NCHRP

REPORT 553

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Crashworthy Work-Zone Traffic Control Devices

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NCHRP REPORT 553

Crashworthy Work-Zone Traffic Control Devices

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Subject Areas
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Charles W. Niessner
Staff Officer
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This report presents the findings of a research project to develop nonproprietary, crashworthy work-zone traffic control devices that are constructed of readily available material. The report will be of particular interest to design, construction, and maintenance personnel with responsibility for work-zone safety.

The Federal Highway Administration (FHWA) requires that all work-zone traffic control devices used on the National Highway System (NHS) meet the evaluation criteria in *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features.* Certain low-mass items, referred to by FHWA as Category 2 devices, must meet *NCHRP Report 350* criteria if they are purchased new or fabricated after October 1, 2000. Category 2 devices include the *Manual on Uniform Traffic Control Devices* (MUTCD) Type I, II, and III barricades; vertical panels; and temporary sign supports. Many of the designs that meet *NCHRP Report 350* criteria are proprietary and can cost considerably more than comparable shop-fabricated designs. Although the shop-fabricated devices in use are made from readily available, low-cost materials, not all designs have been properly crash tested and evaluated to permit their continued use on the NHS.

Because all Category 2 work-zone traffic control devices used on the NHS must meet *NCHRP Report 350* criteria, a number of nonproprietary, crashworthy work-zone traffic control devices need to be identified or developed and their plans and specifications made available to state transportation agencies. These devices need to be easily fabricated of readily available materials, be cost efficient, and meet *NCHRP Report 350* crash test criteria.

Under NCHRP Project 22-18, “Crashworthy Work-Zone Traffic Control Devices,” Texas Transportation Institute designed and successfully crash tested two Type III barricades with attached sign panel; three low-mounting-height, portable sign supports; and a high-mounting-height, portable sign support.

In Phase I, the research team reviewed the literature and ongoing research to identify Category 2 devices that have been crash tested and conducted a survey of state and federal transportation agencies to obtain information on Category 2 work-zone traffic control devices currently being used. The focus was on identifying widely used sets of devices that have few or no nonproprietary, crashworthy designs. Based on this information, the panel selected sets of work-zone traffic control devices for investigation under Phase II.

In Phase II, the research team developed several design variations for each of the device sets selected in Phase I. The designs were reviewed and prioritized by the project panel, and the prioritization served as the basis for the full-scale crash testing matrix. In addition to providing detailed drawings and specifications for the successfully crash tested systems, the report presents a description of the other design concepts for future consideration and testing.

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CHAPTER 1

INTRODUCTION

1.1 RESEARCH PROBLEM STATEMENT

FHWA requires that Category 2 work-zone traffic control devices used on the National Highway System (NHS) and purchased after October 1, 2000, meet the evaluation criteria in *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features.* (*1*) Soon all such work-zone traffic control devices used on the NHS will have been purchased or fabricated after October 2000 and, therefore, will need to meet *NCHRP Report 350* criteria. Many of the devices that meet these criteria are proprietary and can cost considerably more than comparable shop-fabricated devices. While the shop-fabricated devices in use are made from readily available, low-cost materials, some devices had not been properly crash tested and evaluated to permit their continued use on the NHS. Therefore, it was important that a number of nonproprietary work-zone traffic control devices be identified or developed and that details be made available to state transportation agencies.

1.2 RESEARCH OBJECTIVE

The objective of this research was to develop nonproprietary, crashworthy work-zone traffic control devices that are easily constructed of readily available materials. These devices are intended to meet the evaluation criteria in *NCHRP Report 350* as supplemented by FHWA memorandum, "Identifying Acceptable Highway Safety Features," dated July 25, 1997, and the FHWA windshield damage classification criteria. Commonly used work-zone traffic control devices include the *Manual on Uniform Traffic Control Devices* (MUTCD) Type I, II, and III barricades; vertical panels; and temporary sign supports. (*2*) These low-mass devices, defined as Category 2 devices in the previously referenced FHWA memorandum, are evaluated for crashworthiness with and without appropriate signs, lights, and flags. In addition to crashworthiness, due consideration is given to cost and functionality. In regard to temporary sign supports, consideration is given to both low-mounting-height (0.3 m [1 ft]) and high-mounting-height (1.5 m to 2.1 m [5 ft to 7 ft]) systems.

This report summarizes the findings of the project. Chapter 2 describes testing requirements for work-zone devices. The state of the practice pertaining to work-zone traffic control devices as determined from a review of the literature and ongoing research and the responses received from a state-of-the-practice survey is summarized in Chapter 3. Chapter 4 reviews design requirements for work-zone traffic control devices. The performance of existing designs and the categorization of devices for Phase II of the project are presented in Chapter 5. Chapter 6 describes the development, crash testing, and evaluation of Type III barricade systems with attached sign panels. The development, crash testing, and evaluation of low-mounting-height and high-mounting-height sign supports are presented in Chapter 7 and Chapter 8, respectively. Chapter 9 contains a summary and recommendations regarding the generic work-zone traffic control devices developed under this project.

CHAPTER 2

TESTING REQUIREMENTS FOR WORK-ZONE DEVICES

Proper traffic control and delineation is critical to achieving safety in work zones. However, 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 MUTCD require that the crashworthiness of work-zone traffic control devices be demonstrated before they are implemented on the nation's highways.

2.1 *NCHRP REPORT 350* GUIDANCE

Guidance for evaluating the safety performance of work-zone traffic control devices is contained in *NCHRP Report 350. NCHRP Report 350* presents a comprehensive set of procedures for crash testing both permanent and temporary highway safety features and the evaluation criteria used to assess the test results. These guidelines reflect an evolution of knowledge in this area over the last 30 years and incorporate current technology and the collective judgment and expertise of roadside safety professionals.

Before the publication of *NCHRP Report 350*, test matrices for work-zone devices were not well defined. As a result, few devices were crash tested and the impact performance of many commonly used devices was largely unknown. Thus, there was a need to research the safety performance of work-zone traffic control devices to assure they performed satisfactorily and met the new *NCHRP Report 350* guidelines, which have been formally adopted by FHWA by a final rule in the Federal Register.

2.2 CATEGORIES OF WORK-ZONE DEVICES

Along with FHWA's formal adoption of *NCHRP Report 350* came many questions from the manufacturers, suppliers, and user agencies regarding the requirements for testing various work-zone devices ranging from traffic cones, delineators, and drums to barricades, temporary sign supports, work-zone barriers, and truck-mounted attenuators. Although some of these devices are obviously benign in nature, others can represent significant hazards to occupants of the impacting vehicle, surrounding traffic, and nearby workers. *NCHRP Report 350* recognizes that, depending on the nature of the device, less rigorous test procedures may be appropriate (refer to Section 3.2.3.2 of *NCHRP Report 350*). For example, for tests of free-standing objects with masses less than 45 kg (99 lb), instrumentation can be reduced. However, to remove some of the subjectivity and provide further clarification of this issue, FHWA defined four categories of work-zone devices in the July 25, 1997, memorandum, "Identifying Acceptable Highway Safety Features." These categories are used to determine an appropriate level of effort needed to demonstrate crashworthiness. These categories are defined as follows:

- Category 1 includes small and lightweight channelizing and delineating devices that have been in common use for many years and are known to be crashworthy by crash testing of similar devices or years of demonstrable safe performance. These devices include cones, tubular markers, flexible delineator posts, and plastic drums with and without warning lights securely attached. These devices may be allowed for use on the NHS based on the developer's self-certification subject to approval by the individual highway agencies.
- Category 2 includes devices that are not expected to produce significant vehicular velocity change but may otherwise be hazardous. Examples of this class are barricades, portable sign supports, intrusion alarms, and drums with sign panels attached. Testing of devices in this category is required. However, they may qualify for the reduced testing requirements, and less instrumentation than required in *NCHRP Report 350* may be acceptable.
- Category 3 is for hardware that is expected to cause significant velocity change or other potentially harmful reactions to impacting vehicles. Hardware in this category must be tested to the full requirement of *NCHRP Report 350.* Barriers, fixed sign supports, crash cushions, and other work-zone devices not meeting the definitions of Category 1 or 2 are examples from this category.
- Category 4 includes portable or trailer-mounted devices such as flashing arrow panels, temporary traffic signals, area lighting supports, and portable changeable message signs. Per FHWA Acceptance Letter WZ-161, dated December 24, 2004, FHWA will look at the state of the art of the portable sign industry and the number and severity of real-world crashes with these devices in order to establish policy on their use. The current deadline for this policy review is October 1, 2006.

2.3 TEST MATRIX MODIFICATIONS

The test matrix for work-zone traffic control devices consists of two tests with an 820-kg (1808-lb) passenger car: a low-speed (35 km/h [22 mi/h]) test and a high-speed (100 km/h [62 mi/h]) test. *NCHRP Report 350* allows the omission of the low-speed test (test designation 3-70) when the high-speed test (test designation 3-71) can be clearly determined to be more critical. High-speed tests are often more critical for various work-zone traffic control devices having a relatively small mass because the propensity for occupant compartment intrusion increases at higher speeds.

In the initial testing of work-zone traffic control devices performed by Texas Transportation Institute (TTI) for the Texas Department of Transportation (TxDOT) (*3*), the test vehicles were fully instrumented in accordance with *NCHRP Report 350* requirements, which included a tri-axial accelerometer to measure accelerations in the longitudinal, lateral, and vertical directions and rate transducers to measure the roll, pitch, and yaw rates. However, after several tests of Type III barricades and temporary sign supports, the accelerations and vehicle dynamics resulting from impacts with these devices were observed to be very minor and of little significance. As a result, researchers concluded that instrumentation of the test vehicle was unnecessary in the evaluation of most work-zone traffic control devices, including Type III barricades and temporary sign supports.

2.4 IMPACT CONDITIONS

In the July 25, 1997, memorandum, FHWA also presented additional requirements related to the impact conditions under which work-zone traffic control devices are evaluated. In addition to the common scenario involving an 820-kg (1808-lb) passenger car impacting the device head on (i.e., 0 degree) at a nominal speed of 100 km/h (62 mi/h), an impact with a second device is required with the device either turned 90 degrees or laid on the ground, whichever is judged the more critical case. This test condition accounts for the common field practice of rotating or laying a device down out of view of traffic until it is needed again and/or picked up and moved to the next job site. Many testing agencies commonly evaluate both the 0- and 90-degree orientations with two separate devices impacted in sequence in a single crash test. However, certain types of work-zone devices are more prone to affect or interfere with subsequent impacts. In such cases, the devices should be placed and oriented to minimize possible conflicts, or the evaluation of the different device orientations should be evaluated in separate tests.

The type of surface on which a device is tested is also a consideration. Many work-zone barricades and sign supports are deployed and crash tested on a paved surface. Under these conditions, yielding-type devices of metal construction will often wrap around the front of the vehicle and be carried along by the vehicle until the vehicle comes to rest. In some instances, barricades or sign supports may be placed on a soil or grassy surface, as is typically found on the roadside. Under such conditions, the skids or legs of a barricade or sign support may dig into the ground. The failure mode of the device can then change from yielding to fracture, which can increase the probability of windshield contact and occupant compartment intrusion.

Some smaller portable work-zone signs have shown a potential for occupant compartment intrusion through the vehicle floor pan. Whether a result of a geometric contribution (e.g., length of the tubular legs), material contribution (e.g., steel v. aluminum), or testing surface type, floor pan intrusions seem to be experienced more frequently with small, thin-walled steel, portable sign supports tested on soil or asphalt surfaces.

The influence of the test surface was also demonstrated in otherwise identical tests of a Type III barricade with square, perforated steel-tube skids and vertical supports and plastic horizontal rail elements. (*3*) In a test conducted on a concrete apron, the vertical supports yielded and wrapped around the bumper and hood of the impacting vehicle and the barricade frame was carried forward as a unit until the vehicle came to rest. Because the barricade remained intact, there was no debris that could result in occupant compartment deformation. In a subsequent test of a similar barricade placed on a soil surface, the behavior was significantly different. As with the barricade on pavement, the metal barricade frame initially wrapped around the front of the vehicle. However, both vertical supports subsequently fractured as the metal skids dug into the ground. Although there was no intrusion into the occupant compartment, pieces of the fractured barricade contacted the hood, windshield, and roof of the vehicle. Fragments of the barricade were scattered over an area 12.6 m (42 ft) wide and 121 m (396 ft) long.

2.5 EVALUATION CRITERIA

The evaluation criteria contained in *NCHRP Report 350* to assess the performance of the work-zone traffic control devices consist of several factors:

- *Occupant risk.* Occupant impact velocity (recommended limit: 5 m/s [16 ft/s]) and ridedown acceleration (recommended limit: 20 g's) are used to measure risk to the occupant. For devices with relatively small mass, the measured values for these criteria are often well below the recommended limits and, therefore, instrumentation of the test vehicles for purposes of computation of occupant risk is not always necessary.
- *Occupant compartment integrity*. Of primary concern regarding the impact behavior of a work-zone traffic control device is intrusion of the test article or parts of the test article into the occupant compartment. To minimize the potential for injury during impact, there should not be any significant intrusion into the occupant compartment. Further, the windshield should not be shattered

or damaged to the extent that it obstructs the vision of the driver.
- *Test article debris.* Debris from the test article should not pose a potential hazard to the vehicle occupants, other traffic, pedestrians, or workers in the immediate vicinity. Debris projected forward along the path of the vehicle is common and does not typically constitute a hazard more critical than the vehicle itself.
- *Vehicle stability.* The test vehicle should remain upright and stable throughout impact sequence, i.e., both during and after the impact.

One difficulty in evaluating occupant compartment integrity (specifically, windshield damage) in tests with Category 2 devices is that the criteria are somewhat subjective and can be interpreted in different ways by different crash test agencies. In FHWA's July 25, 1997, memorandum, a windshield damage rating scale was suggested. However, because the scale did not classify the resulting damage as passing or failing, interpretation of the scale remained subjective. In August 1999, FHWA introduced draft guidelines for evaluating windshield damage at a meeting of TRB Committee A2A04 (Roadside Safety Features). The guidelines present seven classes of damage, each of which constitutes a pass or fail event (see Appendix A). Although there is still room for some subjectivity and interpretation among damage classes, these guidelines introduce an added measure of consistency among test agencies evaluating these types of tests. FHWA now requires use of these windshield damage classifications in the evaluation of tests with work-zone traffic control devices.

CHAPTER 3

STATE OF THE PRACTICE

3.1 RECENT RESEARCH AND TESTING

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. These TxDOT-sponsored research projects were administered by TxDOT's Traffic Operations Division through a partnering relationship with the Associated General Contractors (AGC) of Texas and the Texas Chapter of the American Traffic Safety Services Association (ATSSA). Input from the manufacturers, contractors, and user agencies was considered to be a key to the success of these studies.

The overall objective of the TxDOT research was to provide generic, cost-effective work-zone traffic control devices that meet the national safety performance guidelines contained in *NCHRP Report 350*. The research was conducted in two phases. In the first phase, the impact performance of existing work-zone devices (e.g., barricades of common wooden construction, easel-type sign supports) was evaluated. The second phase involved the development, crash testing, and evaluation of improved designs that address the deficiencies of the existing systems identified in Phase I. Since 1992, more than 90 full-scale crash tests have been conducted on various work-zone devices including channelizing drums, vertical panels, two-piece cones, temporary and portable sign supports, and barricades. The results, findings, and recommendations from these studies have been summarized in several research reports and journal papers. (*3, 4, 5, 6, 7, 8, 9, 10*) This work also formed the basis for much of an August 28, 1998, FHWA memorandum entitled "Crash Tested Work Zone Traffic Control Devices" (Acceptance Letter WZ-3) and 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 acceptable systems and components, approved suppliers and vendors, and sketches illustrating the assembly of some of the generic designs. The document continues to be updated as a result of ongoing research and testing. It is available electronically at the following web site: http://www.dot.state.tx.us/trf/ctrldvcs/trfteps1.htm.

To gain additional insight into the performance of work-zone traffic control devices, members of the project team interviewed researchers at the Midwest Roadside Safety Facility at the University of Nebraska and E-Tech Testing Services regarding their observations related to testing of proprietary work-zone devices. Failed tests of proprietary devices are almost never reported by private sector manufacturers. Therefore, information related to these failures is limited. However, general trends on failed proprietary devices are often noted by researchers, and a few significant findings and research results are incorporated into the following discussions.

3.1.1 Barricades

Standard wooden Type III barricade construction was found to be unacceptable. During full-scale crash testing, the vertical supports of existing wooden barricades tend to fracture upon impact and rotate with the attached rail elements into the windshield of the impacting vehicle, resulting in shattering and penetration of the windshield. (*3, 9*) In one test conducted at 100 km/h (62 mi/h), a 533-mm (21-in) long fragment of one of the 102-mm × 102-mm (4-in × 4-in) supports was found in the rear of the occupant compartment. Because of the widespread use of wooden barricades in construction zones, the development of improved alternative barricade designs that would perform satisfactorily to *NCHRP Report 350* criteria was considered important. After analyzing the performance of the wooden barricades in the failed tests, two approaches were developed to address the problem. The first approach is to change the failure mechanism of the vertical supports to prevent them from fracturing or separating from the base, thus eliminating the potential for the detached vertical supports and rail elements to rotate into the windshield. Vertical supports constructed with steel frames tend to yield and wrap around the front end of the vehicle rather than fracture and form projectiles. A steel-frame Type III barricade with skids and vertical supports composed of square, perforated steel tubing was successfully designed and tested using both plastic and wooden horizontal rail elements. (*3, 9*)

A second approach is to use lighter weight materials for the vertical supports and horizontal rail elements so that, in the event the vertical supports fracture or become detached from the base during impact, they will not have sufficient mass to shatter and penetrate the windshield. This approach was investigated using hollow-profile plastic lumber (HPPL) manufactured from a variety of materials such as poly-vinyl chloride (PVC) and high-density polyethylene (HDPE). The material is lightweight and can be cut and fastened similar to wood materials. By replacing the 102-mm × 102-mm (4-in × 4-in) wood supports with similarly sized HPPL supports, the basic barricade design was retained and the same wooden skids could be used. This barricade design was successfully tested with both HPPL and wooden horizontal rails. (*3, 9*) Other testing agencies have experienced crash test failures with HPPL in Type III barricades. Failures were generally related to projectile penetration of the windshield by horizontal rails. Impact or penetration failures were precipitated by connection failures at the vertical support.

Other Type III barricade designs, such as one manufactured from fiber-reinforced plastic (FRP) components, have also been successfully tested in accordance with *NCHRP Report 350* criteria. (*4*) One exception was a barricade manufactured from solid, recycled-plastic lumber, which behaved in a similar manner to wood and was found to be unacceptable. (*3*)

The results of the crash tests indicate that the type of vertical support and connection to the support is much more important in terms of impact performance than the type of horizontal rail element. Several barricade frames have been successfully tested with both hollow-profile plastic and wooden rail elements. (*3, 4*) Some proprietary barricades that experienced unsatisfactory impact performance were made acceptable with stronger vertical supports and/or increased connection capacity.

3.1.2 Other Traffic Control Devices

In addition to barricades, research and testing programs have also emphasized the need to evaluate the impact performance of portable sign supports, channelizing drums, and alternative sign substrates. A few brief findings are summarized in the following paragraphs.

Portable Sign Supports

Research has demonstrated the need to design and evaluate a portable sign support as a system consisting of a support structure and a sign substrate. In several instances, crash testing has demonstrated that a particular support structure can be crashworthy for one type of sign substrate but not another and vice versa. In a test of a spring-loaded, portable sign support structure with a plywood sign panel mounted at a height of 305 mm (1 ft), the bracket holding the sign panel broke upon impact, allowing the sign panel and a segment of the support structure to impact and penetrate the windshield. (*3, 10*) The spring-loaded, portable sign support structure was retested successfully with a plastic/fabric sign panel at both 305-mm (1-ft) and 610-mm (2-ft) mounting heights. (*3, 10*)

In a test of a steel, easel-type, portable sign support structure with a plastic/fabric sign panel mounted at a height of 305 mm (1 ft), the easel structure rotated into and penetrated the windshield. (*3, 10*) A 1.2-m × 1.2-m (4-ft × 4-ft) FRP sign panel was successfully tested when mounted at a height of 305 mm (1 ft) to a generic easel structure fabricated from PVC tubing. (*11*) When the same FRP sign panel was attached to a T-leg structure with an HPPL vertical support, the system failed because of extensive windshield damage. (*11*) The same T-leg structure performed acceptably when evaluated in combination with a corrugated plastic sign substrate. (*11*)

Generally, researchers have found good performance in small, portable sign support structures with most sign substrates when the sign is mounted below 457 mm (18 in). Although there are exceptions, good performance is also reported on most portable sign support structures for both low and high mounting heights when fabric sign panels are used. However, there have been some instances when horizontal fiberglass stays have penetrated the windshield when the stay material has exceeded 4.8 mm ($^{3}\!/_{16}$ in) in thickness.

High-mounting-height (i.e., 1.5 m to 2.1 m [5 ft to 7 ft] from ground to bottom of sign panel), portable sign support structures have been problematic with rigid aluminum or plywood substrates. Problems have been encountered at both ends of the range, but more so at the lower 1.5-m (5-ft) mounting height. Most failures involve the sign panel and upper mast section impacting the top of the windshield and roof of the vehicle. Impacts with the system oriented 90 degrees to the travel path of the vehicle have caused the rigid substrate on some systems to penetrate the windshield and/or the roof sheet metal. Some successful crash tests have involved the early release of the rigid substrate or fracture of the support mast at or near bumper height.

Plastic Drums

Numerous crash tests with plastic drums manufactured from different materials and incorporating different base and ballasting systems have been conducted. (*5, 6, 7*) The results indicate that, almost without exception, the impact performance of plastic drums meets the evaluation criteria set forth in the *NCHRP Report 350* guidelines. Damage to the vehicles was mostly superficial, i.e., scrapes and scratches, and the test vehicles could be reused for multiple impacts. Occupant compartment integrity was maintained in all the tests. In fact, the level of occupant risk is so low that a live driver was used in many of the tests to reduce turnaround time between tests.

Plastic channelizing drums with warning lights attached were originally classified as Category 2 devices that required crash testing. Successful test experience with various combinations of drums with warning lights has led to their reclassification as Category 1 devices in a September 15, 2000, memorandum, “Work Zone Safety: Generic Crashworthy Barricade Designs, Drums with Warning Lights, Generic Lightweight Warning Lights” (Acceptance Letter WZ-54). Drums with Type A or C warning lights firmly affixed with vandal resistant hardware are considered crashworthy and may be self-certified by the vendor.

Sign Substrates for Plastic Drums

Results of the crash tests indicate that the impact performance of sign substrates mounted on plastic drums was satisfactory for some sign substrates and unsatisfactory for others. (*5*) The unsatisfactory impact performance of some sign substrates was mainly due to the shattering of windshields and the potential for penetration or intrusion into the occupant compartment. In addition, debris resulting from some of the sign substrate tests was judged to be a potential hazard to workers in the area. Both plywood and polycarbonate sign substrates were considered to be unsatisfactory for this application. Aluminum sign substrates had marginal performance.

Two-Piece Traffic Cones

In tests with two-piece traffic cones, the cone body readily separated from the base and subsequently traveled with the vehicle. (*3, 10*) The cone body sustained only minor scrapes and there was no damage to the vehicle. The tests were judged to have met all evaluation criteria set forth in *NCHRP Report 350.* In subsequent testing, the practice of using two weighted bases was determined not to adversely affect the impact performance of the two-piece traffic cone.

Vertical Panels

Three different supports for generic vertical panels—nominal 51-mm × 102-mm (2-in × 4-in) wooden post, 1.8-kg/m (1.2-lb/ft) channel delineator post, and 38-mm × 38-mm (1.5-in × 1.5-in) steel angle—all performed satisfactorily in full-scale crash testing. (*4*) However, vertical panels with lights have yielded mixed results. Comments received from various testing agencies have indicated the problematic devices tend to have weak connections or brittle material properties allowing early release of the light apparatus.

3.2 MANUFACTURERS AND SUPPLIERS

Much of the testing and evaluation of work-zone traffic control devices has been independently sponsored by private manufacturers and suppliers of these products. Because of their desire to market and sell their product, most manufacturers submit the results of their testing to FHWA for review and approval. Thus, FHWA's acceptance letters for work-zone devices (designated WZ-##) are the single best source of information on what has been successfully tested by manufacturers and suppliers. To date, 193 acceptance letters have been issued by FHWA in this area. Most of the devices in these letters can be categorized as Type I, II, and III barricades and portable sign supports. Many of these devices are patented proprietary products that are sold as units by a limited number of distributors. A review of the design and performance of these devices provided insight for the development of new, generic products under this project. However, as mentioned previously, failed tests of proprietary devices are typically not reported; thus, the researchers relied on their own experiences and the general observations shared by other testing agencies to determine features that result in undesirable performance.

3.3 FEDERAL HIGHWAY ADMINISTRATION

As mentioned previously, FHWA has played a key role in work-zone safety through the adoption of *NCHRP Report 350* criteria, development of additional guidelines that clarify the testing and evaluation of work-zone devices, administration of pooled fund research studies, sponsorship of the National Work Zone Safety Information Clearinghouse, issuance of product acceptance letters, and maintenance of a database and web site of approved products and associated information.

FHWA guidance on crash testing of work-zone traffic control devices is contained in several memoranda. The first, dated July 25, 1997, titled "Identifying Acceptable Highway Safety Features," established the four categories of work-zone devices mentioned in Chapter 2:

- Category 1 devices are those lightweight devices that could be self-certified by the vendor.
- Category 2 devices are other lightweight devices that needed individual crash testing.
- Category 3 devices are barriers and other fixed or massive devices also needing crash testing.
- Category 4 devices are trailer-mounted lighted signs, arrow panels, etc.

The second guidance memorandum, "Crash Tested Work Zone Traffic Control Devices," was issued on August 28, 1998. This memorandum listed devices that were acceptable under Categories 1, 2, and 3 at that time and provided crash testing compliance dates for hardware to be used on the NHS. FHWA acceptance of a device for use in work zones on the NHS is limited to the crashworthiness characteristics of the device and does not cover its structural features (e.g., resistance to service loads), durability, or conformity with the MUTCD.

A September 13, 2000, memorandum, "Crashworthy Work Zone Devices as of October 1, 2000" (Acceptance Letter WZ-45), provided supplemental information to assist in meeting the *NCHRP Report 350* compliance deadlines for Category 2 channelizing devices. The memorandum indicated there was no national cut-off date for phasing out noncompliant Category 2 devices and that existing untested devices could remain in use until the end of their service life.

A memorandum dated September 15, 2000, entitled "Work Zone Safety: Generic Crashworthy Barricade Designs, Drums with Warning Lights, and Generic Lightweight Warning Lights" (Acceptance Letter WZ-54), provided additional information and guidance to help highway agencies implement crash-tested barricades, drums, and warning lights. The memorandum contained details of a set of generic steel-frame barricade designs that were tested by a private manufacturer but provided for use free of charge. Drums with Type A or C warning lights firmly affixed with vandal-resistant hardware were reclassified as Category 1 devices, meaning they are considered crashworthy and may be self-certified by the vendor. The memorandum also provided information on the testing and use of lightweight warning lights that have either

(1) a separate battery pack located at the base of the device with only the lens assembly attached to the top of the barricade or (2) the lens assembly attached to a small battery pack, which has a combined unit weight of less than 1.5 kg (3.3 lb).

A memorandum entitled "Design and Materials of Crashworthy Work Zone Traffic Control Devices: Portable Sign Stands, Type III Barricades, and Category IV Devices" (Acceptance Letter WZ-85), dated November 15, 2001, distributed additional information on the materials used and the design of crashworthy work-zone traffic control devices. It includes information on sign substrates, sign shape and size, and installation issues related to portable sign supports and presents information on generic Type III barricade designs and Type III barricades used as sign supports. The memorandum also includes frequently asked questions and answers related to work-zone traffic control devices.

As mentioned, numerous acceptance letters have been issued for crashworthy, *NCHRP Report 350*–compliant, Category 2 work-zone devices to various manufacturers, state DOTs, and others, and the list continues to be updated on a regular basis. These acceptance letters and other useful information pertaining to work-zone devices can be accessed via the FHWA web site: http://safety.fhwa.dot.gov/roadway_dept/road_hardware/cat2.htm. As of April 2005, FHWA had posted 193 letters of acceptance for work-zone devices on its web site.

FHWA also administered a pooled fund contract (Contract No. DTFH61-97-C-00064) entitled "Work Zone Appurtenances Tested to *NCHRP Report 350*." The states participating in the study included Arkansas, Florida, Illinois, Maryland, Minnesota, Montana, Nebraska, New Jersey, North Carolina, and Oregon. The objective of this study was to design, develop, and test, for use by the states, work-zone appurtenances that meet *NCHRP Report 350* criteria. Category 2 work-zone devices successfully developed and/or tested under this project included a generic Type III barricade fabricated from perforated steel tubing with a 1.2-m × 1.2-m (4-ft × 4-ft) plywood sign panel attached at a 2.1-m (7-ft) mounting height, a generic Type III barricade fabricated from steel angle with wooden rails, and a portable sign stand with a 1.2-m × 1.2-m (4-ft × 4-ft) vinyl roll-up sign panel mounted at a height of 1.5 m (5 ft).

3.4 STATE-OF-THE-PRACTICE SURVEY

As part of the Phase I effort, the project team developed and administered a state-of-the-practice survey to assist with identifying and evaluating the performance of existing Category 2 work-zone traffic control devices. The survey solicited information, plans, and specifications as a means to help assess performance, crashworthiness, and usage of these devices. The survey was mailed nationwide in accordance with a distribution list reviewed and approved by the project panel. In addition to representatives of state and federal transportation agencies, the distribution list for the survey included ATSSA, American Road and Transportation Builders Association (ARTBA), National Association of County Engineers (NACE), and American Public Works Association (APWA). At the state level, the distribution list focused on construction, maintenance, and standards engineers. Follow-up personal communication (either by e-mail or phone call) was conducted to help improve the response rate. Out of 55 surveys mailed, 25 responses were received, which is a response rate of 45%. The survey responses were reviewed, and current designs and practices were synthesized. A summary of the survey responses is provided in Appendix B.

3.5 NATIONAL WORK ZONE SAFETY INFORMATION CLEARINGHOUSE

In February 1998, ARTBA partnered with the FHWA in an effort to improve safety in highway work zones by creating the National Work Zone Safety Information Clearinghouse. The purpose of the Clearinghouse is to provide information and referrals to government agencies, public and private organizations, and the general public concerning the safe and effective operation of traffic work zones.

The Clearinghouse is a cooperative venture between the FHWA and ARTBA. ARTBA is responsible for the Clearinghouse's operations. FHWA provided leadership and funding assistance for the first 3 years of operation. The Clearinghouse began operations in February 1998 under FHWA funding and was fully self-sustaining by October 1, 2000.

ARTBA's partners in establishing and operating this Clearinghouse are TTI, the Institute of Transportation Engineers (ITE), and the National Utility Contractors Association (NUCA). TTI operates the Clearinghouse, while ITE and NUCA assist ARTBA in marketing and publicizing it. Researchers at TTI have been compiling information and organizing it into databases since the Clearinghouse opened. The contents of the Clearinghouse include comprehensive, up-to-date information on work zone–related topics such as laws, products, public education, public outreach, regulations, research reports, specifications, statistics, training courses, and key experts in each of these areas.

The general web address for the Clearinghouse is http://wzsafety.tamu.edu. In the specific area of work-zone safety technology and equipment, the Clearinghouse offers a searchable equipment database, listings of manufacturers and distributors of products (including links to ATSSA and ARTBA member sites), and *NCHRP Report 350* crashworthiness information (including links to FHWA guidance memorandums, approved products lists, compliance dates, etc.).

CHAPTER 4

DESIGN CONSIDERATIONS

Many factors need to be understood and appropriately considered when designing work-zone barricades and sign supports. Of foremost importance are those factors influencing the impact performance of the device. Also, many functional requirements must be considered to ensure a device can be effectively and efficiently used for its intended purpose. A general discussion of crashworthiness factors and a brief discussion of some functional considerations are presented in this chapter.

4.1 FACTORS INFLUENCING CRASHWORTHINESS

First and foremost, a work-zone traffic control device must be compliant with *NCHRP Report 350* guidelines before it can be implemented on the NHS. Factors that can affect the impact performance of a device include but are not limited to the mass of the primary components, failure mode of the structural members, connection details between the structural members, sign substrate material, sign panel size, and sign panel mounting height. Although many of these factors are somewhat obvious, their influence on impact performance is not always intuitive. For example, small variations in sign panel installation height (i.e., less than 50 mm [2 in]) have yielded different results in full-scale crash tests with all other factors being the same.

Depending on the failure mode of the structure, the mass of the components can directly influence the propensity for occupant compartment intrusion. For example, wood supports used in barricades and sign support construction will fracture during impact and the resulting debris has sufficient mass to shatter and penetrate the windshield of the impacting vehicle. (*3*, *10*, *11*) Testing has shown that a simple substitution of a lighter weight plastic section of the same shape and size can dramatically improve performance. (*11*) Although these lighter members may still fracture or release from their base and contact the windshield, the mass of the resulting debris is not sufficient to penetrate the windshield.

The failure mode of a device can be integral to its impact performance. In many ways, the behavior of work-zone barricades and temporary sign supports are analogous to permanent breakaway sign supports. Some designs, such as those that incorporate hollow-profile plastic or FRP components, break away or fracture on impact. (*3*, *4*) Other devices, such as those constructed from perforated steel tubing or steel angle sections (e.g., Illinois DOT barricade), are designed as base bending or yielding structures. (*3*, *12*) If properly designed, a base-bending/yielding device can reduce the probability of occupant compartment intrusion by keeping the structure intact and reducing or eliminating the separation of components that might penetrate the windshield. Conversely, improperly designed flexible supports may actually carry the sign panel substrate into the windshield. For devices designed to utilize this type of failure mode, the mass of the frame or structure becomes less significant but is not necessarily inconsequential.

Just as the type of structural member used can dictate the failure mode and subsequent behavior of a work-zone device, so can the connection details between the members. The connections between the base/skids, vertical supports, horizontal rails, and sign panel can influence not only which components separate from each other during impact, but the resulting mass of the separated components as well. Therefore, the connection details must be considered together with the failure mode of the supports and rails in order to have a more complete understanding of how a device will perform during an impact.

The failure mode (as dictated by either the connections or material type of the structural members) can vary with impact speed. For example, some barricade systems are designed to permit the vertical supports to rotate about a connection pin after failing a smaller positioning bolt in shear. At low impact speeds, the supports may indeed rotate as designed and permit the impacting vehicle to simply override the system. However, at high impact speeds, the supports will yield around the front of the vehicle and subsequently be carried along or fracture rather than rotate under the vehicle.

For temporary sign supports and barricades with sign attachments, the sign panel size, substrate material, and mounting height can all dramatically influence the crashworthiness of the device. (*3*, *4*, *10*, *11*) Lower mounting heights often result in direct contact of the sign panel with the windshield and roof of the impacting vehicle. In such instances, relatively heavy, stiff substrates such as plywood are typically unacceptable. (*4*, *11*) Lighter weight, more flexible substrate alternatives such as corrugated plastic are more forgiving and have been shown to be suitable at various mounting heights. (*11*) Variations in sign size can influence both the mass and height at which the sign panel interacts with the vehicle. As an illustration, a 914-mm × 914-mm (36-in × 36-in) plywood sign panel was successfully tested on a T-leg base at a 305-mm (1-ft) mounting height without any windshield damage. (*11*) When the same system was tested at a 610-mm (2-ft) mounting height, the performance was marginal as a result of extensive windshield damage. When the size of the sign panel was increased to 1.2 m × 1.2 m (4 ft × 4 ft) in a subsequent test, the result was unsatisfactory. Another test with the larger sign panel at a 610-mm (2-ft) mounting height was successful when the sign substrate material was changed from plywood to corrugated plastic. (*11*)

Attachments on work-zone devices, such as warning lights and flags, can also influence impact performance. Testing has demonstrated that the use of warning lights attached to the top of a Type III barricade may be undesirable depending on the method of attachment and its position on the barricade frame. (*4*) Note that the 1.5-m (5-ft) height of a Type III barricade can create direct contact of a warning light with the windshield even if it remains positively attached. When warning lights are attached to a sign support structure at a mounting height of 2.1 m (7 ft), the performance has been found to be acceptable. (*4*) When designing a work-zone device with attachments, the size, mass, attachment mechanism, and mounting height should all be considered.

4.2 FUNCTIONAL DESIGN CONSIDERATIONS

In addition to being crashworthy, a barricade or temporary sign support should also satisfy the various functional requirements of the application. The device should have sufficient structural capacity to withstand anticipated service loads, be durable enough to accommodate frequent handling, and be able to accommodate common variations in site conditions that may exist in the field.

4.2.1 Wind Resistance

When designing barricades or temporary work-zone signs, the vertical supports should be designed to accommodate the flexural stresses induced by the anticipated wind loading and sufficient ballast should be provided to prevent overturn of skid-mounted designs. The wind loads on a structure are determined by applying the appropriate wind pressure to the exposed areas of any vertical supports, horizontal elements, and/or sign panels. Once the loads have been determined, the stresses in the support members can be computed and compared to their allowable stresses.

Calculations of wind pressure follow the procedures prescribed in the AASHTO *Standard Specifications for Structural Supports for Highway Signs, Luminaries, and Traffic Signals.* (*13*) Given a design wind speed, the associated wind pressure is computed by the following formula:

$$P_z = 0.00256K_zGV^2I_rC_d \tag{4.1}$$

where

P_z = wind pressure (psf),
K_z = height exposure factor = 0.87 for sign heights of 5 m (16.4 ft) or less,
G = gust effect factor = 1.14,
V = wind speed (mi/h),
I_r = importance factor, and
C_d = drag coefficient = 1.12 for sign with length/width ratio of 1.

The design wind speed varies with geographic location and the life expectancy of the structure. Since permanent roadside sign structures are considered to have a relatively short life expectancy, they are typically designed for wind speeds based on a 10-year mean recurrence interval per AASHTO specifications. The duration of work-zone activities is typically much less than 10 years. No formal guidance is given regarding an appropriate design wind speed or mean recurrence interval for use in the design of work-zone traffic control devices. R. P. Bligh derived wind loads for use in the design of barricades and temporary sign supports based on different mean recurrence intervals more appropriate for work-zone activities. (*14*)

Depending on the site conditions and the nature of its application, a barricade can be designed as a skid-mounted system or as a ground-mounted system. A skid-mounted design is more portable and can be easily moved or relocated on the job site as necessary to accommodate work-zone access, etc. Ground-mounted systems are often used in work zones when the barricade is required to be placed on uneven terrain or in applications such as road closures, which often require a more permanent system. The vertical supports of both types of systems should be designed to have sufficient strength to accommodate the flexural stresses induced by the prescribed wind loads applied to the horizontal rails and sign panel. In addition, proper ballast should be provided to prevent overturn of skid-mounted systems when subjected to the selected design wind event.

Wind load analyses have been conducted to determine the structural adequacy of various vertical barricade and sign support members and the amount of ballast required for different wind speeds. (*3*, *12*) Using the exposed areas of both the sign panel and the horizontal rail, the maximum overturning moment for a Type III barricade with sign panel attachment was computed. This moment was then used to determine the amount of ballast required on the skids to prevent overturn. Details of a wind load analysis for high-mounting-height work-zone sign supports conducted under this project are presented in Chapter 8.

The researchers have seen instances where guy wires were run from the barricade supports to the ground to anchor barricades in high-wind locations. This practice has not been crash tested and has the potential for adversely affecting the crashworthiness of the device as well as vehicle stability.

4.2.2 Durability

An important consideration when designing any work-zone traffic control device is the ability to accommodate frequent handling, on-site relocation, transportation, and repair. In other words, to be cost effective, the device must be durable. Insight can be gained from contractors, suppliers, and users of these devices regarding the nature of abuse to which devices are subjected in daily use and common problems that are encountered in the field. For example, many suppliers/contractors have a preference for using channelizing drums with rubber bases rather than a ballasted plastic base. They have observed that these devices are typically moved by using the handle on the top of the drum and dragging it on its base. While the rubber bases extend beyond the edges of the drum and protect it from damage, the ballasted plastic bases frequently wear through and require replacement.

Some suppliers/contractors have a preference for using plastic horizontal barricade rails over the more commonly used wood. Although the initial cost may be slightly higher, the probability of saving the reflective sheeting (which is often the most expensive part of a barricade) during an impact is greatly improved because the rail members do not fracture. When wood rails are used, they tend to fracture easily even in relatively minor impacts resulting in the loss of both the rail and its reflective sheeting. Further, wooden rails require painting while plastic rails, which can be provided in a white color, do not.

One supplier/contractor prefers to use hose clamp–type connectors rather than through bolts to attach rails or sign panels to hollow-profile plastic vertical supports. When moving from job to job, the barricade rails or sign panels often require slight adjustments in height. If holes are drilled each time to accommodate through bolts, the support will soon be rendered structurally inadequate. By using the clamps for the connections, the need for drilling holes is eliminated and the life of the support can potentially be prolonged.

As mentioned previously, some barricade designs incorporate bracing to enhance transportation, handling, and durability. Use of the vertical braces permits the barricade rails to be preassembled and then attached or detached from the barricade supports as a unit, which assists with transportation and on-site erection. Use of horizontal cross braces can provide more rigidity to the barricade frame when flexible barricade rails (e.g., plastic) are used. This rigidity helps improve handling characteristics and the ability to withstand wind and other service loads.

4.2.3 Site Adaptability

The site conditions encountered in work zones can vary considerably from one job to the next. Ideally, a well-designed work-zone barricade or sign support will be able to accommodate some of the more common variations in site conditions. When barricades are placed on the roadside, for instance, varying degrees of sloped terrain or tall grass are commonly encountered. If the vertical supports of the barricade or sign support are designed to be readily adjustable, accommodating the differential elevation caused by the sloped terrain or increasing the mounting height to position the warning or guide sign above the tall grass is a simple matter. Adjustability can be accomplished by using sleeves into which the vertical supports can be easily inserted and adjusted to the required height. Barricades or temporary sign stands with fixed, non-adjustable supports and bases lack this type of adjustment and are sometimes raised or leveled on a slope using blocks under the skids or legs. This practice can potentially have an adverse affect on the crashworthiness of the device and its ability to withstand wind loads. Alternatively, the attachment of the sign panel to the uprights can be adjusted provided adequate support for the sign panel is still provided.

4.2.4 Environmental Effects

Because of the unacceptable impact performance experience with rigid substrates (e.g., plywood) with some sign support systems, many alternative substrates have been evaluated for use as temporary sign panels. The type of substrate used and its means of attachment to the vertical support(s) can affect the functionality of the device. To meet crashworthiness requirements, many devices incorporate lightweight materials such as vinyl/fabric roll-up signs, plastic sheeting, corrugated plastic, fiberglass, and thin-gage aluminum. Most of these materials are very flexible in nature and some, such as the plastic materials, may be susceptible to warpage; both of these behaviors can decrease retro-reflectivity and legibility of the warning or guide sign. Bracing can be used to reduce this behavior, but the effects of the bracing on the impact performance of the device must be carefully evaluated. If a proper combination of support and substrate are selected, some of these environmental design considerations can be accommodated in the design process.

Another concern is the long-term durability of plastics (e.g., PVC, HDPE, polypropylene [PP]) and FRP components used in barricade and temporary sign support construction. Although admixtures are typically incorporated into these products to enhance their resistance to degradation from ultraviolet rays and other types of environmental attack, their long-term susceptibility and, thus, their life expectancy are not fully known.

4.2.5 Functional Performance Rating

Under Phase I of the project, a rating scheme was developed to help evaluate the functional performance of a work-zone barricade or sign support in the areas of wind resistance, durability, handling, fabrication/repair, and site adaptability. The rating scale for each area was “high,” “average,” and “low.” The assessment of functional performance is subjective and relative and reflects the opinions of the researchers and not necessarily those of TRB, the National Research Council, FHWA, and AASHTO.

The rating of wind resistance reflects the strength and stiffness of the support member and sign substrate. For example, support systems that incorporate vinyl roll-up signs are generally rated as average because of their propensity to lean and deflect in the wind thus reducing legibility and retroreflectivity. Rigid substrates (e.g., aluminum, plywood) with sufficiently strong support members are generally rated as high due to their ability to retain their shape and orientation in windy conditions.

The durability rating is intended to primarily reflect the durability of the materials used in the construction of the sign support. Systems composed of steel, aluminum, and wood are generally rated as high because of their resistance to environmental attack. Systems with vinyl sign substrates and plastic or fiberglass components are generally rated as average based on uncertainty regarding the long-term susceptibility of these materials to degradation from environmental attack (e.g., exposure to ultraviolet rays, wind, rain, etc.).

The handling assessment is intended to rate general ease of handling, transportation, and erection of the device. A rating of high generally reflects the device's ability to be readily assembled and disassembled for ease of transportation and to minimize exposure during on-site deployment. A high rating is also generally indicative of durable connections and a reasonable weight that enables the device to be moved short distances as an assembled unit during on-site handling. More bulky assemblies or units that cannot be readily disassembled or folded would be rated as average or low.

The fabrication/repair rating provides a general assessment of the cost and availability of materials used to construct and repair the device. Units that use readily available materials that can be easily cut to length, drilled, etc. (e.g., wood, steel tubing, or hollow profile plastic) would be given a higher rating than devices that require specially molded parts or are constructed from more expensive materials such as fiberglass. The fabrication/repair rating is also based on the types of connections and ease of assembly of the device. Devices composed of components that are easily nailed, bolted, or pinned together would rate higher than those that require welding or more labor-intensive fabrication.

The rating on site adaptability refers to the degree of adjustment that a device has to accommodate variations in field conditions. For example, a device with a reasonable range of height adjustment and/or an ability to adjust to uneven terrain would be given a site-adaptability rating of high. A telescoping or sleeved system that allows height adjustment of the sign and its support would receive a high rating. Of course, the device would need to be crashworthy for the range of heights to which it might be adjusted in the field. A few devices have a tilt adjustment on the mast/support, which enables the sign to be plumb when the base is placed on a sloping roadside or otherwise unlevel terrain. Such a feature would warrant a high site adaptability rating. Devices with fixed supports and bases that are not adjustable would be given a rating of average or low depending on the features of the design.

Finally, the overall rating is intended to assess the overall functionality of each device. The overall rating is determined by averaging the wind, durability, handling, fabrication/repair, and site-adaptability ratings. This rating scheme was used by the project team members to assess current designs and determine desirable characteristics and features for incorporation into new designs developed under this project.

CHAPTER 5

PERFORMANCE ASSESSMENT AND CATEGORIZATION

Although the state of the practice presented in Chapter 3 shows that considerable progress has been made, further research in the area of work-zone traffic control devices is certainly warranted. Many of the existing crashworthy designs that are compliant with *NCHRP Report 350* guidelines are proprietary. Although these devices meet performance requirements, they sometimes cost considerably more than some of the devices shop-fabricated from readily available materials. Primary among the Category 2 applications of interest under this project are portable sign supports, barricades, and barricades with sign attachments. A discussion of these applications is presented in the following sections.

5.1 PORTABLE TEMPORARY SIGN SUPPORTS

Portable temporary sign supports are typically free-standing systems that have sign panels mounted at various heights. Low-mounting-height systems have mounting heights that range from 0.3 m to 0.9 m (1 ft to 3 ft) from the ground to the bottom of the sign. High mounting heights are defined as those with a mounting height between 1.5 m and 2.1 m (5 ft to 7 ft). The low-mounting-height systems present a design challenge because of their propensity to rotate into the windshield of the impacting vehicle. Most of the acceptable alternatives available for this application are proprietary sign stands that must be used in combination with a roll-up fabric or vinyl sign panel. Although some of these systems can offer advantages such as portability, ease of erection, and adjustable mounting height, their cost can sometimes be prohibitive. Furthermore, the use of a more rigid sign substrate is desirable to improve legibility and retro-reflectivity in windy conditions.

High-mounting-height, portable sign stands are typically fabricated with larger support members. If the supports do not readily fracture or release upon impact, they may yield around the front of the impacting vehicle and carry either the sign panel and/or top of supports into the windshield. As with low-mounting-height sign stands, rigid sign panel substrates are more problematic with collisions of this nature. Remedial measures for these types of problems have involved weakening the supports at or near bumper height, installing breakaway mechanisms at bumper height, or providing sign panel release mechanisms. Sometimes combinations of these design modifications are incorporated.

As mentioned previously, the configuration of the sign stand and selection of an appropriate sign substrate are equally important in the design of a portable sign support system. Several generic sign stands with various sign substrates including plywood, aluminum, FRP, and corrugated plastic have been successfully tested. However, further work is needed to develop additional generic sign stand alternatives that can be used with rigid or semi-rigid sign substrates at different mounting heights.

A review of the existing portable sign support systems yielded the following observations:

- A large number of the devices are proprietary.
- Most proprietary support devices are fabricated from square steel or aluminum tubing and are available with both rigid and non-rigid sign substrates.
- Many of the proprietary X-base supports are adjustable for varying site conditions.
- A small portion of the proprietary supports are fabricated from various plastics.
- Generic supports are mostly fabricated with wood or plastic lumber, perforated steel tubing, and/or PVC pipe and are generally not well suited for varying site conditions.
- Generic rigid sign substrates are generally fabricated with sign-grade plywood or aluminum.
- Proprietary rigid sign substrates include laminated composites and extruded plastics.
- Portable sign supports with signs mounted at 1.5 m (5 ft) or higher experience more favorable results in crash tests when some type of fracture or release of the support occurs near bumper height of the impacting vehicle or when early release of the sign panel is achieved.

5.2 BARRICADES AND BARRICADES WITH SIGN ATTACHMENTS

Because the standards of some states permit the use of a barricade as a sign support for various project limit and guide signs, sign attachment mechanisms for some of the crashworthy Type III barricade designs should be developed. Results of full-scale crash testing indicate that existing wooden

Type III barricades, with or without sign panel attachment, pose potential hazards to impacting vehicles because of the propensity for the sign panel and/or fractured vertical supports to impact and penetrate the windshield. (*3*) Testing has also shown that, because of their rigidity and mass, the use of plywood sign substrates can be problematic at mounting heights ranging from 0.3 m to 1.5 m (1 ft to 5 ft). (*3*) Depending on the specific barricade design and sign attachment mechanism, a mounting height of 2.1 m (7 ft) is more accommodating of plywood sign substrates because direct windshield contact can be avoided.

As mentioned in previous sections, full-scale crash testing has demonstrated the crashworthiness of improved Type III barricade designs constructed from materials such as perforated steel tubing, steel angle sections, hollow-profile plastic (e.g., HDPE or PVC), and FRP. (*3*, *4*, *10*) Given that these generic barricades are crashworthy, the next step is to develop and evaluate appropriate sign panel attachment mechanisms.

There are two basic sign attachment mechanisms. If the mounting height is sufficiently low, the sign panel can be attached directly to the barricade rails and supports. If a rigid sign substrate is used, the sign panel must be attached to the supports and not the rails alone. Wooden rails will fracture on impact and, therefore, can permit the sign panel to release and travel into the windshield of the impacting vehicle. Plastic rails may not possess sufficient stiffness to support the sign panel and accommodate wind loads.

When taller mounting heights (e.g., 1.5 m to 2.1 m [5 ft to 7 ft]) are desired, the sign panel must be attached to support members that extend above the barricade. These support members can be attached to the barricade structure in one of two ways. In the first alternative, the sign support members are bolted directly to the barricade rails. This alternative requires the use of wooden rail elements since, as mentioned previously, hollow-profile plastic rails are typically too flexible to support the sign panel and the required wind loads. Direct attachment to the wooden rails may be acceptable at the higher mounting heights if contact of the sign panel with the windshield can be avoided.

In the second alternative, the sign supports can be bolted to cross braces extended between barricade supports or to the barricade supports themselves if the barricade width is not too great. The cross braces are provided in two locations behind the upper and lower barricade rails. Because the loads applied to the sign panel are not transferred through the barricade rails, i.e., the barricade rails are not used as structural members, the rails can be either hollow-profile plastic or wood. The specific design details (e.g., sign support material type and size, connection methods, sign panel substrate, acceptable mounting height) may vary depending on the configuration of the barricade system to which the sign is being attached.

Under the FHWA pooled fund project mentioned previously (*12*), a perforated steel-tube barricade with a 1.2-m × 1.2-m (4-ft × 4-ft) plywood sign panel attached at a 2.1-m (7-ft) mounting height was successfully designed, developed, and tested. Under this same project, a barricade system with PVC uprights and sign support members having a plywood sign panel of the same dimensions attached at the same mounting height did not pass crash testing. The researchers believe the deficiencies of this system can be overcome by using HDPE instead of PVC material for the barricade uprights and sign supports. The HDPE is more ductile than PVC and would prevent fracture of the supports, thereby eliminating exposure of the connection bolts that penetrated the windshield of the test vehicle.

A review of existing barricades and barricades with signs yielded the following observations:

- A significant number of states use all-wood barricades that have not been crash tested.
- A number of states have adopted the generic, crash-tested, perforated steel-tube design using both wood and hollow-plastic horizontal rails.
- Proprietary Type I and II barricades are largely molded plastic, A-frame installations.
- Generic Type I and II barricades are generally fabricated with steel angle and wood for A-frame installations and perforated steel tube and wood for other Type I and II installations.
- There are a wide variety of proprietary Type III barricades using many combinations of steel, PVC, HDPE, PP, aluminum, and wood.
- Some states have indicated successful crash testing of all-wood Type III barricades, but reports have not been provided.
- Information on barricades with signs indicates a limited number of successfully crash-tested devices.

5.3 RECOMMENDATIONS FOR PHASE II

Based on the state-of-the-practice review and the availability of generic, crashworthy designs manufactured from readily available materials in the different categories of interest, the researchers prepared a list of devices for consideration by the panel for further development and testing under Phase II of this project. The following sets of generic work-zone traffic control devices were selected by the panel for further development and testing under Phase II of the project:

1. Type III barricade with rectangular sign attached.
2. Small, portable work-zone sign with 1.2-m × 1.2-m (4-ft × 4-ft) rigid sign panel substrate mounted 0.3 m (1 ft) above ground. If design with rigid substrate is unsuccessful, use of a semi-rigid (hollow-plastic) substrate will be investigated.
3. Portable work-zone sign with rigid sign panel substrate mounted 1.5 m (5 ft) to 2.1 m (7 ft) above ground.

4. Type III barricade with good functionality, site adaptability, and attached warning lights.

The scope of the first set was later expanded by the panel to also include 1.2-m × 1.2-m (4-ft × 4-ft) diamond-oriented sign panels in addition to the originally specified 0.8-m × 1.5-m (2.5-ft × 5-ft) rectangular sign panel. The first and fourth sets were combined such that testing of the barricade with sign also included an evaluation of attached warning lights.

For each of these sets of work-zone devices, the researchers developed several design alternatives for review and prioritization by the panel. The researchers used the panel's prioritization of the designs to formulate a full-scale crash testing plan for each set of devices. A total of 10 crash tests were conducted on the selected barricade and sign support systems. Details of the design, development, testing, and evaluation for each set of devices are presented in the following chapters of this report.

CHAPTER 6

BARRICADES WITH SIGN ATTACHMENTS

The development of crashworthy, functional barricades with attached sign panels was given the highest priority among the three sets of work-zone traffic control devices selected for development and testing under the project. Because the standards of many states permit the use of a barricade as a sign support for various project limit and guide signs, development of sign attachment mechanisms to crashworthy Type III barricade designs is desirable. Further, the state-of-the-practice review indicated Type III barricades with sign panels is one of the sets of work-zone devices with the fewest number of crashworthy generic alternatives. This chapter discusses some of the design considerations for barricades with sign attachments and describes the development and testing of some new generic systems. While impact performance requirements dictated many of the design decisions, effort was devoted toward developing designs that also meet a variety of functional design requirements.

6.1 DESIGN CONSIDERATIONS

6.1.1 Sign Substrate

A few generic barricade systems with attached signs fabricated from various types of readily available materials have been tested with mixed results. Sign panel mounting height will, to a certain extent, dictate substrate material and vertical barricade support types that will be acceptable. For example, rigid substrates fabricated from readily available materials (e.g., plywood and aluminum) are often preferred by user agencies and contractors because of their durability. However, testing has shown that the use of rigid sign substrates can be problematic for mounting heights ranging from 0.6 m to 1.5 m (2 ft to 5 ft) because of their rigidity and mass. At greater mounting heights (e.g., 2.1 m [7 ft]), the use of rigid sign substrates has been shown to be acceptable, primarily because direct windshield contact can be avoided. However, the additional structure required to support the sign and resist wind loads at these heights can make the barricade difficult to handle and transport. From a functional standpoint, the handling disadvantage of plywood may be offset by its low material cost, availability, ease of fabrication, and durability. For these reasons, plywood was selected as the sign substrate for the new barricades designed for sign attachment. Because a plywood sign panel tends to be more critical from a crashworthiness standpoint due to its greater weight, a successful test with a plywood substrate was considered to be sufficient for receiving approval of a similar design with a comparably sized aluminum sign substrate or other lightweight substrate materials (e.g., corrugated plastic).

For purposes of this project, the panel initially specified a rectangular sign at a low mounting height. The maximum size of the rectangular sign panel was specified to be 1524 mm × 762 mm (60 in wide × 30 in tall). During the design and review process, several panel members expressed interest in accommodating a 1.2-m × 1.2-m (4-ft × 4-ft) diamond-oriented sign. Methods of attachment were, therefore, developed for both sign types. In the opinion of the researchers, the sign panel must be secured to the barricade uprights rather than just the barricade rails. This procedure helps prevent the sign panel from becoming a projectile that could impact the windshield when the wooden rails fracture upon impact. However, it limits the width at which the barricade uprights can be spaced unless additional structural members are added to the barricade frame.

6.1.2 Mounting Height

For purposes of this project, the panel initially specified a rectangular sign at a low mounting height. A low mounting height provides for the possibility of attaching the sign panel directly to the barricade structure without the need for additional support. Direct attachment reduces the overall weight of the barricade and facilitates handling and transportation. From a structural design standpoint, the sign panel should overlap two horizontal rails rather than be cantilevered off the top rail alone. Attachment of a 0.8-m (2.5-ft) tall sign to the upper rails of a 1.5-m (5-ft) tall Type III barricade provides for a mounting height of about 0.8 m (2.5 ft). Designs incorporating the taller 1.2-m × 1.2-m (4-ft × 4-ft) diamond-oriented sign panels utilized a 0.3-m (1-ft) mounting height, which is considered to be a practical minimum.

6.1.3 Barricade Construction

Full-scale crash testing has demonstrated that wooden Type III barricades pose a serious hazard to impacting vehicles because of the propensity for the fractured vertical supports to penetrate the windshield of the impacting vehicle. As documented in the state-of-the-practice review, Type III barricade designs constructed from materials such as perforated steel tubing, steel angle sections, HPPL (e.g., HDPE, LDPE, PP or PVC), and FRP have been successfully tested. Given that these generic barricades are crashworthy, it was necessary to select suitable designs for the desired sign substrate and mounting height, and develop appropriate sign panel attachment mechanisms.

The barricade design plays a role in determining the nature of any windshield contact from an attached sign panel and the damage resulting from it. A system that permits release of the uprights will behave differently than one that yields around the front of the car. The key evaluation criterion is the extent of the resulting windshield damage, which is a function of the contact forces. For a barricade design in which the uprights release more readily from the base, the released uprights, rails, and sign panel will typically more fully engage the windshield. The resulting contact forces are a function of the mass of the upper barricade assembly and the amount it is accelerated by the vehicle before its release from the barricade skids.

6.1.4 Warning Lights

One of the priorities established by the project panel was to develop a Type III barricade with good functionality capable of accommodating an attached warning light. It was decided to address this objective during the testing of barricades with sign attachments.

Inadequate connection strength is known to be a major contributing factor in failed crash tests of barricades with attached warning lights. However, previous testing has also demonstrated that attaching warning lights to the top of Type III barricades is sometimes undesirable even if the light is positively attached and does not release from the barricade. Any attachment (e.g., warning light) mounted above the standard 1.5-m (5-ft) height of a Type III barricade generally results in direct contact of the attachment with the windshield. Depending on the weight of the warning light and the type of barricade construction, this contact may result in sufficient damage to constitute failure per the FHWA windshield damage criteria. In fact, in one test known by the researchers, a 0.45-kg (1-lb) Lexan lens attached to the top of a Type III barricade and connected to a battery at the base of the barricade created sufficient windshield damage to fail a crash test. It is, therefore, preferable to limit the distance the warning light extends above the top of the barricade as much as practical. Any reduction in mounting height reduces the potential for windshield contact if a positive connection is maintained between the barricade and warning light.

When designing a barricade to accommodate a warning light attachment, the failure mode of the barricade and the size, mass, attachment mechanism, and mounting height of the warning light should all be considered. For example, a barricade that functions acceptably through fracture of the uprights can be viewed as permitting early release of the light and can negate the benefits provided by a strong, positive connection between the warning light and barricade. For yielding-type barricades, a well-designed connection will prevent the warning light from becoming a projectile, but the light may still slap down on the windshield depending on mounting height and position of the light and strength of the barricade uprights. If contact between the warning light and vehicle windshield does occur, reducing the mass of the light attachment can reduce the degree of damage. Mass can be reduced by separating the battery from the lens. In such situations, the battery can be attached to the base of the barricade out of harms way. However, this practice presents additional barricade handling and transportation issues due to the need to protect the exposed wires. Of course, contact of a warning light with the windshield can be altogether avoided if the mounting height is sufficiently high. For example, when warning lights are attached to a sign support structure at a mounting height of 2.1 m (7 ft), the performance has been found to be acceptable.

6.2 DESIGN ALTERNATIVES

6.2.1 Perforated Steel Tubing

The first two conceptualized designs were constructed from perforated steel tubing. With the low mounting height, it is desirable to prevent or at least significantly delay fracture and/or separation of the vertical uprights from the base or skids, thus reducing the potential for the detached vertical supports, rail elements, and sign panel to rotate into the windshield. The tubular steel uprights initially yield and wrap around the front end of the vehicle. On a paved surface, the barricade is then carried along by the vehicle as a unit until the vehicle comes to a stop. On a dirt surface, the motion of the barricade is often impeded by the skids digging into the ground. The increased moment on the uprights eventually causes them to fracture and release from the skids. However, by this time, momentum has been transferred to the barricade and the relative speed between the barricade projectile and vehicle is significantly reduced. Thus, if the top of the sign panel can be maintained at a height below which it will contact the windshield during the initial bending and yielding of the tubular supports, the rigid sign substrate has a reasonable probability of meeting impact performance requirements.

A Geo Metro is the typical vehicle make and model used for the 820C design vehicle specified in *NCHRP Report 350.* The distance from the ground, around the bumper, and across the hood to the base of the windshield of the Geo Metro is approximately 1.6 m (5.25 ft). Therefore, if the sign panel mounting height can be maintained at or below a height of 1.6 m (5.25 ft) in conjunction with yielding barricade supports, there is a reasonable probability that windshield contact can be avoided. The top edge of a 0.8-m × 1.5-m (2.5-ft × 5-ft) rectangular sign panel mounted 0.8 m (2.5 ft) above ground is

1.5 m (5 ft), which happens to be flush with the top of the Type III barricade. When attached to tubular steel uprights, a sign at this height should not contact the windshield provided the uprights yield and wrap around the front of the vehicle. This mounting height also permits the sign panel to be attached to two barricade rails, which is desirable from a functional standpoint in terms of resisting wind loads and accommodating handling and transportation.

The diagonal of a 1.2-m × 1.2-m (4-ft × 4-ft) sign measures 1.7 m (5.6 ft). Thus, if a 1.2-m × 1.2-m (4-ft × 4-ft) sign is mounted in a diamond configuration at a 0.3-m (1-ft) mounting height (a practical minimum mounting height), the top of the sign panel will be 2.0 m (6.6 ft) above ground. Since the wraparound distance of a Geo Metro from the ground to the base of the windshield is approximately 1.6 m (5.25 ft), the top corner of the sign panel above the upper barricade rail will contact the windshield of the vehicle.

A 1.2-m × 1.2-m (4-ft × 4-ft) diamond-oriented sign panel mounted 0.3 m (1 ft) above ground constitutes a more critical condition than the 0.8-m × 1.5-m (2.5-ft × 5-ft) rectangular sign mounted 0.8 m (2.5 ft) above ground. Therefore, a successful test with the diamond-oriented sign panel should validate the use of the rectangular sign panel, but not vice versa. At the direction of the panel, the test matrix for barricades with signs included a test with a 1.2-m × 1.2-m (4-ft × 4-ft) diamond-oriented sign with the understanding that a successful outcome would negate the need to conduct a similar test of the same barricade with a 0.8-m × 1.5-m (2.5-ft × 5-ft) rectangular sign mounted at 0.8 m (2.5 ft).

As noted previously, steel-frame Type III barricades with skids and vertical uprights composed of square, perforated steel tubing have been successfully tested with both plastic and wooden horizontal rail elements. Plastic rails are lighter weight than wood, which makes the barricade a little easier to handle. Because they do not fracture and break apart like wood rails, plastic rails are sometimes reusable after an impact. Since the reflective sheeting adhered to the rails is a high-cost item, this reusability can make plastic more economical than wood from a life-cycle cost standpoint. Because plastic rails generally lack the stiffness to directly support a sign panel, the sign panel must be secured to vertical braces or barricade uprights to improve handling characteristics and provide the ability to withstand wind and other service loads.

The barricades with sign panel attachments tested under this project were evaluated with wooden rails. Wooden rails are sometimes preferred for their low cost, availability, ease of fabrication, and durability. Further, since wooden rails tend to be more critical from a crashworthiness standpoint because of their greater weight and propensity to fracture upon impact, a successful test with wooden rails should be sufficient for receiving approval of a similar design with lighter weight plastic rails. Because wooden rails tend to fracture on impact, the sign panel must be directly attached to vertical braces or barricade uprights to prevent the sign and fractured rails from rotating into the windshield of the impacting vehicle. Connection of the horizontal rails and sign panel to the vertical members was achieved with low-grade carriage bolts.

Design B1: Perforated Steel Uprights with Wooden Braces

The first design variation that uses square, perforated steel tubing for construction of the barricade frame is shown in Figure 6.1 for the 0.8-m × 1.5-m (2.5-ft × 5-ft) rectangular sign panel mounted 0.8 m (2.5 ft) above ground and in Figure 6.2 for the 1.2-m × 1.2-m (4-ft × 4-ft) diamond-oriented sign panels mounted 0.3 m (1 ft) above ground. The barricade design shown in Figure 6.1 and Figure 6.2 incorporates vertical braces manufactured from standard 51-mm × 102-mm (2-in × 4-in) dimensional lumber. The use of vertical braces is optional and is shown because it represents a more critical configuration for impact performance evaluation and provides added functionality to the system. Use of the vertical braces permits the rails and sign panel to be preassembled and then attached or detached from the barricade supports as a unit. This capability can assist with transportation, on-site erection, and site adaptability.

The horizontal rails and sign panel are attached to the wooden 51-mm × 102-mm (2-in × 4-in) vertical braces. This assembled unit is then bolted to the 38-mm (1½-in) square, perforated steel-tube uprights through the rails and sign panel. The uprights telescope inside a 44-mm (1¾-in) square, perforated steel-tube sleeve that is welded to 44-mm (1¾-in) square, perforated steel-tube skids. Site adaptability to roadside slopes is achieved by raising one of the uprights inside its sleeve. The height of the sleeve and distance between uprights determines the degree of slope that can be accommodated. For a support spacing of 1.4 m (4 ft, 7 in), a .3-m (1-ft) long sleeve can accommodate a 6:1 slope.

Design B2: Perforated Steel Uprights with Steel Braces

The second design variation is shown in Figure 6.3 for the 0.8-m × 1.5-m (2.5-ft × 5-ft) rectangular sign panel mounted 0.8 m (2.5 ft) above ground and in Figure 6.4 for the 1.2-m × 1.2-m (4-ft × 4-ft) diamond-oriented sign panels mounted 0.3 m (1 ft) above ground. This design option uses vertical braces fabricated from the same size perforated steel tubing used for the barricade uprights. The horizontal rails and sign panel are attached to these vertical braces. The difference between this design and the first barricade design alternatives is that the braces rather than the rails are bolted to the barricade uprights using existing holes in the perforated tubing. In other words, the assembled unit with rails and sign panel is attached to the barricade uprights through the braces. This process eliminates the need for pre-drilling or field drilling as many as 12 holes through the horizontal rails at a spacing that matches the existing holes in the perforated steel-tube uprights. Site adaptability for accommodating roadside slopes is achieved by raising or lowering the vertical braces with respect to the uprights. For a support spacing of 1.4 m (4 ft, 7 in) and a 6:1 roadside slope, the vertical brace on the downhill side of the barricade would extend 229 mm (9 in) above the upright.

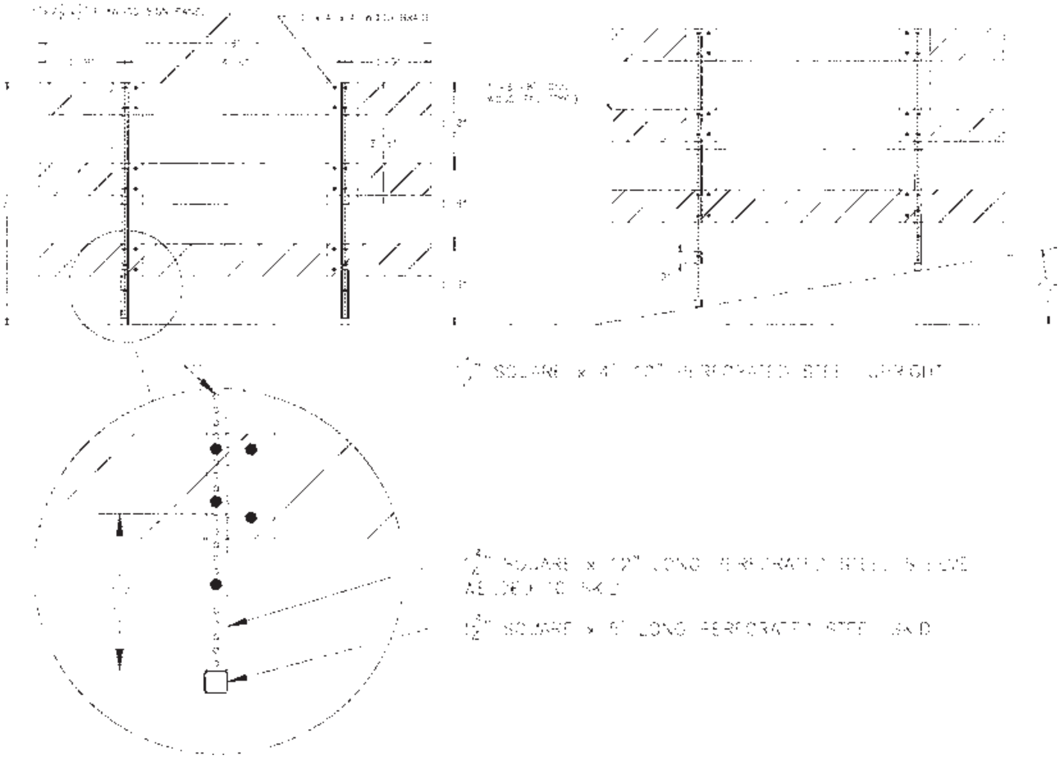


Figure 6.1. Perforated steel Type III barricade with wooden braces and telescoping base (sign mounted at 0.8 m [2.5 ft]).

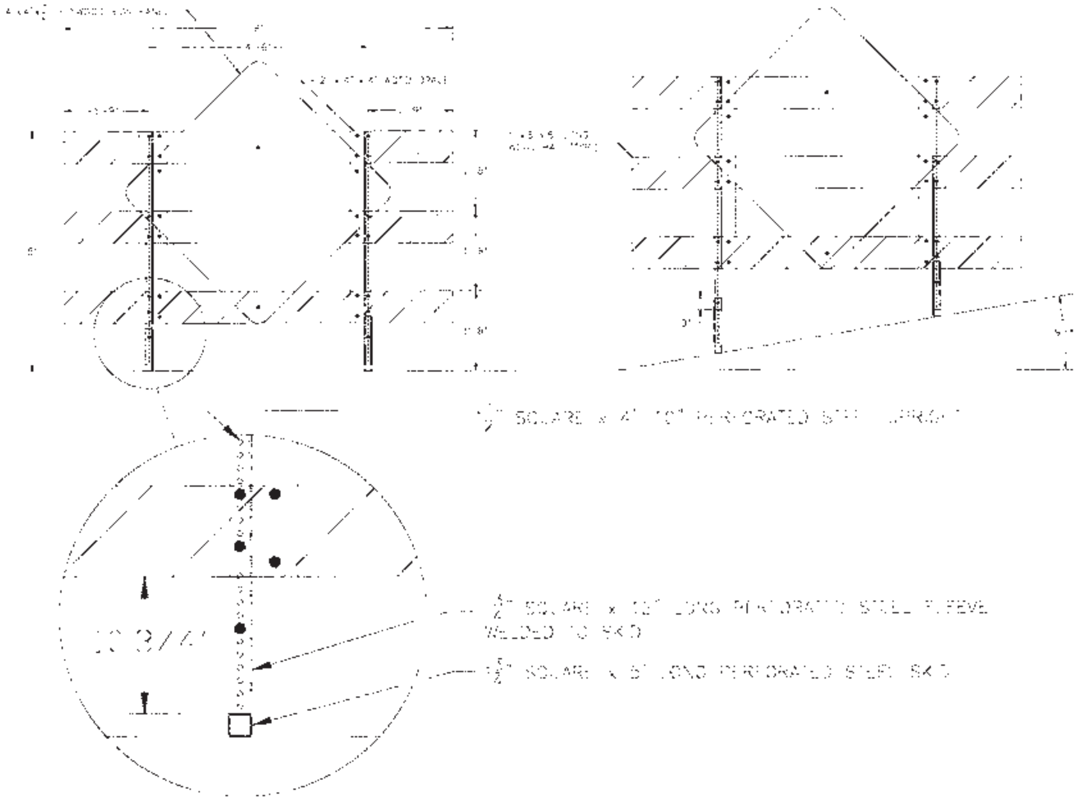


Figure 6.2. Perforated steel Type III barricade with wooden braces and telescoping base (sign mounted at 0.3 m [1 ft]).

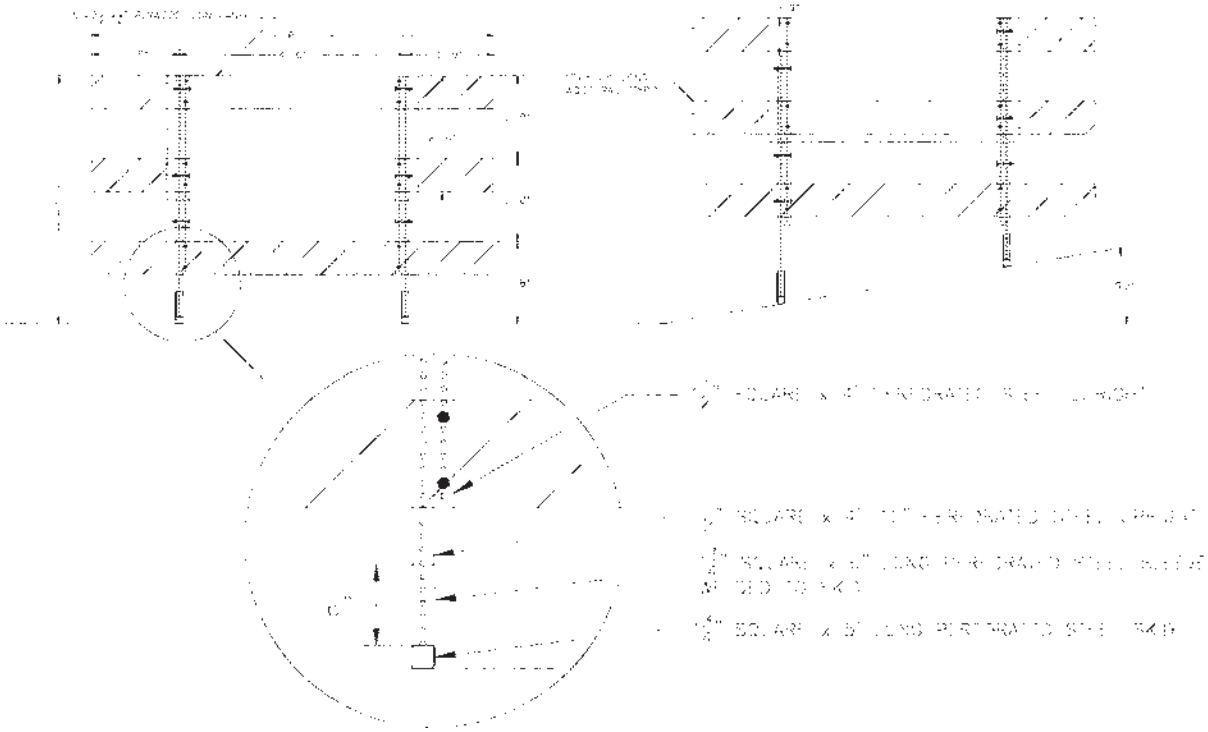


Figure 6.3. Perforated steel Type III barricade with steel braces and adjustable panel (sign mounted at 0.8 m [2.5 ft]).

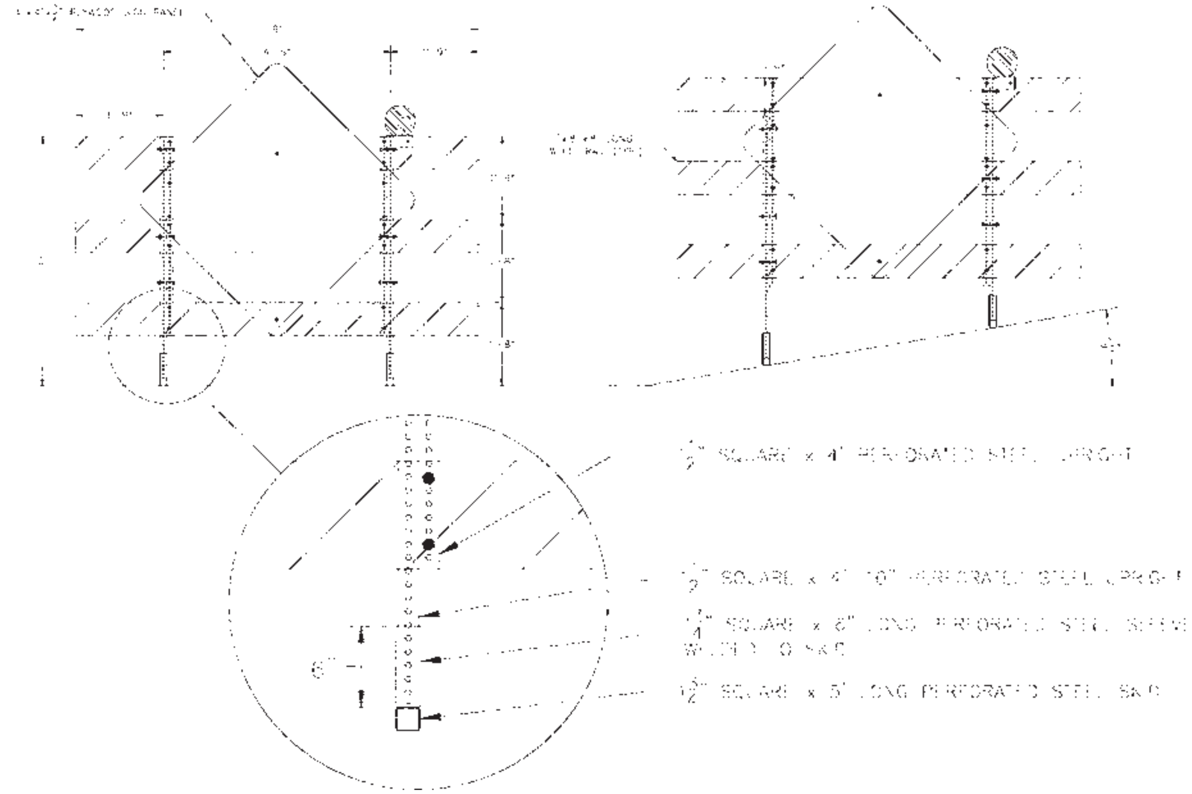


Figure 6.4. Perforated steel Type III barricade with steel braces and adjustable panel (sign mounted at 0.3 m [1 ft]).

Since the slope adjustment is accommodated through height adjustment of the vertical braces rather than telescoping the upright in a sleeve, the height of the 44-mm (1¾-in) square, perforated steel-tube sleeve is reduced to 152 mm (6 in).

6.2.2 Hollow-Profile Plastic

Another cost-effective, crashworthy option for Type III barricades incorporates HPPL for the barricade uprights. Other than replacing the 102-mm × 102-mm (4-in × 4-in) wooden uprights with similarly sized HPPL members, the basic wooden barricade construction used by many state DOTs is unchanged. Such designs have been successfully tested using HPPL uprights manufactured from a variety of materials such as PVC and HDPE, and horizontal rails manufactured from both HPPL and wood.

The HPPL supports are significantly lighter than dimensional lumber of a comparable size and can be cut and fastened in a manner similar to wooden materials. In the event the vertical supports fracture or become detached from the barricade base during an impact, the reduced mass decreases the propensity for penetration of the windshield.

Figure 6.5 and Figure 6.6 present a Type III barricade system with HPPL uprights that has been adapted for use with an attached sign panel. The system in Figure 6.5 incorporates a 0.8-m × 1.5-m (2.5-ft × 5-ft) rectangular sign panel mounted 0.8 m (2.5 ft) above ground, while Figure 6.6 shows the system with a 1.2-m × 1.2-m (4-ft × 4-ft) diamond-oriented sign panel mounted 0.3 m (1 ft) above ground. The researchers recommend using HDPE instead of PVC material for the barricade uprights in this application. PVC is more brittle and tends to fracture more readily under impact loads. If the uprights fracture in a brittle manner, the sign panel and rails could rotate into the windshield in a manner analogous to that observed with wooden barricades. The added mass of the sign panel significantly increases the probability that this contact would result in some degree of windshield penetration. The HDPE is more ductile than PVC and should prevent or significantly delay fracture or detachment of the supports from the barricade base, thereby reducing the potential for occupant compartment intrusion.

The designs shown in Figure 6.5 and Figure 6.6 incorporate wooden rails. Alternatively, plastic rails manufactured from HPPL could be used. Wooden rails were recommended for testing because they constitute a more critical configuration from a crashworthiness standpoint because of their greater weight. A successful test with wooden rails should be sufficient for receiving approval of a similar design with lighter weight plastic rails.

As with the steel-frame barricade designs, the horizontal rails and sign panel are attached to the vertical braces. The vertical braces are fabricated from the same size HPPL used for the barricade uprights. Connection of the horizontal panels and sign panel to the vertical members can be achieved with low-grade carriage bolts. Oversize washers are recommended where bolting against the HPPL members to provide further resistance against bolt pullout during impact or repeated handling. As with the steel-frame barricade shown in Figure 6.3 and Figure 6.4, the assembled unit with rails and sign panel is attached to the barricade by bolting the HPPL vertical braces to the HPPL uprights. This bolting requires pre-drilling or field drilling holes in both the braces and uprights.

Site adaptability for accommodating roadside slopes is achieved by raising or lowering the vertical braces with respect to the barricade uprights. For a support spacing of 1.4 m (4 ft, 7 in) and a 6:1 roadside slope, the vertical brace on the downhill side of the barricade would extend 229 mm (9 in) above the barricade upright. The bolt holes in the vertical braces and uprights can be pre-drilled and reused from site to site. If the elevation requires that the braces be moved relative to the uprights to accommodate a slope, the location on the upright corresponding to the new location of the pre-drilled hole in the brace can be marked and field drilled. This process may eventually require the replacement of a barricade upright, but the other barricade components should be reusable

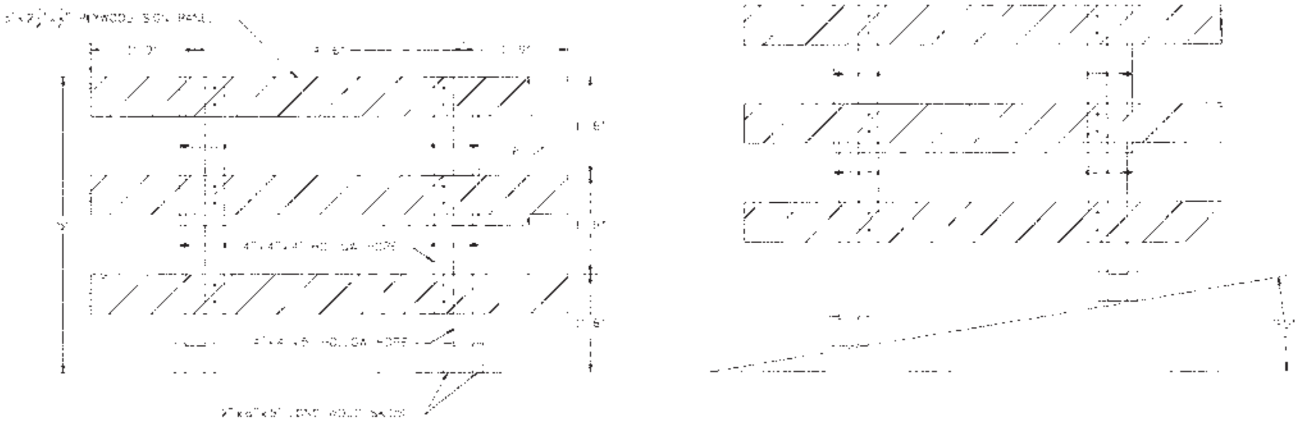


Figure 6.5. Hollow-HDPE/wooden Type III barricade (sign mounted at 0.8 m [2.5 ft]).

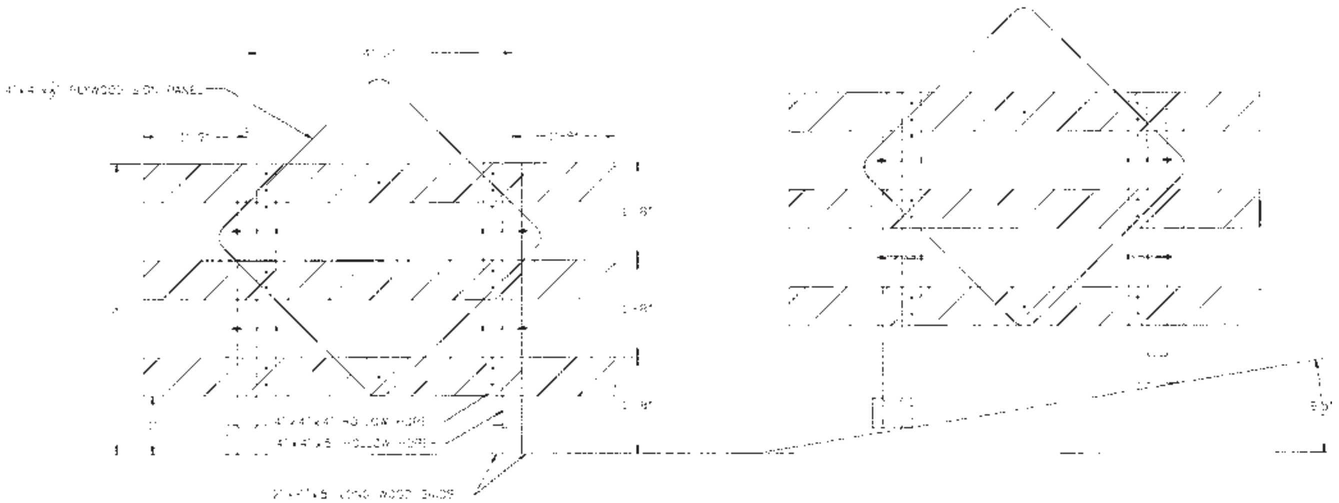


Figure 6.6. Hollow-HDPE/wooden Type III barricade (sign mounted at 0.3 m [1 ft]).

for an indefinite period of time. An advantage to this design is that, other than the uprights and braces, all of the barricade components (rail, skids, sign panel, etc.) are fabricated from commonly available wooden materials.

6.3 FUNCTIONAL CHARACTERISTICS

Per the objectives of the project, an effort was made to develop barricade systems with sign attachments that possess good functional characteristics. As previously described in Chapter 4, a rating scheme that assessed wind resistance, durability, handling, fabrication/repair, and site adaptability was developed to help evaluate the functional performance of barricade systems designed for this phase of the project.

The ratings for the three barricade systems with sign attachment are provided in Table 6.1. The steel and wood systems are generally rated high in each category and, thus, have an overall rating of high as well.

The system incorporating the HPPL uprights and braces has average to high ratings in each category. The durability rating of average is based on uncertainty regarding the long-term susceptibility of these materials to degradation from environmental attack (e.g., exposure to ultraviolet rays). However, manufacturers of HPPL products claim to address these issues in the manufacturing process and often warrant the life of their products. The handling rating of average is based on the overall weight of the system and its overall effect on handling, transporting, and erecting the device. With a high percentage of wooden components, the weight of the system can be substantial. While the system is designed to accommodate placement on slopes, the rating of average on site adaptability stems from the need to field drill some holes in the HPPL uprights to accommodate the change in height of one of the vertical braces. Some of the perceived limitations of this design (e.g., greater weight) may be offset by the low cost and availability of the wooden components.

6.4 PRIORITIZATION

The project panel reviewed and prioritized the three alternatives for barricade systems with attached sign panels. A weighted average was used to prioritize the designs for testing. Three points were allocated for a first place vote, two for second place, and one for third place. The points allocated for each device by each panel member were then totaled to establish a ranking. The device with the greatest number of points was considered to be the one with the highest priority. The weighted ranking analysis resulted in the following priority:

TABLE 6.1 Functional assessment of proposed barricades with sign attachments

Device Description*					Functional Performance					
Figure No.	Frame	Rails	Sign	Bracing	Wind Resist.	Durability	Handling	Fabricate/ Repair	Site Adapt.	Overall Rating
6.1, 6.2	Perforated steel	Wood or plastic	Wood or aluminum	Wood or perforated steel	High	High	High	High	High	**High**
6.3, 6.4	Perforated steel	Wood or plastic	Wood or aluminum	Perforated steel	High	High	High	High	High	**High**
6.5, 6.6	HPPL	Wood or plastic	Wood or aluminum	HPPL	High	Average	Average	High	Average	**Average**

* All mounting heights 0.8 m (2.5 ft)

1. Design B2: perforated steel uprights with steel braces (13 points)
2. Design B1: perforated steel uprights with wooden braces (12 points)
3. Design B3: HDPE uprights and braces (11 points)

Several panel members recommended testing all three designs. Based on the weighted rankings, the steel-frame designs were given initial priority in the testing program. However, because of the narrow margin of difference among the systems, the HDPE design was also tested. Details of the testing program for barricades with sign attachment are provided in the following sections.

6.5 FULL-SCALE CRASH TESTING

All crash test and data analysis procedures were in accordance with the guidelines presented in *NCHRP Report 350.* Appendix C presents brief descriptions of these procedures. Additionally, the FHWA windshield damage classification criteria were followed in assessing damage to the windshield.

The tests followed the impact conditions of test designation 3-71 of *NCHRP Report 350.* Test 3-71 involves an 820-kg (1808-lb) passenger car impacting the device at a speed of 100 km/h (62 mi/h). This test is considered to be the critical one for work-zone devices because the propensity for occupant compartment intrusion increases at higher speeds. A 50th-percentile male anthropomorphic dummy was placed in the driver's position and restrained with standard equipment lap and shoulder belts, thus increasing the test inertial weight of the vehicle to approximately 900 kg (1984 lb).

As discussed in Section 2.4, FHWA requires the impact performance of temporary work-zone sign supports to be evaluated for two different orientations. Two separate sign support systems were offset 6 m (15 ft) from one another and placed at different orientations with respect to the path of the vehicle. The first support was oriented perpendicular to the vehicle path for a head-on impact at 0 degree. The second support, placed behind the first sign support, was oriented parallel to the vehicle path for an end-on impact at 90 degrees. The supports were placed on soil because that was considered to represent a more critical condition than if they were placed on a paved surface.

6.5.1 Test 1

Test Article

Test details of Design B2, described previously, are shown in Figure 6.7. A 152-mm (6-in) long vertical sleeve fabricated from 44-mm ($1\frac{3}{4}$-in) square, perforated steel tubing was welded to the center of each 1.5-m (5-ft) long skid fabricated from the same material. A 38-mm ($1\frac{1}{2}$-in) square × 1.48-m (4-ft, 10-in) long perforated steel upright was inserted into the sleeves and connected using a 9.5 mm ($\frac{3}{8}$-in) diameter through bolt. Three 25-mm × 203-mm × 2.4-m (1-in × 8-in × 8-ft) wooden rails were bolted to 38-mm ($1\frac{1}{2}$-in) square × 1.2-m (4-ft) long perforated steel braces spaced 1.3 m (4 ft, 3 in) apart. The top of the upper rail was flush with the ends of the braces, and the center and lower rails were spaced 0.51 m (1 ft-8 in) apart from each other. A 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × $\frac{1}{2}$-in) plywood sign panel was attached to the face of the rails in a diamond orientation. The bottom corner of the sign panel was mounted flush with the bottom edge of the lower rail, and the top of the sign panel extended approximately 0.51 m (1 ft, 8 in) above the top edge of the upper rail, or 2.0 m (6 ft, 8 in) above ground. Given the wraparound distance of a Geo Metro is approximately 1.6 m (5 ft, 3 in), contact between the sign panel and windshield of the vehicle is expected as the barricade wraps around the front end of the vehicle during a head-on impact.

Because wooden rails tend to fracture on impact, direct attachment of the sign panel to the barricade support members is recommended to prevent the sign and fractured rails from independently rotating into the windshield of the impacting vehicle. For this test, the sign panel was bolted to each vertical brace in two locations and was additionally bolted to the center of the upper and lower rails. The assembled rails and sign panel were subsequently attached to the barricade frame by bolting the vertical braces to the inside edges of the uprights.

For the crash test, the barricade was placed on level terrain and the top rail was flush with the top of the uprights. As depicted in Figure 6.7, the barricade can be adjusted for placement on uneven terrain by extending the height of one of the vertical braces relative to one of the uprights.

A Type A (low-intensity flashing) warning light was cantilevered off the top of the right-side vertical brace using a 216-mm × 76-mm × 6-mm ($8\frac{1}{2}$-in × 3-in × $\frac{1}{4}$-in) steel connector plate. The weight of the warning light was 1.8 kg (4 lb). It was a self-contained unit composed of battery, casing, and light/lens. The height of the unit placed the light/lens just above the top edge of the upper barricade rail.

Two barricades were placed in the path of the vehicle approximately 6 m (19.7 ft) apart from one another—one perpendicular to the path of the vehicle and one parallel to the path of the vehicle. Two 9-kg (20-lb) sandbags were placed on the front and back of each skid for a total of eight sandbags per device. A photograph of the completed test installation is shown in Figure 6.8.

In most previous barricade testing, the barricades were constructed with a narrow (e.g., 1.2-m [4-ft]) width to enable the vehicle to impact both uprights, thereby maximizing the potential for the upper portion of the barricade to rotate into the windshield of the impacting vehicle. The barricades evaluated under this project were 2.4 m (8 ft) wide. To prevent the wooden rails from fracturing and releasing the sign panel, the corners of the sign panel were bolted directly to the vertical braces which, in turn, were bolted to the uprights. The spacing of the uprights was, thus, dictated by the width of the sign panel. For the testing, the uprights were spaced 1.4 m (4 ft, 7 in) apart and the barricade rails extended 0.5 m (1 ft, 9 in) beyond each upright for a total barricade width of 2.4 m (8 ft).

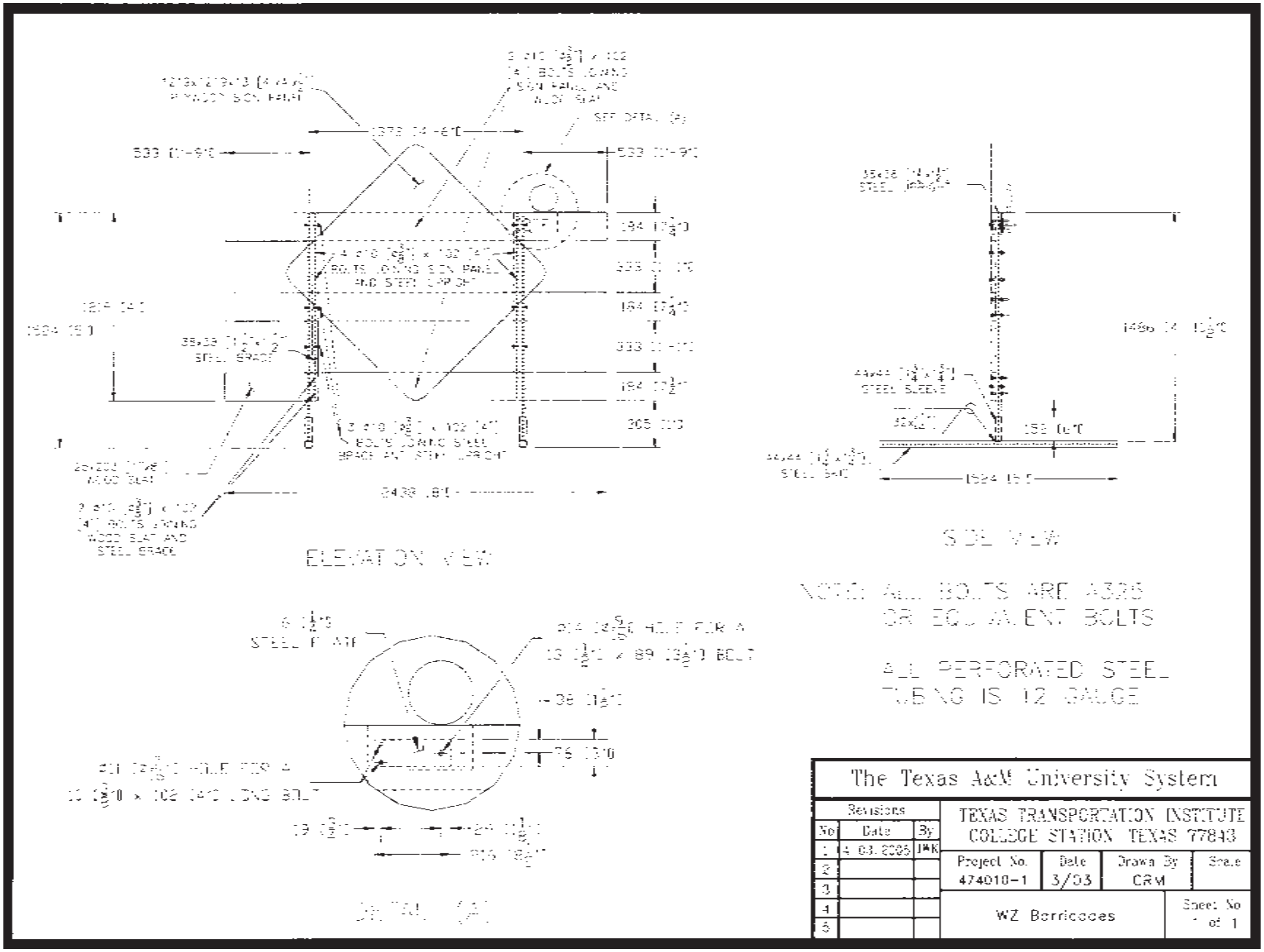


Figure 6.7. Details of the barricade with diamond-oriented sign used in Test 1.

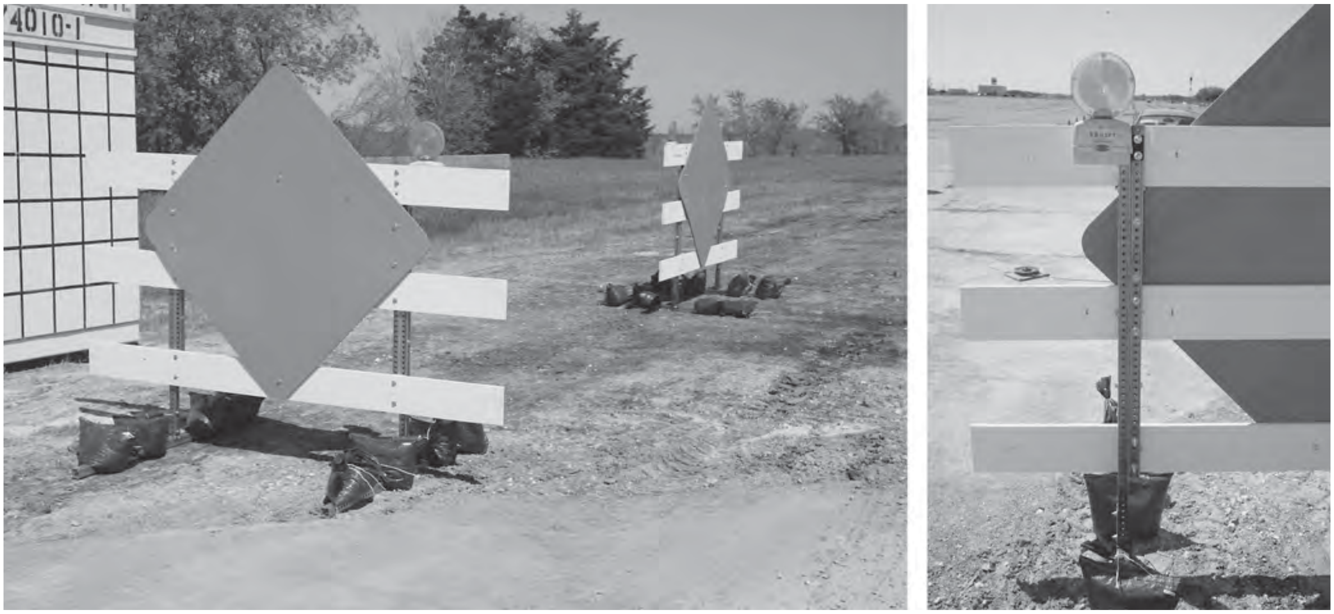


Figure 6.8. Barricade with diamond-oriented sign used for Test 1.

The researchers identified two scenarios for the head-on impact into this barricade design—one with the centerline of the vehicle aligned with the center of the barricade, and one with the vehicle centerline offset from the center of the barricade to engage one of the two uprights. The centered impact is designed to evaluate the interaction of the sign panel and upper barricade members with the windshield of the impacting vehicle. Because of its taller height, the 1.2-m × 1.2-m (4-ft × 4-ft) diamond-oriented sign panel was considered more critical (i.e., provided more potential for windshield contact and damage) than the rectangular 1.5-m × 0.8-m (5-ft × 2.5-ft) sign panel.

The width of the small passenger car typically used to test and evaluate work-zone traffic control devices is approximately 1.45 m (4 ft, 9 in). Therefore, there is little or no interaction between the vehicle and the warning light attachment during the centered impact. The offset impact is intended to evaluate the interaction of the warning light attachment with the windshield of the impacting vehicle.

Test Vehicle

A 1997 Geo Metro, shown in Figure 6.9, was used for the crash test. Test inertia weight of the vehicle was 820 kg (1808 lb), and its gross static weight was 897 kg (1978 lb). The height to the lower edge of the vehicle front bumper was 400 mm (15.7 in), and the height to the upper edge of the front bumper was 525 mm (20.7 in). Additional dimensions and information on the vehicle are given in Appendix D, Figure D.1. The vehicle was directed into the installation using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just before impact.

Figure 6.9. Vehicle before Test 1.

Test Description

An 897-kg (1978-lb) passenger car, traveling at a speed of 98.6 km/h (61.3 mi/h), impacted the first barricade head-on at 0 degrees with the centerline of the vehicle aligned with the centerline of the barricade. Shortly after impact the barricade began to move, and at 0.005 s, the bottom horizontal rail fractured. The upper portion of the barricade wrapped around the front end of the vehicle, rotating the top of the sign panel toward the windshield. The top of the sign panel contacted the windshield at 0.049 s, and the top and middle horizontal rails fractured just inside the left upright at 0.056 s. At 0.058 s, the top horizontal rail fractured at the right upright. At 0.061 s, the middle rail fractured at the right upright, and the warning light contacted the right side mirror, which separated from the vehicle. At 0.126 s, the vehicle lost contact with the sign panel and the vehicle was traveling at a speed of 84.6 km/h (52.6 mi/h).

At 0.254 s, the vehicle contacted the second barricade end-on at a speed of 83.6 km/h (51.9 mi/h) with the centerline of the vehicle aligned with the barricade. At 0.327 s, the second barricade pushed the first barricade into the windshield. The vehicle fractured the lower horizontal rail and contacted the left upright of the second barricade. The perforated steel tube upright deformed around the front of the vehicle, and the end of the middle horizontal rail rotated into the hood of the vehicle. At 0.628 s, the vehicle exited the view of the high-speed cameras at a speed of 70.7 km/h (43.9 mi/h) with the barricades being pushed in front of the vehicle. Brakes on the vehicle were applied at 2.0 s after impact, and the vehicle subsequently came to rest 64.8 m (212.6 ft) downstream of impact and 4.6 m (15.1 ft) to the left of centerline of impact. Although the first barricade maintained contact with the windshield during contact with the second barricade, the second barricade only contacted the hood of the vehicle and had no interaction with the windshield area. Thus, the second impact was considered to be a valid evaluation of the performance of the barricade when struck end-on. Sequential photographs of the test period are in Appendix E, Figure E.1.

Test Results

Both barricades readily activated as designed by yielding and fracturing. Debris was scattered over an area 48.8 m (160.1 ft) long and 9.9 m (32.5 ft) to the left and 2.3 m (7.5 ft) to the right. The largest debris fragment weighed 23 kg (50.7 lb). The warning lights remained attached to the vertical braces.

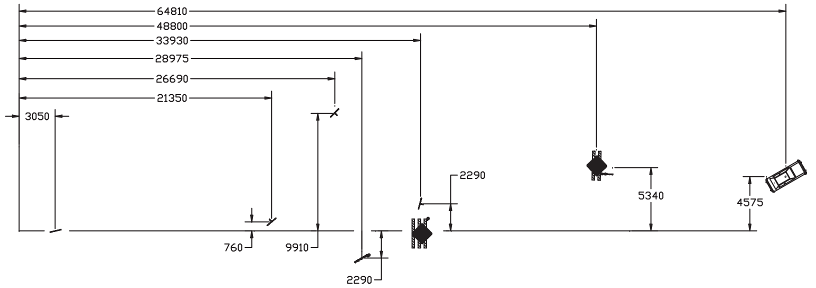
The vehicle remained upright throughout and after the crash period. Damage to the vehicle is shown in Figure 6.10. The front bumper, hood, radiator, and radiator support were damaged, and the right side A-post was dented. Maximum exterior crush was 250 mm (9.8 in) in the center front of the vehicle. The windshield was shattered and deformed inward 50 mm (2.0 in) (a combination of Case 5 and Case 6 of the FHWA windshield damage classification criteria). There were no holes or tears in the windshield, nor was the windshield separated from its frame.

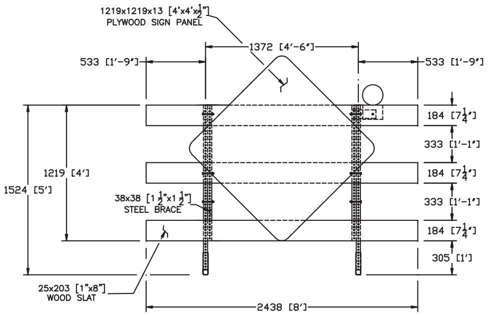
Figure 6.10. Damage to vehicle after Test 1.

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 3.8 m/s (12.5 ft/s) at 0.217 s, the highest 0.010-s occupant ridedown acceleration was –7.8 g’s from 0.286 s to 0.296 s, and the maximum 0.050-s average acceleration was –5.0 g’s between 0.018 s and 0.068 s. In the lateral direction, the occupant impact velocity was 0.3 m/s (1.0 ft/s) at 0.217 s, the highest 0.010-s occupant ridedown acceleration was –2.1 g’s from 0.287 s to 0.297 s, and the maximum 0.050-s average was –0.9 g’s between 0.271 s and 0.321 s. These data and other pertinent information from the test are summarized in Figure 6.11. Vehicle angular displacements and accelerations versus time traces are presented in Appendix F, Figures F.1 through F.7.

A summary of the test evaluation is presented in Table 6.2. The 50-mm (2.0-in) deformation of the windshield is considered to be marginally acceptable in terms of the FHWA windshield damage classification criteria. Therefore, since the barricade met all other relevant evaluation criteria of *NCHRP Report 350,* the perforated steel-tube barricade with wooden rails and 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in)

0.000 s | 0.049 s | 0.172 s | 0.492 s





General Information	
Test Agency	Texas Transportation Institute
Test No.	474010-1
Date	03-31-2003
Test Article	
Type	Type III Barricade
Name	Type III Barricade w/Diamond Sign
Installation Height, m (ft)	1.5 (5.0)
Material or Key Elements	Three wood barricade rails bolted to perforated steel braces
Soil Type and Condition	Native Soil, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	1997 Geo Metro
Mass, kg	
Curb	798
Test Inertial	820
Dummy	77
Gross Static	897

Impact Conditions	
Angle, deg	0 & 90
Speed, km/h (mi/h) @ 0 deg	98.6 (61.3)
Speed, km/h (mi/h) @ 90 deg	83.6 (51.9)
Exit Conditions	
Speed, km/h (mi/h)	70.7 (43.9)
Occupant Risk Values	
Impact Velocity, m/s (ft/s)	
Longitudinal	3.8 (12.5)
Lateral	0.3 (1.0)
THIV, km/h	13.6
Ridedown Accelerations, g's	
Longitudinal	-7.8
Lateral	-2.1
PHD, g's	8.0
ASI	0.43
Max. 0.050-s Average, g's	
Longitudinal	-5.0
Lateral	-0.9
Vertical	-2.1

Test Article Debris Pattern	
Length, m (ft)	48.8 (160.1)
Width, m (ft)	
Left	9.9 (32.5)
Right	2.3 (7.5)
Vehicle Damage	
Exterior	
VDS	12FD2
CDC	12FDAW2
Max. Exterior Vehicle Crush, mm (in)	250 (9.8)
Interior	
OCDI	FS0000000
Max. Occupant Compartment Deformation, mm (in)	50 (2.0) (windshield)
Post-Impact Behavior (during 1.0 sec after impact)	
Max. Yaw Angle, deg	-5
Max. Pitch Angle, deg	4
Max. Roll Angle, deg	5

Figure 6.11. Summary of results for Test 1.

TABLE 6.2 Performance evaluation summary for Test 1

Test Agency: Texas Transportation Institute Test No.: 474010-1 Test Date: 03/31/2003

<table>
<tr><th colspan="4"><i>NCHRP Report 350</i> Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td colspan="6">Structural Adequacy</td></tr>
<tr><td><i>B.</i></td><td colspan="3"><i>The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</i></td><td>Both barricades readily activated as designed by yielding and fracturing.</td><td>Pass</td></tr>
<tr><td colspan="6">Occupant Risk</td></tr>
<tr><td><i>D.</i></td><td colspan="3"><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. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</i></td><td>Debris was scattered along the vehicle path. The largest debris fragment weighed 23 kg (50.7 lb). The windshield was shattered and deformed inward 50 mm (2 in) (FHWA Case 5 and 6). There were no holes or tears in the windshield, nor was the windshield separated from its frame. There was no other measurable occupant compartment deformation.</td><td>Marginal</td></tr>
<tr><td><i>E.</i></td><td colspan="3"><i>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.</i></td><td>The driver's vision was not blocked.</td><td>Pass</td></tr>
<tr><td><i>F.</i></td><td colspan="3"><i>The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</i></td><td>The vehicle remained upright throughout and after the crash period.</td><td>Pass</td></tr>
<tr><td rowspan="4"><i>H.</i></td><td colspan="3"><i>Occupant impact velocities should satisfy the following:</i></td><td rowspan="4">Longitudinal occupant impact velocity was 3.8 m/s (12.5 ft/s).</td><td rowspan="4">Pass</td></tr>
<tr><td colspan="3"><i>Occupant Velocity Limits (m/s)</i></td></tr>
<tr><td><i>Component</i></td><td><i>Preferred</i></td><td><i>Maximum</i></td></tr>
<tr><td><i>Longitudinal</i></td><td><i>3</i></td><td><i>5</i></td></tr>
<tr><td rowspan="4"><i>I.</i></td><td colspan="3"><i>Occupant ridedown accelerations should satisfy the following:</i></td><td rowspan="4">Longitudinal ridedown acceleration was -7.8 g's, and lateral ridedown acceleration was -2.1 g's.</td><td rowspan="4">Pass</td></tr>
<tr><td colspan="3"><i>Occupant Ridedown Acceleration Limits (g's)</i></td></tr>
<tr><td><i>Component</i></td><td><i>Preferred</i></td><td><i>Maximum</i></td></tr>
<tr><td><i>Longitudinal and lateral</i></td><td><i>15</i></td><td><i>20</i></td></tr>
<tr><td colspan="6">Vehicle Trajectory</td></tr>
<tr><td><i>K.</i></td><td colspan="3"><i>After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</i></td><td>The vehicle continued on a straightforward path all along the trajectory path and did not intrude into adjacent lanes.</td><td>Pass*</td></tr>
<tr><td><i>N.</i></td><td colspan="3"><i>Vehicle trajectory behind the test article is acceptable.</i></td><td>The vehicle came to rest behind the test articles.</td><td>Pass</td></tr>
</table>

*Criterion K preferable, not required.

plywood sign panel mounted 0.3 m (1 ft) above ground is considered to be marginally acceptable.

Discussion

Because the taller 1.2-m × 1.2-m (4-ft × 4-ft) diamond-oriented sign panel constitutes a more critical condition than the 0.8-m × 1.5-m (2.5 ft × 5 ft) rectangular sign, the successful test with the diamond-oriented sign panel is considered sufficient for approving the use of the rectangular sign panel. The barricade that was tested incorporated wooden rails fabricated from dimensional lumber. Wooden rails are generally preferred for their low cost, availability, ease of fabrication, and durability. Because wooden rails are considered more critical from a crashworthiness standpoint due to their greater weight and propensity to fracture upon impact, the successful test with wooden rails is considered sufficient for approval of a similar barricade design with plastic rails of lighter weight.

The use of the vertical braces in the barricade framing is optional. The tested design incorporated the vertical braces because their presence represents a more critical configuration for impact performance evaluation. Use of the vertical braces may provide added functionality to the system. They permit the barricade rails and sign panel to be preassembled and then attached or detached from the barricade uprights as a unit. In absence of the vertical braces, the barricade rails and sign panel must be directly attached to the barricade uprights to prevent the sign and fractured rails from rotating into the windshield of the impacting vehicle.

6.5.2 Test 2

Test Article

A second test used an offset, head-on impact condition that aligned one of the barricade uprights with the center of the vehicle. For a wide barricade, this impact condition is more likely to occur in the field and is more conducive to evaluating the performance of a warning light attachment. As described previously, the spacing of the barricade uprights did not permit evaluation of the warning light attachment in the centered, head-on impact. Because a 1.2-m × 1.2-m (4-ft × 4-ft) sign panel was already found to be marginally acceptable in the previous test, the researchers decided to use a 0.8-m × 1.5-m × 13-mm (2.5-ft × 5-ft × ½-in) rectangular plywood sign panel in the offset test. The lower rectangular panel should induce less windshield damage, thereby making evaluation of any damage induced by the warning light more straightforward.

Details of the barricade design used in Test 2, which correspond to Design B1 previously described, are shown in Figure 6.12. The design uses vertical braces manufactured from standard 51-mm × 102-mm (2-in × 4-in) dimensional lumber. The horizontal rails and sign panel are attached to these vertical braces. The 0.8-m × 1.5-m × 13-mm (2.5-ft × 5-ft × ½-in) rectangular plywood sign panel was mounted at a height of 0.8 m (2.5 ft) above ground. This placed the top of the sign panel flush with the top edge of the upper horizontal rail. The assembled rail and sign panel unit was bolted to the 38-mm (1½-in) square, perforated steel-tube uprights through the rails and sign panel. The uprights, which were spaced 1.37 m (4.5 ft) apart, telescope inside a 44-mm (1¾-in) square, 248-mm (9¾-in) long, perforated steel-tube sleeve that was welded to 44-mm (1¾-in) square, perforated steel-tube skids. The longer tube sleeves permit telescoping of the uprights to provide adjustability for placement of the barricade on sloping terrain.

A Type A warning light with self-contained battery compartment was attached to the top of the left upright using a 216-mm × 76-mm × 6-mm (8½-in × 3-in × ¼-in) steel connector plate. The warning light was mounted such that the lens extended above the top of the upper rail. Two barricades were placed in the path of the vehicle approximately 6 m (19.7 ft) apart from one another—one perpendicular to the path of the vehicle and one parallel to the path of the vehicle. Two sandbags were placed on the front and back of each skid for a total of eight sandbags per device. A photograph of the completed test installation is shown in Figure 6.13.

Test Vehicle

A 1997 Geo Metro, shown in Figure 6.14, was used for the crash test. Test inertia weight of the vehicle was 820 kg (1808 lb), and its gross static weight was 897 kg (1978 lb). The height to the lower edge of the vehicle front bumper was 400 mm (15.7 in), and the height to the upper edge of the front bumper was 525 mm (20.7 in). Additional dimensions and information on the vehicle are given in Appendix D, Figure D.2. The vehicle was directed into the installation using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just before impact.

Test Description

An 897-kg (1808-lb) vehicle, traveling at a speed of 102.4 km/h (63.6 mi/h), impacted the first barricade head-on at 0 degree. The barricade was shifted 610 mm (24.0 in) to the right to align the left barricade upright with the centerline of the vehicle to allow a better opportunity for the vehicle to interact with the warning light that was mounted to the top of the left upright. Shortly after impact, the lower horizontal rail fractured, and, at 0.039 s, the center horizontal rail broke at the right upright. The offset impact condition caused some torsional energy to build up in the barricade. The left side of the barricade was being accelerated and rotated as a result of direct contact with the vehicle, while the right side of the barricade remained relatively stationary and upright. This differential movement and rotation caused the barricade to twist and store energy. As a result, the top horizontal rail and sign panel snapped off of the right upright at 0.058 s and subsequently contacted the windshield at 0.073 s. At 0.104 s, the right upright separated from its skid, and, at 0.113 s, this upright broke the right side door glass.

At 0.229 s, the vehicle contacted the second barricade end-on at a speed of 83.3 km/h (51.8 mi/h) with the centerline of the vehicle aligned with the end of the barricade. The second barricade began to move at 0.244 s and became airborne at 0.278 s. As in the previous test, the perforated steel-tube upright deformed around the front of the vehicle, and the end of the middle horizontal rail rotated into the hood of the vehicle. At 0.537 s, the vehicle exited the view of the high-speed cameras with the barricades riding along on the front of the vehicle. At the time, the vehicle was traveling at a speed of 76.7 km/h (47.7 mi/h). Brakes on the vehicle were applied at 2.0 s after impact, and the vehicle subsequently came to rest 74.4 m (244.1 ft) downstream of impact and 3.8 m (12.5 ft) to the right of centerline of impact. Although the first barricade was still in contact with the vehicle during the impact with the second barricade, the second barricade only contacted the hood of the vehicle and did not interact with the windshield area. Thus, the second impact was considered to be a valid evaluation of the performance of the barricade when struck end-on. Sequential photographs of the test period are shown in Appendix E, Figure E.2.

Test Results

Both barricades readily activated at impact by yielding and fracturing. Debris was scattered over an area 56.1 m (184.0 ft) long and 1.5 m (5.0 ft) to the left and 0.8 m (2.5 ft) to the right. The warning lights remained attached to their respective barricade uprights.

The vehicle remained upright throughout and after the crash period. Damage to the vehicle is shown in Figure 6.15. The front bumper, radiator, radiator support, hood, and right door were deformed. Maximum crush to the exterior of the vehicle was 285 mm (11.2 in) at the center front at bumper height. The glass in the right door was completely broken out, and

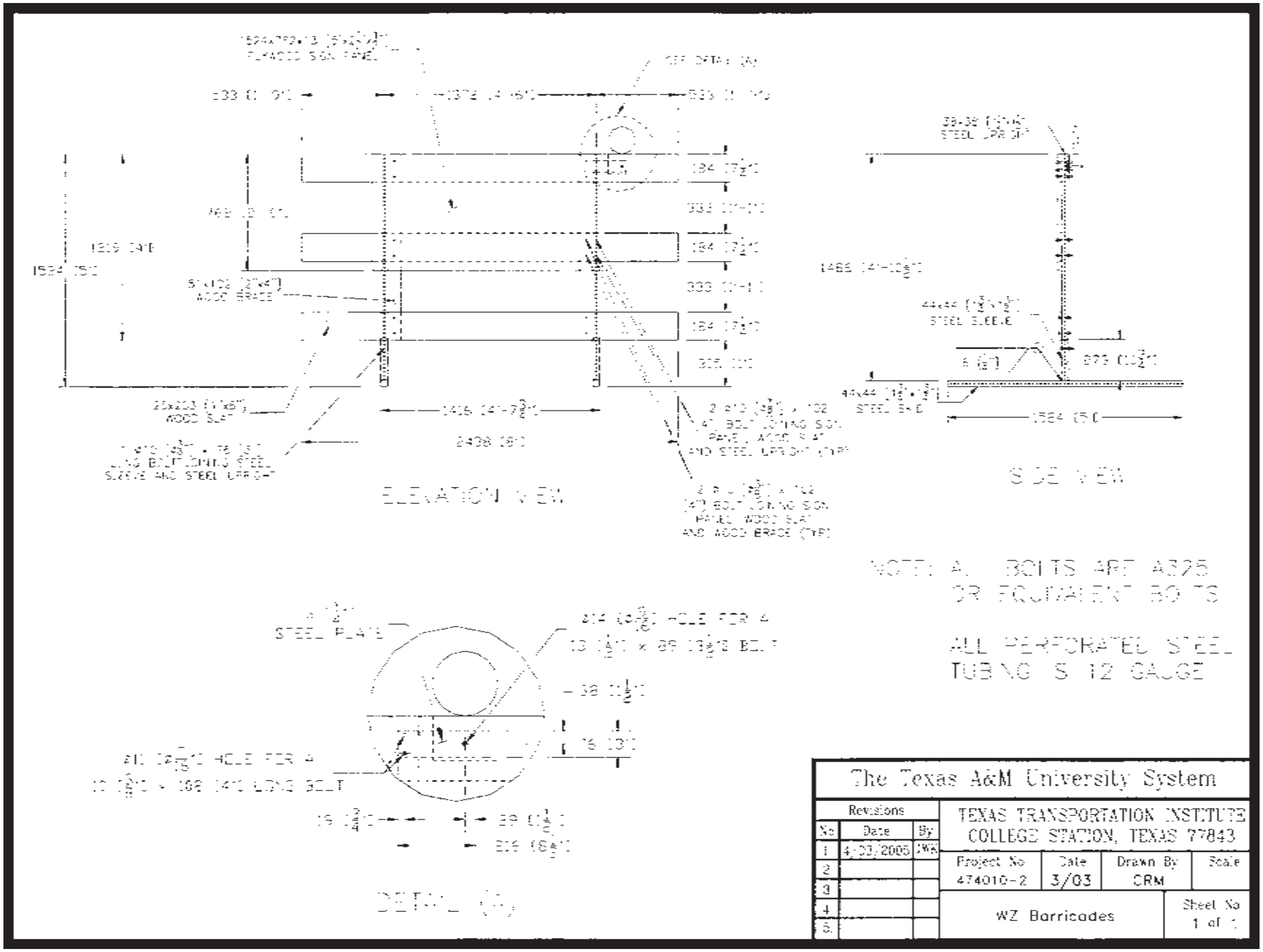


Figure 6.12. Details of the barricade with rectangular sign used in Test 2.

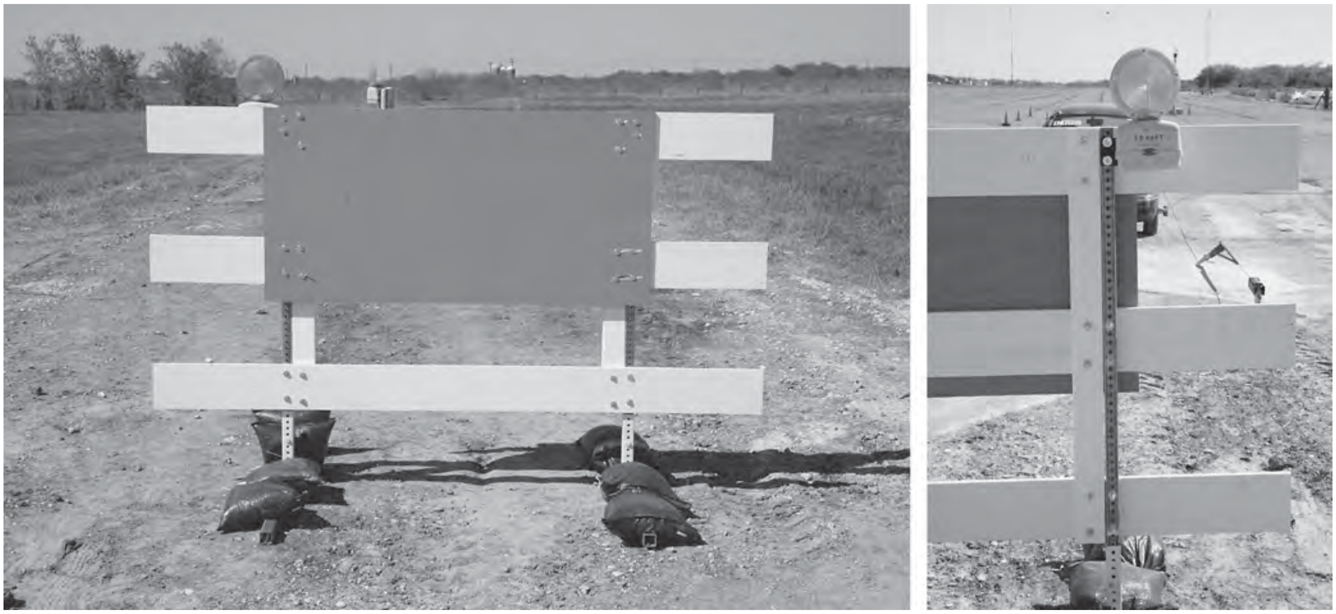


Figure 6.13. Barricade with rectangular sign used in Test 2.

Figure 6.14. Vehicle before Test 2.

Figure 6.15. Vehicle after Test 2.

there was a dent in the door measuring 300 mm × 200 mm × 25 mm deep (11.8 in by 7.5 in by 1 in). There was also a dent in the right side A-post with a very small hole in the windshield next to this dent. The windshield was shattered but intact on the right side with no damage to the left side. The windshield was also deformed inward 50 mm (2.0 in). There was no other measurable occupant compartment deformation.

Data from the accelerometer, located at the vehicle center of gravity, were digitized for evaluation of occupant risk and were computed as follows. In the longitudinal direction, the occupant impact velocity was 4.4 m/s (14.4 ft/s) at 0.286 s, the highest 0.010-s occupant ridedown acceleration was –4.1 g's from 0.286 s to 0.296 s, and the maximum 0.050-s average acceleration was –4.6 g's between 0.251 s and 0.301 s. In the lateral direction, the occupant impact velocity was 1.1 m/s (3.6 ft/s) at 0.286 s, the highest 0.010-s occupant ridedown acceleration was –1.7 g's from 0.344 s to 0.354 s, and the maximum 0.050-s average was 1.0 g between 1.595 s and 1.645 s. These data and other pertinent information from the test are summarized in Figure 6.16. Vehicle angular displacements and accelerations versus time traces are presented in Appendix F, Figures F.8 through F.14.

The test evaluation is summarized in Table 6.3. With the small hole in the windshield (FHWA windshield damage classification Case 1), the test is considered to be a failure.

Discussion

Although these test results apply only to this particular design, the failure mode observed in the test may apply to other barricades as well. Although barricades are often implemented with lengths of 2.4 m (8 ft) or greater, they are commonly tested with shorter lengths (e.g., 1.2 m [4 ft]) to enable the impacting vehicle to engage both supports. While the impact of both supports is indeed a critical condition for evaluating rotation of the barricade components into the windshield, the offset impact condition and resulting torsional failure mode may have been overlooked as another critical impact scenario. Indeed, because barricades in the field are more likely to be struck in an offset condition than directly along their centerline, this impact condition and failure mode may need to be more fully explored for barricades in general.

6.5.3 Test 3

Test Article

To address the problem observed in the previous test, a horizontal cross brace was added to the barricade to tie the two uprights together and give it more torsional rigidity. The brace, which was fabricated from 38-mm ($1\frac{1}{2}$-in) square, perforated steel tubing, was placed at a height of 457 mm (18 in) (behind and below the upper edge of the lower rail) to engage the vehicle bumper. The objective was to get the barricade to move together as a unit during an offset impact. Because of the low mounting height, the addition of the horizontal brace should not influence the impact performance for end-on impacts or centered, head-on impacts such as those in Test 1.

Details of the barricade design evaluated in Test 3 are shown in Figure 6.17. Other than the addition of the horizontal brace, the barricade system was identical to the design used in Test 2. A warning light with self-contained battery compartment was once again attached to the top of the left barricade upright using a steel plate connector. The warning light was mounted such that the lens extended above the top of the upper rail. Two barricades were placed in the path of the vehicle approximately 6 m (19.7 ft) apart from one another—one perpendicular to the path of the vehicle and one parallel to the path of the vehicle. Two sandbags were placed on the front and back of each skid for a total of eight sandbags per barricade. A photograph of the completed test installation is shown in Figure 6.18.

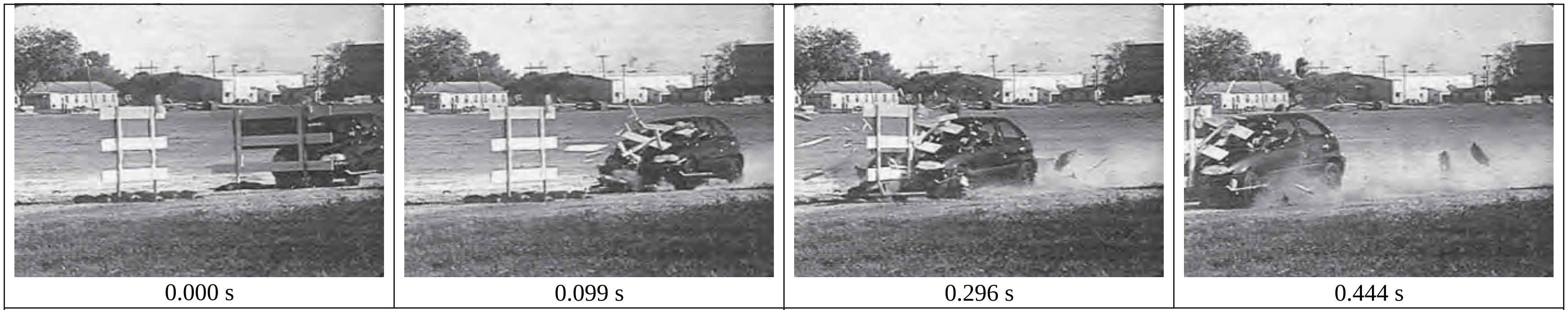
Test Vehicle

A 1997 Geo Metro, shown in Figure 6.19, was used for the crash test. Test inertia weight of the vehicle was 839 kg (1850 lb), and its gross static weight was 916 kg (2019 lb). The height to the lower edge of the vehicle front bumper was 400 mm (15.7 in), and the height to the upper edge of the front bumper was 525 mm (20.7 in). Additional dimensions and information on the vehicle are given in Appendix D, Figure D.3. The vehicle was directed into the installation using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just before impact.

Test Description

A 916-kg (2019-lb) vehicle, traveling at a speed of 100.2 km/h (62.3 mi/h), impacted the first barricade head-on at 0 degree. The barricade was shifted 610 mm (24.0 in) to the right to align the left barricade upright with the centerline of the vehicle. This offset impact condition was intended to evaluate the torsional failure mode of the barricade and provide a better opportunity for the vehicle to interact with the warning light that was mounted to the left support. Shortly after impact, the lower horizontal rail fractured, and, at 0.015 s, the lower horizontal rail separated from the right upright. The center horizontal rail fractured at the right upright at 0.044 s. The top horizontal rail and right upright contacted the windshield and the side of the vehicle at 0.065 s. The end of the rail that was cantilevered off the upright wrapped around the A-post and slapped and shattered the right door window. At 0.145 s, the vehicle lost contact with the first barricade, and the vehicle was traveling at a speed of 85.3 km/h (53.0 mi/h).

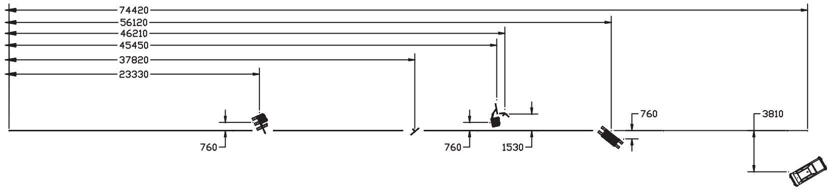
At 0.145 s, the vehicle contacted the second barricade end-on at a speed of 81.3 km/h (50.5 mi/h) with the centerline of the vehicle aligned with the end of the barricade. Shortly

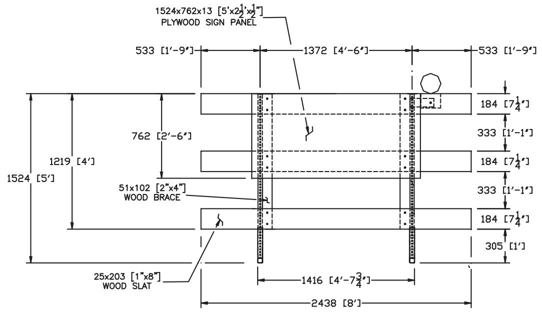

0.000 s

0.099 s

0.296 s

0.444 s





General Information	
Test Agency	Texas Transportation Institute
Test No.	474010-2
Date	03-31-2003
Test Article	
Type	Type III Barricade
Name	Type III Barricade w/Rectangular Sign
Installation Height, m (ft)	1.5 (5.0)
Material or Key Elements	Three wood barricade rails and braces bolted to perforated steel legs
Soil Type and Condition	Native Soil, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	1997 Geo Metro
Mass, kg (lb)	
Curb	861
Test Inertial	820
Dummy	77
Gross Static	897

Impact Conditions	
Angle, deg	0 & 90
Speed, km/h (mi/h) @ 0 deg	102.4 (63.6)
Speed, km/h (mi/h) @ 90 deg	83.3 (51.8)
Exit Conditions	
Speed, km/h (mi/h)	76.7 (47.7)
Occupant Risk Values	
Impact Velocity, m/s (ft/s)	
Longitudinal	4.4 (14.4)
Lateral	1.1 (3.6)
THIV, km/h	16.2
Ridedown Accelerations, g's	
Longitudinal	-4.1
Lateral	-1.7
PHD, g's	3.9
ASI	0.40
Max. 0.050-s Average, g's	
Longitudinal	-4.6
Lateral	1.0
Vertical	1.1

Test Article Debris Pattern	
Length, m (ft)	56.1 (184.0)
Width, m (ft)	
Left	1.5 (5.0)
Right	0.8 (2.5)
Vehicle Damage	
Exterior	
VDS	12FD2
CDC	12FDAW2
Max. Exterior Vehicle Crush, mm (in)	285 (11.2)
Interior	
OCDI	FS0000000
Max. Occupant Compartment Deformation, mm (in)	50 (2.0)
Post-Impact Behavior	(windshield)
(during 1.0 sec after impact)	
Max. Yaw Angle, deg	22
Max. Pitch Angle, deg	10
Max. Roll Angle, deg	-23

Figure 6.16. Summary of results for Test 2.

TABLE 6.3 Performance evaluation summary for Test 2

Test Agency: Texas Transportation Institute Test No.: 474010-2 Test Date: 03/31/2003

<table>
<tr><th><i>NCHRP Report 350</i> Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td>Structural Adequacy
B. <i>The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</i></td><td>Both barricades readily activated as designed by yielding and fracturing.</td><td>Pass</td></tr>
<tr><td>Occupant Risk
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. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</i></td><td>Debris was scattered along the vehicle path. The windshield had a very small hole (FHWA Case 1) and was shattered but intact on the right side. There was no damage to the left side of the windshield. The windshield was deformed inward 50 mm (2.0 in). There was no other measurable occupant compartment deformation.</td><td>Fail</td></tr>
<tr><td>E. <i>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.</i></td><td>The driver's vision was not blocked.</td><td>Pass</td></tr>
<tr><td>F. <i>The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</i></td><td>The vehicle remained upright throughout and after the crash period.</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 (m/s)</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>3</i></td><td><i>5</i></td></tr>
</table></td><td>Longitudinal occupant impact velocity was 4.4 m/s (14.4 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 (g's)</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</i></td><td><i>20</i></td></tr>
</table></td><td>Longitudinal ridedown acceleration was -4.1 g's, and lateral ridedown acceleration was -1.7 g's.</td><td>Pass</td></tr>
<tr><td>Vehicle Trajectory
K. <i>After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</i></td><td>The vehicle continued on a straightforward path all along the trajectory path and did not intrude into adjacent lanes.</td><td>Pass *</td></tr>
<tr><td>N. <i>Vehicle trajectory behind the test article is acceptable.</i></td><td>The vehicle came to rest behind the test articles.</td><td>Pass</td></tr>
</table>

*Criterion K preferable, not required.

after impact, the barricade began to move, and, at 0.286 s, the barricade became airborne. As in the previous tests, the perforated steel-tube upright deformed around the front of the vehicle, and the end of the barricade rotated into the hood of the vehicle without contacting the windshield. At 0.491 s, the vehicle lost contact with the second barricade while traveling at a speed of 75.7 km/h (47.0 mi/h). Brakes on the vehicle were applied at 3.9 s. The vehicle subsequently came to rest 87.7 m (287.8 ft) downstream of impact and 3.8 m (12.5 ft) to the left of centerline. Sequential photographs of the test period are shown in Appendix E, Figure E.3.

Test Results

Both barricades readily activated at impact by yielding and fracturing. Debris was scattered over an area 49.6 m (162.7 ft) long and 3.8 m (12.5 ft) to the left and 3.8 m (12.5 ft) to the right of the initial point of vehicle contact. The largest of the debris weighed 20 kg (44.1 lb). The warning light remained attached to both barricades and did not result in any occupant compartment deformation.

Damage to the vehicle is shown in Figure 6.20. The front bumper, radiator, radiator support, hood, right front quarter panel, right door, and right rear quarter panel were deformed. Maximum crush to the exterior of the vehicle was 260 mm (10.2 in) at the center front at bumper height. The glass in the right door was completely broken out by contact with one of the barricade rails, but high-speed film indicated there was no intrusion of the barricade rail into the passenger compartment. There were dents in the right side A-post and rocker panel. The windshield was shattered on the right side but was intact and not deformed inward (FHWA windshield damage classification Case 5). The left side of the windshield sustained only minimal damage. There was no measurable occupant compartment deformation. The vehicle remained upright during and after the crash period.

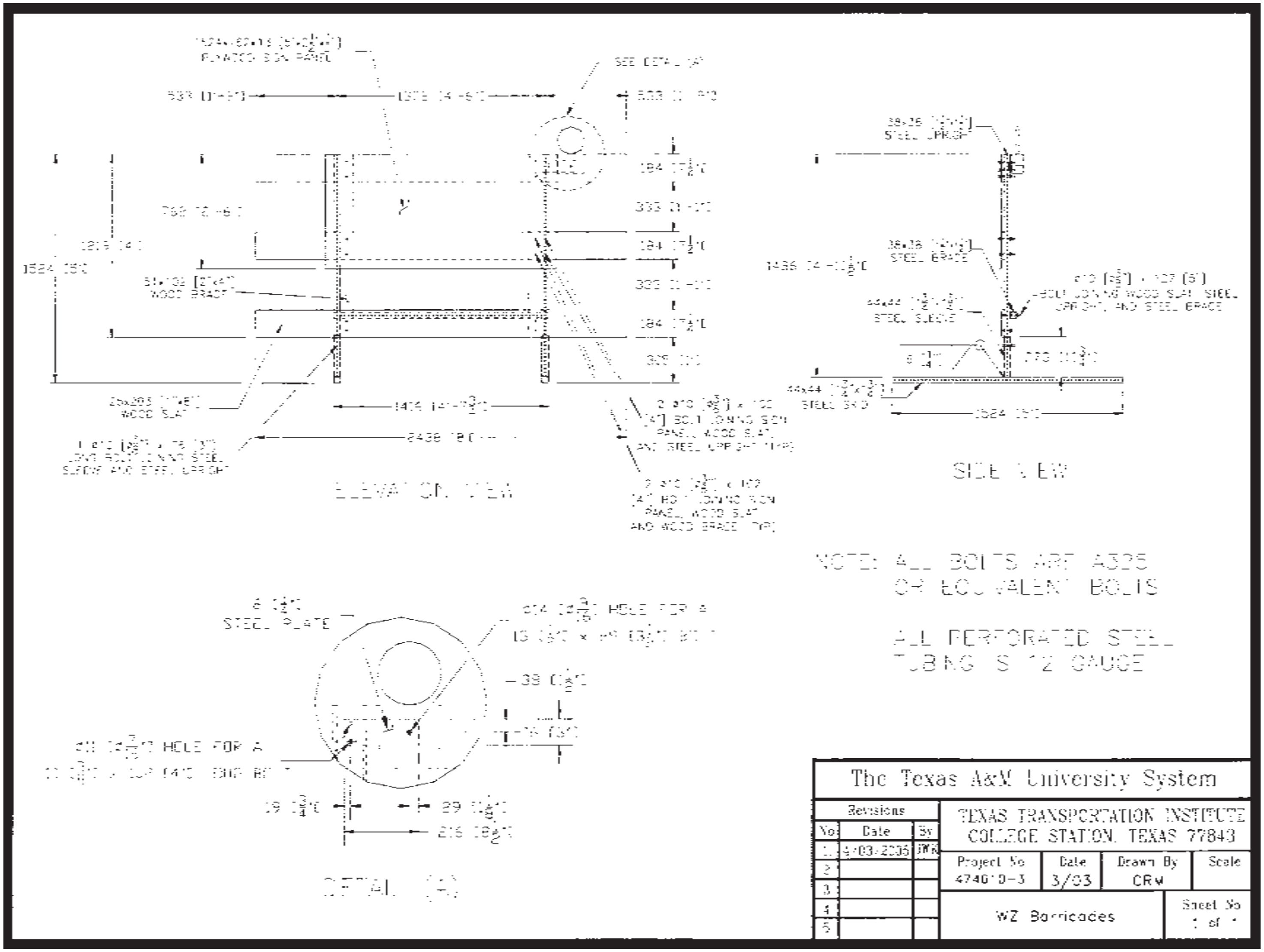


Figure 6.17. Details of the modified barricade with rectangular sign used in Test 3.

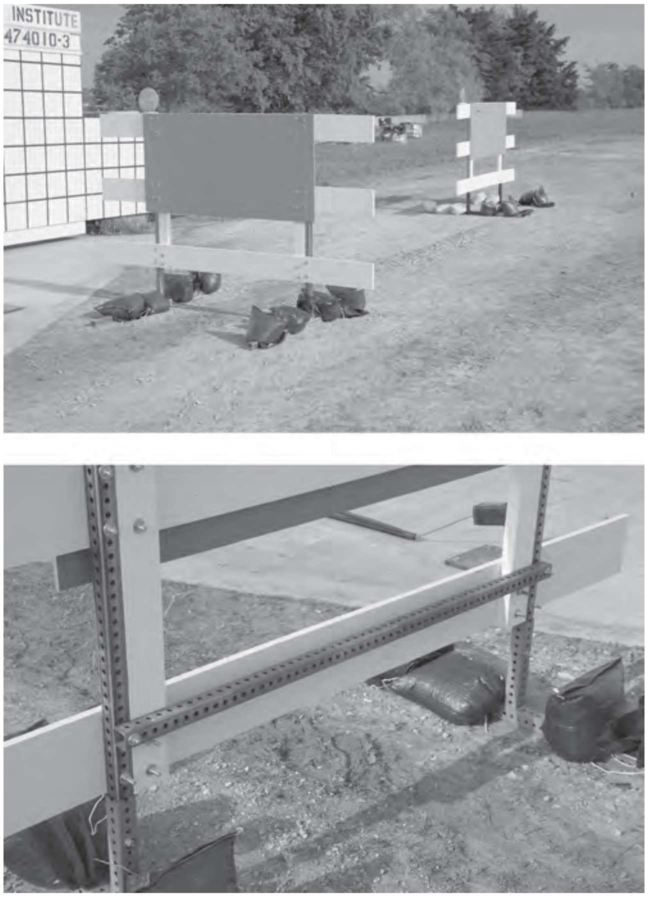


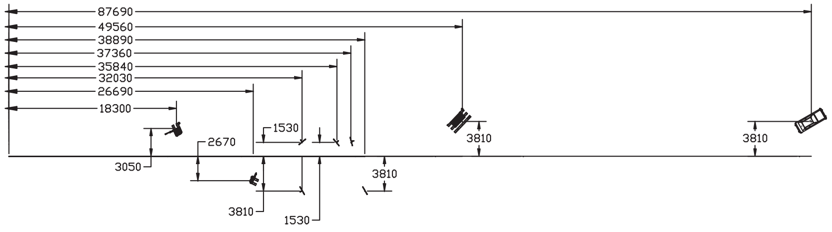
Figure 6.18. Modified barricade with rectangular sign used in Test 3.

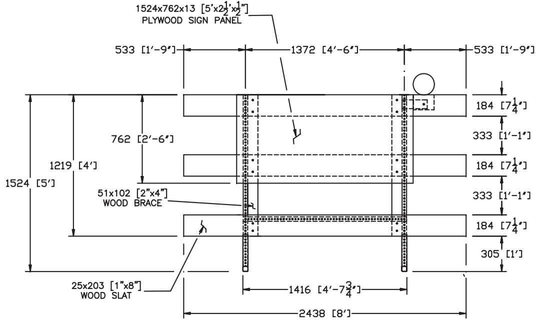
Figure 6.19. Vehicle before Test 3.

Data from the accelerometer, located at the vehicle center of gravity, were digitized for evaluation of occupant risk and were computed as follows. In the longitudinal direction, the occupant impact velocity was 2.9 m/s (9.5 ft/s) at 0.248 s, the highest 0.010-s occupant ridedown acceleration was –7.6 g’s from 0.277 s to 0.287 s, and the maximum 0.050-s average acceleration was –4.1 g’s between 0.002 s and 0.052 s. In the lateral direction, the occupant impact velocity was 0.6 m/s (2.0 ft/s) at 0.248 s, the highest 0.010-s occupant ridedown acceleration was 2.6 g’s from 0.282 s to 0.292 s, and the maximum 0.050-s average was 1.2 g’s between 0.243 s and 0.293 s. These data and other pertinent information from the test are summarized in Figure 6.21. Vehicle angular

Figure 6.20. Vehicle after Test 3.

0.000 s 0.098 s 0.294 s 0.417 s





General Information	
Test Agency	Texas Transportation Institute
Test No.	474010-3
Date	04-08-2003
Test Article	
Type	Type III Barricade
Name	Type III Barricade w/Rectangular Sign
Installation Height, m (ft)	1.5 (5.0)
Material or Key Elements	Three wood barricade rails and braces bolted to perforated steel legs
Soil Type and Condition	Native Soil, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	1997 Geo Metro
Mass, kg	
Curb	857
Test Inertial	839
Dummy	77
Gross Static	916

Impact Conditions	
Angle, deg	0 & 90
Speed, km/h (mi/h) @ 0 deg	100.2 (62.3)
Speed, km/h (mi/h) @ 90 deg	81.3 (50.5)
Exit Conditions	
Speed, km/h (mi/h)	75.7 (47.0)
Occupant Risk Values	
Impact Velocity, m/s (ft/s)	
Longitudinal	2.9 (9.5)
Lateral	0.6 (2.0)
THIV, km/h	10.3
Ridedown Accelerations, g's	
Longitudinal	-7.6
Lateral	2.6
PHD, g's	7.7
ASI	0.34
Max. 0.050-s Average, g's	
Longitudinal	-4.1
Lateral	1.2
Vertical	-1.0

Test Article Debris Pattern	
Length, m (ft)	49.6 (162.7)
Width, m (ft)	
Left	3.8 (12.5)
Right	3.8 (12.5)
Vehicle Damage	
Exterior	
VDS	12FD2
CDC	12FDAW2
Max. Exterior Vehicle Crush, mm (in)	260 (10.2)
Interior	
OCDI	FS0000000
Max. Occupant Compartment Deformation, mm (in)	0
Post-Impact Behavior	
(during 1.0 sec after impact)	
Max. Yaw Angle, deg	12
Max. Pitch Angle, deg	11
Max. Roll Angle, deg	6

Figure 6.21. Summary of results for Test 3.

displacements and accelerations versus time traces are presented in Appendix F, Figures F.15 through F.21.

The test evaluation is summarized in Table 6.4. The barricade met all required evaluation criteria for both the head-on and end-on impact scenarios.

Discussion

Although the upper rail and sign panel still contacted the A-post and windshield, the horizontal brace induced movement in the right barricade upright as intended. The movement of the upright limited the torsional energy stored in the barricade, thus reducing the contact force imparted by the rails and sign panel to the windshield and limiting the resulting windshield damage to acceptable levels. This result is proved by the windshield being only cracked and not deformed inward.

6.5.4 Test 4

Test Article

Having successfully tested the perforated steel-tube barricade, the researchers used the final test to evaluate the performance of a barricade fabricated from wood and HPPL. Details of the barricade design, which correspond to Design B3 previously described, are shown in Figure 6.22. The barricade uprights were 102-mm (4-in) square HPPL manufactured from HDPE. The uprights were bolted between the legs of the 51-mm × 152-mm (2-in × 6-in) wood skids in two locations to form a moment connection to resist rotation. Short lengths of the (102-mm [4-in] square) HPPL were used as spacers at the front and back of the skids. As with the steel-frame barricade designs, the 12-mm × 203-mm (1-in × 8-in)

TABLE 6.4 Performance evaluation summary for Test 3

Test Agency: Texas Transportation Institute Test No.: 474010-3 Test Date: 04/08/2003

<table>
<tr><th colspan="3">*NCHRP Report 350* Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td colspan="3">**Structural Adequacy**
B. *The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.*</td><td>Both barricades readily activated as designed by yielding and fracturing.</td><td>Pass</td></tr>
<tr><td colspan="3">**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. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.*</td><td>Debris was scattered along the vehicle path. The largest debris was 20.0 kg (44.1 lb). The windshield was shattered on the right side but was intact and not deformed inward (FHWA Case 5). The left side of the windshield sustained only minimal damage. The glass in the right door was broken out by contact with one of the rails, but there was no intrusion of the rail into the passenger compartment. There was no measurable occupant compartment deformation.</td><td>Pass</td></tr>
<tr><td colspan="3">E. *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.*</td><td>The driver's vision was not blocked.</td><td>Pass</td></tr>
<tr><td colspan="3">F. *The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.*</td><td>The vehicle remained upright throughout and after the crash period.</td><td>Pass</td></tr>
<tr><td colspan="3">H. *Occupant impact velocities should satisfy the following:*</td><td rowspan="4">Longitudinal occupant impact velocity was 2.9 m/s (9.5 ft/s).</td><td rowspan="4">Pass</td></tr>
<tr><td colspan="3">*Occupant Velocity Limits (m/s)*</td></tr>
<tr><td>*Component*</td><td>*Preferred*</td><td>*Maximum*</td></tr>
<tr><td>*Longitudinal*</td><td>*3*</td><td>*5*</td></tr>
<tr><td colspan="3">I. *Occupant ridedown accelerations should satisfy the following:*</td><td rowspan="4">Longitudinal ridedown acceleration was -7.6 g's, and lateral ridedown acceleration was 2.6 g's.</td><td rowspan="4">Pass</td></tr>
<tr><td colspan="3">*Occupant Ridedown Acceleration Limits (g's)*</td></tr>
<tr><td>*Component*</td><td>*Preferred*</td><td>*Maximum*</td></tr>
<tr><td>*Longitudinal and lateral*</td><td>*15*</td><td>*20*</td></tr>
<tr><td colspan="3">**Vehicle Trajectory**
K. *After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.*</td><td>The vehicle continued on a straightforward path all along the trajectory path and did not intrude into adjacent lanes.</td><td>Pass*</td></tr>
<tr><td colspan="3">N. *Vehicle trajectory behind the test article is acceptable.*</td><td>The vehicle came to rest behind the test articles.</td><td>Pass</td></tr>
</table>

*Criterion K preferable, not required.

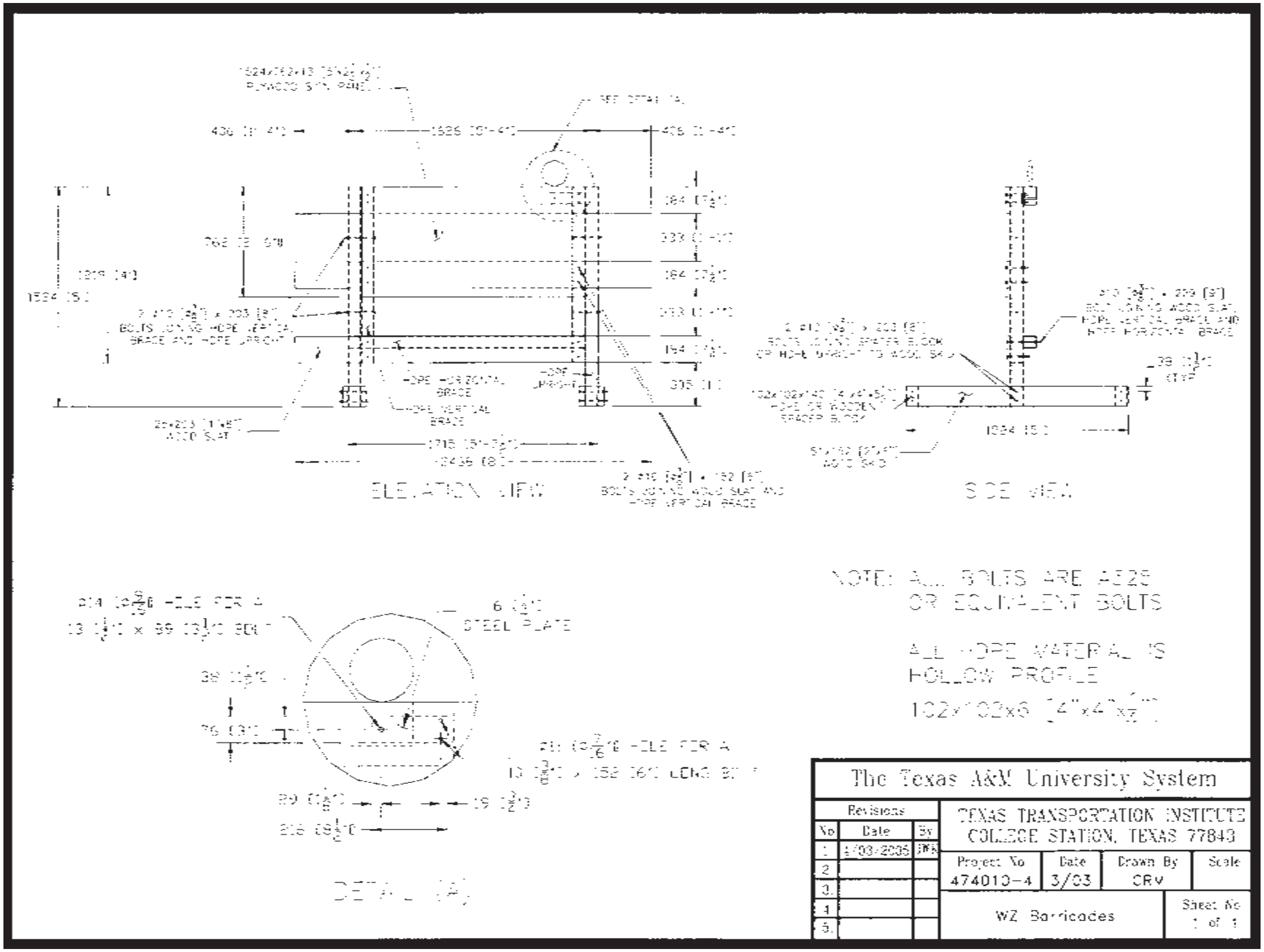


Figure 6.22. Details of hollow-HDPE/wooden barricade with rectangular sign used in Test 4.

wooden horizontal rails and 0.8-m × 1.5-m × 13-mm (2.5-ft × 5-ft × ½-in) plywood sign panel were attached to the vertical braces. The vertical braces were fabricated from the same size HPPL used for the barricade uprights.

Connection of the horizontal rails and sign panel to the vertical braces was achieved with low-grade (i.e., A307 or equivalent) bolts. Oversize (i.e., fender) washers were used under the nut of the bolts adjacent to the HPPL member to provide further resistance against bolt pullout during impact or repeated handling. Similar to the steel-frame barricade with perforated steel-tube vertical braces, the assembled unit with horizontal rails and sign panel is attached to the barricade by bolting the HPPL vertical braces to the HPPL uprights. This process requires pre-drilling or field drilling holes in both the braces and uprights. Fender washers were used under both the head and nut of the A307 or equivalent bolts used to connect these members. As depicted in Figure 6.22, the barricade can be adjusted for placement on uneven terrain by extending the height of one of the vertical braces relative to one of the uprights.

Based on the test results of the perforated steel-tube barricade, a horizontal brace was added to the barricade system. The brace was fabricated from 102-mm (4-in) square HPPL and was placed behind the lower rail. The brace was bolted to the vertical braces using two of the bolts used to connect the lower rail to the braces.

A Type A warning light with self-contained battery compartment was attached to the top of the left vertical brace using a steel plate connector. The warning light was mounted such that the lens extended above the top of the upper rail. Two barricades were placed in the path of the vehicle approximately 6 m (19.7 ft) apart from one another—one perpendicular to the path of the vehicle and one parallel to the path of the vehicle. Two sandbags were placed on the front and back of each skid for a total of eight sandbags per barricade. A photograph of the completed test installation is shown in Figure 6.23.

Based on the test results of the perforated steel-tube barricade systems, the offset impact condition was selected as the most critical impact orientation. In addition to evaluating the torsional failure mode of the barricade, the offset impact condition also provides better opportunity to evaluate the interaction of the warning light with the vehicle.

Test Vehicle

A 2000 Geo Metro, shown in Figure 6.24, was used for the crash test. Test inertia weight of the vehicle was 839 kg (1850 lb), and its gross static weight was 916 kg (2019 lb). The height to the lower edge of the vehicle front bumper was 400 mm (15.7 in), and the height to the upper edge of the front bumper was 525 mm (20.7 in). Additional dimensions and information on the vehicle are given in Appendix D, Figure D.4. The vehicle was directed into the installation using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just before impact.

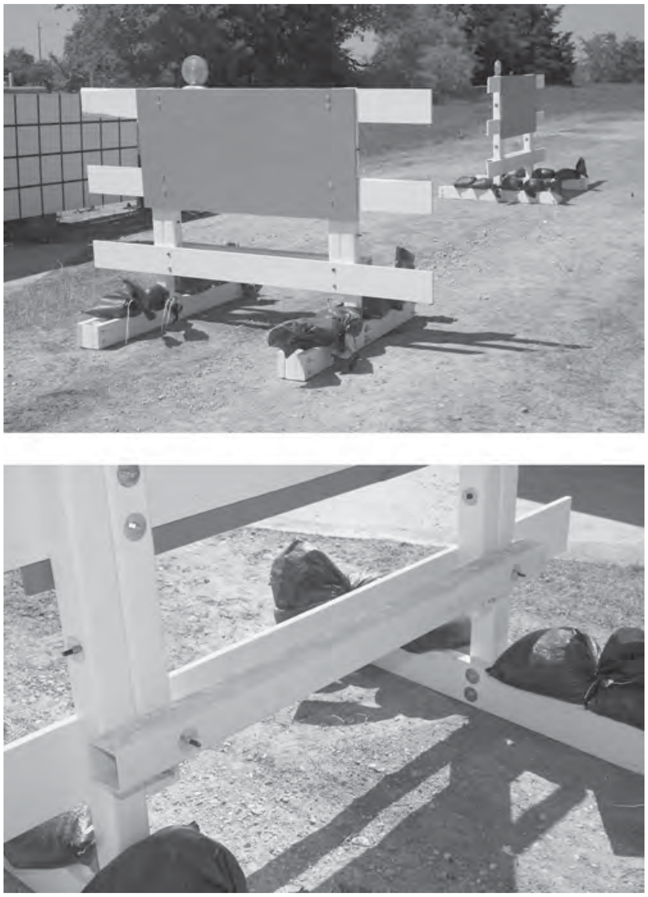


Figure 6.23. Hollow-HDPE/wooden barricade with rectangular sign used for Test 4.

Test Description

A 916-kg (2019-lb) vehicle, traveling at a speed of 100.2 km/h (62.3 mi/h), impacted the first barricade head-on at 0 degree with the left upright aligned with the centerline of the vehicle. Shortly after contact, the lower horizontal rail fractured, and, at 0.012 s, the middle rail began to fracture. The lower rail separated from the support at 0.041 s, and the top rail contacted the windshield at 0.061 s. The top rail then swung around the A-post of the vehicle and contacted the window on the right side at 0.075 s, which broke the glass. At 0.142 s, the vehicle lost contact with the barricade while traveling at a speed of 85.9 km/h (53.4 mi/h).

At 0.246 s, the vehicle, traveling at a speed of 82.7 km/h (51.4 mi/h), impacted the second barricade end-on at 90 degrees with the centerline of the vehicle aligned with the barricade. Shortly after impact with the second barricade, the barricade began to move, and at 0.280 s, the skid and upright on the side opposite impact became airborne and the middle horizontal rail contacted the hood. The lower rail fractured into two pieces at 0.309 s. At 0.501 s, the vehicle lost contact with the second barricade while traveling at a speed of 69.1 km/h (42.9 mi/h). Brakes on the vehicle were applied at 1.9 s after

Figure 6.24. Vehicle before Test 4.

Figure 6.25. Damage to vehicle after Test 4.

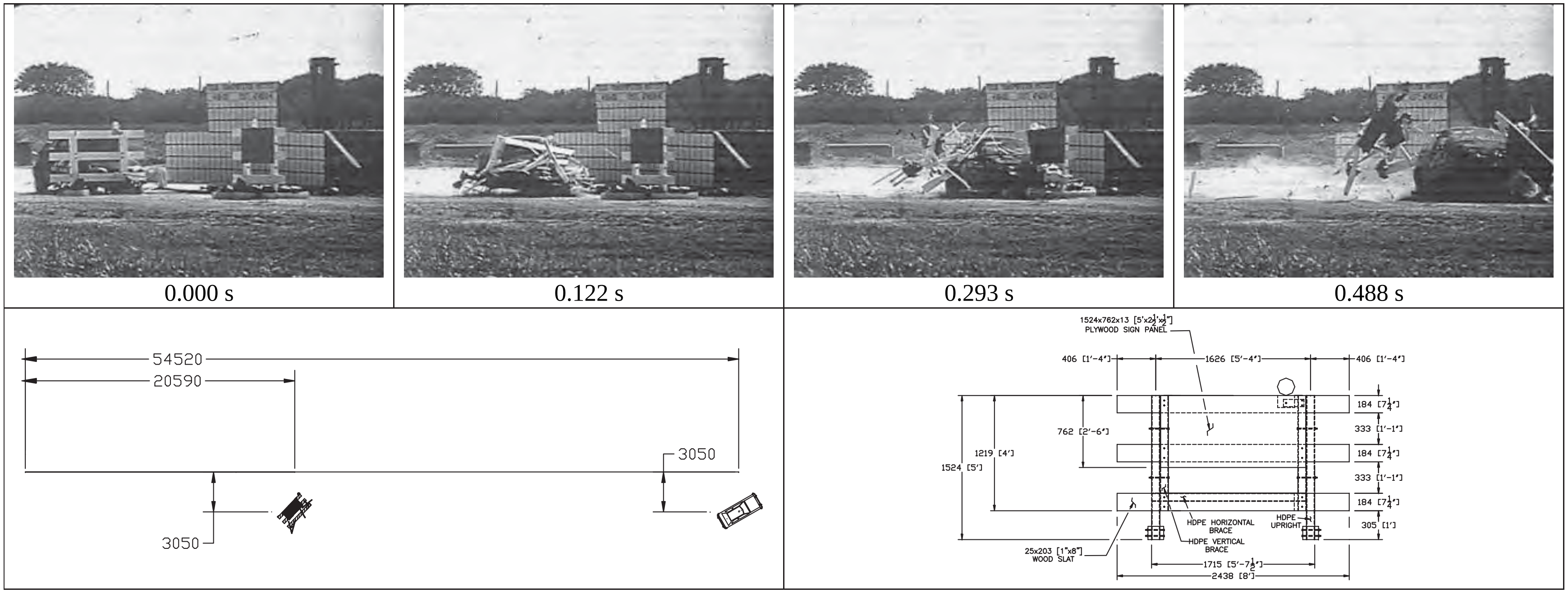
impact. The vehicle subsequently came to rest 54.5 m (178.8 ft) downstream of impact and 3.1 m (10.2 ft) to the right of centerline. Sequential photographs of the test period are shown in Appendix E, Figure E.4.

Test Results

Both barricades readily activated at impact by yielding and fracturing. The second barricade came to rest under the vehicle. The next largest piece of debris weighed approximately 22 kg (48.5 lb). The debris was scattered over an area 54.5 m (178.8 ft) long and 3.1 m (10.2 ft) to the right of the initial impact point. The warning light remained attached to both barricades and did not result in any occupant compartment deformation.

Damage to the vehicle is shown in Figure 6.25. The front bumper, radiator, radiator support, hood, and right door were deformed. Maximum crush to the exterior of the vehicle was 220 mm (8.7 in) at the center front at bumper height. There was a dent in the right side A-post, and the windshield was shattered on the right side but remained intact and was not deformed inward (FHWA windshield damage classification Case 5). The left side of the windshield sustained only minimal damage. The glass in the right door was completely broken out by contact with the end of the top rail after it folded around the A-post. The high-speed film indicated that the end of the rail intruded a couple inches beyond the door glass into the passenger compartment. There was a hole cut in the hood and a dent in the lower center of the door. There was no other measurable occupant compartment deformation. The vehicle remained upright during and after the collision event.

Data from the accelerometer, located at the vehicle center of gravity, were digitized for evaluation of occupant risk and were computed as follows. In the longitudinal direction, the occupant impact velocity was 2.9 m/s (9.5 ft/s) at 0.269 s, the highest 0.010-s occupant ridedown acceleration was –8.4 g’s from 0.286 s to 0.296 s, and the maximum 0.050-s average acceleration was –5.1 g’s between 0.268 s and 0.318 s. In the lateral direction, the occupant impact velocity was 0.7 m/s (2.3 ft/s) at 0.269 s, the highest 0.010-s occupant ridedown acceleration was 1.8 g’s from 0.281 s to 0.291 s, and the maximum 0.050-s average was 1.0 g between 1.692 s and 1.742 s. These data and other pertinent information from the test are summarized in Figure 6.26. Vehicle angular displacements and accelerations versus time traces are presented in Appendix F, Figures F.22 through F.28.


0.000 s

0.122 s

0.293 s

0.488 s

General Information	
Test Agency	Texas Transportation Institute
Test No.	474010-4
Date	04-08-2003
Test Article	
Type	Type III Barricade
Name	HPPL/Wood Barricade w/Rect. Sign
Installation Height, m (ft)	1.5 (5.0)
Material or Key Elements	Three wood barricade rails and braces bolted to HPPL legs
Soil Type and Condition	Native Soil, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	2000 Geo Metro
Mass, kg	
Curb	838
Test Inertial	839
Dummy	77
Gross Static	916

Impact Conditions	
Angle, deg	0 & 90
Speed, km/h (mi/h) @ 0 deg	100.2 (62.3)
Speed, km/h (mi/h) @ 90 deg	82.7 (51.4)
Exit Conditions	
Speed, km/h (mi/h)	69.1 (42.9)
Occupant Risk Values	
Impact Velocity, m/s (ft/s)	
Longitudinal	2.9 (9.5)
Lateral	0.7 (2.3)
THIV, km/h	10.7
Ridedown Accelerations, g's	
Longitudinal	-8.4
Lateral	1.8
PHD, g's	8.5
ASI	0.53
Max. 0.050-s Average, g's	
Longitudinal	-5.1
Lateral	1.0
Vertical	-3.3

Test Article Debris Pattern	
Length, m (ft)	54.5 (178.8)
Width, m (ft)	
Left	0
Right	3.1 (10.2)
Vehicle Damage	
Exterior	
VDS	12FD3
CDC	12FDAW2
Max. Exterior Vehicle Crush, mm (in)	220 (8.7)
Interior	
OCDI	FS0000000
Max. Occupant Compartment Deformation, mm (in)	0
Post-Impact Behavior (during 1.0 sec after impact)	
Max. Yaw Angle, deg	17
Max. Pitch Angle, deg	18
Max. Roll Angle, deg	-8

Figure 6.26. Summary of results for Test 4.

The test evaluation is summarized in Table 6.5. The barricade met all required evaluation criteria for both the head-on and end-on impact scenarios.

Discussion

Although the right side door window was shattered by the end of the upper rail, the slight intrusion of the rail beyond the window was not considered to constitute a risk of serious injury in a frontal collision. This behavior can be mitigated by reducing the overhang distance of the barricade rails past the uprights. The spacing of the uprights is limited by the width of the sign panel, which must be attached to either the uprights or vertical braces. By increasing the spacing of the uprights from 1.4 m to 1.6 m (4 ft, 6 in to 5 ft, 4 in) (see Figure 6.27), the overhang distance of the barricade rails is reduced from 0.5 m to 0.4 m (1 ft, 9 in to 1 ft, 4 in).

TABLE 6.5 Performance evaluation summary for Test 4

Test Agency: Texas Transportation Institute Test No.: 474010-4 Test Date: 04/08/2003

<table>
<tr><th colspan="4"><i>NCHRP Report 350</i> Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td colspan="4">Structural Adequacy</td><td></td><td></td></tr>
<tr><td>B.</td><td colspan="3"><i>The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</i></td><td>Both barricades readily activated as designed by yielding and fracturing.</td><td>Pass</td></tr>
<tr><td colspan="4">Occupant Risk</td><td></td><td></td></tr>
<tr><td>D.</td><td colspan="3"><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. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</i></td><td>The second barricade came to rest under the vehicle. The remaining debris was scattered along the vehicle path with the largest weighing 22.0 kg (48.5 lb). The windshield was shattered on the right side but was intact and not deformed inward (FHWA Case 5). The left side of the windshield sustained only minimal damage. The end of one of the rails folded around the A-post and broke out the glass in the right door. The end of the rail intruded a couple inches beyond the door glass into the passenger compartment, but was not considered to constitute a potential for serious injury in a frontal collision. There was no measurable occupant compartment deformation.</td><td>Pass</td></tr>
<tr><td>E.</td><td colspan="3"><i>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.</i></td><td>The driver's vision was not blocked.</td><td>Pass</td></tr>
<tr><td>F.</td><td colspan="3"><i>The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</i></td><td>The vehicle remained upright throughout and after the crash period.</td><td>Pass</td></tr>
<tr><td rowspan="4">H.</td><td colspan="3"><i>Occupant impact velocities should satisfy the following:</i></td><td rowspan="4">Longitudinal occupant impact velocity was 2.9 m/s (9.5 ft/s).</td><td rowspan="4">Pass</td></tr>
<tr><td colspan="3"><i>Occupant Velocity Limits (m/s)</i></td></tr>
<tr><td><i>Component</i></td><td><i>Preferred</i></td><td><i>Maximum</i></td></tr>
<tr><td><i>Longitudinal</i></td><td><i>3</i></td><td><i>5</i></td></tr>
<tr><td rowspan="4">I.</td><td colspan="3"><i>Occupant ridedown accelerations should satisfy the following:</i></td><td rowspan="4">Longitudinal ridedown acceleration was -8.4 g's, and lateral ridedown acceleration was 1.8 g's.</td><td rowspan="4">Pass</td></tr>
<tr><td colspan="3"><i>Occupant Ridedown Acceleration Limits (g's)</i></td></tr>
<tr><td><i>Component</i></td><td><i>Preferred</i></td><td><i>Maximum</i></td></tr>
<tr><td><i>Longitudinal and lateral</i></td><td><i>15</i></td><td><i>20</i></td></tr>
<tr><td colspan="4">Vehicle Trajectory</td><td></td><td></td></tr>
<tr><td>K.</td><td colspan="3"><i>After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</i></td><td>The vehicle continued on a straightforward path all along the trajectory path and did not intrude into adjacent lanes.</td><td>Pass*</td></tr>
<tr><td>N.</td><td colspan="3"><i>Vehicle trajectory behind the test article is acceptable.</i></td><td>The vehicle came to rest behind the test articles.</td><td>Pass</td></tr>
</table>

*Criterion K preferable, not required.

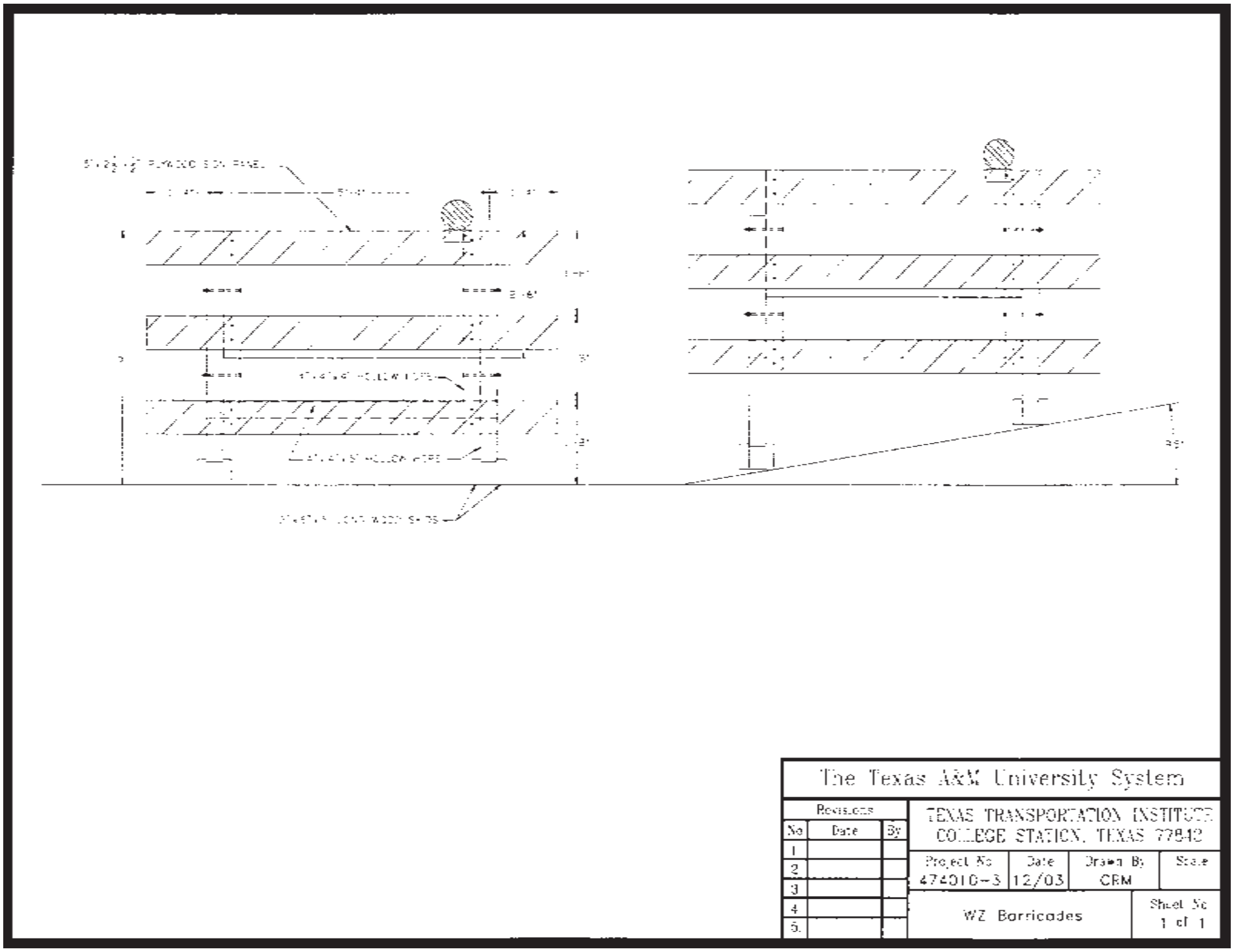


Figure 6.27. *Barricade with increased spacing of upright.*

CHAPTER 7

LOW-MOUNTING-HEIGHT SIGN SUPPORTS WITH RIGID SIGN SUBSTRATES

One of the devices selected by the panel for development under Phase II of the project was a low-mounting-height, generic sign support system with rigid substrate that can be fabricated from inexpensive, readily available materials. Most of the acceptable alternatives currently available are proprietary sign stands that must be used in combination with a roll-up–type fabric or vinyl sign panel. Although some of these systems can offer advantages such as portability, ease of erection, and adjustable mounting height, their cost can sometimes be prohibitive.

Factors that can affect the impact performance of a sign support system include but are not limited to the mass of the primary components, failure mode of the structural members, connection details between the structural members, sign substrate material, sign panel size, and sign panel mounting height. Research has demonstrated the need to design and evaluate a portable sign support as a system consisting of a support structure and a sign substrate. In several instances, crash testing has demonstrated that a particular support structure can be crashworthy for one type of sign substrate but not another and vice versa.

Rigid sign substrates fabricated from materials such as plywood are sometimes preferred by user agencies and contractors because of their low cost, availability, rigidity, durability, and ease of fabrication. Whereas the legibility and retro-reflectivity of vinyl roll-up signs supported on flexible stays may be reduced in windy conditions because of their propensity to lean and deflect, the rigidity of a plywood sign panel enables it to retain its shape and orientation in windy conditions. However, while these characteristics are desirable from a functional standpoint, the rigidity and mass of a plywood sign panel make plywood more critical than other substrate materials from a crashworthiness standpoint. Because of its greater weight, a successful test with a plywood substrate is generally considered to be sufficient for receiving approval of a similar sign support with a comparably sized aluminum sign substrate.

In addition to being crashworthy, the support and base to which the sign substrate is mounted must provide sufficient strength and stability to accommodate wind and other service loads. A generic sign support fabricated from perforated steel tubing or angle has many desirable attributes. With the low mounting height, it is desirable to prevent or at least significantly delay fracture and/or separation of the uprights from the base or skids, thus reducing the potential for the detached uprights and sign panel to rotate into the windshield. The ductility of tubular or angle steel uprights permits them to initially yield and wrap around the front end of the vehicle. On a paved surface, the sign support system is then carried along by the vehicle as a unit until the vehicle comes to a stop. By keeping the structure intact and reducing or eliminating the separation of components that might penetrate the windshield, the probability of occupant compartment intrusion is reduced. On a dirt surface, the translational motion of the sign support system can be impeded if the system’s legs or skids dig into the ground. Under such circumstances, the increased moment generated on the uprights can eventually cause them to fracture and release from the skids. However, by this time, momentum has been transferred to the sign support components and the relative speed between the sign support projectile and vehicle is significantly reduced.

7.1 DESIGN ALTERNATIVES

Per instructions from the project panel, the mounting height from the ground to the bottom of the sign panel was taken to be 305 mm (12 in) for the proposed sign support designs. At a 305-mm (12-in) mounting height, the top of a diamond-oriented 1.2-m × 1.2-m (4-ft × 4-ft) sign panel is approximately 2.0 m (6.7 ft) above the ground. For a Geo Metro, which is the typical vehicle used to represent the 820C design vehicle specified in *NCHRP Report 350*, the distance from the ground, around the bumper, and across the hood to the base of the windshield is approximately 1.6 m (5.25 ft). Therefore, it is anticipated that as the support structure yields around the front end of the test vehicle during a 0-degree impact, the top of the sign panel will contact the windshield. However, the low mounting height provides some direct contact and acceleration to the sign panel, thereby reducing the contact velocity with the windshield. During a 90-degree impact, the corner of the sign panel should initially contact the hood, rather than the windshield, as it rotates toward the vehicle. Thus, although some windshield damage is expected, a rigid sign substrate was thought to have a reasonable probability of meeting impact performance requirements when incorporated into a sign support system at a mounting height of 305 mm (12 in).

Once the basic characteristics of the system (e.g., mounting height, sign substrate, support material type) were defined, an effort was made to develop design alternatives that provide some desirable functional characteristics. Durability, handling, fabrication/repair, and site adaptability were considered.

Most of the designs developed incorporate square, perforated steel tubing as the support material. Holes punched on all faces of the 25-mm (1-in) square supports simplify construction and adjustability. Cost could be reduced if angle shapes are substituted for the tubular structural members. In either case, the galvanized steel will provide good durability and resistance to environmental attack. In regard to handling, systems composed of perforated steel tubing or angles can generally be readily assembled for relatively quick on-site deployment and disassembled for ease of transportation. The bolted connections used in these systems facilitate repair by permitting selected components to be readily removed and replaced.

The degree of site adaptability (i.e., the degree of adjustment that a device provides to accommodate variations in field conditions) varies among the different design alternatives. Some of the designs that are least expensive to construct do not have a high degree of adjustability. Designs with a high degree of site adaptability tend to be more complex and expensive to construct.

A total of eight low-mounting-height, small sign support designs were developed for review and prioritization by the project panel. The following sections briefly summarize each of these systems.

7.1.1 Design L1: Independent Dual Uprights

The sign support shown in Figure 7.1 uses two identical but independent uprights to support the plywood sign panel. The use of two uprights improves the torsional stability of the sign panel. Short sleeves are welded to 1.2-m (4-ft) long skids. Uprights are inserted and bolted into the sleeves. The rigid sign panel is then bolted to the uprights with a minimum of two bolts in each. The sign panel serves as the cross bracing for the system. Transportation and erection is facilitated by the removal of bolts connecting the uprights to the skids. While the design is simple, there is only minimal adjustability to account for varying terrain considerations. Although it may not be needed, there is no front-to-back tilt adjustment to accommodate vertical grade. If the sign support is placed on the roadside, horizontal slope can be accommodated by adjusting the height of the downhill upright by either extending the tube out of the sleeve and/or lowering the attachment points to the sign panel.

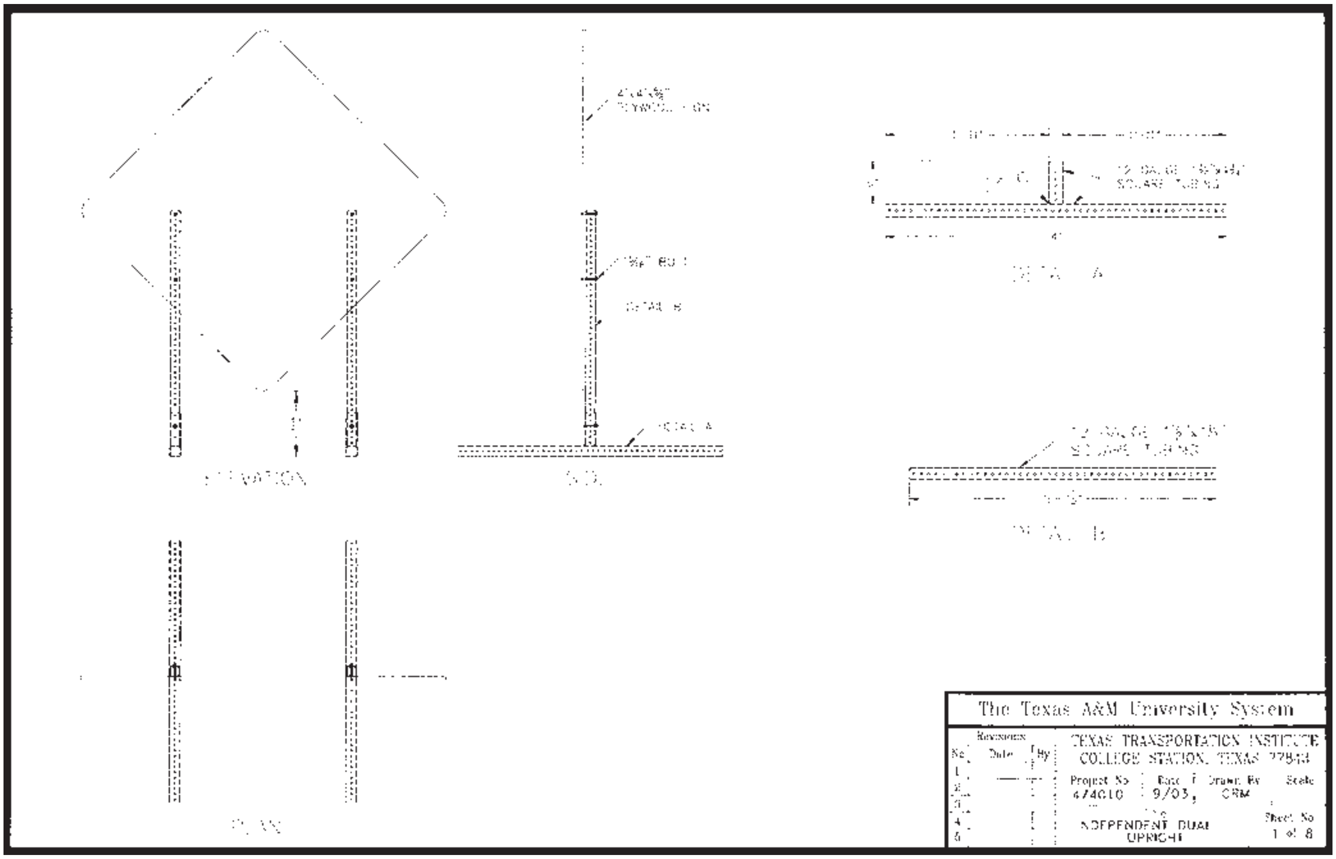


Figure 7.1. Design L1: independent dual uprights.

7.1.2 Design L2: H-Base with Single Upright

The sign support shown in Figure 7.2 has an H-shaped base with single center upright. The central member of the H-shaped base is welded to the center of each skid. A short sleeve is then welded to the center of this cross member. An upright is inserted and bolted into the sleeve. The rigid sign panel is then mounted to the single upright using a minimum of two bolts. This design is relatively simple and is comparable to Design L1 in terms of material quantities. It requires fewer bolts but more welding than Design L1. Assembly and disassembly is faster because there is only one upright with a single bolt or pin to insert or remove. However, signs mounted on single vertical supports will be more susceptible to flutter in windy conditions. This design does not possess any side-to-side or front-to-back adjustability.

7.1.3 Design L3: Pivoting Dual Uprights

Design L3, shown in Figure 7.3, is similar in many respects to Design L1. However, this design incorporates some front-to-back adjustability by using pin plates at the base of each upright. These adjustment plates can be either welded or bolted to the skids. The plates are used to attach the 305-mm (12-in) long sleeves to the skids. Similar to Design L1, the uprights insert and bolt into the sleeves. The rigid sign panel is then bolted to the uprights with a minimum of two bolts in each vertical member.

To tilt the sign panel to the front or back, the upper adjustment bolt/pin is removed and reinserted after aligning the sleeve with one of the other holes in the plate. As with Design L1, side-to-side adjustment can be accommodated by telescoping of one of the vertical members inside its sleeve or adjusting the attachment of one of the uprights to the sign panel. The top adjusting pin on each plate can be removed to lay the sign down for easy transport as a single unit. If desired (for ease of repair, etc.), the sign panel and uprights can be readily detached from the base by removing the bolts through the sleeves.

7.1.4 Design L4: H-Base with Dual Uprights

The H-base shown in Figure 7.4 is a combination of Designs L1 and L2. It uses the H-base in combination with two uprights. The cross member can be attached to the skids using sleeves as shown or by direct welding (see Design L2). This design uses a little more material and requires a little more welding than Design L2, but should be more stable and elim-

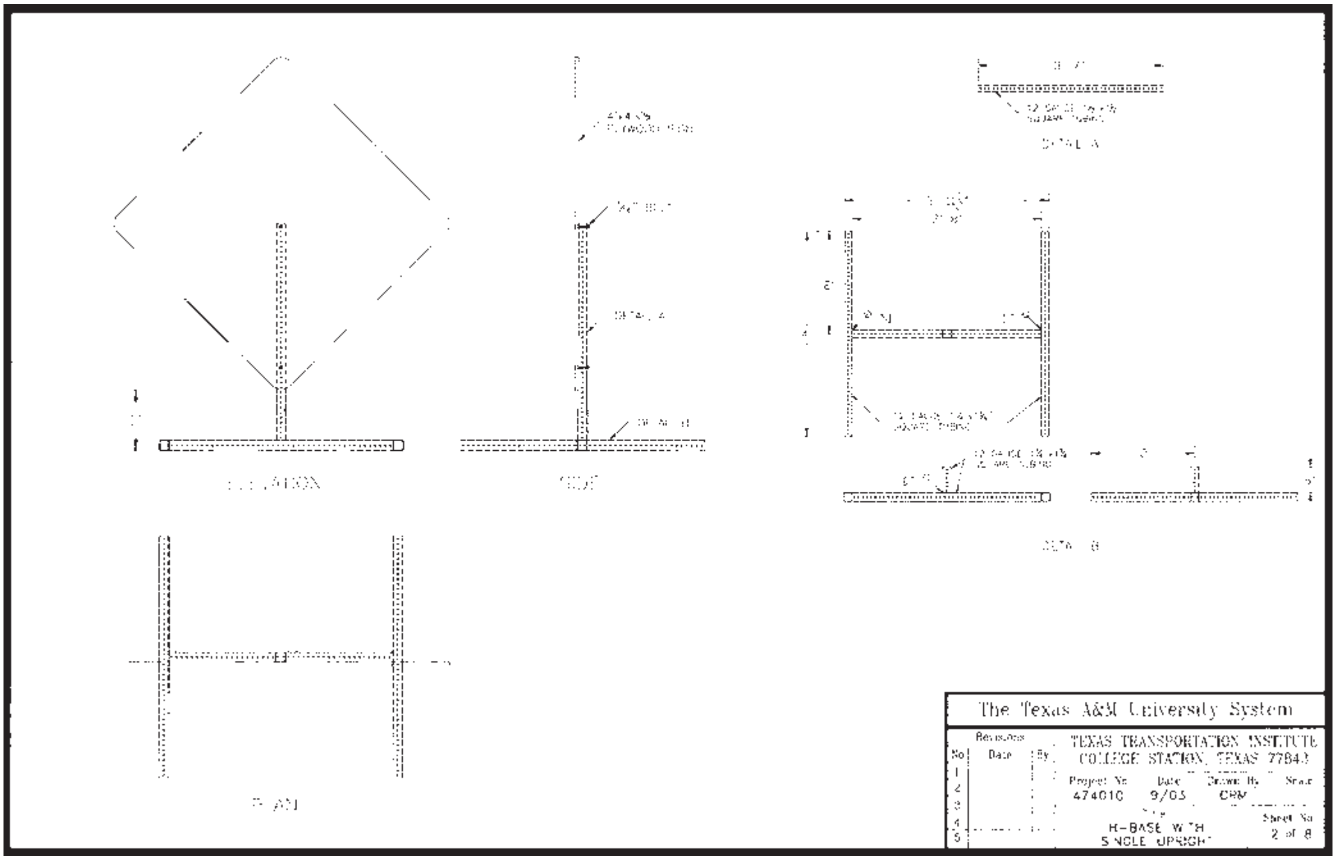


Figure 7.2. Design L2: H-base with single upright.

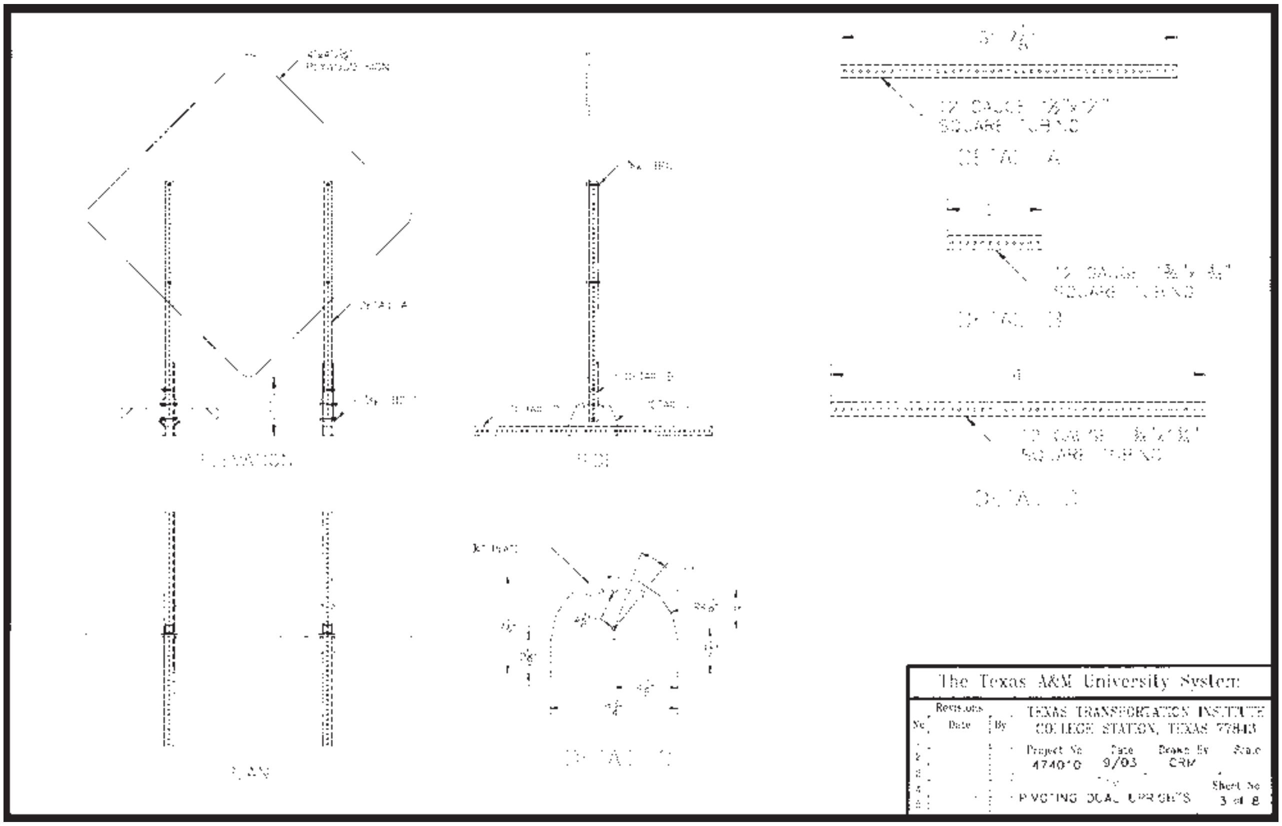


Figure 7.3. Design L3: pivoting dual uprights.

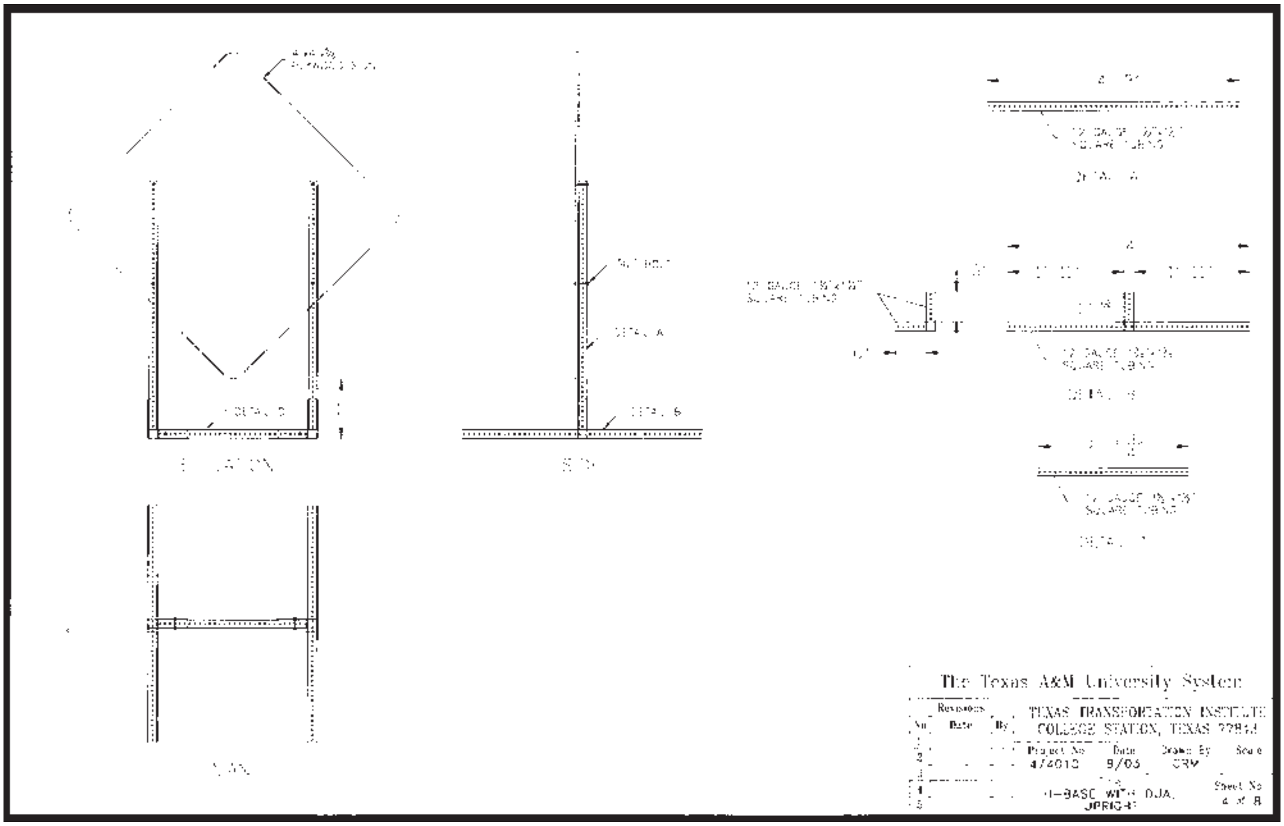


Figure 7.4. Design L4: H-base with dual uprights.

inate flutter. As with Design L2, the H-base with dual uprights does not have side-to-side or front-to-back adjustability.

7.1.5 Design L5: X-Base with Single Upright

Another alternative for a single upright is the X-base shown in Figure 7.5. The details of the base connection are shown in Detail B of the drawing. Sleeves are welded to the center of a 1.2-m (4-ft) long skid on three sides. The two horizontal sleeves accept a short piece of perforated tubing to complete the X-base. The upright is inserted and bolted to the vertical sleeve. The rigid sign panel is bolted to the upright at two locations.

This system is lighter in weight than the other designs because less material is used. As with Design L2, some flutter of the sign is anticipated in strong winds. Removal of the bolt connecting the upright to the base allows for easy transport of the system in two sections. As with the H-bases, the X-base design does not possess side-to-side or front-to-back adjustability.

7.1.6 Design L6: X-Base with Pivoting Upright

Design L6, shown in Figure 7.6, incorporates the adjusting plate used in Design L3 with the X-base used in Design L5 to provide side-to-side or front-to-back adjustment on a single vertical support. The horizontal sleeves are welded to the adjusting plates, which in turn are welded or bolted to the skid. The two horizontal sleeves accept a short piece of perforated tubing to complete the X-base. The upright is inserted and bolted into the vertical sleeve. The rigid sign panel is bolted to the upright at two locations.

The adjustment plates can be used to provide side-to-side adjustment of the sign panel. To tilt the sign panel to either side, the upper adjustment bolt/pin is removed and reinserted after aligning the sleeve with one of the other holes in the adjusting plate. If the upright and sign panel are rotated 90 degrees from the orientation shown in the drawing before insertion into the vertical sleeve, the same sign support system can be used to provide front-to-back adjustment. Only one type of adjustment can be accommodated at a given time.

When oriented for front-to-back adjustment, the top adjusting pin can be removed to lay the sign down for easy transport as a single unit. When oriented for side-to-side adjustment, the sign panel and upright can be readily detached from the base by removing the bolt connecting the upright to the vertical sleeve. As with other single support systems, some flutter should be expected in high-wind conditions.

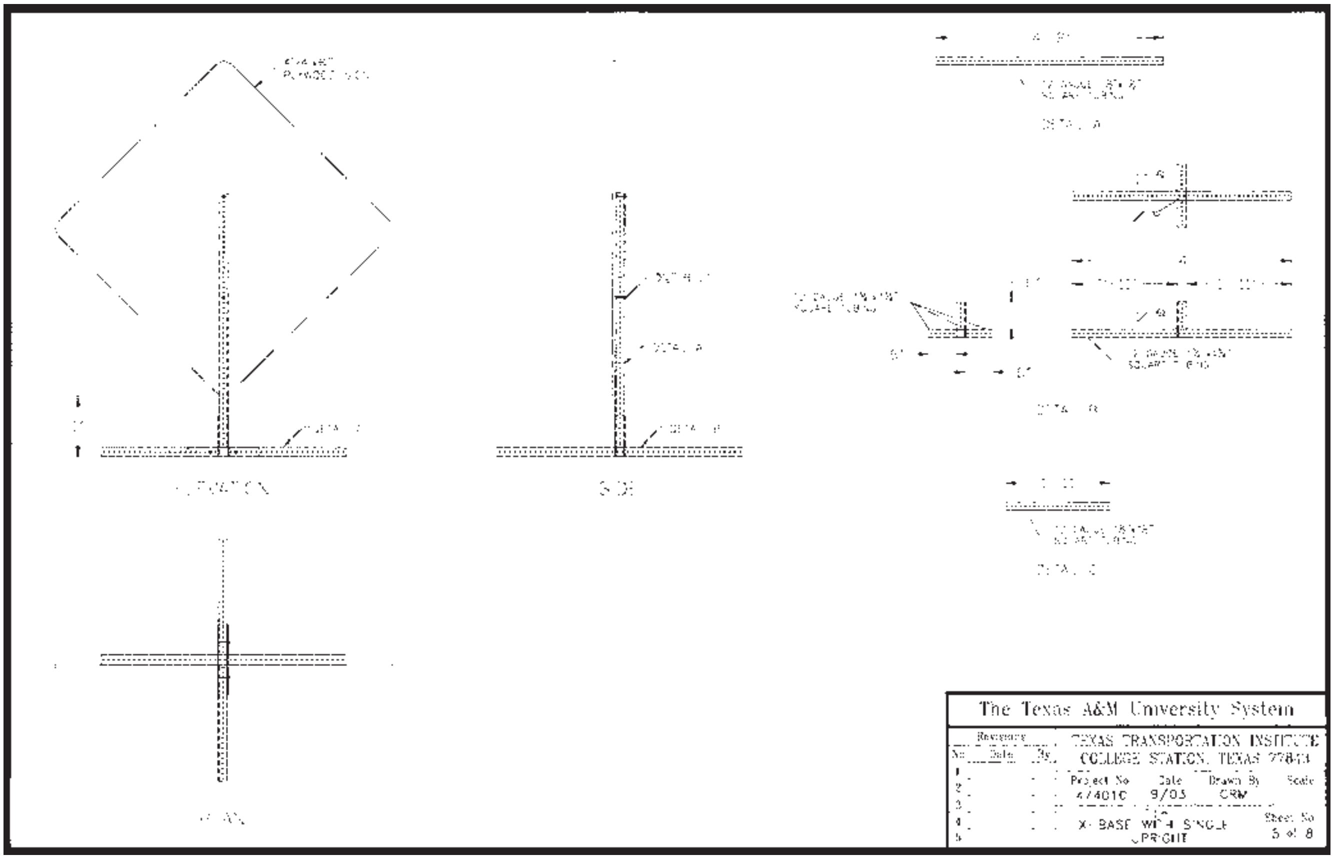


Figure 7.5. Design L5: X-base with single upright.

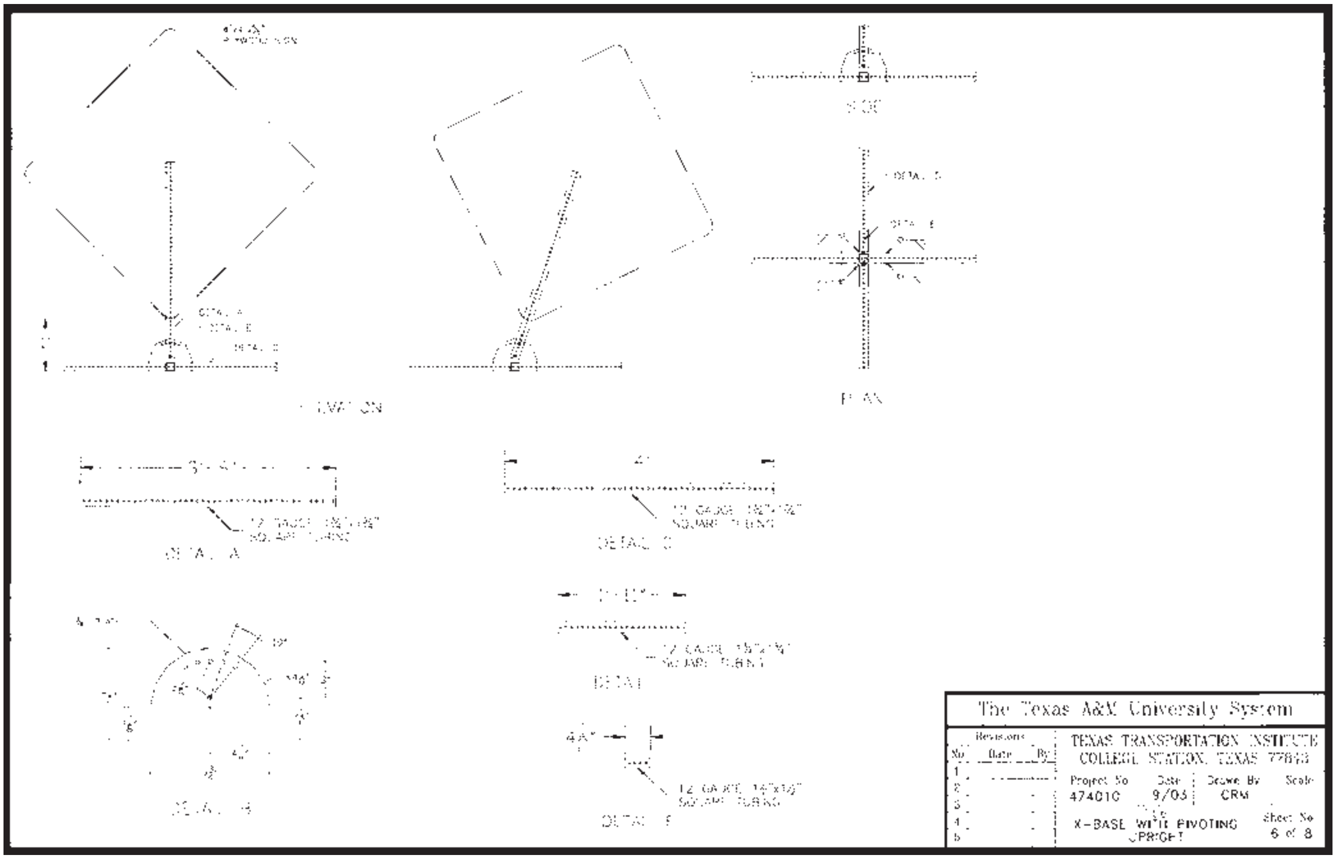


Figure 7.6. Design L6: X-base with pivoting upright.

7.1.7 Design L7: Adjustable Tripod

Figure 7.7 depicts an adjustable tripod support. Both front legs have telescoping sections of square, perforated tubing to provide side-to-side adjustability for placement on roadside slopes. The front legs are connected using two horizontal cross braces. The bolts that attach the cross members to the legs are also used to attach the sign panel. The top of a third leg/support is connected to the upper cross member through the use of angles welded or bolted to the center of the cross member. A short strut (also fabricated from tubing) connects the third leg to the lower cross member.

In addition to good stability, this design has good adjustability in all directions. Side-to-side adjustment for accommodation of placement on slopes is achieved by telescoping one or both of the front legs as needed. Fabrication of the system can be simplified by making one or both of the front legs out of a single piece of tubing. However, if both legs are continuous, side-to-side adjustment is sacrificed. The front-to-back adjustment for accommodating placement on vertical grades is achieved by adjusting the attachment point of the strut to the third leg. By unbolting the strut from the third leg, the unit can be folded for easy transport.

7.1.8 Design L8: HDPE/Wooden Support

The sign support system shown in Figure 7.8 is fabricated from a combination of wooden and plastic materials. The I-shaped skid is fabricated from 51-mm × 152-mm (2-in × 6-in) dimensional lumber. The upright is a lightweight, hollow-profile, 102-mm (4-in) square tube fabricated from HDPE similar to those used in some barricade designs. The HDPE upright is pinned between the legs of the skid. A knee brace fabricated from steel plate or angle runs from the upright to the back of the base. Some front-to-back adjustability can be accommodated by rotating the upright about its pivot point and adjusting the attachment point of the knee brace to the skid. Such adjustability can be facilitated by pre-drilling a number of longitudinal holes in the rear of the skid. If front-to-back tilt adjustability is not needed, the design can be simplified by removing the knee brace and using two bolts to connect the HDPE upright to the skids to develop a moment connection and prevent rotation. There is no direct means of side-to-side adjustment.

Removal of the pin/bolt connecting the knee brace to the skid will facilitate folding and transportation of the system as a unit. If desired, the bolt connecting the upright to the skid

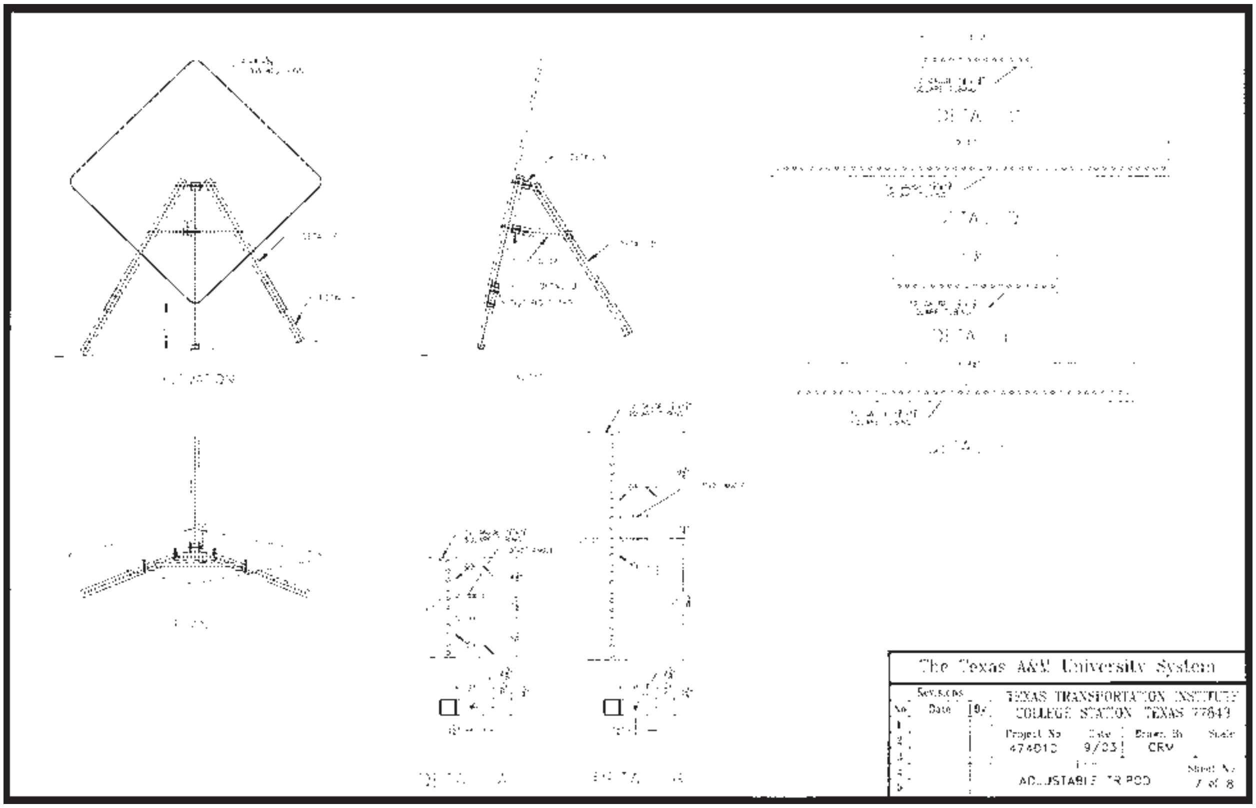


Figure 7.7. Design L7: adjustable tripod.

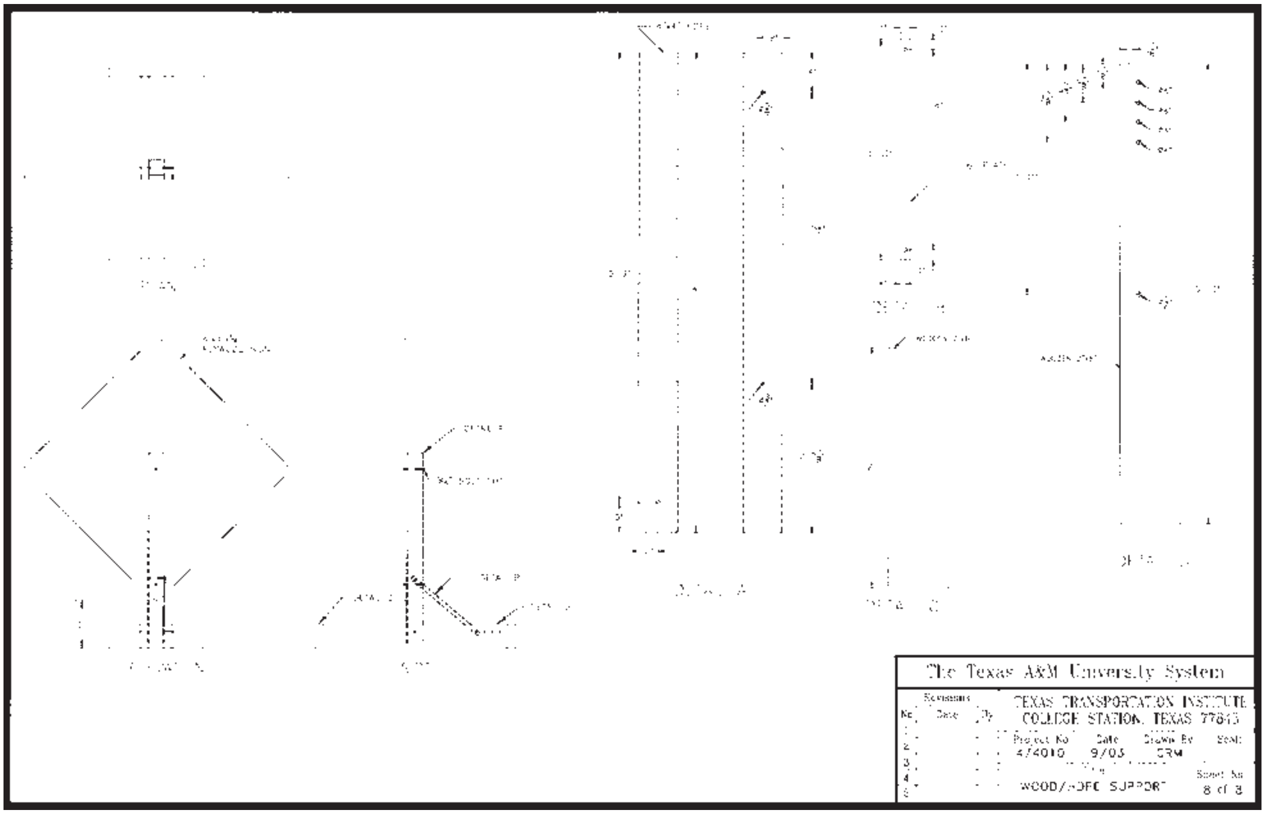


Figure 7.8. Design L8: HDPE/wooden support.

can also be removed to separate the system into two parts to facilitate transportation and/or repair.

This design is relatively inexpensive and easily constructed from readily available materials. However, Design L8 will likely be less durable than the steel-frame designs, and handling will be more difficult because of increased weight. As with other single vertical-support designs, some flutter is likely in high-wind conditions.

7.1.9 Design Summary

The least expensive system to construct is the HDPE/wooden system described as Design L8. However, this system will weigh more and may not be as durable as the steel-frame designs. The least expensive steel-frame design is the X-base system shown as Design L5. Both Design L5 and Design L8 are single-support systems that may be susceptible to flutter in windy conditions.

Design L1 is the next least expensive steel-frame design. The dual uprights are more cumbersome for on-site erection, but they provide more torsional stability of the sign panel to resist possible flutter. The tripod system, described herein as Design L7, provides a reasonable compromise between economy, stability, and adjustability. The incorporation of the adjustment plates into Design L3 (dual support) and Design L6 (single support) increases the fabrication complexity and cost, but provides for adjustability of the sign panel in at least one direction.

Impact performance of low-mounting-height sign support systems is generally enhanced by keeping the sign panel attached to the support members during the collision. Therefore, those sign support systems with connections to multiple uprights may perform better. These systems include Designs L1, L3, L4, and L7. However, some contact of the sign panel with the windshield is expected in most cases, and the degree and severity of the resulting windshield damage will dictate the performance assessment.

7.2 PRIORITIZATION

The design alternatives developed for low-mounting-height sign supports with rigid sign substrates were reviewed and prioritized by the project panel. A weighted average was used to prioritize the designs for testing. Eight points were allocated for a first place vote, seven for second place, and so on. The points allocated for each device by each panel member were then summed to establish a ranking. The device with the greatest number of points is the device with the highest priority. The weighted ranking analysis resulted in the following priority:

1. Design L7: adjustable tripod (51 points)
2. Design L3: pivoting dual uprights (46 points)
3. Design L1: independent dual uprights (40 points)
4. Design L4: H-base with dual uprights (39 points)
5. Design L6: X-base with single pivoting upright (21 points)
6. Design L2: H-base with single upright (20 points)
7. Design L8: wood base with HDPE upright (17 points)
8. Design L5: X-base with single upright (13 points)

Some of the panel members who provided priorities for testing did not rank all eight designs. As a consequence, some of the designs did not receive points in the weighted ranking analysis from all panel members.

Based on the input received, the top four designs were clearly separated from the last four designs in the rankings. The top four designs are all dual-support alternatives, while the last four designs are all single-support systems. The lower ranking of the single-support systems reflects concern of the panel members regarding their ability to function in windy conditions.

7.3 FULL-SCALE CRASH TESTING

All crash test and data analysis procedures used to evaluate the low-mounting-height sign support systems were in accordance with the guidelines presented in *NCHRP Report 350.* Appendix C presents brief descriptions of these procedures. Additionally, the FHWA windshield damage classification criteria were followed in assessing damage to the windshield.

The tests followed the impact conditions of test designation 3-71 of *NCHRP Report 350.* Test 3-71 involves an 820-kg (1808-lb) passenger car impacting the device at a speed of 100 km/h (62 mi/h). This test is considered to be the critical one for most work-zone devices because the propensity for occupant compartment intrusion increases at higher speeds. A 50th-percentile male anthropomorphic dummy was placed in the driver's position and restrained with standard equipment lap and shoulder belts, thus increasing the test inertial weight of the vehicle to approximately 900 kg (1984 lb).

Two separate sign support systems were offset approximately 9 m (30 ft) from one another and placed at different orientations with respect to the path of the vehicle. The first support was oriented perpendicular to the vehicle path for a head-on impact at 0 degree. The second support, placed behind the first sign support, was oriented parallel to the vehicle path for an end-on impact at 90 degrees. The supports were placed on a paved concrete surface.

7.3.1 Test 5

Test Article

In accordance with the established priorities, the first low-mounting-height sign support tested was the adjustable tripod system (referred to previously as Design L7). Figure 7.9 presents details for the variation of this support system that was tested. The two telescoping front legs were composed of a

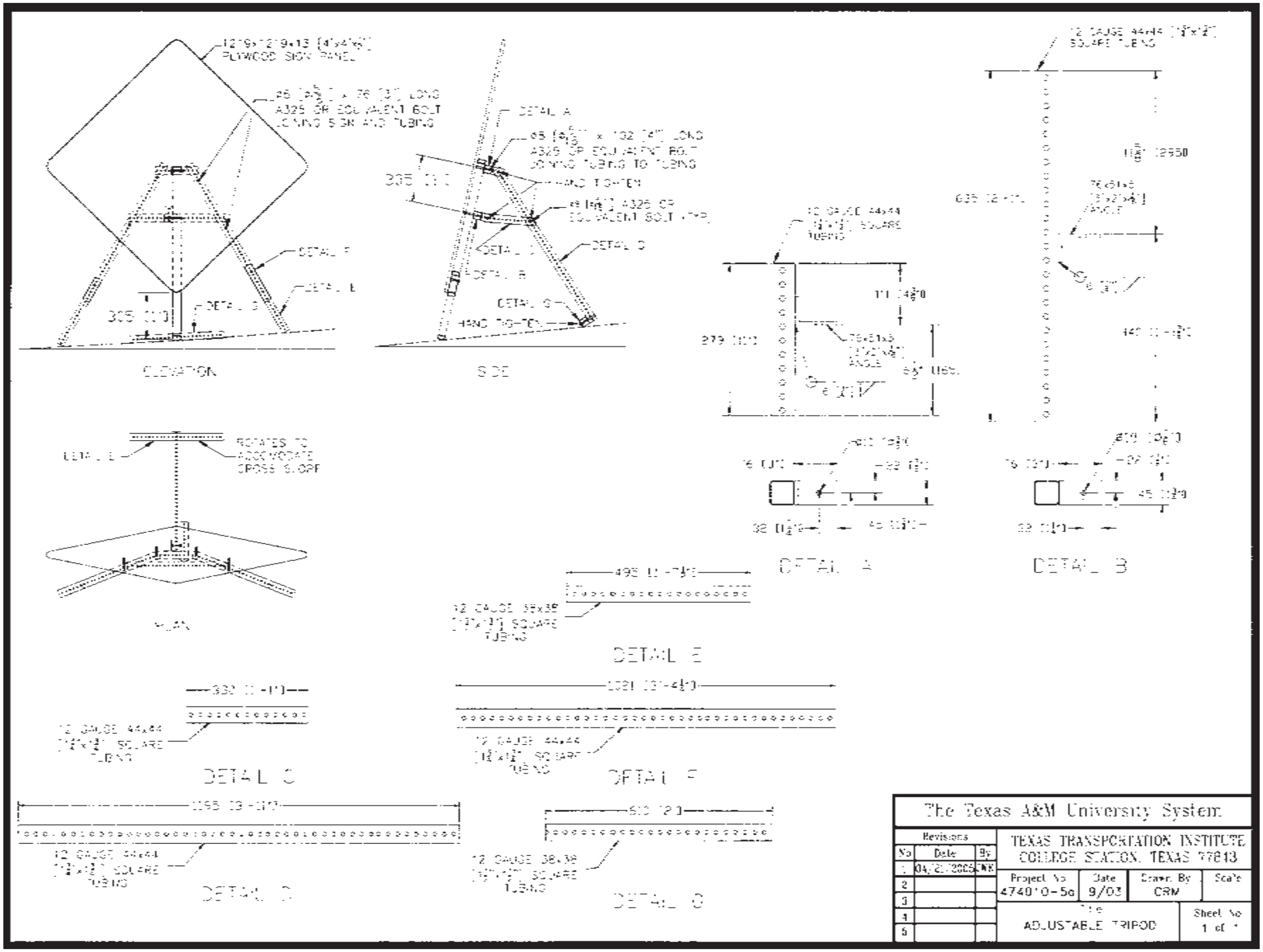


Figure 7.9. Details of the adjustable tripod system used in Test 5.

(continued on next page)

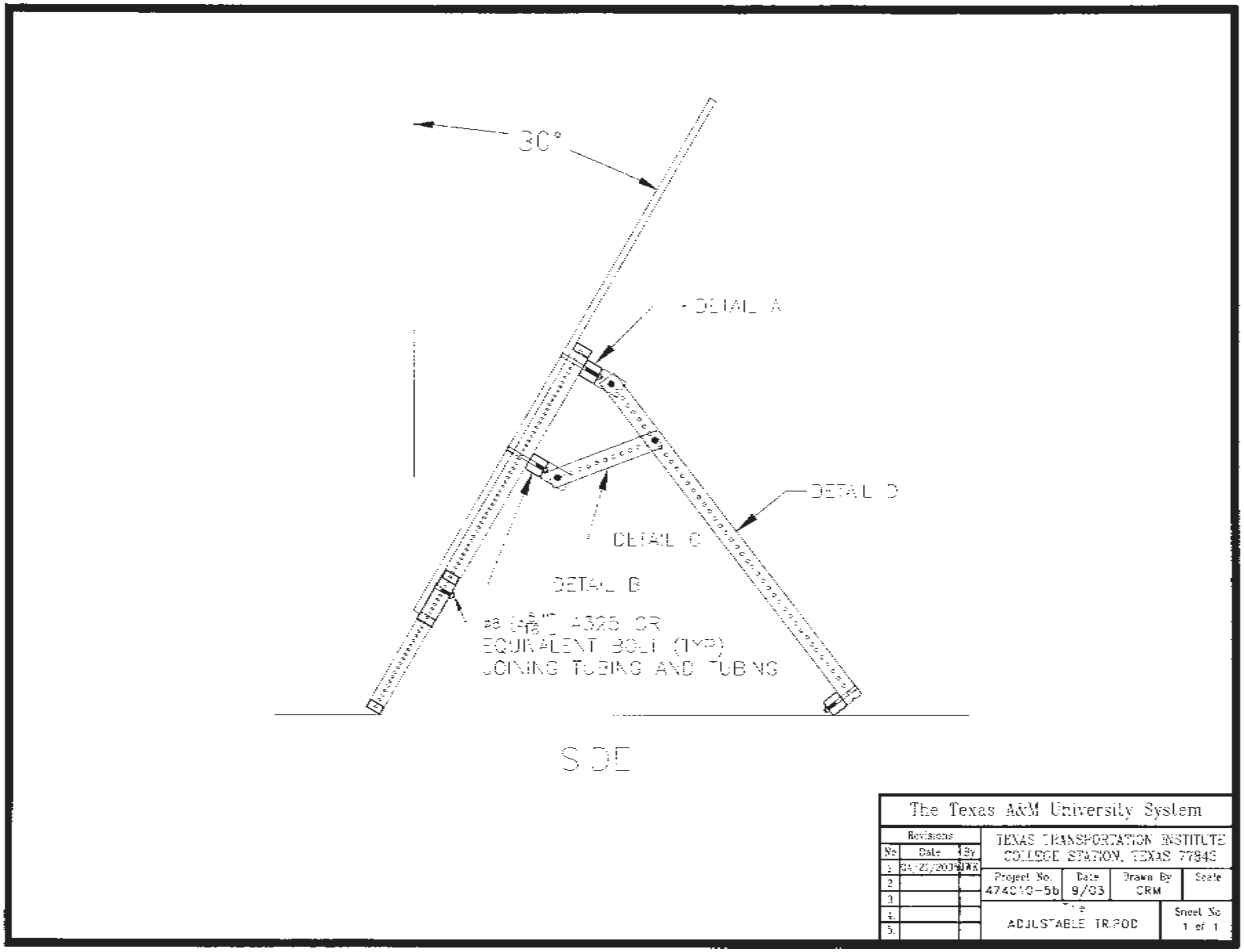


Figure 7.9. (*Continued*)

0.5-m (1-ft, 7½-in) section of 38-mm (1½-in) square, 12-gauge perforated steel tubing inserted into the bottom of a 1.0-m (3-ft, 4½-in) section of 44-mm (1¾-in) square, 12-gauge perforated steel tubing. The front legs are connected together using two horizontal cross braces fabricated from 44-mm (1¾-in) square, 12-gauge perforated steel tubing. The 8-mm (5⁄16-in) diameter, A325 or equivalent bolts that attach the cross members to the front legs are also used to attach the 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in) plywood sign panel to the frame. The mounting height from the ground to the bottom edge of the sign panel was 0.3 m (1 ft). The rear leg of the tripod-style frame is a 1.2-m (3-ft, 11-in) long section of 44-mm (1¾-in) square, 12-gauge perforated steel tubing. The top of the rear leg is connected to the upper cross member through the use of a 44-mm (1¾-in) piece of 76-mm × 51-mm × 5-mm (3-in × 2-in × 3⁄16-in) steel angle welded to the center of the cross member. A short strut (also fabricated from 44-mm [1¾-in] square, 12-gauge perforated steel tubing) connects the rear leg to the lower cross member. An optional cross bar was bolted to the bottom of the rear leg to provide a means of ballasting the system. The single-bolt attachment permits the cross bar to rotate to accommodate placement on a cross slope. Two 18-kg (40-lb) sandbags were placed on the cross bar for the test.

One of the variables related to the tripod design that can affect both impact performance and functionality is the tilt angle of the sign panel. A greater tilt angle will make the system less prone to rotate back into the windshield and will give it more stability. However, as mentioned, the legibility of the sign may be compromised if the tilt angle becomes too large. For the crash test, the tilt angle of the sign panel was set at 30 degrees from vertical. This angle was chosen in consultation with researchers who are recognized experts in signing and retro-reflectivity. The selected tilt angle should provide a visible, legible sign in both daytime and nighttime conditions.

Two tripod sign support systems were placed on a paved concrete surface in the path of the vehicle approximately 9 m (30 ft) apart from one another—one perpendicular to the path of the vehicle and one parallel to the path of the vehicle. Photographs of the completed test installation are shown in Figure 7.10.

Test Vehicle

A 1998 Geo Metro, shown in Figure 7.11, was used for the crash test. Test inertia weight of the vehicle was 820 kg (1808 lb), and its gross static weight was 897 kg (1978 lb). The height to the lower edge of the vehicle front bumper was

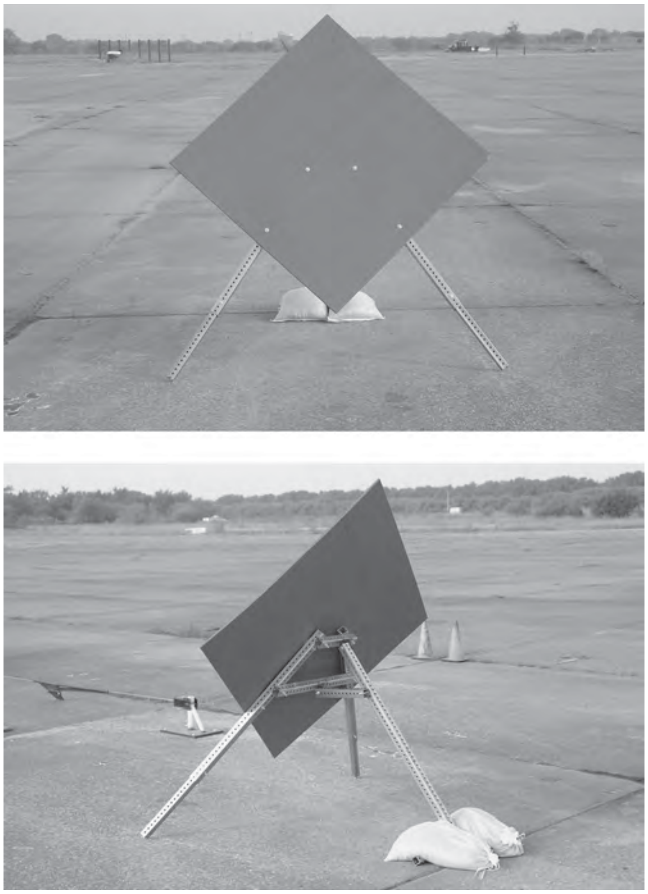


Figure 7.10. Adjustable tripod system used in Test 5.

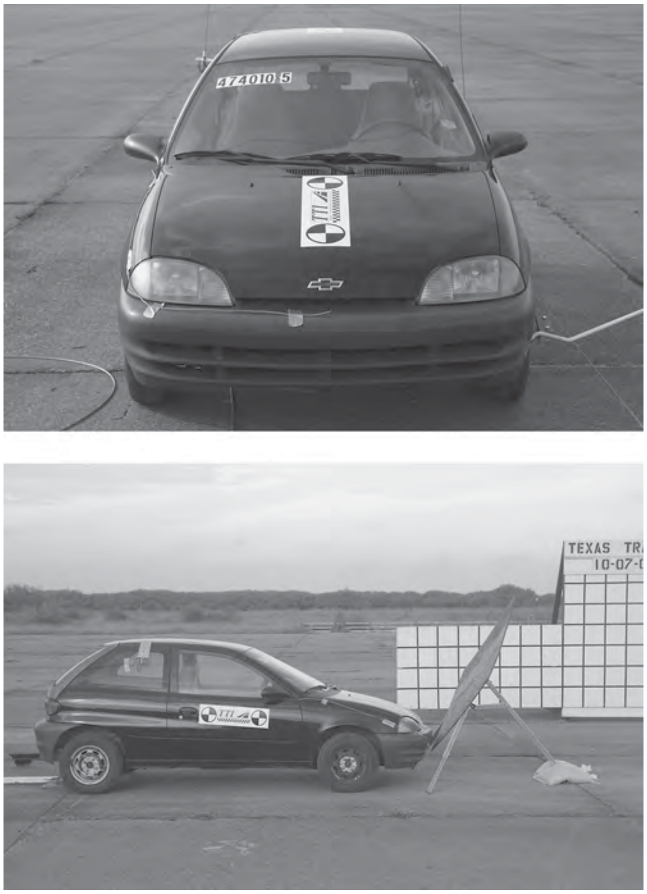


Figure 7.11. Vehicle before Test 5.

400 mm (15.7 in), and the height to the upper edge of the front bumper was 525 mm (20.7 in). Additional dimensions and information on the vehicle are given in Appendix D, Figure D.5. The vehicle was directed into the installation using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just before impact.

Impact Description

An 897-kg (1978-lb) vehicle, traveling at a speed of 100.1 km/h (62.2 mi/h), impacted the first sign support head-on at 0 degree with the centerline of the sign support aligned with the centerline of the vehicle. Shortly after contact, the lower corner of the sign panel deformed, and, at 0.010 s, the legs began to deform. The sign panel began to separate from the frame at 0.015 s. The legs began to slide on the concrete pavement at 0.018 s and, at 0.034 s, the tripod frame closed together and the rear leg contacted the bottom edge/corner of the sign panel. At 0.045 s, the lower fourth of the sign panel fractured; at 0.061 s, the top of the sign panel contacted the windshield at the roofline; and at 0.083 s, the sign panel fractured across its centerline. At 0.095 s, the front of the vehicle lost contact with the legs of the first tripod while traveling at a speed of 94.9 km/h (59.0 mi/h). As the vehicle continued forward, the legs lost contact with the hood at 0.112 s, and the sign panel lost contact with the roof at 0.207 s. The legs continued to travel in front of the vehicle and the right leg of the first tripod contacted the sign panel of the second easel at 0.288 s. However, this contact did not appear to substantially alter the impact behavior of the second support.

At 0.234 s, the vehicle impacted the second sign support end-on at 90 degrees with the centerline of the vehicle aligned with the center of the tripod. Speed of the vehicle at time of contact was 94.4 km/h (58.7 mi/h). Shortly after impact with the second sign support, the support began to slide on the concrete pavement. At 0.398 s, the support began to rotate counterclockwise. At 0.601 s, the vehicle traveled out of view of the perpendicular camera while traveling at a speed of 84.1 km/h (52.3 mi/h).

Brakes on the vehicle were applied at 1.9 s. The vehicle came to rest 82.9 m (272.0 ft) downstream of impact and 4.3 m (14.0 ft) to the left of centerline. Sequential photographs of the test period are shown in Appendix E, Figure E.5.

Test Results

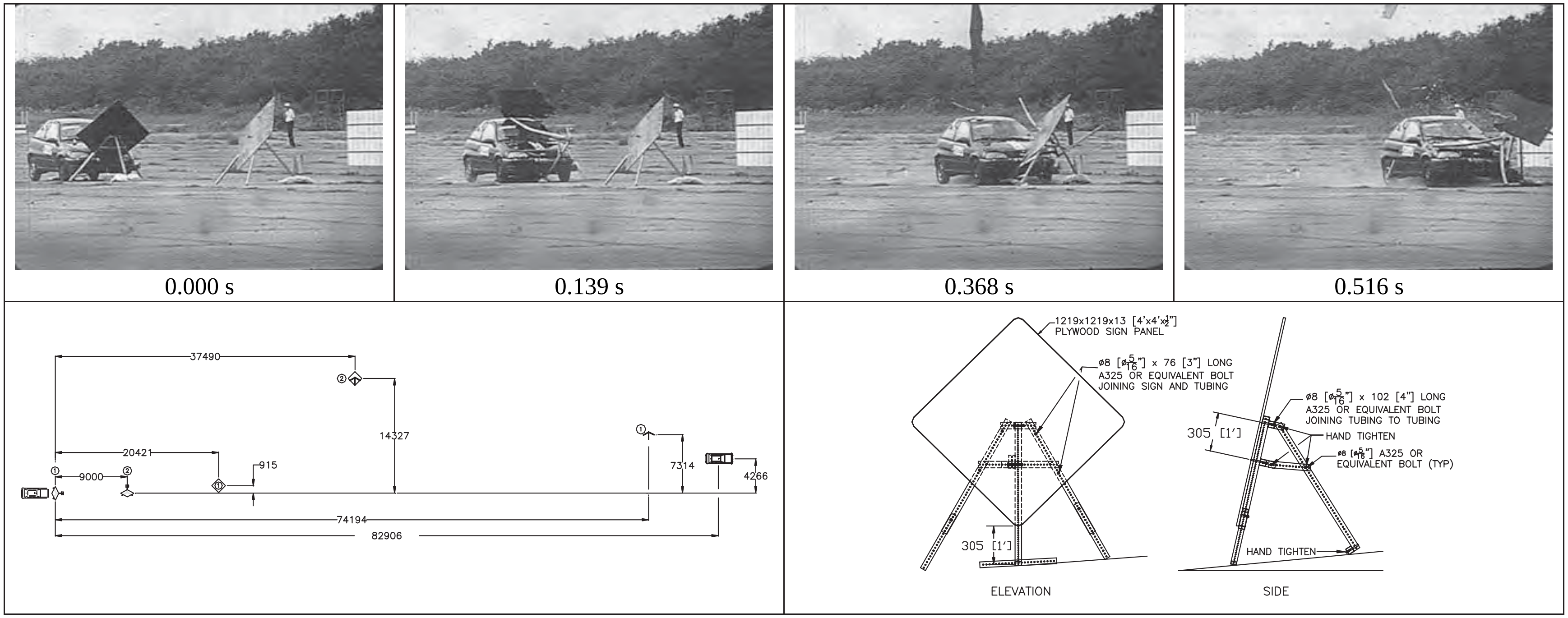
Both sign supports readily activated at impact by yielding and fracturing. The debris was scattered over an area 74.2 m (243.5 ft) long and 14.3 m (47.0 ft) to the left of the initial impact point.

The vehicle remained upright during and after the collision event. Damage to the vehicle is shown in Figure 7.12. The front bumper, left headlight, hood, and roof were deformed. Maximum crush to the exterior of the vehicle was 30 mm (1.2 inches) at the left front at bumper height. The windshield was cracked on the right side over an area 75 mm × 20 mm (3.0 in × 0.8 in) wide, but remained intact and was not deformed inward (FHWA windshield damage classification Case 5). The roof sustained only scuff marks. There was no other measurable occupant compartment deformation.

Figure 7.12. Vehicle after Test 5.

In the longitudinal direction, occupant impact velocity was 2.6 m/s (8.5 ft/s) at 0.440 s, the highest 0.010-s occupant ridedown acceleration was –1.0 g from 0.496 s to 0.506 s, and the maximum 0.050-s average acceleration was –2.0 g's between 0.377 s and 0.427 s. In the lateral direction, the occupant impact velocity was 0.1 m/s (0.3 ft/s) at 0.440 s, the highest 0.010-s occupant ridedown acceleration was –1.3 g's from 0.494 s to 0.504 s, and the maximum 0.050-s average was –0.7 g's between 0.489 s and 0.539 s. The test results are summarized in Figure 7.13. Vehicle angular displacements and accelerations versus time traces are presented in Appendix F, Figures F.29 through F.35.

As summarized in Table 7.1, the perforated steel-tube, tripod sign support system with 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in) plywood sign panel mounted 0.3 m (1 ft) above ground met all required evaluation criteria of *NCHRP Report 350* for both the head-on and end-on impact scenarios. The impact performance of the sign support system is, therefore, considered acceptable.



General Information	
Test Agency	Texas Transportation Institute
Test No.	474010-5
Date	10-07-2004
Test Article	
Type	Low-Mounting-Height Sign Support
Name	Adjustable Tripod System
Installation Height, m (ft)	0.3 (1.0) to Bottom of Sign Panel
Material or Key Elements	Three telescoping, perforated steel-tube legs with plywood sign
Soil Type and Condition	Pavement, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	1998 Geo Metro
Mass, kg	
Curb	805
Test Inertial	820
Dummy	77
Gross Static	897

Impact Conditions	
Angle, deg	0 & 90
Speed, km/h (mi/h) @ 0 deg	100.1 (62.2)
Speed, km/h (mi/h) @ 90 deg	94.4 (58.7)
Exit Conditions	
Speed, km/h (mi/h)	84.1 (52.3)
Occupant Risk Values	
Impact Velocity, m/s (ft/s)	
Longitudinal	2.6 (8.5)
Lateral	0.1 (0.3)
THIV, km/h	9.5
Ridedown Accelerations, g's	
Longitudinal	-1.0
Lateral	-1.3
PHD, g's	1.5
ASI	0.17
Max. 0.050-s Average, g's	
Longitudinal	-2.0
Lateral	-0.7
Vertical	0.7

Test Article Debris Pattern	
Length, m (ft)	74.2 (243.5)
Width, m (ft)	
Left	14.3 (47.0)
Right	0
Vehicle Damage	
Exterior	
VDS	12FD1
CDC	12FDEN1
Max. Exterior Vehicle Crush, mm (in)	30 (1.2 in)
Interior	
OCDI	FS0000000
Max. Occupant Compartment Deformation, mm (in)	0
Post-Impact Behavior	
(during 1.0 sec after impact)	
Max. Yaw Angle, deg	-7
Max. Pitch Angle, deg	2
Max. Roll Angle, deg	4

Figure 7.13. Summary of results for Test 5.

TABLE 7.1 Performance evaluation summary for Test 5

Test Agency: Texas Transportation Institute Test No.: 474010-5 Test Date: 10/07/2004

<table>
<tr><th colspan="2"><i>NCHRP Report 350</i> Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td colspan="2">Structural Adequacy</td><td></td><td></td></tr>
<tr><td><i>B.</i></td><td><i>The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</i></td><td>Both easels readily activated as designed by yielding and fracturing.</td><td>Pass</td></tr>
<tr><td colspan="2">Occupant Risk</td><td></td><td></td></tr>
<tr><td><i>D.</i></td><td><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. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</i></td><td>Debris was scattered along the vehicle path and did not show potential for hazard. The windshield was cracked on the right side but remained intact and was not deformed inward (FHWA Case 5). The left side of the windshield sustained only scuff marks. There was no measurable occupant compartment deformation.</td><td>Pass</td></tr>
<tr><td><i>E.</i></td><td><i>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.</i></td><td>The driver's vision was not blocked.</td><td>Pass</td></tr>
<tr><td><i>F.</i></td><td><i>The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</i></td><td>The vehicle remained upright throughout and after the crash period.</td><td>Pass</td></tr>
<tr><td><i>H.</i></td><td><i>Occupant impact velocities should satisfy the following:</i>
<table>
<tr><th colspan="3"><i>Occupant Velocity Limits (m/s)</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>3</i></td><td><i>5</i></td></tr>
</table></td><td>Longitudinal occupant impact velocity was 2.6 m/s (8.5 ft/s).</td><td>Pass</td></tr>
<tr><td><i>I.</i></td><td><i>Occupant ridedown accelerations should satisfy the following:</i>
<table>
<tr><th colspan="3"><i>Occupant Ridedown Acceleration Limits (g's)</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</i></td><td><i>20</i></td></tr>
</table></td><td>Longitudinal ridedown acceleration was -1.0 g's, and lateral ridedown acceleration -1.3 g's.</td><td>Pass</td></tr>
<tr><td colspan="2">Vehicle Trajectory</td><td></td><td></td></tr>
<tr><td><i>K.</i></td><td><i>After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</i></td><td>The vehicle continued on a straightforward path all along the trajectory path and did not intrude into adjacent lanes.</td><td>Pass*</td></tr>
<tr><td><i>N.</i></td><td><i>Vehicle trajectory behind the test article is acceptable.</i></td><td>The vehicle came to rest behind the test articles.</td><td>Pass</td></tr>
</table>

*Criterion K preferable, not required.

Discussion

The telescoping front legs of this sign support system provide side-to-side adjustability to accommodate placement of the sign stand on roadside slopes. Fabrication of the system can be simplified by making one or both of the front legs out of a single piece of tubing. However, if both legs are fabricated in this manner, side-to-side adjustment is sacrificed. The front-to-back adjustment for accommodating placement on vertical grades is achieved by adjusting the attachment point of the strut to the third leg.

If it is desired to help ensure the tripod is installed in the field with a tilt angle at or near the tested angle of 30 degrees, the rear support leg can be fabricated from thin-wall steel tubing that is non-perforated, and the hole for attachment of the strut can be drilled at the proper location. Use of a single attachment hole would help emphasize the importance of installing the sign at the proper angle. Additional holes can be drilled into the support leg if a range of angles is considered acceptable and some degree of front-to-back adjustment is desired.

The unit can be folded for easy transport by unbolting the strut from the third leg. The assembly and disassembly can be further enhanced by using a pin rather than a bolt to attach the strut to the rear leg.

The cross bar at the bottom of the rear leg is considered optional and can be used when placement of ballast is desired for additional stability. The tested condition, which incorporated the cross bar and ballast, is believed to represent a worst case condition. The ballast provides additional resistance to sliding, which can increase the resulting rotational velocity of the sign stand. Since the tested configuration performed well, the system should perform equally well without the cross bar and ballast.

The steel angles can optionally be attached to the perforated steel-tube cross members using an 8-mm ($\frac{5}{16}$-in) diameter, A325 or equivalent bolt. Such attachment would, if desired, eliminate the need for any welded fabrication in the system.

7.3.2 Test 6

Test Article

Following the priorities established by the project panel, the second low-mounting-height sign support system crash tested was Design L3, which incorporates pivoting dual uprights. Details of the tested system are shown in Figure 7.14. The two uprights are 1.1 m (3 ft, 7 in) long and are fabricated from 38-mm (1½-in) square, 12-gauge perforated steel tubing. A 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in) plywood sign panel is bolted to the uprights using two 8-mm (5⁄16-in) diameter, A325 or equivalent bolts. The uprights telescope inside 0.3-m (1-ft) sleeves fabricated from 44-mm (1¾-in) square, 12-gauge perforated steel tubing such that the bottom edge of the sign panel is 0.3 m (1 ft) above ground. The uprights are secured inside the sleeves using an 8-mm (5⁄16-in) diameter, A325 or equivalent bolt. Each sleeve is bolted to a 5-mm (3⁄16-in) thick, steel pivot plate, which in turn is bolted to the center of a 1.2-m (4-ft) long skid fabricated from 44-mm (1¾-in) square, 12-gauge perforated steel tubing using three 8-mm (5⁄16-in) diameter, A325 or equivalent bolts. The sleeves are bolted to the pivot plates in two locations using 8-mm (5⁄16-in) diameter, A325 or equivalent bolts. A bolt through the center of the pivot plates serves as a point of rotation for the sign panel assembly. A second bolt near the top edge of the pivot plate secures the upright at the desired angle and provides moment resistance to accommodate service loads. In the crash test, the sign panel and uprights were oriented perpendicular to the skids as shown in Figure 7.14.

Two identical sign support systems were placed on a paved concrete surface in the path of the vehicle approximately 9 m (30 ft) apart from one another—one perpendicular to the path of the vehicle and one parallel to the path of the vehicle. Each system was ballasted with four 18-kg (40-lb) sandbags. Photographs of the completed test installation are shown in Figure 7.15.

Test Vehicle

A 1998 Geo Metro, shown in Figure 7.16, was used for the crash test. Test inertia weight of the vehicle was 820 kg (1808 lb), and its gross static weight was 897 kg (1978 lb). The height to the lower edge of the vehicle front bumper was 400 mm (15.7 in), and the height to the upper edge of the front bumper was 525 mm (20.7 in). Additional dimensions and information on the vehicle are given in Appendix D, Figure D.6. The vehicle was directed into the installation using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just before impact.

Impact Description

The 897-kg (1978-lb) vehicle, traveling at a speed of 99.8 km/h (62.0 mi/h), impacted the first sign support at 0 degree with the centerline of the vehicle aligned with the centerline of the sign. Shortly after impact, the legs began to deform to the bumper, and, at 0.007 s, the sign panel fractured at the lower corner on the right side and separated from the right leg at the lower connection point. At 0.017 s, the left leg fractured at bumper height, and, at 0.020 s, the right leg fractured at bumper height. The left leg lost contact with the vehicle at 0.046 s, and the top of the sign panel contacted the windshield at roofline at 0.049 s. At 0.054 s, the right leg lost contact with the vehicle while the vehicle was traveling at a speed of 95.3 km/h (59.2 mi/h). The sign panel lay across the windshield from 0.076 s to 0.119 s. By 0.305 s, the sign panel was completely clear of the windshield and was sliding across the roof.

At 0.368 s, the vehicle contacted the second temporary sign support end-on at 90 degrees with the centerline of the vehicle aligned with the sign panel. The speed of the vehicle at time of impact was 90.4 km/h (56.2 mi/h). As the vehicle continued forward, the leg and skid on the impact side of the sign support folded under the vehicle and the sign panel was carried along in front of the vehicle. The vehicle lost contact with the first sign panel at 0.466 s (sign panel slid off the roof), and the vehicle lost contact with the second sign panel at 0.560 s. At loss of contact with the second panel, the vehicle was traveling at a speed of 76.8 km/h (47.7 mi/h).

Brakes on the vehicle were applied at 1.9 s. The vehicle came to rest 83.5 m (274.0 ft) downstream of impact and 6.1 m (20.0 ft) to the right of centerline. Sequential photographs of the test period are shown in Appendix E, Figure E.6.

Test Results

Both sign supports readily activated at impact by yielding and fracturing. The debris was scattered over an area 86.9 m (285.0 ft) long and 11.7 m (38.5 ft) to the left of the initial impact point.

The vehicle remained upright during and after the collision event. Damage sustained by the vehicle is shown in Figure 7.17. The front bumper, hood, radiator, and roof were deformed and the right front tire was deflated. Maximum crush to the exterior of the vehicle was 180 mm (7.1 in) at the center front at bumper height. The windshield was shattered and deformed inward 60 mm (2.3 in). The FHWA windshield damage classification was a combination of Case 5 and Case 6. There were no holes or tears in the windshield, nor was the windshield separated from its frame. There was no other measurable occupant compartment deformation.

In the longitudinal direction, the occupant impact velocity was 2.4 m/s (7.9 ft/s) at 0.382 s, the highest 0.010-s occupant ridedown acceleration was –4.5 g’s from 0.411 s to 0.421 s, and the maximum 0.050-s average acceleration was –2.8 g’s between 0.372 and 0.422 s. In the lateral direction, the occupant impact velocity was 0.2 m/s (0.7 ft/s) at 0.382 s, the highest 0.010-s occupant ridedown acceleration was 1.3 g’s from 0.430 s to 0.440 s, and the maximum 0.050-s average

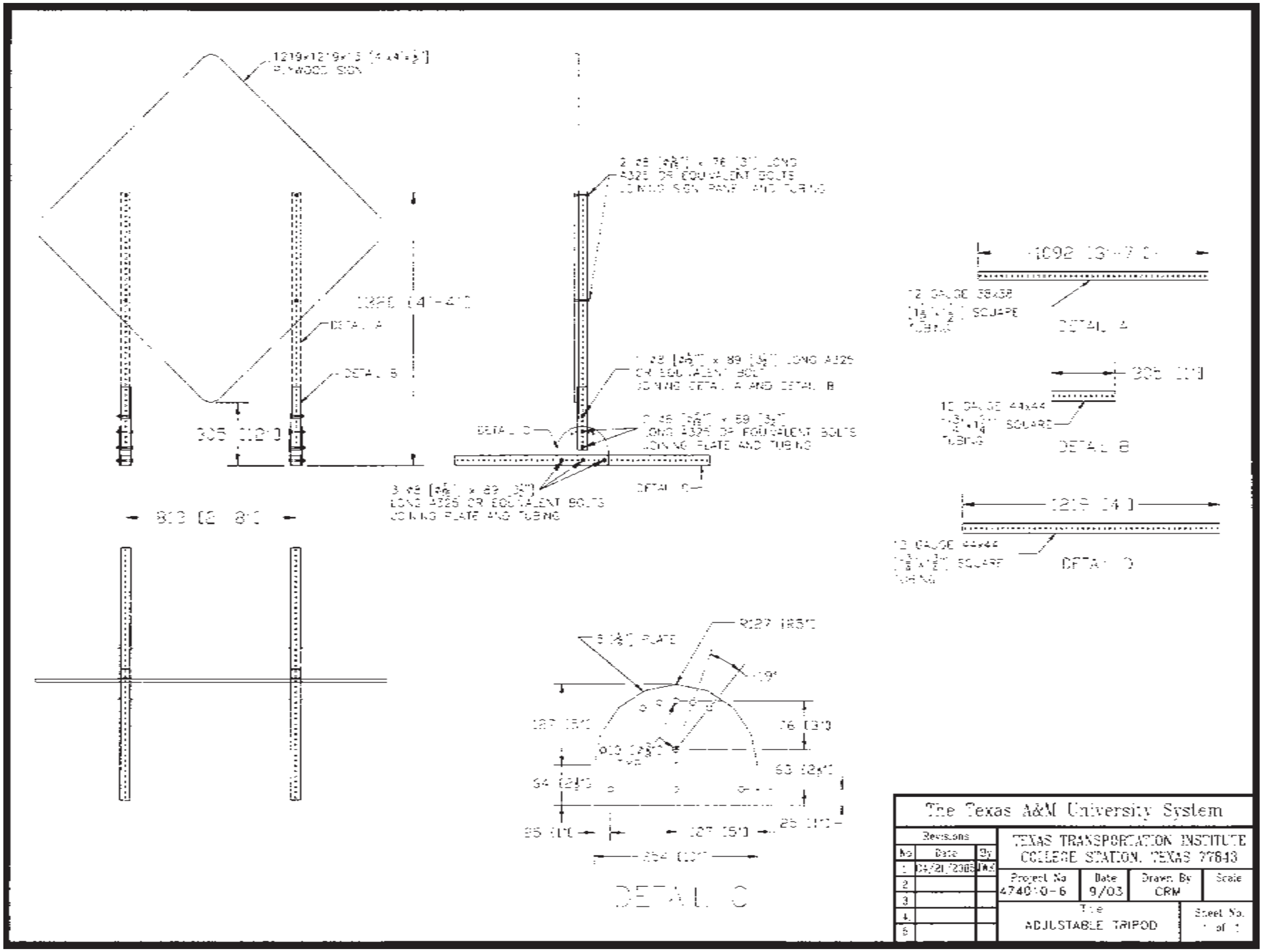


Figure 7.14. Details of the pivoting dual-upright system used in Test 6.

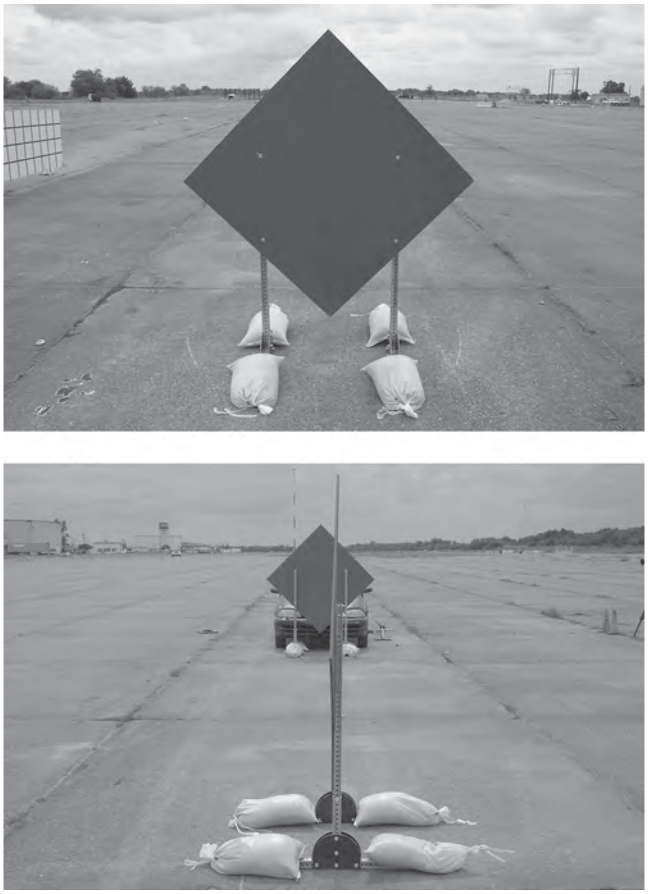


Figure 7.15. Pivoting dual-upright system used in Test 6.

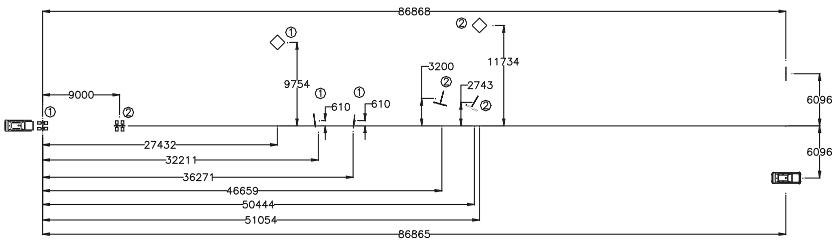
Figure 7.16. Vehicle before Test 6.

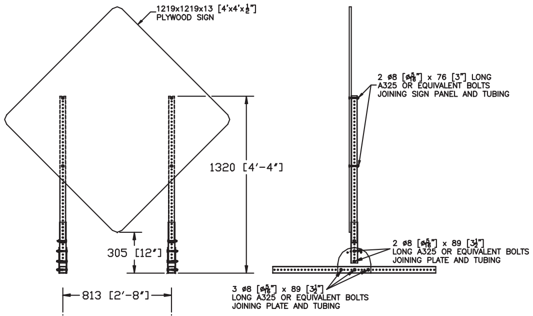
was –0.4 g's between 0.062 s and 0.112 s. These data and other pertinent information from the test are summarized in Figure 7.18. Vehicle angular displacements and accelerations versus time traces are presented in Appendix F, Figures F.36 through F.42.

The 60-mm (2.3-in) deformation of the windshield is considered to be marginally acceptable in terms of the FHWA windshield damage classification scheme. Therefore, since the short dual-leg, perforated steel-tube sign support met all other relevant evaluation criteria of *NCHRP Report 350* (see Table 7.2), the sign support system with dual pivoting uprights and 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in) plywood sign panel mounted 0.3 m (1 ft) above ground is considered marginally acceptable.

Figure 7.17. Vehicle after Test 6.

0.000 s 0.171 s 0.368 s 0.495 s





General Information	
Test Agency	Texas Transportation Institute
Test No.	474010-6
Date	10-07-2004
Test Article	
Type	Low-Mounting-Height Sign Support
Name	Pivoting Dual-Upright System
Installation Height, m (ft)	0.3 (1.0) to Bottom of Sign Panel
Material or Key Elements	Two telescoping, perforated steel-tube legs with plywood sign
Soil Type and Condition	Pavement, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	1998 Geo Metro
Mass, kg	
Curb	805
Test Inertial	820
Dummy	77
Gross Static	897

Impact Conditions	
Angle, deg	0 & 90
Speed, km/h (mi/h) @ 0 deg	99.8 (62.0)
Speed, km/h (mi/h) @ 90 deg	90.4 (56.2)
Exit Conditions	
Speed, km/h (mi/h)	76.8 (47.7)
Occupant Risk Values	
Impact Velocity, m/s (ft/s)	
Longitudinal	2.4 (7.9)
Lateral	0.2 (0.7)
THIV, km/h	9.1
Ridedown Accelerations, g's	
Longitudinal	-4.5
Lateral	1.3
PHD, g's	4.6
ASI	0.25
Max. 0.050-s Average, g's	
Longitudinal	-2.8
Lateral	-0.4
Vertical	-1.3

Test Article Debris Pattern	
Length, m (ft)	86.9 (285.0)
Width, m (ft)	
Left	11.7 (38.5)
Right	0
Vehicle Damage	
Exterior	
VDS	12FD2
CDC	12FDEW2
Max. Exterior Vehicle Crush, mm (in)	180 (7.1)
Interior	
OCDI	FS0000000
Max. Occupant Compartment Deformation, mm (in)	60 (2.3) (windshield)
Post-Impact Behavior (during 1.0 sec after impact)	
Max. Yaw Angle, deg	4
Max. Pitch Angle, deg	3
Max. Roll Angle, deg	2

Figure 7.18. Summary of results for Test 6.

Discussion

Side-to-side adjustment of the sign support system to accommodate placement of the sign stand on roadside slopes is achieved by telescoping one of the uprights inside its sleeve or adjusting the attachment of one of the uprights to the sign panel. To tilt the sign panel to the front or back to accommodate placement on vertical grade, the upper adjustment bolt/pin used to connect the sleeve to the pivot plate is removed and reinserted after aligning the sleeve with one of the other holes in the plate.

The unit can be easily folded for transport as a single unit by removing the top adjusting bolt and laying the sign down. The assembly and disassembly can be further enhanced by using a pin rather than a bolt at this upper connection point on the pivot plate. If desired (e.g., for ease of repair), the sign panel and uprights can be readily detached from the base by removing both bolts from the sleeves.

If front-to-back adjustment is neither needed nor desired, fabrication of the pivot plate can be simplified by using only two holes—one in the center of the plate and one at the top edge. A two-hole pivot plate eliminates the angle adjustment of the uprights, but retains the ability to readily fold the system down for transport. The absence of the additional holes in the pivot plate will not affect the impact performance of the system. If desired, the pivot plates can be welded rather than bolted to the skids. This alternative fabrication method should not adversely affect impact performance.

7.3.3 Test 7

Test Article

The final low-mounting-height sign support system crash tested was Design L1. Details of the tested system are shown in Figure 7.19. The design uses two 1.1-m (3-ft, 7-in) long

TABLE 7.2 Performance evaluation summary for Test 6

Test Agency: Texas Transportation Institute Test No.: 474010-6 Test Date: 10/07/2004

<table>
<tr><th><i>NCHRP Report 350</i> Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td>Structural Adequacy
B. <i>The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</i></td><td>Both short, dual-leg sign supports readily activated as designed by yielding and fracturing.</td><td>Pass</td></tr>
<tr><td>Occupant Risk
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. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</i></td><td>Debris remained along the vehicle path. The windshield was shattered and deformed inward 60 mm (2.3 in) (FHWA Case 5 and 6). There were no holes or tears in the windshield, nor was the windshield separated from its frame. There was no other measurable occupant compartment deformation.</td><td>Marginal</td></tr>
<tr><td>E. <i>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.</i></td><td>The sign panel completely covered the windshield from 0.076 s to 0.119 s; however, this was for only 0.043 s.</td><td>Pass</td></tr>
<tr><td>F. <i>The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</i></td><td>The vehicle remained upright throughout and after the crash period.</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 (m/s)</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>3</i></td><td><i>5</i></td></tr>
</table></td><td>Longitudinal occupant impact velocity was 2.4 m/s (7.9 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 (g's)</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</i></td><td><i>20</i></td></tr>
</table></td><td>Longitudinal ridedown acceleration was -4.5 g's, and lateral ridedown acceleration was 1.3 g's.</td><td>Pass</td></tr>
<tr><td>Vehicle Trajectory
K. <i>After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</i></td><td>The vehicle continued on a straightforward path all along the trajectory path, and did not intrude into adjacent lanes.</td><td>Pass*</td></tr>
<tr><td>N. <i>Vehicle trajectory behind the test article is acceptable.</i></td><td>The vehicle came to rest behind the test articles.</td><td>Pass</td></tr>
</table>

*Criterion K preferable, not required.

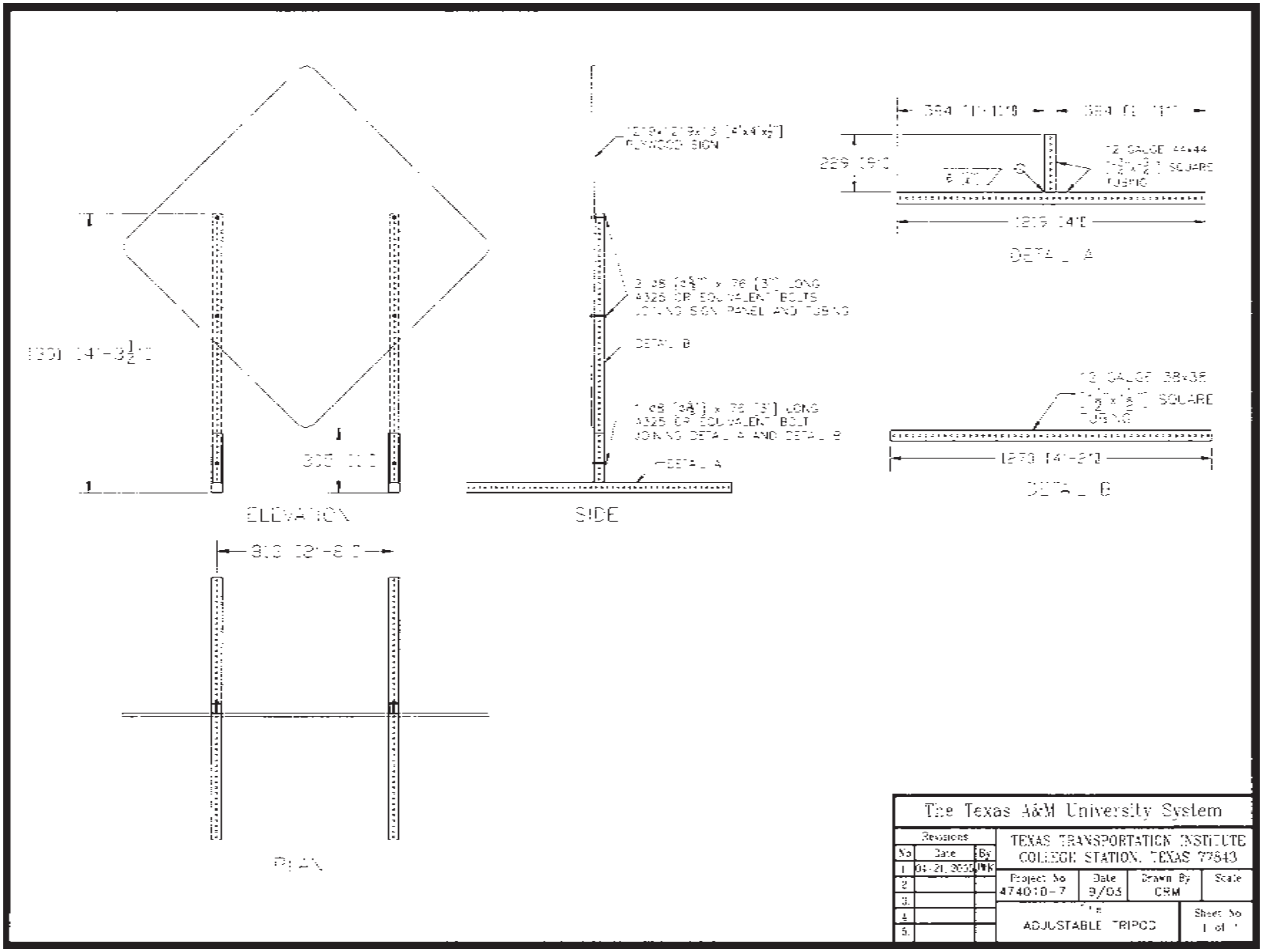


Figure 7.19. Details of the low-mounting-height system used in Test 7.

uprights fabricated from 38-mm (1½-in) square, 12-gauge perforated steel tubing. The uprights telescope inside 229-mm (9-in) sleeves fabricated from 44-m (1¾-in) square, 12-gauge perforated steel tubing. The uprights are secured inside the sleeves at the desired height using an 8-mm (5⁄16-in) diameter, A325 or equivalent bolt. Each sleeve is welded to the center of a 1.2-m (4-ft) long skid fabricated from 44-mm (1¾-in) square, 12-gauge perforated steel tubing. A 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in) plywood sign panel is bolted to the uprights using two 8-mm (5⁄16-in) diameter, A325 or equivalent bolts in each upright. The sign panel serves as the cross bracing for the otherwise independent uprights. The bottom edge of the sign panel was mounted 0.3 m (1 ft) above ground.

Two identical sign support systems were placed on a paved concrete surface in the path of the vehicle approximately 9 m (30 ft) apart from one another—one perpendicular to the path of the vehicle and one parallel to the path of the vehicle. Each system was ballasted with four 18-kg (40-lb) sandbags. Photographs of the completed test installation are shown in Figure 7.20.

Test Vehicle

A 1995 Geo Metro, shown in Figure 7.21, was used for the crash test. Test inertia weight of the vehicle was 820 kg (1808 lb), and gross static weight was 897 kg (1978 lb). The height to the lower edge of the vehicle front bumper was 400 mm (15.7 in), and the height to the upper edge of the front bumper was 525 mm (20.7 in). Additional dimensions and information on the vehicle are given in Appendix D, Figure D.7. The vehicle was directed into the installation using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just before impact.

Impact Description

The 897-kg (1978-lb) vehicle, traveling at a speed of 98.3 km/h (61.1 mi/h), impacted the first sign support head-on at 0 degree with the centerline of the support aligned with the centerline of the vehicle. Shortly after contact, the legs began to deform. At 0.007 s, the sign panel separated from the right leg at the lower connection, and, at 0.012 s, the sign panel separated from the upper connection on the right side. The vehicle lost contact with the left leg at 0.024 s and the right leg at 0.041 s. At this time, the vehicle was traveling at a speed of 94.6 km/h (58.8 mi/h). At 0.053 s, the top of the sign panel contacted the windshield. As the sign panel slid across the windshield, the windshield was substantially covered from 0.073 s to 0.131 s. By 0.216 s, the lower end of the panel cleared the windshield and the sign panel continued to slide across the roof of the vehicle. At 0.271 s, the vehicle lost contact with the sign panel while traveling at a speed of 92.3 km/h (57.4 mi/h).

At 0.373 s, the vehicle contacted the second sign system end-on at 90 degrees with the centerline of the vehicle aligned with the sign panel. Speed of the vehicle at impact was 89.4 km/h (55.6 mi/h). Shortly after impact, the legs began to deform. At 0.374 s, the edge of the sign panel contacted the hood of the vehicle. The vehicle lost contact with the legs of the support at 0.462 s, and with the sign panel at

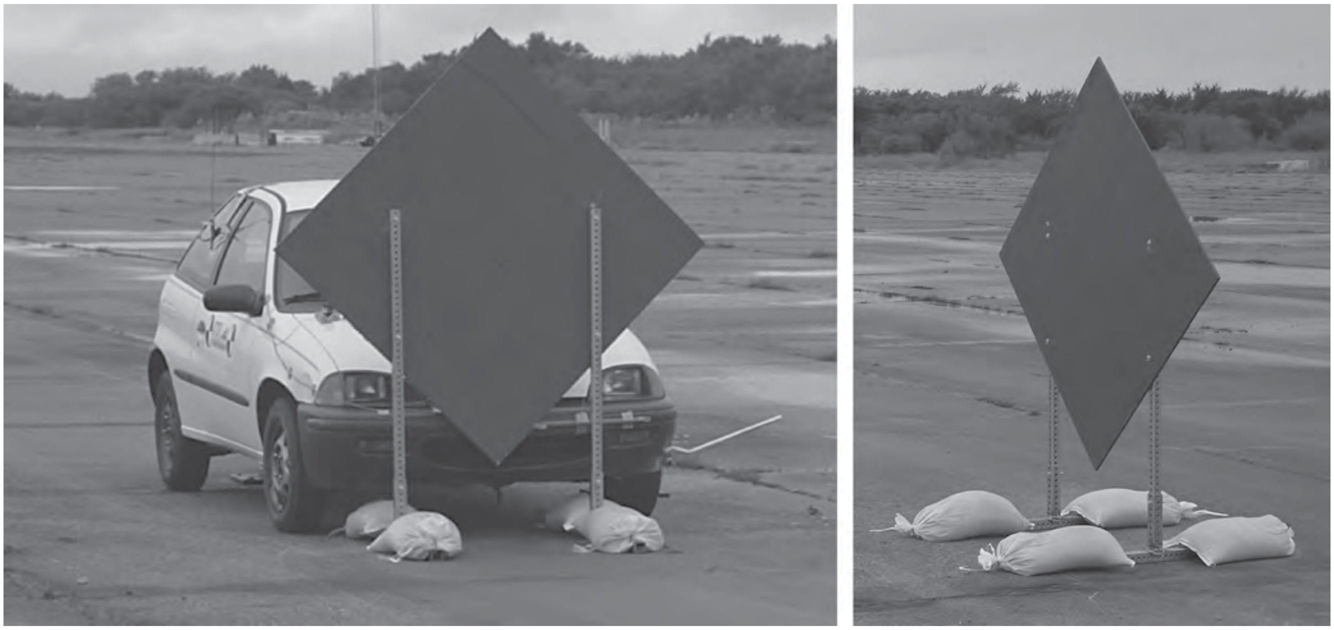


Figure 7.20. Low-mounting-height system before Test 7.

Figure 7.21. Vehicle before Test 7.

Figure 7.22. Vehicle after Test 7.

0.455 s. At this time, the vehicle was traveling at a speed of 76.4 km/h (47.5 mi/h).

Brakes on the vehicle were applied at 1.9 s. The vehicle came to rest 78.3 m (257.0 ft) downstream of impact and 0.3 m (1.0 ft) to the right of centerline. Sequential photographs of the test period are shown in Appendix E, Figure E.7.

Test Results

Both sign supports readily activated at impact by yielding and fracturing. The debris was scattered over an area 60.9 m (200.0 ft) long and 12.0 m (39.4 ft) to the right and 1.7 m (5.5 ft) to the left of the initial impact point.

The vehicle remained upright during and after the collision event. Damage to the vehicle is shown in Figure 7.22. The front bumper, hood, and roof were deformed. Maximum crush to the exterior of the vehicle was 90 mm (3.5 in) at the center front at bumper height. The windshield was shattered and deformed inward 35 mm (1.4 in). The FHWA windshield damage classification was a combination of Case 5 and Case 6. There were no holes or tears in the windshield, nor was the windshield separated from its frame. There was no other measurable occupant compartment deformation.

In the longitudinal direction, the occupant impact velocity was 2.3 m/s (7.5 ft/s) at 0.319 s, the highest 0.010-s occupant ridedown acceleration was –5.6 g's from 0.443 s to 0.453 s, and the maximum 0.050-s average acceleration was –3.4 g's between 0.408 s and 0.458 s. In the lateral direction, the occupant impact velocity was 0.0 m/s (0.0 ft/s) at 0.319 s, the highest 0.010-s occupant ridedown acceleration was –1.2 g's from 0.430 s to 0.440 s, and the maximum 0.050-s average was 0.5 g's between 0.448 s and 0.498 s. These data and other pertinent information from the test are summarized in Figure 7.23. Vehicle angular displacements and accelerations versus time traces are presented in Appendix F, Figures F.43 through F.49.

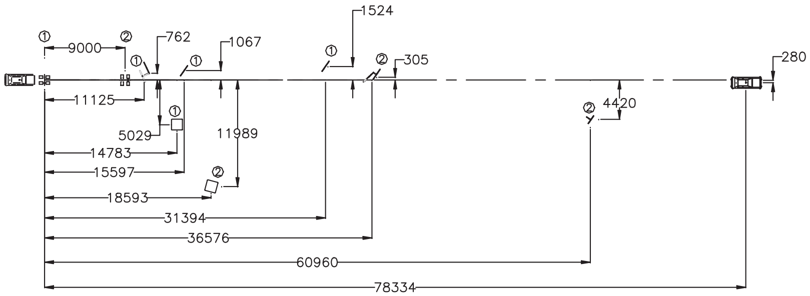
As summarized in Table 7.3, the sign support system with independent perforated steel-tube uprights and 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in) plywood sign panel mounted at 0.3 m (1 ft) above ground met all required evaluation criteria of *NCHRP Report 350* for both the head-on and end-on impact scenarios. The impact performance of the sign support system is, therefore, considered acceptable.

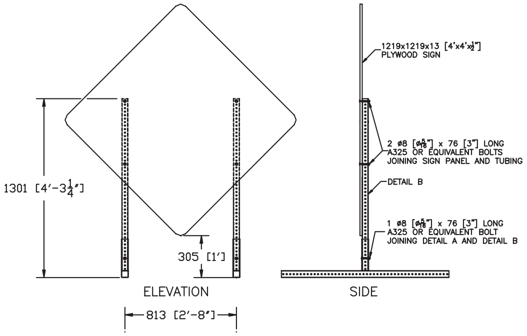
0.000 s

0.126 s

0.373 s

0.470 s





General Information	
Test Agency	Texas Transportation Institute
Test No.	474010-7
Date	10-08-2004
Test Article	
Type	Low-Mounting-Height Sign Support
Name	Dual Vertical-Upright Telescoping Sys.
Installation Height, m (ft)	0.3 (1.0) to Bottom of Sign Panel
Material or Key Elements	Two telescoping, perforated steel-tube legs with plywood sign
Soil Type and Condition	Pavement, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	1995 Geo Metro
Mass, kg (lb)	
Curb	808
Test Inertial	820
Dummy	77
Gross Static	897

Impact Conditions	
Angle, deg	0 & 90
Speed, km/h (mi/h) @ 0 deg	98.3 (61.1)
Speed, km/h (mi/h) @ 90 deg	89.4 (55.6)
Exit Conditions	
Speed, km/h (mi/h)	76.4 (47.5)
Occupant Risk Values	
Impact Velocity, m/s (ft/s)	
Longitudinal	2.3 (7.5)
Lateral	0.0 (0.0)
THIV, km/h	8.1
Ridedown Accelerations, g's	
Longitudinal	-5.6
Lateral	-1.2
PHD, g's	5.6
ASI	0.30
Max. 0.050-s Average, g's	
Longitudinal	-3.4
Lateral	0.5
Vertical	-1.3

Test Article Debris Pattern	
Length, m (ft)	60.9 (200.0)
Width, m (ft)	
Left	1.7 (5.5)
Right	12.0 (39.4)
Vehicle Damage	
Exterior	
VDS	12FD2
CDC	12FDEW2
Max. Exterior Vehicle Crush, mm (in)	90 (3.5)
Interior	
OCDI	FS0000000
Max. Occupant Compartment Deformation, mm (in)	35 (1.4) (windshield)
Post-Impact Behavior (during 1.0 sec after impact)	
Max. Yaw Angle, deg	6
Max. Pitch Angle, deg	2
Max. Roll Angle, deg	-1

Figure 7.23. Summary of results for Test 7.

TABLE 7.3 Performance evaluation summary for Test 7

Test Agency: Texas Transportation Institute Test No.: 474010-7 Test Date: 10/08/2004

<table>
<tr><th colspan="2">NCHRP Report 350 Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td colspan="2">Structural Adequacy</td><td></td><td></td></tr>
<tr><td>B.</td><td>The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</td><td>Both short, dual-leg sign supports readily activated as designed by yielding and fracturing.</td><td>Pass</td></tr>
<tr><td colspan="2">Occupant Risk</td><td></td><td></td></tr>
<tr><td>D.</td><td>Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</td><td>Debris remained along the vehicle path. The windshield was shattered and deformed inward 35 mm (1.4 in) (FHWA Case 5 and 6). There were no holes or tears in the windshield, nor was the windshield separated from its frame. There was no other measurable occupant compartment deformation.</td><td>Pass</td></tr>
<tr><td>E.</td><td>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.</td><td>The windshield was covered briefly from 0.073 s until 0.131 s; however, this was only for 0.058 s.</td><td>Pass</td></tr>
<tr><td>F.</td><td>The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</td><td>The vehicle remained upright throughout and after the crash period.</td><td>Pass</td></tr>
<tr><td>H.</td><td>Occupant impact velocities should satisfy the following:
<table>
<tr><th colspan="3">Occupant Velocity Limits (m/s)</th></tr>
<tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr>
<tr><td>Longitudinal</td><td>3</td><td>5</td></tr>
</table></td><td>Longitudinal occupant impact velocity was 2.3 m/s (7.5 ft/s).</td><td>Pass</td></tr>
<tr><td>I.</td><td>Occupant ridedown accelerations should satisfy the following:
<table>
<tr><th colspan="3">Occupant Ridedown Acceleration Limits (g's)</th></tr>
<tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr>
<tr><td>Longitudinal and lateral</td><td>15</td><td>20</td></tr>
</table></td><td>Longitudinal ridedown acceleration was -5.6 g's, and lateral ridedown acceleration was -1.2 g's.</td><td>Pass</td></tr>
<tr><td colspan="2">Vehicle Trajectory</td><td></td><td></td></tr>
<tr><td>K.</td><td>After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</td><td>The vehicle continued on a straightforward path all along the trajectory path and did not intrude into adjacent lanes.</td><td>Pass*</td></tr>
<tr><td>N.</td><td>Vehicle trajectory behind the test article is acceptable.</td><td>The vehicle came to rest behind the test articles.</td><td>Pass</td></tr>
</table>

*Criterion K preferable, not required.

Discussion

Design L1 was designed to be a very inexpensive and simple-to-construct system. It is the simplest, most inexpensive design from among those considered under the project. As such, the functionality may not be as high as for some of the other designs. However, enhanced adjustability tends to increase the cost and complexity of a system. Placement of the sign support on a roadside slope can be accommodated by adjusting the height of the downhill upright by extending it out of the sleeve. Transportation and erection is facilitated by the removal of bolts connecting the uprights to the skids.

In the opinion of the researchers, the additional of a horizontal cross brace for added stability should not adversely affect the impact performance of this low-mounting-height sign support system if the cross brace is placed across the sleeves at or near the skids.

CHAPTER 8

HIGH-MOUNTING-HEIGHT SIGN SUPPORTS WITH RIGID SIGN SUBSTRATES

The final set of work-zone traffic control devices selected by the project panel for development under Phase II of the project was a high-mounting-height, generic sign support system with rigid sign substrate that can be fabricated from inexpensive, readily available materials. For purposes of this project, high-mounting-height systems were defined as those with a mounting height from 1.5 m to 2.1 m (5 ft to 7 ft).

Many of the acceptable proprietary alternatives available for this set are single-support sign stands that are used in combination with a roll-up–type fabric or vinyl sign panel. The use of a fabric/vinyl sign substrate reduces the weight of the unit and enables it to shed some wind, thereby, reducing the wind load requirements on the support and the amount of ballast required to resist overturn. Although some of these systems can offer advantages such as portability, ease of erection, and adjustable mounting height, more rigid sign substrates are sometimes preferred by user agencies because of their lower cost, availability, and stiffness. Whereas the legibility and retroreflectivity of vinyl roll-up signs may be reduced in windy conditions due to their propensity to lean and deflect (sometimes by design), more rigid sign panels can better retain their shape and orientation in windy conditions if adequate structural support is provided.

However, while some of the characteristics of a rigid substrate may be desirable from a cost or functional standpoint, their rigidity and mass make them more critical than other substrate materials from a crashworthiness standpoint. High-mounting-height, portable sign supports with rigid aluminum or plywood substrates have been problematic in terms of impact performance. If the supports do not release or fracture readily upon impact, they may deform around the front of the impacting vehicle and carry either the sign panel and/or top of the supports into the windshield and roof of the vehicle. In particular, impacts with high-mounting-height sign supports oriented 90 degrees to the travel path of the vehicle have caused the rigid substrate to penetrate the windshield and/or the roof sheet metal.

Successful crash tests usually involve the early release of the sign panel or fracture of the support mast at or near bumper height by installing breakaway mechanisms at bumper height, providing sign panel release mechanisms, or increasing the stiffness of the support to prevent yielding around the front of the vehicle. Sometimes combinations of these design modifications are incorporated. Wooden sign supports fabricated with 102-mm × 102-mm (4-in × 4-in) uprights have been successfully crash tested with rigid sign substrates. A single 102-mm × 102-mm (4-in × 4-in) upright can accommodate a 0.9-m × 0.9-m (3-ft × 3-ft) plywood sign panel (*11*), while dual 102-mm × 102-mm (4-in × 4-in) uprights can readily support a 1.2-m × 1.2-m (4-ft × 4-ft) plywood sign panel. (*3, 4*) Upon impact, the wooden uprights generally fracture at bumper height and near the tops of the skids. The sign panel and fractured supports rotate above and toward the vehicle. Although secondary contact may occur between the sign components and vehicle, the degree of damage is acceptable. An example of a crashworthy, wooden sign support system is shown in Figure 8.1.

The configuration of the sign stand and selection of an appropriate sign substrate are equally important in the design of a portable sign support system. Various design options have been evaluated by different testing agencies. Although some success has been achieved, further work was deemed necessary to develop additional generic sign support alternatives that can be used with rigid or semi-rigid sign substrates.

Under this project, the researchers developed a number of high-mounting-height, portable sign supports for review and prioritization by the project panel. In the development of the systems, design considerations included impact performance, fabrication cost, handling, durability, and adjustability for varying site conditions. Details of these systems are described later in this chapter.

8.1 WIND LOAD ANALYSIS

In addition to being crashworthy, a barricade or temporary sign support should have the ability to withstand anticipated service loads. The uprights of temporary work-zone sign supports should be designed to accommodate the flexural stresses induced by wind loading, and sufficient ballast should be provided to prevent overturn of skid-mounted designs. If a temporary sign support fails or overturns, it cannot perform its intended function and the safety of the work zone may be compromised.

The wind loads on a structure are determined by applying the appropriate wind pressure to the exposed areas of any

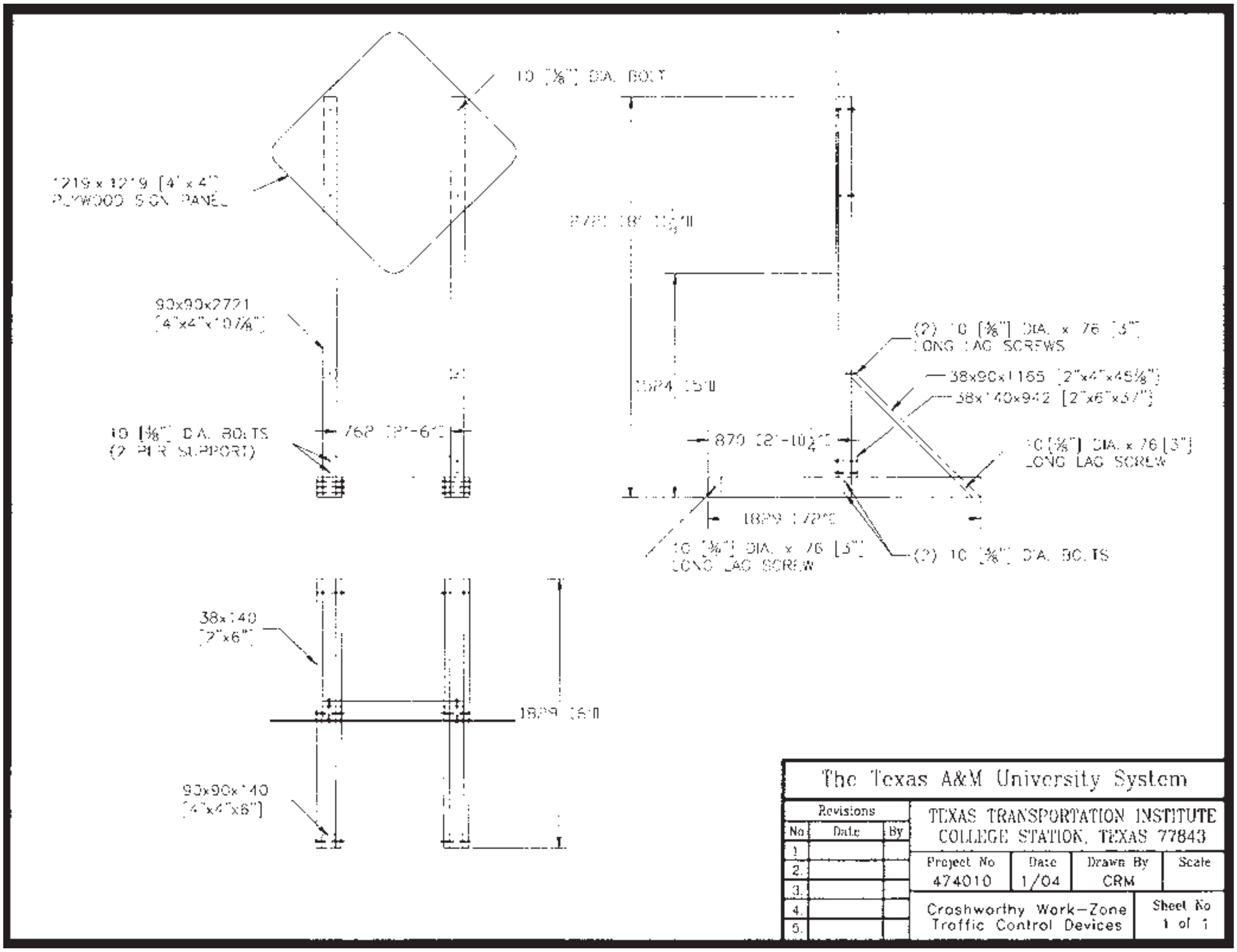


Figure 8.1. High-mounting-height sign support with wooden uprights.

vertical supports, horizontal elements, and/or sign panels. Once the loads have been determined, the stresses in the support members can be computed and compared to the allowable stresses.

Calculations of wind pressure follow the procedures prescribed in the AASHTO *Standard Specifications for Structural Supports for Highway Signs, Luminaries, and Traffic Signals.* (*13*) Given a design wind speed, the associated wind pressure is computed by the following formula:

$$P_z = 0.00256 K_z G V^2 I_r C_d \tag{8.1}$$

where

P_z = wind pressure (psf),
K_z = height exposure factor = 0.87 for sign heights of 5 m (16.4 ft) or less,
G = gust effect factor = 1.14,
V = wind speed (mi/h),
I_r = importance factor, and
C_d = drag coefficient = 1.12 for sign with length/width ratio of 1.

The design wind speed varies with geographic location and the life expectancy of the structure. Because permanent roadside sign structures are considered to have a relatively short life expectancy, they are typically designed for wind speeds based on a 10-year mean recurrence interval per AASHTO specifications. The duration of work-zone activities is typically much less than 10 years. No formal guidance is given regarding an appropriate design wind speed or mean recurrence interval for use in the design of work-zone traffic control devices.

In a 2004 article, R. P. Bligh recommends design wind loads for work-zone traffic control devices. (*14*) The results from field trials indicate that truck-induced wind loading is not a critical design issue for skid-mounted barricades and sign supports. The recommendations are thus based on an analytical determination of design wind speeds associated with different recurrence intervals that correspond to the duration of work-zone activities. Because there are no standard isotach maps for mean recurrence intervals of less than 10 years, the design wind speeds associated with shorter mean recurrence intervals had to be extrapolated. Design wind speeds were determined for mean recurrence intervals ranging from 5 years to 6 months. These design wind loads can be used to size the support members and determine the amount of ballast required to prevent overturn of free-standing, skid-mounted devices.

The results of the analysis are shown in Table 8.1 for four different 50-year wind speeds ranging from 113 km/h to 161 km/h (70 mi/h to 100 mi/h). This range is expected to cover most of the United States except for some extreme coastal locations. The analysis can be extended to other 50-year wind speeds as dictated by local geographic conditions. The peak wind speed for a given mean recurrence interval is determined by multiplying the design wind speed for a 50-year mean recurrence interval by the corresponding conversion factor. For example, the 1-year peak wind speed would be 69 km/h (43 mi/h) given a 50-year wind speed of 113 km/h (70 mi/h), or 79 km/h (49 mi/h) for a 50-year wind speed of 129 km/h (80 mi/h).

The researchers consider a 6-month to 12-month recurrence interval reasonable for purposes of designing work-zone barricades and temporary sign supports. The wind speed associated with this recurrence interval will vary with geographic location based on the region’s 50-year wind speed (see Table 8.1). However, beyond the duration of the activity, other considerations may enter into the determination of an appropriate design wind speed. For instance, if the selected wind speed is too high, it may dictate larger support members that could pose an increased safety hazard to errant vehicles that impact the device. It may also result in an impractical amount of ballast to prevent overturn of skid-mounted systems. Such issues can be partially offset by having personnel check work zones more frequently during adverse weather conditions when blowdowns or other wind-related problems are most likely to occur.

There is no point in designing the structural capacity of the barricade and sign supports for a wind speed significantly greater than the wind speed that will cause overturn. Further, there is little point establishing a design wind speed to address overturn if the required amount of ballast will not be used. For example, along some coastal regions, a 6-month mean recurrence interval is associated with a design wind speed ranging from 59 km/h to 93 km/h (37 mi/h to 58 mi/h). The amount of ballast required to prevent overturn of skid-mounted systems for even the low end of this wind speed range exceeds common practice and may be considered impractical.

Based on the results presented in Table 8.1, with consideration given to the duration of common work-zone activities, a peak wind speed of 72 km/h (45 mi/h) was selected for use in designing the high-mounting-height sign support systems developed under this project. Reducing the wind load requirements to lower levels would reduce ballast requirements to resist overturn but would also necessitate more frequent checks of a work zone in some regions to correct any wind-related problems with the work-zone traffic control devices during adverse weather conditions. If local experience dictates that an unacceptable number of overturns is occurring when the sign support is properly ballasted for this wind speed, a higher design wind speed can be selected to minimize the maintenance aspect.

From equation 8.1, it is determined that a 72-km/h (45-mi/h) wind will create a pressure of 275 Pa (5.75 psf). A wind load analysis was conducted to determine the structural adequacy of various vertical sign support members and the amount of ballast required on the sign support skids to prevent overturn for this wind pressure.

8.1.1 Overturn

The maximum overturning moment that needs to be resisted by the sign support was determined for two different mounting heights (1.5 m and 2.1 m [5 ft and 7 ft]) by applying the design wind pressure on the exposed area of the sign panel. This moment was then used to determine the amount of ballast (i.e., number of 11-kg [25-lb] sandbags) required at or near the ends of the skids to prevent overturn of the sign support when subjected to a design wind speed of 72 km/h (45 mi/h).

As shown in Table 8.2, the number of sandbags required varies with sign panel mounting height and sign panel size.

TABLE 8.1 Peak wind speed as a function of mean recurrence interval

Mean Recurrence Interval		Conversion Factor	Peak Wind Speed, km/h (mi/h)			
Months	Years					
600	50	1.00[*]	161 (100)	145 (90)	129 (80)	113 (70)
300	25	0.93[*]	150 (93)	135 (84)	119 (74)	105 (65)
120	10	0.84[*]	135 (84)	122 (76)	108 (67)	95 (59)
60	5	0.78[*]	126 (78)	113 (70)	100 (62)	89 (55)
24	2	0.68[†]	109 (68)	98 (61)	87 (54)	77 (48)
18	1.5	0.65[†]	105 (65)	95 (59)	84 (52)	72 (45)
12	1	0.61[†]	98 (61)	89 (55)	79 (49)	69 (43)
6	0.5	0.53[†]	85 (53)	77 (48)	68 (42)	60 (37)

[*] Values published in ANSI/ASCE 7-95 (*15*)

[†] Values computed from probability distribution

Source: Bligh (*14*)

TABLE 8.2 Number of 11 kg (25 lb) sandbags required on each side of sign support base

Sign Panel Mounting Height, m (ft)	Sign Panel Size	
	0.9 m x 0.9 m (3 ft x 3 ft)	1.2 m x 1.2 m (4 ft x 4 ft)
1.5 (5)	3	7
2.1 (7)	4	9

Note: Sandbags are assumed to be placed at or near the ends of 1.5-m (5-ft) long skids.

Note that the number of sandbags indicated is for one side of the sign support only. The total number of sandbags required to accommodate wind from either direction would be twice the number shown in Table 8.2. For example, a sign support system with a 1.2-m × 1.2-m (4-ft × 4-ft) sign panel attached at a 2.1-m (7-ft) mounting height would require 9 sandbags on both the front and back sides (for a total of 18) to accommodate a 72-km/h (45-mi/h) design wind speed. Note that the analyses were conducted assuming a skid length of 1.5 m (5 ft). An increase in the length of the skids will permit the ballast to be moved further out from the barricade, thus decreasing the number of sandbags required to resist the overturning moment generated from the applied wind loads.

If the sign mounting height is reduced, the amount of ballast required to resist overturn for a given wind speed is also reduced. Using the same example of a 1.2-m × 1.2-m (4-ft × 4-ft) sign panel, the total number of 11-kg (25-lb) sandbags required to accommodate a 72-km/h (45-mi/h) design wind speed is reduced from 18 to 14 (7 on each side) when the mounting height is reduced from 2.1 m to 1.5 m (7 ft to 5 ft).

Although practices vary, the number of sandbags required to resist overturn of a high-mounting-height sign support in a 72-km/h (45-mi/h) design wind is more than is typically provided in the field. If these quantities are impractical, the design wind speed can be decreased such that the amount of ballast required is reduced to a more practical level. However, as the design wind speed is decreased, the probability or percentage of blowdowns or overturns should be expected to increase. Given the almost daily activity at many work-zone locations, a certain percentage of blowdowns during storms or other high-wind-speed events can probably be tolerated and quickly corrected.

8.1.2 Structural Adequacy

Another consideration is the structural adequacy of the support members. There is no need to provide ballast to prevent a system from overturning in a 72-km/h (45-mi/h) design wind speed if the supports can only withstand a 56-km/h (35-mi/h) design wind speed. Thus, additional analyses were conducted to determine the support member sizes required to accommodate the selected design wind speed. Two types of materials were considered: perforated steel tubing and HPPL. The moment generated by the wind load at the base of the supports (see Table 8.3) was compared to the allowable moment capacity of various support sizes to identify those with sufficient flexural strength for two different mounting heights (i.e., 1.5 m and 2.1 m [5 ft and 7 ft]) and two different sign panel sizes (i.e., 0.9 m × 0.9 m and 1.2 m × 1.2 m [3 ft × 3 ft and 4 ft × 4 ft]). The allowable moment for a given support is a function of both the dimensions and material properties of the support.

Perforated Steel Tube

The square, perforated tube used in steel-framed barricades and sign support systems is commonly manufactured from ASTM A-446 steel, which has a yield stress of 227.5 MPa (33,000 psi). A cross section through the perforated section of the tubing was used in the analyses. As shown in Table 8.4, the section modulus varies with the size and thickness of the tubing. For example, the section modulus for a 44-mm ($1\frac{3}{4}$-in) square, 12-gauge tube is 6.7 mm^3 (0.265 in^3). Thus, the allowable moment capacity based on yield is 988 N·m (729 ft-lb). When compared to the required moment capacities presented in Table 8.3, a single 44-mm ($1\frac{3}{4}$-in) square, 12-gauge tube can be seen to have sufficient flexural capacity to accommodate a 1.2-m × 1.2-m (4-ft × 4-ft) sign panel at a mounting height of 1.5 m (5 ft). Table 8.5 shows the smallest tube needed to support the moment produced by a 72 km/h (45 mi/h) design wind on a 1.2 m × 1.2 m (4 ft × 4 ft) sign panel at different mounting heights for both single and dual supports.

Unless the proper amount of ballast (see Table 8.2) is provided at the base of the structure, the system will overturn before the structural capacity of the supports is reached. If the ability to accommodate a greater design wind speed is desired, the size of the supports could be increased beyond the sizes indicated in Table 8.5. However, the effect of the larger supports on the crash performance of the system would need to be considered.

Hollow-Profile Plastic

The sign support system also can be fabricated from a variety of virgin or recycled plastics including PVC and HDPE. One of the advantages of the hollow-profile plastic is its light weight. Further, it can be readily cut and drilled using standard woodworking tools.

TABLE 8.3 Wind-induced moment at sign support base

Sign Panel Mounting Height, m (ft)	Sign Panel Size	
	0.9 m x 0.9 m (3 ft x 3 ft)	1.2 m x 1.2 m (4 ft x 4 ft)
1.5 (5)	549 N·m (405 ft-lb)	976 N·m (720 ft-lb)
2.1 (7)	690 N·m (509 ft-lb)	1226 N·m (904 ft-lb)

TABLE 8.4 Section properties of common perforated steel-tube sizes

Tube Size	Thickness (gauge)	Area (in^2)	Section Modulus (in^3)
44 mm x 44 mm (1¾ in x 1¾ in)	14	0.392	0.201
51 mm x 51 mm (2 in x 2 in)	14	0.474	0.296
38 mm x 38 mm (1½ in x 1½ in)	12	0.38	0.172
44 mm x 44 mm (1¾ in x 1¾ in)	12	0.485	0.265
51 mm x 51 mm (2 in x 2 in)	12	0.59	0.372
57 mm x 57 mm (2¼ in x 2¼ in)	12	0.695	0.499
64 mm x 64 mm (2½ in x 2½ in)	12	0.803	0.643
64 mm x 64 mm (2½ in x 2½ in)	10	1.01	0.783

Note: Section properties taken through perforated section

The flexural capacity of the support can vary depending on the type of material used and the cross section of the member. HDPE has a tensile strength of approximately 276 Pa (4000 psi). The computed allowable moment for a particular 102-mm (4-in) square, hollow-profile, recycled-plastic support that has been successfully crash tested in barricade applications without signs is approximately 784 N·m (578 ft-lb). (*6*) According to Table 8.3, two of these supports will accommodate a 1.2-m × 1.2-m (4-ft × 4-ft) sign panel mounted at a height of 2.1 m (7 ft). Again, if proper ballast (see Table 8.2) is not provided at the base of the structure, the sign support system will overturn before the structural capacity of the supports is reached.

A sign support system with 102-mm (4-in) square, hollow-profile PVC uprights supporting a 1.2-m × 1.2-m (4-ft × 4-ft) plywood sign panel attached at a 2.1-m (7-ft) mounting height did not pass crash testing. (*5*) The researchers believe the deficiencies of this system can be overcome by using HDPE instead of PVC material for the barricade uprights and sign supports. HDPE is more ductile than PVC and would prevent fracture of the supports, thereby eliminating exposure of the connection bolts, which punched a small hole in the windshield of the test vehicle.

TABLE 8.5 Minimum perforated steel-tube sizes required to accommodate 72-km/h (45-mi/h) design wind speed

Sign Panel Mounting Height, m (ft)	Sign Support Configuration	
	Single Support	Dual Support
1.5 (5)	44 mm x 44 mm (1¾ in x 1¾ in) (12 gauge)	44 mm x 44 mm (1¾ in x 1¾ in) (14 gauge)
2.1 (7)	51 mm x 51 mm (2 in x 2 in) (12 gauge)	44 mm x 44 mm (1¾ in x 1¾ in) (14 gauge)

Note: Results based on wind loading applied to 1.2-m x 1.2-m (4-ft x 4-ft) sign panel

Based on the light weight of the hollow-profile plastic and the good results of the crash tests conducted on this material to date, its use in a high-mounting-height sign support system would have a reasonable probability of meeting impact performance requirements.

8.2 DESIGN ALTERNATIVES

Having defined the basic requirements for the system to accommodate service loads (e.g., mounting height, sign substrate, support material type and size), the researchers developed design alternatives with the potential to meet impact performance requirements and provide some desirable functional characteristics. Factors that were considered are durability, handling, fabrication/repair, and site adaptability.

As for the low-mounting-height sign supports, most of the designs developed for the high-mounting-height sign supports incorporate square, perforated tubing as the support material. Holes punched on all faces of 25-mm (1-in) supports simplify construction and adjustability. Such systems also weigh less than similar systems fabricated from dimensional lumber.

The degree of site adaptability (i.e., the degree of adjustment that a device provides to accommodate variations in field conditions) varies slightly among the design alternatives. While some degree of adjustability is certainly desirable, designs with a high degree of site adaptability tend to be more complex and expensive to construct.

A total of eight high-mounting-height, temporary sign support designs were developed for review and prioritization by the project panel. A brief summary of each of these systems is presented in the following subsections.

8.2.1 Design H1: Dual Uprights with Slip Connection

The sign support shown in Figure 8.2 uses two uprights fabricated from 14-gauge, 44-mm (1¾-in) square, perforated steel tubing to support a 1.2-m × 1.2-m (4-ft × 4-ft) plywood sign panel mounted 2.1 m (7 ft) above ground. This square, perforated steel tubing is considered to be the smallest, lightest, and least expensive size that will resist the selected 72-km/h (45-mi/h) design wind speed for this size sign panel and mounting height (see Table 8.5). The rigid sign panel is bolted to the uprights with a minimum of two bolts in each upright. The use of two uprights improves the torsional stability of the sign support system, which helps reduce sign flutter in windy conditions.

Short, 102-mm (4-in) long sleeves are welded to 1.5-m (5-ft) long skids. The vertical supports are inserted into the sleeves but are not bolted to them. The short sleeve and unbolted connection are incorporated to provide a slip connection

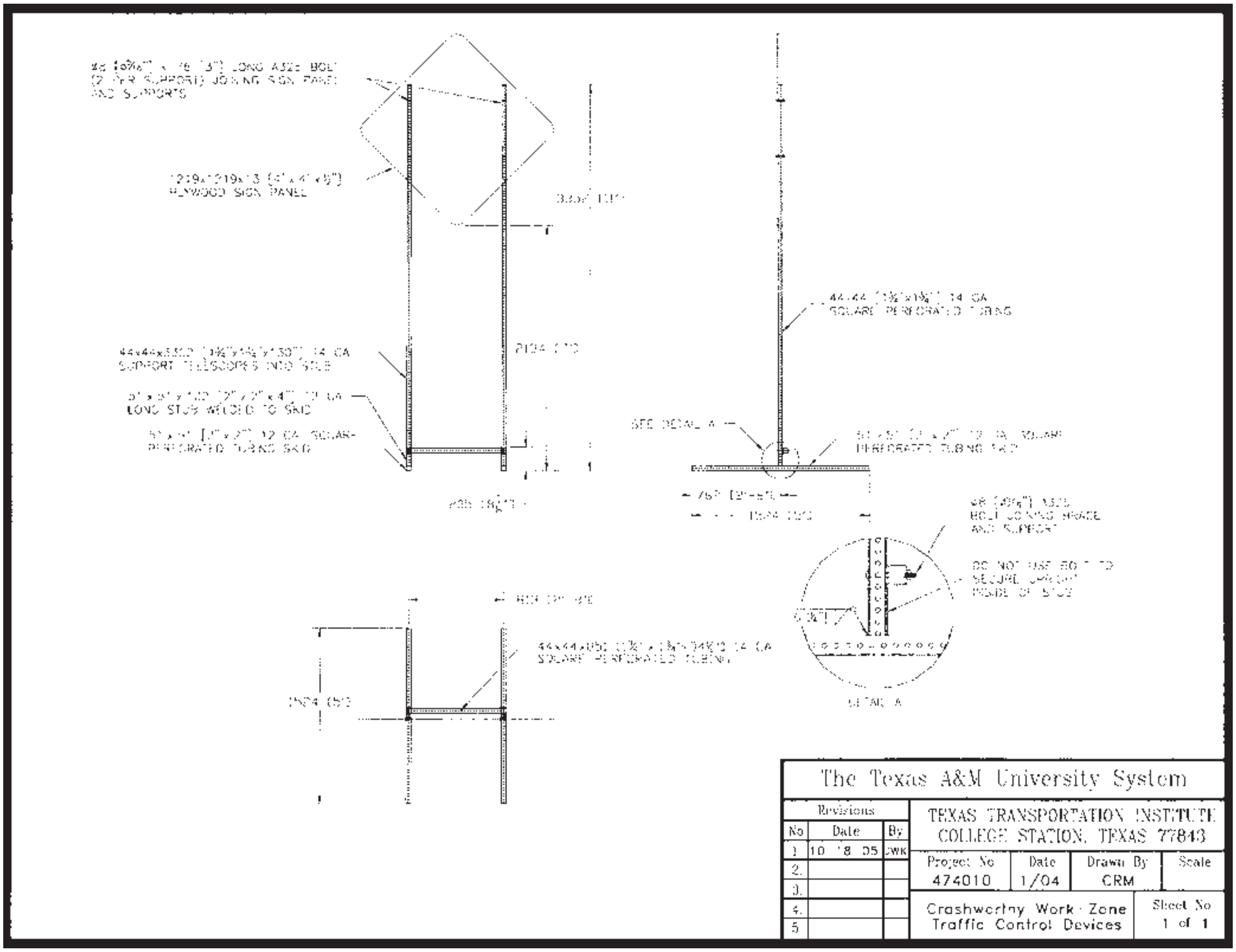


Figure 8.2. Design H1: dual steel-upright sign support with slip connection.

that will facilitate the release of the uprights after impact. The 102-mm (4-in) sleeve is considered sufficient for developing the moment capacity of the upright to accommodate service loads. A horizontal cross brace connects the two uprights just above the sleeves to provide some lateral stability to the sign support frame. The sign panel provides additional cross bracing of the system.

Transportation and erection of this system are also facilitated by the unbolted slip connection of the uprights inside the sleeves. The simple design allows minimal adjustability to account for varying terrain considerations. Roadside slope can be accommodated by lowering the attachment points of the downhill upright on the sign panel as shown in Figure 8.3. Any telescopic adjustment of the uprights is limited by the short sleeve.

A version of this design with a 1.5-m (5-ft) mounting height is shown in Figure 8.4. This design is similar to that shown in Figure 8.2 with the exception of the upright length, which has been decreased to accommodate the lower mounting height. The 1.5-m (5-ft) mounting height is generally believed to be more critical 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 create an increased propensity for secondary impacts of the supports and sign panel with the windshield and roof of the impacting vehicle. Thus, if a 1.5-m (5-ft) mounting height is desired, it is recommended that any crash testing be conducted using a 1.5-m (5-ft) mounting height. If successful, the same sign support system would generally be considered acceptable for a 2.1-m (7-ft) mounting height.

A similar temporary sign support design in which the uprights were bolted inside 152-mm (6-in) long sleeves exhibited unacceptable impact performance. (*11*) In the absence of a release or slip mechanism, the uprights yielded around the front end of the impacting vehicle, causing the sign panel and uprights to contact the top of the windshield and front edge of the roof with sufficient force to induce unacceptable damage. The shorter sleeve and unbolted connection are in-

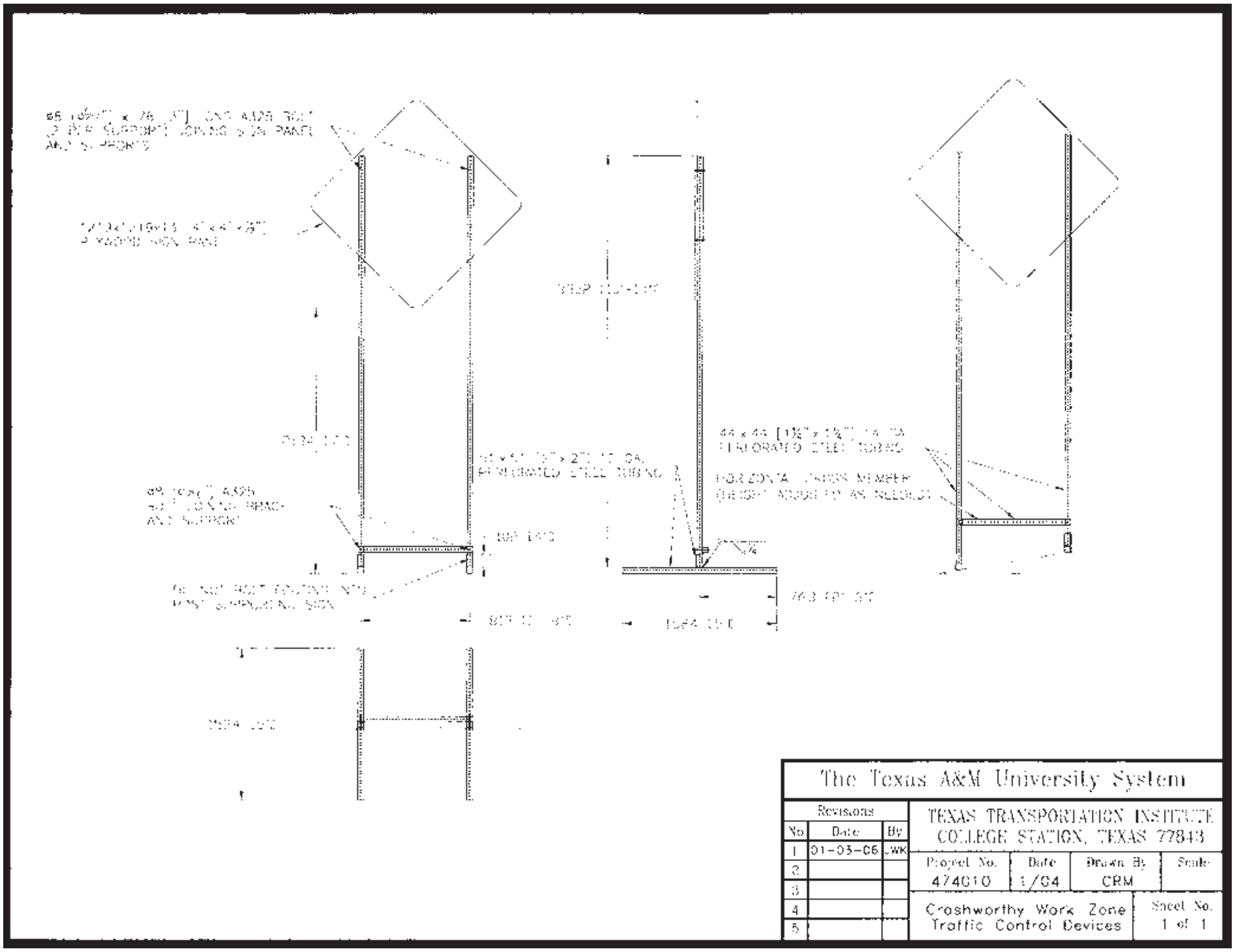


Figure 8.3. Adjustability of dual-support system for placement on slopes.

tended to incorporate a slip mechanism into the design that provides a better probability of meeting impact performance requirements. However, while the uprights in this design are considered to be adequate for resisting wind loads, there is concern that the relatively light 44-mm (1¾-in), 14-gauge tubing may still deform appreciably around the front of the impacting vehicle before releasing from the sleeves. Should such a circumstance occur, the uprights and sign panel would likely contact the windshield and roof of the vehicle with sufficient force to induce an unacceptable level of damage.

8.2.2 Design H2: Strong Dual Uprights with Slip Connection

The sign support system shown in Figure 8.5 is a variation of Design H1 that incorporates larger, stronger sections of perforated steel tubing. The 57-mm (2¼-in) square, perforated steel-tube uprights are inserted into 64-mm (2½-in) sleeves. As in the previous design, the uprights are not bolted into the sleeves but are left unconnected to release the uprights during impact.

The more the supports deform and wrap around the front of the vehicle, the more likely they are to contact the windshield and roof. While the larger uprights are more expensive, their increased flexural strength should reduce deformation before their release, thus improving the likelihood that the system will meet crash test requirements. In addition to being more expensive, the larger members will also be heavier, making the sign support system more difficult to handle. Thus, the trade-off between a higher probability of successful impact performance and greater material cost and weight must be considered.

8.2.3 Design H3: Dual Nested Uprights

Another means of increasing the flexural strength of the uprights to reduce deformation during impact is to nest smaller sections of perforated steel tubing inside slightly larger tubing

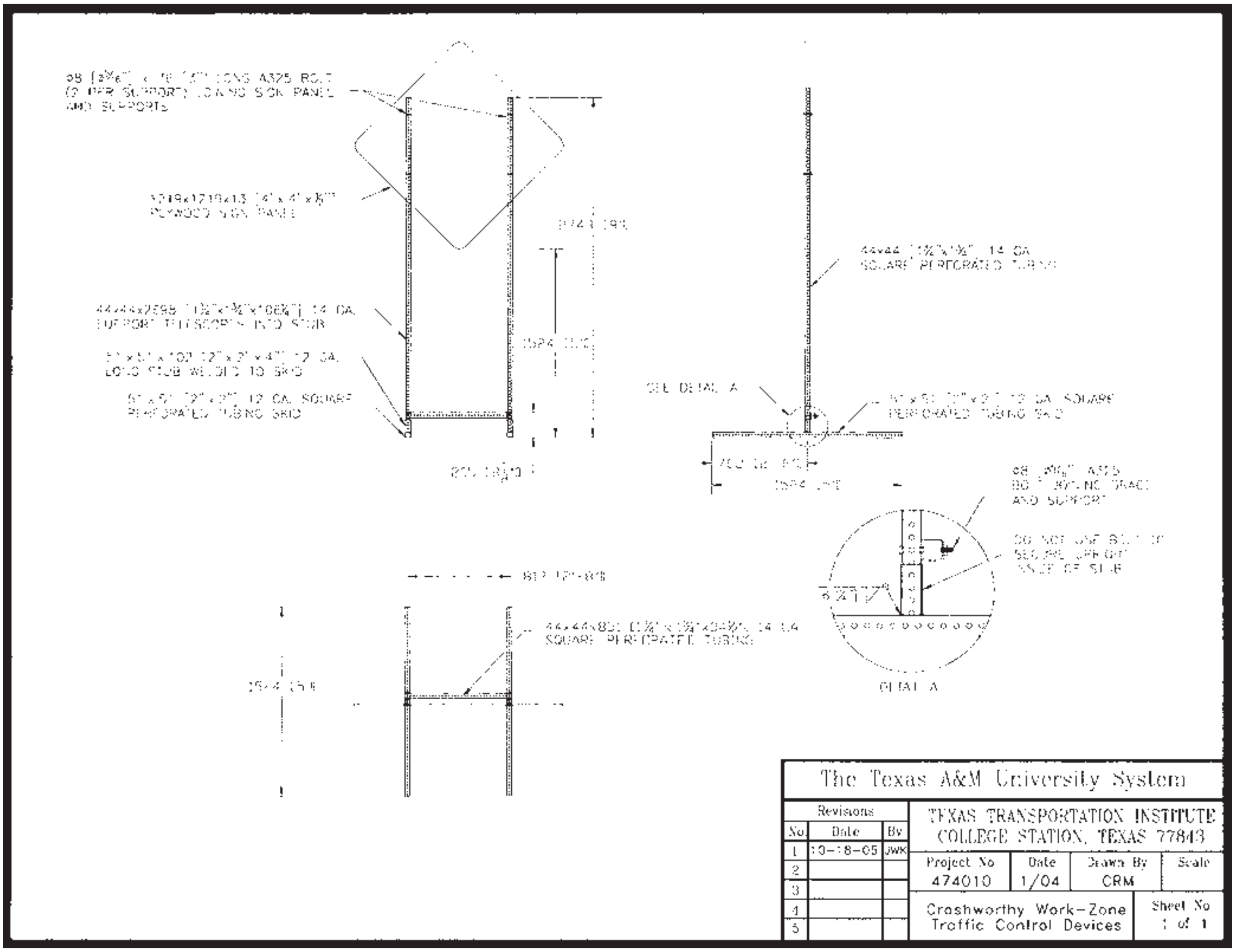


Figure 8.4. Dual steel-upright sign support with 1.5-m (5-ft) mounting height.

to form a composite section. In the design shown in Figure 8.6, a 44-mm (1¾-in) square, perforated steel tube is nested inside a 51-mm (2-in) square tube. To maintain the slip connection without using a third size of tubing for the sleeves and skids, the nested uprights are bolted together in a manner that leaves a 102-mm (4-in) portion of the 44-mm (1¾-in) square inner tube extended past the end of the outer tube. This extended portion is inserted into a 51-mm (2-in) square, 102-mm (4-in) long sleeve that is welded to a 51-mm (2-in) square, perforated steel-tube skid.

When finalizing the designs of high-mounting-height systems for consideration by the panel, the researchers learned that a system similar to Design H3 was successfully crash tested for the Michigan DOT. (*16*) The successful crash test of the similar system led the panel to not prioritize Design H3 under this study. However, this design is discussed in the report for informational purposes and to make readers aware of the successfully crash-tested sign support system.

8.2.4 Design H4: Dual Uprights with Knee Braces

Another potential method for controlling deformation of the uprights without increasing their size is to add a knee brace between the supports and skids as shown in Figure 8.7. The knee brace is attached to the uprights above the bumper height of the impacting vehicle. In theory, upon impact, the deformation and rotation of the uprights toward the car will be initially resisted by the knee brace. Typically, the uprights will hinge and rotate about a point near the vehicle bumper, which is the first point of contact between the uprights and vehicle. The presence of the knee braces above bumper height will constrain the movement of the uprights toward the vehicle until a hinge forms in the uprights above the height of the knee braces or the uprights fracture near the points of attachment to the knee braces. The concept is that the sign support system will have been accelerated by the impacting vehicle

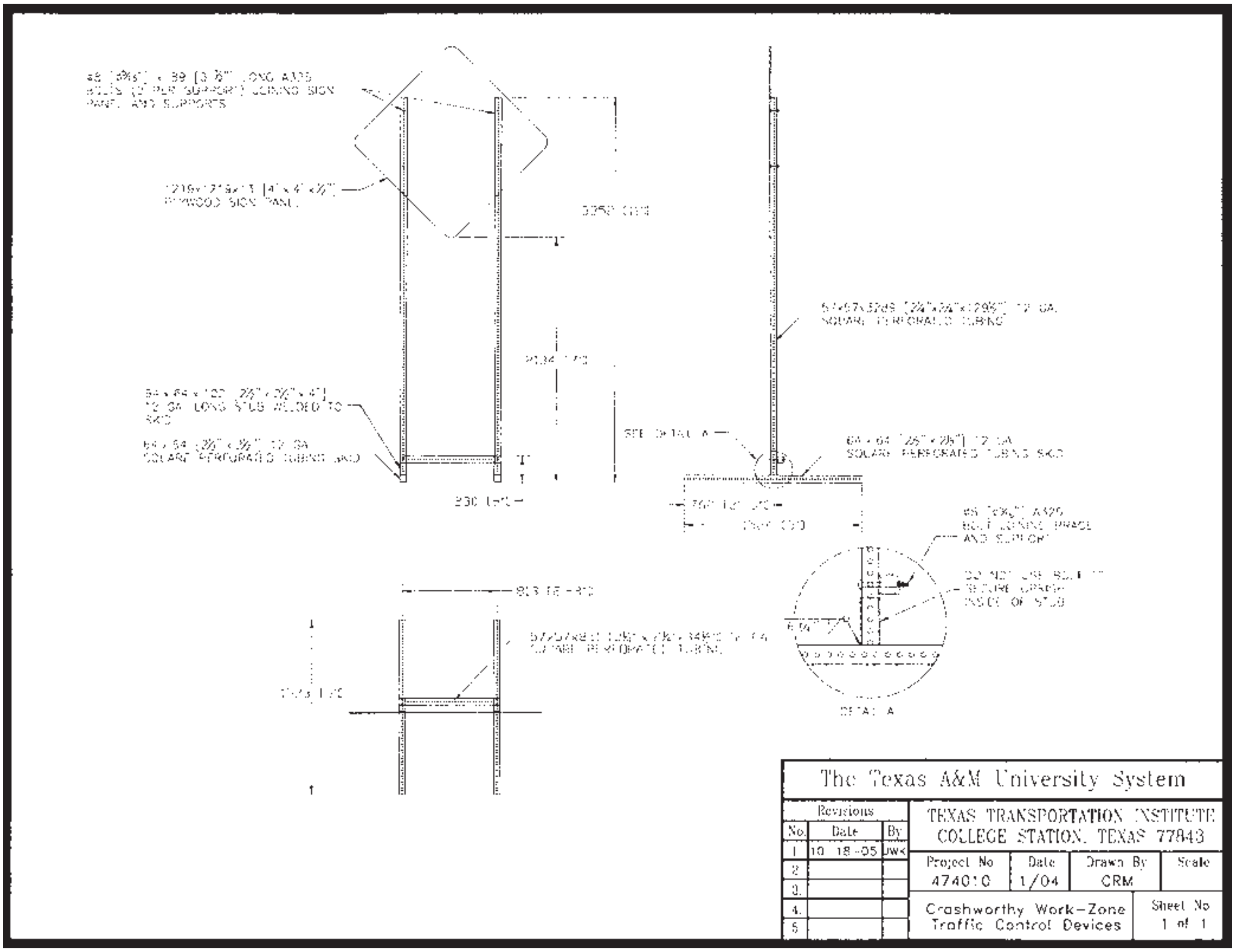


Figure 8.5. Design H2: steel-frame sign support with strong dual uprights.

before fracture or hinging of the uprights, thus reducing the rotational velocity of the uprights toward the vehicle.

Because release of the uprights out of the sleeves will be restricted by the knee braces, a slip mechanism is not required in this design. Thus, the sleeve height can be increased (e.g., 152 mm to 229 mm [6 in to 9 in]) and the uprights can be bolted inside the sleeve. Bolting the uprights into the sleeves can facilitate the telescopic adjustment of the uprights to accommodate placement of the sign support system on roadside slopes. The upright on the downhill side of the slope can be raised within the sleeve and bolted to it to maintain the desired elevation. This ability eliminates the need for adjusting the connection points of the downhill upright on the sign panel.

Transportation and on-site erection of this system will be more difficult than those designs incorporating a slip connection. The bolts connecting the knee braces to the uprights and the bolts connecting the uprights to the sleeves will need to be removed to disassemble the system for transportation. These same bolts will need to be installed to erect the system.

Although Figure 8.7 illustrates this design concept using 14-gauge, 44-mm (1¾-in) uprights (the lightest considered acceptable for the selected design wind load), the knee braces can be used in combination with larger upright sizes to further delay the hinging or fracture of the uprights. The same considerations discussed for Design H2 would be relevant to such a change.

The discussion of this system has thus far focused on a frontal, 0-degree impact. The researchers have concerns regarding the impact performance of this system in a 90-degree impact, because the ability of the knee braces to control the deformation of the uprights will be reduced. Because the uprights would not be permitted to release from the sleeves, the uprights may deform around the front end of the impacting vehicle and permit undesirable damage to the windshield and

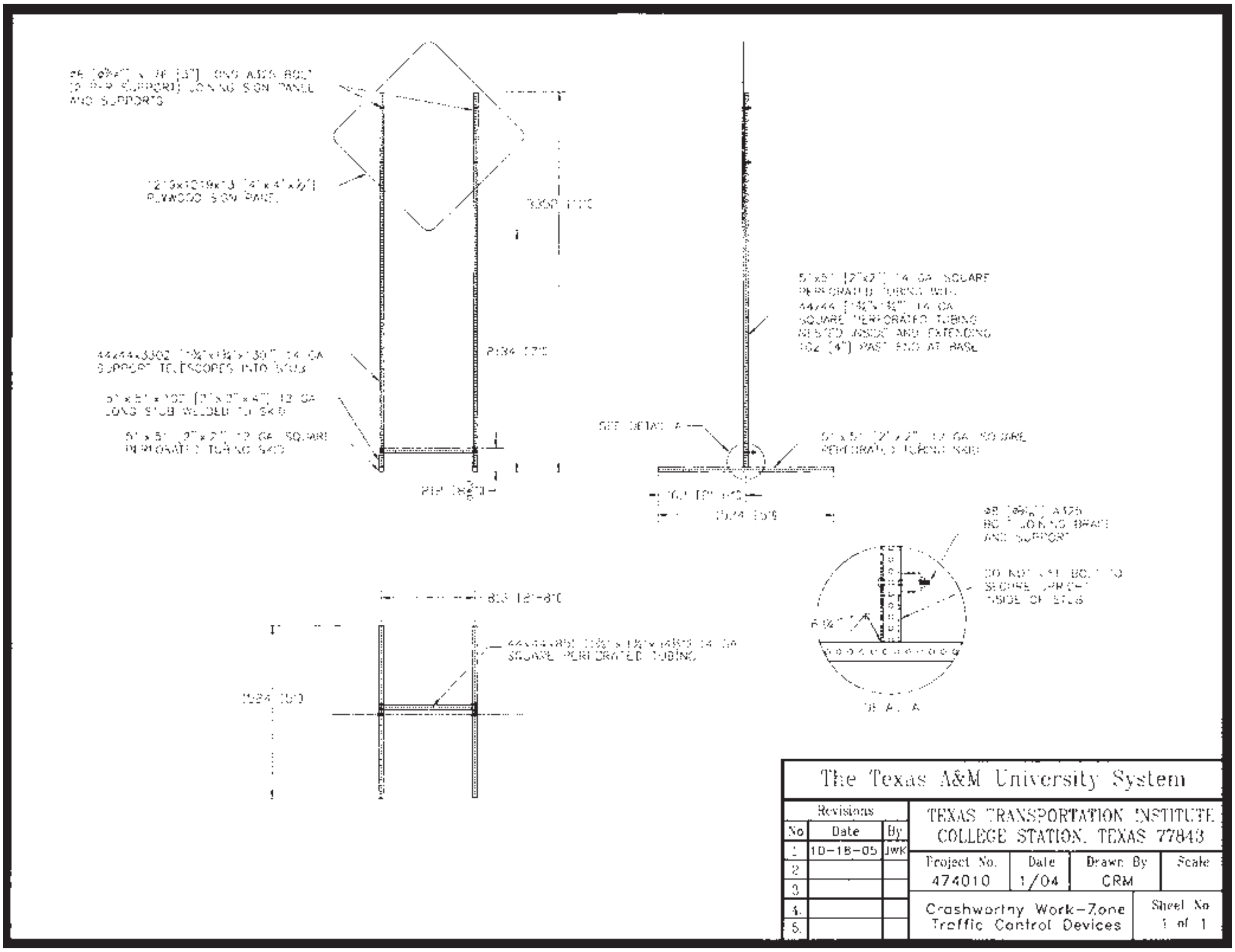


Figure 8.6. Design H3: steel-frame sign support with dual nested uprights.

roof. Such behavior may be overcome through the use of a larger, stronger perforated tube for the uprights.

8.2.5 Design H5: Single Upright with Slip Connection

As has been discussed, increasing the size of the dual perforated steel-tube uprights above the minimum sizes required to handle wind loads may be desirable in order to incrementally increase the probability of successful impact performance. If the size of the upright is 51-mm (2-in) square, 12 gauge or larger, Table 8.5 indicates that a single support can accommodate service loads associated with a 1.2-m × 1.2-m (4-ft × 4-ft) sign panel mounted at a height of 2.1 m (7 ft).

The sign support system shown in Figure 8.8 has an I-shaped base with one central upright fabricated from 51-mm (2-in) square, perforated steel tubing. The central member of the I-shaped base is welded to the center of each skid and a short sleeve is welded to the center of this central member. The upright is inserted into the sleeve but is not bolted to it. This slip mechanism is similar to that incorporated into Design H1. The rigid sign panel is mounted to the single upright using a minimum of two bolts.

This system is a relatively simple design and requires less material than a dual-upright system. However, the savings in material cost are likely offset by a small increase in the required amount of welding. Handling may be facilitated by the lighter weight of the single upright. Assembly and disassembly also may be nominally faster because there is only one upright to insert or remove from a sleeve.

However, signs mounted on single vertical supports will be more susceptible to flutter in windy conditions. Further, this design does not possess any side-to-side adjustability for placement on slopes.

8.2.6 Design H6: Dual Uprights with Raised Slip Joint

Another alternative for a dual-upright sign support system is shown in Figure 8.9. The sizes of the uprights, sleeves, and

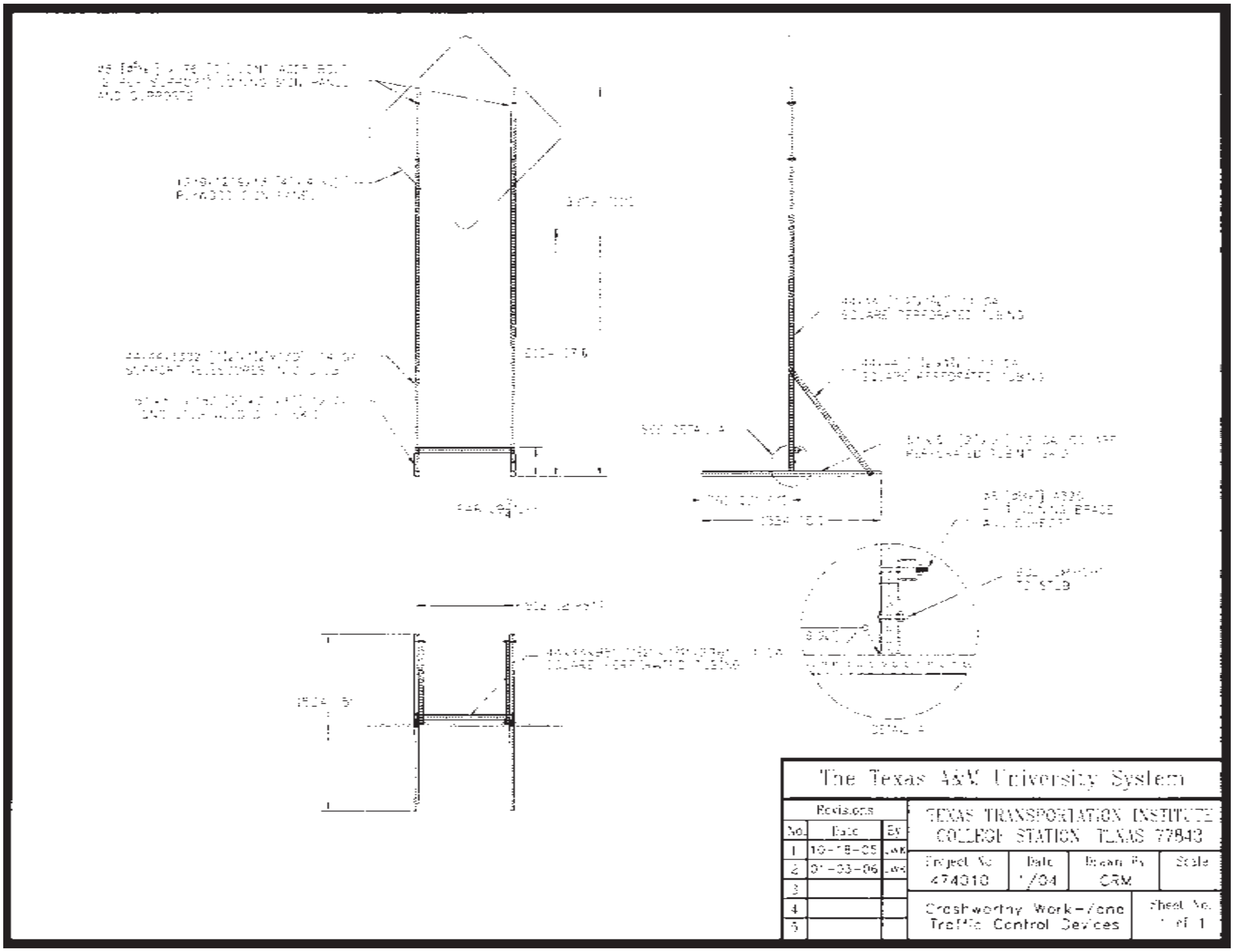


Figure 8.7. Design H4: dual steel-upright sign support with knee braces.

skids are similar to those used in Design H1. The 44-mm ($1\frac{3}{4}$-in) square, perforated steel-tube uprights are inserted into 51-mm (2-in) square sleeves that are welded to 1.5-m (5-ft) long skids. The plywood sign panel is bolted to each upright at two locations.

The difference between this design and Design H1 is the increased length of the sleeve. The sleeve is increased in length from 102 mm to 863 mm (4 in to 34 in). The top of the sleeve is 914 mm (36 in) above ground, which is greater than the bumper height of passenger vehicles. The uprights are inserted inside the sleeves only to a depth of 102 mm (4 in) and they are not bolted to the sleeves. A bolt through the sleeve is used as a shelf for the inserted upright to rest on.

This connection detail effectively raises the height of the slip joint from near ground level to above bumper height. In theory, this higher slip joint will reduce deformation of the uprights before their release from the slip connection and will result in a higher point of rotation of the uprights and sign panel after their release. The probability of secondary contact between the sign panel and the windshield of the impacting vehicle should thereby be reduced.

The taller sleeves welded to the skids may make transportation of this system more cumbersome than some of the other designs. The cross braces can be attached to uprights just above the sleeves rather than to the bottom of the sleeves to permit each skid to be handled separately and laid down for ease of transport. As with the other systems incorporating a similar connection, the deployment of this system is facilitated by the simple slip connection.

8.2.7 Design H7: Dual Three-Piece Uprights

The sign support system shown in Figure 8.10 has a raised slip joint similar to Design H6. It is differentiated from Design H6 through the addition of an upper slip joint below the sign panel. Thus, the upright is effectively composed of three pieces of tubing. The middle section of the three-piece upright slides into the sleeve to form a slip connection similar to the one used in Design H6. The insertion depth into the

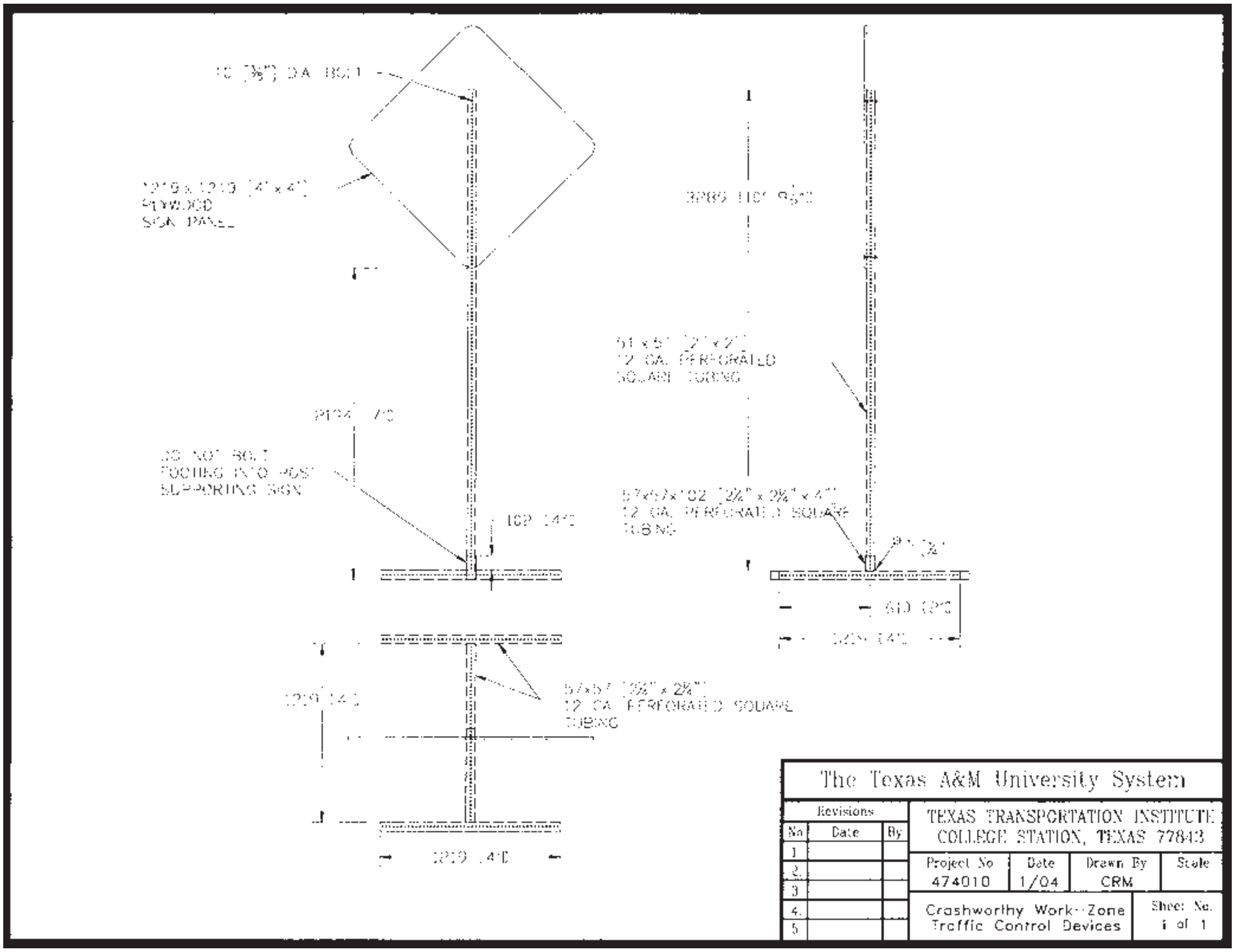


Figure 8.8. Design H5: single steel-upright sign support with slip connection.

sleeve is limited to 102 mm (4 in) by a stop bolt on which the lower end of the middle section rests. The upper section of the three-piece upright is the same size as the sleeve and slides over the top end of the middle section. The insertion depth of the middle section into the upper section is limited to 102 mm (4 in) by a stop bolt on which the lower end of the upper section rests. Thus, there are two slip connections in this system.

In theory, this design should permit the upright to separate into two pieces during impact. Each component will thus have a mass that is less than the combined mass of the system, which should help reduce the severity of contact with the vehicle should a secondary impact occur. Release of the sign panel at an increased height above ground will also potentially increase the height of its point of rotation, thereby reducing the likelihood of secondary contact with the impacting vehicle.

The slip connections should result in quick assembly. However, fabrication and handling may be complicated by the multiple components that compose the system.

8.2.8 Design H8: Dual HDPE Uprights

Design H8, shown in Figure 8.11, is a combination wood and plastic support system. The skids are fabricated from wooden 51-mm × 152-mm (2-in × 6-in) dimensional lumber. The uprights are lightweight, hollow-profile, 102-mm × 102-mm (4-in × 4-in) tubes fabricated from HDPE similar to those used in some barricade designs. The HDPE uprights are inserted between the legs of each skid. Rotation of the uprights is resisted by two short, hollow-profile plastic blocks bolted inside the skids on either side of the uprights. This slip connection will permit the uprights to release from the skids upon impact.

This design is relatively inexpensive and easily constructed from readily available materials. However, the hollow-profile plastic and dimensional lumber may be less durable than the steel-frame designs, and handling will be more difficult because the wooden skids increase the weight. If desired, the weight of the system can be reduced to improve handling

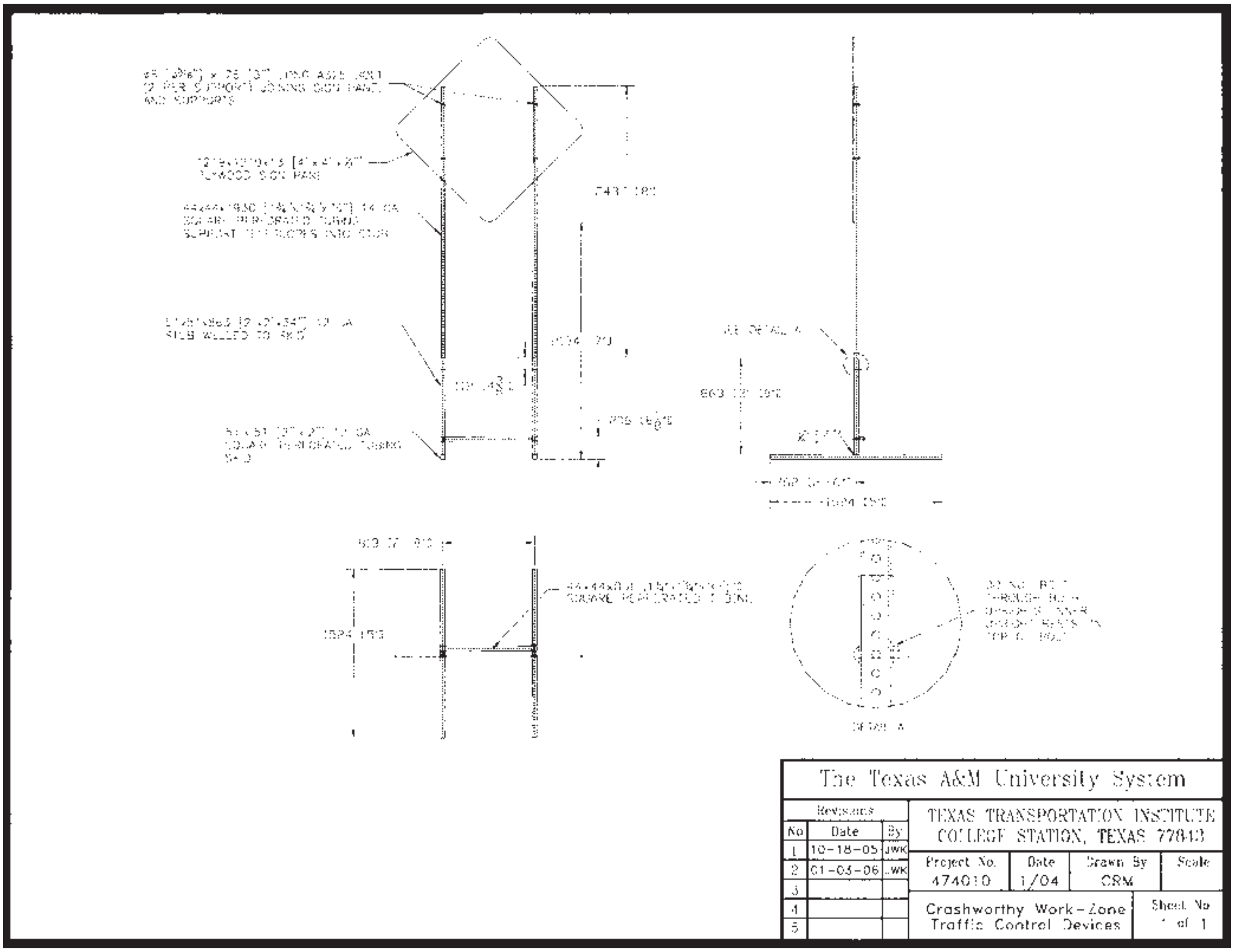


Figure 8.9. Design H6: dual steel-upright sign support with raised slip joint.

characteristics by using 51-mm × 152-mm (2-in × 6-in) HPPL in lieu of the dimensional lumber.

As with the other designs, placement of the sign support on roadside slopes can be accommodated in the HDPE/wooden sign support system by adjusting the attachment of one of the uprights to the sign panel. This adjustment will require drilling additional holes in the upright or sign panel.

8.3 PRIORITIZATION

The design alternatives developed for high-mounting-height sign supports with rigid sign substrates were reviewed and prioritized by the project panel. A weighted average was used to prioritize the designs for testing. Eight points were allocated for a first place vote, seven for second place, and so on. The points allocated for each device by each panel member were then summed to establish a ranking. The device with the greatest number of points is the device with the highest priority. The weighted ranking analysis resulted in the following priority:

1. Design H1: dual uprights with slip connection (36 points)
2. Design H2: strong dual uprights with slip connection (29 points)
3. Design H6: dual uprights with raised slip joint (29 points)
4. Design H7: dual three-piece uprights (23 points)
5. Design H8: dual HDPE uprights (17 points)
6. Design H4: dual uprights with knee braces (12 points)
7. Design H5: single upright with slip connection (9 points)
8. Design H3: dual nested uprights (0 points)

Some of the panel members who provided priorities for testing did not rank all eight designs. As a consequence, some of the designs did not receive points in the weighted ranking analysis from all panel members. Design H3 was effectively removed from consideration because of its similarity to another system that has been successfully crash tested.

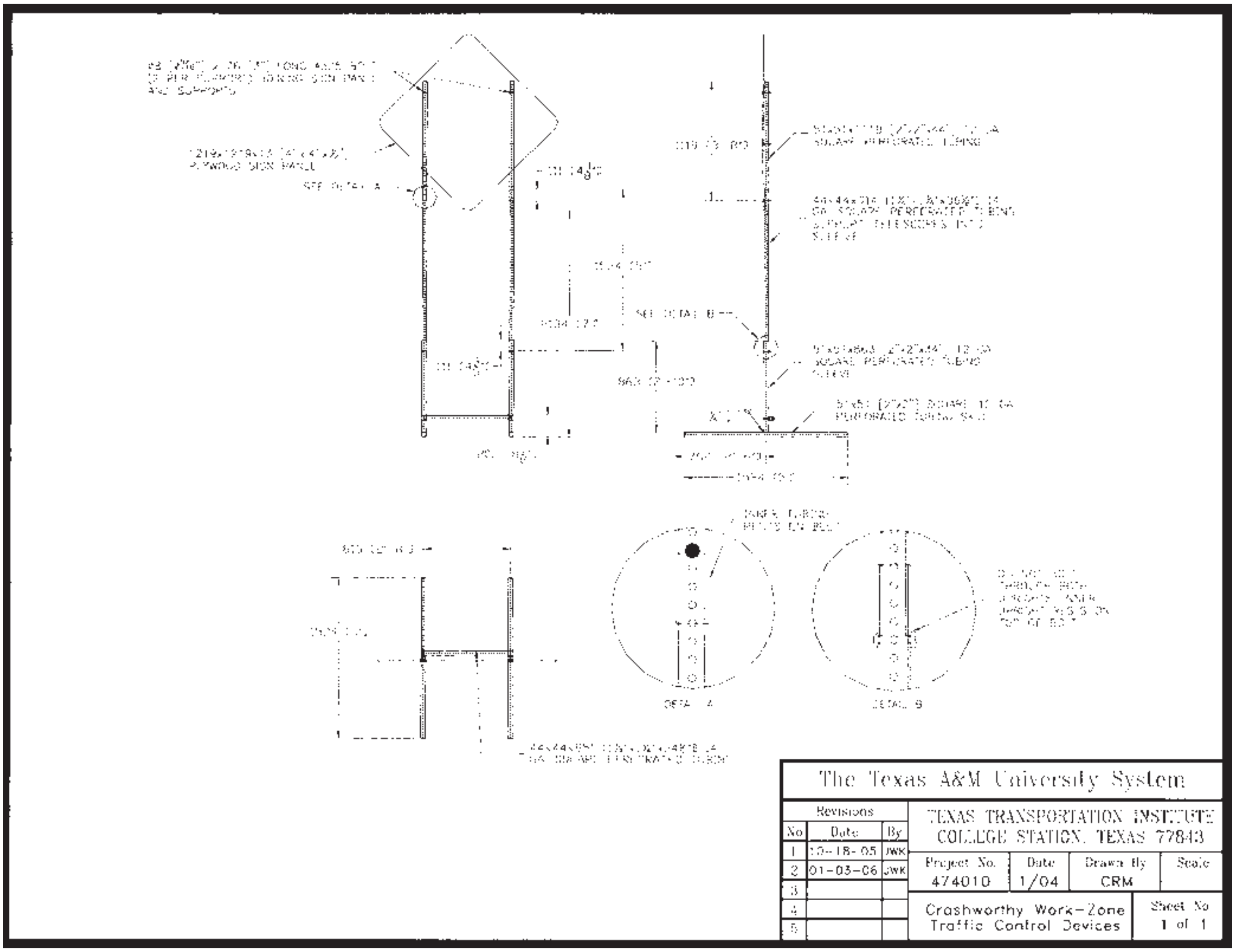


Figure 8.10. Design H7: steel-frame sign support with three-piece uprights.

The panel's rankings were used to establish a plan for crash testing high-mounting-height work-zone sign supports with rigid sign substrates. Details of the full-scale crash tests conducted on these designs are described in the following section.

8.4 FULL-SCALE CRASH TESTING

All crash test and data analysis procedures used to evaluate the high-mounting-height sign support systems were in accordance with the guidelines presented in *NCHRP Report 350.* Appendix C presents brief descriptions of these procedures. Additionally, the FHWA windshield damage classification criteria were followed in assessing damage to the windshield.

The tests followed the impact conditions of test designation 3-71 of *NCHRP Report 350.* Test 3-71 involves an 820-kg (1808-lb) passenger car impacting the device at a speed of 100 km/h (62 mi/h). This test is considered to be the critical one for most work-zone devices because the propensity for occupant compartment intrusion is increased. A 50th percentile male anthropomorphic dummy was placed in the driver's position and restrained with standard equipment lap and shoulder belts, thus increasing the test inertial weight of the vehicle to approximately 900 kg (1984 lb).

NCHRP Report 350 suggests considering the use of a 2000-kg (4409-lb) pickup truck for evaluation of work-zone traffic control devices in lieu of or in addition to the 820-kg (1808-lb) passenger car. The choice depends on the geometry of the test article in relation to the front profile of each vehicle. The choice of test vehicle is not as obvious for high-mounting-height sign supports as it is for barricades and low-mounting-height sign supports.

The frontal profile of pickup trucks is "squared off" (i.e., the angle of the hood with respect to the front end of the vehicle is close to 90 degrees), whereas the Geo Metro has a more aerodynamic, highly sloped profile. The hood height of a $^3\!/_4$-ton pickup truck is approximately 42 in. On the Geo Metro, the edge of the hood is offset from the top of the bumper and the "breakover point" on the front end is the top

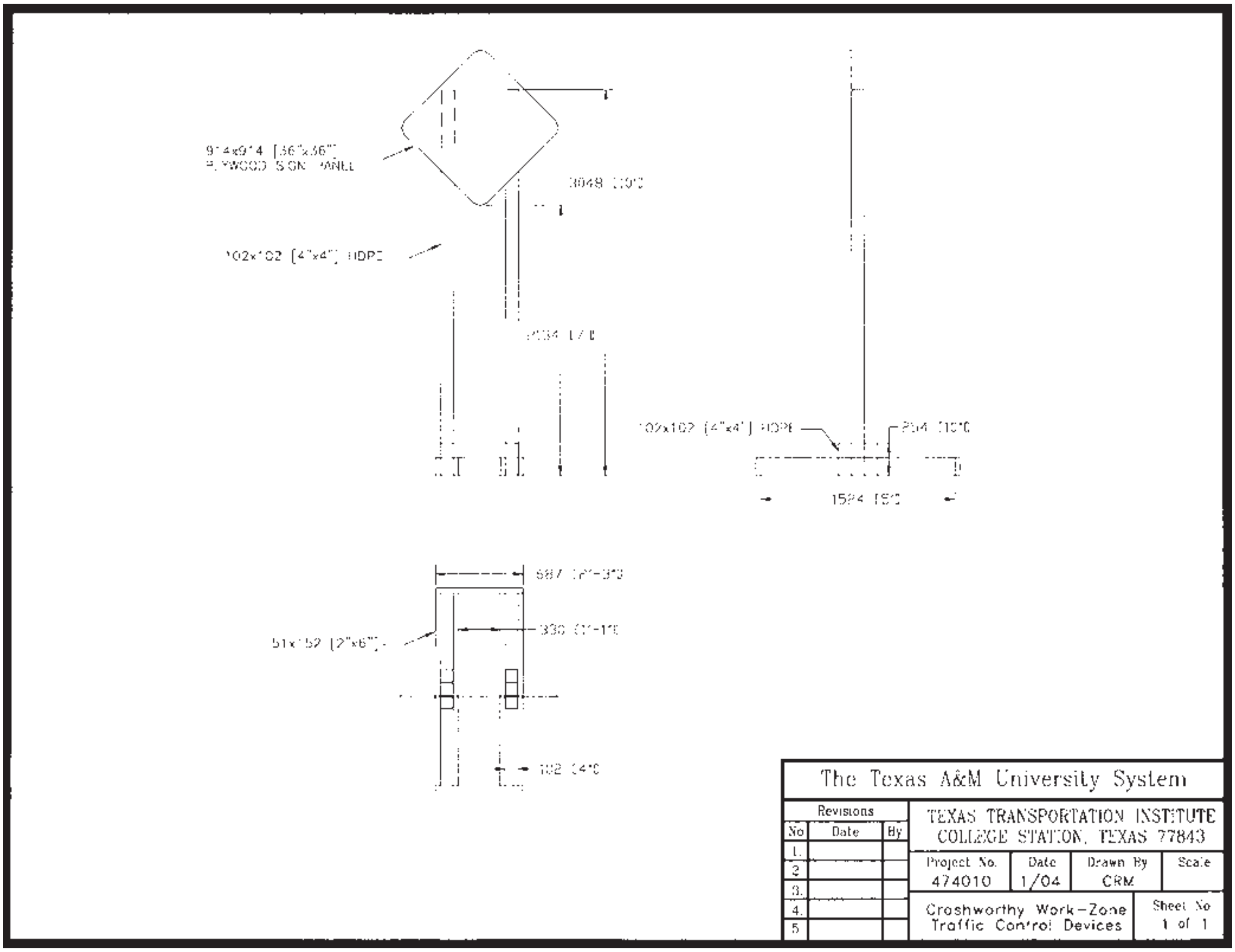


Figure 8.11. Design H8: dual HDPE-upright sign support with slip connection.

of the bumper, which is at a height of approximately 20 in. Thus, the application point of the impact load on a sign support by a pickup truck will be higher and nearer to center of mass of the support system than the impact load applied by a Geo Metro. The higher point of load application from the pickup truck will induce more forward (i.e., translational) motion and less rotational velocity of a sign support system than a small passenger car. Thus, the severity of any secondary contact that may occur between the sign support and the windshield or roof of a pickup truck would be reduced.

Therefore, while the possibility of undesirable interaction of a pickup truck with high-mounting-height sign support systems should not be discounted, the small car is generally regarded to be more critical in most cases. Because available resources precluded testing with both vehicles, the researchers decided to evaluate the high-mounting-height sign support systems solely with the 820-kg passenger car. It should be noted that precedence has been set through numerous crash tests for using the 820-kg passenger car in tests of both permanent and temporary high-mounting-height sign support systems.

Crash tests on the high-mounting-height sign support were conducted with a plywood sign panel at a mounting height of 1.5 m (5 ft). The 1.5-m (5-ft) mounting height is considered more critical than the 2.1-m (7-ft) mounting height in regard to impact performance. Therefore, if a system demonstrates acceptable impact performance at a 1.5-m (5-ft) mounting height, a similar system with a 2.1-m (7-ft) mounting height also would generally be considered acceptable.

Two separate sign support systems were offset approximately 9 m (30 ft) from one another and placed at different orientations with respect to the path of the vehicle. The first support was oriented perpendicular to the vehicle path for a head-on impact at 0 degree. The second support, placed behind the first sign support, was oriented parallel to the vehicle path for an end-on impact at 90 degrees. The supports were placed on a paved concrete surface and ballasted with sandbags.

8.4.1 Test 8

Test Article

In accordance with the established priorities, the first high-mounting-height sign support tested was Design H1: dual uprights with slip connection. Although this system did not have the highest probability of meeting impact performance requirements from among the various design alternatives, it was the most economical of the dual-upright support systems fabricated from perforated steel tubing. Figure 8.12 presents details of this support system as it was tested. The sign support uses two uprights fabricated from 44 mm (1¾-in) square, 14-gauge perforated steel tubing. A 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in) plywood sign panel is attached to each upright using two 8-mm (5⁄16-in) diameter, 76-mm (3-in) long, A325 or equivalent grade bolts. The mounting height from the ground to the bottom edge of the sign panel was 1.5 m (5 ft).

A 102-mm (4-in) long sleeve fabricated from 51-mm (2-in) square, 12-gauge perforated steel tubing is vertically welded to the center of a 1.5-m (5-ft) long skid fabricated from the same material. The uprights are inserted into the sleeves but are not bolted to them. A horizontal cross brace fabricated from 44-mm (1¾-in) square, 14-gauge perforated steel tubing is bolted to each upright just above the height of the sleeve using 8-mm (5⁄16-in) diameter, A325 or equivalent bolts.

Two identical sign support systems were placed on a paved concrete surface in the path of the vehicle approximately 9 m (30 ft) apart from one another—one perpendicular to the path of the vehicle and one parallel to the path of the vehicle. Each system was ballasted with four 18-kg (40-lb) sandbags. Photographs of the completed test installation are shown in Figure 8.13.

Test Vehicle

A 1995 Geo Metro, shown in Figure 8.14, was used for the crash test. Test inertia weight of the vehicle was 820 kg (1808 lb), and its gross static weight was 897 kg (1978 lb). The height to the lower edge of the vehicle front bumper was 400 mm (15.7 in), and the height to the upper edge of the front bumper was 525 mm (20.7 in). Additional dimensions and information on the vehicle are given in Appendix D, Figure D.8. The vehicle was directed into the installation using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just before impact.

Impact Description

The 897-kg (1978-lb) vehicle, traveling at a speed of 100.1 km/h (62.2 mi/h), impacted the first sign support head-on at 0 degree with the centerline of the vehicle aligned with the centerline of the support. Shortly after impact, the legs of the sign support began to deform around the front of the vehicle, causing the sign panel to begin rotating toward the vehicle. By 0.063 s, the vehicle lost contact with the legs, and the vehicle was traveling at a speed of 96.9 km/h (60.2 mi/h). The sign panel contacted the vehicle at its roofline at 0.086 s. The left leg separated from the sign panel at the lower connection at 0.115 s; the right leg separated from the sign panel at the lower connection at 0.144 s; and the right leg separated from the sign panel at the upper connection at 0.162 s. At 0.232 s, the vehicle lost contact with the sign panel and was traveling at a speed of 94.8 km/h (58.9 mi/h).

At 0.343 s, the vehicle contacted the second temporary sign support end-on at 90 degrees. Speed of the vehicle at time of impact was 92.5 km/h (57.5 mi/h). The legs began to deform and wrap around the front of the vehicle at 0.348 s. The corner of the sign panel rotated into the vehicle and contacted the windshield at 0.414 s. The corner of the panel penetrated the windshield at 0.426 s and reached a maximum penetration of 302 mm (11.9 in) at 0.466 s. As the vehicle continued forward, the sign panel rose up to the roof, and the vehicle traveled out of view of the cameras at 0.627 s, at a speed of 79.2 km/h (49.2 mi/h).

Brakes on the vehicle were applied at 1.9 s. The vehicle came to rest 104.9 m (344.0 ft) downstream of impact and 2.1 m (7.0 ft) to the left of centerline. Sequential photographs of the test period are shown in Appendix E, Figure E.8.

Test Results

Both sign supports readily activated at impact by yielding to the vehicle. The debris was scattered over an area 90.5 m (297.0 ft) long and 18.2 m (60.0 ft) to the right and 4.0 m (13.0 ft) to the left of the initial impact point.

The vehicle remained upright during and after the collision event. Damage to the vehicle is shown in Figure 8.15. The front bumper, hood, and roof were deformed. Maximum crush to the exterior of the vehicle was 10 mm (0.4 in) centered along the front at bumper height. The roof was deformed at centerline near the edge of the windshield and pushed downward 200 mm (7.9 in). The windshield was torn and separated from its frame. The FHWA windshield damage classification was a combination of Case 1 and Case 2. There was no other measurable occupant compartment deformation.

In the longitudinal direction, the occupant impact velocity was 2.5 m/s (8.2 ft/s) at 0.450 s, the highest 0.010-s occupant ridedown acceleration was –2.0 g’s from 0.466 s to 0.476 s, and the maximum 0.050-s average acceleration was –1.6 g’s between 0.002 s and 0.052 s. In the lateral direction, the occupant impact velocity was 0.2 m/s (0.7 ft/s) at 0.450 s, the highest 0.010-s occupant ridedown acceleration was –0.9 g from 0.462 s to 0.472 s, and the maximum 0.050-s average was –0.3 g between 0.004 s and 0.054 s. These data and other pertinent information from the test are summarized in Figure 8.16. Vehicle angular displacements and accelerations versus time traces are presented in Appendix F, Figures F.50 through F.56.

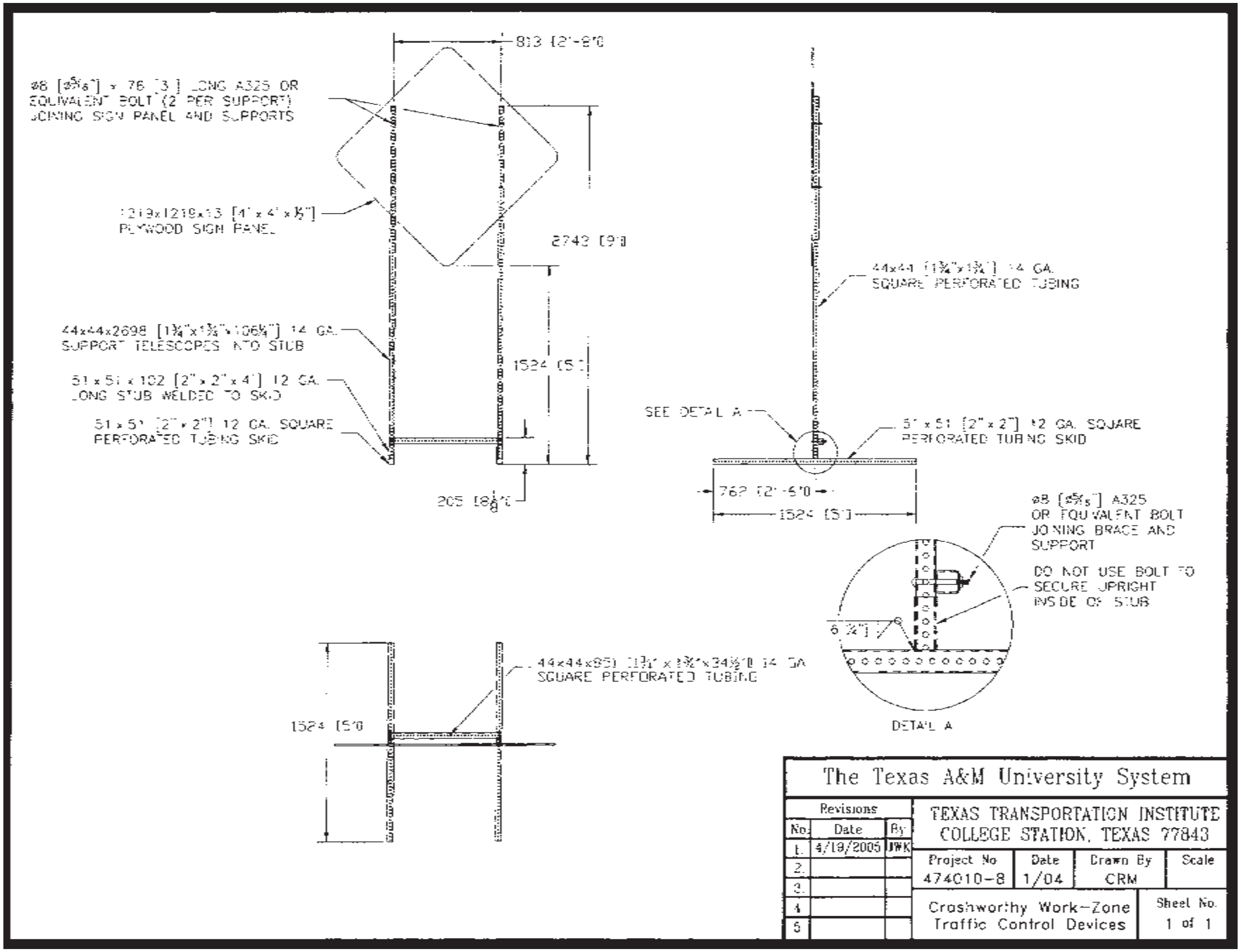


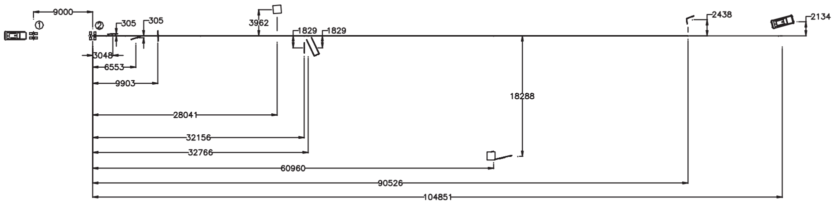
Figure 8.12. Details of the dual uprights with slip connection for Test 8.

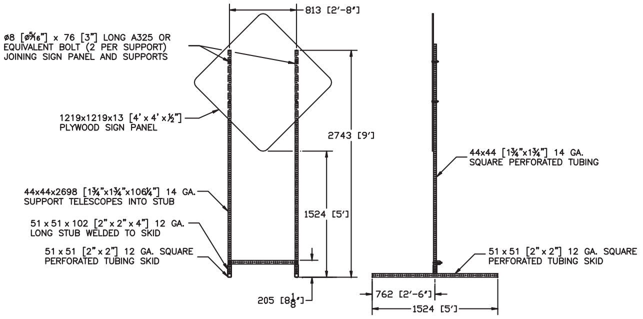
Figure 8.13. Dual uprights with slip connection before Test 8.

Figure 8.14. Vehicle before Test 8.

Figure 8.15. Vehicle after Test 8.

0.000 s | 0.146 s | 0.342 s | 0.466 s





General Information	
Test Agency	Texas Transportation Institute
Test No.	474010-8
Date	10-08-2004
Test Article	
Type	High-Mounting-Height Sign Support
Name	Dual Uprights with Slip Connection
Installation Height, m (ft)	1.5 (5.0) to Bottom of Sign Panel
Material or Key Elements	Two perforated steel-tube legs, skids, and brace with plywood sign
Soil Type and Condition	Pavement, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	1995 Geo Metro
Mass, kg	
Curb	805
Test Inertial	820
Dummy	77
Gross Static	897

Impact Conditions	
Angle, deg	0 & 90
Speed, km/h (mi/h) @ 0 deg	100.1 (62.2)
Speed, km/h (mi/h) @ 90 deg	92.5 (57.5)
Exit Conditions	
Speed, km/h (mi/h)	79.2 (49.2)
Occupant Risk Values	
Impact Velocity, m/s (ft/s)	
Longitudinal	2.5 (8.2)
Lateral	0.2 (0.7)
THIV, km/h	9.1
Ridedown Accelerations, g's	
Longitudinal	-2.0
Lateral	-0.9
PHD, g's	2.2
ASI	0.14
Max. 0.050-s Average, g's	
Longitudinal	-1.6
Lateral	-0.3
Vertical	-1.1

Test Article Debris Pattern	
Length, m (ft)	90.5 (297.0)
Width, m (ft)	
Left	4.0 (13.0)
Right	18.2 (60.0)
Vehicle Damage	
Exterior	
VDS	12FD1
CDC	12FDEN1
Max. Exterior Vehicle Crush, mm (in)	10 (0.4)
Interior	
OCDI	FS0000000
Max. Occupant Compartment Deformation, mm (in)	200 (7.9)
Post-Impact Behavior	
(during 1.0 sec after impact)	
Max. Yaw Angle, deg	-1
Max. Pitch Angle, deg	2
Max. Roll Angle, deg	1

Figure 8.16. Summary of results for Test 8.

A summary of the evaluation of the impact performance of the high-mounting-height sign support with dual uprights with slip connection is presented in Table 8.6. Because the windshield was dislodged and torn, and the roof deformed downward into the occupant compartment 200 mm (7.9 in), Design H1 failed the crash test.

Discussion

This sign support system is considered to be the smallest, lightest, and least expensive dual-support system fabricated from square, perforated steel tubing that can resist the selected 72 km/h (45 mi/h) design wind speed for a 1.2-m × 1.2-m (4-ft × 4-ft) sign panel mounted at a height of 1.5 m to 2.1 m (5 ft to 7 ft). However, while the uprights in this design alternative are considered to be adequate for resisting wind loads, there was concern that the relatively light 44-mm ($1\frac{3}{4}$-in), 14-gauge tubing would still deform appreciably around the front of the impacting vehicle before releasing from the sleeves. Such behavior was observed in the crash test and resulted in the uprights and sign panel contacting the windshield and roof of the vehicle with sufficient force to induce an unacceptable level of damage.

Because the most economical design did not perform satisfactorily, the uprights needed to be strengthened and/or alternative release mechanisms needed to be incorporated that would limit the amount of deformation to the uprights and reduce the rotational velocity of the sign panel into the vehicle. A logical next step was to test Design H2, which is a variation of Design H1 that incorporates larger, stronger sections of perforated steel tubing. In theory, the increased flexural strength of the larger uprights would reduce the uprights' deformation around the front of the vehicle before their

TABLE 8.6 Performance evaluation summary for Test 8

Test Agency: Texas Transportation Institute | Test No.: 474010-8 | Test Date: 10/08/2004

<table>
<tr><th><i>NCHRP Report 350</i> Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td colspan="3">Structural Adequacy</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>Both tall, dual-leg sign supports readily activated as designed by yielding and fracturing.</td><td>Pass</td></tr>
<tr><td colspan="3">Occupant Risk</td></tr>
<tr><td><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. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</i></td><td>Debris remained scattered along the vehicle path. The roof of the vehicle was deformed inward 200 mm (7.9 in). The windshield was torn and separated from its frame (FHWA Case 1 and 2). During the test, the sign panel reached a maximum penetration of 302 mm (11.9 in). There was no other measurable occupant compartment deformation.</td><td>Fail</td></tr>
<tr><td><i>E. 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.</i></td><td>The driver's vision was not blocked.</td><td>Pass</td></tr>
<tr><td><i>F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</i></td><td>The vehicle remained upright throughout and after the crash period.</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 (m/s)</i></th></tr>
<tr><td><i>Component</i></td><td><i>Preferred</i></td><td><i>Maximum</i></td></tr>
<tr><td><i>Longitudinal</i></td><td><i>3</i></td><td><i>5</i></td></tr>
</table></td><td>Longitudinal occupant impact velocity was 2.5 m/s (8.2 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 (g's)</i></th></tr>
<tr><td><i>Component</i></td><td><i>Preferred</i></td><td><i>Maximum</i></td></tr>
<tr><td><i>Longitudinal and lateral</i></td><td><i>15</i></td><td><i>20</i></td></tr>
</table></td><td>Longitudinal ridedown acceleration was -2.0 g's, and lateral ridedown acceleration was -0.9 g's.</td><td>Pass</td></tr>
<tr><td colspan="3">Vehicle Trajectory</td></tr>
<tr><td><i>K. After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</i></td><td>The vehicle continued on a straightforward path all along the trajectory path and did not intrude into adjacent lanes.</td><td>Pass*</td></tr>
<tr><td><i>N. Vehicle trajectory behind the test article is acceptable.</i></td><td>The vehicle came to rest behind the test articles.</td><td>Pass</td></tr>
</table>

*Criterion K preferable, not required.

release, thus improving the likelihood that the system would meet crash-test requirements. This progression in design also conformed to the panel's prioritization.

8.4.2 Test 9

Test Article

In keeping with the priorities of the project panel, and with consideration of the outcome of Test 8, the next high-mounting-height sign support system tested was Design H2: strong dual uprights with slip connection. Figure 8.17 presents details of this support system as it was tested. The two uprights are fabricated from 57-mm (2¼-in) square, 12-gauge perforated steel tubing. A 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in) plywood sign panel is attached to each upright using two 8-mm (5⁄16-in) diameter, A325 or equivalent grade bolts. The mounting height from the ground to the bottom edge of the sign panel was 1.5 m (5 ft).

A 102-mm (4-in) long sleeve fabricated from 64-mm (2½-in) square, 12-gauge perforated steel tubing is vertically welded to the center of a 1.5-m (5-ft) long skid fabricated from the same material. The uprights are inserted into the sleeves but are not bolted to them. A horizontal cross brace fabricated from 57-mm (2¼-in) square, 12-gauge perforated steel tubing is bolted to each upright 0.5 m (1 ft-6½ in) above ground using 8-mm (5⁄16-in) diameter, A325 or equivalent bolts. The height of the cross brace corresponds to the centerline of the bumper of a small passenger car. In the 90-degree impact, the theory was that the cross brace would help transfer momentum to both uprights simultaneously and reduce the degree of deformation that might otherwise be experienced by the first upright that is contacted.

Two identical sign support systems were placed on a paved concrete surface in the path of the vehicle approximately 9 m (30 ft) apart from one another—one perpendicular to the path of the vehicle and one parallel to the path of the vehicle. Each system was ballasted with four 18-kg (40-lb) sandbags. Photographs of the completed test installation are shown in Figure 8.18.

Test Vehicle

A 1999 Geo Metro, shown in Figure 8.19, was used for the crash test. Test inertia weight of the vehicle was 820 kg (1808 lb), and its gross static weight was 897 kg (1978 lb). The height to the lower edge of the vehicle front bumper was 400 mm (15.7 in), and the height to the upper edge of the front bumper was 525 mm (20.7 in). Additional dimensions and information on the vehicle are given in Appendix D, Figure D.9. The vehicle was directed into the installation using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just before impact.

Impact Description

The 897-kg (1978-lb) vehicle, traveling at 99.9 km/h (62.1 mi/h), impacted the first sign support head-on at 0 degree, with the centerline of the vehicle aligned with the centerline of the sign support. Shortly after impact, the legs deformed slightly and then the skids began to slide on the paved concrete surface. The sign panel separated from the lower connection on the right upright at 0.056 s. At 0.071 s, the vehicle lost contact with the uprights with the vehicle traveling at a speed of 90.6 km/h (56.3 mi/h). The sign panel separated from the right leg at the top connection at 0.085 s. As the sign support frame rotated, the vehicle contacted the skids at 0.102 s. At 0.103 s, the left leg separated from its skid, and at 0.112 s, the sign panel contacted the passenger side of the roof of the vehicle at the top edge of the passenger door. The vehicle lost contact with the right skid at 0.117 s, and the sign panel separated from the upper connection with the left leg at 0.129 s. At 0.275 s, the vehicle lost contact with the sign panel, and the vehicle was traveling at a speed of 89.2 km/h (55.4 mi/h).

At 0.356 s, the vehicle contacted the second temporary sign support end-on at 90 degrees. Speed at time of impact was 89.0 km/h (55.3 mi/h). The right leg separated from its skid at 0.388 s. At 0.504 s, the vehicle lost contact with the uprights, and the vehicle was traveling at a speed of 78.6 km/h (48.9 mi/h). The sign panel contacted the roof of the vehicle at 0.532 s and contacted the windshield at 0.560 s. The vehicle lost contact with the sign panel at 0.731 s.

Brakes on the vehicle were applied at 1.9 s. The vehicle came to rest 86.9 m (285.0 ft) downstream of impact and 1.9 m (6.3 ft) to the right of centerline. Sequential photographs of the test period are shown in Appendix E, Figure E.9.

Test Results

Both sign supports readily yielded to the vehicle at impact. The debris was scattered over an area 80.8 m (265.0 ft) long and 3.8 m (12.5 ft) to the right and 4.9 m (16.0 ft) to the left of the initial impact point.

The vehicle remained upright during and after the collision event. Damage to the vehicle is shown in Figure 8.20. The front bumper, hood, and roof were deformed. Maximum crush to the exterior of the vehicle was 170 mm (3.7 in) at the center front at bumper height. The roof was deformed inward 25 mm (1.0 inch). There was no damage to the windshield, nor was the windshield separated from its frame. There was no other measurable occupant compartment deformation.

In the longitudinal direction, the occupant impact velocity was 2.5 m/s (8.2 ft/s) at 0.280 s, the highest 0.010-s occupant ridedown acceleration was −10.0 g's from 0.379 s to 0.389 s, and the maximum 0.050-s average acceleration was −4.7 g's between 0.361 s and 0.411 s. In the lateral direction, the occupant impact velocity was 0.3 m/s (1.0 ft/s) at 0.280 s, the highest 0.010-s occupant ridedown acceleration was 2.2 g's from

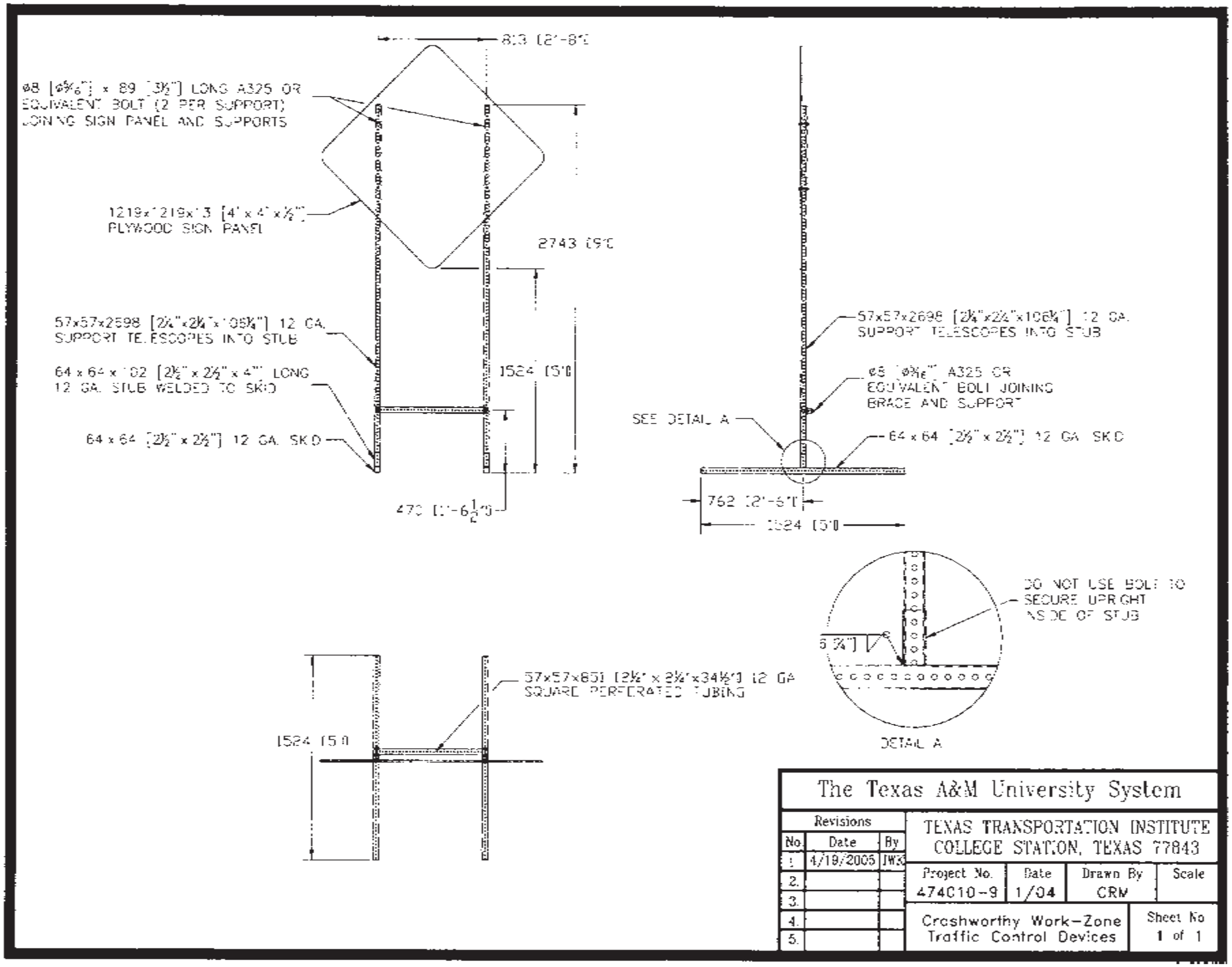


Figure 8.17. Details of the strong dual uprights with slip connection for Test 9.

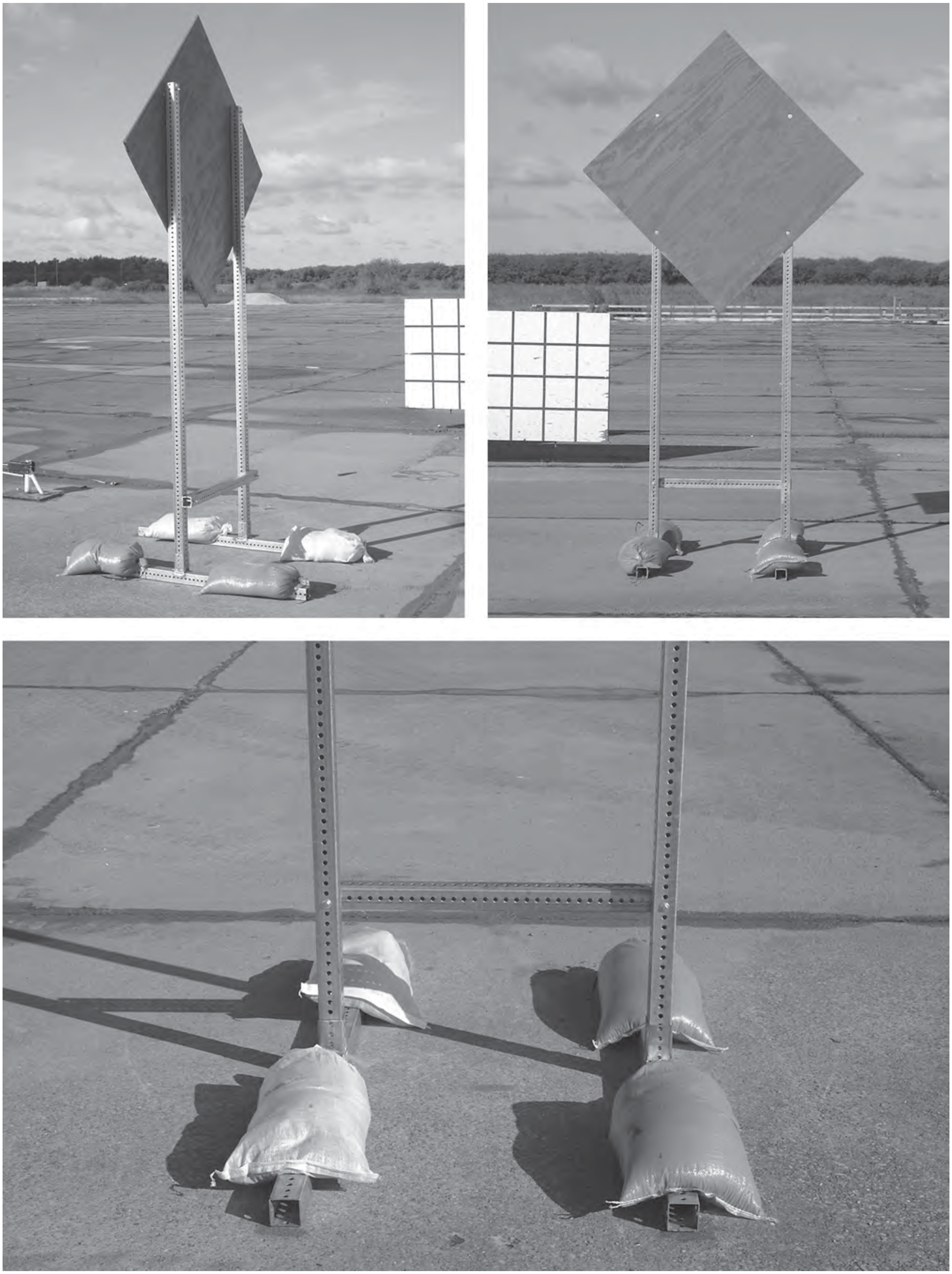


Figure 8.18. Strong dual uprights with slip connection for Test 9.

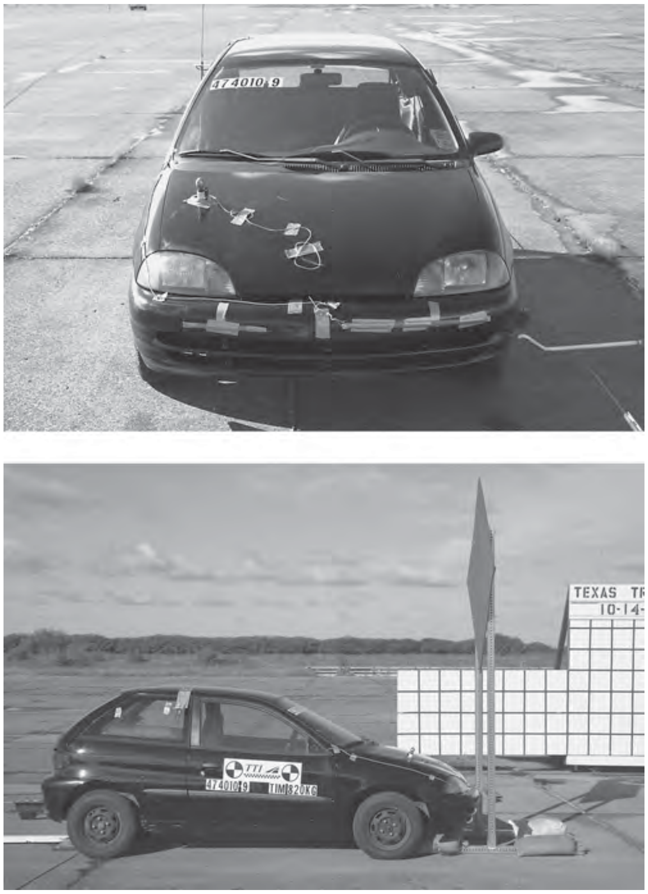


Figure 8.19. Vehicle before Test 9.

Figure 8.20. Vehicle after Test 9.

0.376 s to 0.386 s, and the maximum 0.050-s average was 0.5 g between 0.404 s and 0.454 s. These data and other pertinent information from the test are summarized in Figure 8.21. Vehicle angular displacements and accelerations versus time traces are presented in Appendix F, Figures F.57 through F.63.

As summarized in Table 8.7, the strong, dual-leg perforated steel-tube sign support with 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in) plywood sign panel mounted at a height of 1.5 m (5 ft) met all required evaluation criteria for both the head-on and end-on impact scenarios. The impact performance of the sign support system is, therefore, considered acceptable.

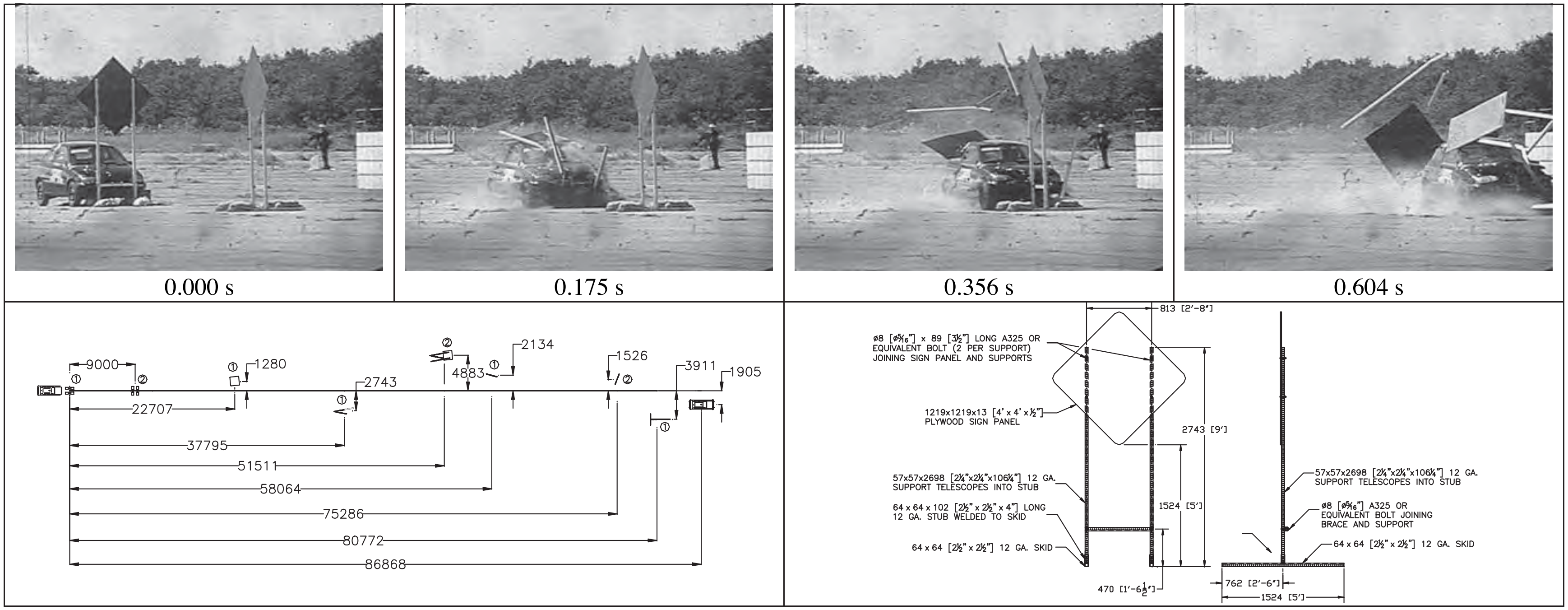
Discussion

The incorporation of larger, stronger uprights into the design limited the deformation of the uprights and prevented them from wrapping around the front of the vehicle. The point of rotation was changed from bumper height (i.e., approximately 457 mm [18 in] above ground) to a point that closely coincides with the overall center of mass of the sign support system. In addition to raising the point of rotation, the stronger uprights also effectively decreased rotational velocity. These factors combined to reduce the severity of the secondary impact of the support structure with the windshield and roof of the vehicle, thus limiting the extent of vehicle deformation to an acceptable level.

Using larger tubular members to achieve acceptable impact performance increases the system's weight and cost of fabrication. The increased weight will make the sign support system more difficult to handle.

The 1.5-m (5-ft) mounting height is generally believed to be more critical than a 2.1-m (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 severity of secondary impacts of the supports and sign panel with the windshield and roof of the impacting vehicle. Because the strong, dual-upright sign support system met all required evaluation criteria with the sign panel mounted at 1.5 m (5 ft), the researchers consider the same sign support system to be acceptable for a 2.1-m (7-ft) mounting height as well.

As discussed previously, the rigidity and mass of a plywood sign panel make plywood more critical than most other substrate materials from a crashworthiness standpoint. Because of the greater weight of plywood, the successful test of the strong, dual-upright sign support system with a plywood substrate is considered to be sufficient, in the opinion of the researchers, to indicate acceptable impact performance of the



General Information	
Test Agency	Texas Transportation Institute
Test No.	474010-9
Date	10-14-2004
Test Article	
Type	High-Mounting-Height Sign Support
Name	Strong Dual Uprights w/Slip Connection
Installation Height, m (ft)	1.5 (5.0) to Bottom of Sign Panel
Material or Key Elements	Two perforated steel-tube legs, skids, and brace with plywood sign
Soil Type and Condition	Pavement, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	1999 Geo Metro
Mass, kg	
Curb	805
Test Inertial	820
Dummy	77
Gross Static	897

Impact Conditions	
Angle, deg	0 & 90
Speed, km/h (mi/h) @ 0 deg	99.9 (62.1)
Speed, km/h (mi/h) @ 90 deg	89.0 (55.3)
Exit Conditions	
Speed, km/h (mi/h)	78.6 (48.9)
Occupant Risk Values	
Impact Velocity, m/s (ft/s)	
Longitudinal	2.5 (8.2)
Lateral	0.3 (1.0)
THIV, km/h	9.1
Ridedown Accelerations, g's	
Longitudinal	-10.0
Lateral	2.2
PHD, g's	10.1
ASI	0.41
Max. 0.050-s Average, g's	
Longitudinal	-4.7
Lateral	0.5
Vertical	-1.9

Test Article Debris Pattern	
Length, m (ft)	80.8 (265.0)
Width, m (ft)	
Left	4.9 (16.0)
Right	3.8 (12.5)
Vehicle Damage	
Exterior	
VDS	12FD3
CDC	12FDEW2
Max. Exterior Vehicle Crush, mm (in)	170 (3.7)
Interior	
OCDI	FS0000000
Max. Occupant Compartment Deformation, mm (in)	25 (1.0)
Post-Impact Behavior	
(during 1.0 sec after impact)	
Max. Yaw Angle, deg	4
Max. Pitch Angle, deg	2
Max. Roll Angle, deg	-1

Figure 8.21. Summary of results for Test 9.

TABLE 8.7 Performance evaluation summary for Test 9

Test Agency: Texas Transportation Institute Test No.: 474010-9 Test Date: 10/14/2004

<table>
<tr><th><i>NCHRP Report 350</i> Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td>Structural Adequacy</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 tall, dual-leg sign supports readily activated as designed by yielding and fracturing.</td><td>Pass</td></tr>
<tr><td>Occupant Risk</td><td></td><td></td></tr>
<tr><td>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. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</i></td><td>Debris remained scattered along the vehicle path. The roof was deformed inward 25 mm (1.0 in). The windshield was not damaged (no holes or tears), nor was the windshield separated from its frame. There was no other measurable occupant compartment deformation.</td><td>Pass</td></tr>
<tr><td>E. <i>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.</i></td><td>The driver's vision was not blocked.</td><td>Pass</td></tr>
<tr><td>F. <i>The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</i></td><td>The vehicle remained upright throughout and after the crash period.</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 (m/s)</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>3</i></td><td><i>5</i></td></tr>
</table></td><td>Longitudinal occupant impact velocity was 2.5 m/s (8.2 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 (g's)</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</i></td><td><i>20</i></td></tr>
</table></td><td>Longitudinal ridedown acceleration was -10.0 g's and lateral ridedown acceleration was 2.2 g's.</td><td>Pass</td></tr>
<tr><td>Vehicle Trajectory</td><td></td><td></td></tr>
<tr><td>K. <i>After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</i></td><td>The vehicle continued on a straightforward path all along the trajectory path and did not intrude into adjacent lanes.</td><td>Pass*</td></tr>
<tr><td>N. <i>Vehicle trajectory behind the test article is acceptable.</i></td><td>The vehicle came to rest behind the test articles.</td><td>Pass</td></tr>
</table>

*Criterion K preferable, not required.

same sign support system with a comparably sized aluminum sign substrate.

During analysis of the high-speed film of the test, the slip mechanism was observed to not activate as designed. Upon impact, the sign support system moved as a unit. The uprights remained inside the sleeves until well after momentum was transferred to the entire system. This behavior indicates that the slip mechanism did not affect the impact response of the system; as a result, a longer sleeve (e.g., 152 mm to 229 mm [6 in to 9 in]) can be used without adversely affecting impact performance. For the same reasons, the researchers concluded that bolting or pinning the uprights inside the sleeves would not compromise impact performance. Such design modifications would provide better adjustability to accommodate placement of the sign support on a roadside slope by permitting the length of the downhill upright to be extended within the sleeve. Although not considered to be a problem in the test, bolting of the uprights inside the sleeves would permit the system to travel as a unit and reduce any potential debris hazard associated with the skids releasing from the uprights.

8.2.3 Test 10

Test Article

The final high-mounting-height sign support system tested under this project was Design H6: dual uprights with raised slip joint. The objective of this test was to determine if raising the slip joint from a height of 152 mm to 870 mm (6 in to 34¼ in) can improve impact performance and permit smaller, lighter weight tubular sections to be used in lieu of the larger, heavier sections evaluated in Test 9 (Design H2).

The as-tested details of this system are provided in Figure 8.22. The uprights are fabricated from 38-mm (1½-in)

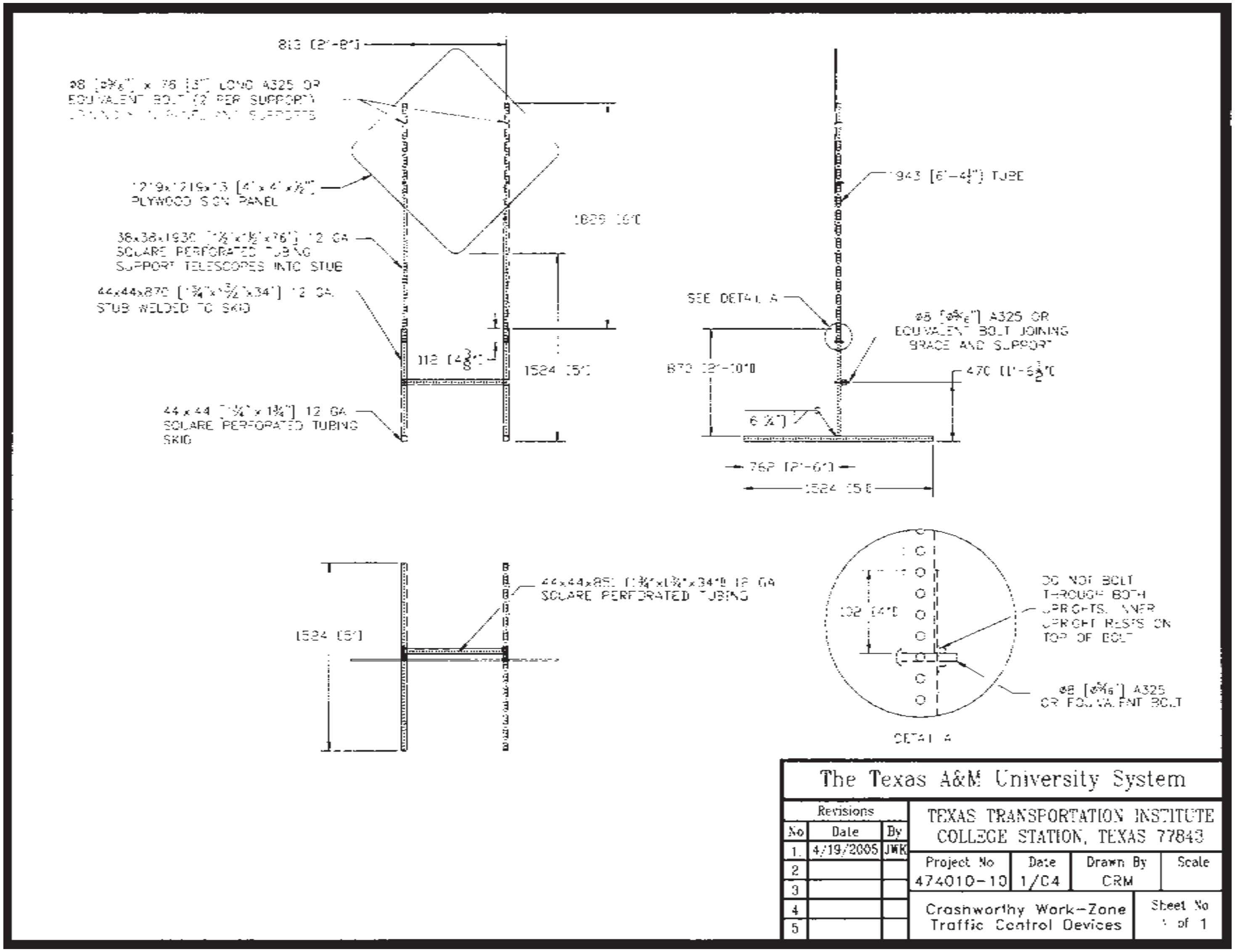


Figure 8.22. Details of the dual uprights with raised slip joint for Test 10.

square, 12-gauge perforated steel tubing. A 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × $\frac{1}{2}$-in) plywood sign panel is attached to each upright using two 8-mm ($\frac{5}{16}$-in) diameter, 76-mm (3-in) long, A325 or equivalent grade bolts. The mounting height from the ground to the bottom edge of the sign panel was 1.5 m (5 ft).

An 870-mm ($34\frac{1}{4}$-in) long sleeve fabricated from 44-mm ($1\frac{3}{4}$-in) square, 12-gauge perforated steel tubing is vertically welded to the center of a 1.5-m (5-ft) long skid fabricated from the same material. The uprights are inserted into the sleeves but are not bolted to them. The insertion depth of the uprights inside the sleeves is only 102 mm (4 in). An 8-mm ($\frac{5}{16}$-in) diameter bolt through the sleeve is used as a shelf for the inserted upright to rest upon. A horizontal cross brace fabricated from 44-mm ($1\frac{3}{4}$-in) square, 12-gauge perforated steel tubing is bolted to each sleeve 470 mm ($18\frac{1}{2}$ in) above ground using 8-mm ($\frac{5}{16}$-in) diameter, A325 or equivalent bolts.

Two identical sign support systems were placed on a paved concrete surface in the path of the vehicle approximately 9 m (30 ft) apart from one another—one perpendicular to the path of the vehicle and one parallel to the path of the vehicle. Each system was ballasted with four 18-kg (40-lb) sandbags. Photographs of the completed test installation are shown in Figure 8.23.

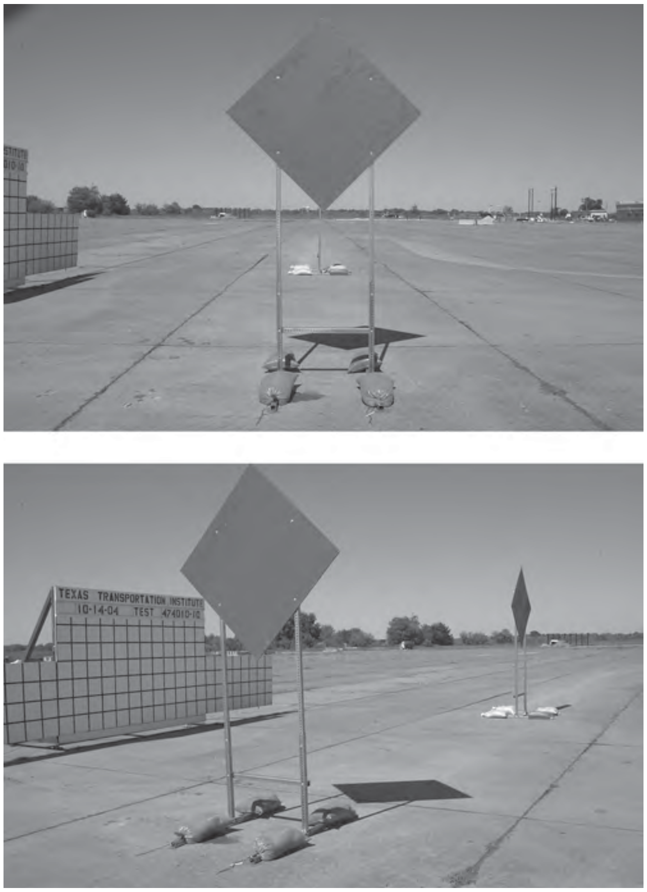


Figure 8.23. Dual uprights with raised slip joint before Test 10.

Test Vehicle

A 1995 Geo Metro, shown in Figure 8.24, was used for the crash test. Test inertia weight of the vehicle was 820 kg (1808 lb), and its gross static weight was 897 kg (1978 lb). The height to the lower edge of the vehicle front bumper was 400 mm (15.7 in), and the height to the upper edge of the front bumper was 525 mm (20.7 in). Additional dimensions and information on the vehicle are given in Appendix D, Figure D.10. The vehicle was directed into the installation using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just before impact.

Impact Description

The 897-kg (1978-lb) vehicle, traveling at a speed of 99.6 km/h (61.9 mi/h), impacted the first sign support head-on at 0 degree with the centerline of the vehicle aligned with the centerline of the support. Shortly after impact, the uprights began to deform. The sign panel separated from the lower connection to the left upright at 0.015 s and from the upper connection to the left upright at 0.027 s. At 0.029 s, the sign panel separated from the lower connection to the right upright, and, at 0.034 s, the sign panel separated at the upper connection to the right upright. The sign panel went over the vehicle without contacting the roof or windshield. At 0.172 s, the vehicle lost contact with the legs, and the vehicle was traveling at a speed of 91.3 km/h (56.7 mi/h). The top of the left leg slightly contacted the roof at 0.257 s, and the legs continued to travel in front of the vehicle as it continued forward.

At 0.346 s, the vehicle contacted the second sign support end-on at 90 degrees. Vehicle speed at impact was 89.8 km/h (55.8 mi/h). Shortly after impact, the uprights began to deform, and, at 0.369 s, both legs separated just above bumper height. The corner of the sign panel contacted the windshield at 0.429 s and reached maximum penetration at 0.472 s. At 0.543 s, the vehicle lost contact with the sign panel, and the vehicle was traveling at a speed of 84.4 km/h (52.4 mi/h).

Brakes on the vehicle were applied at 1.9 s. The vehicle came to rest 83.2 m (273.0 ft) downstream of impact and 1.2 m (4.0 ft) to the right of centerline. Sequential photographs of the test period are shown in Appendix E, Figure E.10.

Test Results

Both sign supports readily yielded to the vehicle. The debris was scattered over an area 73.8 m (242.0 ft) long and 3.0 m (10.0 ft) to the left of the initial impact point.

Figure 8.24. Vehicle before Test 10.

Figure 8.25. Vehicle after Test 10.

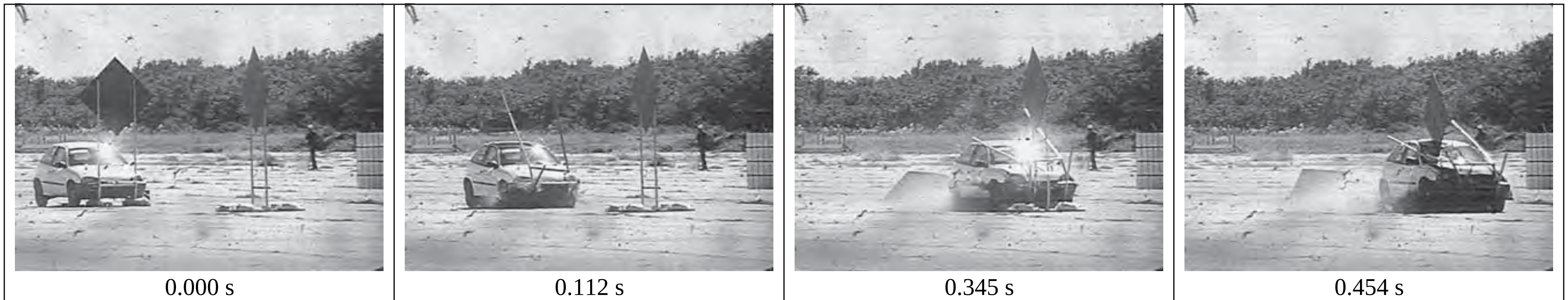
The vehicle remained upright during and after the collision event. Damage to the vehicle is shown in Figure 8.25. The front bumper, hood, and roof were deformed. Maximum crush to the exterior of the vehicle was 50 mm (2.0 in) at the center front at bumper height. The roof was deformed downward 62 mm (2.4 in) near the windshield and 40 mm (1.6 in) near the center. The windshield was shattered and deformed inward 92 mm (3.6 in), and a small hole was noted (FHWA windshield damage classification Case 1). The windshield did not separate from its frame, and there was no other measurable occupant compartment deformation.

In the longitudinal direction, the occupant impact velocity was 2.1 m/s (6.9 ft/s) at 0.327 s, the highest 0.010-s occupant ridedown acceleration was –4.8 g's from 0.392 s to 0.402 s, and the maximum 0.050-s average acceleration was –2.8 g's between 0.000 s and 0.050 s. In the lateral direction, the occupant impact velocity was 0.0 m/s (0.0 ft/s) at 0.327 s, the highest 0.010-s occupant ridedown acceleration was 2.4 g's from 0.418 s to 0.428 s, and the maximum 0.050-s average was 0.8 g between 0.527 s and 0.577 s. These data and other pertinent information from the test are summarized in Figure 8.26. Vehicle angular displacements and accelerations versus time traces are presented in Appendix F, Figures F.64 through F.70.

The evaluation of the impact performance of the high-mounting-height sign support with dual uprights and raised slip connection is summarized in Table 8.8. With the small hole in the windshield and deformation of the windshield of 92 mm (3.6 in), the impact performance of Design H6 is considered unacceptable.

Discussion

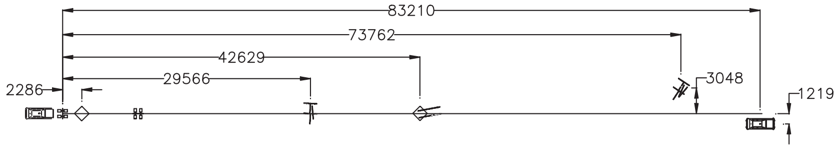
The connection detail used in this design effectively creates a raised slip joint at a height of 870 mm (34¼ in). It was theorized that activation of the slip joint during impact would result in a higher point of rotation of the uprights and sign panel after their release, which would help reduce the probability of secondary contact between the sign panel and windshield of the impacting vehicle. Such behavior was observed in the 0-degree impact, where contact between the sign panel and vehicle was avoided. However, in the 90-degree impact, the deformation of the sleeves generated rotation of the sign panel into the vehicle before the uprights released from the sleeves and the subsequent contact between the sign panel and vehicle windshield resulted in an unacceptable level of damage.

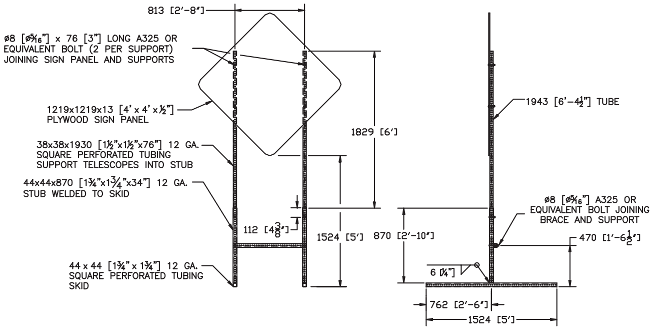

0.000 s

0.112 s

0.345 s

0.454 s





General Information	
Test Agency	Texas Transportation Institute
Test No.	474010-10
Date	10-14-2004
Test Article	
Type	High-Mounting-Height Sign Support
Name	Dual Uprights with Raised Slip Joint
Installation Height, m (ft)	1.5 (5.0) to Bottom of Sign Panel
Material or Key Elements	Two perforated steel-tube legs, skids, and brace with plywood sign
Soil Type and Condition	Pavement, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	1995 Geo Metro
Mass, kg	
Curb	808
Test Inertial	820
Dummy	77
Gross Static	897

Impact Conditions	
Angle, deg	0 & 90
Speed, km/h (mi/h) @ 0 deg	99.6 (61.9)
Speed, km/h (mi/h) @ 90 deg	89.8 (55.8)
Exit Conditions	
Speed, km/h (mi/h)	84.4 (52.4)
Occupant Risk Values	
Impact Velocity, m/s (ft/s)	
Longitudinal	2.1 (6.9)
Lateral	0
THIV, km/h	7.7
Ridedown Accelerations, g's	
Longitudinal	-4.8
Lateral	2.4
PHD, g's	4.8
ASI	0.29
Max. 0.050-s Average, g's	
Longitudinal	-2.8
Lateral	0.8
Vertical	-2.1

Test Article Debris Pattern	
Length, m (ft)	73.8 (242.0)
Width, m (ft)	
Left	3.0 (10.0)
Right	0
Vehicle Damage	
Exterior	
VDS	12FD2
CDC	12FDEN2
Max. Exterior Vehicle Crush, mm (in)	50 (2.0)
Interior	
OCDI	FS0000000
Max. Occupant Compartment Deformation, mm (in)	92 (3.6)
Post-Impact Behavior	
(during 1.0 sec after impact)	
Max. Yaw Angle, deg	8
Max. Pitch Angle, deg	4
Max. Roll Angle, deg	-2

Figure 8.26. Summary of results for Test 10.

TABLE 8.8 Performance evaluation summary for Test 10

Test Agency: Texas Transportation Institute Test No.: 474010-10 Test Date: 10/14/2004

<table>
<tr><th colspan="4">NCHRP Report 350 Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td colspan="4">Structural Adequacy</td><td></td><td></td></tr>
<tr><td>B.</td><td colspan="3">The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</td><td>Both tall, dual-leg sign supports readily activated as designed by yielding and fracturing.</td><td>Pass</td></tr>
<tr><td colspan="4">Occupant Risk</td><td></td><td></td></tr>
<tr><td>D.</td><td colspan="3">Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</td><td>Debris remained scattered along the vehicle path. The roof of the vehicle was deformed inward 62 mm (2.4 in) near the windshield, and 40 mm (1.6 in) near the center. The windshield was shattered and deformed inward 92 mm (3.6 in) with a small hole (FHWA Case 1). The windshield was not separated from its frame. There was no other measurable occupant compartment deformation.</td><td>Fail</td></tr>
<tr><td>E.</td><td colspan="3">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.</td><td>The driver’s vision was not blocked.</td><td>Pass</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</td><td>The vehicle remained upright throughout and after the crash period.</td><td>Pass</td></tr>
<tr><td rowspan="4">H.</td><td colspan="3">Occupant impact velocities should satisfy the following:</td><td rowspan="4">Longitudinal occupant impact velocity was 2.1 m/s (6.9 ft/s).</td><td rowspan="4">Pass</td></tr>
<tr><td colspan="3">Occupant Velocity Limits (m/s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal</td><td>3</td><td>5</td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">Occupant ridedown accelerations should satisfy the following:</td><td rowspan="4">Longitudinal ridedown acceleration was -4.8 g’s, and lateral ridedown acceleration was 2.4 g’s.</td><td rowspan="4">Pass</td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits (g’s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and lateral</td><td>15</td><td>20</td></tr>
<tr><td colspan="4">Vehicle Trajectory</td><td></td><td></td></tr>
<tr><td>K.</td><td colspan="3">After collision, it is preferable that the vehicle’s trajectory not intrude into adjacent traffic lanes.</td><td>The vehicle continued on a straightforward path all along the trajectory path and did not intrude into adjacent lanes.</td><td>Pass*</td></tr>
<tr><td>N.</td><td colspan="3">Vehicle trajectory behind the test article is acceptable.</td><td>The vehicle came to rest behind the test articles.</td><td>Pass</td></tr>
</table>

*Criterion K preferable, not required.

CHAPTER 9

FINDINGS AND RECOMMENDATIONS

The objective of this research was to develop nonproprietary, crashworthy work-zone traffic control devices constructed of readily available materials. A state-of-the-practice review helped identify sets of work-zone devices for which additional generic designs were needed. The sets for which new devices were developed include Type III barricades with attached sign panel; low-mounting-height (i.e., 0.3 m [1 ft]), portable sign supports with rigid sign substrate; and high-mounting-height (i.e., 1.5 m and 2.1 m [5 ft and 7 ft]), portable sign supports with rigid sign substrate. Numerous designs were developed for each of these sets. In addition to crashworthiness, consideration was given to cost and functionality (e.g., durability, handling, site adaptability, etc.) The designs were reviewed and prioritized by the project panel, and the prioritization served as the basis for the full-scale crash testing. In addition to providing details of the crash-tested systems, this report presents a description of the other design concepts for future consideration and testing.

A total of 10 full-scale crash tests were conducted under the project. The square, perforated steel tubing used to fabricate the framing of the various devices tested was manufactured from ASTM A570 grade 50 steel. The use of a rigid plywood sign substrate in each application presented a distinct design challenge, but at least one design was successfully crash tested in each set of work-zone devices investigated. Findings and recommendations resulting from these tests are summarized in the following sections.

9.1 TYPE III BARRICADES WITH SIGNS

9.1.1 Perforated Steel-Tube Barricades

Based on successful test results for both centered (Test 1) and offset (Test 3) impact conditions, a perforated steel-tube barricade with wooden rails and plywood sign panel is considered to be an acceptable device for use in work zones. Both a 1.2-m × 1.2-m (4-ft × 4-ft) sign panel mounted at 1 ft in a diamond configuration and a 0.8-m × 1.5-m (2.5-ft × 5-ft) sign panel mounted at 0.8 m (2.5 ft) are considered acceptable for use on this barricade frame. However, the taller 1.2-m × 1.2-m (4-ft × 4-ft) sign panel produced greater windshield damage. The measured windshield deformation for the perforated steel-tube barricade with 1.2-m × 1.2-m (4-ft × 4-ft) sign panel was 50 mm (2 in). The FHWA windshield damage classification states that "It is desirable that the maximum permanent deflection of the windshield not exceed 55 mm (2.2 in). A maximum permanent deflection exceeding 75 mm (3 in) shall be considered a failure."

Plywood sign substrates were used in the crash testing of perforated steel-tube barricades with attached sign panels. Because a plywood sign panel tends to be more critical from a crashworthiness standpoint because of its greater weight, the successful testing with a plywood substrate is considered to be sufficient for acceptance of a similar design with a comparably sized aluminum sign substrate or other lightweight substrate materials (e.g., corrugated plastic).

Because the wooden rails used in the successfully tested barricades are considered more critical from an impact performance standpoint than lighter, hollow-profile plastic rails, both types of rails are considered acceptable. Wooden rails are often preferred for their low cost, availability, ease of fabrication, and durability. Plastic rails are lighter in weight than wood and, therefore, can make the barricade easier to handle. Because they do not fracture and break apart like wooden rails, plastic rails are sometimes reusable after an impact. Because the reflective sheeting adhered to the rails is a high-cost item, this reusability can make plastic rails more economical than wooden rails from a life-cycle cost standpoint. Additionally, plastic rails are available in white and do not have to be painted as do wooden rails.

The use of the vertical braces in the barricade framing is optional. The braces were incorporated into the crash-tested systems because their presence represents a more critical configuration for impact performance evaluation. In absence of the vertical braces, the barricade rails and sign panel must be directly attached to the barricade uprights to prevent the sign and fractured rails from rotating into the windshield of the impacting vehicle. If the use of vertical braces is desired to improve the constructability or functionality of the barricade, they can be fabricated from either square, perforated tubing or 51-mm × 102-mm (2-in × 4-in) dimensional lumber. If the perforated steel-tube braces are used, the barricade can be adjusted for placement on uneven terrain by extending the height of one of the vertical braces relative to one of the uprights. The braces are then bolted to the uprights through existing holes in the perforated tubes. If the 51-mm

× 102-mm (2-in × 4-in) lumber braces (or no braces) are used, adjustability can be incorporated into the barricade through the use of taller sleeves and the extension of one of the uprights within its sleeve. Because the lumber braces are not attached to the uprights, the sign panel must be attached directly to the uprights.

The use of a Type A or C warning light with self-contained battery compartment is considered acceptable for use with this barricade design when attached to a perforated steel-tube upright or perforated steel-tube vertical brace in a secure manner using a steel-plate connector (as tested) or other approved attachment means. The warning light should be positioned such that the height of the light/lens is just above the top edge of the upper barricade rail.

A horizontal brace should be incorporated into the design to help distribute the impact load to both uprights during an offset impact. During the offset impact, the left side of the barricade was being accelerated and rotated as a result of direct contact with the vehicle, while the right side of the barricade remained relatively stationary and upright. This differential movement and rotation caused the barricade to twist and store energy. The buildup of internal energy eventually caused the connection of the top rail and sign panel to the right upright to fail. The released rail and sign panel subsequently "snapped" into the windshield of the vehicle, causing an unacceptable level of damage.

The extent to which this failure mode may apply to other barricade designs is unknown. Although barricades are often used in the field with lengths of 2.4 m (8 ft) or greater, they are commonly crash tested with shorter lengths (e.g., 1.2 m [4 ft]) to enable the impacting vehicle to engage both supports. While this condition is indeed critical for evaluating rotation of the barricade components into the windshield, the offset impact condition and resulting torsional failure mode may have been overlooked as another critical impact scenario. Because barricades in the field are more likely to be struck in an offset condition than directly along their centerline, this impact condition and failure mode may need to be more fully explored for barricades in general.

To address the problem observed in the offset test, a horizontal cross brace is added to the barricade to tie the two uprights together. The brace, fabricated from 38-mm (1½-in) perforated steel tubing, is placed at a height of 457 mm (18 in) to engage the vehicle bumper. The objective behind the use of the brace is to help get the barricade moving together as a unit during an offset impact. Because of the low mounting height, the addition of the horizontal brace should not influence the impact performance for end-on impacts or centered, head-on impacts.

Recommended details of the perforated steel-tube Type III barricade with 1.2-m × 1.2-m (4-ft × 4-ft) sign panel with a 0.3-m (1-ft) mounting height are shown in Figure 9.1. Details of a corresponding design with a 1.5-m × 0.8-m (5-ft × 2.5-ft) sign panel mounted at a height of 0.8 m (2.5 ft) are shown in Figure 9.2.

9.1.2 Hollow-HDPE/Wooden Barricade

A barricade fabricated from wood and HPPL was found to have acceptable impact performance in a full-scale crash test (Test 4). The 102-mm × 102-mm (4-in × 4-in) HPPL barricade uprights and vertical braces were manufactured from HDPE. Both a 1.2-m × 1.2-m (4-ft × 4-ft) sign panel mounted at 0.3 m (1 ft) and a 0.8-m × 1.5-m (2.5-ft × 5-ft) sign panel mounted at 0.8 m (2.5 ft) are considered acceptable. However, the performance of the taller 1.2-m × 1.2-m (4-ft × 4-ft) sign panel is expected to be marginal.

A plywood sign substrate was used in the crash test of the hollow-HDPE/wooden barricade with attached sign panel. Because a plywood sign panel tends to be more critical from a crashworthiness standpoint because of its greater weight, the successful test with a plywood substrate is considered to be sufficient for acceptance of a similar design with a comparably sized aluminum sign substrate or other lightweight substrate materials (e.g., corrugated plastic).

Because the wooden rails used in the successfully tested barricades are considered more critical from an impact performance standpoint than lighter, hollow-profile plastic rails, both types of rails are considered acceptable. A brief discussion of the advantages and disadvantages of each is provided in Section 9.1.1.

The use of the vertical braces in the barricade framing is optional. They were incorporated into the crash-tested system because their presence represents a more critical configuration for impact performance evaluation. In absence of the vertical braces, the barricade rails and sign panel must be directly attached to the barricade uprights to prevent the sign and fractured rails from rotating into the windshield of the impacting vehicle. If the HPPL braces are used, the barricade can be adjusted for placement on uneven terrain by extending the height of one of the vertical braces relative to one of the uprights before bolting them together. Because the braces are attached directly to the uprights, the sign panel need be attached only to the vertical braces and not directly to the uprights.

The use of a Type A or C warning light with self-contained battery compartment is considered acceptable for use with this barricade design when attached to an HPPL upright or vertical brace in a secure manner using a steel-plate connector (as tested) or other approved attachment means. The warning light should be positioned such that the height of the light/lens is just above the top edge of the upper barricade rail.

A horizontal brace should be incorporated into the design to help distribute the impact load to both uprights during an offset impact. This design feature was added to address a failure mode observed during the testing of the perforated steel-tube Type III barricade with sign panel.

Although the right-side door window was shattered by the end of the upper rail during the head-on, offset impact with the hollow-HDPE/wooden barricade, the slight intrusion of the rail beyond the window was not considered to constitute a risk of serious injury in a frontal collision. This behavior can be mitigated by reducing the overhang distance of the

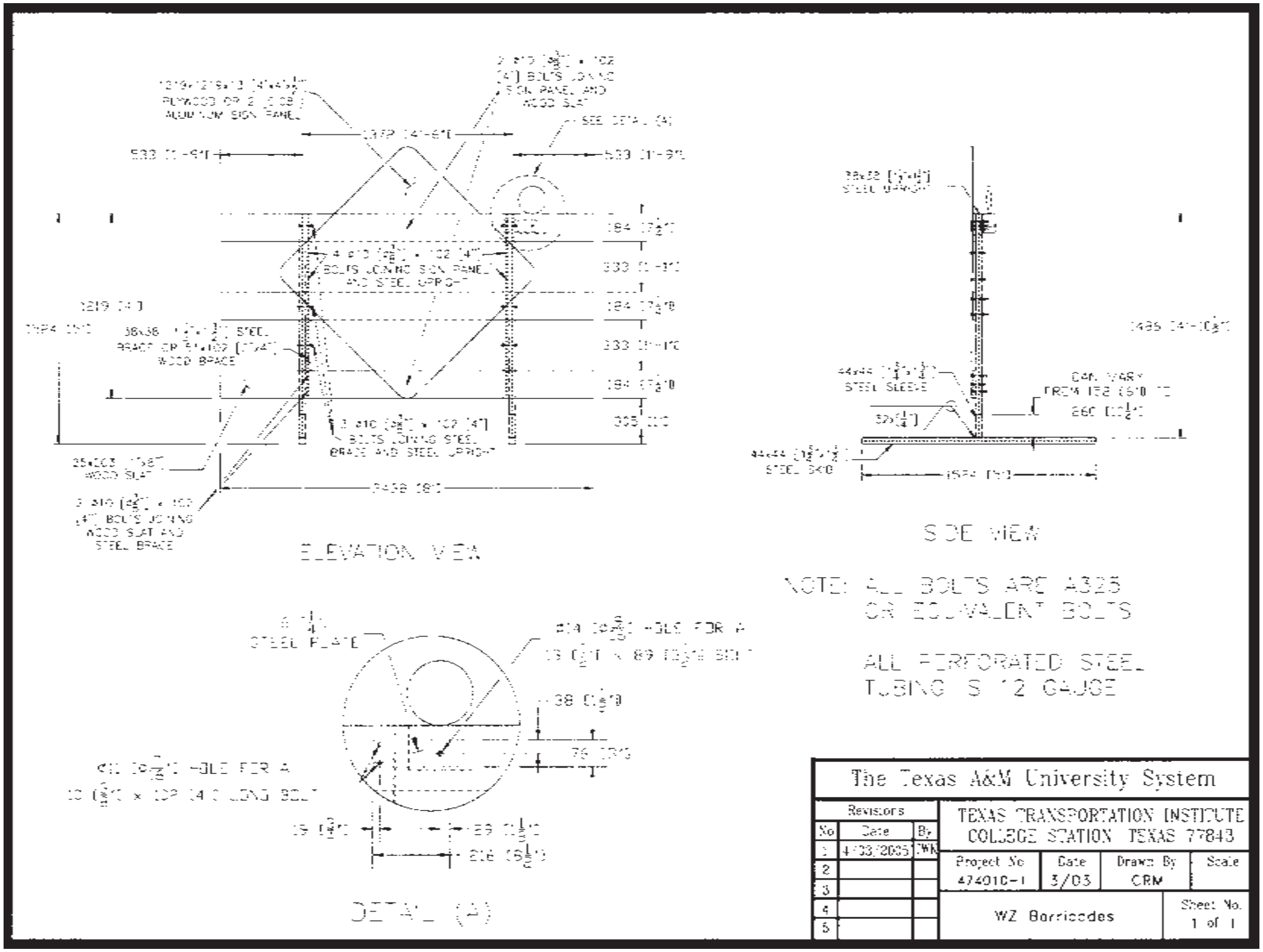


Figure 9.1. *Details of the perforated steel-tube Type III barricade with sign panel mounted at a height of 0.3 m (1 ft).*

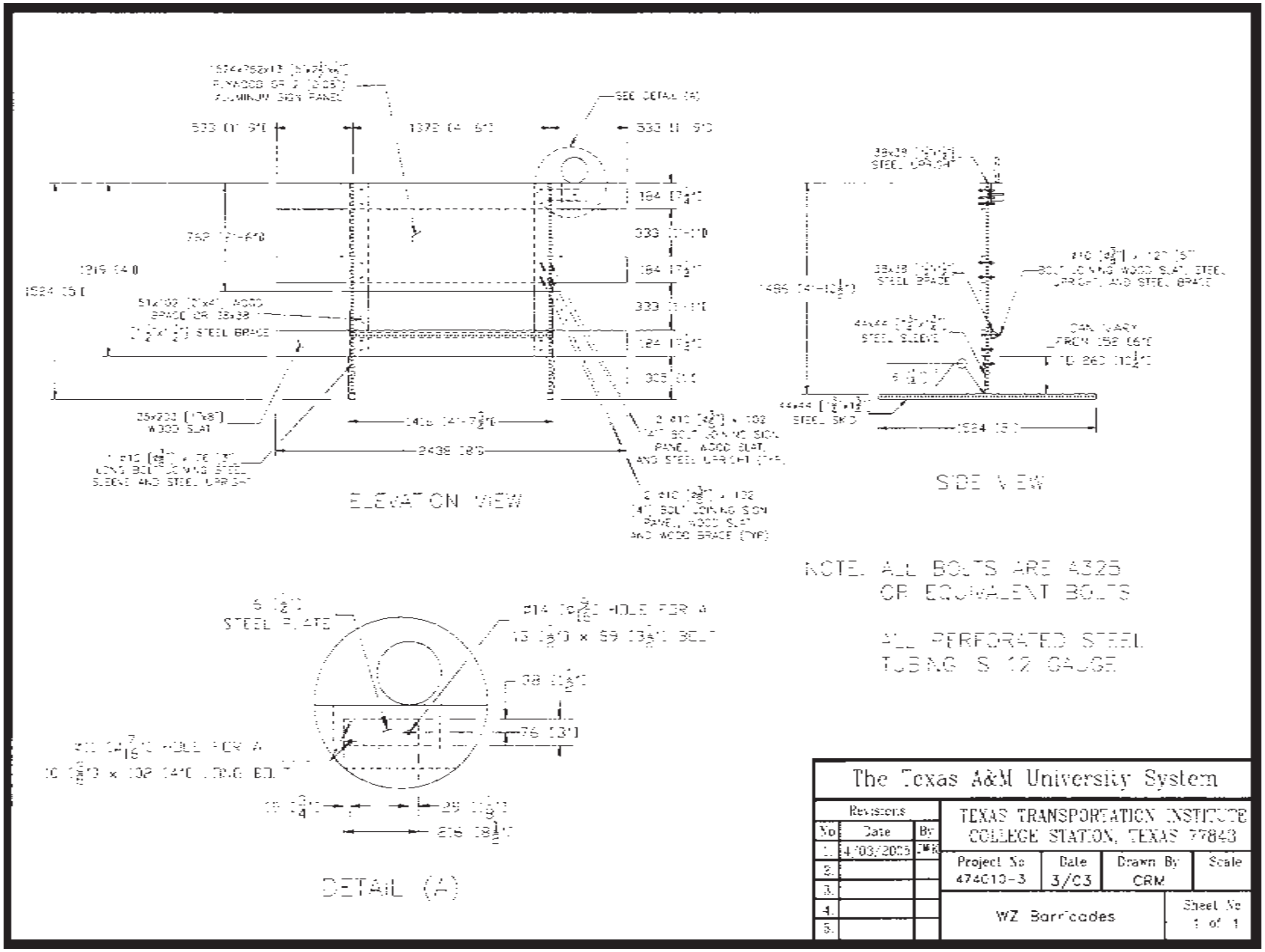


Figure 9.2. Details of the perforated steel-tube Type III barricade with sign panel mounted at a height of 0.8 m (2.5 ft).

rails past the uprights. The spacing of the uprights is limited by the width of the sign panel, which must be attached to either the uprights or vertical braces. By increasing the spacing of the uprights from 1.4 m to 1.6 m (4 ft, 6 in to 5 ft, 4 in), the overhang distance of the barricade rails is reduced from 0.5 m to 0.4 m (1 ft, 9 in to 1 ft, 4 in).

Recommended details of the hollow-HDPE/wooden Type III barricade with 1.2-m × 1.2-m (4-ft × 4-ft) sign panel with a 0.3 m (1 ft) mounting height are shown in Figure 9.3. Details of a similar design incorporating a 1.5-m × 0.8-m (5-ft × 2.5-ft) sign panel mounted at a height of 0.8 m (2.5 ft) are shown in Figure 9.4.

9.2 LOW-MOUNTING-HEIGHT SIGN SUPPORTS

Several low-mounting-height sign supports were designed for use with rigid sign substrates mounted 0.3 m (1 ft) above ground. The designs were prioritized by the panel based on considerations such as cost, ease of fabrication, functionality, stability, etc. The three designs receiving the highest priority were evaluated through full-scale crash testing. All three designs were fabricated from square, perforated steel tubing.

A plywood sign substrate was used in each crash test. Because its greater weight tends to make a plywood sign panel more critical from a crashworthiness standpoint, the sign supports successfully tested with a plywood substrate are also considered to be acceptable when used with a comparably sized aluminum sign substrate or other lightweight substrate materials (e.g., corrugated plastic).

9.2.1 Adjustable Tripod

The adjustable tripod system (Test 5) produced the least amount of damage to the vehicle. Damage to the windshield was limited to a small crack, and the driver's view was not obstructed by the sign panel or windshield damage.

One of the variables related to the tripod design that can affect both impact performance and functionality is the tilt angle of the sign panel. A greater tilt angle makes the system less prone to rotate back into the windshield and will give it more stability against overturn due to wind. However, the legibility of the sign may be compromised if the tilt angle becomes too large. For the crash test, the tilt angle of the sign panel was set at 30 degrees from vertical. This tilt angle should provide a visible, legible sign in both daytime and nighttime conditions. The good impact performance achieved with this system is attributed in large part to the 30-degree lay back angle of the sign. While the crash performance indicates some deviation from this angle would be tolerable, the role of the tilt angle in achieving acceptable impact performance should be properly noted and considered during implementation.

In addition to good stability, this design has good adjustability in all directions. Side-to-side adjustment for accommodating placement on roadside slopes is achieved by telescoping one or both of the front legs as needed. Fabrication of the system can be simplified by making one or both of the front legs out of a single piece of tubing. However, if both legs are continuous, side-to-side adjustment is sacrificed. If needed, front-to-back adjustment for accommodating placement on vertical grades is achieved by adjusting the attachment point of the strut to the rear leg. Unbolting the strut from the rear leg allows the unit to be folded flat for easy transportation.

Use of the cross bar at the bottom of the rear leg is optional. The cross bar can be used to provide a means of ballasting the system with sandbags if desired. The cross bar is bolted to the bottom of the rear leg with a single bolt. The cross bar can then rotate as needed to accommodate placement of the system on a roadside slope. If additional ballast is desired in high wind-speed locations, cross bars can also be added to the front legs of the tripod frame.

Details of the adjustable tripod sign support are shown in Figure 9.5.

9.2.2 Pivoting Dual Uprights

The sign support system with pivoting dual uprights (Test 6) deformed the windshield to classify its performance as marginal. The windshield was shattered and deformed inward 60 mm (2.3 in). The FHWA windshield damage classification guidelines state that "It is desirable that the maximum permanent deflection of the windshield not exceed 55 mm (2.2 in). A maximum permanent deflection exceeding 75 mm (3 in) shall be considered a failure."

The sign support system is considered acceptable for use. Although the sign panel briefly obscured the driver's vision, the 0.043 s interval during which the panel substantially covered the windshield is not considered to be of long enough duration to adversely influence the driver's ability to control the vehicle.

Side-to-side adjustment of the sign support system to accommodate placement on roadside slopes is achieved by extending the upright on the downhill side of the slope the desired distance out of its sleeve or adjusting the attachment of one of the uprights to the sign panel. To tilt the sign panel to the front or back to accommodate placement on vertical grades, the upper bolt used to connect the sleeve to the pivot plate is removed and reinserted after aligning the sleeve with one of the other holes in the plate.

The top adjusting bolt on each plate can be removed to fold the sign down for easy transport as a single unit. This process can be further simplified by using a pin rather than a bolt at this upper connection point on the pivot plate. If desired (for ease of repair, etc.), the sign panel and uprights can be readily detached from the base by removing the bolts that attach the uprights inside the sleeves.

If front-to-back adjustment is neither needed nor desired, fabrication of the pivot plate can be simplified by using only two holes—one in the center of the plate and one at the top edge. This simplification eliminates the angle adjustment of the uprights, but retains the ability to readily fold the system down for transport. The absence of the additional holes in the

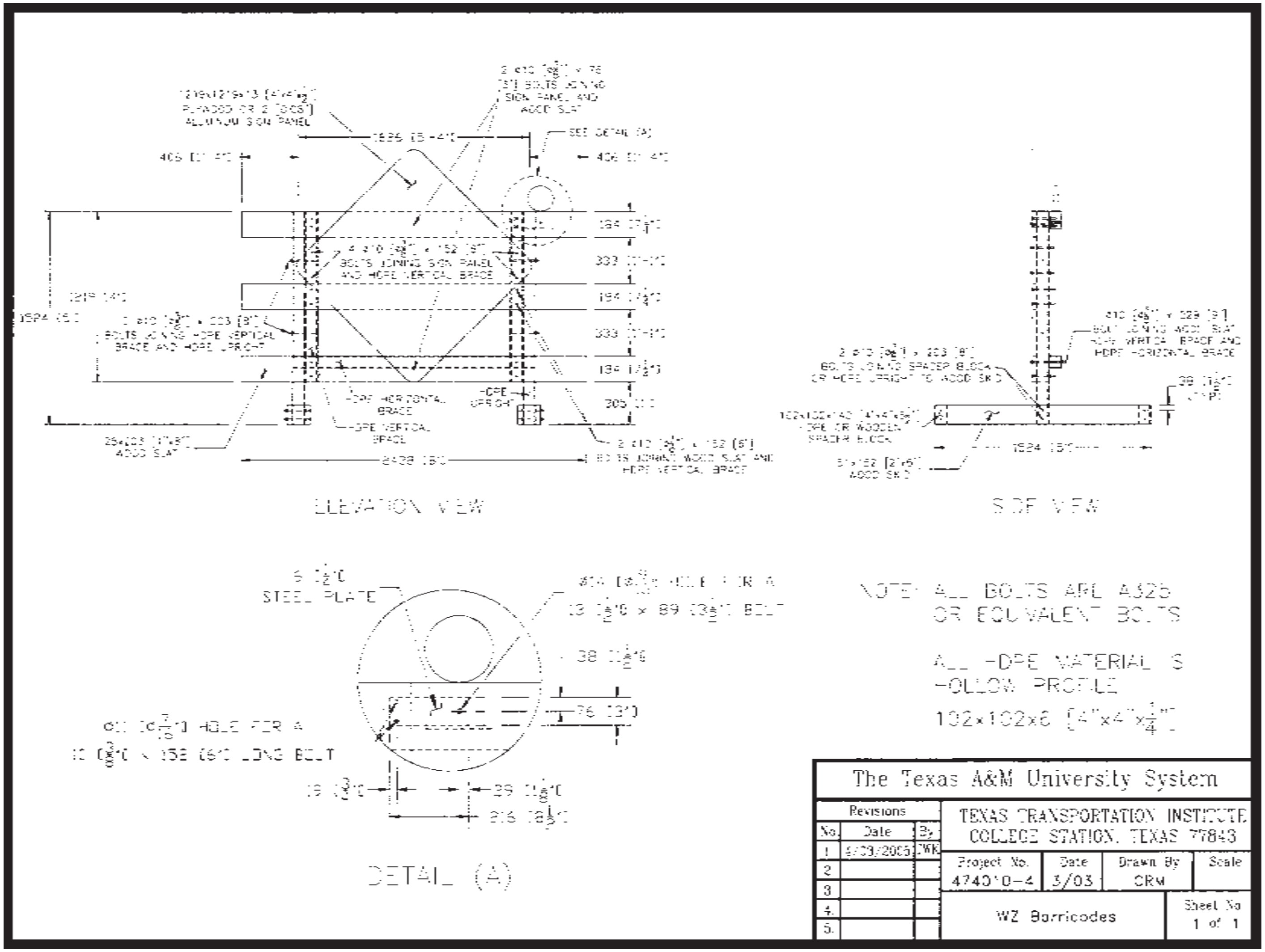


Figure 9.3. Details of the hollow-HDPE/wooden Type III barricade with sign panel mounted at a height of 0.3 m (1 ft).

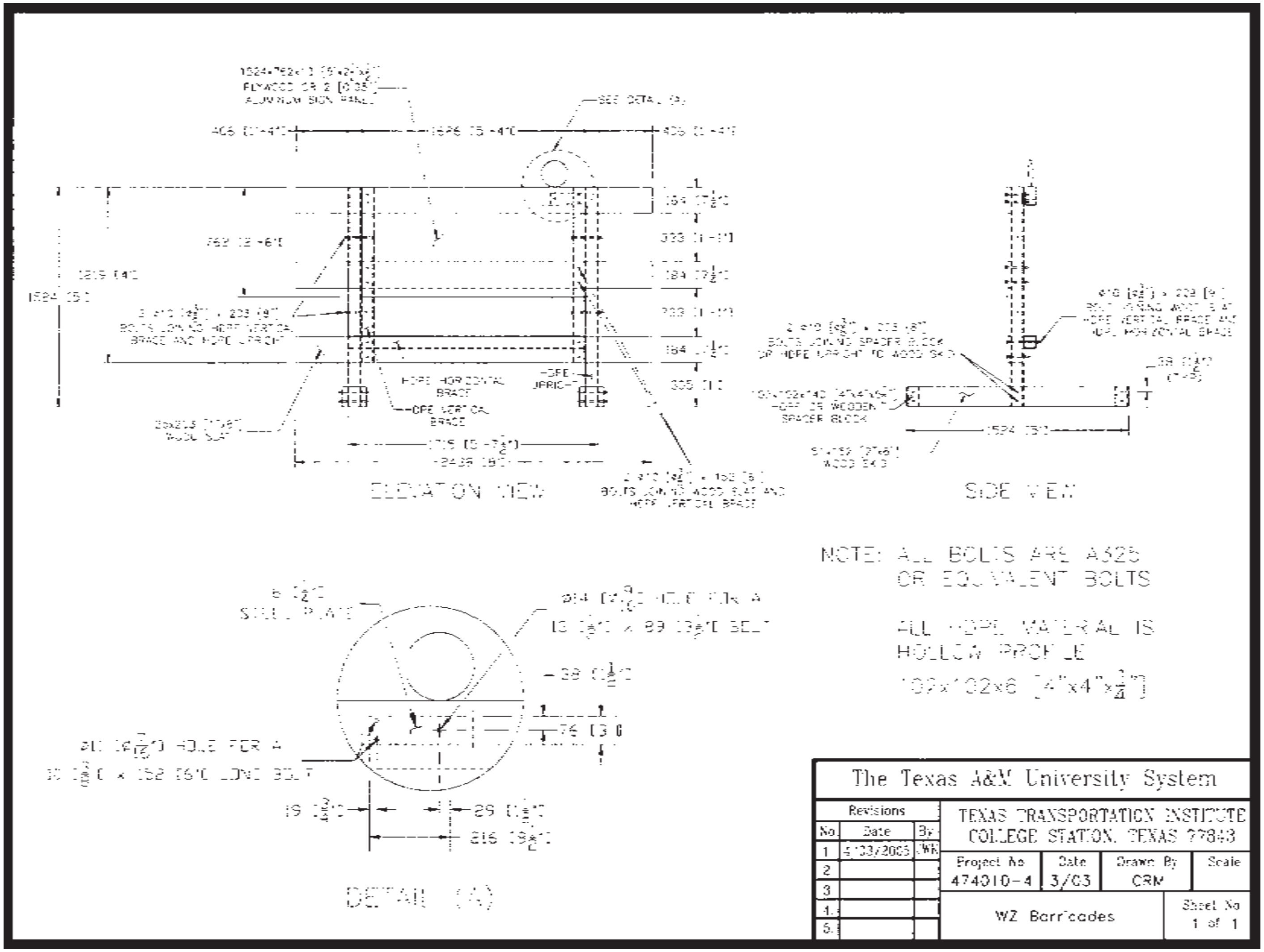


Figure 9.4. Details of the hollow-HDPE/wooden Type III barricade with sign panel mounted at a height of 0.8 m (2.5 ft).

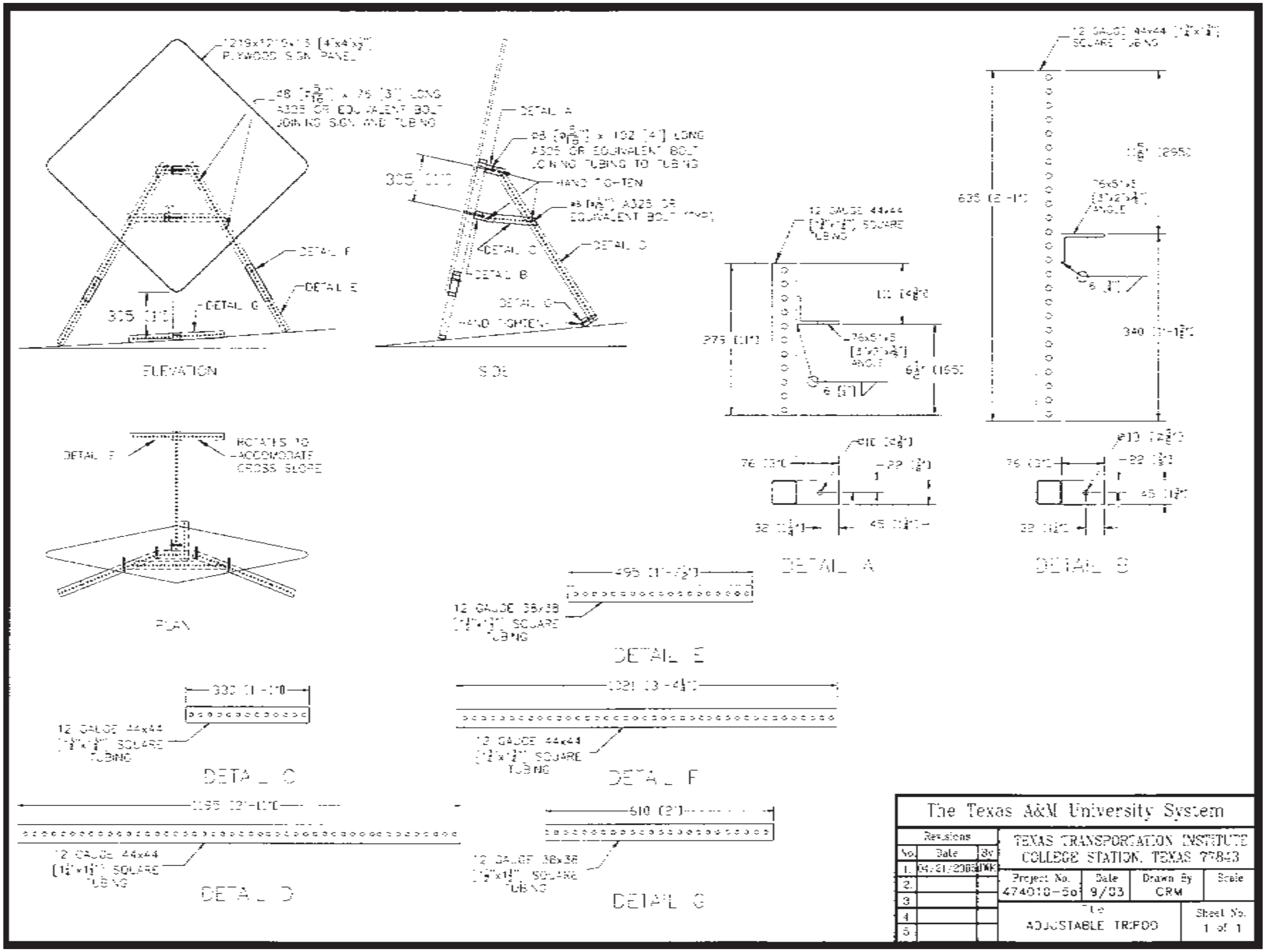


Figure 9.5. Details of the adjustable tripod sign support.

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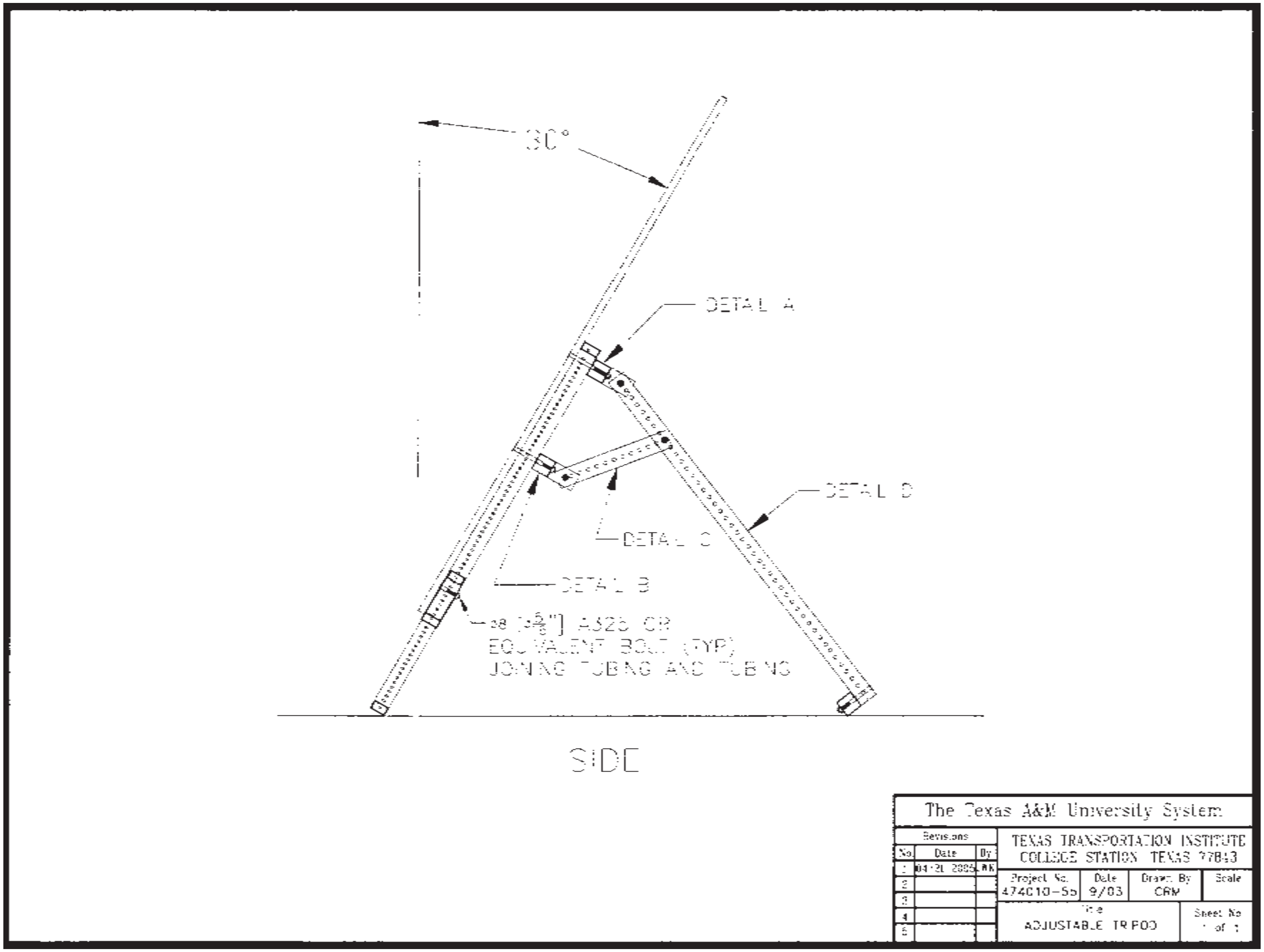

Figure 9.5. (Continued)

pivot plate will not affect the impact performance of the system. If desired, the pivot plates can be welded rather than bolted to the skids. This alternative fabrication method should not adversely affect impact performance.

Details of the sign support system with pivoting dual uprights are shown in Figure 9.6.

9.2.3 Independent Dual Uprights

The sign support system with independent dual uprights (Test 7) is the simplest and least expensive of the low-mounting-height sign support systems designed or tested under this project. The system comprises two identical, independent uprights that, when bolted to their respective skids, form inverted, T-shaped legs. The sign panel is bolted to the uprights and serves as the cross bracing for the system.

The impact performance of the system is considered acceptable and the system is deemed suitable for use in work zones. Although the sign panel briefly covered the windshield during the test, the 0.06-s interval during which the driver's vision would have been obscured is not considered to be of long enough duration to adversely influence the driver's ability to control the vehicle.

Side-to-side adjustability to accommodate placement of the sign support on a roadside slope is achieved by extending the downhill upright out of its sleeve. Transportation is facilitated by the removal of the bolts or pins connecting the uprights inside the sleeves. Although the ability may not be needed, the system does not adjust front to back to accommodate vertical grade.

In the opinion of the researchers, the addition of a horizontal cross brace for added stability should not adversely affect the impact performance of this low-mounting-height sign support system if the cross brace is placed across the sleeves at or near the skids.

Details of the sign support system with independent dual uprights are shown in Figure 9.7.

9.3 HIGH-MOUNTING-HEIGHT SIGN SUPPORTS

Several high-mounting-height sign supports were designed for use with rigid sign substrates mounted 1.5 m to 2.1 m (5 ft to 7 ft) above ground. The designs were prioritized by the panel based on considerations such as cost, ease of fabrication, functionality, stability, etc. The three designs receiving the highest priority were evaluated through full-scale crash testing. All three designs were fabricated from square, perforated steel tubing. Findings and recommendations regarding the high-mounting-height sign supports evaluated under the project are summarized in the following subsections.

9.3.1 Dual Uprights with Slip Connection

This sign support system was considered to be the smallest, lightest, and least expensive dual-support system fabricated from square, perforated steel tubing that can resist the selected 72-km/h (45-mi/h) design wind speed for a 1.2-m × 1.2-m (4-ft × 4-ft) sign panel mounted at a height of 1.5 m to 2.1 m (5 ft to 7 ft). Impact performance of similar designs was unacceptable when the uprights were bolted inside their respective sleeves. The tested design incorporated a short sleeve and unbolted connection as a slip mechanism intended to permit release of the uprights from their skids before substantial plastic deformation was experienced. However, the relatively light 44-mm (1¾-in), 14-gauge perforated steel-tube uprights still deformed around the front of the impacting vehicle before releasing from the sleeves. This behavior resulted in the uprights and sign panel contacting the windshield and roof of the vehicle with sufficient force to induce an unacceptable level of damage. With the windshield dislodged and torn, and the roof deformed downward into the occupant compartment 200 mm (7.9 in), the system failed the test.

Because the most economical design did not perform satisfactorily, the uprights needed to be strengthened and/or alternative release mechanisms evaluated with the intent of limiting the amount of deformation to the uprights. Limiting upright deformation, in turn, would reduce the rotational velocity of the sign panel and decrease the contact forces between the sign panel and vehicle windshield.

9.3.2 Dual Uprights with Raised Slip Joint

A potential solution to the failure observed with the high-mounting-height sign support system with slip connection was a dual-upright sign support system with raised slip joint. In this design, the length of the sleeve was extended and the slip connection between the uprights and sleeves was effectively raised from near ground level to above bumper height. In theory, activation of the slip joint during impact would result in a higher point of rotation of the uprights and sign panel after their release, which would help reduce the probability of secondary contact between the sign panel and windshield of the impacting vehicle.

Such behavior was observed in the 0-degree impact, and contact between the sign panel and vehicle was avoided. However, in the 90-degree impact, the deformation of the sleeves generated rotation of the sign panel into the vehicle before the release of the uprights from the sleeves, and the subsequent contact between the sign panel and vehicle windshield resulted in an unacceptable level of damage. With a small hole in the windshield and permanent deformation of the windshield of 92 mm (3.6 in), the system was considered to have failed the test.

9.3.3 Strong Dual Uprights with Slip Connection

The high-mounting-height sign support system with strong, dual uprights is a variation of the slip connection concept that incorporates larger, stronger sections of perforated steel tubing. Uprights of 57-mm (2¼-in) square, perforated steel

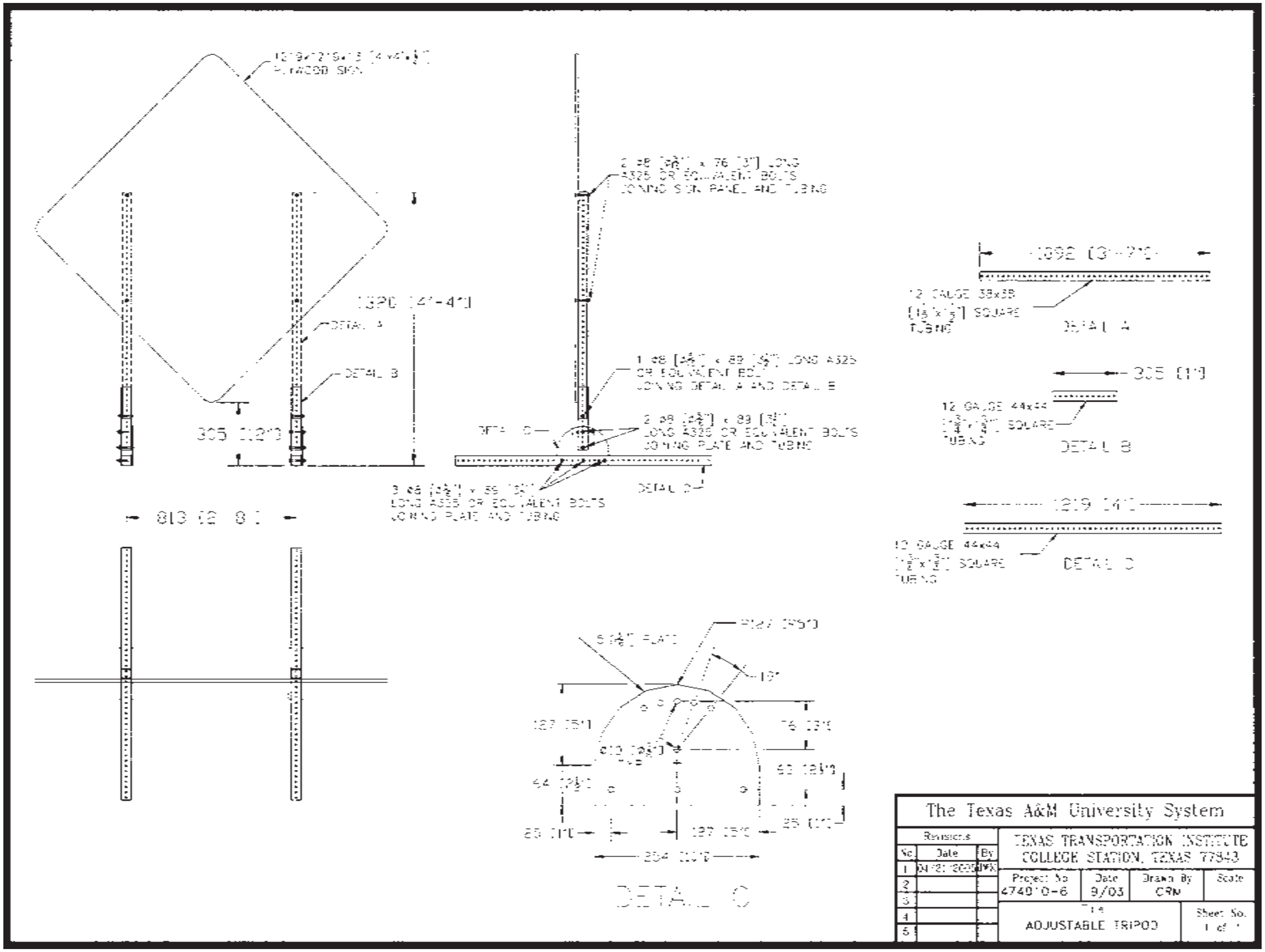

Figure 9.6. Details of the sign support system with pivoting dual uprights.

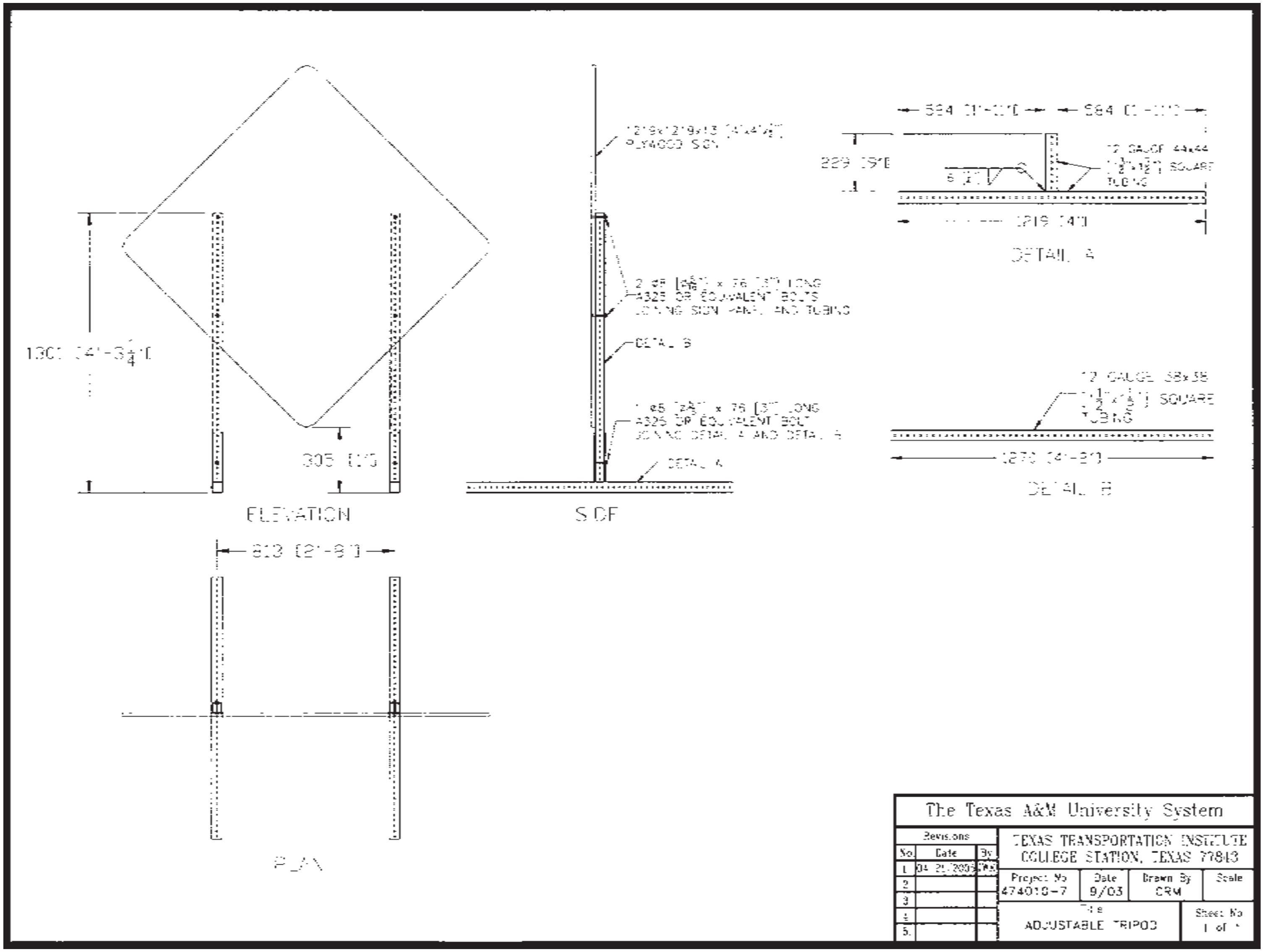

Figure 9.7. Details of the sign support system with independent dual uprights.

tubing are inserted into 64-mm (2½-in) square, perforated steel sleeves. In theory, the increased flexural strength of the larger uprights would reduce the deformation of the uprights around the front of the vehicle before they released from the sleeves, thus improving the likelihood that the system would meet crash-test requirements.

The strong, dual-upright perforated steel-tube sign support with 1.2-m × 1.2-m × 13-mm (4-ft × 4-ft × ½-in) plywood sign panel mounted at a height of 1.5 m (5 ft) met all required evaluation criteria for both the head-on and end-on impact scenarios. The incorporation of larger, stronger uprights into the design limited the deformation of the uprights and prevented them from wrapping around the front of the vehicle. The point of rotation changed from bumper height (i.e., approximately 457 mm [18 in] above ground) to a point that closely coincides with the overall center of mass of the sign support system. In addition to raising the point of rotation, the stronger uprights also effectively decreased the rotational velocity. These factors combined to reduce the severity of the secondary impact of the support structure with the windshield and roof of the vehicle, thus limiting the extent of vehicle deformation to an acceptable level.

Using larger tubular members to achieve acceptable impact performance increases the system's weight and cost of fabrication. The increased weight will make the sign support system more difficult to handle.

The 1.5-m (5-ft) mounting height is generally believed to be more critical than a 2.1-m (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 severity of secondary impacts of the supports and sign panel with the windshield and roof of the impacting vehicle. Since the strong, dual-upright sign support system met all required evaluation criteria with the sign panel mounted at 1.5 m (5 ft), the researchers consider the same sign support system to be acceptable for a 2.1-m (7-ft) mounting height.

As discussed previously, the rigidity and mass of a plywood sign panel make plywood more critical than most other substrate materials from a crashworthiness standpoint. Because of the greater weight of plywood, the successful test of the strong, dual-upright sign support system with a plywood substrate is considered to be sufficient to indicate acceptable impact performance of the same sign support system with a comparably sized aluminum sign substrate or lighter weight corrugated plastic sign substrate.

During analysis of the high-speed film of the test, the slip mechanism was observed not to activate as designed. Upon impact, the sign support system moved as a unit. The uprights remained inside the sleeves until well after momentum was transferred to the entire system. This behavior indicates that the slip mechanism did not affect the impact response of the system; as a result, a longer sleeve (e.g., 152 mm to 229 mm [6 in to 9 in]) can be used without adversely affecting impact performance. For the same reasons, the researchers have concluded that bolting or pinning the uprights inside the sleeves would not compromise impact performance. Such design modifications would provide better adjustability to accommodate placement of the sign support on a roadside slope by permitting the length of the downhill upright to be extended within the sleeve. Although not considered to be a problem in the test, bolting of the uprights inside the sleeves would permit the system to travel as a unit and reduce any potential debris hazard associated with the skids releasing from the uprights.

Recommended details of the strong, dual-upright sign support system are shown in Figure 9.8 and Figure 9.9 for a 1.5-m (5-ft) sign panel mounting height and 2.1-m (7-ft) sign panel mounting height, respectively. These drawings incorporate some of the changes suggested by the researchers and vary from the tested configuration.

9.3.4 Additional Designs

Another means of increasing the flexural strength of the uprights to reduce deformation during impact is to nest two smaller sections of perforated steel tubing inside each other to form a stronger composite section. When finalizing the design details for such a system for consideration under this project, the researchers learned that a similar system had been successfully crash tested for the Michigan DOT. (*16*) In this design, 44-mm (1¾-in) square, perforated steel-tube uprights nest within 51-mm (2-in) square tubes. The tops of the nested portions extend 1067 mm (42 in) above ground. The bottoms of the nested uprights extend below the ends of the 51-mm (2-in) square tubes and are inserted into 152-mm (6-in) long sleeves. The sleeves and skids are fabricated from 51-mm (2-in) square, perforated steel tubing. The system was tested with a 1.2-m × 1.2-m (4-ft × 4-ft) plywood sign panel at a mounting height of 1.5 m (5 ft).

Another high-mounting-height sign support system using nested uprights was successfully crash tested concurrent with those being tested under this project. (*17*) In this design, a 1.2-m (4-ft) long vertical sleeve fabricated from 51-mm (2-in) square, 12-gauge perforated steel tubing was welded to the center of a 1.5-m (5-ft) long skid fabricated from the same material using two lines of weld parallel to the length of the skid along the inside and outside edges of the sleeve. The sleeves were not welded to the skids along their front or back edges. A 44-mm × 44-mm × 3.4-m (1¾-in × 1¾-in × 11-ft), 12-gauge perforated steel upright was inserted into the sleeve until it rested on a bolt passing through the bottom of the sleeve. The system was tested with a 1.2-m × 1.2-m × 10-mm (4-ft × 4-ft × ⅜-in) corrugated plastic sign panel attached to the vertical supports in a diamond configuration at a mounting height of 2.1 m (7 ft) above ground. The sign substrate and mounting height for this system should not be changed unless further testing is conducted to demonstrate acceptable performance.

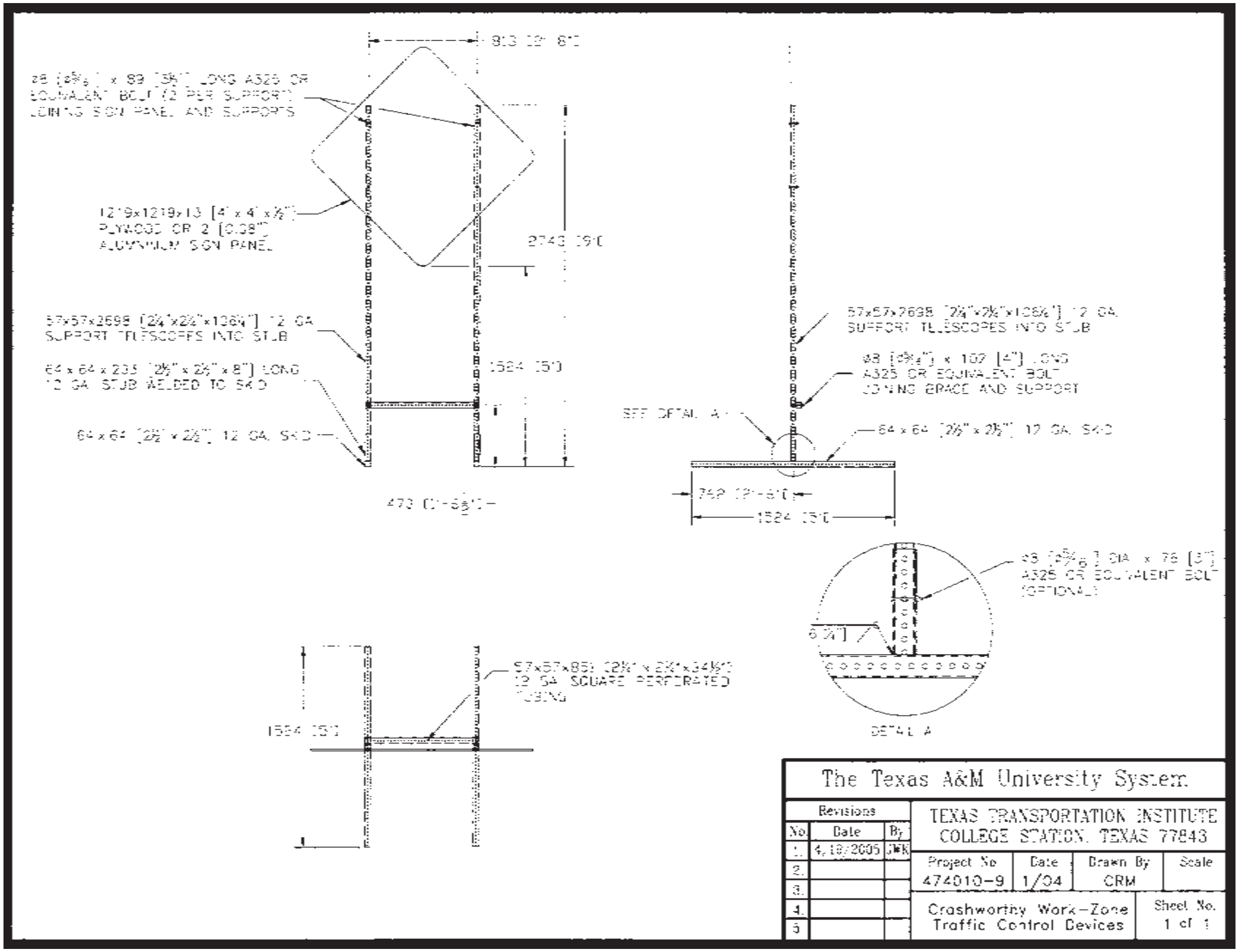

Figure 9.8. Details of the strong dual-upright sign support system with sign panel mounted at a height of 1.5 m (5 ft).

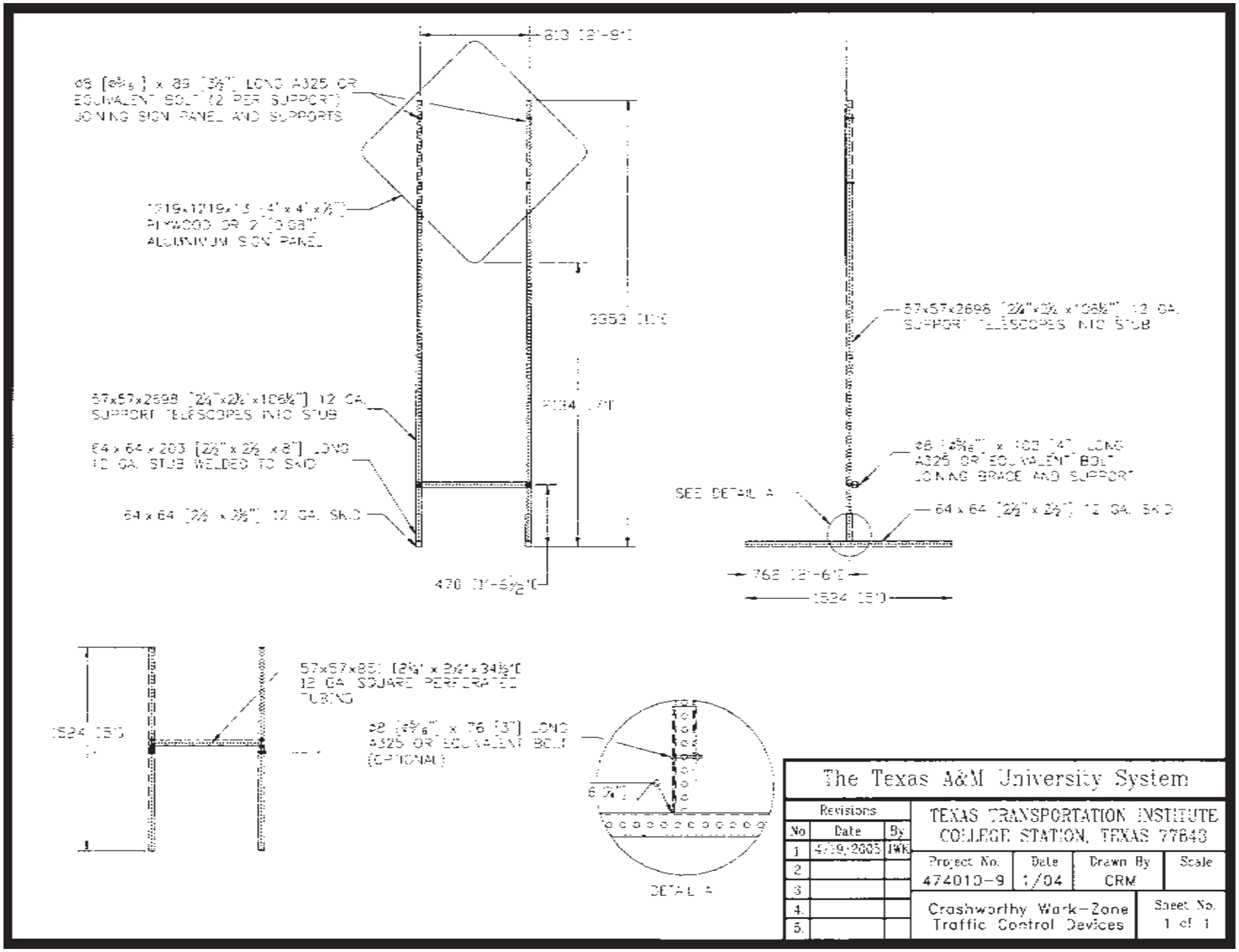

Figure 9.9. Details of the strong dual-upright sign support system with sign panel mounted at a height of 2.1 m (7 ft).

These two systems are briefly described and referenced to inform the reader of their availability for use in work zones. These systems—together with the barricades with signs, low-mounting-height sign supports, and high-mounting-height sign supports successfully crash tested under this project—will provide user agencies with more generic, crashworthy design alternatives to use for traffic control in their work-zone operations.

9.4 FUNCTIONALITY

A rating scheme was developed to assist with the comparative evaluation of the functional performance of various work-zone traffic control devices in the following categories: wind resistance, durability, handling, fabrication/repair, and site adaptability. The rating scale for each category includes "high," "average," and "low." A discussion of each category and its associated rating scale is presented in Section 4.2.5, Functional Performance Rating.

The overall functionality of a device is assessed by averaging the wind resistance, durability, handling, fabrication/repair, and site-adaptability ratings. This rating scheme was used to assess the relative functionality of the various work-zone traffic control devices successfully developed and crash tested under this project to assist user agencies with device selection. The results of this assessment are presented in Table 9.1.

The low level of distinction among the ratings assigned to the various work-zone devices is not surprising. Indeed, the objective of the project was to develop crashworthy work-zone devices that can be fabricated from readily available materials and that possess a high degree of functionality. Thus, the various aspects of functionality were considered during the design process. If this rating scheme were applied to other existing devices, the range of the individual and overall ratings would vary more widely.

The assessment of functional performance is somewhat subjective and relative in nature and reflects the opinions of the researchers. User agencies may have different opinions regarding the assigned functionality ratings and/or give more weight to other criteria (e.g., cost) when deciding among these devices.

Experience with full-scale crash testing of work-zone traffic control devices suggests that the impact performance of most devices is not very sensitive to the amount of ballast applied to the base. Sandbags are readily ripped open during an impact, thus dispersing the sand. Any amount of ballast that can be practically applied to the base of a device is not likely to adversely affect its impact performance. However, even if the device is adequately designed and has a "high" wind rating, insufficient ballast can increase the probability of a device overturning during windy conditions. The amount of ballast (e.g., number of sandbags) required to prevent overturn of a barricade or sign support system varies depending on the selected design wind speed and characteristics of the design such as size of the sign panel and mounting height of the sign and/or rails. Guidance on the amount of ballast required for different design wind speeds is provided in Section 8.1, Wind Load Analysis.

The devices developed under this project are not only crashworthy, but also considered to provide a high degree of practicality and functionality. These devices provide user agencies with additional alternatives for relaying information and controlling traffic in work zones.

TABLE 9.1 Functional assessment of successfully tested work-zone devices

Device Description					Functional Performance*					
Figure No.	**Frame**	**Rails**	**Sign**	**Bracing**	**Wind Resist.**	**Durability**	**Handling**	**Fabricate/ Repair**	**Site Adapt.**	**Overall Rating**
Barricades with Signs										
9.1, 9.2	Perforated steel	Wood or plastic	Wood or aluminum	Wood or perforated steel	High	High	High	High	High	**High**
9.3, 9.4	HPPL	Wood or plastic	Wood or aluminum	HPPL	High	Average	Average	High	Average	**Average**
Low-Mounting-Height Sign Supports										
9.5	Perforated steel	N.A.	Wood or aluminum	Perforated steel	Average	High	High	Average	High	**High**
9.6	Perforated steel	N.A.	Wood or aluminum	N.A.	High	High	High	Average	High	**High**
9.7	Perforated steel	N.A.	Wood or aluminum	N.A.	High	High	Average	High	High	**High**
High-Mounting-Height Sign Supports										
9.8, 9.9	Perforated steel	N.A.	Wood or aluminum	Perforated steel	High	High	Average	High	Average	**High**

* See Section 4.2.5, Functional Performance Rating, for description of rating categories and scale.

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APPENDIX A

FHWA WINDSHIELD DAMAGE CLASSIFICATION

WINDSHIELD DAMAGE FOR CATEGORY 2 WORK ZONE TRAFFIC CONTROL DEVICES:

Draft Guidance for Pass / Fail

Safety glass used in vehicle windshields has been designed as a laminated system to resist penetration. A windshield can withstand a severe blow and show extensive cracking, yet protect the occupants by resisting penetration by all or parts of the test article. Crash records are not sufficiently detailed to tell us how the damage to a windshield relates to the severity of a crash. However there is a need to be able to evaluate various safety features by observing the results of crash tests.

Report 350 states:

> Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.

This provision has been interpreted in different ways by the crash test agencies when evaluating windshield damage resulting from tests with category 2 work zone devices. The most conservative evaluations have failed a device when the cracking extended to the inner layer of glass. The most liberal interpretation considered the test article acceptable even when the entire windshield was shattered sending glass particles into the occupant compartment, as long as the test article itself did not penetrate the windshield. The ability of the driver to see through the damaged windshield also must be considered. An informal survey conducted during the Transportation Research Board's meetings of January, 1999, showed a similar diversity of opinion among researchers, manufacturers, and users of the devices.

In FHWA's July 25, 1997, memorandum, it was suggested that windshield damage and intrusion each be rated on a scale. Those scales did not classify the damage as passing or failing. Based upon full-scale crash testing FHWA has reviewed subsequent to that memorandum, the following seven classes of damage are offered as a guideline for evaluating windshield damage. It is realized that there is still room for interpretation between these classes, but that some measure of consistency will be introduced. Sketches are included as an aid in describing the damage and assessing the results. Please note that the amount and extent of cracking shown in the sketches is far less than will be seen in a real windshield.

Case 1. Fail: Any impact that causes a hole through the windshield glass whether or not part of the test article enters the occupant compartment.

Case 2. Fail: Any impact that destroys or deforms the windshield to the extent that it separates from the frame.

Case 3. Fail: Any impact where the windshield is cracked overall to such a degree that the driver cannot readily see to navigate.

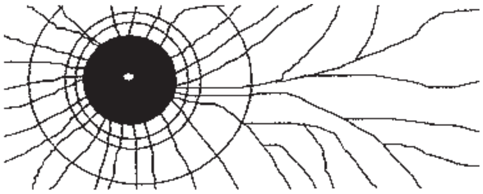
Case 4. Pass: Any impact where the windshield is cracked overall and the windshield deflects in towards the occupants without causing a hole in the plastic layer. Glass particles from the inner layer of glass are permitted in the passenger compartment. The driver can still readily see through the damage and bring the vehicle to a safe stop. (One test house uses a criterion of 2-inch maximum permanent deflection of the windshield as a pass/fail measure.)

Case 5. Pass: An impact that causes a roughly circular area of localized cracking / shattering completely obscuring vision to a diameter of no greater than one foot. No penetration of the test article through the glass occurs. Extensive cracking throughout the remainder of the windshield is permitted but no deformation occurs other than at the point(s) of impact.

Case 6. Pass: An impact on the roof line that causes shattering of the windshield near the point of impact and/or other cracking that extends throughout the windshield. (This is primarily for taller devices that "bridge" between the front of the hood and the roof.)

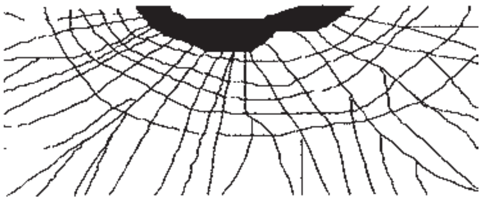
Case 7. Pass: An impact that causes only minor cracking or dings on the windshield. (Not illustrated.)

The NCHRP committee pursuing the next generation crash test guidance should consider guidelines for evaluating passenger compartment intrusion. These seven criteria may be used as a starting point for windshield damage. FHWA solicits comments from all concerned as to the appropriateness of these criteria, both in terms of measuring windshield damage using these seven classes, and in terms of expected injury severity in real-world crashes. Please contact Mr. Nicholas Artimovich of the Office of Highway Safety Infrastructure with comments or questions regarding these guidelines at (202) 366-1331 or via E-mail at nick.artimovich@fhwa.dot.gov.



Case 1: Impact causes a hole in the windshield.

Fail

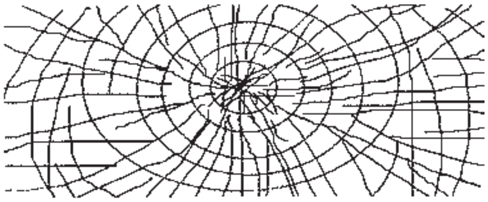


Case 2: Impact causes separation of windshield from frame.

Fail

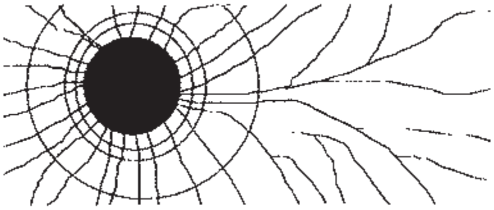
Case 3: Significant overall damage. Driver cannot readily see ahead to navigate to a safe stop.

Fail



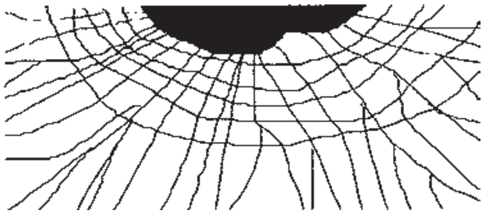
Case 4: Significant overall damage but no hole. Driver can readily see to bring the vehicle to a safe stop.

Pass (Maximum permanent deflection criteria may apply)



Case 5: Significant local damage but no hole.

Pass



Case 6: Significant damage where test object struck roof line but caused no penetration of windshield nor separation of windshield from roof.

Pass

[The black areas above indicate extensive damage to the glass restricting visibility, and some deflection of the windshield inward. The white dot in Case 1 indicates a hole. The white area at the top of case 2 indicates separation of the windshield from the frame.]

APPENDIXES B THROUGH F

Appendixes B through F are available from TRB upon request.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation