-31-2006

<table>
<tr><th><i>NCHRP Report 350</i> Update Test 3-62 Evaluation Criteria</th><th><i>Test Results</i></th><th><i>Assessment</i></th></tr>
<tr><td><u><i>Structural Adequacy</i></u></td><td></td><td></td></tr>
<tr><td><i>B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</i></td><td>The wedge sign support yielded to the vehicle by pulling out of the ground.</td><td>Pass</td></tr>
<tr><td><u><i>Occupant Risk</i></u>
<i>D. 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.</i>
<i>Deformations of, or intrusions into, the occupant compartment should not exceed limits specified.</i></td><td>The detached support and sign panel did not penetrate, nor show potential for penetrating the occupant compartment, nor present undue hazard to others in the area.
No occupant compartment deformation occurred.</td><td>Pass</td></tr>
<tr><td><i>F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</i></td><td>The 2270P vehicle remained upright during and after the collision event. Maximum roll angle was -1 degree, and maximum pitch angle was 1 degree.</td><td>Pass</td></tr>
<tr><td><i>H. Occupant impact velocities should satisfy the following:</i>
<table>
<tr><th colspan="3"><i>Occupant Velocity Limits</i></th></tr>
<tr><th><i>Component</i></th><th><i>Preferred</i></th><th><i>Maximum</i></th></tr>
<tr><td><i>Longitudinal</i></td><td><i>9.8 ft/s</i></td><td><i>16.4 ft/s</i></td></tr>
</table></td><td>Longitudinal occupant impact velocity was 3.9 ft/s, and lateral occupant impact velocity was 0.3 ft/s.</td><td>Pass</td></tr>
<tr><td><i>I. Occupant ridedown accelerations should satisfy the following:</i>
<table>
<tr><th colspan="3"><i>Occupant Ridedown Acceleration Limits</i></th></tr>
<tr><th><i>Component</i></th><th><i>Preferred</i></th><th><i>Maximum</i></th></tr>
<tr><td><i>Longitudinal and lateral</i></td><td><i>15.0 G’s</i></td><td><i>20.0 G’s</i></td></tr>
</table></td><td>Longitudinal ridedown acceleration was -0.3 G’s, and lateral ridedown acceleration was -0.3 G’s.</td><td>Pass</td></tr>
<tr><td><u><i>Vehicle Trajectory</i></u></td><td></td><td></td></tr>
<tr><td><i>N. Vehicle trajectory behind the test article is acceptable.</i></td><td>The vehicle came to rest 275 ft behind the sign support installation.</td><td>Pass</td></tr>
</table>

Table 6-2. Performance Evaluation Summary for *NCHRP Report 350* Update Test 3-62 on the Triangular Slip Base and Wedge Anchor Sign Support Systems.

Test Agency: Texas Transportation Institute Test No.: 455266-2 Test Date: 08-31-2006

<table>
<tr><th><i>NCHRP Report 350</i> Update Test 3-62 Evaluation Criteria</th><th><i>Test Results</i></th><th><i>Assessment</i></th></tr>
<tr><td><u>Structural Adequacy</u></td><td></td><td></td></tr>
<tr><td>B. <i>The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</i></td><td>Both sign supports yielded to the 2270P vehicle. The slip base support slipped away at the base, and the wedge support pulled out of the ground.</td><td>Pass</td></tr>
<tr><td><u>Occupant Risk</u>
D. <i>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.</i>
<i>Deformations of, or intrusions into, the occupant compartment should not exceed limits specified.</i></td><td>The detached supports and sign panels did not penetrate, nor show potential for penetrating the occupant compartment, nor present undue hazard to others in the area.
Maximum occupant compartment deformation was 3 inches in the roof area on the passenger side.</td><td>Pass</td></tr>
<tr><td>F. <i>The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</i></td><td>The 2270P vehicle remained upright during and after the collision event. Maximum roll angle was 4 degrees, and maximum pitch angle was 1 degree.</td><td>Pass</td></tr>
<tr><td>H. <i>Occupant impact velocities should satisfy the following:</i>
<table>
<tr><th colspan="3"><i>Occupant Velocity Limits</i></th></tr>
<tr><th><i>Component</i></th><th><i>Preferred</i></th><th><i>Maximum</i></th></tr>
<tr><td><i>Longitudinal</i></td><td><i>9.8 ft/s</i></td><td><i>16.4 ft/s</i></td></tr>
</table></td><td>Longitudinal occupant impact velocity was 5.2 ft/s, and lateral occupant impact velocity was 0.3 ft/s.</td><td>Pass</td></tr>
<tr><td>I. <i>Occupant ridedown accelerations should satisfy the following:</i>
<table>
<tr><th colspan="3"><i>Occupant Ridedown Acceleration Limits</i></th></tr>
<tr><th><i>Component</i></th><th><i>Preferred</i></th><th><i>Maximum</i></th></tr>
<tr><td><i>Longitudinal and lateral</i></td><td><i>15.0 G's</i></td><td><i>20.0 G's</i></td></tr>
</table></td><td>Longitudinal occupant ridedown acceleration was -0.7 G's, and lateral occupant ridedown acceleration was 0.7 G's.</td><td>Pass</td></tr>
<tr><td><u>Vehicle Trajectory</u></td><td></td><td></td></tr>
<tr><td>N. <i>Vehicle trajectory behind the test article is acceptable.</i></td><td>The vehicle came to rest 287 ft behind the test article.</td><td>Pass</td></tr>
</table>

CHAPTER 7.

IMPLEMENTATION STATEMENT

The product of this research is an impact performance assessment of roadside safety hardware used in Texas in relation to the proposed update to *NCHRP Report 350* (Update) and a prioritization of this hardware in terms of additional research needed to achieve compliance with the Update. The list of TxDOT-utilized roadside safety hardware evaluated under the project is presented in Table 5-1 of this report. The devices are grouped by applicable roadside safety category for ease of reference. The categories of roadside appurtenances include guard fence, median barriers, portable and precast barriers, transitions from approach guard fence to bridge rails, bridge rails, work zone traffic control devices, and breakaway small sign supports. Proprietary devices such as crash cushions and guardrail end treatments are not addressed. The manufacturers of these devices will be required to assess the impact performance of their devices and ultimately demonstrate compliance of their devices with the new test and evaluation guidelines.

Each device included in the evaluation is assigned a performance assessment based on their ability to comply with the Update. The performance assessment was based on crash test results, engineering analyses, and engineering judgment. Each device is further assigned a prioritization ranking for any additional crash testing and evaluation deemed necessary to bring the device into compliance with the new impact performance guidelines. The prioritization ranking is based on the degree of testing to the Update (if any), the performance assessment, usage and/or perceived importance of the device to TxDOT operations, and other applicable factors.

The prioritized list will assist TxDOT personnel in the Bridge, Design, and Traffic Operations Divisions in developing research projects under which the additional testing and evaluation required to bring Texas roadside safety hardware into compliance with the Update can be accomplished. The prioritization of hardware will help ensure efficient use of resources and provide a relatively seamless transition to the Update. Further, the performance information provided in this report should assist TxDOT personnel in understanding the implications of adopting the Update as it progresses through the AASHTO review and publication process.

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APPENDIX A. TEST PROCEDURES

TEST FACILITY

The Texas Transportation Institute Proving Ground is a 2000-acre complex of research and training facilities located 10 mi northwest of the main campus of Texas A&M University. The site, formerly an Air Force base, has large expanses of concrete runways and parking aprons well suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and safety evaluation of roadside safety hardware. The site selected for construction and testing of the sign supports evaluated under this project is along the edge of an out-of-service runway apron. The runway apron consists of an unreinforced jointed-concrete pavement in 12.5 ft × 15 ft blocks nominally 8-12 inches deep. The aprons and runways are over 50 years old, and the joints have some displacement, but are otherwise flat and level.

VEHICLE TOW AND GUIDANCE SYSTEM

The test vehicle was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. An additional steel cable was connected to the test vehicle, passed around a pulley near the impact point, through a pulley on the tow vehicle, and then anchored to the ground such that the tow vehicle moved away from the test site. A two-to-one speed ratio between the test and tow vehicle existed with this system. Just prior to impact with the installation, the test vehicle was released to be free-wheeling and unrestrained. The vehicle remained free-wheeling, i.e., no steering or braking inputs, until the vehicle cleared the immediate area of the test site, at which time brakes on the vehicle were activated to bring it to a safe and controlled stop.

DATA ACQUISITION SYSTEMS

Vehicle Instrumentation and Data Processing

The test vehicle was instrumented with three solid-state angular rate transducers to measure roll, pitch, and yaw rates; a triaxial accelerometer near the vehicle center of gravity to measure longitudinal, lateral, and vertical acceleration levels; and a backup biaxial accelerometer in the rear of the vehicle to measure longitudinal and lateral acceleration levels. These accelerometers were ENDEVCO® Model 2262CA, piezoresistive accelerometers with a ±100 g range.

The accelerometers are strain gage type with a linear millivolt output proportional to acceleration. Angular rate transducers are solid state, gas flow units designed for high-"g" service. Signal conditioners and amplifiers in the test vehicle increase the low-level signals to a ±2.5 volt maximum level. The signal conditioners also provide the capability of an R-cal (resistive calibration) or shunt calibration for the accelerometers and a precision voltage calibration for the rate transducers. The electronic signals from the accelerometers and rate transducers are transmitted to a base station by means of a 15-channel, constant-bandwidth, Inter-Range Instrumentation Group (IRIG), FM/FM telemetry link for recording and for display. Calibration signals from the test vehicle are recorded before the test and immediately afterwards. A crystal-controlled time reference signal is simultaneously recorded with the data. Wooden dowels actuate pressure-sensitive switches on the bumper of the impacting vehicle prior to impact by wooden dowels to indicate the elapsed time over a known distance to provide a measurement of impact velocity. The initial contact also produces an “event” mark on the data record to establish the instant of contact with the installation.

The multiplex of data channels, transmitted on one radio frequency, is received and demultiplexed onto a TEAC® instrumentation data recorder. After the test, the data are played back from the TEAC® recorder and digitized. A proprietary software program (WinDigit) converts the analog data from each transducer into engineering units using the R-cal and pre-zero values at 10,000 samples per second, per channel. WinDigit also provides Society of Automotive Engineers (SAE) J211 class 180 phaseless digital filtering and vehicle impact velocity.

All accelerometers are calibrated annually according to the (SAE) J211 *4.6.1* by means of an ENDEVCO® 2901, precision primary vibration standard. This device and its support instruments are returned to the factory annually for a National Institute of Standards Technology (NIST) traceable calibration. The subsystems of each data channel are also evaluated annually, using instruments with current NIST traceability, and the results are factored into the accuracy of the total data channel, per SAE J211. Calibrations and evaluations are made any time data are suspect.

The Test Risk Assessment Program (TRAP) uses the data from WinDigit to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and the highest 10-milliseconds (ms) average ridedown acceleration. WinDigit calculates change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms intervals in each of the three directions are computed. For reporting purposes, the data from the vehicle-mounted accelerometers are filtered with a 60-Hz digital filter, and acceleration versus time curves for the longitudinal, lateral, and vertical directions are plotted using TRAP.

TRAP uses the data from the yaw, pitch, and roll rate transducers to compute angular displacement in degrees at 0.0001-s intervals and then plots yaw, pitch, and roll versus time. These displacements are in reference to the vehicle-fixed coordinate system with the initial position and orientation of the vehicle-fixed coordinate systems being initial impact.

Photographic Instrumentation and Data Processing

Photographic coverage of the test included two high-speed cameras: one placed behind the installation at a 45 degree angle; and a second placed to have a field of view perpendicular to the test article and vehicle path. A flashbulb activated by pressure-sensitive tape switches was positioned on the impacting vehicle to indicate the instant of contact with the installation and was visible from each camera. The films from these high-speed cameras were analyzed on a computer-linked motion analyzer to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A mini-DV camera and still cameras recorded and documented conditions of the test vehicle and installation before and after the test.

APPENDIX B. CRASH TEST NO. 455266-1

B1. VEHICLE PROPERTIES AND INFORMATION

Date: 8-31-2006 Test No.: 455266-1 VIN No.: 1D7HA18N23S232412

Year: 2003 Make: Dodge Model: Ram 1500

Tire Inflation Pressure: 35 psi Odometer: 28424 Tire Size: 245 70 R17

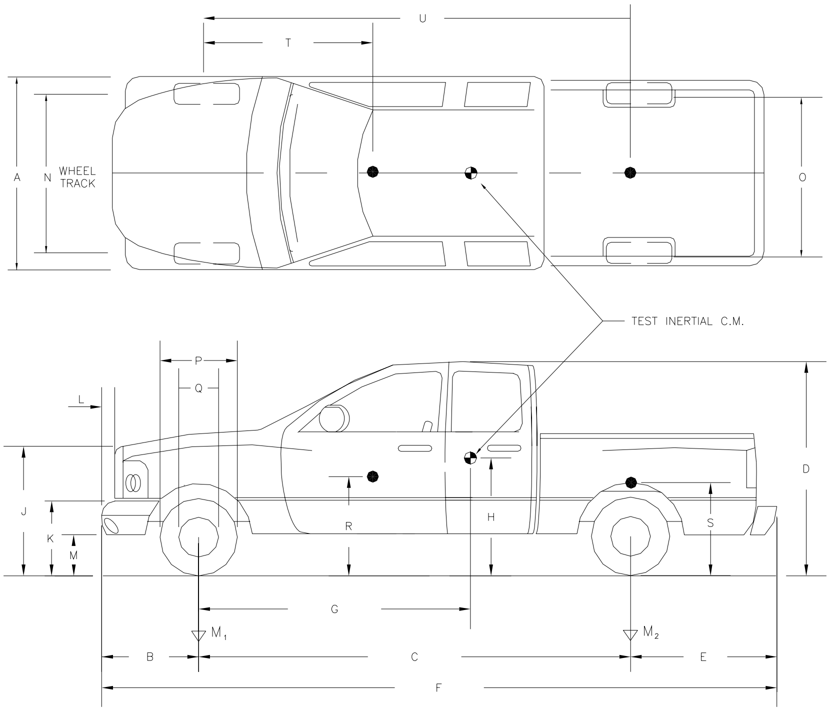
Describe any damage to the vehicle prior to test:

● Denotes accelerometer location.

NOTES:

Engine Type: V-8
Engine CID: 4.7 Liter
Transmission Type:
X Auto
Manual
Optional Equipment:

Dummy Data:
Type: None
Mass:
Seat Position:



Geometry (inches)

A	77.6	E	47.2	J	44.5	N	68.1	R	27.6
B	38.8	F	225.8	K	26.9	O	67.7	S	
C	139.8	G	62.1	L	3.4	P	30.1	T	61.4
D	74.0	H		M	14.4	Q	18.5	U	

Mass (lb)	Curb	Test Inertial	Gross Static
M_1	2743	2784	
M_2	1992	2229	
M_{Total}	4735	5013	

Mass Distribution (lb): LF: 1414 RF: 1370 LR: 1143 RR: 1086

Figure B1-1. Vehicle Properties for Test No. 455266-1.

Table B1-1. Exterior Crush Measurements for Test 455266-1.

VEHICLE CRUSH MEASUREMENT SHEET[1]

Complete When Applicable	
End Damage	Side Damage
Undeformed end width ________ Corner shift: A1 ________ A2 ________ End shift at frame (CDC) (check one) < 4 inches ________ ≥ 4 inches ________	Bowing: B1 _____ X1 _____ B2 _____ X2 _____ Bowing constant $\frac{X1+X2}{2} =$ _______

Note: Measure C_1 to C_6 from Driver to Passenger side in Front or Rear impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage		Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
		Width** (CDC)	Max*** Crush								
1	N/A										

[1] Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc.
Record the value for each C-measurement and maximum crush.

**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

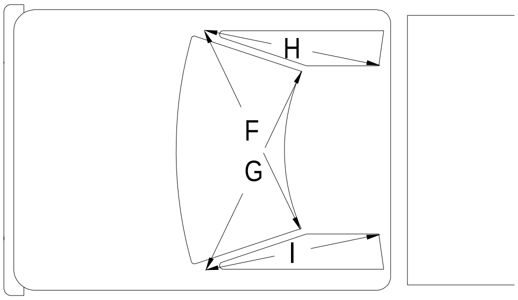
***Measure and document on the vehicle diagram the location of the maximum crush.

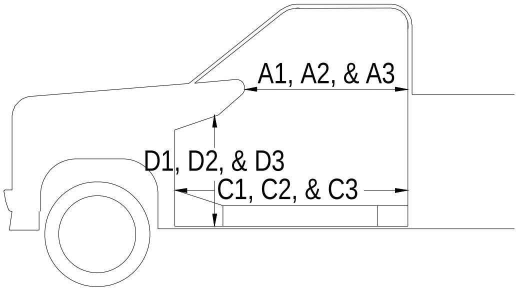
Note: Use as many lines/columns as necessary to describe each damage profile.

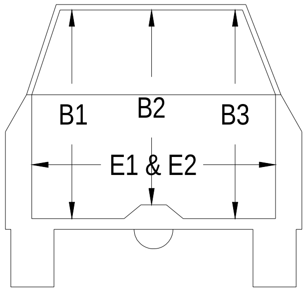
Table B1-2. Occupant Compartment Measurements for Test 455266-1.

Truck

Occupant Compartment Deformation







	BEFORE (inches)	AFTER (inches)
A1	65.4	65.4
A2	65.8	65.8
A3	66.3	66.3
B1	43.8	43.8
B2	39.2	39.2
B3	45.5	45.5
C1	29.1	29.1
C2		
C3	27.6	27.6
D1	12.6	12.6
D2	2.8	2.8
D3	11.4	11.4
E1	64.4	64.4
E2	64.0	64.0
F	60.0	60.0
G	60.0	60.0
H	40.0	40.0
I	39.8	39.8
J*	62.4	62.4

*Lateral area across the cab from
driver’s side kickpanel to passenger’s side kickpanel.

B2. SEQUENTIAL PHOTOGRAPHS

0.000 s

0.011 s

0.023 s

0.035 s

Figure B2-1. Sequential Photographs for Test 455266-1 (Oblique and Perpendicular Views).

0.047s

0.059 s

0.094 s

0.130 s

Figure B2-1. Sequential Photographs for Test 455266-1 (Oblique and Perpendicular Views) (Continued).

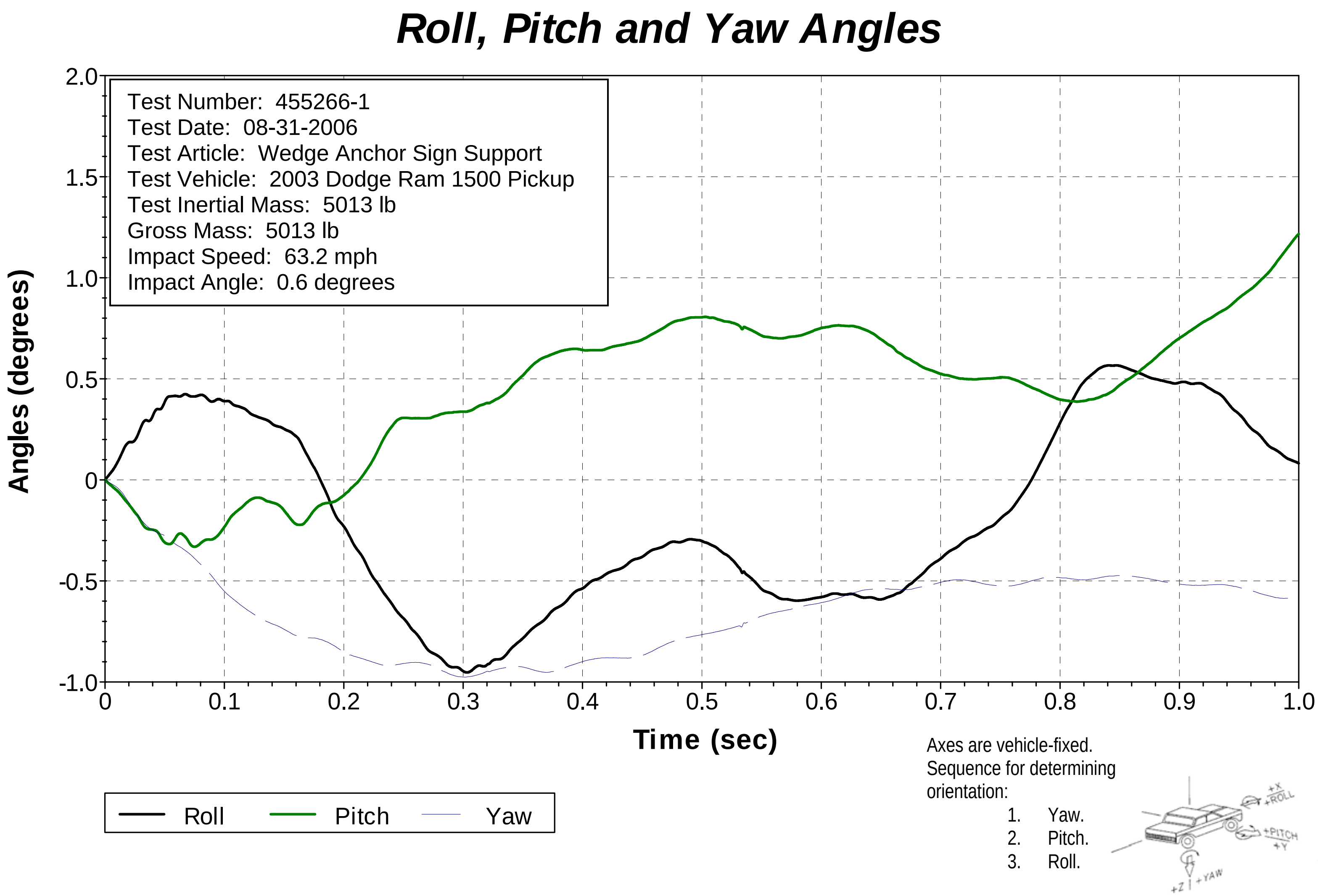


Figure B3-1. Vehicle Angular Displacements for Test 455266-1.

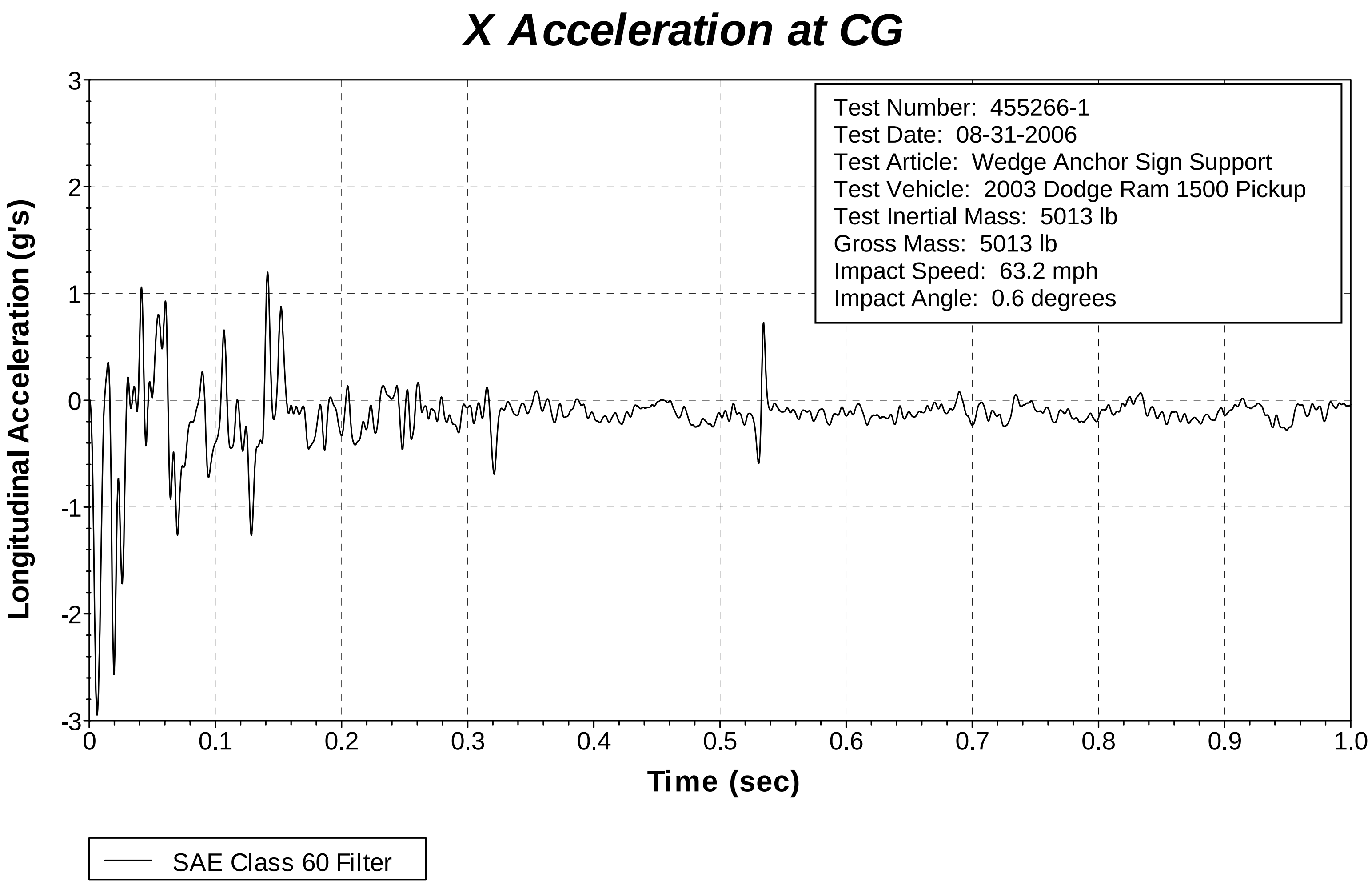
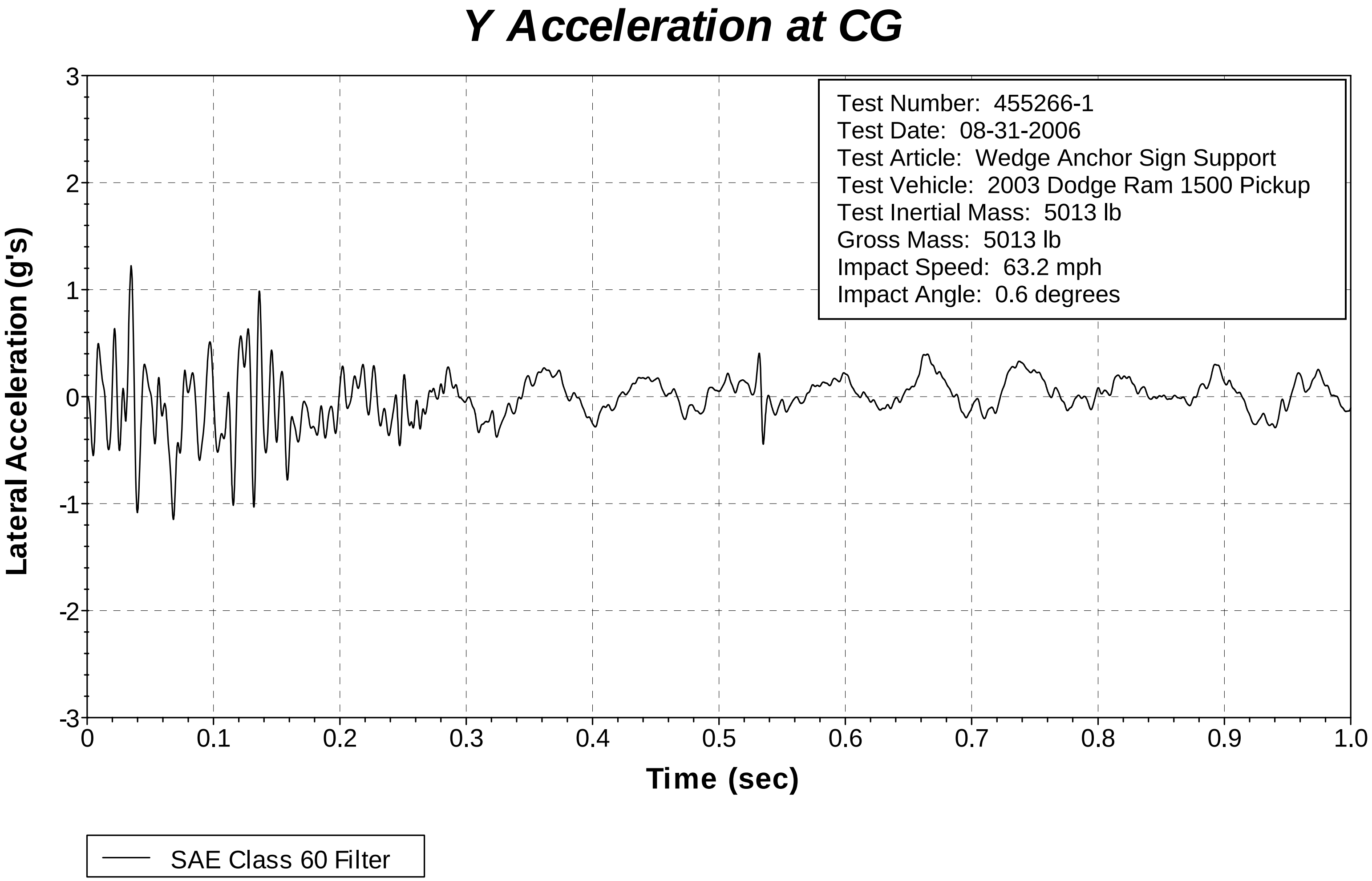


Figure B4-1. Vehicle Longitudinal Accelerometer Trace for Test 455266-1 (Accelerometer Located at Center of Gravity).



Test Number: 455266-1
Test Date: 08-31-2006
Test Article: Wedge Anchor Sign Support
Test Vehicle: 2003 Dodge Ram 1500 Pickup
Test Inertial Mass: 5013 lb
Gross Mass: 5013 lb
Impact Speed: 63.2 mph
Impact Angle: 0.6 degrees

Figure B4-2. Vehicle Lateral Accelerometer Trace for Test 455266-1 (Accelerometer Located at Center of Gravity).

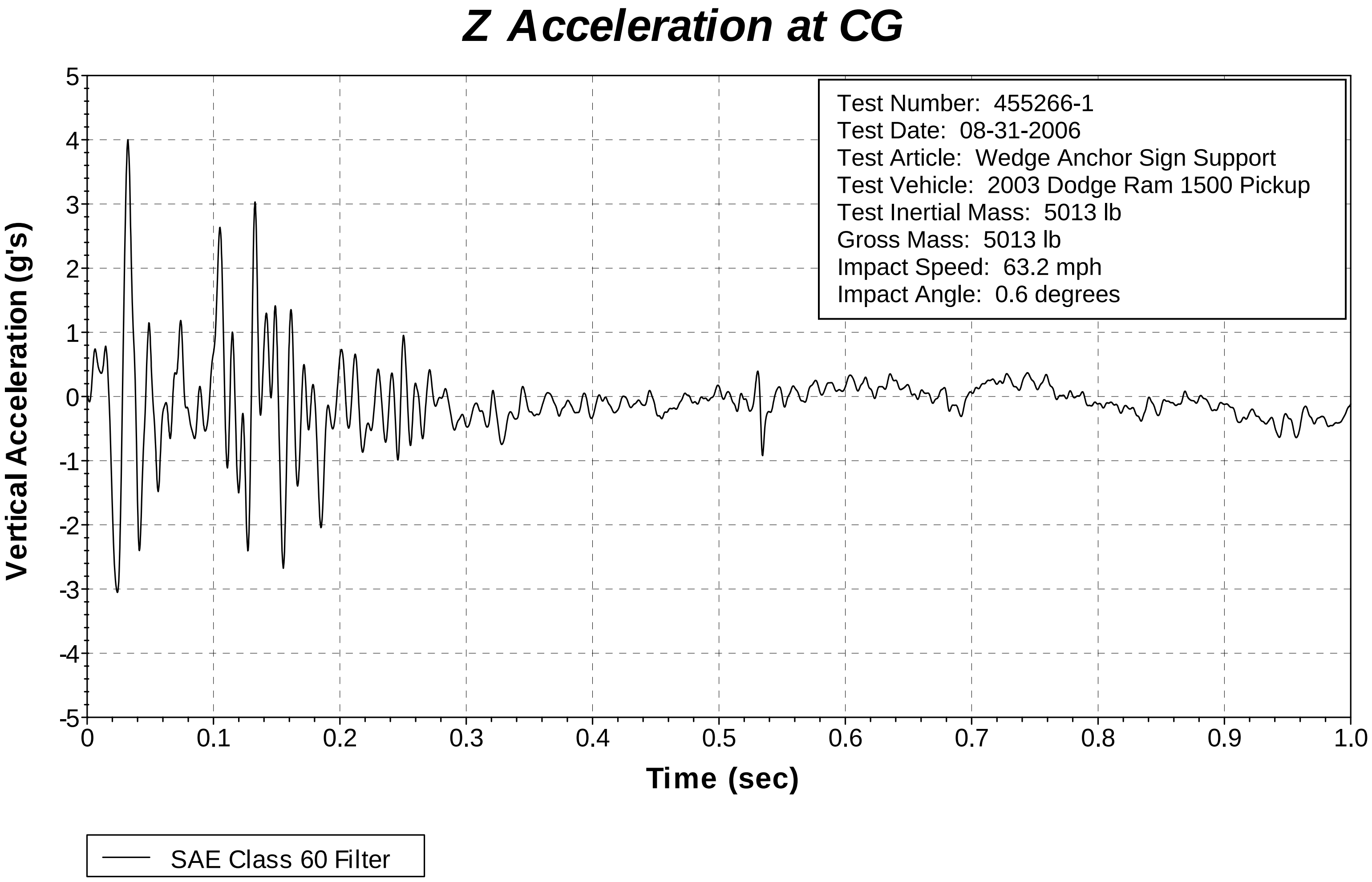
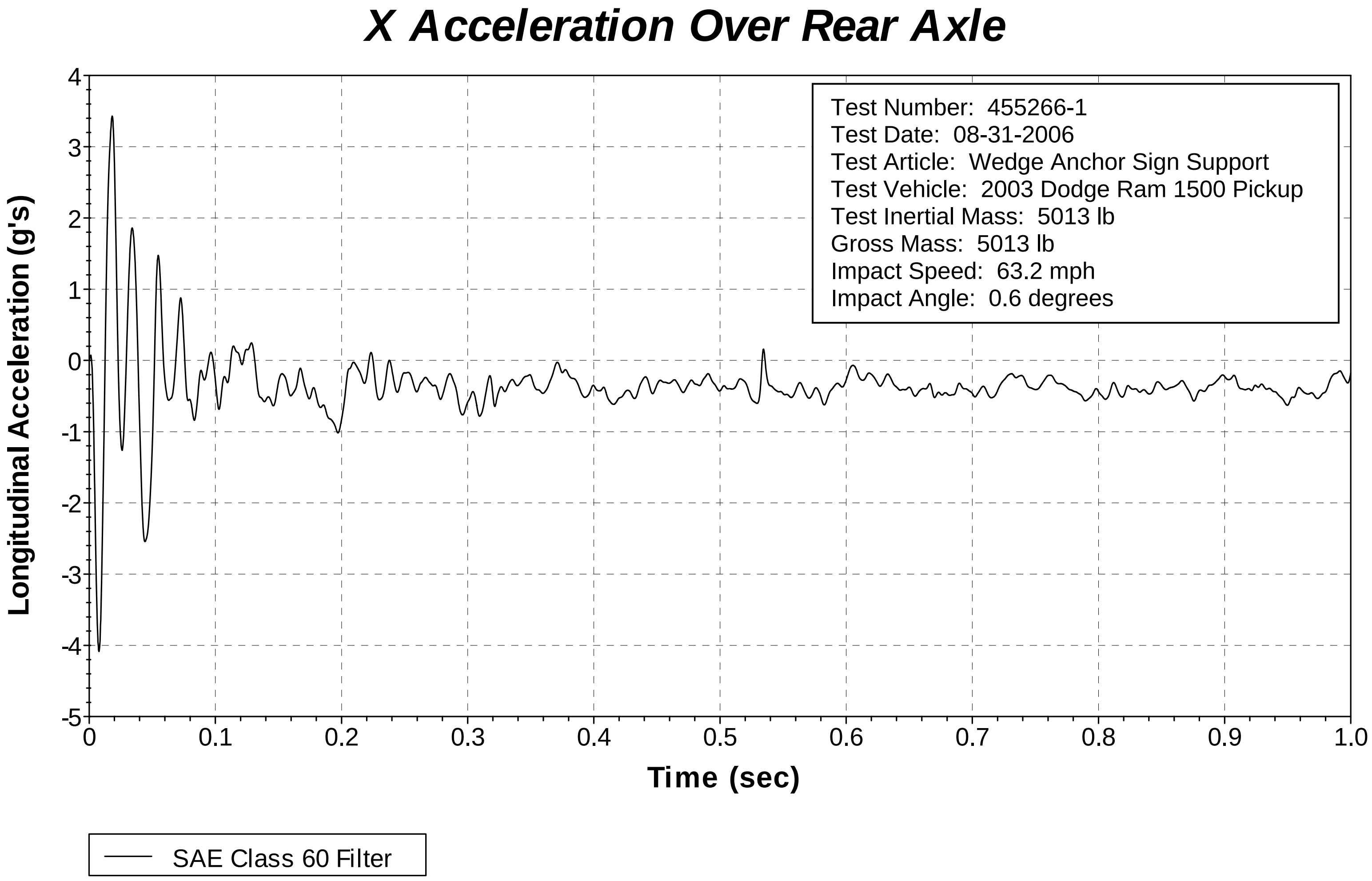


Figure B4-3. Vehicle Vertical Accelerometer Trace for Test 455266-1 (Accelerometer Located at Center of Gravity).



Test Number: 455266-1
Test Date: 08-31-2006
Test Article: Wedge Anchor Sign Support
Test Vehicle: 2003 Dodge Ram 1500 Pickup
Test Inertial Mass: 5013 lb
Gross Mass: 5013 lb
Impact Speed: 63.2 mph
Impact Angle: 0.6 degrees

Figure B4-4. Vehicle Longitudinal Accelerometer Trace for Test 455266-1 (Accelerometer Located over Rear Axle).

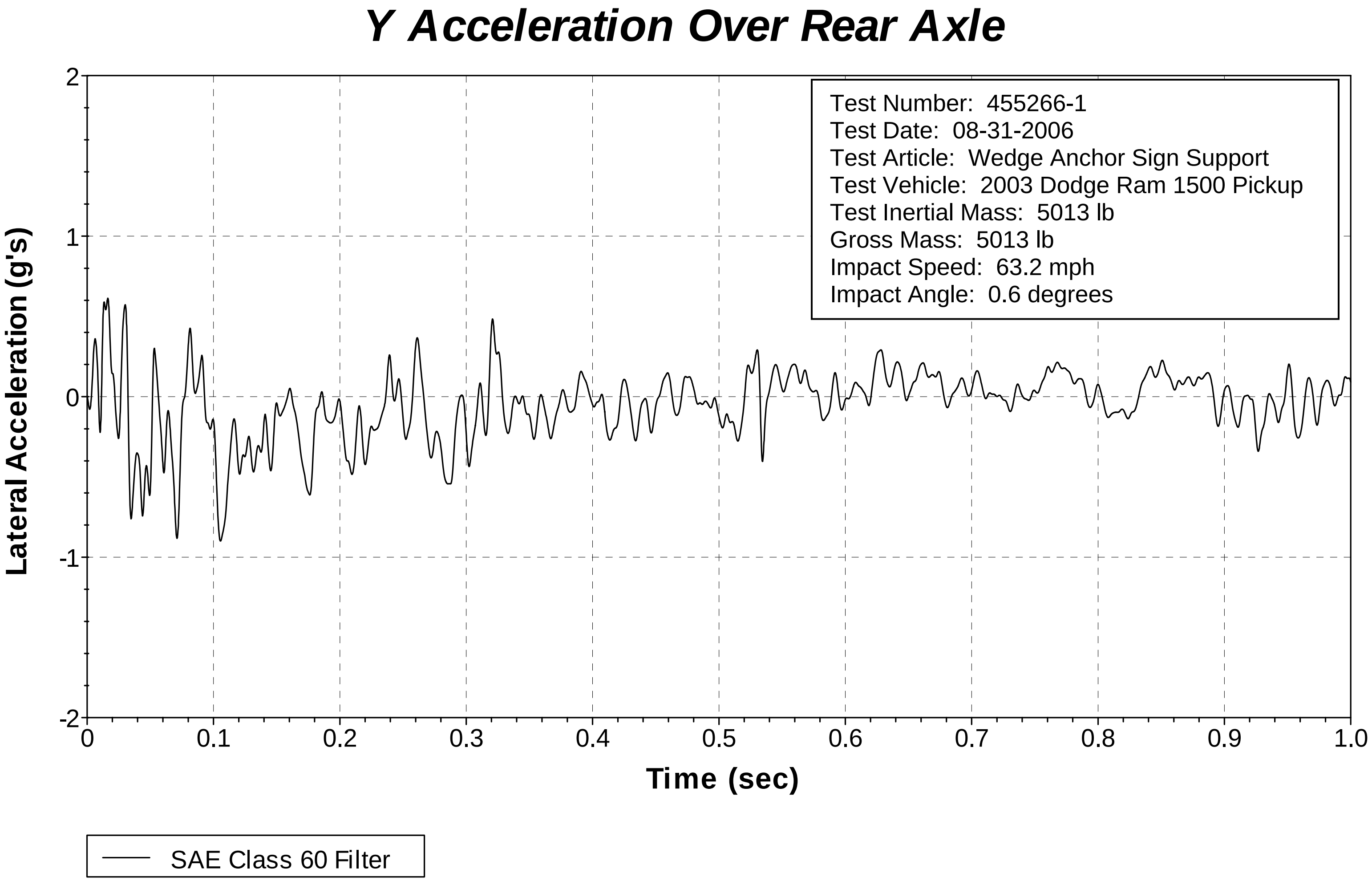


Figure B4-5. Vehicle Lateral Accelerometer Trace for Test 455266-1 (Accelerometer Located over Rear Axle).

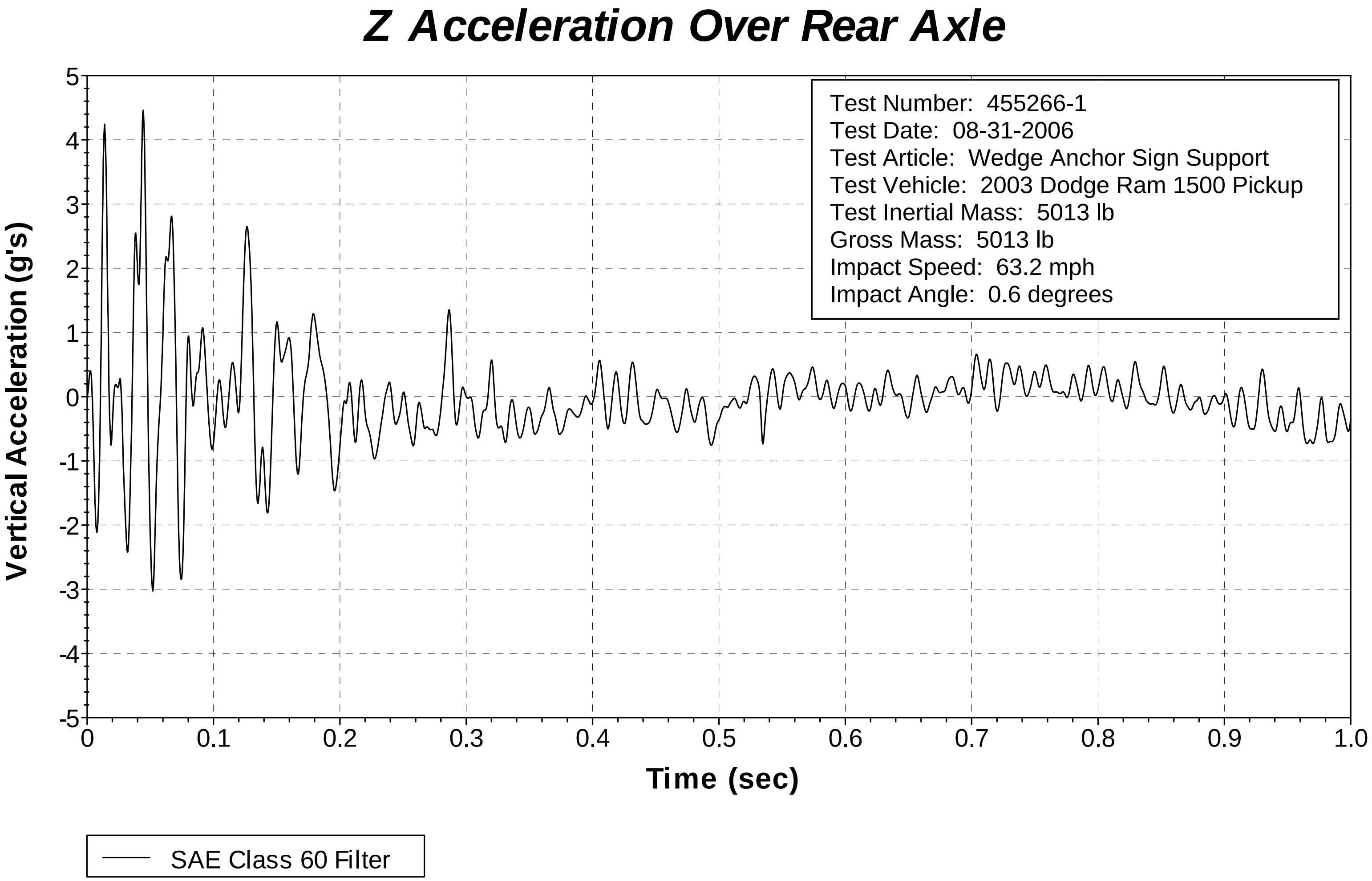


Figure B4-6. Vehicle Vertical Accelerometer Trace for Test 455266-1 (Accelerometer Located over Rear Axle).

APPENDIX C. CRASH TEST NO. 455266-2

C1. VEHICLE PROPERTIES AND INFORMATION

Date: 8-31-2006 Test No.: 455266-2 VIN No.: 1D7HA18N23S232412

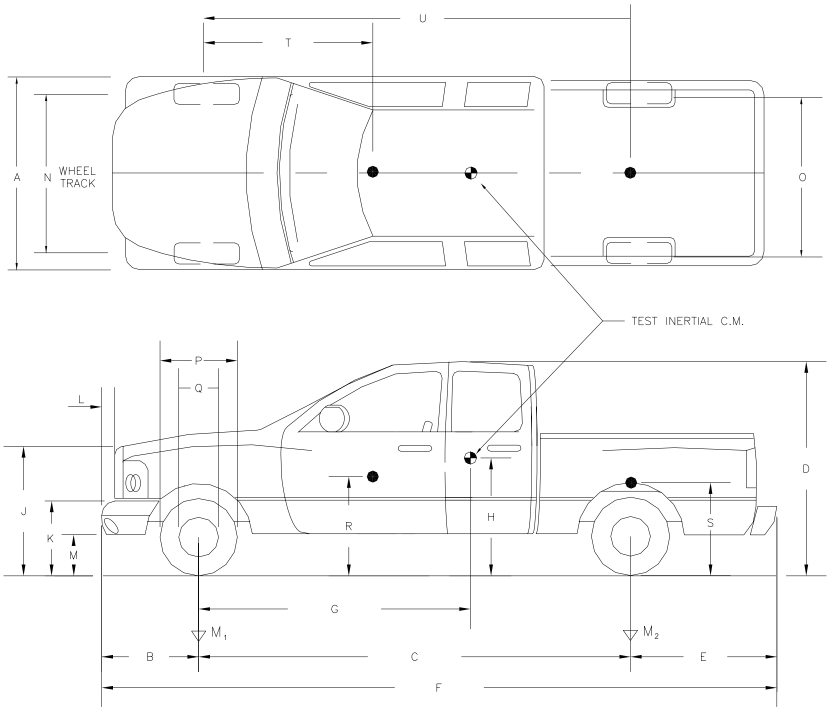
Year: 2003 Make: Dodge Model: Ram 1500

Tire Inflation Pressure: 35 psi Odometer: 28424 Tire Size: 245 70 R17

Describe any damage to the vehicle prior to test:

● Denotes accelerometer location.

NOTES:



Engine Type: V-8
Engine CID: 4.7 Liter
Transmission Type:
X Auto
___ Manual
Optional Equipment:

Dummy Data:
Type: None
Mass:
Seat Position:

Geometry (inches)

A	77.6	E	47.2	J	44.5	N	68.1	R	27.6
B	38.8	F	225.8	K	26.9	O	67.7	S	
C	139.8	G	62.1	L	3.4	P	30.1	T	61.4
D	74.0	H		M	14.4	Q	18.5	U	

Mass (lb)	Curb	Test Inertial	Gross Static
M_1	2743	2784	
M_2	1992	2229	
M_{Total}	4735	5013	

Mass Distribution (lb): LF: 1414 RF: 1370 LR: 1143 RR: 1086

Figure C1-1. Vehicle Properties for Test No. 455266-2.

Table C1-1. Exterior Crush Measurements for Test 455266-2.

VEHICLE CRUSH MEASUREMENT SHEET[1]

Complete When Applicable	
End Damage	Side Damage
Undeformed end width ________	Bowing: B1 _____ X1 _____
Corner shift: A1 ________	B2 _____ X2 _____
A2 ________	
End shift at frame (CDC)	Bowing constant
(check one)	$\frac{X1+X2}{2} =$ _______
< 4 inches ________	
≥ 4 inches ________	

Note: Measure C_1 to C_6 from Driver to Passenger side in Front or Rear impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage		Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
		Width** (CDC)	Max*** Crush								
1	At front bumper	40.9	9.8	74.8	-3.1	0.4	7.5	9.8	0.4	-3.1	0

[1] Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

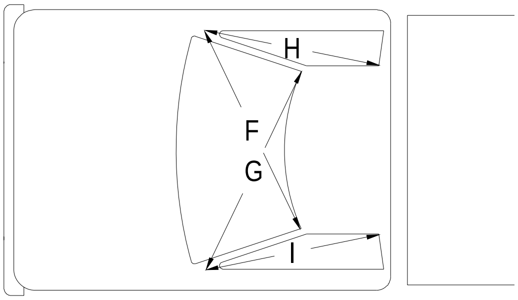
***Measure and document on the vehicle diagram the location of the maximum crush.

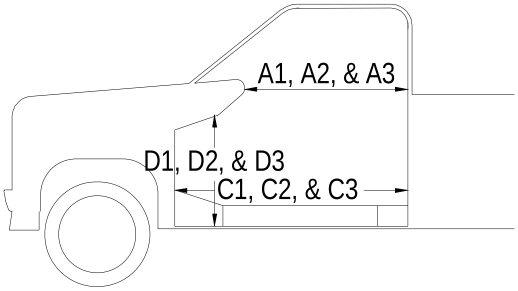
Note: Use as many lines/columns as necessary to describe each damage profile.

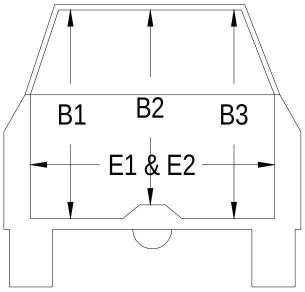
Table C1-2. Occupant Compartment Measurements for Test 455266-2.

Truck

Occupant Compartment Deformation



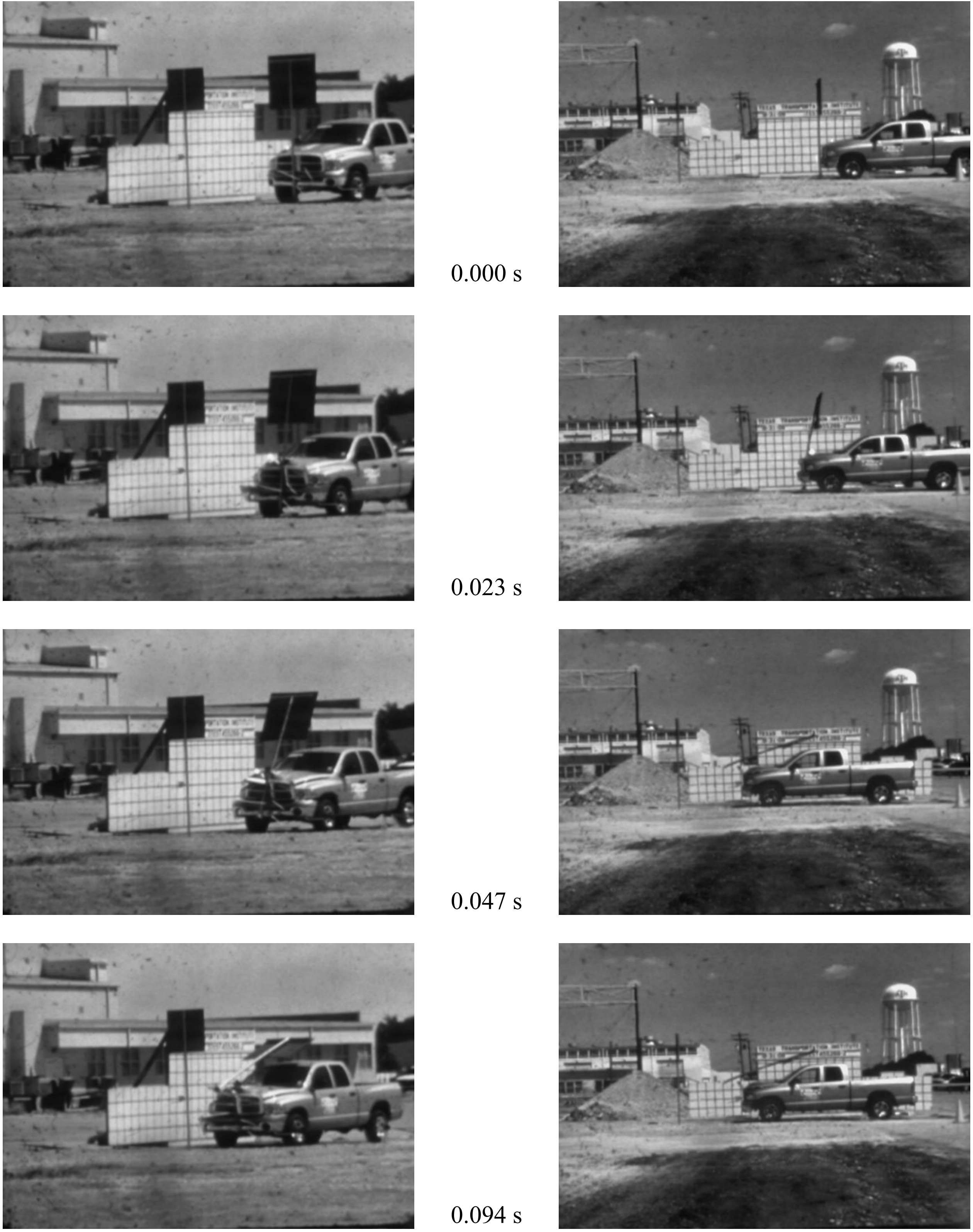




	BEFORE (inches)	**AFTER** (inches)
A1	65.4	65.4
A2	65.8	65.8
A3	66.3	66.3
B1	42.3	42.3
B2	39.2	39.2
B3	42.3	42.3
C1	29.1	29.1
C2		
C3	27.6	27.6
D1	12.6	12.6
D2	2.8	2.8
D3	11.4	11.4
E1	64.4	64.4
E2	64.0	64.0
F	60.0	60.0
G	60.0	60.0
H	40.0	40.0
I	39.8	39.8
J*	62.4	62.4

*Lateral area across the cab from
driver’s side kickpanel to passenger’s side kickpanel.

C2. SEQUENTIAL PHOTOGRAPHS



0.000 s

0.023 s

0.047 s

0.094 s

Figure C2-1. Sequential Photographs for Test 455266-2 (Oblique and Perpendicular Views).

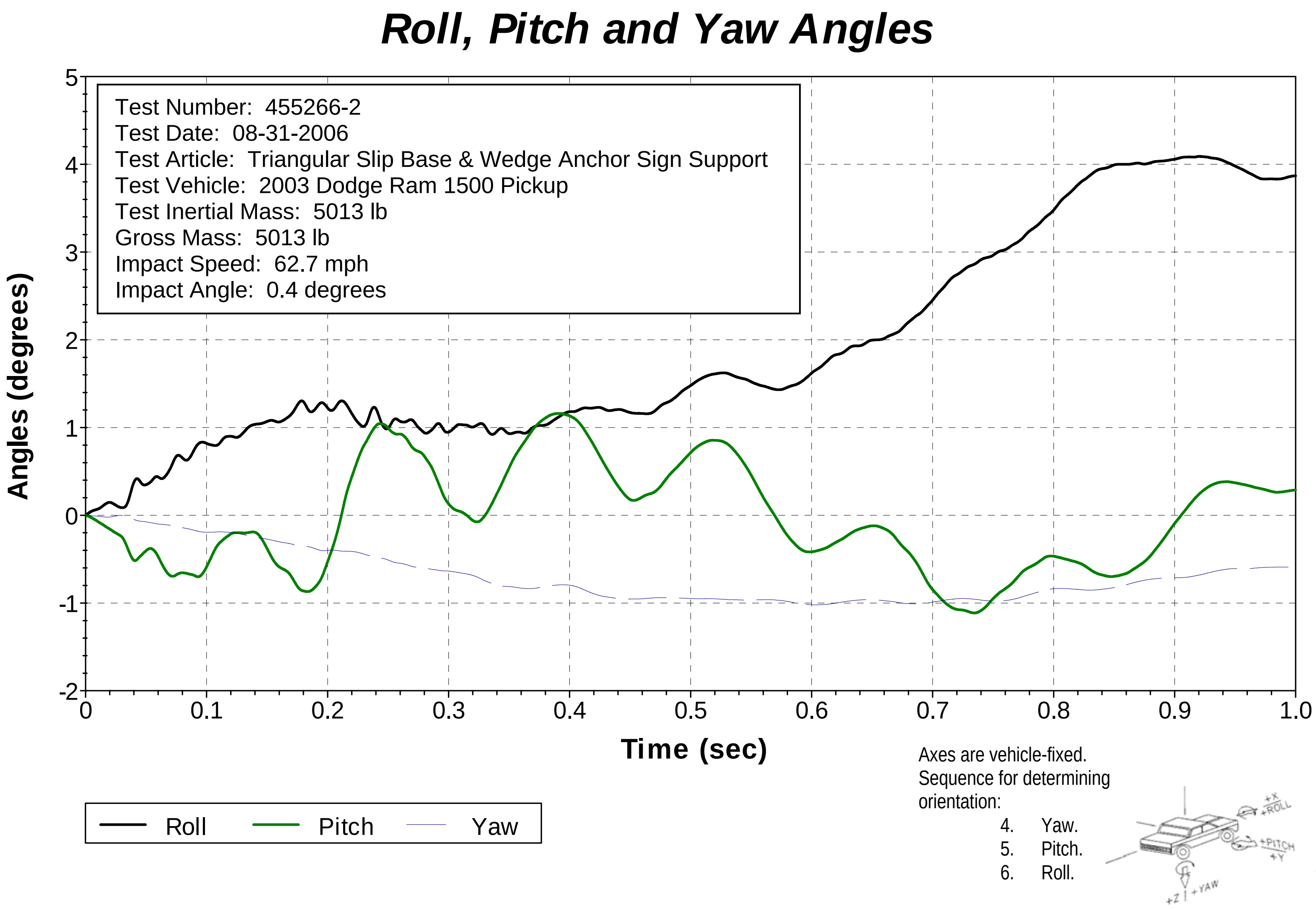
0.141s

0.189 s

0.236 s

0.307 s

Figure C2-1. Sequential Photographs for Test 455266-2 (Oblique and Perpendicular Views) (Continued).



Test Number: 455266-2
Test Date: 08-31-2006
Test Article: Triangular Slip Base & Wedge Anchor Sign Support
Test Vehicle: 2003 Dodge Ram 1500 Pickup
Test Inertial Mass: 5013 lb
Gross Mass: 5013 lb
Impact Speed: 62.7 mph
Impact Angle: 0.4 degrees

Axes are vehicle-fixed.
Sequence for determining orientation:
4. Yaw.
5. Pitch.
6. Roll.

Figure C3-1. Vehicle Angular Displacements for Test 455266-2.

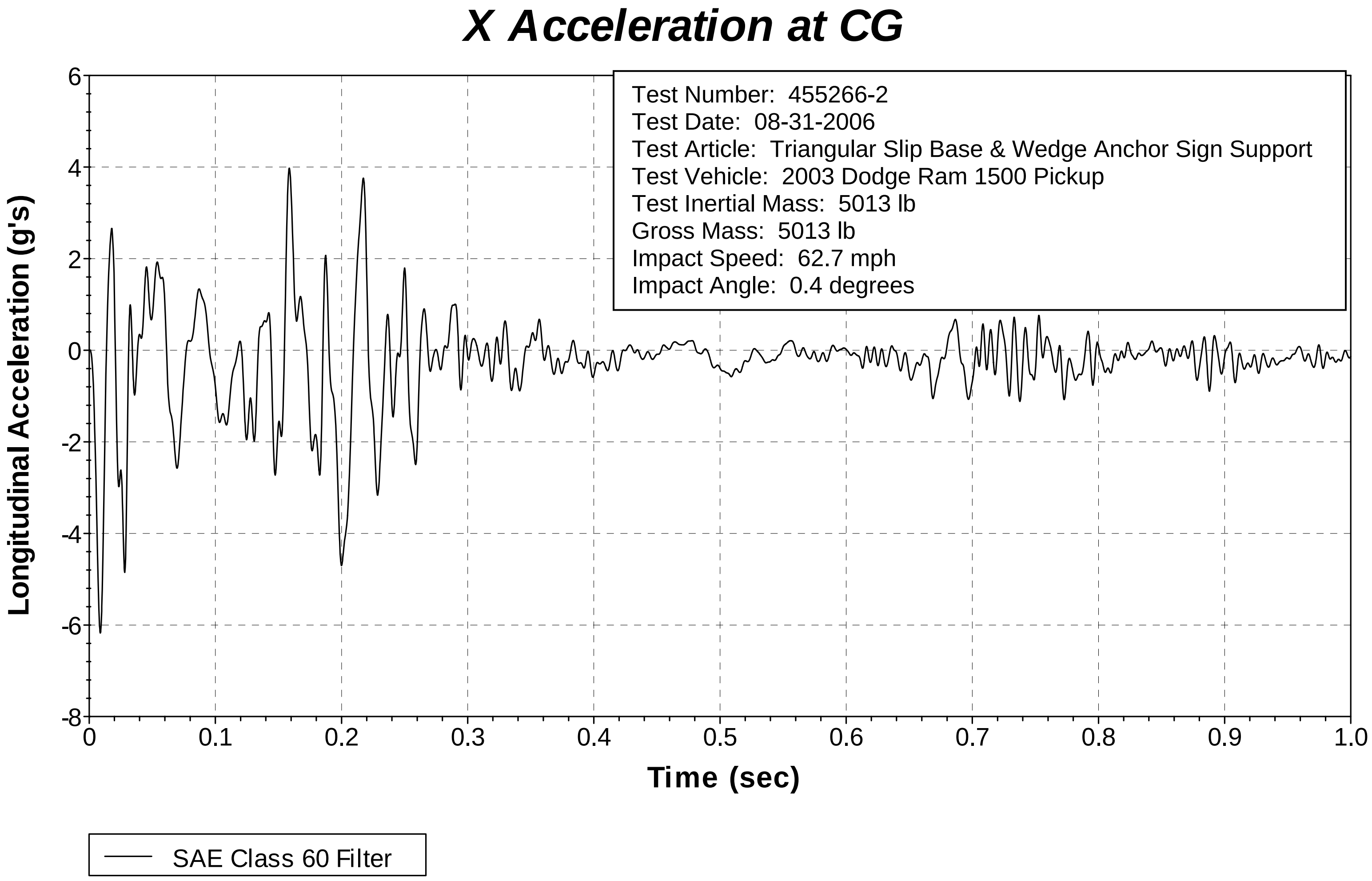


Figure C4-1. Vehicle Longitudinal Accelerometer Trace for Test 455266-2 (Accelerometer Located at Center of Gravity).

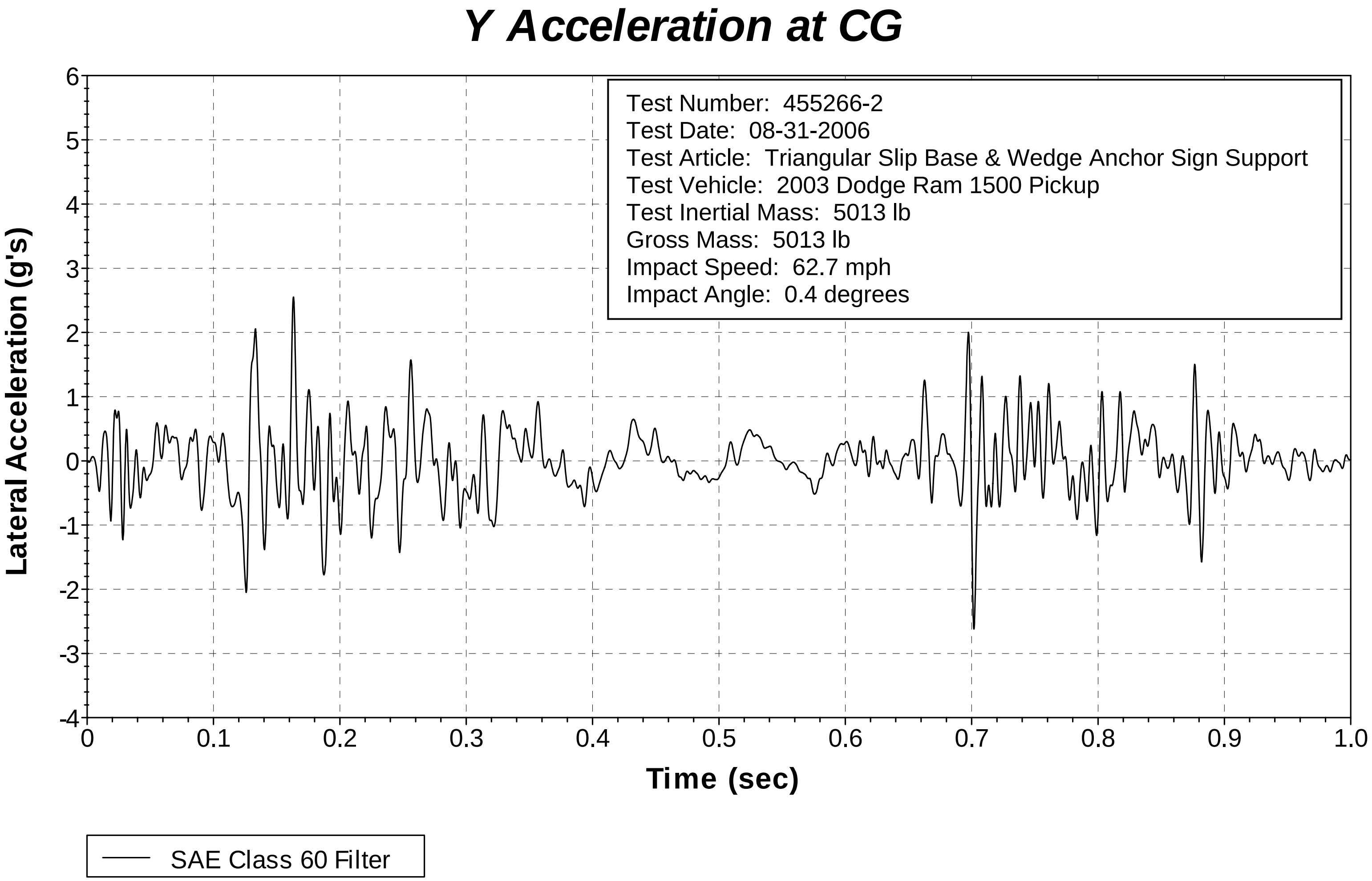


Figure C4-2. Vehicle Lateral Accelerometer Trace for Test 455266-2 (Accelerometer Located at Center of Gravity).

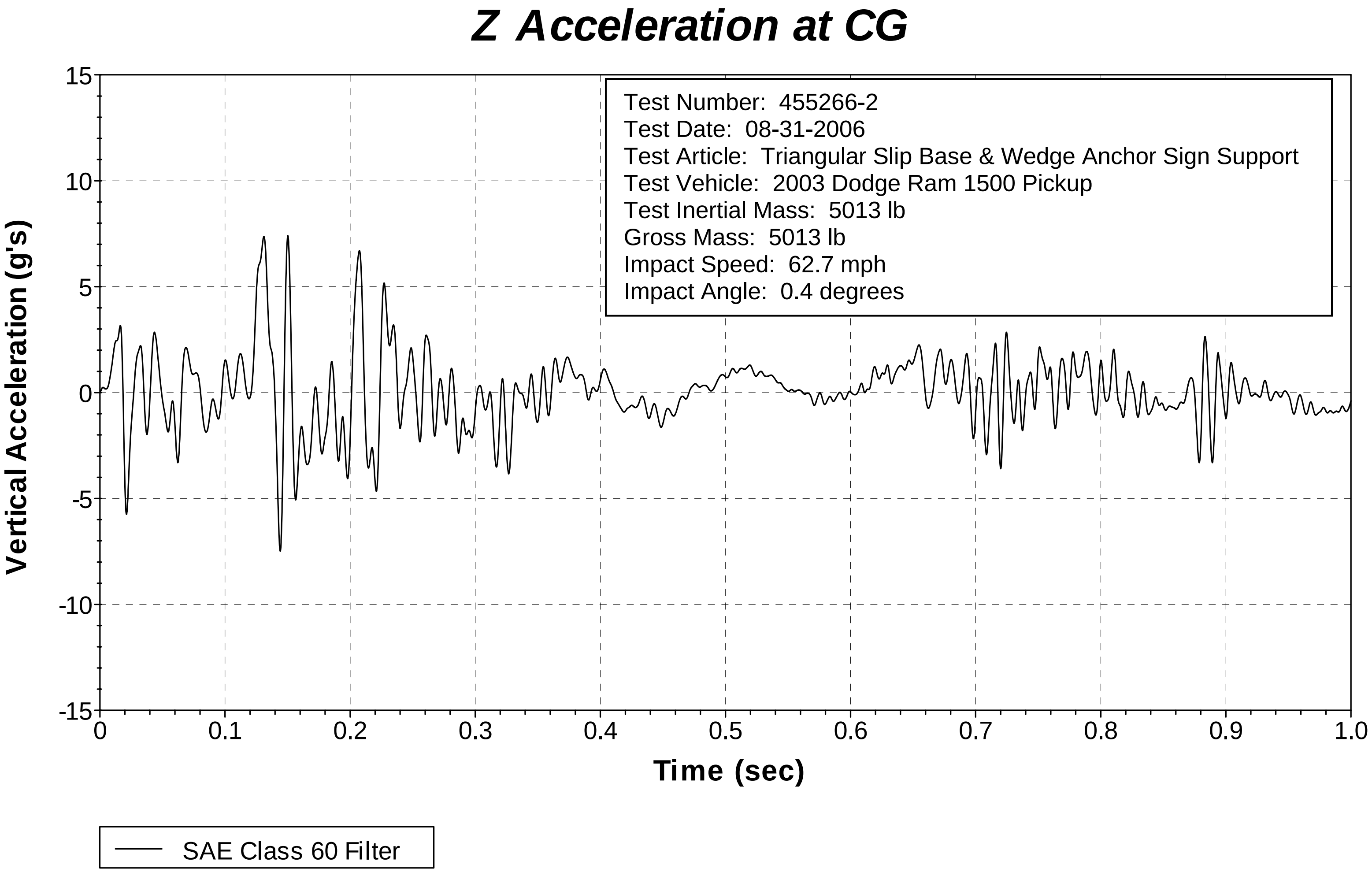


Figure C4-3. Vehicle Vertical Accelerometer Trace for Test 455266-2 (Accelerometer Located at Center of Gravity).

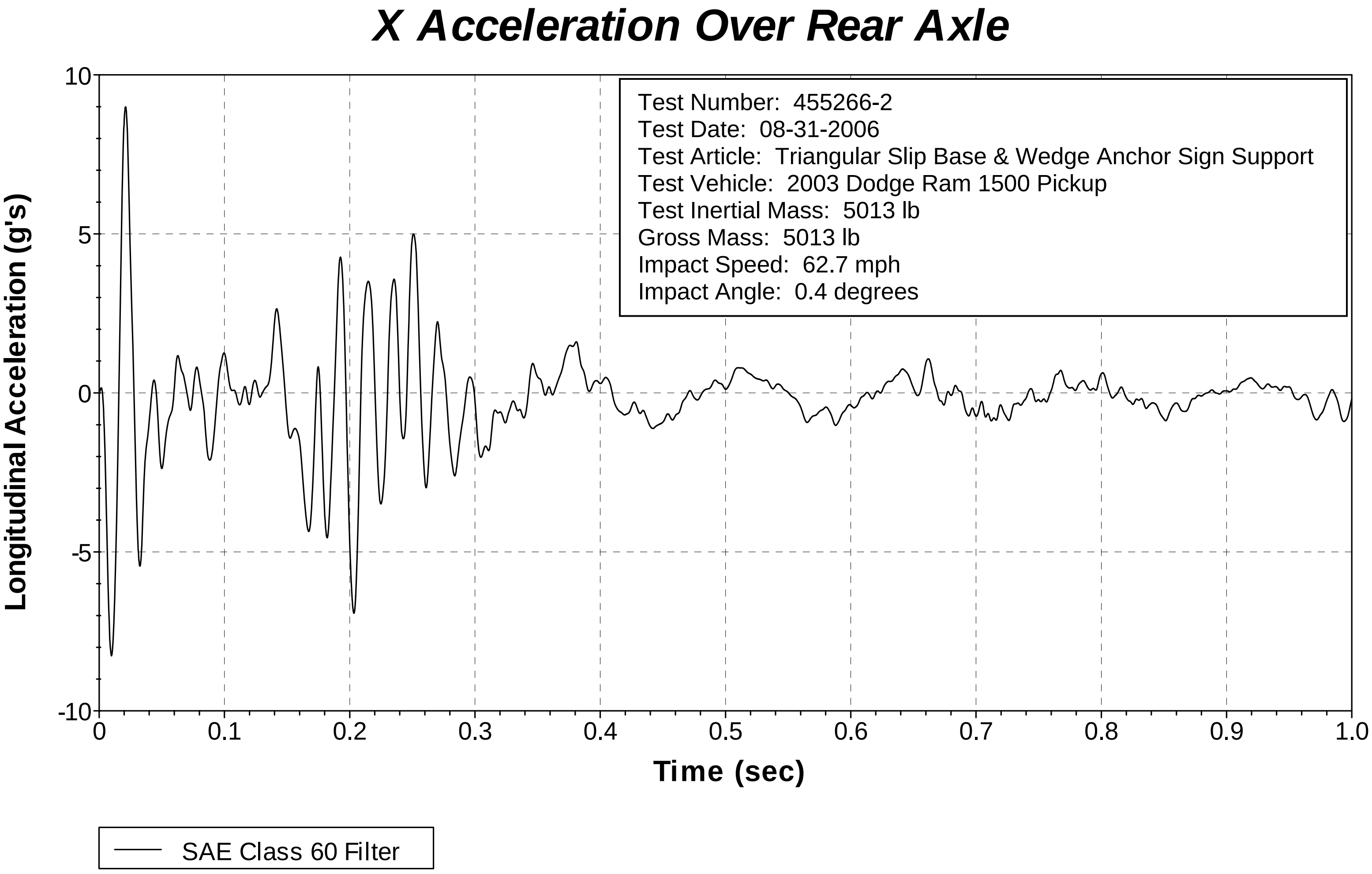


Figure C4-4. Vehicle Longitudinal Accelerometer Trace for Test 455266-2 (Accelerometer Located over Rear Axle).

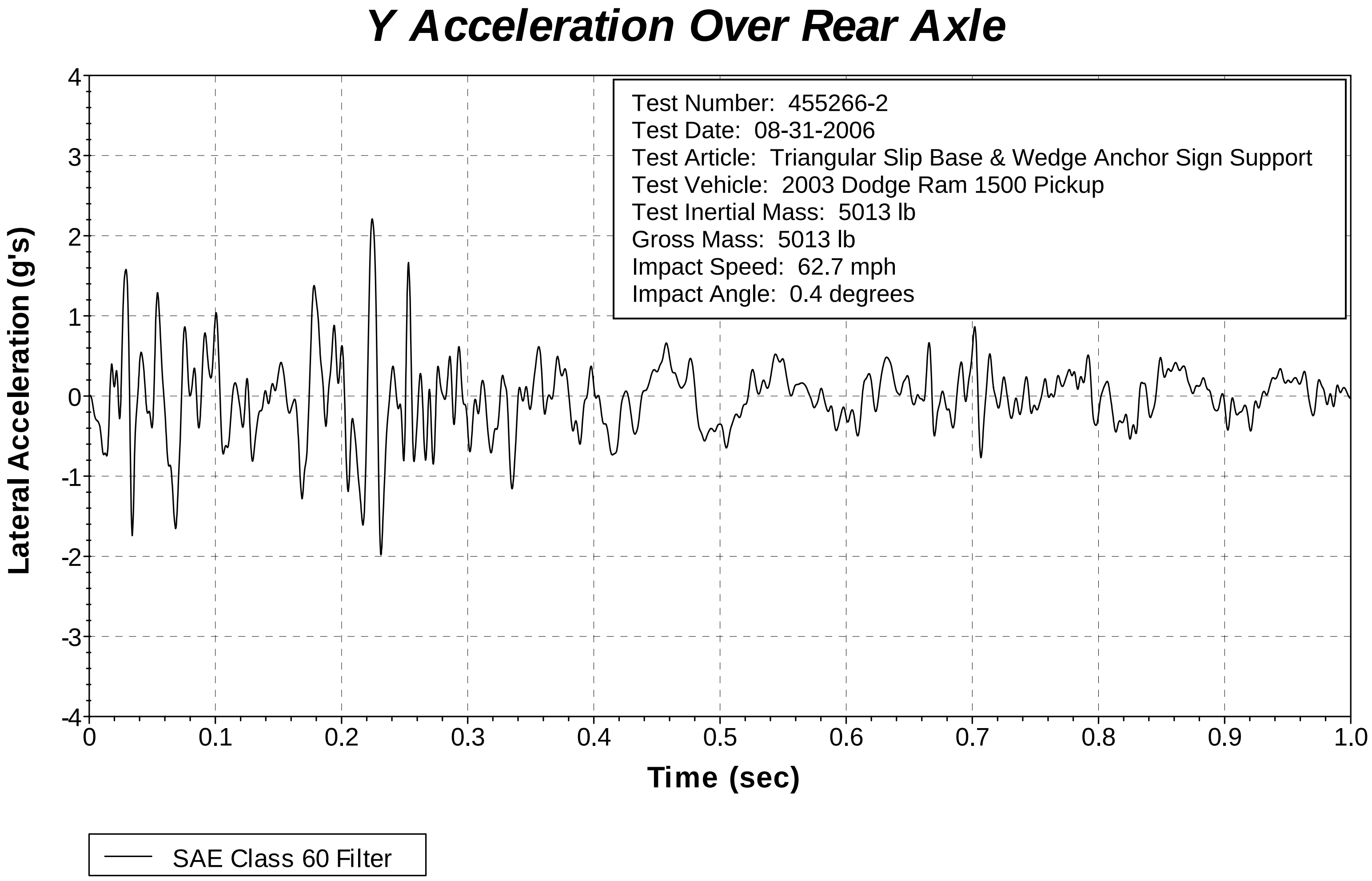


Figure C4-5. Vehicle Lateral Accelerometer Trace for Test 455266-2 (Accelerometer Located over Rear Axle).

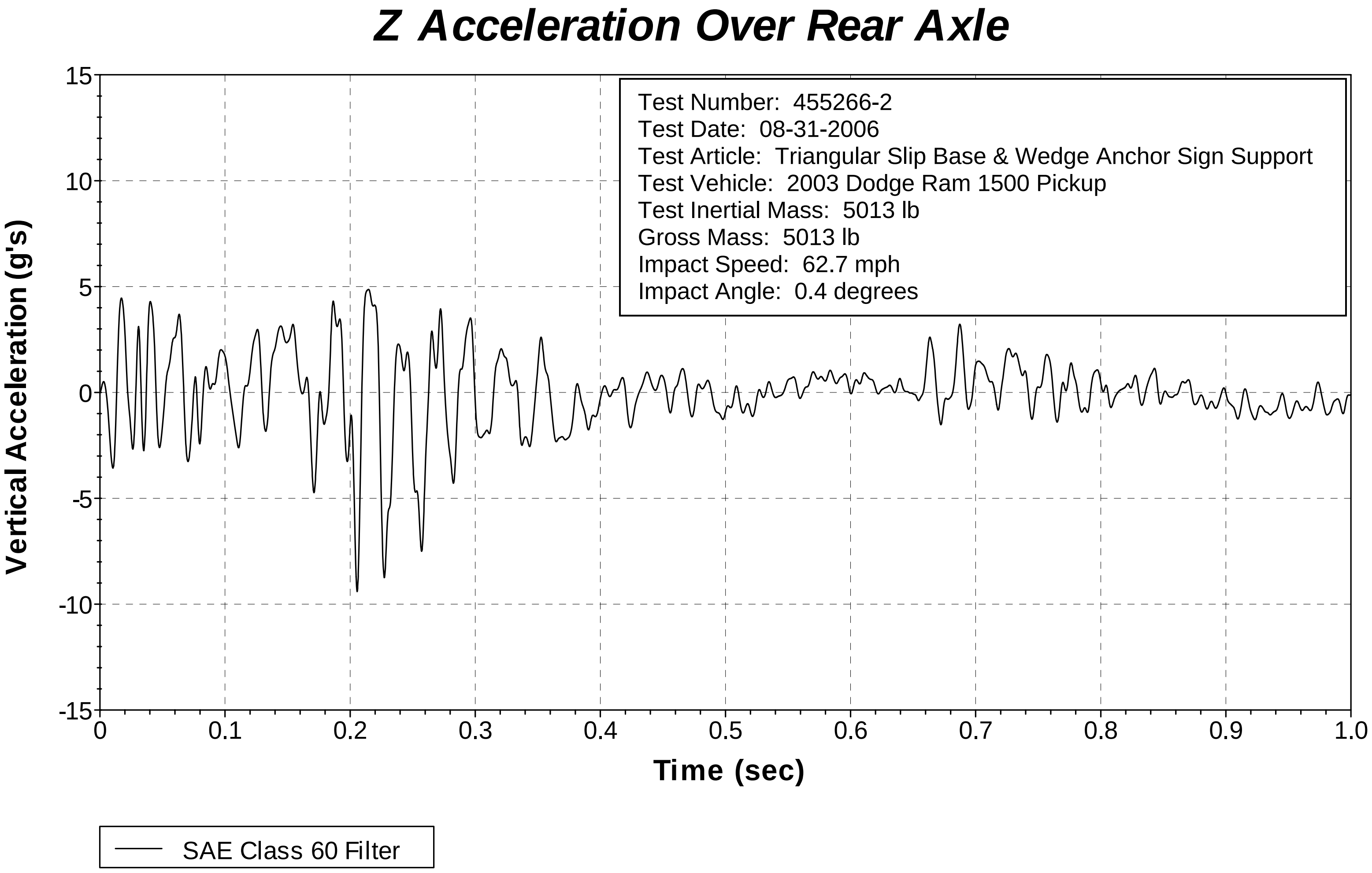


Figure C4-6. Vehicle Vertical Accelerometer Trace for Test 455266-2 (Accelerometer Located over Rear Axle).