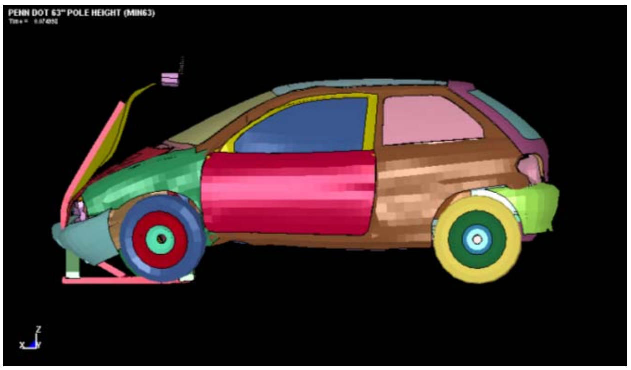
COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

PENNDOT RESEARCH



PENNDOT

PORTABLE SIGN CRASH TEST

Final Report

PennDOT/MAUTC Partnership, Work Order No. 7
Research Agreement No. 510401

December 2007

By D. G. Linzell and Z. Radó

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16. Abstract

Portable sign post structures currently in use by the Pennsylvania Department of Transportation, supporting signs less than 36 inches square at heights of 7 ft off the ground, are assembled using varying techniques and materials and do not meet crash testing standards established in NCHRP 350. This project was performed to review available crash-tested portable sign post structures and, based on this review, design and crash test a new model to meet the NCHRP 350 criteria and establish a standard PennDOT support design protocol. The objectives of the project were to: (1) search available literature to establish the state of the art for portable sign post structures in the United States for further study; (2) perform numerical modeling of selected sign posts' designs to present optimal designs for crash testing according to NCHRP 350 [1]; (3) develop a crash testing plan for sign posts recommended by PennDOT and have the plan approved by relevant PennDOT personnel; and (4) perform crash tests of selected sign post designs, report on the findings of the crash tests and develop standard drawings.

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Prepared for

Bureau of Planning and Research
Commonwealth of Pennsylvania
Department of Transportation

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1 Introduction

1.1 Problem Statement

Portable sign post structures currently in use by the Pennsylvania Department of Transportation (PennDOT), supporting signs less than 36 inches square at heights of 7 ft off the ground, are assembled using varying techniques and materials and do not meet crash testing standards established in NCHRP 350 [1]. This project was performed to review available crash-tested portable sign post structures and, based on this review, design and crash test a new model to meet the NCHRP 350 [1] criteria and establish a standard PennDOT support design protocol.

1.2 Objectives

The objectives of this project were to: (1) search available literature to establish the state of the art for portable sign post structures in the United States for further study; (2) perform numerical modeling of selected sign posts' designs to present optimal designs for crash testing according to NCHRP 350 [1]; (3) develop a crash testing plan for sign posts recommended by PennDOT and have the plan approved by relevant PennDOT personnel; and (4) perform crash tests of selected sign post designs, report on the findings of the crash tests and develop standard drawings.

1.3 Scope

The following scope was developed for this project:

Task 1: Investigate State of the Art for Portable Sign Structure Design in the United States. Current literature will be examined to establish what portable sign post structures are being used by PennDOT and what sign post structures have been successfully tested following NCHRP 350 [1] criteria by other government entities in the United States. The literature search will incorporate commercially available sign support structures' designs and their crash worthiness results, if available. At the completion of the literature search, an interim report summarizing the findings will be submitted to PennDOT. A meeting describing the findings will follow and PennDOT will choose no more than five sign post designs for further study.

Task 2: Perform Numerical Modeling. After PennDOT has selected no more than five sign post designs for further study, models of the selected designs will be developed in LS-DYNA. The models will be developed by taking advantage of the inherent optimization feature of LS-DYNA to ensure that modifications for the improvement of the analyzed structures can be performed efficiently. The structures will be crash tested numerically; the virtual crash test simulation will be prepared to replicate the conditions of the full-scale crash testing scenario of the NCHRP 350 [1] test levels 3-60 and 3-61 for support structures. The simulation results will be evaluated according to NCHRP 350 [1] section 3.2.3.2, the evaluation standard for breakaway utility poles. The performance of these designs will be examined and compared. The findings will be presented in an interim report. A meeting describing the findings will follow and PennDOT will choose no more than two sign post designs for further study.

Task 3: Develop Crash Test Plans and Conduct Crash Test. After PennDOT has selected no more than two sign post designs for further study, crash testing plans will be developed and submitted to relevant PennDOT personnel for approval. Two tests are recommended for the selected support structures using the recommended 820C vehicle: a low-speed test at 35 km/h and a high-speed test at 100 km/h. The low-speed test is generally intended to evaluate the breakaway, fracture, or yielding mechanism of the support, whereas the high-speed test is intended to evaluate vehicle and test article trajectory. Occupant risk is of concern in both tests. If the primary concern regarding the impact behavior of the selected support systems based upon the simulation results is penetration of the test article or parts thereof into the occupant compartment, as opposed to occupant impact velocity, ride-down acceleration and vehicular stability, it may be preferable to use the 2000P vehicle in lieu of the 820C vehicle. The choice will depend on the front profile of the two vehicles in relation to the geometry of the selected sign post structures and footings that could potentially penetrate the occupant compartment. The obtained simulation results also will be used for the planning of the critical impact point and angle of the crash tests. If the LS-DYNA results warrant, then the left or right quarter point of the impact vehicle bumper will be recommended to be aligned with the vertical centerline of the support structures. NCHRP 350 [1] has a provision to allow the same vehicle to be used to conduct both required tests (60 and 61) provided damage to the vehicle from the first test (usually the low-speed test) has no appreciable effect on impact performance of the vehicle in the second test. Once the plans have been approved, crash testing following NCHRP 350 [1] “3.2.3 Support Structures, Work Zone Traffic Control Devices, and Breakaway Utility Poles” guidelines will occur. Findings from the tests will be examined.

Task 4: Prepare Final Report and Standard Drawings. At the completion of the crash test and review of the data, a final report will be developed that will recommend final designs for portable sign post structures. In addition, standard drawings of the crashed sign post designs will be prepared following PennDOT guidelines.

Task 5: Summary of the Problem Statement and Findings.

The present report contains the description and results of all the work performed to achieve the objectives of the study. It contains the final design documentation of the developed portable sign structure with manufacturing instructions and material lists. The report also contains the full material submitted to FHWA for the approval of the portable sign material.

2 Current PennDOT Portable Sign Structure

Current portable sign post structures being used by PennDOT, supporting signs less than or equal to 36 inches square at heights of 7 ft off the ground, are assembled using varying techniques and materials. The engineering drawings with material descriptions, assembly instructions, and dimensions were not available. The presently used sign structure design is built from the documentation shown in "14 APPENDIX F - Pennsylvania structure – X-shape" and "15 APPENDIX G - Pennsylvania structure – H-shape."

The new sign structure designed and crash tested within the present project is described in "5 Sign Post Design" and the complete engineering drawings are included in APPENDIX L – FHWA REPORT.

3 Task 1: Investigate State of the Art for Portable Sign Structure Design in the United States

Included herein are classifications and discussions of crashworthy traffic control devices provided by FHWA. This information is largely reprinted verbatim from a FHWA Memorandum dated 8/28/98 [2].

3.1 Crashworthy Devices

3.1.1 Category 1 Devices

"Low-mass, single-piece traffic cones, tubular markers, single-piece drums and delineators are category 1 devices and are, by definition, considered crashworthy devices meeting NCHRP Report 350 TL-3 criteria. At this time, no auxiliary lights or signs may be attached to devices certified under category 1 devices. Through formal and informal crash testing, and because of years of experience, these low-mass devices have shown that they will not cause an appreciable change in the speed of an impacting vehicle and it is unlikely that any part of these devices will intrude into the passenger compartment of a striking vehicle. For a list of these devices, including maximum mass and maximum height of the devices that were satisfactorily crash tested, see [2]. That information may assist engineers in making an analysis and assessment for the use of their specific devices. For details of specific tests that were conducted on some of these devices, see Attachment A, Table I.2 in [2]. Please note that the data in Table 1.2 are for information purposes only. Not all information for each test was available from the reports on file and some of the entries are incomplete.

"While the States may place additional conditions on features to be used in highway projects, the FHWA suggests that States accept category 1 devices based on the self-certification by the vendor. It is the responsibility of the vendor of the device to determine if, and to certify that, their product is crashworthy--that it will meet the evaluation criteria of the NCHRP Report 350.

This certification may be a one-page affidavit signed by the vendor with documentation supporting the certification (crash tests and/or engineering analysis) kept on file by the certifying organization. This procedure was developed to reduce the regulatory burden on the highway community in light of the great number of obviously similar crashworthy devices being used today. If subsequent analysis or crash testing shows that a device is not crashworthy as certified by the vendor, the device may be prohibited from use on the NHS." **It is the responsibility of the States to ascertain that the authorized and used devices are not prohibited by the NHS.**

3.1.2 Category 2 Devices

"Like category 1 devices, certain other low-mass traffic control devices qualify for a reduced level of crash testing and/or reporting under NCHRP Report 350. Individual crash testing will be required and FHWA letters of acceptance may be requested. Because of the great variety of styles and sizes of devices and their attachments within category 2, the implementation to continue crash testing and to permit analysis of the various devices is a continuous process.

"Category 2 hardware that has been crash tested and that has received an acceptance letter from the FHWA includes various plastic barricades, vertical panel assemblies, portable sign supports, and Type III barricades. The FHWA acceptance letters and the specific devices that are considered acceptable are listed in Attachment A, Table II.1 of [2]. Other acceptable category 2 devices that have been tested under State contracts are also listed in that table. Drawings of most of the devices that passed the testing under these State contracts are illustrated in Attachment A in Figures II.1 through II.20 of [2]."

It is important to note that failures of certain devices that are in common use have occurred during crash testing. These tests are listed in Attachment A, Table II.2 of [2] and are highlighted with grey shading. Information in the reports from these tests should provide useful starting points for the design of crashworthy replacements for these failing devices.

"It is likely that many other devices have been successfully tested over the years and have been placed in service. However, the available details on the devices referenced in this report were only sufficient to make an engineering judgment as to the suitability and performance of these devices for the use in this study. Manufacturers are continuously submitting reports of crash testing conducted on their devices to the FHWA Office of Engineering for review. It should be noted that in order to accelerate the acceptance of crashworthy work zone traffic control devices and reduce the costs of full-scale crash testing, the FHWA will review the results of informal crash testing for category 2 work zone traffic control devices that meet the reduced instrumentation requirements of Section 3.2.3.2 of NCHRP Report 350. Although this section specifies a maximum mass of 45 kg, FHWA will consider devices on a case-by-case basis if it is evident that they will not cause a significant velocity change (generally this would encompass stand-alone devices up to a mass of 100 kg). See the guidance contained in [3]."

3.1.3 Category 3 Devices

"Category 3 devices are subject to the full testing and reporting requirements of NCHRP Report 350. Individual acceptance letters for NCHRP Report 350 crashworthy truck-mounted attenuators (TMAs) and traffic barriers--impact attenuators (crash cushions), barrier terminals, and longitudinal barriers (temporary and/or permanent)--are listed in Attachment A, Table III.l. A in [2]. Each item is listed with the FHWA acceptance letter number and date of that letter, the NCHRP Report 350 test level to which it was tested, and the name of the device.

"New work zone crash cushions (including TMAs) purchased after October 1, 1998, must meet NCHRP Report 350 guidelines. The States can phase out existing barriers as they complete their normal service life, except that barriers with joints that fail to transfer tension and moment from one segment to another will not be acceptable after October 1, 2000, unless demonstrated to be crashworthy. The five "Tested and Operational Connections" shown in Chapter 9 of the *AASHTO Roadside Design Guide* will meet this requirement. New precast temporary concrete barriers purchased after October 1, 2002, must meet the NCHRP Report 350 criteria.

"Because various sizes of breakaway sign supports are used in work zones, the entire list of FHWA breakaway sign support acceptance letters can be found in [4]."

3.1.4 Category 4 Devices

"The last category, which is actually a subset of category 3, includes portable, usually trailer - mounted, devices such as area lighting supports, flashing arrow panels, temporary traffic signals, and changeable message signs used in or adjacent to the traveled way. The AASHTO/FHWA agreement states that time is needed to conceive and evaluate alternative measures for making these devices crashworthy, to examine the use and crash histories of existing devices, and to review and, if needed, develop safer, cost-effective strategies for the placement or replacement of these devices that will provide motorists with needed information for driving in work zones."

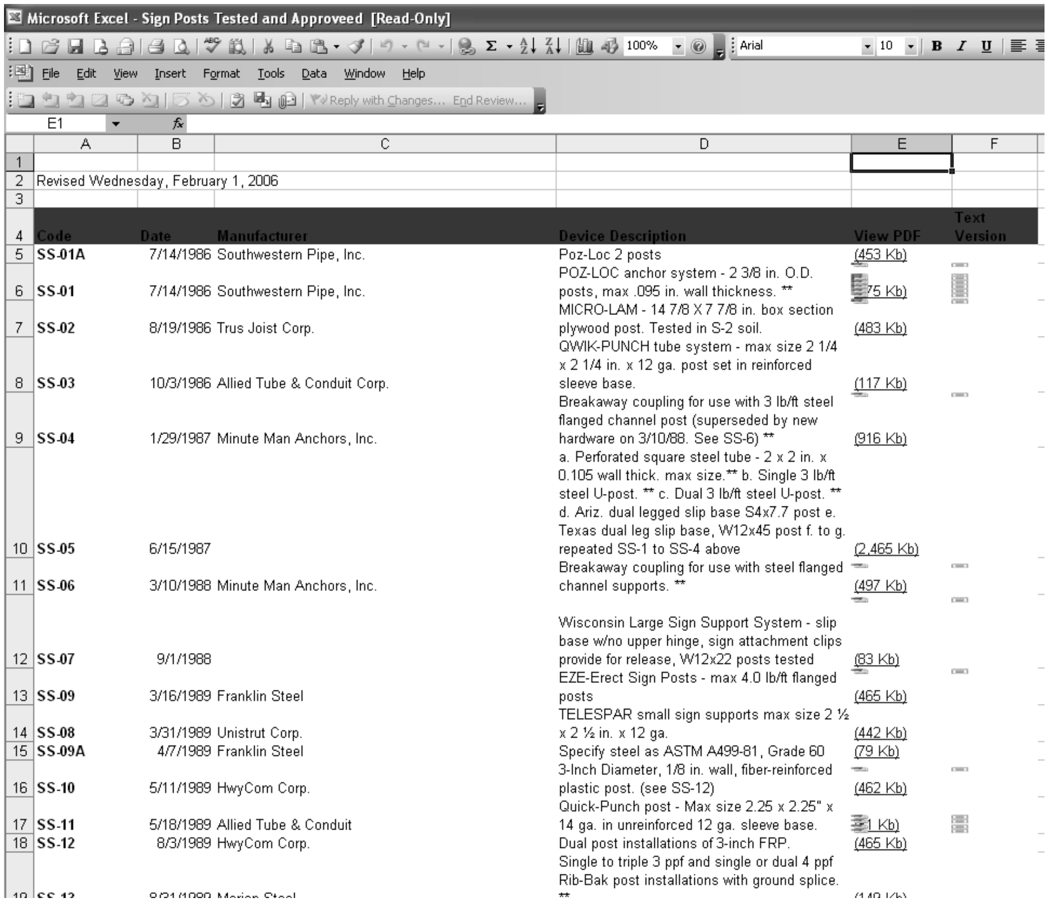
3.2 Literature Search – Recommended Portable Sign Structures

3.2.1 Sources and Filtering Criterion

The portable sign structures being investigated for this project would be classified as category 2 devices according to FHWA. Therefore, in general the literature search focused on these types of structures and attempted to utilize existing FHWA sources for a list of possible candidates for the tests planned herein.

So that the most current sources of information available on the subject were examined, the search focused on Internet sources. As a result of this search, two databases were located that contained information on sign structures that appeared appropriate for Category II structures (see [4] and [5] for reference). These databases were in MS Excel format and contained information

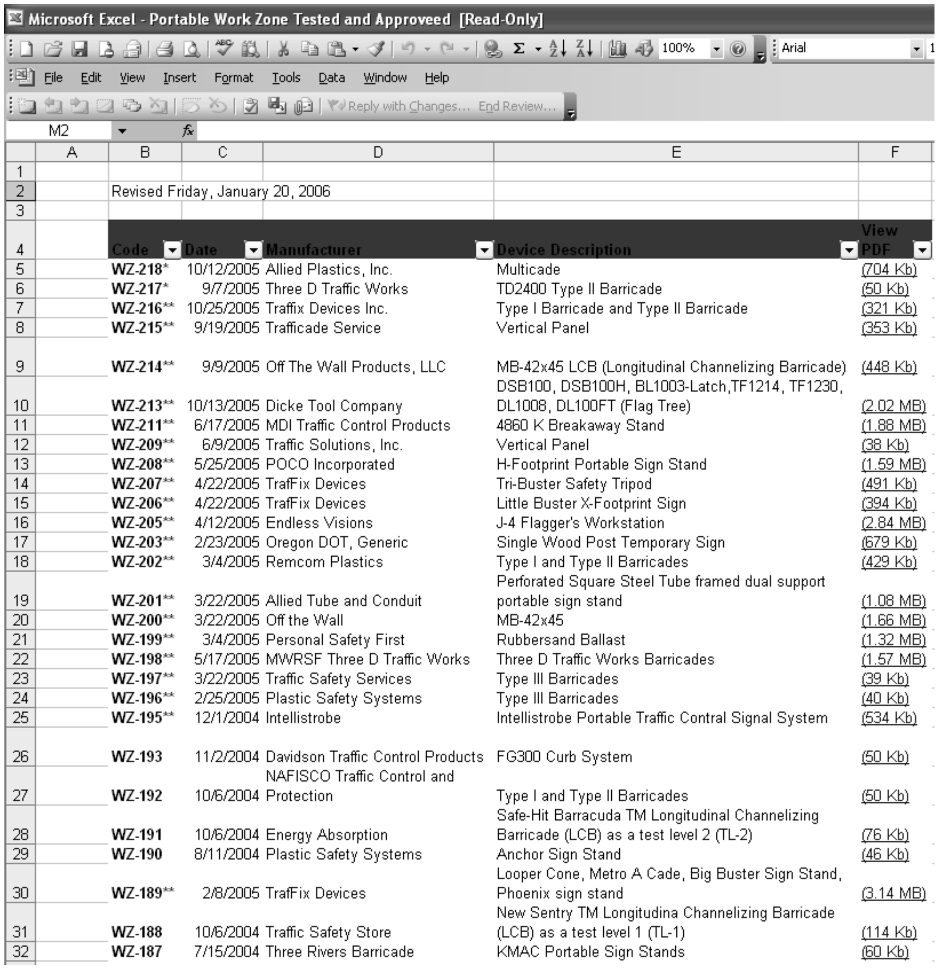
for structures that were successfully tested following NCHRP 350 [1] guidelines and approved by FHWA. Representative figures showing the format of the two databases that were examined can be found in Figure 1 and
Figure 2. Database 1 contained 165 individual tests and Database 2 contained 220 individual tests.



Revised Wednesday, February 1, 2006

	Code	Date	Manufacturer	Device Description	View PDF	Text Version
5	SS-01A	7/14/1986	Southwestern Pipe, Inc.	Poz-Loc 2 posts	(453 Kb)	
6	SS-01	7/14/1986	Southwestern Pipe, Inc.	POZ-LOC anchor system - 2 3/8 in. O.D. posts, max .095 in. wall thickness. **	75 Kb)	
7	SS-02	8/19/1986	Trus Joist Corp.	MICRO-LAM - 14 7/8 X 7 7/8 in. box section plywood post. Tested in S-2 soil.	(483 Kb)	
8	SS-03	10/3/1986	Allied Tube & Conduit Corp.	QWIK-PUNCH tube system - max size 2 1/4 x 2 1/4 in. x 12 ga. post set in reinforced sleeve base.	(117 Kb)	
9	SS-04	1/29/1987	Minute Man Anchors, Inc.	Breakaway coupling for use with 3 lb/ft steel flanged channel post (superseded by new hardware on 3/10/88. See SS-6) **	(916 Kb)	
10	SS-05	6/15/1987		a. Perforated square steel tube - 2 x 2 in. x 0.105 wall thick. max size.** b. Single 3 lb/ft steel U-post. ** c. Dual 3 lb/ft steel U-post. ** d. Ariz. dual legged slip base S4x7.7 post e. Texas dual leg slip base, W12x45 post f. to g. repeated SS-1 to SS-4 above	(2,465 Kb)	
11	SS-06	3/10/1988	Minute Man Anchors, Inc.	Breakaway coupling for use with steel flanged channel supports. **	(497 Kb)	
12	SS-07	9/1/1988		Wisconsin Large Sign Support System - slip base w/no upper hinge, sign attachment clips provide for release, W12x22 posts tested	(83 Kb)	
13	SS-09	3/16/1989	Franklin Steel	EZE-Erect Sign Posts - max 4.0 lb/ft flanged posts	(465 Kb)	
14	SS-08	3/31/1989	Unistrut Corp.	TELESPAR small sign supports max size 2 ½ x 2 ½ in. x 12 ga.	(442 Kb)	
15	SS-09A	4/7/1989	Franklin Steel	Specify steel as ASTM A499-81, Grade 60	(79 Kb)	
16	SS-10	5/11/1989	HwyCom Corp.	3-Inch Diameter, 1/8 in. wall, fiber-reinforced plastic post. (see SS-12)	(462 Kb)	
17	SS-11	5/18/1989	Allied Tube & Conduit	Quick-Punch post - Max size 2.25 x 2.25" x 14 ga. in unreinforced 12 ga. sleeve base.	1 Kb)	
18	SS-12	8/3/1989	HwyCom Corp.	Dual post installations of 3-inch FRP.	(465 Kb)	
19	SS-13	8/31/1989	Marion Steel	Single to triple 3 ppf and single or dual 4 ppf Rib-Bak post installations with ground splice. **	(149 Kb)	

Figure 1. Database 1 - approved and tested sign post structures (http://safety.fhwa.dot.gov/roadway_dept/road_hardware/listing.cfm?code=signs).


Microsoft Excel - Portable Work Zone Tested and Approveed [Read-Only]

Revised Friday, January 20, 2006

Code	Date	Manufacturer	Device Description	View PDF
WZ-218*	10/12/2005	Allied Plastics, Inc.	Multicade	(704 Kb)
WZ-217*	9/7/2005	Three D Traffic Works	TD2400 Type II Barricade	(50 Kb)
WZ-216**	10/25/2005	Traffix Devices Inc.	Type I Barricade and Type II Barricade	(321 Kb)
WZ-215**	9/19/2005	Trafficade Service	Vertical Panel	(353 Kb)
WZ-214**	9/9/2005	Off The Wall Products, LLC	MB-42x45 LCB (Longitudinal Channelizing Barricade)	(448 Kb)
WZ-213**	10/13/2005	Dicke Tool Company	DSB100, DSB100H, BL1003-Latch,TF1214, TF1230, DL1008, DL100FT (Flag Tree)	(2.02 MB)
WZ-211**	6/17/2005	MDI Traffic Control Products	4860 K Breakaway Stand	(1.88 MB)
WZ-209**	6/9/2005	Traffic Solutions, Inc.	Vertical Panel	(38 Kb)
WZ-208**	5/25/2005	POCO Incorporated	H-Footprint Portable Sign Stand	(1.59 MB)
WZ-207**	4/22/2005	TrafFix Devices	Tri-Buster Safety Tripod	(491 Kb)
WZ-206**	4/22/2005	TrafFix Devices	Little Buster X-Footprint Sign	(394 Kb)
WZ-205**	4/12/2005	Endless Visions	J-4 Flagger's Workstation	(2.84 MB)
WZ-203**	2/23/2005	Oregon DOT, Generic	Single Wood Post Temporary Sign	(679 Kb)
WZ-202**	3/4/2005	Remcom Plastics	Type I and Type II Barricades	(429 Kb)
WZ-201**	3/22/2005	Allied Tube and Conduit	Perforated Square Steel Tube framed dual support portable sign stand	(1.08 MB)
WZ-200**	3/22/2005	Off the Wall	MB-42x45	(1.66 MB)
WZ-199**	3/4/2005	Personal Safety First	Rubbersand Ballast	(1.32 MB)
WZ-198**	5/17/2005	MWRSF Three D Traffic Works	Three D Traffic Works Barricades	(1.57 MB)
WZ-197**	3/22/2005	Traffic Safety Services	Type III Barricades	(39 Kb)
WZ-196**	2/25/2005	Plastic Safety Systems	Type III Barricades	(40 Kb)
WZ-195**	12/1/2004	Intellistrobe	Intellistrobe Portable Traffic Contral Signal System	(534 Kb)
WZ-193	11/2/2004	Davidson Traffic Control Products	FG300 Curb System	(50 Kb)
WZ-192	10/6/2004	NAFISCO Traffic Control and Protection	Type I and Type II Barricades	(50 Kb)
WZ-191	10/6/2004	Energy Absorption	Safe-Hit Barracuda TM Longitudinal Channelizing Barricade (LCB) as a test level 2 (TL-2)	(76 Kb)
WZ-190	8/11/2004	Plastic Safety Systems	Anchor Sign Stand	(46 Kb)
WZ-189**	2/8/2005	TrafFix Devices	Looper Cone, Metro A Cade, Big Buster Sign Stand, Phoenix sign stand	(3.14 MB)
WZ-188	10/6/2004	Traffic Safety Store	New Sentry TM Longitudina Channelizing Barricade (LCB) as a test level 1 (TL-1)	(114 Kb)
WZ-187	7/15/2004	Three Rivers Barricade	KMAC Portable Sign Stands	(60 Kb)

Figure 2. Database 2 - approved and tested portable work zone sign structures (http://safety.fhwa.dot.gov/roadway_dept/road_hardware/listing.cfm?code=workzone).

A filtering criterion was used to establish a short list of five different signs that would be recommended for further study for the project. The databases were divided into thirds so that the two investigators and the single graduate research assistant could actively participate in the filtering process. Three filtering stages were performed. Stage 1 consisted of the following:

1. Review of each document reported in the databases.
2. Selection of those reports that had contained the following items for the next filtering stage:
    a. Met PennDOT portable sign structure requirements as discussed in Section 1.1.
    b. Contained drawings detailing the type of sign structure being examined.

All filtering was completed within MS Excel. After Stage 1 was completed for both of the databases, it became apparent that Database 2 was more appropriate for the current study and examination of Database 1 was terminated.

At the completion of Stage 1 filtering for Database 2, approximately 30% of the 220 tests contained in the original file were eliminated. During this examination, it became apparent that the portable sign structures contained within Database 2 consisted of five general types, classified as follows:

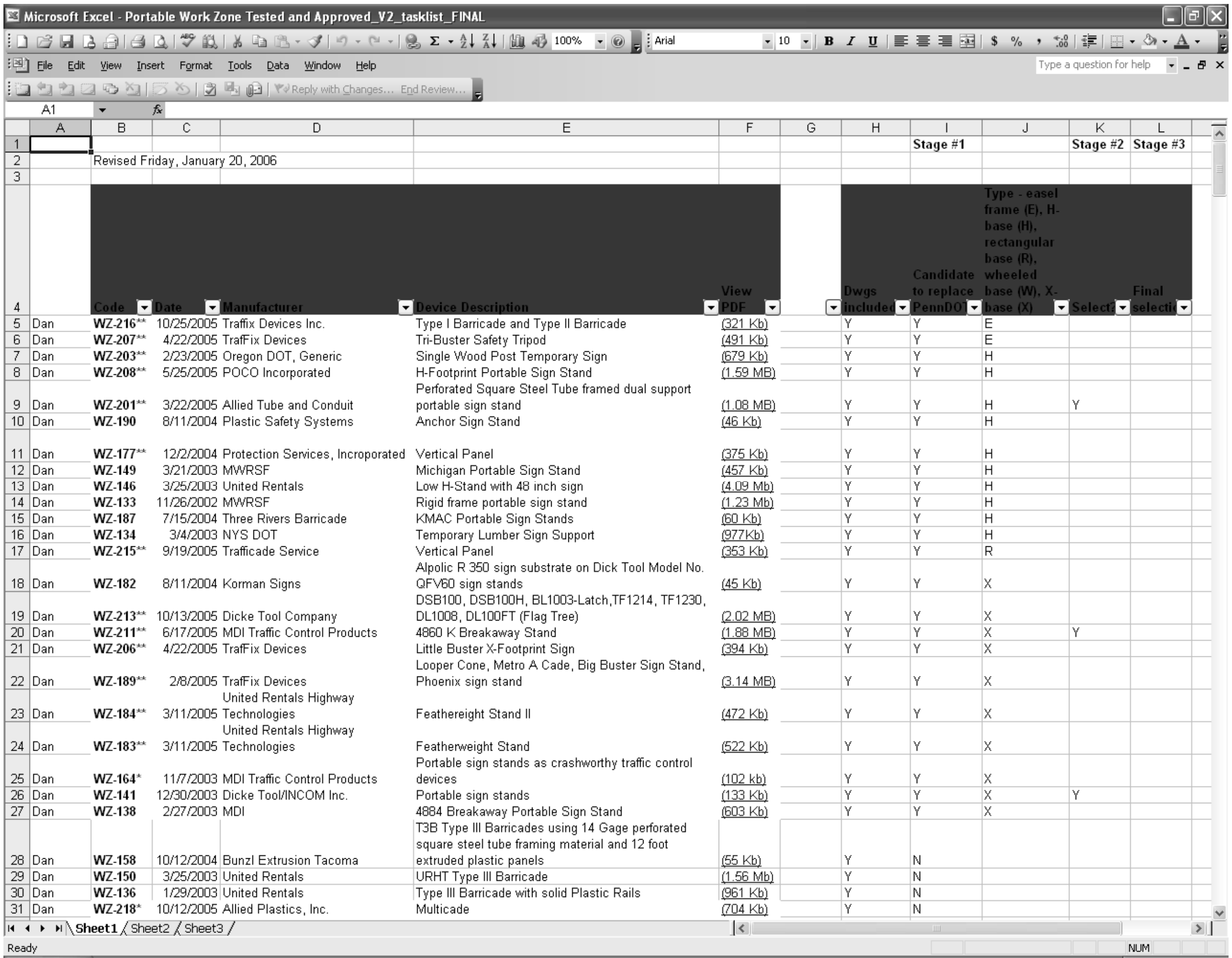
1. Portable sign structures that had support systems that were based on an easel configuration in elevation, termed easel framed structures (E),
2. Portable sign structures that had base support systems that appeared H-shaped in plan, termed H-shaped base structures (H),
3. Portable sign structures that had support systems that had rectangular plate bases, termed rectangular base structures (R).
4. Portable sign structures that had support systems that had wheels as their base, termed wheeled base structures (W), and
5. Portable sign structures that had base support systems that appeared X-shaped in plan, termed X-shaped base structures (X).

These broad classifications were utilized for the Stage 2 filtering process. Again, all filtering was completed within MS Excel.

Stage 2 filtering, which was completed to further reduce the size of the list from Database 2, was initiated by doing the following:

1. Assignment of the aforementioned E, H, R, W and X criteria to signs that remained in Database 2 at the completion of Stage 1 filtering.
2. Selection, by the three personnel involved with the filtering, of one structure in each of the categories as a best candidate for the study from their portion of the database. This selection was based upon:
    a. The structure's operating height range (near PennDOT requirements?),
    b. The level of detail provided in the plans that accompanied the crash testing report (are they acceptable for Task 2 of the project?), and
    c. The apparent structural integrity of the sign post structure (do the components appear adequate to support their required loads and perform acceptably in a crash testing scenario?).

At the completion of this stage, 15 structures would be available for the application of the Stage 3 filtering, the final stage in the process. Stage 3 filtering consisted of further examination of the 15 structures that were available by the entire group and a final collective decision-making process based largely upon the criteria listed for Stage 2 above. A final version of Database 2, containing all of the filters for Stages 1 through 3, can be found in Figure 3.



	A	B	C	D	E	F	G	H	I	J	K	L
1									Stage #1		Stage #2	Stage #3
2		Revised Friday, January 20, 2006										
3												
4		**Code**	**Date**	**Manufacturer**	**Device Description**	**View PDF**		**Dwgs included**	**Candidate to replace PennDOT**	**Type - easel frame (E), H-base (H), rectangular base (R), wheeled base (W), X-base (X)**	**Select?**	**Final selectio**
5	Dan	**WZ-216****	10/25/2005	Traffix Devices Inc.	Type I Barricade and Type II Barricade	(321 Kb)		Y	Y	E		
6	Dan	**WZ-207****	4/22/2005	TrafFix Devices	Tri-Buster Safety Tripod	(491 Kb)		Y	Y	E		
7	Dan	**WZ-203****	2/23/2005	Oregon DOT, Generic	Single Wood Post Temporary Sign	(679 Kb)		Y	Y	H		
8	Dan	**WZ-208****	5/25/2005	POCO Incorporated	H-Footprint Portable Sign Stand	(1.59 MB)		Y	Y	H		
9	Dan	**WZ-201****	3/22/2005	Allied Tube and Conduit	Perforated Square Steel Tube framed dual support portable sign stand	(1.08 MB)		Y	Y	H	Y	
10	Dan	**WZ-190**	8/11/2004	Plastic Safety Systems	Anchor Sign Stand	(46 Kb)		Y	Y	H		
11	Dan	**WZ-177****	12/2/2004	Protection Services, Incroporated	Vertical Panel	(375 Kb)		Y	Y	H		
12	Dan	**WZ-149**	3/21/2003	MWRSF	Michigan Portable Sign Stand	(457 Kb)		Y	Y	H		
13	Dan	**WZ-146**	3/25/2003	United Rentals	Low H-Stand with 48 inch sign	(4.09 Mb)		Y	Y	H		
14	Dan	**WZ-133**	11/26/2002	MWRSF	Rigid frame portable sign stand	(1.23 Mb)		Y	Y	H		
15	Dan	**WZ-187**	7/15/2004	Three Rivers Barricade	KMAC Portable Sign Stands	(60 Kb)		Y	Y	H		
16	Dan	**WZ-134**	3/4/2003	NYS DOT	Temporary Lumber Sign Support	(977Kb)		Y	Y	H		
17	Dan	**WZ-215****	9/19/2005	Trafficade Service	Vertical Panel	(353 Kb)		Y	Y	R		
18	Dan	**WZ-182**	8/11/2004	Korman Signs	Alpolic R 350 sign substrate on Dick Tool Model No. QFV60 sign stands	(45 Kb)		Y	Y	X		
19	Dan	**WZ-213****	10/13/2005	Dicke Tool Company	DSB100, DSB100H, BL1003-Latch,TF1214, TF1230, DL1008, DL100FT (Flag Tree)	(2.02 MB)		Y	Y	X		
20	Dan	**WZ-211****	6/17/2005	MDI Traffic Control Products	4860 K Breakaway Stand	(1.88 MB)		Y	Y	X	Y	
21	Dan	**WZ-206****	4/22/2005	TrafFix Devices	Little Buster X-Footprint Sign	(394 Kb)		Y	Y	X		
22	Dan	**WZ-189****	2/8/2005	TrafFix Devices	Looper Cone, Metro A Cade, Big Buster Sign Stand, Phoenix sign stand	(3.14 MB)		Y	Y	X		
23	Dan	**WZ-184****	3/11/2005	United Rentals Highway Technologies	Feathereight Stand II	(472 Kb)		Y	Y	X		
24	Dan	**WZ-183****	3/11/2005	United Rentals Highway Technologies	Featherweight Stand	(522 Kb)		Y	Y	X		
25	Dan	**WZ-164***	11/7/2003	MDI Traffic Control Products	Portable sign stands as crashworthy traffic control devices	(102 kb)		Y	Y	X		
26	Dan	**WZ-141**	12/30/2003	Dicke Tool/INCOM Inc.	Portable sign stands	(133 Kb)		Y	Y	X	Y	
27	Dan	**WZ-138**	2/27/2003	MDI	4884 Breakaway Portable Sign Stand	(603 Kb)		Y	Y	X		
28	Dan	**WZ-158**	10/12/2004	Bunzl Extrusion Tacoma	T3B Type III Barricades using 14 Gage perforated square steel tube framing material and 12 foot extruded plastic panels	(55 Kb)		Y	N			
29	Dan	**WZ-150**	3/25/2003	United Rentals	URHT Type III Barricade	(1.56 Mb)		Y	N			
30	Dan	**WZ-136**	1/29/2003	United Rentals	Type III Barricade with solid Plastic Rails	(961 Kb)		Y	N			
31	Dan	**WZ-218***	10/12/2005	Allied Plastics, Inc.	Multicade	(704 Kb)		Y	N			

Figure 3. Modified Database 2 with Stage 1 to Stage 3 criteria.

3.2.2 Recommended Structures for Further Study

At the completion of the filtering process, the following five structures were recommended for further study:

1. Easel framed structures (E) – Structure Code WZ-75
2. H-shaped base structures (H) – Structure Code WZ-129
3. Rectangular base structures (R) – Structure Code WZ-110
4. Wheeled base structures (W) – Structure CodeWZ-119
5. X-shaped base structures (X) – Structure Code WZ-114

Copies of the crash testing reports for these structures, which were obtained using Database 2, are found in the appendices of this report.

3.3 Literature Search - NCHRP 350

In order to be approved at Level 3, NCHRP Report 350 [1] requires testing at 100 km/hr as a minimum for work zone traffic control devices in Category 2. In test designation 3-61, the 820C vehicle impacts the sign (normal orientation to the flow of traffic) at 100 km/h. In addition to the normal orientation, an orientation of 90 degrees from the normal is often required when there is a reasonable potential for such an orientation to be more critical than the normal orientation. Often devices can be tested in both orientations during one crash unless the device has the potential to lie across the test vehicle's windshield and affect the results of the second impact.

For devices that weigh in excess of 45 kg, a second test in accordance with test designation 3-60 is also required to meet Level 3 NCHRP Report 350 standards. This test is performed using the same vehicle type and work zone traffic control device orientations as test designation 3-61, but is performed at 35 km/h instead of 100 km/h.

One last variable for work zone devices is the use of the 2000P vehicle in lieu of or in addition to the 820C vehicle when the primary concern is the penetration of the test article into the occupant compartment. This determination depends on the profile of the two different vehicles in relation to the geometry of the test article. This determination should be made by the Federal Highway Administration in conjunction with the sponsor prior to finalizing a test plan, as the cost of the 2000P vehicle can be substantially higher than the cost of the 820C.

Test Designation 3-61: Work Zone Traffic Control Devices

Test Vehicle. PTI personnel located and purchased two test vehicles within the specifications of NCHRP 350 [1] for the 820C classification. To meet these specifications, the vehicle must weigh between 795 and 845 kg, have a wheelbase of 230 cm, have a track width of 135 cm, and have the engine located in the front. NCHRP suggests that the vehicle be a Geo Metro or a Ford Festiva. Both test vehicles were Geo Metros. The vehicles were in sound structural condition and free from previous accident damage. The model years (1994 and 1997) were approved by a FHWA representative prior to conducting the test.

Each test vehicle was prepared for the test. The vehicle's specifications were recorded, including vehicle dimensions, curb weight, test inertial weight, tire size and inflation pressure, odometer reading, vehicle identification number, and engine number. The vehicle was taken to a local shop where a computer alignment was performed. The results of the alignment were recorded and kept as part of the data file. An attachment point was mounted to the vehicle for the purpose of towing the vehicle to the impact zone. The guidance system was connected to the steering linkage. All fluids were drained from the vehicle and the battery was removed. White and black targets were placed on the vehicle body, a checkered tape placed down the centerline of the vehicle body, and bright stripes painted on the tires for the purpose of high-speed video data collection.

Test Parameters. The parameters of test level 3-61 are designated by NCHRP Report 350 as an 820C vehicle impacting the test article at a speed of 100 km/h and at an angle of 0 and/or 90 degrees. The high-speed test is intended to evaluate the occupant risk, vehicular stability, and test article trajectory. If the mass of a free-standing work zone traffic control device is 45 kg or less, no occupant impact velocity or occupant ridedown accelerations were calculated.

Evaluation criteria for this test include activation of the work zone traffic control device in a predictable manner (breakaway, fracture, yield); penetration (or potential penetration) into occupant compartment; hazard to other traffic, pedestrians, or work zone personnel; blockage of driver vision; occupant impact velocity and ridedown acceleration remaining within suggested limits; the vehicle remaining upright throughout the test; and vehicle trajectory (adjacent traffic should not be affected, and the path of the vehicle must be acceptable).

3.4 Summary of Task 1

A literature search was completed to select five portable sign structures for future study in association with this project. This search was completed using up-to-date information obtained via the Internet. So that the five structures were rationally chosen, a systematic filtering process was applied to FHWA databases of approved structures tested according to NCHRP 350 [1]. From this search, the following five structures were recommended for further study:

1. Easel framed structures (E) – Structure Code WZ-75
2. H-shaped base structures (H) – Structure Code WZ-129
3. Rectangular base structures (R) – Structure Code WZ-110
4. Wheeled base structures (W) – Structure Code WZ-119
5. X-shaped base structures (X) – Structure Code WZ-114

The selected five structures (code named WZ-75, WZ-129, WZ-110, WZ-119, and WZ-114) are illustrated in Appendix A through Appendix E, respectively.

4 Task 2: Numerical Modeling

The results obtained in the first task of this project recommended that five sign structures be examined numerically. These structures were selected using a filtering approach centered around information presented in two Federal Highway Administration databases[4],[5]. The structures that were recommended were as follows:

1. Easel framed structures (E) – Structure Code WZ-75
2. H-shaped base structures (H) – Structure Code WZ-129
3. Rectangular base structures (R) – Structure Code WZ-110
4. Wheeled base structures (W) – Structure Code WZ-119
5. X-shaped base structures (X) – Structure Code WZ-114

PennDOT did not select any of the recommended structures and chose five other structures using criteria that were unknown to the research team. The following five signs were those chosen by PennDOT for finite element analysis:

1. Pennsylvania structure – X-shape
2. Pennsylvania structure – H-shape
3. Minnesota structure
4. Oregon structure
5. New York structure

The selected five structures are illustrated in Appendix F through Appendix J.

Numerical crash-testing was performed using LS-DYNA for each of the five PennDOT-selected structures. Each sign structure was subjected to virtual crash tests using a Geo Metro vehicle (a standard 820C vehicle according to NCHRP 350 designation) with the sign oriented facing the vehicle and at 90º with respect to the vehicle. These tests were run with the top of the sign between 63 inches (1,600 mm) and 95 inches (2,413 mm) from the ground. Detailed information related to model construction, constitutive models, support conditions, and load application (i.e., vehicle geometry, construction, and speed) is provided in the sections that follow.

4.1 Model Construction

4.1.1 Sign Structure Construction

The five selected sign structures were modeled in two groups. The first group consists of steel-supported structures and aluminum sign panels. The Pennsylvania structures (X-shape and H-shape) and the Minnesota structure were included in the first group. The second group was comprised of timber-supported structures and plywood sign panels (Oregon and New York structures).

The Pennsylvania sign structures are depicted as shown in Appendices F and G. The horizontal legs and vertical stands having 0.109-inch (2.77-mm) thickness were modeled using shell elements provided by LS-DYNA. The aluminum sign panels consisting of a 36-inch (914.4-mm) by 36-inch (914.4-mm) square plate with a 0.1-inch (2.54-mm) thickness were also created using shell elements. The Minnesota sign structure design plans are illustrated in Appendix H. The steel H-support, vertical mast and sleeve with 0.109'' (2.77mm) thicknesses were modeled using shell elements. The 30-inch (762-mm) by 30-inch (762-mm) square sign panel with a 0.1-inch (2.54-mm) thickness was modeled using shell elements. Steel stands were modeled using nominal A36 steel properties available in LS-DYNA and standard aluminum properties (i.e., 6061-T6) were used for representing the aluminum panels.

The design plans for the Oregon and New York sign structures are illustrated in Appendices D and E, respectively. The single post structure from Appendix I, consisting of the I-shaped base and 36-inch (914.4-mm) by 36-inch (914.4-mm) plywood sign panel, was selected as the Oregon structure to be modeled. The Oregon single post was modeled using 3D solid elements to represent the timber stand, the I-shape base and the plywood sign panel, respectively. The New York sign structure was composed of a wooden stand and 36-inch (914.4-mm) by 36-inch (914.4-mm) plywood sign panel and was modeled using solid elements as well. Material models for pine available in LS-DYNA were used to represent the nominal properties for both structures.

All sign structures were constructed according to the design plans. All sign panels were modeled separately from their support structures and placed onto them using constrained rivets provided by LS-DYNA, which couple the models together. The safety light placed on top of the sign was modeled matching published dimensions and weights to represent a worst-case scenario with respect to low-speed crash tests. It was modeled using a hard plastic material and affixed to the top of the sign using the constrained rivets.

4.1.2 Vehicle Model Construction

A standard NCHRP-approved vehicle model developed by the FHWA/NHTSA National Crash Analysis Center (NCAC) was used for the numerical crash tests. Model information is as follows:

1.	Number of parts	230
2.	Number of nodes	100,348
3.	Number of solids	1,209
4.	Number of springs	8
5.	Number of mass elements	76
6.	Number of elements	16,000

The vehicle model can be observed in Figure 4.

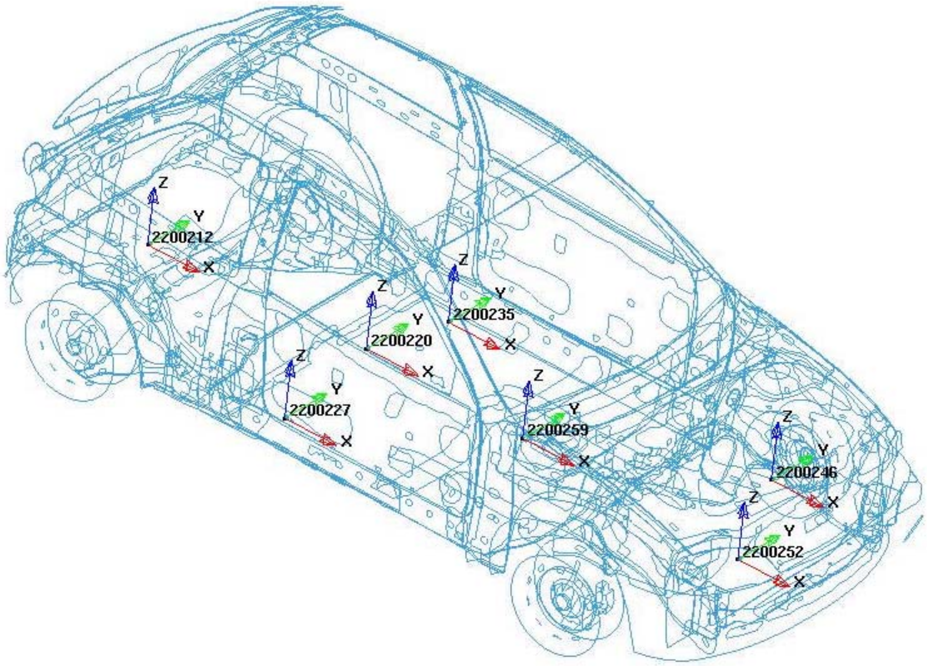


Figure 4. Detailed vehicle model (http://www.ncac.gwu.edu/vml/models.html).

4.1.3 Crash Scenario Modeling

The crash scenarios were selected following consultation with an FHWA official [6] familiar with NCHRP 350 [1] Section 3.2.3, "Support Structures, Work Zone Traffic Control Devices, and Breakaway Utility Poles." Using a test matrix from the guide, it was decided in cooperation with the FHWA official to employ Level 3 test requirements of the "support structures" category with test levels 3-60 and 3-61.

These tests included a low-speed crash scenario as well as a high-speed crash scenario, as listed below:

Test Level 3-60. The test comprised two separate full crash scenarios at 35 km/h (22 mph) with the 820C vehicle (Geo Metro) using sign impact angles of 0 and 90 degrees, as described above. Each portable sign structure crash scenario was analyzed twice. The first analysis was performed with the sign structure facing the approaching vehicle and impacting its front either at the vehicle's geometric middle or at one of the quarter points with respect to its longitudinal centerline, according to NCHRP 350 requirements. The second analysis had the sign structure rotated 90 degrees from its initial position and placed at the middle point of the approaching vehicle.

Test Level 3-61. The test comprised two separate full crash scenarios at 100 km/h (62 mph) with the 820C vehicle (Geo Metro) using sign impact angles of 0 and 90 degrees, as described above. Each portable sign structure crash scenario was analyzed twice. The first analysis was performed with the sign structure facing the approaching vehicle and impacting its front either at the vehicle's geometric middle or at one of the quarter points with respect to its longitudinal centerline. The second analysis had the sign structure rotated 90 degrees from its initial position and placed at the middle or at the other quarter point of the approaching vehicle.

The virtual crash scenarios were developed following these conditions. The model was created so that each support structure was placed at the geometric longitudinal middle of the approaching vehicle to represent the critical scenario for each individual crash test. The structures were placed a short distance from the original location of the vehicle to ensure that the vehicle was in a dynamically stable condition with a constant direction and speed free from dynamic effects before impact. The structure was placed on an infinitely rigid smooth surface representing the ground and was given a nominal coefficient of friction of 0.3 at contact locations with the ground. The portion of the structure in contact was then loaded with a model representing four sand bags on the end of each support leg. The incorporation of the sand bags represented real life conditions.

Prior to the numerical crash test the vehicle was initialized to the following conditions:

- Initial speed of all components was set to the desired nominal test speed.
- Rotational speed of the tires was set to matching angular velocities to avoid differential frictional and inertial effects from the moving vehicle.
- The vehicle, at its defined initial speed and tires' angular velocities, was placed on a perfectly smooth and level, infinitely rigid surface with a friction coefficient of 0.3.

4.2 Modeling Results and Recommendations

4.2.1 Requirements and Technique for Analysis

To ensure compatibility of results obtained from the FEA simulation to the full-scale crash tests, comparable statistics and metrics needed to be developed that were related to NCHRP 350[1] requirements. Parameters required by NCHRP 350[1] to be measured and analyzed and to meet certain requirements were identified and tracked in the virtual crash simulation. To produce these necessary parameters numerically, the procedures outlined below were followed.

In the finite element model, a virtual accelerometer was placed at the vehicle center of gravity (CG). The virtual accelerometer was configured so that all accelerations of the element to which it was assigned were recorded in a local coordinate system, defined by the placement and orientation of the accelerometer, rather than recording these items in a global coordinate system as followed for all other model output. This replicates performance of the accelerometer used during full-scale crash testing. Because the accelerometer could not be placed at the exact CG for the full-scale test, which is typically the case, the distance from the CG to the accelerometer was recorded with accelerations corrected accordingly.

To evaluate virtual crash test data using the accelerometer, the following tasks were completed:

- Recording time spans for all reported data were generally produced from impact until the simulation ended; however, in certain cases simulations were produced until 0.05 sec after impact.
- Accelerations in all three directions (a_x, a_y, a_z) of the accelerometer as a function of time were measured, with measurements being produced at the same time step as the simulation run.
- Displacements (S_x, S_y) at select locations were found by double integrating acceleration data (a_x, a_y):

$$S_x(t) = \iint_t a_x dt \tag{3.1}$$

$$S_y(t) = \iint_t a_y dt \tag{3.2}$$

- The times when $S_x(t_1)$=0.6m and $S_y(t_2)$=0.3m were calculated and recorded. These t_1 and t_2 times represented the instances when a crash dummy head would come into contact with the steering wheel/dashboard and the side door, respectively. However, for all analyses the portable sign structures did not provide enough obstruction and therefore within the allotted time frame these displacements did not occur. The S_x and S_y distance values reached by at the end of the simulations are reported in the data analysis.
- Recorded accelerations (a_x, a_y, a_z) were further reduced as follows:
    - Output values were filtered using a low-pass filter with 10 ms cutoff frequency;
    - Filtered accelerations were used to calculate speeds:

$$V_I^{x,y}(t_1) = \int_0^{t_1} \sqrt[2]{a_x^2 + a_y^2}\ dt \tag{3.3}$$

$$V_I^{x,y}(t_2) = \int_0^{t_2} \sqrt[2]{a_x^2 + a_y^2}\ dt \tag{3.4}$$

$$V_I^{x}(t_1) = \int_0^{t_1} a_x dt \tag{3.5}$$

    - Accelerations corresponding to times t_1 and t_2, as discussed above, were recorded as $a_x(t_1)$ and $a_y(t_2)$.

These procedures were performed for all 10 analysis cases: 5 portable sign structures facing the vehicle and 5 structures rotated 90 degrees with respect to the vehicle's longitudinal centerline. These scenarios were simulated at the 35 km/h and the 100 km/h speeds.

Additional evaluations of deformations and penetrations involved tracking the following data for each case:

- The node and element of the car with the highest permanent deformation.
- A representative node and element on the car that sustained no deformation.
- Generating a trace of each of the previously selected nodes with respect to time.
- Calculating relative distances between the previously selected nodal traces using their recorded data and the relative distance between them:

$$D_{Def}(t) = \sqrt[2]{\left(x(t)_1 - x(t)_2\right)^2 + \left(y(t)_1 - y(t)_2\right)^2 + \left(z(t)_1 - z(t)_2\right)^2} \quad (3.6)$$

- Monitoring collision of the sign structure with different parts of the vehicle model and recording the node and element of the structure that penetrated the vehicle (if penetration occurred).
- Monitoring an adjacent node and element on the vehicle closest to the structure penetration location.
- Generating a trace of each of the previously selected nodes with respect to time.
- Calculating relative distances between the previously selected nodal traces using their recorded data and the relative distance between them:

$$D_{Pen}(t) = \sqrt[2]{\left(x(t)_1 - x(t)_2\right)^2 + \left(y(t)_1 - y(t)_2\right)^2 + \left(z(t)_1 - z(t)_2\right)^2} \quad (3.7)$$

- Recording the maximum absolute value of the relative distance for each analysis case:

$$Max\left|D_{Def}(t)\right| \text{ and } Max\left|D_{Pen}(t)\right|$$

The data were collected and reported in the format shown in Table 1.

Table 1. NCHRP parameters from simulation.

Structure Name	**Position**	**Vehicle Speed**	t_1	t_2	$V_I^{xy}(t_1)$	$V_I^{xy}(t_2)$	$V_I^{x}(t_1)$	$a_x(t_1)$	$a_y(t_2)$	$Max\left\|D_{Def}(t)\right\|$	$Max\left\|D_{Pen}(t)\right\|$
Minnesota	0 degree	100km/h									
Minnesota	90 degree	100km/h									
Minnesota	0 degree	35km/h									
Minnesota	90 degree	35km/h									

The data in Table 1 provide a solid quantitative foundation based on the NCHRP 350 crash evaluation criteria to compare the performance of the different sign structures. The calculated performance parameters were compared to the NCHRP guidelines and compared within the group of structures to aid the selection of a design for full scale crash test. The different parameters were balanced in an evaluation metric so that a structure with the highest likelihood to pass full-scale crash testing could be selected for further tests.

4.2.2 Results

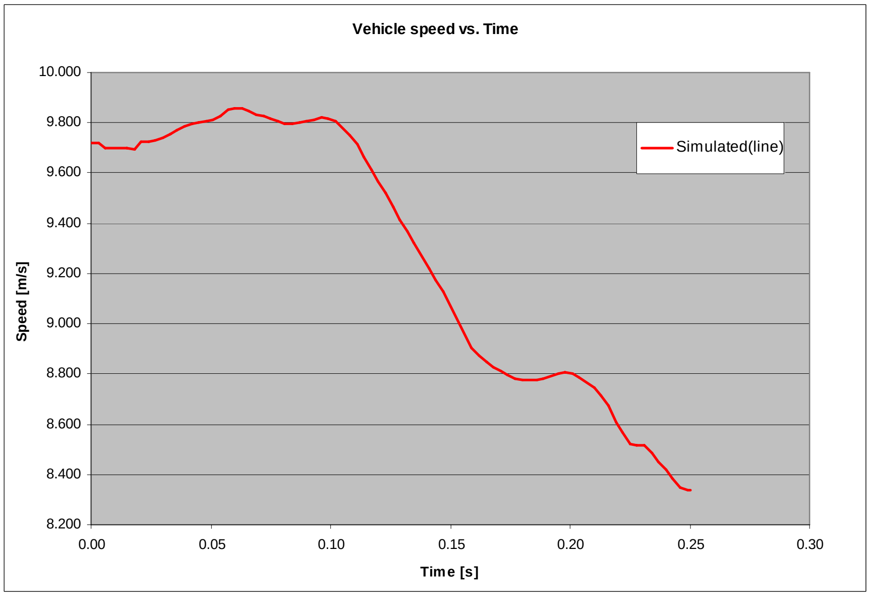
This section contains representative results from the analyses. Filtered results from the LS-DYNA finite element models for each of the structures are shown that depict vehicle speeds and accelerations as a function of time throughout the crash test. These figures are augmented with illustrations of the crash tests from LS-DYNA and summary tables similar to that presented in the previous section.

For each structure, results are shown for the critical speed and sign height (35km/hr, sign a lower height). They are shown for two sign orientations relative to the vehicle: 0 degrees (sign facing vehicle) and 90 degrees (sign perpendicular to vehicle).

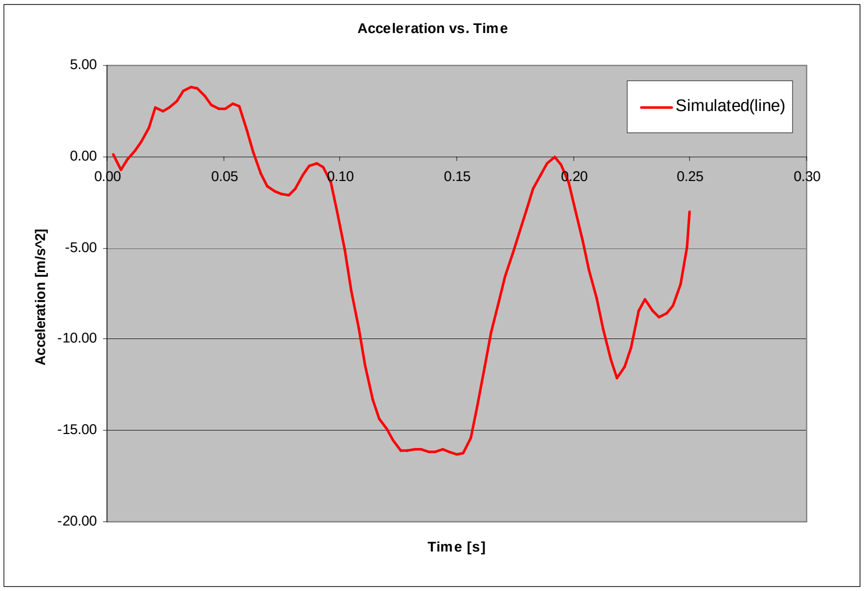
4.2.2.1 Pennsylvania structure – X-shape

4.2.2.1.1 35 km/h with 0 deg orientation

Measured speeds and decelerations are presented in the following figures.

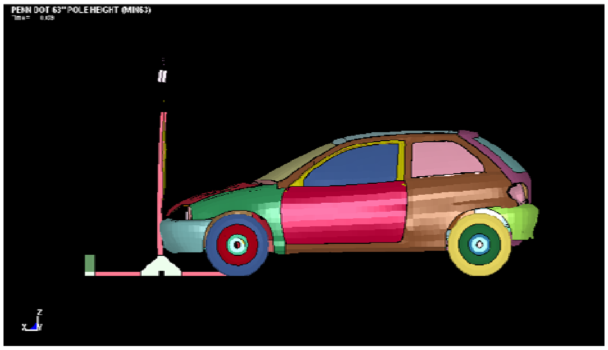
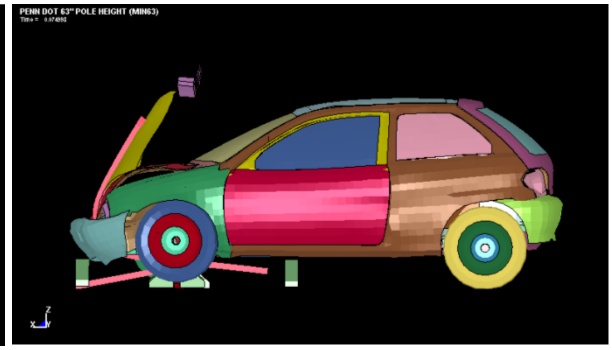


(a) Measured vehicle speed vs. time

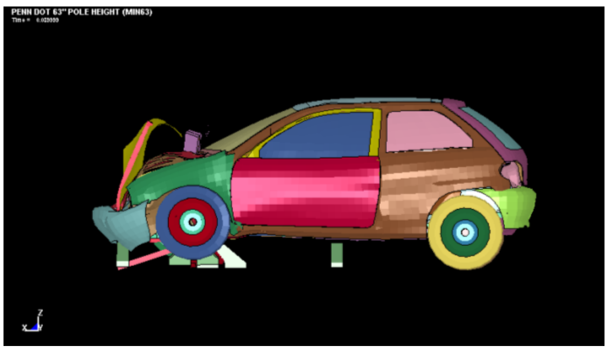
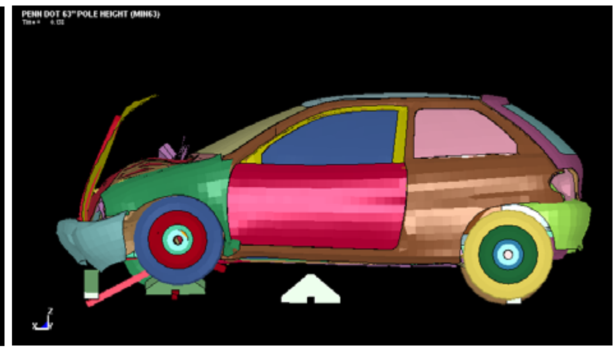


(b) Measured vehicle acceleration vs. time

Figure 5. Speed and deceleration for 35 km/hr with 0 deg orientation.

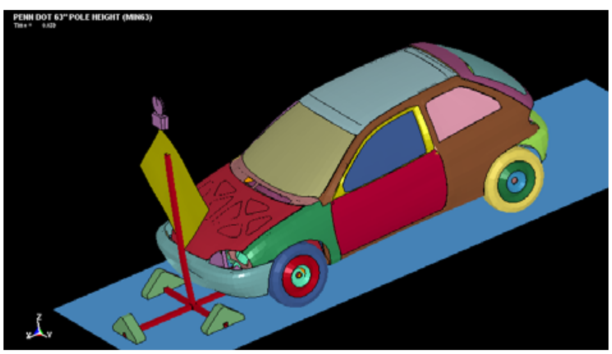
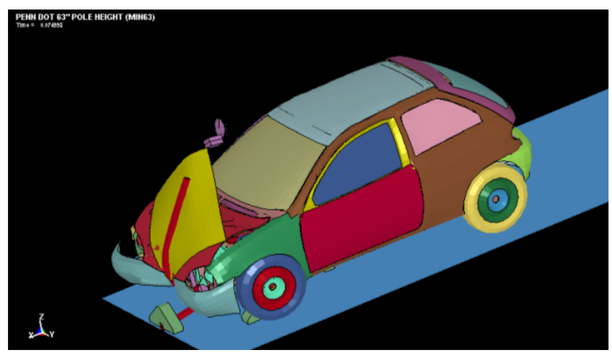
 

(a) at the point of impact (b) 0.035s after impact

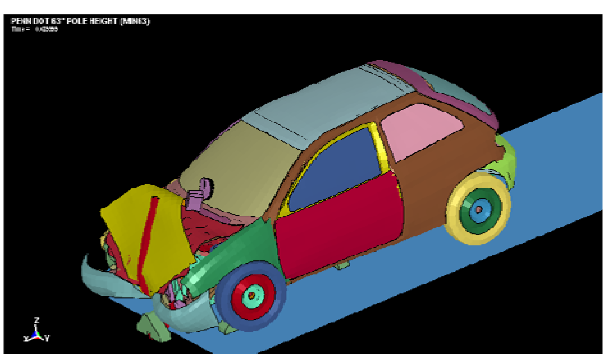
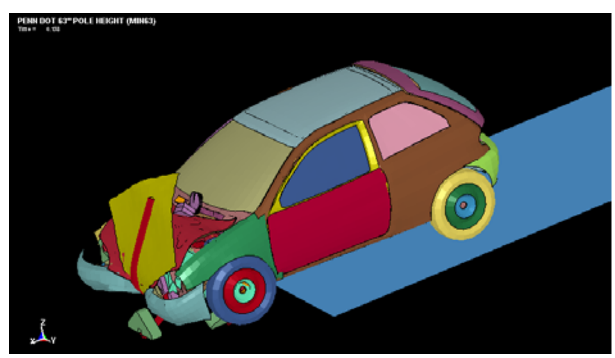
 

(c) 0.05s after impact (d) 0.1s after impact

Figure 6. Right view of crashing simulation.

(a) at the point of impact (b) 0.035s after impact

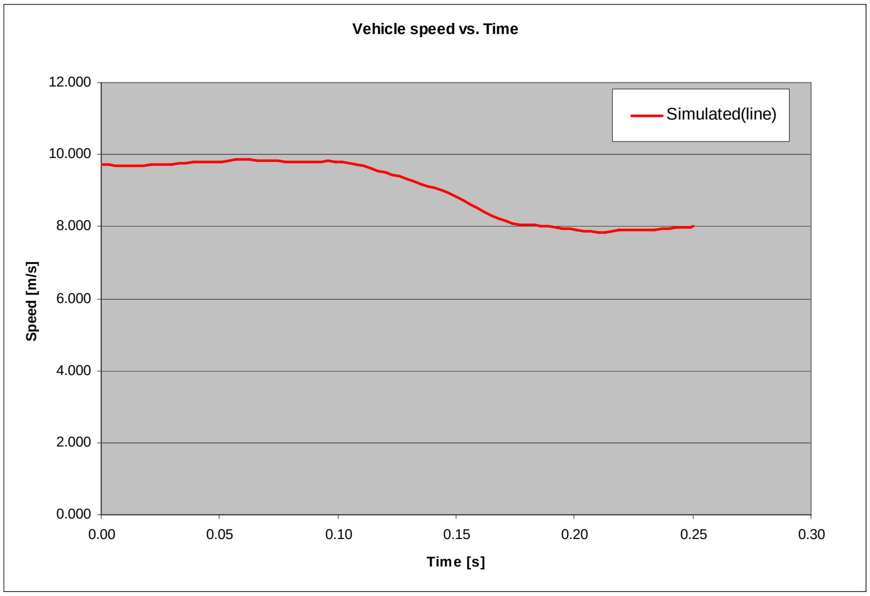
 

(c) 0.05s after impact (d) 0.1s after impact

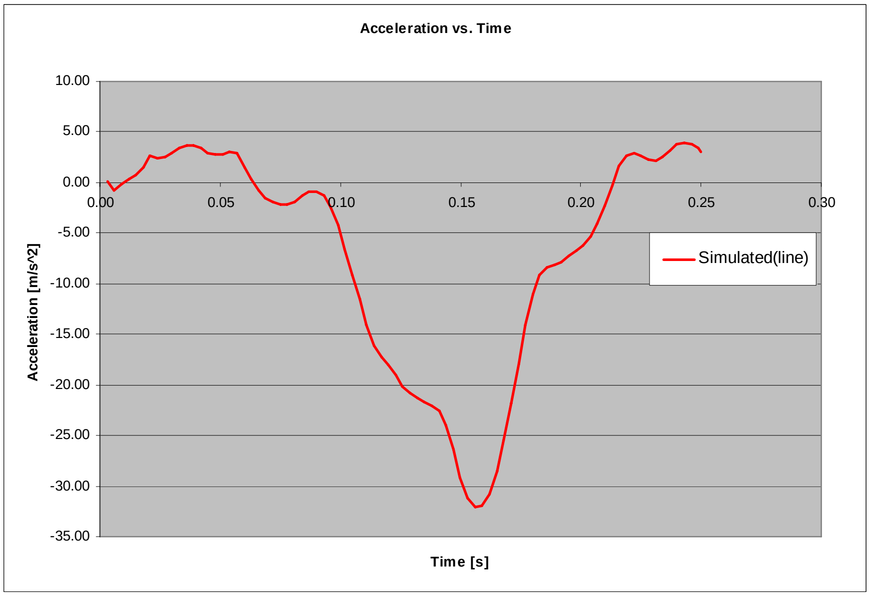
Figure 7. ISO view of crashing simulation.

4.2.2.1.2   35 km/h with 90 deg orientation

Measured speeds and decelerations are presented in the following figures.

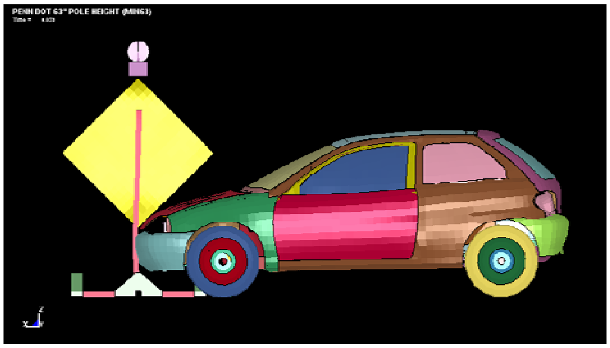


(a) Measured vehicle speed vs. time

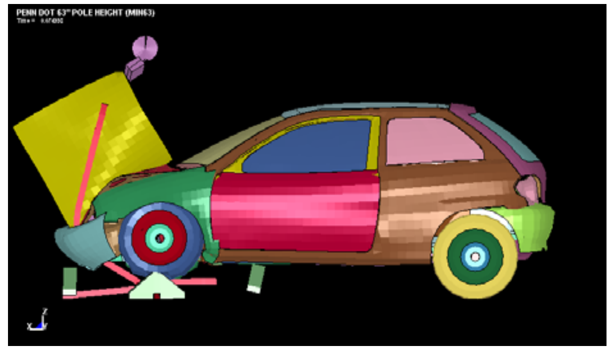


(b) Measured vehicle acceleration vs. time

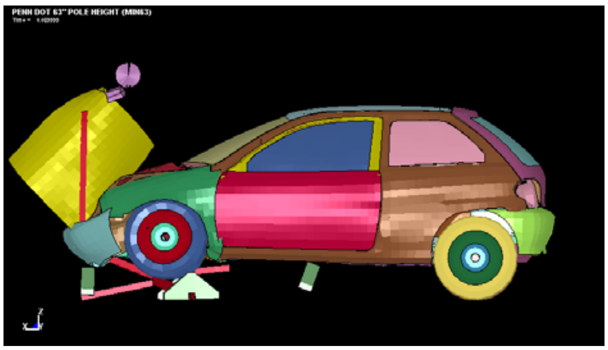
Figure 8. Speed and deceleration for 35 km/hr with 90 deg orientation.



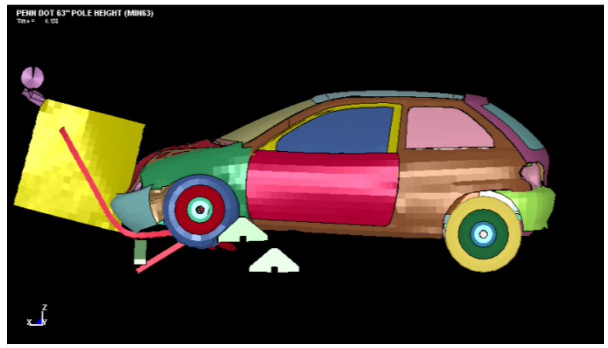
(a) at the point of impact



(b) 0.035s after impact

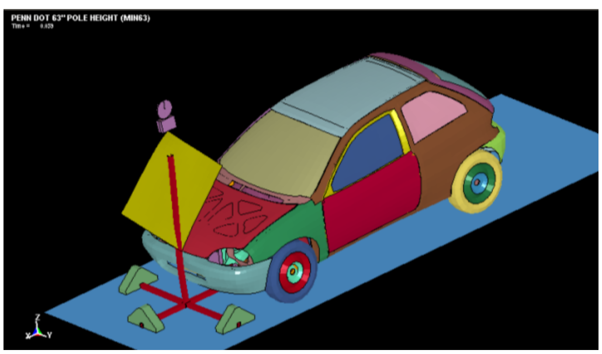


(c) 0.05s after impact

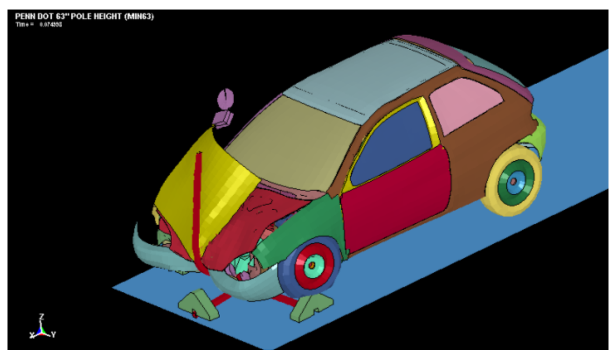


(d) 0.1s after impact

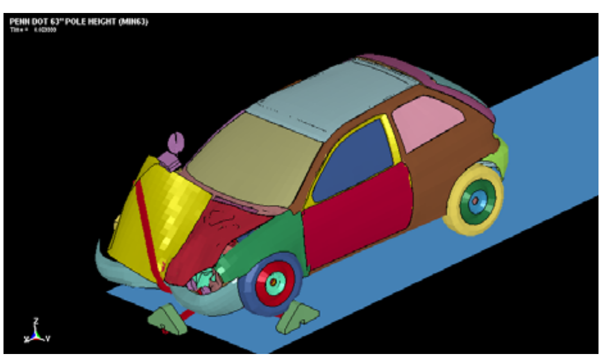
Figure 9. Right view of crashing simulation.



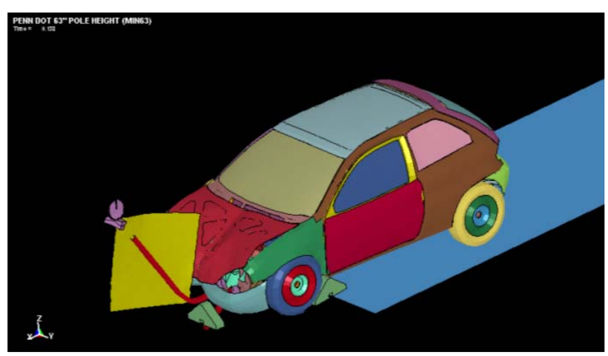
(a) at the point of impact



(b) 0.035s after impact



(c) 0.05s after impact



(d) 0.1s after impact

Figure 10. ISO view of crashing simulation.

Results for the Pennsylvania X-shape structure are summarized in the following table.

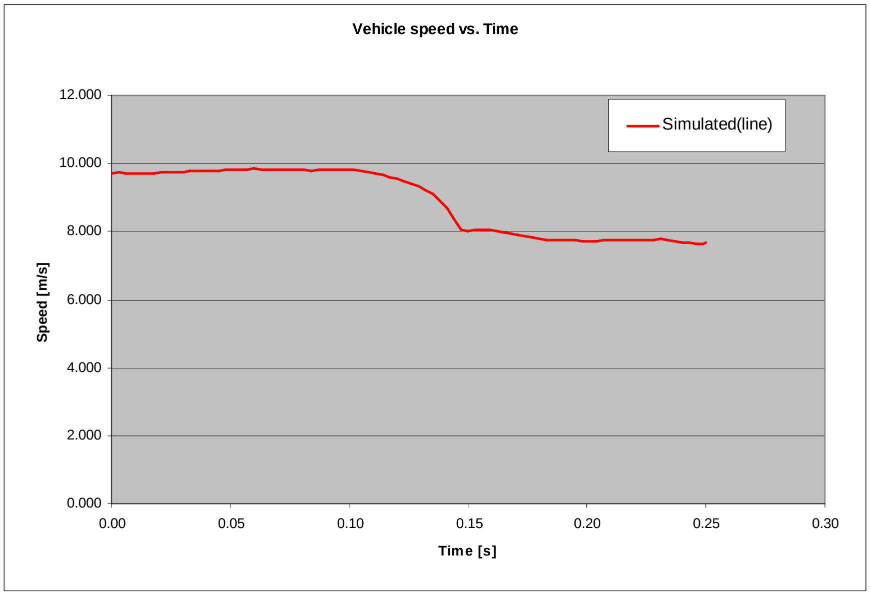
Table 2. Simulation results from Pennsylvania (Penn) X-shape.

Sign Post Name	Position	Vehicle Speed	t1(sec)	t2(sec)	V1x(t1), m/sec	V1y(t1), m/sec	Sx, m	Sy, m	ax(t1), m/s^2	ay(t2), m/s^2	Ddef(t) mm	Dpen(t) mm
Penn X-shape	0 degree	100km/h	(n/a 0.110)	(n/a 0.110)	4.200	0.375	0.152	0.018	-94.782	26.601	355.193	77.200
Penn X-shape	90 degree	100km/h	(n/a 0.110)	(n/a 0.110)	4.432	0.132	0.165	0.007	-82.691	18.613	357.737	136.000
Penn X-shape	0 degree	35km/h	(n/a 0.148)	(n/a 0.148)	1.410	0.120	0.090	0.010	-16.310	-4.440	69.783	0.000
Penn X-shape	90 degree	35km/h	(n/a 0.148)	(n/a 0.148)	1.881	0.166	0.091	0.010	-32.043	-7.803	162.396	10.000

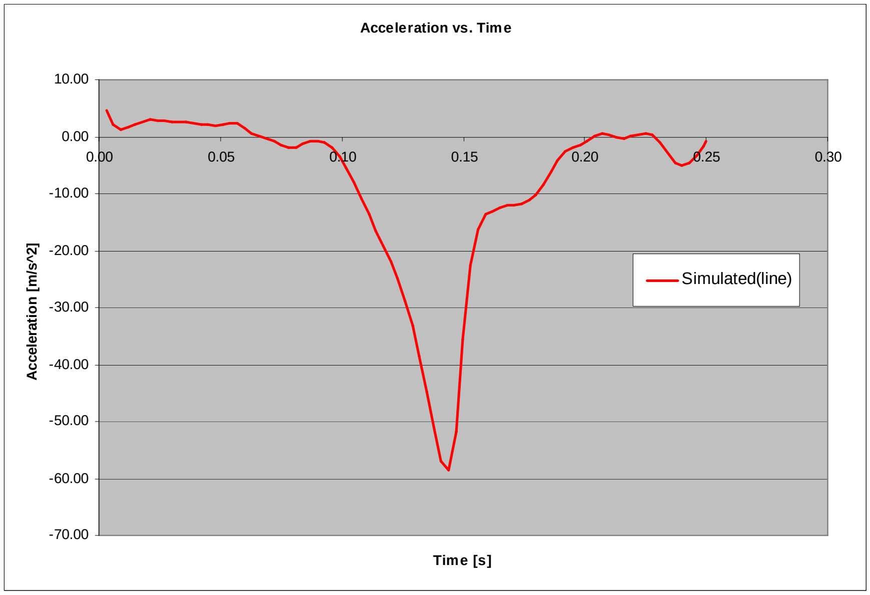
4.2.2.2 Pennsylvania structure – H-shape

4.2.2.2.1 35 km/h with 0 deg orientation

Measured speeds and decelerations are presented in the following figures.

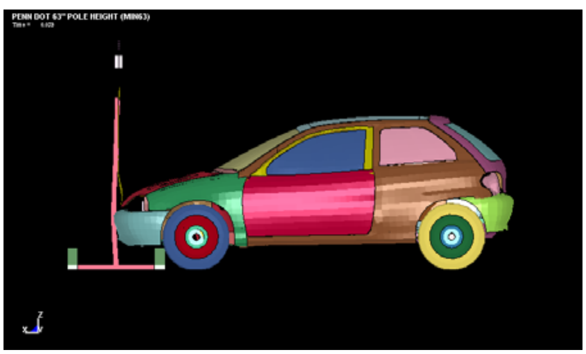


(a) Measured vehicle speed vs. time

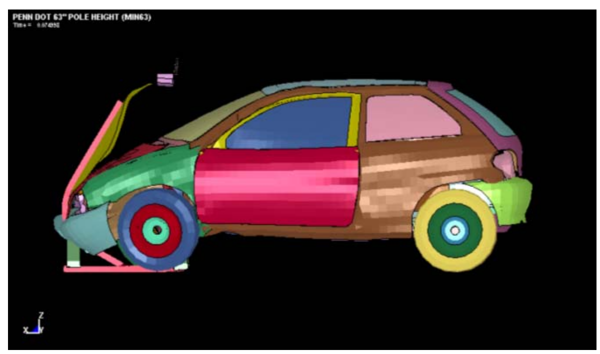


(b) Measured vehicle acceleration vs. time

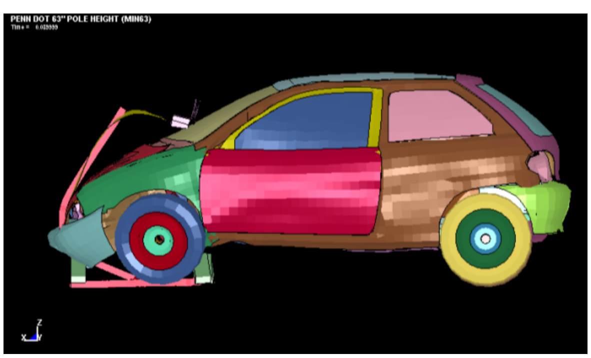
Figure 11. Speed and deceleration for 35 km/hr with 0 deg orientation.



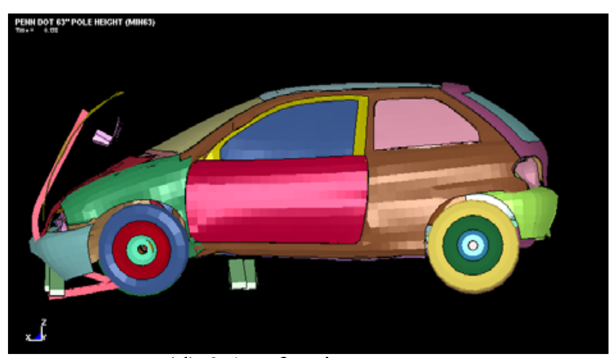
(a) at the point of impact



(b) 0.035s after impact

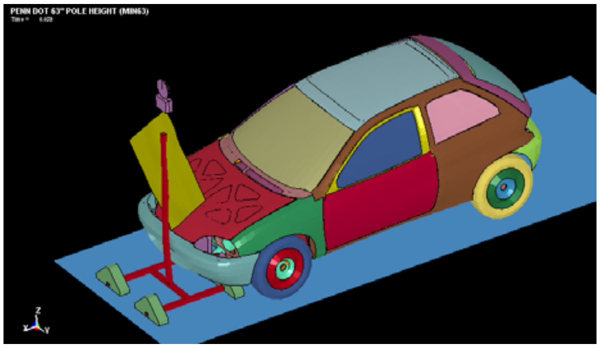


(c) 0.05s after impact

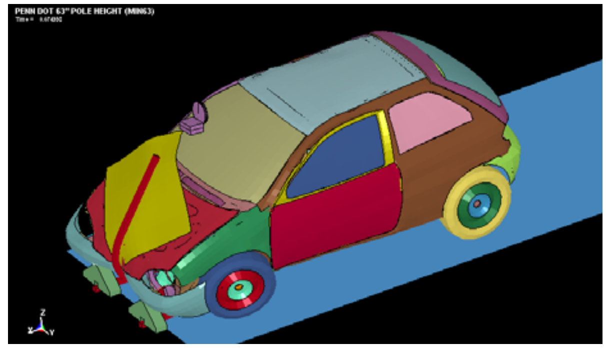


(d) 0.1s after impact

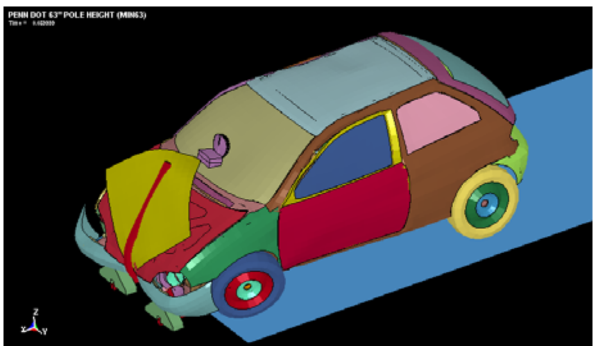
Figure 12. Right view of crashing simulation.



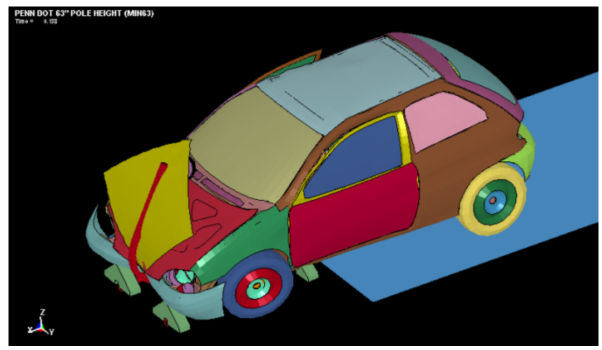
(a) at the point of impact



(b) 0.035s after impact



(c) 0.05s after impact

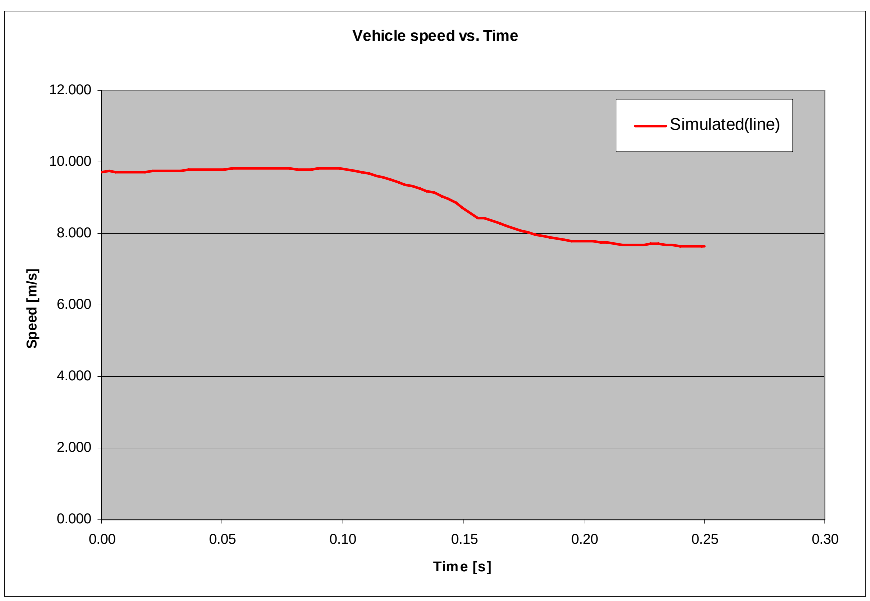


(d) 0.1s after impact

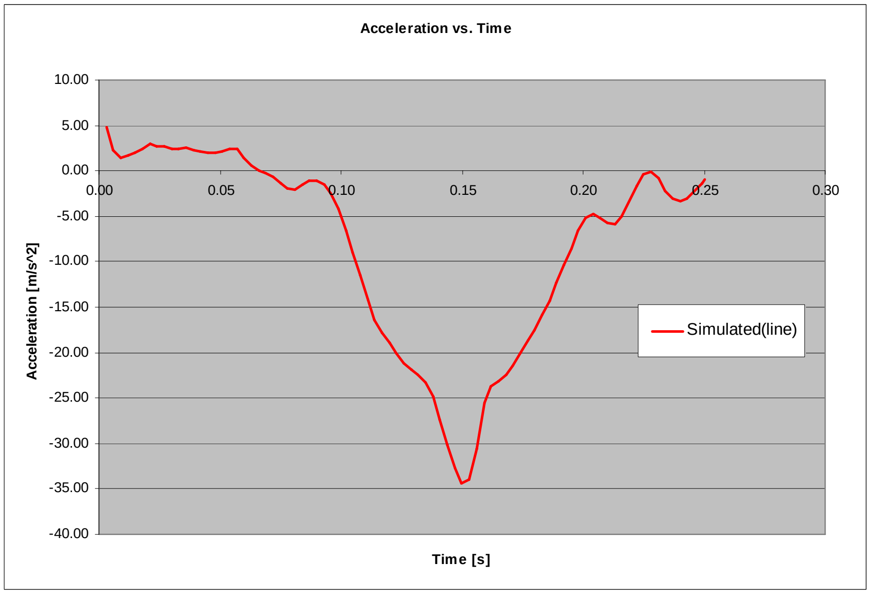
Figure 13. ISO view of crashing simulation.

4.2.2.2.2 35 km/h with 90 deg orientation

Measured speeds and decelerations are presented in the following figures.

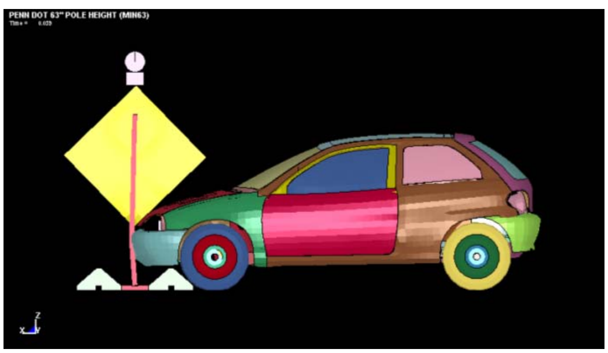


(a) Measured vehicle speed vs. time

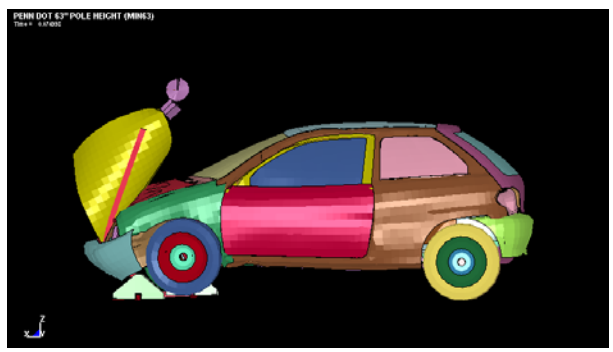


(b) Measured vehicle acceleration vs. time

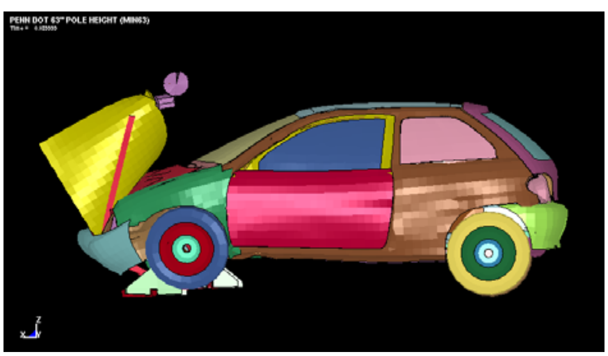
Figure 14. Speed and deceleration for 35 km/hr with 90 deg orientation.



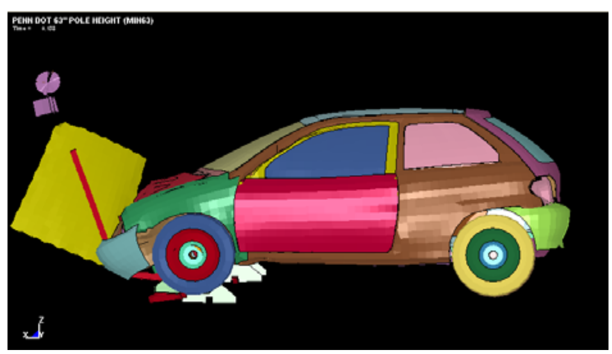
(a) at the point of impact



(b) 0.035s after impact

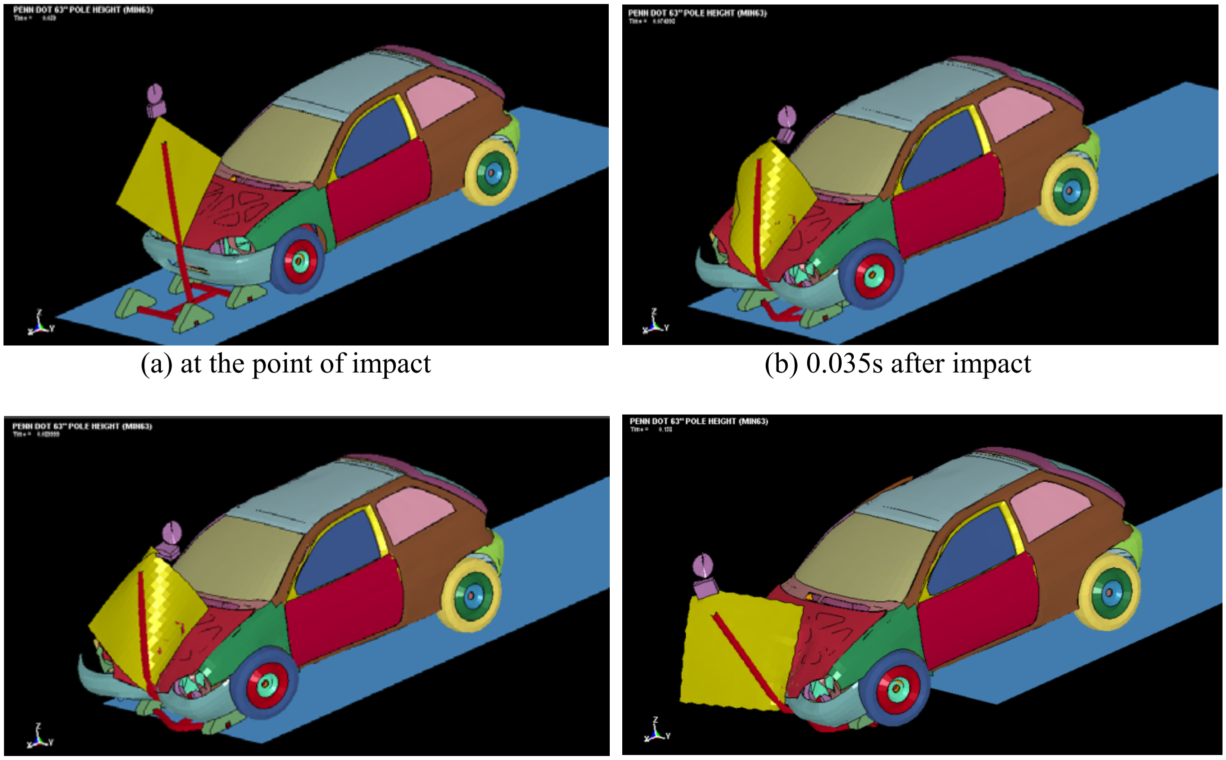


(c) 0.05s after impact



(d) 0.1s after impact

Figure 15. Right view of crashing simulation.



(a) at the point of impact (b) 0.035s after impact

(c) 0.05s after impact (d) 0.1s after impact

Figure 16. ISO view of crashing simulation.

Results for the Pennsylvania H-shape structure are summarized in the following table.

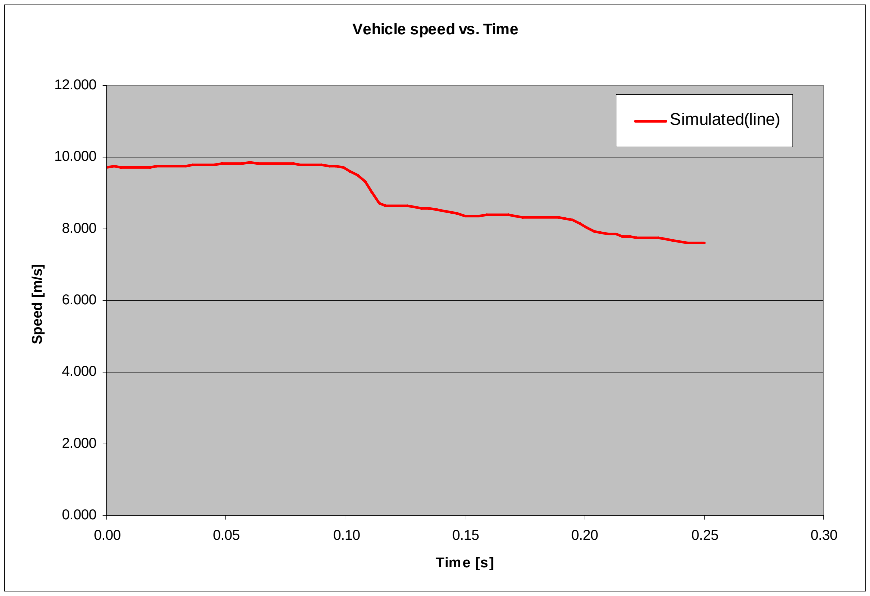
Table 3. Simulation results from Pennsylvania (Penn) H-shape.

Sign Post Name	Position	Vehicle Speed	t1(sec)	t2(sec)	V1x(t1), m/sec	V1y(t1), m/sec	Sx, m	Sy, m	ax(t1), m/s^2	ay(t2), m/s^2	Ddef(t) mm	Dpen(t) mm
Penn H-shape	0º	100km/h	(n/a 0.110)	(n/a 0.110)	4.870	0.165	0.168	0.007	-122.648	12.420	354.381	90.840
Penn H-shape	90 º	100km/h	(n/a 0.110)	(n/a 0.110)	4.979	0.715	0.171	0.028	-119.036	35.034	373.545	110.500
Penn H-shape	0 º	35km/h	(n/a 0.148)	(n/a 0.148)	2.099	0.091	0.090	0.009	-58.616	-13.513	86.341	0.000
Penn H-shape	90 º	35km/h	(n/a 0.148)	(n/a 0.148)	2.123	0.111	0.112	0.008	-34.340	-11.611	205.830	12.868

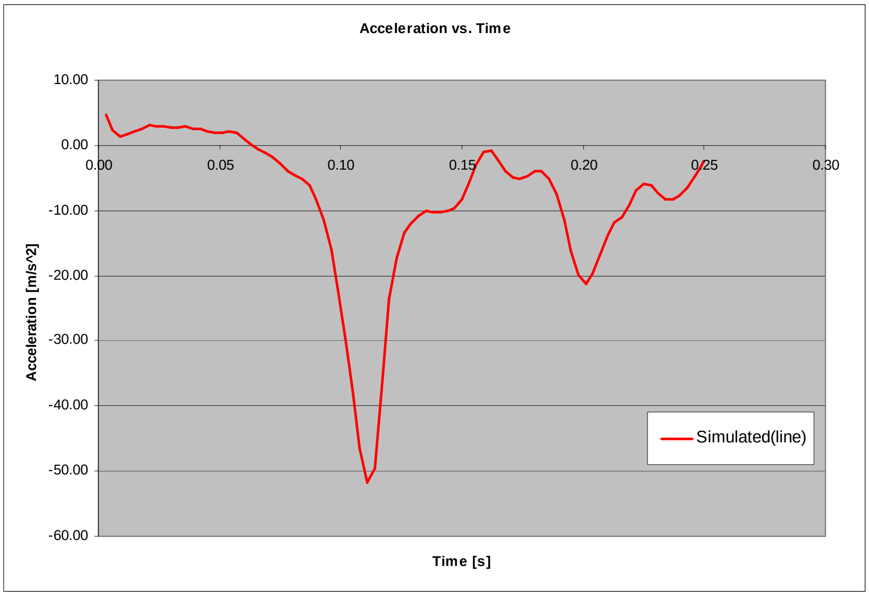
4.2.2.3 Minnesota structure

4.2.2.3.1 35 km/h with 0 deg orientation

Measured speeds and decelerations are presented in the following figures.

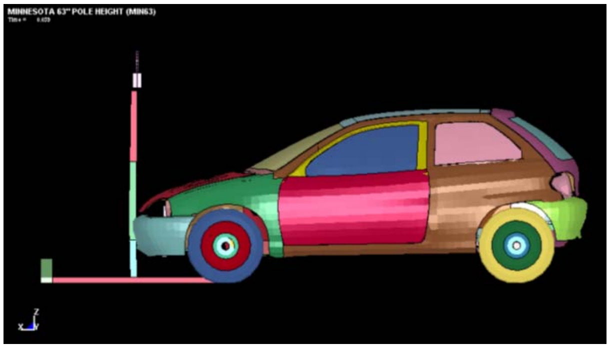


(a) Measured vehicle speed vs. time

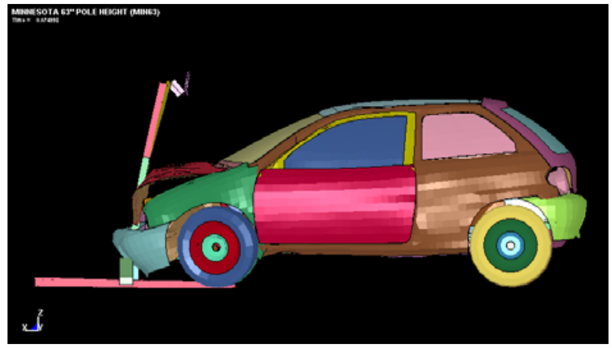


(b) Measured vehicle acceleration vs. time

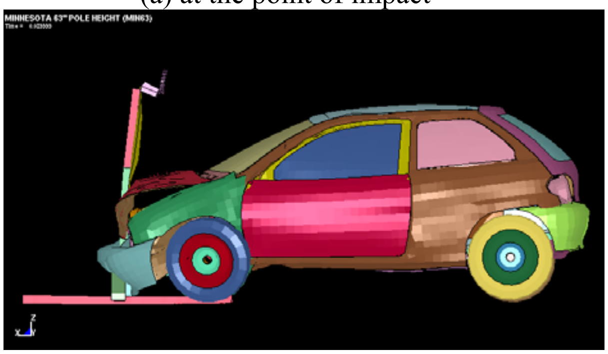
Figure 17. Speed and deceleration for 35 km/hr with 0 deg orientation.



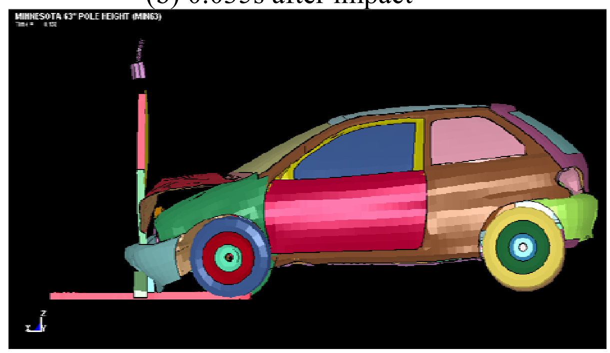
(a) at the point of impact



(b) 0.035s after impact

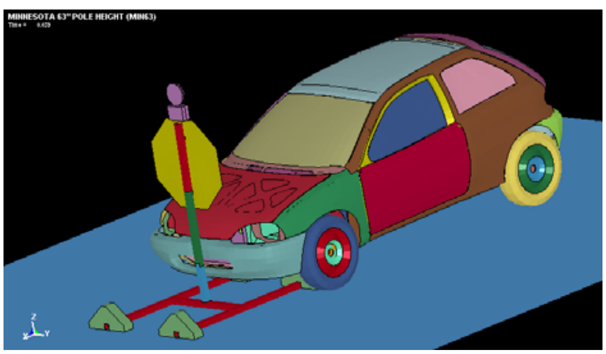


(c) 0.05s after impact

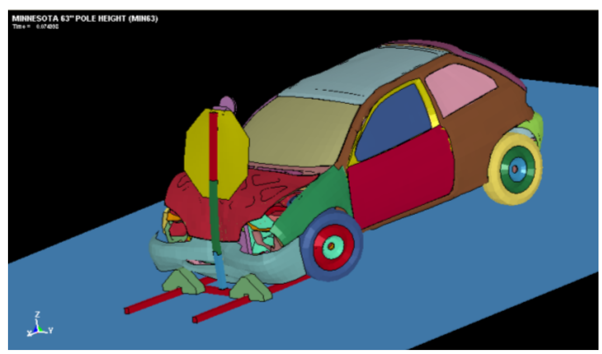


(d) 0.1s after impact

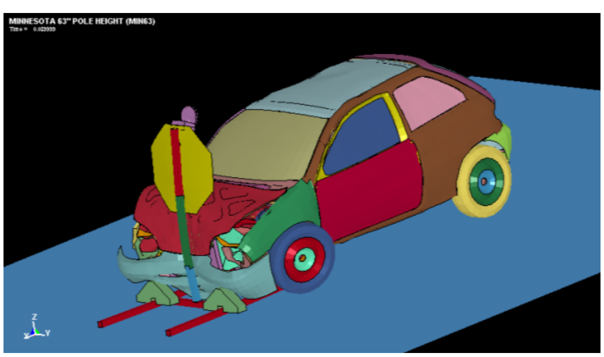
Figure 18. Right view of crashing simulation.



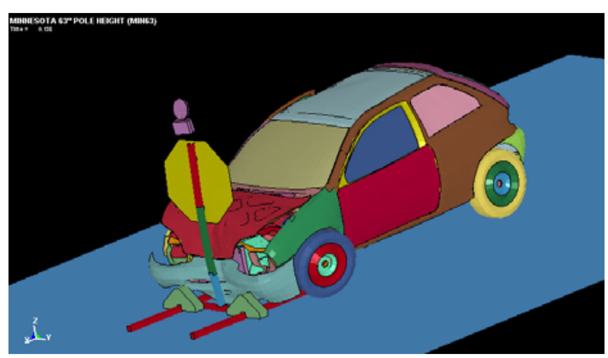
(a) at the point of impact



(b) 0.035s after impact



(c) 0.05s after impact

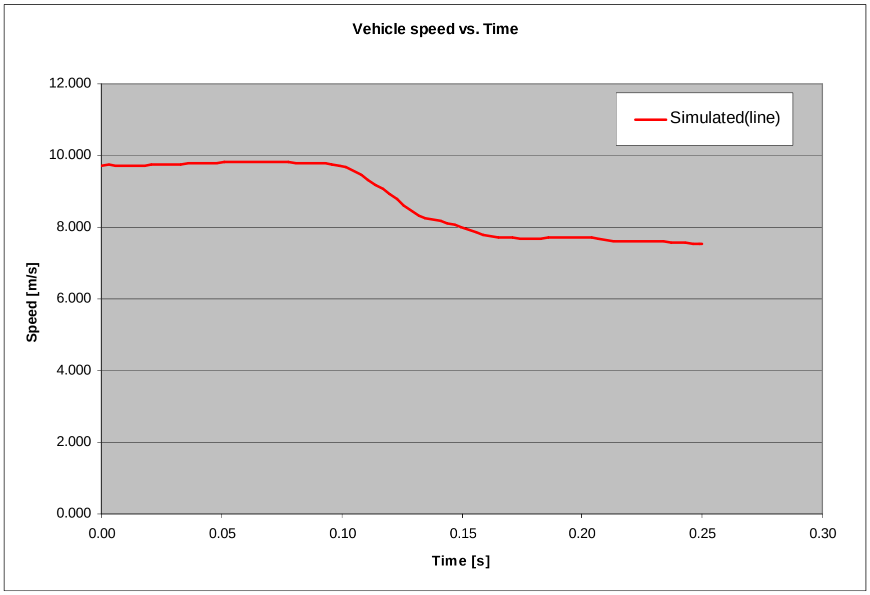


(d) 0.1s after impact

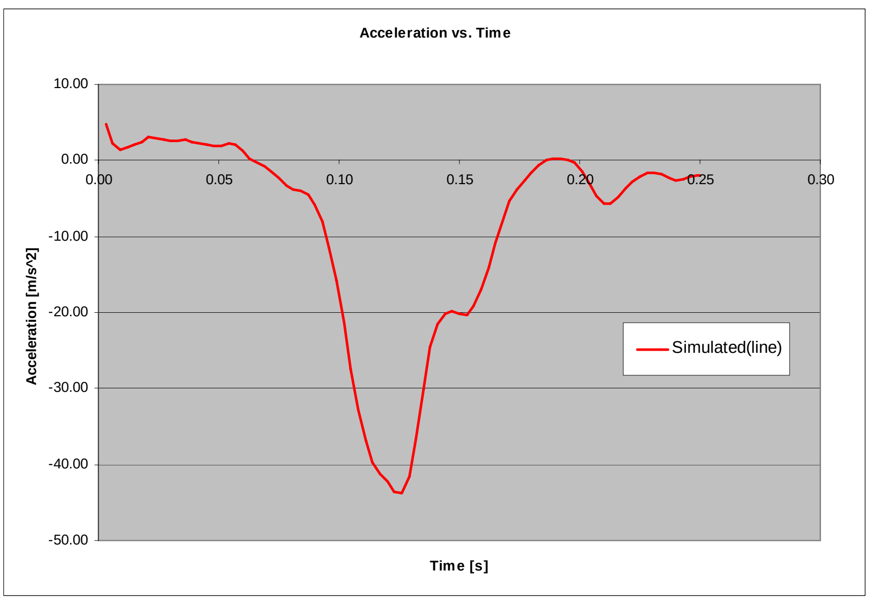
Figure 19. ISO view of crashing simulation.

4.2.2.3.2 Minnesota sign post (35 km/h with 90 deg orientation)

Measured speeds and decelerations are presented in the following figures.

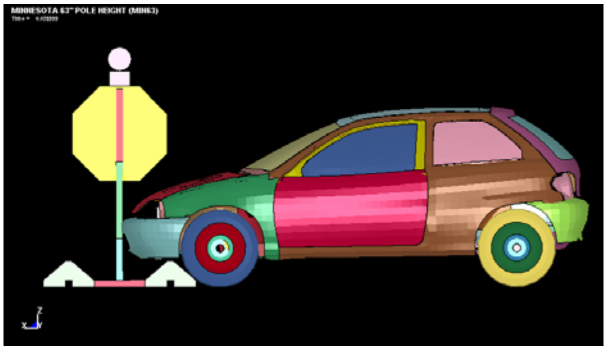


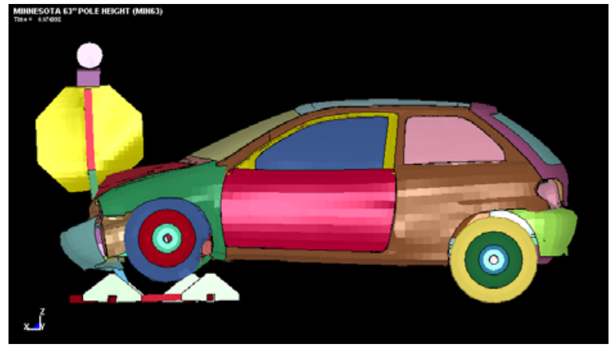
(a) Measured vehicle speed vs. time



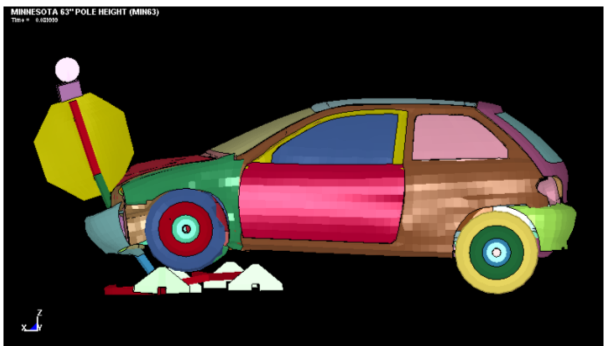
(b) Measured vehicle acceleration vs. time

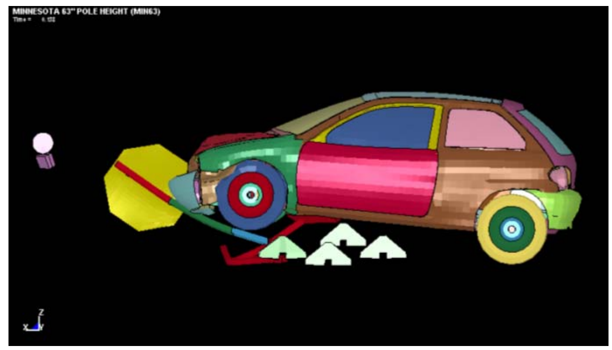
Figure 20. Speed and deceleration for 35 km/hr with 90 deg orientation.





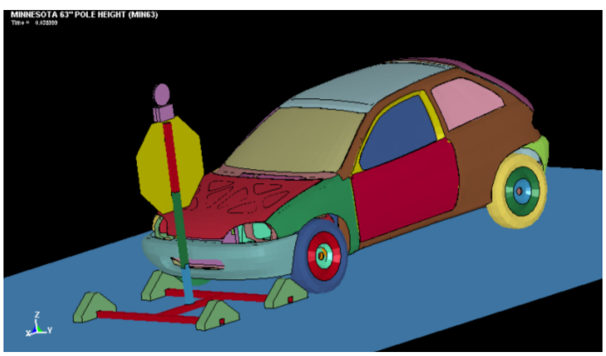
(a) at the point of impact (b) 0.035s after impact

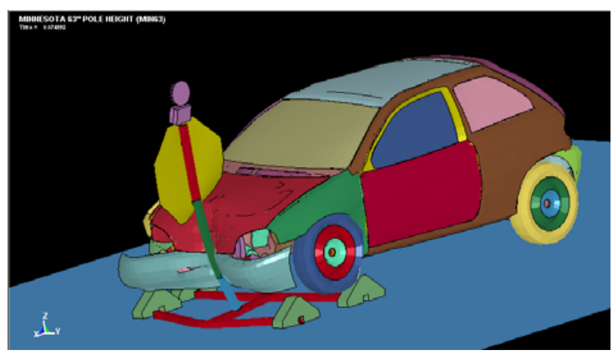




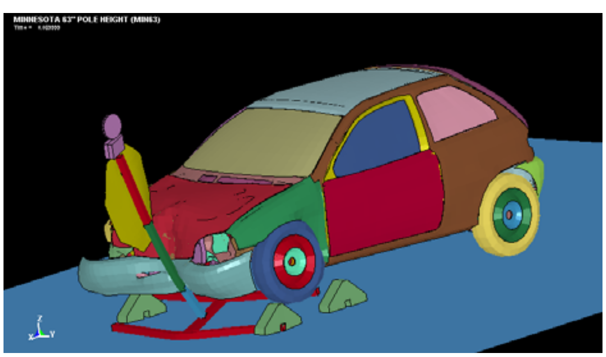
(c) 0.05s after impact (d) 0.1s after impact

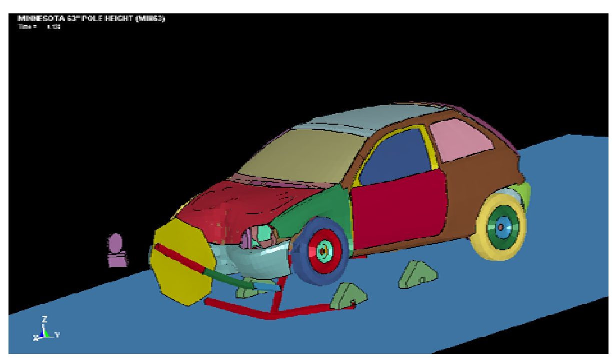
Figure 21. Right view of crashing simulation.





(a) at the point of impact (b) 0.035s after impact





(c) 0.05s after impact (d) 0.1s after impact

Figure 22. ISO view of crashing simulation.

Results for the Minnesota structure are summarized in the following table.

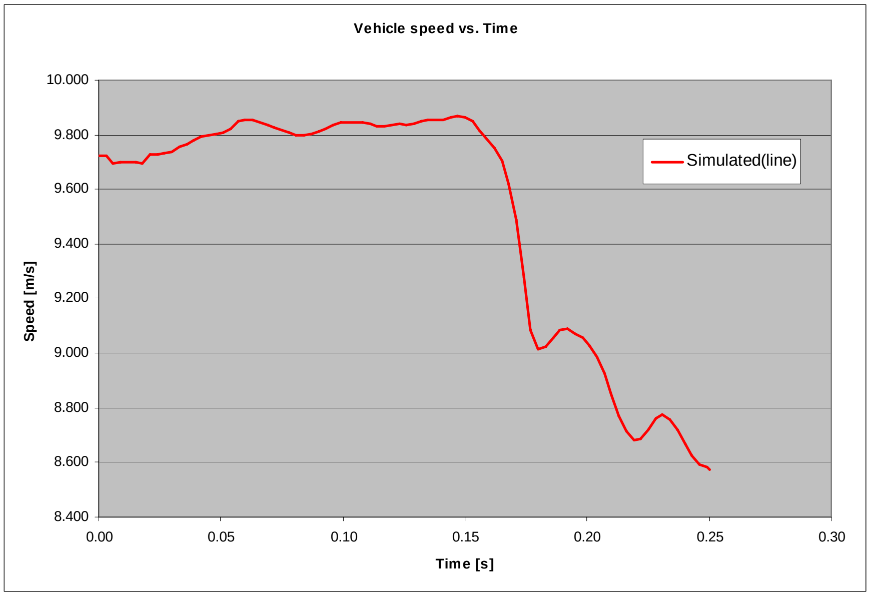
Table 4. Simulation results from Minnesota structure.

Sign Post Name	Position	Vehicle Speed	t1(sec)	t2(sec)	V1x(t1), m/sec	V1y(t1), m/sec	Sx, m	Sy, m	ax(t1), m/s^2	ay(t2), m/s^2	Ddef(t) mm	Dpen(t) mm
Minnesota	0º	100km/h	(n/a 0.110)	(n/a 0.110)	5.076	0.423	0.159	0.022	-113.277	16.888	386.360	101.560
Minnesota	90 º	100km/h	(n/a 0.110)	(n/a 0.110)	3.372	0.550	0.092	0.024	-81.565	11.001	473.048	12.600
Minnesota	0 º	35km/h	(n/a 0.148)	(n/a 0.148)	1.920	0.066	0.102	0.005	-51.678	-12.757	98.185	0.000
Minnesota	90 º	35km/h	(n/a 0.148)	(n/a 0.148)	2.060	0.398	0.073	0.010	-43.780	10.306	279.321	10.000

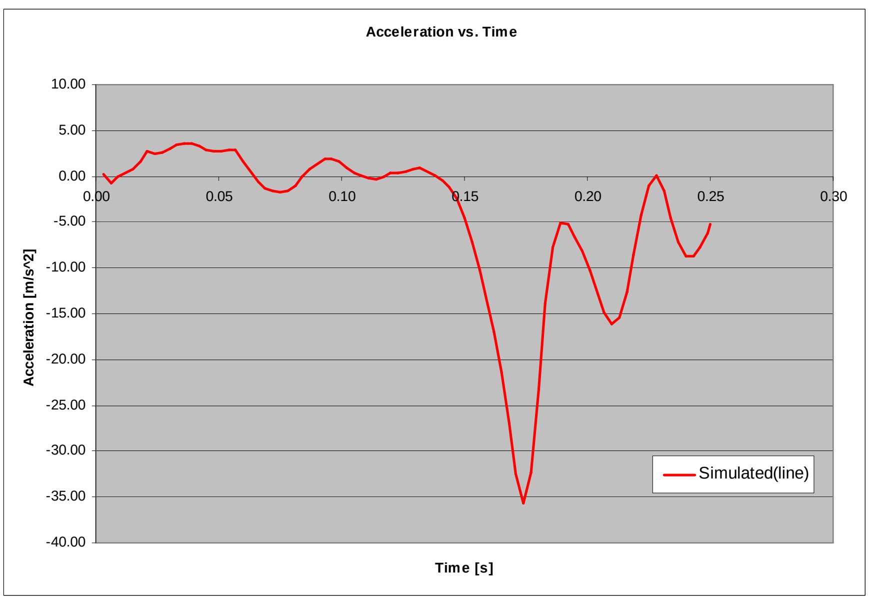
4.2.2.4 Oregon structure

4.2.2.4.1 35 km/h with 0 deg orientation

Measured speeds and decelerations are presented in the following figures.

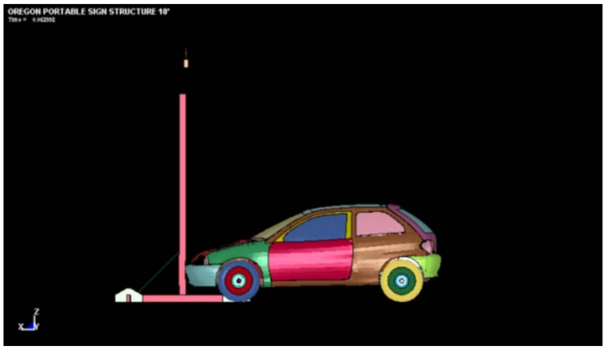


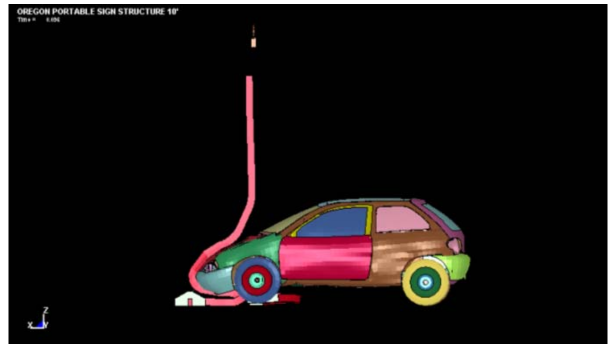
(a) Measured vehicle speed vs. time



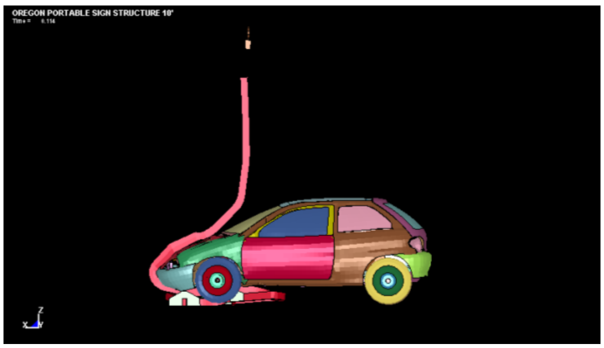
(b) Measured vehicle acceleration vs. time

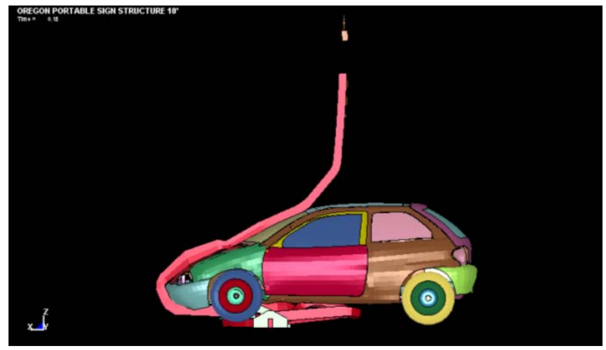
Figure 23. Speed and deceleration for 35 km/hr with 0 deg orientation.





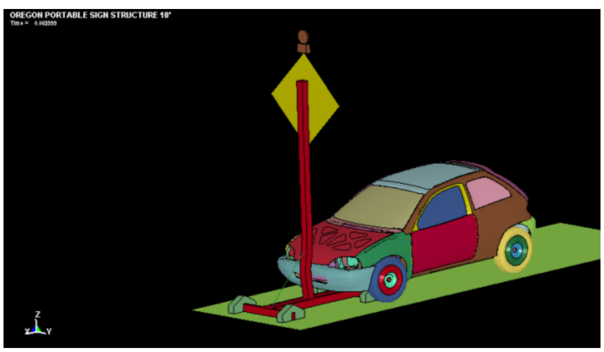
(a) at the point of impact (b) 0.035s after impact

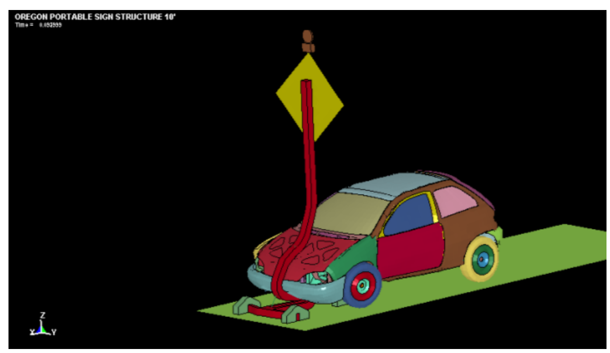




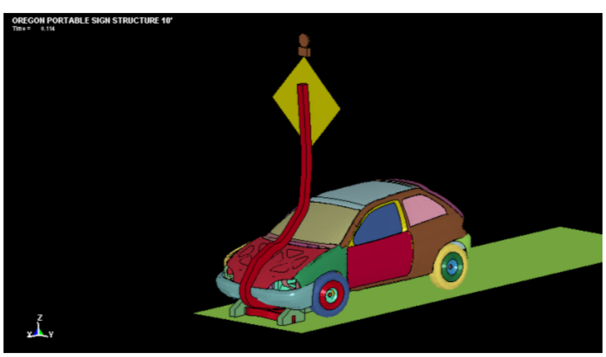
(c) 0.05s after impact (d) 0.1s after impact

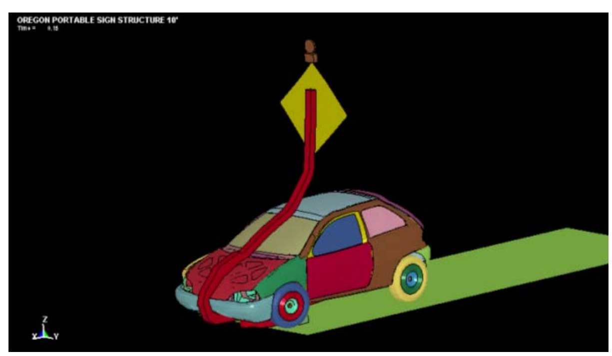
Figure 24. Right view of crashing simulation.





(a) at the point of impact (b) 0.035s after impact



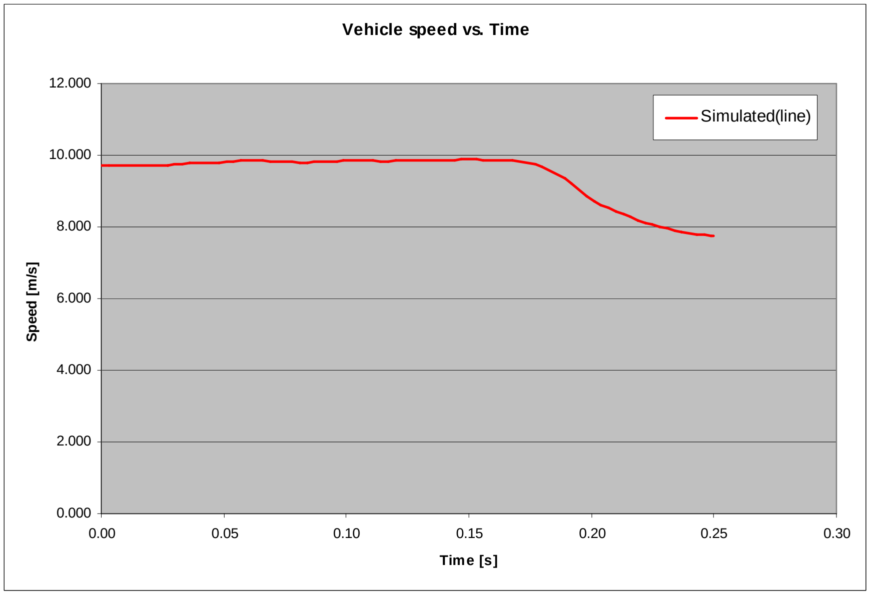


(c) 0.05s after impact (d) 0.1s after impact

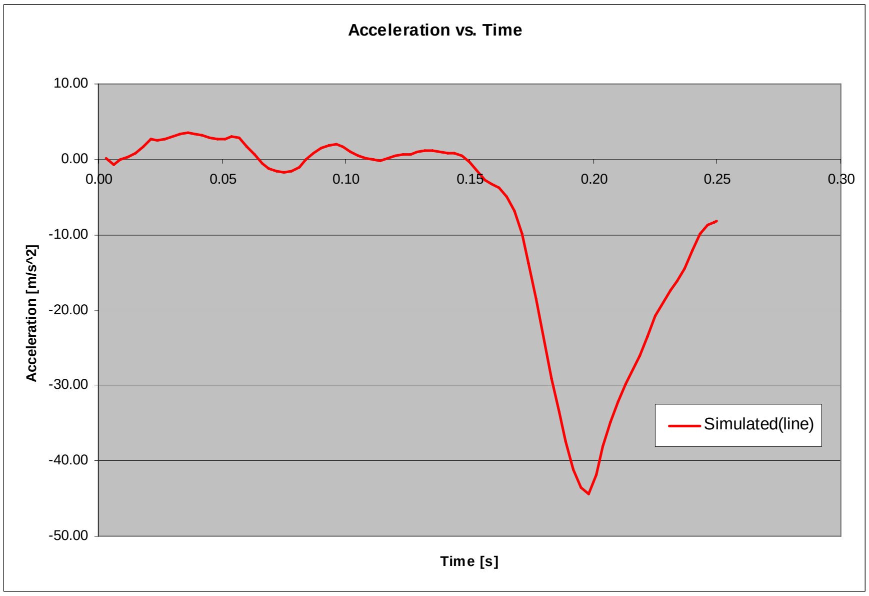
Figure 25. ISO view of crashing simulation.

4.2.2.4.2   35 km/h with 90 deg orientation

Measured speeds and decelerations are presented in the following figures.

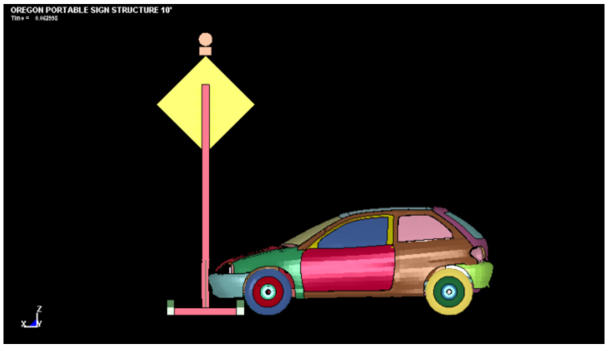


(a) Measured vehicle speed vs. time

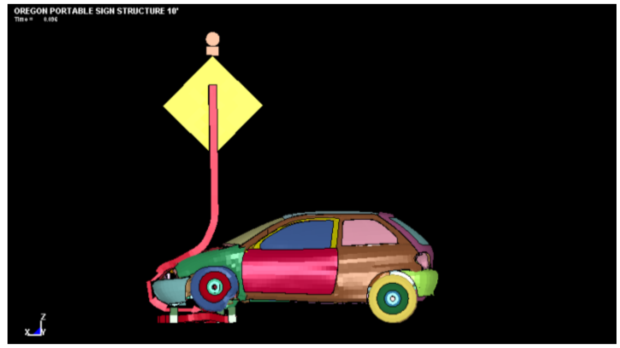


(b) Measured vehicle acceleration vs. time

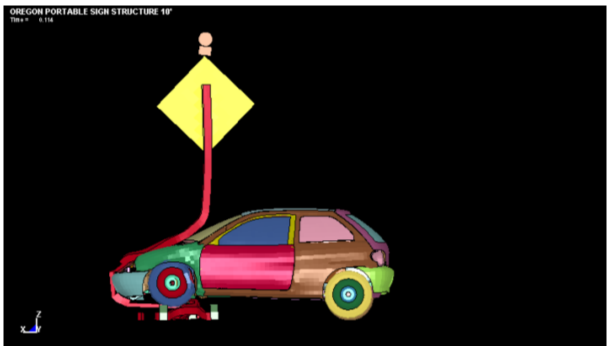
Figure 26. Speed and deceleration for 35 km/hr with 90 deg orientation.



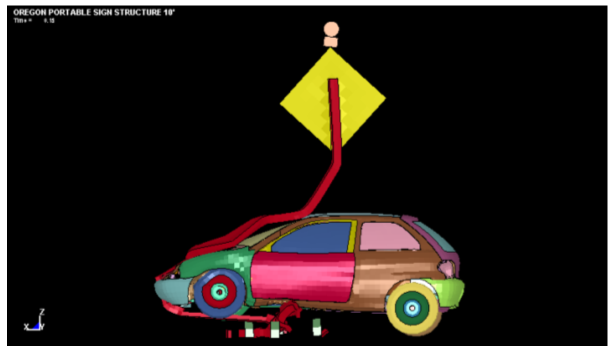
(a) at the point of impact



(b) 0.035s after impact

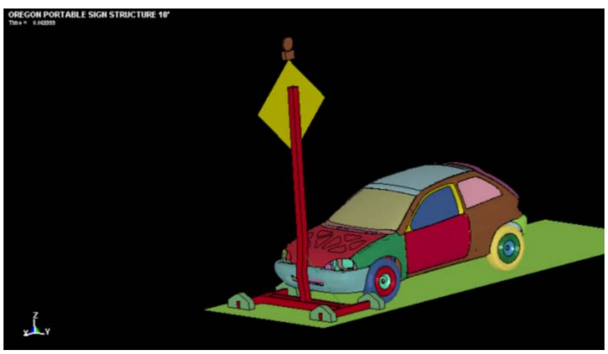


(c) 0.05s after impact

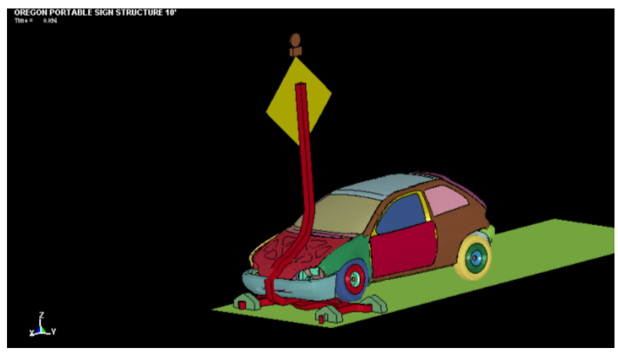


(d) 0.1s after impact

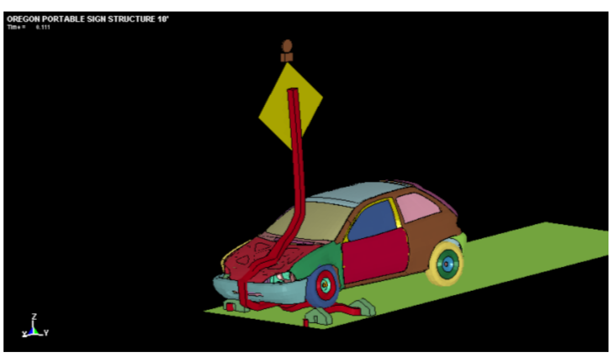
Figure 27. Right view of crashing simulation



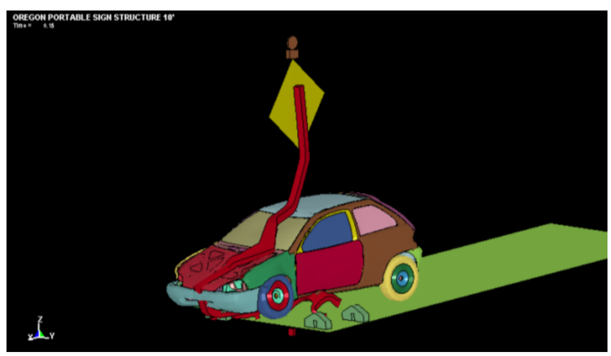
(a) at the point of impact



(b) 0.035s after impact



(c) 0.05s after impact



(d) 0.1s after impact

Figure 28. ISO view of crashing simulation.

Results for the Oregon structure are summarized in the following table.

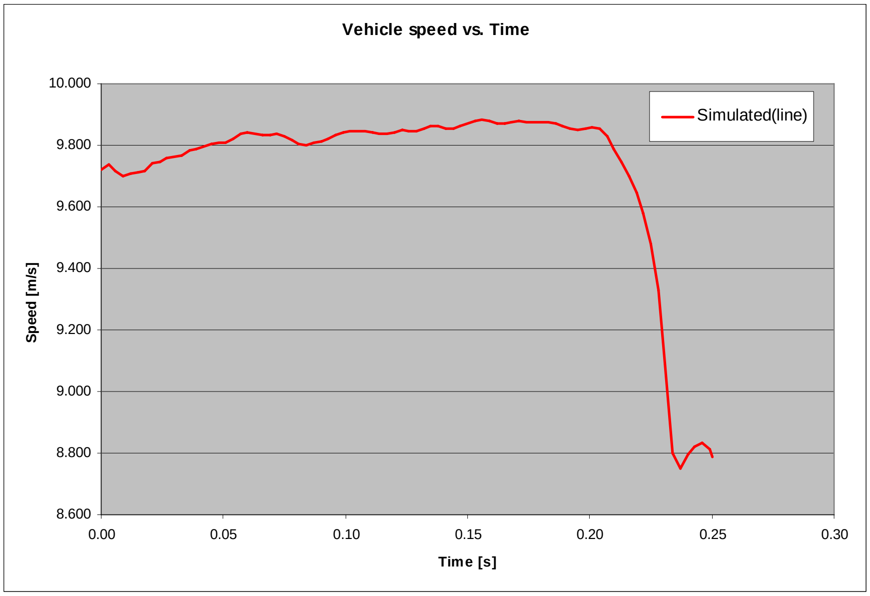
Table 5. Simulation results from Oregon structure.

Sign Post Name	Position	Vehicle Speed	t1(sec)	t2(sec)	V1x(t1), m/sec	V1y(t1), m/sec	Sx, m	Sy, m	ax(t1), m/s^2	ay(t2), m/s^2	Ddef(t) mm	Dpen(t) mm
Oregon	0º	100km/h	(n/a 0.110)	(n/a 0.110)	4.194	0.667	0.100	0.024	-101.352	46.592	127.308	0.000
Oregon	90º	100km/h	(n/a 0.110)	(n/a 0.110)	4.233	0.256	0.173	0.016	-65.268	15.572	105.700	0.000
Oregon	0º	35km/h	(n/a 0.148)	(n/a 0.148)	1.233	0.130	0.107	0.010	-35.711	8.867	43.200	0.000
Oregon	90º	35km/h	(n/a 0.148)	(n/a 0.148)	2.067	0.258	0.210	0.015	-44.321	-26.029	41.800	0.000

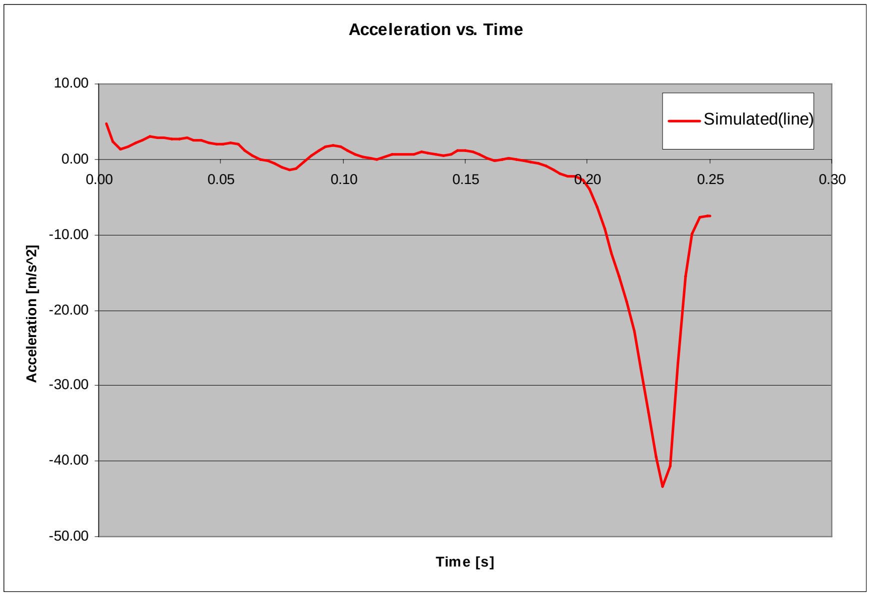
4.2.2.5 New York structure

4.2.2.5.1 35 km/h with 0 deg orientation

Measured speeds and decelerations are presented in the following figures.



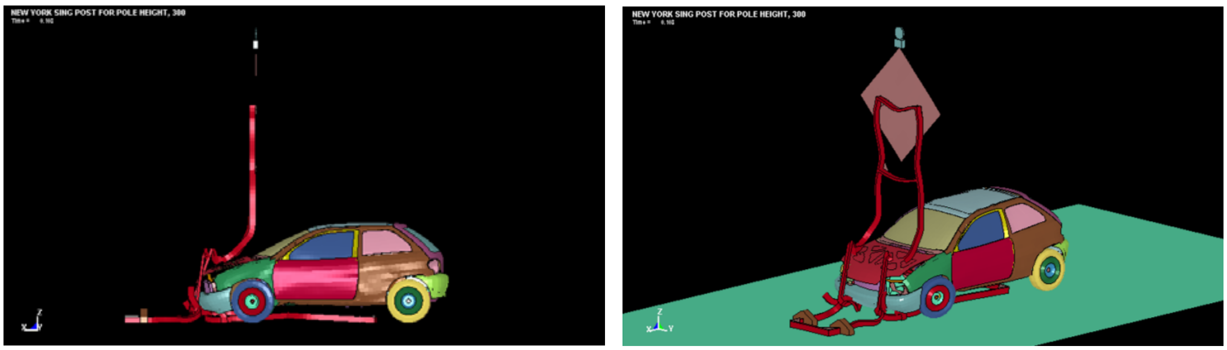
(a) Measured vehicle speed vs. time



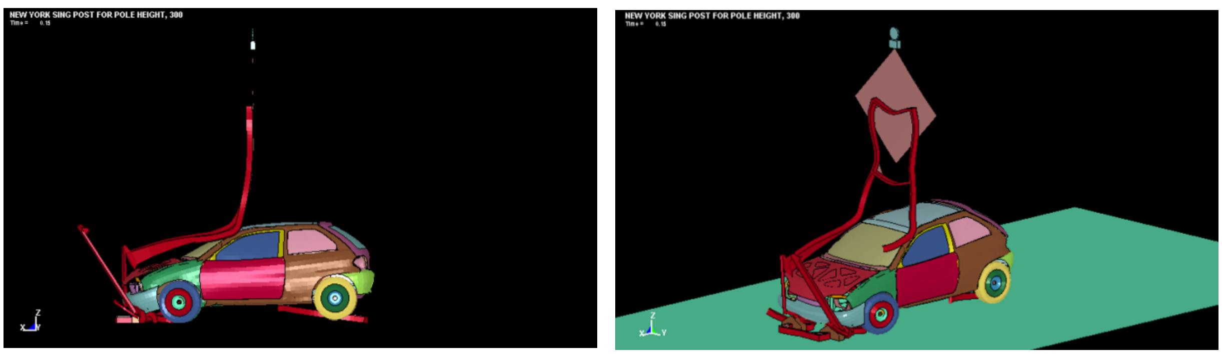
(b) Measured vehicle acceleration vs. time

Figure 29. Speed and deceleration for 35 km/hr with 0 deg orientation.

(a) at the point of impact



(b) 0.035s after impact

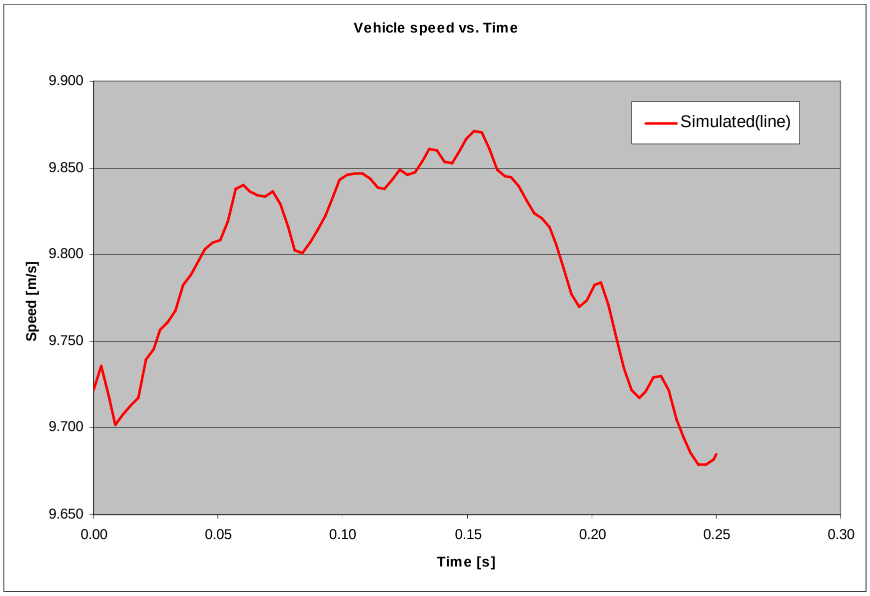


(c) 0.05s after impact

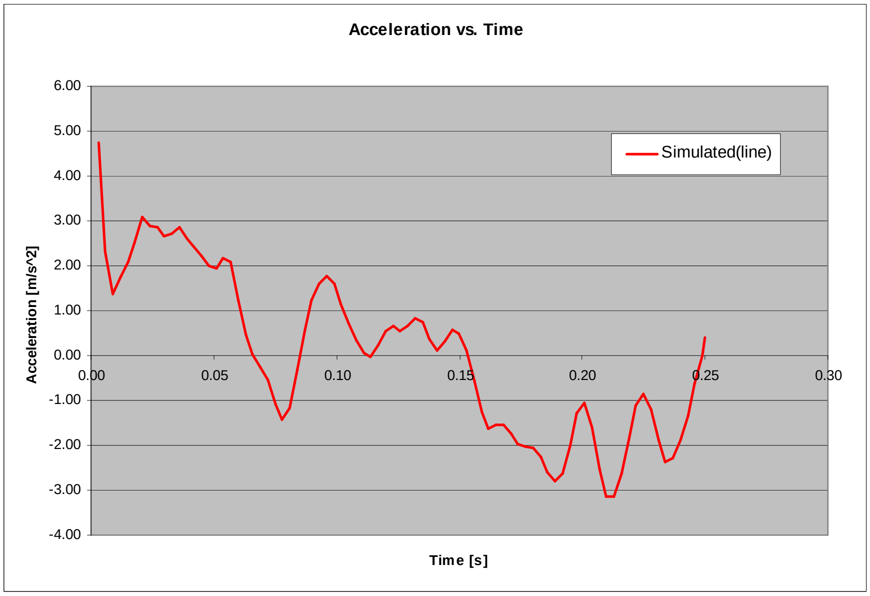
Figure 30. View of crashing simulation (i.e., right and ISO view).

4.2.2.5.2 35 km/h with 90 deg orientation

Measured speeds and decelerations are presented in the following figures.

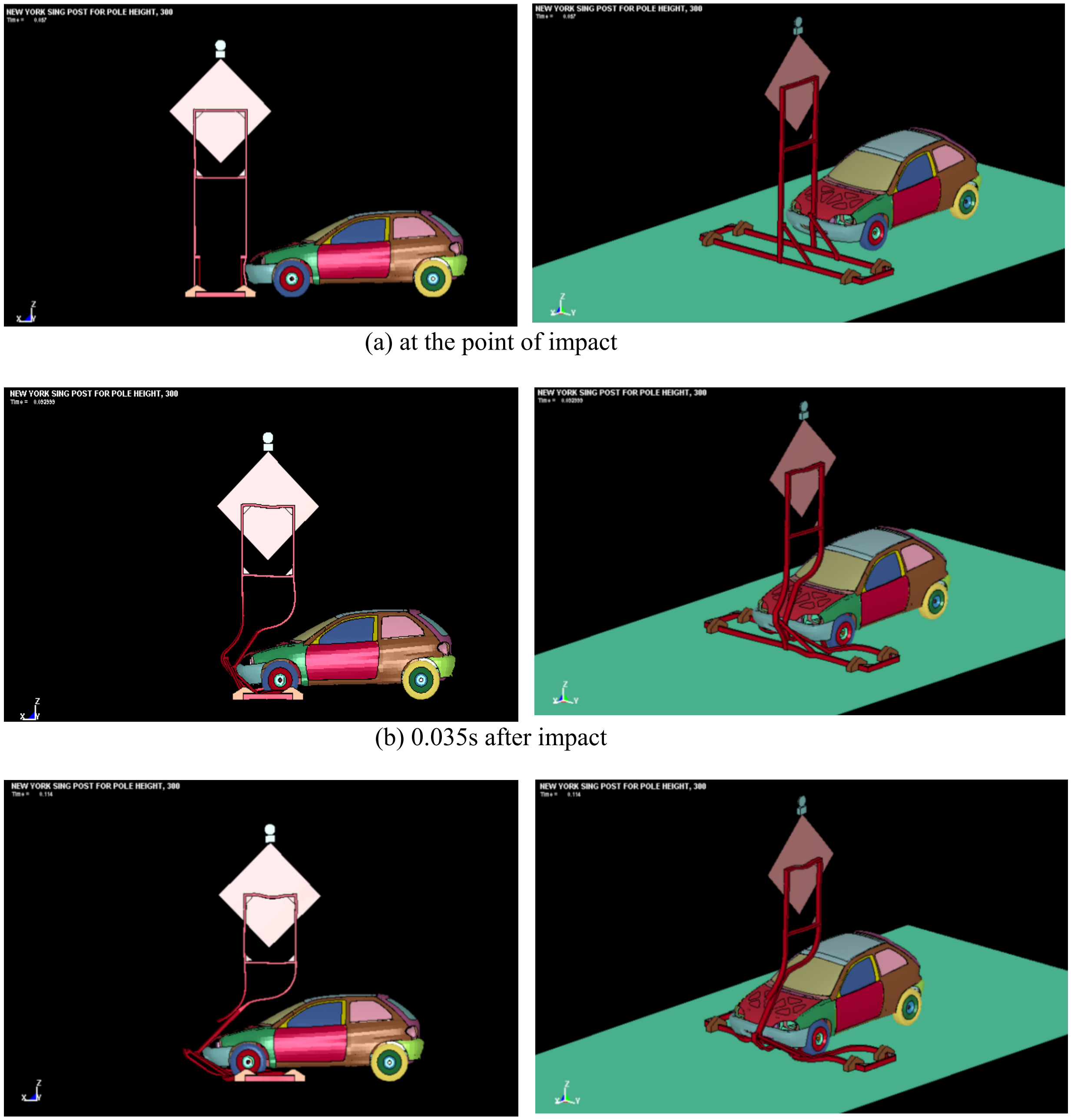


(a) Measured vehicle speed vs. time



(b) Measured vehicle acceleration vs. time

Figure 31. Speed and deceleration for 35 km/hr with 90 deg orientation.



(a) at the point of impact

(b) 0.035s after impact

(c) 0.05s after impact

Figure 32. View of crashing simulation (i.e., right and ISO view).

Results for the New York structure are summarized in the following table.

Table 6. Simulation results from New York structure.

Sign Post Name	Position	Vehicle Speed	t1(sec)	t2(sec)	V1x(t1), m/sec	V1y(t1), m/sec	Sx, m	Sy, m	ax(t1), m/s^2	ay(t2), m/s^2	Ddef(t), mm	Dpen(t), mm
New York	0 °	100km/h	(n/a 0.110)	(n/a 0.110)	6.132	0.744	0.246	0.020	-110.451	21.556	191.696	0.000
New York	90 °	100km/h	(n/a 0.110)	(n/a 0.110)	0.897	0.184	0.046	0.015	-13.526	7.342	69.900	0.000
New York	0 °	35km/h	(n/a 0.148)	(n/a 0.148)	1.022	0.111	0.126	0.007	-43.410	-6.163	10.700	0.000
New York	90 °	35km/h	(n/a 0.148)	(n/a 0.148)	0.149	0.897	0.015	0.007	4.747	-12.387	6.300	0.000

4.3 Examination of Analysis Results

Table 7 summarizes results obtained from the considered sign structure simulations.

Table 7. Table of performance parameters from simulation results.

Sign post name	Position	Vehicle speed	t1(sec)	t2(sec)	V1x(t1), m/sec	V1y(t1), m/sec	Sx, m	Sy, m	ax(t1), m/s^2	ay(t2), m/s^2	Ddef(t), mm	Dpen(t), mm
Penn X-shape	0 degree	100km/h	(n/a 0.110)	(n/a 0.110)	4.200	0.375	0.152	0.018	-94.782	26.601	355.193	77.200
Penn X-shape	90 degree	100km/h	(n/a 0.110)	(n/a 0.110)	4.432	0.132	0.165	0.007	-82.691	18.613	357.737	136.000
Penn X-shape	0 degree	35km/h	(n/a 0.148)	(n/a 0.148)	1.410	0.120	0.090	0.010	-16.310	-4.440	69.783	0.000
Penn X-shape	90 degree	35km/h	(n/a 0.148)	(n/a 0.148)	1.881	0.166	0.091	0.010	-32.043	-7.803	162.396	10.000
Penn H-shape	0 degree	100km/h	(n/a 0.110)	(n/a 0.110)	4.870	0.165	0.168	0.007	-122.648	12.420	354.381	90.840
Penn H-shape	90 degree	100km/h	(n/a 0.110)	(n/a 0.110)	4.979	0.715	0.171	0.028	-119.036	35.034	373.545	110.500
Penn H-shape	0 degree	35km/h	(n/a 0.148)	(n/a 0.148)	2.099	0.091	0.090	0.009	-58.616	-13.513	86.341	0.000
Penn H-shape	90 degree	35km/h	(n/a 0.148)	(n/a 0.148)	2.123	0.111	0.112	0.008	-34.340	-11.611	205.830	12.868
Minnesota	0 degree	100km/h	(n/a 0.110)	(n/a 0.110)	5.076	0.423	0.159	0.022	-113.277	16.888	386.360	101.560
Minnesota	90 degree	100km/h	(n/a 0.110)	(n/a 0.110)	3.372	0.550	0.092	0.024	-81.565	11.001	473.048	12.600
Minnesota	0 degree	35km/h	(n/a 0.148)	(n/a 0.148)	1.920	0.066	0.102	0.005	-51.678	-12.757	98.185	0.000
Minnesota	90 degree	35km/h	(n/a 0.148)	(n/a 0.148)	2.060	0.398	0.073	0.010	-43.780	10.306	279.321	10.000
Oregon	0 degree	100km/h	(n/a 0.110)	(n/a 0.110)	4.194	0.667	0.100	0.024	-101.352	46.592	127.308	0.000
Oregon	90 degree	100km/h	(n/a 0.110)	(n/a 0.110)	4.233	0.256	0.173	0.016	-65.268	15.572	105.700	0.000
Oregon	0 degree	35km/h	(n/a 0.148)	(n/a 0.148)	1.233	0.130	0.107	0.010	-35.711	8.867	43.200	0.000
Oregon	90 degree	35km/h	(n/a 0.148)	(n/a 0.148)	2.067	0.258	0.210	0.015	-44.321	-26.029	41.800	0.000
New York	0 degree	100km/h	(n/a 0.110)	(n/a 0.110)	6.132	0.744	0.246	0.020	-110.451	21.556	191.696	0.000
New York	90 degree	100km/h	(n/a 0.110)	(n/a 0.110)	0.897	0.184	0.046	0.015	-13.526	7.342	69.900	0.000
New York	0 degree	35km/h	(n/a 0.148)	(n/a 0.148)	1.022	0.111	0.126	0.007	-43.410	-6.163	10.700	0.000
New York	90 degree	35km/h	(n/a 0.148)	(n/a 0.148)	0.149	0.897	0.015	0.007	4.747	-12.387	6.300	0.000

In the evaluation of the design structures the "Flail-Space Model" from NCHRP was used. In this analysis the authors have adopted the simplified point mass, flail-space model for assessing risks to occupants within the impacting vehicle due to vehicular accelerations according to the allowed NCHRP procedures. Two measures of risk are used: (1) the velocity at which a hypothetical occupant impacts a hypothetical interior surface, and (2) "ridedown" acceleration subsequently experienced by the occupant. Assumptions made in the current model were:

a. Occupant is positioned at the vehicle's center of mass;
b. Yaw motions of vehicle are ignored and, consequently, motion of the occupant in the lateral direction is completely independent of motion in the longitudinal direction;
c. Vehicular and occupant motion is planar (in x-y plane); and
d. Occupant is contained in a compartment such that ± 0.3 m lateral movement can occur before impact with the sides of the compartment (idealized vehicular side structure), and 0.6 m longitudinal (forward) movement can occur before impact with the front of the compartment (idealized instrument panel/dash/windshield).

The calculation algorithms for these parameters are given in Section 4.2.1, "Requirements and Technique for Analysis." In the simulated tests of the sign structures, the impulse on the vehicle on almost all of the cases was relatively small and of short duration. In all of the tests the displacements (S_x, S_y) (see 4.2.1, "Requirements and Technique for Analysis") was less than 0.6 m and 0.3 m, respectively, during the period in which accelerations were recorded. In such cases it is recommended that the occupant impact velocity be set equal to the vehicle's change in velocity that occurs during contact with the test article, or parts thereof. The V_{1x} and V_{1y} occupant impact velocities in Table 7 were calculated according to these NCHRP guidelines.

For the ridedown acceleration to produce occupant injury, it should have at least a minimum duration ranging from 0.007 to 0.04 sec, depending on the body component. Thus, vehicular acceleration "spikes" of durations less than 0.007 sec are not critical and should be averaged from the pulse. An arbitrary duration of 0.010 sec was selected by NCHRP 350 as a convenient and somewhat conservative time base for averaging accelerations for occupant risk assessment. This is accomplished by taking a moving 10-ms average of vehicular "instantaneous" accelerations in the x and y directions, subsequent to the calculated occupant impact time.

The acceptable and preferred limitations contained in NCHRP 350 pertaining to portable sign structure crash testing test are given in Table 8.

Table 8. NCHRP evaluation limits.

	Preferred	Maximum
Occupant Impact Velocity Limits [m/s]	3	5
Occupant Ridedown Acceleration Limits [G's]	15	20

From Table 7 the aggregate occupant risk factors (the occupant impact velocity and occupant ridedown acceleration) in terms of the NCHRP criteria were calculated. In order to minimize the work necessary to compare the results and to be conservative aggregate risk factors were calculated. The aggregate factors were calculated using the following geometrical vector addition formula:

$$Aggregatevalue = \sqrt[2]{entity_x^2 + entity_y^2} \qquad (4.1)$$

The computed aggregate occupant risk factors are given in
Table 9. The aggregate occupant impact velocities and the highest 10-ms average of the aggregate acceleration values are compared to the recommended limits in Table 8; it is desirable that both values be below the "preferable" limits; values in excess of the "maximum" limits are considered to be unacceptable.

As can be observed from the data, most of the sign structures have delivered results that are within the NCHRP maximum limitations. The only exception is the New York sign structure, which gave an occupant impact velocity that was larger than the acceptable limit. All sign post designs have occupant ridedown accelerations that are much smaller than the given upper limitation, and most of them are also smaller than the preferred value. The only structure that yielded accelerations that are slightly larger than the preferred value is the Pennsylvania H-shape sign post structure.

Table 9. Aggregate occupant risk factors.

Sign Post Name	*Position*	*Vehicle Speed*	*Aggregate Occupant Impact Velocity [m/s]*	*Occupant Ridedown Acceleration [G's]*
Penn X-shape	0 degree	100km/h	4.22	10.04
Penn X-shape	90 degree	100km/h	4.43	8.64
Penn X-shape	0 degree	35km/h	1.42	1.72
Penn X-shape	90 degree	35km/h	1.89	3.36
Penn H-shape	0 degree	100km/h	4.87	12.57
Penn H-shape	90 degree	100km/h	5.03	12.65
Penn H-shape	0 degree	35km/h	2.1	6.13
Penn H-shape	90 degree	35km/h	2.13	3.7
Minnesota	0 degree	100km/h	5.09	11.67
Minnesota	90 degree	100km/h	3.42	8.39
Minnesota	0 degree	35km/h	1.92	5.43
Minnesota	90 degree	35km/h	2.1	4.58
Oregon	0 degree	100km/h	4.25	11.37
Oregon	90 degree	100km/h	4.24	6.84
Oregon	0 degree	35km/h	1.24	3.75
Oregon	90 degree	35km/h	2.08	5.24
New York	0 degree	100km/h	6.18	11.47
New York	90 degree	100km/h	0.92	1.57
New York	0 degree	35km/h	1.03	4.47
New York	90 degree	35km/h	0.91	1.35

4.4 Recommendation

A ranking between the structures with regard to the total occupant risk can be established by calculating the average occupant impact velocities and occupant ridedown accelerations for each sign post design. The ranking is based upon the combined averages of the two risk factors (occupant impact velocities and occupant ridedown accelerations). Based upon this procedure, the ranking for the sign posts is as follows, with number 1 being the safest and number 5 being the least safe:

1. Pennsylvania – X-shape
2. Pennsylvania – H-shape
3. Minnesota
4. Oregon
5. New York

Based upon the analysis of the results it is recommended that the Pennsylvania – X-shape sign post design be selected for further analysis and testing.

5 Sign Post Design

Based upon the request of PennDOT, two separate designs for the temporary sign structure were prepared:

1. A sign post structure based on an "X" shaped ground support structure, and
2. A sign post structure based on an "H" shaped ground support structure.

Both of the structures use the same upright pole and sign elements and use four sand bags (25 lb each) for stabilization. The design work was based on the initial conditions of the materials of the actual traffic sign plates, mandatory top safety lights and sign post pole and footing structure, to accurately represent the elements presently used by PennDOT. A schematic of the basic concept is depicted in Figure 33.

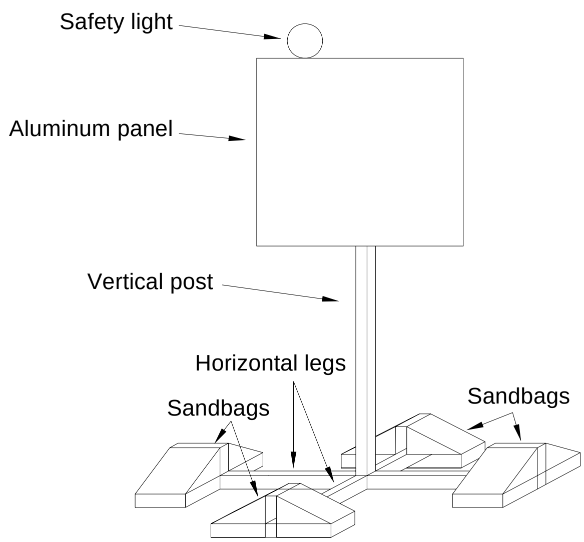
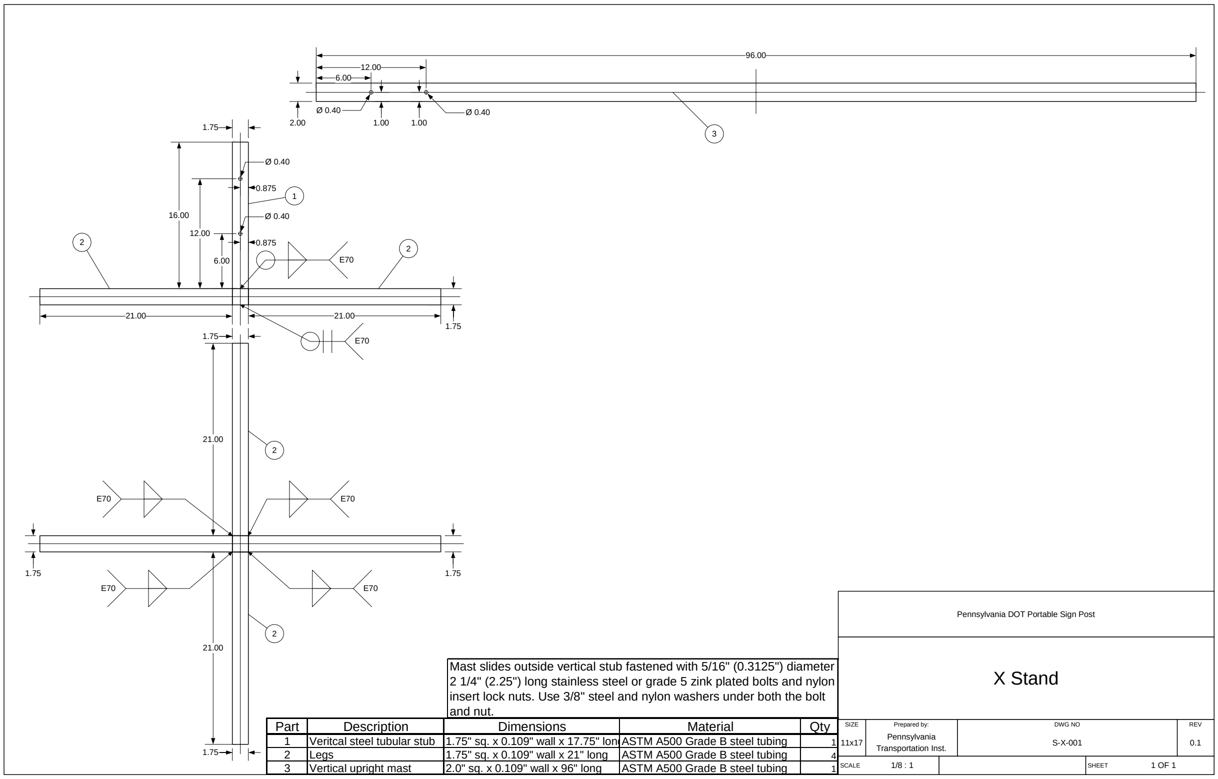


Figure 33. Sign post concept.

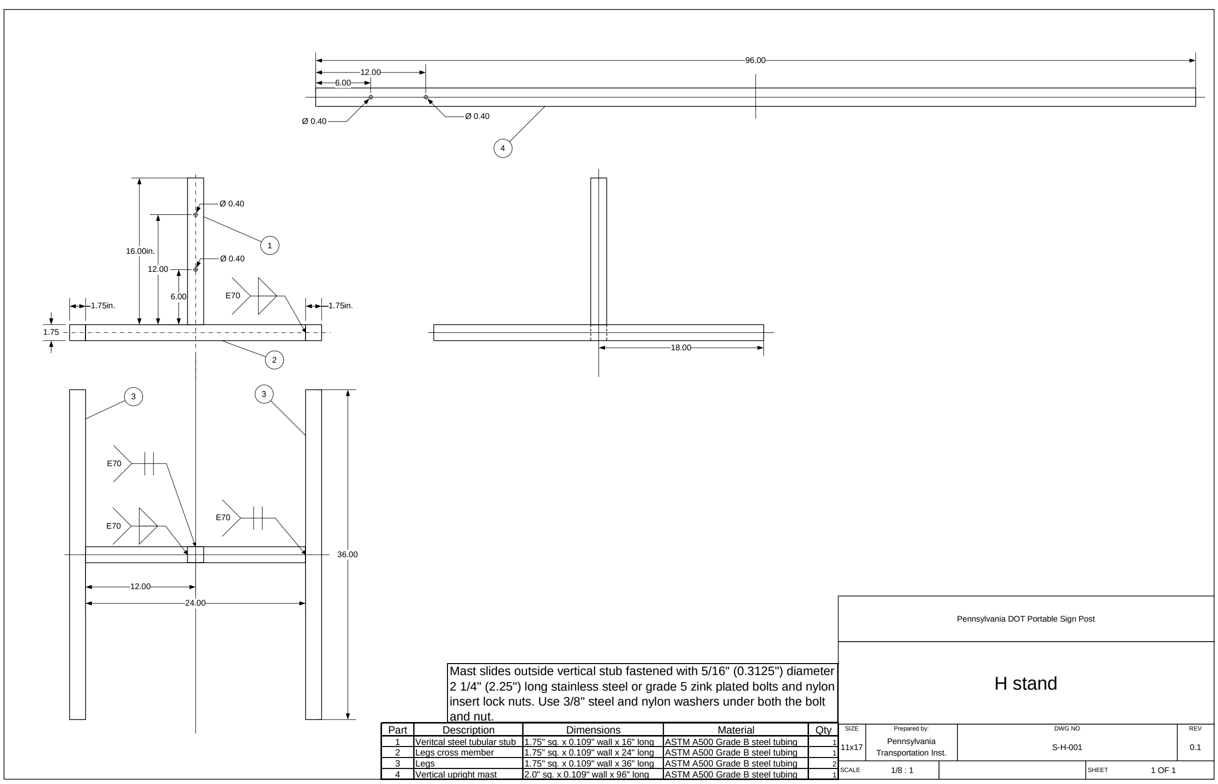
The given constraints provided by PennDOT prior to the sign modeling and design regarding the materials and the available sign panel materials were the following:

1. The sign's horizontal support legs consist of ASTM A500 Grade B steel tubes that are 44.5 mm (1.75 in) × 44.5 mm (1.75 in) × 2.78 mm (0.11 in) thick.
2. The aluminum sign panel hung from the support is 914.4 mm (36 in) × 914.4 mm (36 in) square × 3 mm (0.12 in) thick.
3. The weight of the top safety light is: 4 lb 8 oz.

Based upon this information and the previously completed finite element analysis, a recommended sign post structure was designed and the design was verified by appropriate FEA calculations. The designed structures can be observed in Figure 34.



Part	Description	Dimensions	Material	Qty
1	Veritcal steel tubular stub	1.75" sq. x 0.109" wall x 17.75" lon	ASTM A500 Grade B steel tubing	1
2	Legs	1.75" sq. x 0.109" wall x 21" long	ASTM A500 Grade B steel tubing	4
3	Vertical upright mast	2.0" sq. x 0.109" wall x 96" long	ASTM A500 Grade B steel tubing	1



Part	Description	Dimensions	Material	Qty
1	Veritcal steel tubular stub	1.75" sq. x 0.109" wall x 16" long	ASTM A500 Grade B steel tubing	1
2	Legs cross member	1.75" sq. x 0.109" wall x 24" long	ASTM A500 Grade B steel tubing	1
3	Legs	1.75" sq. x 0.109" wall x 36" long	ASTM A500 Grade B steel tubing	2
4	Vertical upright mast	2.0" sq. x 0.109" wall x 96" long	ASTM A500 Grade B steel tubing	1

Figure 34. Sign post structure design.

The two sign post structures were built, assembled, and prepared for full-scale NCHRP 350 crash testing.

6 Task 3: Full Scale Crash Test

New roadside portable signs and other safety features need to be designed in an effort to reduce injury risks to errant motorists, to lower manufacturing and installation costs, and to conserve our natural resources. The Federal Highway Administration requires that all roadside safety features to be used on the National Highway System (NHS) demonstrate acceptable crashworthy performance per NCHRP Report 350[1]. Many state and local agencies also specify this requirement for local installations. PennDOT has joined the long list of U.S. state agencies requiring unified and crashworthy designs for all portable sign structures used by the state. The standardized procedures presented in NCHRP Report 350 help to evaluate the performance of the safety feature in terms of the hazard posed to occupants of the impacting vehicle, the structural adequacy of the safety feature, the hazard to workers or pedestrians near the impact area, and the post-impact behavior of the impacting vehicle.

6.1 First Full-Scale Crash Test

The objective of the full-scale test was to document and evaluate the performance of the two newly designed portable sign post structures when subjected to NCHRP Report 350 criteria. In order to be approved at Level 3, NCHRP Report 350[1] requires testing at 100 km/hr as a minimum for work zone traffic control devices in Category 2. In test designation 3-61, the 820C vehicle impacts the sign (normal orientation to the flow of traffic) at 100 km/h. In addition to the normal orientation, an orientation of 90 degrees from the normal is often required when there is a reasonable potential for such an orientation to be more critical than the normal orientation. Often devices can be tested in both orientations during one crash, unless the device has the potential to lie across the test vehicle's windshield and affect the results of the second impact.

For devices that weigh in excess of 45 kg, a second test in accordance with test designation 3-60 is also required to meet Level 3 NCHRP Report 350 standards. This test is performed using the same type vehicle and work zone traffic control device orientations as test designation 3-61, but is performed at 35 km/h instead of 100 km/h.

One last variable for work zone devices is the use of the 2000P vehicle in lieu of or in addition to the 820C vehicle when the primary concern is the penetration of the test article into the occupant compartment. This determination depends on the profile of the two different vehicles in relation to the geometry of the test article. This determination should be made by the Federal Highway Administration in conjunction with the sponsor prior to finalizing a test plan, as the cost of the 2000P vehicle can be substantially higher than the 820C.

6.1.1 Test Layout and Preparation

The plans for the testing of the PennDOT portable sign post devices were prepared in cooperation with the FHWA Office of Safety Design (FHWA-HSSD). The test levels, the cars used in the full-scale crashes, and the impact configurations were prepared in accordance with the NCHRP 350 recommendations.

6.1.2 Selected NCHRP Tests

Two tests are recommended for work zone traffic control devices for each test level using either the recommended 820C vehicle or the optional 700C vehicle: a low-speed test and a high-speed test. The low-speed test is generally intended to evaluate the breakaway, fracture, or yielding mechanism of the device, whereas the high-speed test is intended to evaluate vehicular stability and test article trajectory. Occupant risk is of concern in both tests. Test 70 may be omitted when it can be clearly determined that Test 71 is more critical. For example, Test 71 will be more critical than Test 70 for work zone traffic control devices having a relatively small mass, such as plastic drums used as channelization devices, lightweight barricades, and so on. If the mass of a free-standing (resting on but not attached to ground or paved surface) work zone traffic control device is 45 kg or less, evaluation criteria H and I of Table 5.1 are optional. For a device with sand bags or other ballasts at its base (for stability), the mass of the ballast need not be added to the mass of the device provided the ballast effectively does not contribute to the change in the vehicle's velocity upon impact with the device. If the primary concern regarding the impact behavior of a traffic control device is penetration of the test article or parts thereof into the occupant compartment, as opposed to occupant impact velocity and ridedown acceleration and/or vehicular stability, it may be preferable to use the 2000P vehicle in lieu of or in addition to the 820C vehicle. The choice will depend on the front profile of the two vehicles in relation to the geometry of the test article and elements thereon that could potentially penetrate the occupant compartment. In evaluating traffic control devices for test level 3, tests should also be conducted at speeds between 35 and 100 km/h if there is a reasonable potential for such tests to be more critical than those recommended.

For the evaluation of the PennDOT sign support structures the NCHRP 350 Test 3-71 was selected by the FHWA officials. The level 3-70 test proved to be unnecessary, since the weight of the sign structure was less than 100kg.

Following the recommendation of the FHWA safety officers the test was set up to impact two of the sign post structures in the same run. The first structure was placed in the center line of the approaching vehicle at a 90-degree angle, while the second structure was placed behind the first at one vehicle length distance with a head-on (0-degree) position impacting the quarter point of the front of the vehicle on the left side (see Figure 35).

Test Level	Feature	Test Designation	Impact Conditions			Impact Point
			Vehicle	Nominal Speed (km/h)	Nominal Angle (θ)	
3	Work Zone Traffic Control Devices	3-71	820C	100	0	See Figure 35

The two selected sign post structures were tested with identical test setup. The selected crash scenario was repeated twice separately for each structure.

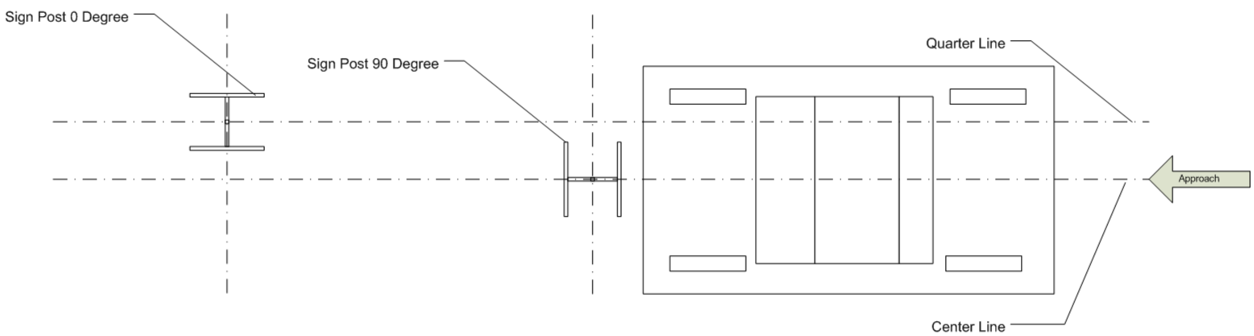


Figure 35. Crash layout.

6.1.3 Test Vehicles

For the tests, small vehicles conforming to the NCHRP 350 designation of 820C were used. The crash test vehicles, a 1994 Geo Metro and a 1997 Geo Metro (both 2-door hatchbacks), were accepted by FHWA for use in the crash tests.

6.1.4 Electronic Instrumentation

The sign posts were tested according to NCHRP 350, test 3-71, at a speed of 100 km/h (64 mi/h). The test vehicles were instrumented with a remotely activated brake system to provide braking for the crash vehicle after the crash occurred. This procedure ensures that after the collision of the crash vehicle with the two sign structures, the vehicle will not roll at high speed off the impact area and collide with other structures, and thus make the post-crash analysis impossible.

The remotely activated brake is triggered after the car has been collided with the intended sign structures and has rolled more than five car lengths after the last intended impact has occurred. This ensures that all high-speed data and other images collected during the crash will be valid for analysis and will depict vehicle behavior and trajectory unaltered by braking action.

6.1.5 Photo Instrumentation

6.1.5.1 Introduction

High-speed digital video recording was used according to the NCHRP 350 requirements to allow post-test analysis, including vehicle speed prior to impact, angle at impact, point-of-impact to the vehicle, and the exit speed for the vehicle. This video was used to analyze the performance of the sign post structures.

6.1.5.2 Setup

Three high-speed video imaging systems were set up to provide test coverage. In addition, two real-time video cameras were used to supplement the high-speed video coverage. Pre- and post-test conditions were documented with several high-resolution digital still picture cameras and one real-time video camera.

6.2 Test Conditions and Results

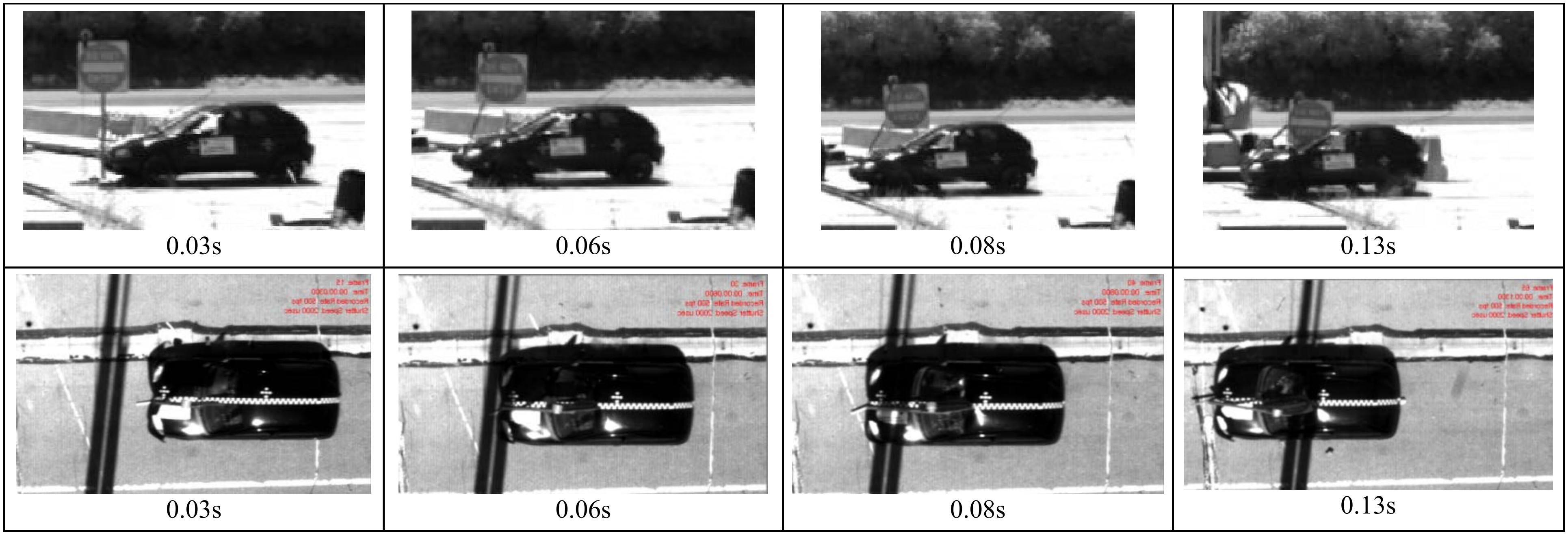
6.2.1 Impact Description/Vehicle Behavior

Based on video analysis of the test conducted on 18 June 2007, the approach speed at impact was 98.7 km/h (61.3 mi/h). The vehicle came into contact with the first sign post placed in the geometric centerline of the vehicle at a 90-degree angle (see Figure 35) at the designated critical impact point. The vertical post of the sign structure started to buckle on impact. The middle portion of the vehicle's front bumper was bent, as was the front hood of the vehicle. On the impact the lower bolt securing the sign panel onto the sign post was sheared while the upper bolt remained intact. The consequence of the rapidly buckling sign post together with the sign panel able to rotate around the upper fixing bolt was that during the impact the sign panel came into contact with the front portion of the vehicle's roof and the geometric middle of the front windshield. The very high stiffness of the sign panel perpendicular to its plane caused it to act as a very high speed stiff and sharp object, in effect slicing into the top front portion of the vehicle roof and the front windshield. The event can be observed in Figure 36.

Figure 36. Sign panel penetration.

The second sign post came into contact with the vehicle at the right side quarter point of the vehicle and buckled also. This post, since it was placed with the panel facing the approaching vehicle, did not cause damage to the windshield or roof, as the sign panel did not come into contact with the vehicle. Test results are summarized in

Figure 37.



General Information

Test Agency	Pennsylvania Transportation Institute
Test No.	PennDOT 01
Date	18 June 2007

Test Article

Type	PennDOT – X Portable Sign Post

Test Vehicle

Type	820C
Designation	
Model	Geo Metro
Mass (Kg)	
Test Inertial	1885 lbs
Gross Static	1760 lbs

Impact Conditions

Speed (km/h)	98.7 km/h (61.3 mi/h)
Angle (deg)	0 and 90 degrees

Test Article Deflections (m)

Dynamic	See Evaluation and Assessment of Test Results
Permanent	See Evaluation and Assessment of Test Results

Figure 37. Test summary sheet.

6.2.2 Evaluation and Assessment of Test Results

6.2.2.1 Test Article Damage

Sign and vehicle crash performance was visually addressed through crash and post-crash images. In addition, crash performance from LS-DYNA simulations and full-scale crash testing were compared and assessed following evaluation criteria from NHCRP 350. Post-crash performance photographs are shown in Figure 38. Figure 38 shows that the 0-degree X-base structure was severely deformed approximately 43.2 cm (17 inches) in height above the ground, which was approximately equal to the front bumper height. It can be seen that the horizontal legs were also severely deformed at their connection joint. Figure 38 also shows that the 90-degree structure was severely deformed at approximately the same location. In particular, for the 90-degree structure the sign panel was totally separated from the vertical post after the two connection bolts failed at impact. Figure 39 shows that the 820C vehicle was also extensively damaged, with the front windshield and bumper fractured and the roof severely deformed.

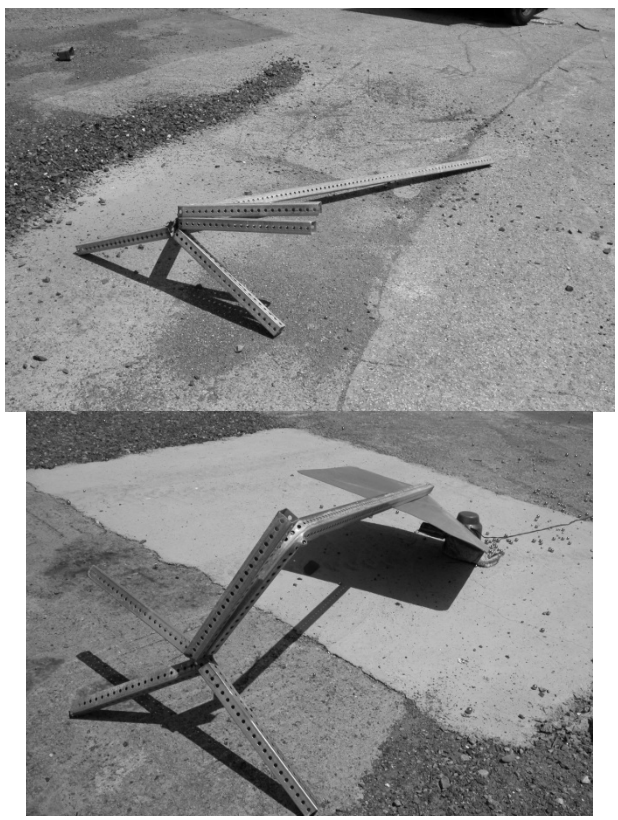


Figure 38. Crash performances for X-base sign structures.

Figure 39. Post-test photographs of test vehicle.

Actual crash performance was well predicted from the LS-DYNA simulations, both qualitatively and quantitatively. Figure 10 contains sequential snapshots of the impact from the 90-degree, full-scale test and compares them qualitatively to the LS-DYNA model. Good correlation is observed, especially at the sign connections to the post that were modeled using the constrained spot welds. The lower bolted connection in the actual sign failed at impact (0.03 sec) while the upper bolt did not fail until 0.13 sec, instances that were accurately predicted with the LS-DYNA simulation. This connection failure sequence rotated the sign panel clockwise and caused it to hit the windshield and vehicle roof, resulting in most of the damage.

6.2.3 Conclusion

The crash testing performance of two X-base temporary sign support structures was examined using full-scale crash testing and performance acceptability according to NCHRP 350 criteria. Results showed that the X-base structures oriented both parallel and perpendicular to the vehicle satisfied the NCHRP Flail-Safe Model requirements with respect to occupant velocities and accelerations/decelerations. The calculated occupant risk factors, together with the required limitations from the NCHRP recommendations, are collected in Table 10.

Table 10. Aggregate occupant risk factors and NCHRP evaluation limits.

Sign Post Name	Vehicle Speed	Aggregate Occupant Impact Velocity, m/s (ft/s)	Occupant Ridedown Acceleration, m/s^2 (ft/s^2)
0 degree	98.7km/hr (61.3mph)	1.77 (5.81)	3.30 (10.83)
90 degree	98.7km/hr (61.3mph)	1.79 (5.87)	3.61 (11.81)
NCHRP Evaluation Limits		**Aggregate Occupant Impact Velocity, m/s (ft/s)**	**Occupant Ridedown Acceleration, m/s^2 (ft/s^2)**
Preferred		3(9.84)	5(16.4)
Maximum		15(49.2)	20(164.0)

However, the X-base structure oriented parallel to the vehicle did not satisfactorily meet NCHRP 350 evaluation criteria, since penetration into the occupant compartment occurred.

The crashed sign post structure was analyzed after the crash to discover the cause of the failure of the crash and to be able to make the necessary changes to the sign post design. The post-crash investigation revealed that two major components of the actually tested sign post structure differed from the given dimensions for the FEA simulation. One important difference was the thickness of the sign panel. The actual thickness of the crash tested sign panel was 0.22 inches (5.54 mm), thus almost twice the thickness given in the preparation phase. This caused the sign panel to be a little bit heavier and almost an order of magnitude more rigid in its own plane. The safety sign attached onto the top edge of the sign panel was, instead of 4 lb 8 oz, less than 2 lb in weight. These two changes caused a structure with overall inertia and weight to be nearly identical to the one numerically investigated, but, in terms of rigidity, almost an order of magnitude stronger. These differences caused the panel to be able to penetrate the car's passenger compartment.

6.3 Modified Sign Post Structure

Based upon the analysis of the full-scale crash test results and the investigation of the sign post structure, a simple modification was suggested that would ensure the successful crash performance of the designed sign post structure. The basic idea behind the proposed modification is that the actual sign panel proved to have inertial properties upon a high-speed impact sufficient to shear off the fastening bolts and become separated from the main sign post structure at a very early stage of the impact. This, in turn, would cause the crash vehicle to pass under the separated sign panel unharmed while the vehicle would push the rest of structure. The main pole of the sign post would still buckle, but without the substantial inertial forces exerted by the sign panel this buckling process would be somewhat limited; therefore, even if the main pole would come into contact with the car's body or windshield, it would not carry the necessary inertial forces to damage either of them to an unacceptable level.

In order to achieve these desired effects two candidate materials were identified as satisfying the material property requirements and with commercially available screws manufactured from them:

- **Nylon 6/6:** This nonconductive material resists chemicals and solvents, except mineral acids. Temperature range is -40 °F to +185 °F. Rockwell hardness is R105. Minimum tensile strength is 11,000 psi.
- **PVC:** Provides excellent corrosion resistance against weak acids, alkalis, and alcohols. Withstands temperatures up to 120 °F. Rockwell hardness is R70. Minimum tensile strength is 5,000 psi.

The revision process has suggested that using these bolts would yield a design where, even with the different weight and inertial properties of the aluminum sign and light assembly, the fastening bolts would shear on impact.

Out of these two candidate materials, the nylon bolts were chosen by the design team because of the materials' superior performance in adverse temperatures, wider acceptable temperature range, resistance to commonly used chemicals in the construction environment, and better tensile strength properties.

All other parameters of the design structure with regard to materials, dimensions and manufacturing processes were retained.

6.4 FEA Analysis of Modified Sign Structure

Numerical crash-testing was performed using LS-DYNA for each of the two PennDOT structures, the "H" footed and the "X" footed structures with the modified properties for the fastening bolts. Each sign structure was subjected to virtual crash tests identical to those performed in pre-crash numerical modeling, using a Geo Metro vehicle (a standard 820C vehicle according to NCHRP 350 designation) with the sign oriented facing the vehicle and at 90º with respect to the vehicle. These tests were run with the top of the sign placed at 96 inches (2,438 mm) from the ground.

6.4.1 Model Construction and Scenario

The FEA analysis of the modified sign post structure fully utilized the built FEA crash scenarios completed for the original numerical modeling and virtual crash analysis. For full details on sign structure construction, vehicle model construction and crash scenario modeling, please refer to section 4.1, "Model Construction."

6.4.2 Results

Since the actual dimensions, materials and construction of the sign posts were kept identical to the original structures the inertial and kinetic properties of the crash with regard to vehicle deceleration, vehicle trajectory and occupant aggregate risk factors caused by vehicle dynamics remained statistically the same. For vehicle critical speeds, Aggregate Occupant Impact Velocity and Occupant Ridedown Acceleration, please see section 4.3, "Examination of Analysis Results."

The only substantial difference expected from the analysis of the modified sign post structures is that upon impact, the sign panel attached to the sign post will shear free from the pole and the crash vehicle will roll under the panel without being harmed by it.

The results from the FEA analysis for the four scenarios are depicted in Figure 40, Figure 41, Figure 42, and Figure 43.

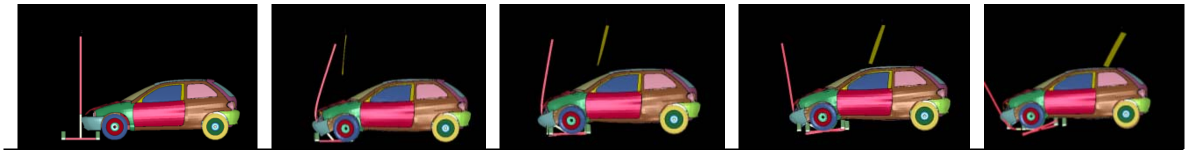


Figure 40. Crash behavior of "H" footed sign at 0 degrees.

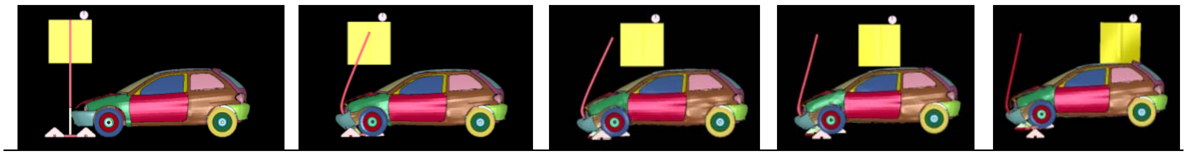


Figure 41. Crash behavior of "H" footed sign at 90 degrees.

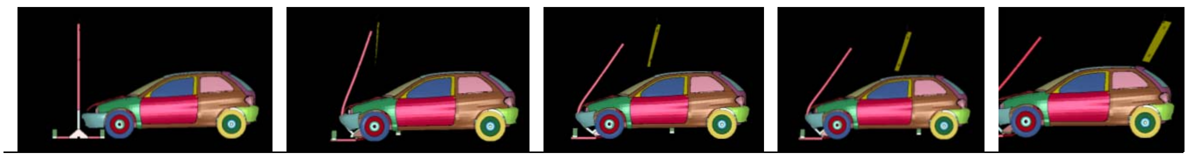


Figure 42. Crash behavior of "X" footed sign at 0 degrees.

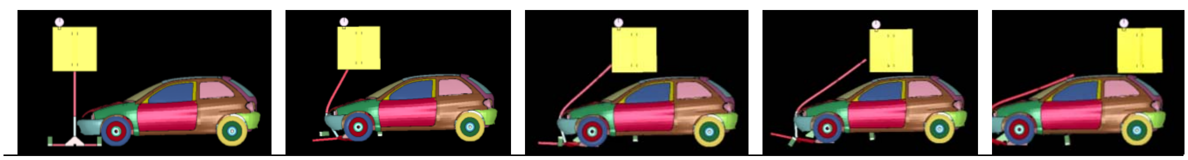


Figure 43. Crash behavior of "X" footed sign at 90 degrees.

In all four virtual crash scenarios for both structures (the "H" shaped foot and the "X" shaped foot structures), the virtual crash simulation indicated the expected crash behavior of the structure. In all four cases the aluminum sign panels have separated from the vertical sign post upon impact. The new fastening bolts from the nylon material have failed, as expected.

In the 0-degree crash setup, where the sign posts were facing the approaching crash vehicle, the tensional forces created by the impact acceleration and inertial forces of the solid aluminum sign panel exceeded the tensile strength of the new bolt material and the screws on both the upper and lower fastening points of the sign panel broke. The sign panel became separated from the rest of the sign structure and, in its free fall to the ground, cleared the vehicle moving underneath. The vertical sign post, free from the relatively high inertial forces that would have been caused by a non-separated sign panel, showed buckling, but with a much slower rate, and the damage to the front bumper and hood of the vehicle was also reduced substantially.

In the 90-degree crash setup, where the sign posts were turned parallel to the approaching crash vehicle, the shear forces created by the impact acceleration and inertial forces of the solid aluminum sign panel exceeded the shear strength of the new bolt material and the screws on both the upper and lower fastening points of the sign panel broke. The sign panel became separated from the rest of the sign structure and, in its free fall to the ground, cleared the vehicle moving underneath. The vertical sign post, free from the relatively high inertial forces that would have been caused by a non-separated sign panel, showed buckling, but with a much slower rate, and the damage to the front bumper and hood of the vehicle was also reduced substantially.

Based upon the simulation results that verified the expected behavior of the sign panel with the modified fastening elements holding the sign panel, the full-scale crash of the modified structure became justified.

6.5 Second Full-Scale Crash Test of H-Base Sign Post

The second crash test conducted on the modified sign post structure was an exact replica of the first crash test. The setup and layout of the selected NCHRP test, speed, selected orientation and geometrical layout were selected to mirror the original setup and to deliver a solid foundation for the crash test report to obtain FHWA approval for the modified structures. The crash tested portable sign was the modified "**PennDOT H-Base Portable Sign.**" The crash test was performed using the second crash vehicle prepared earlier in the project. The vehicle was also Geo Metro 2-door hatchback, but a 1997 model instead of the previous 1994 model. The vehicle was accepted by FHWA as a valid crash vehicle prior to the crash test.

6.5.1 Test Conditions and Results

6.5.1.1 Impact Description/Vehicle Behavior

Based on video analysis of the test conducted on 28 September 2007, the approach speed at impact was 100.4 km/h (62.4 mi/h). The vehicle came into contact with the first sign post placed in the left quarter point of the approaching vehicle at a 90-degree angle (see Figure 44) 2.5 inches to the right of the designated critical impact point, the left quarter point. The vertical post of the sign structure started to buckle on impact, while the solid aluminum sign panel separated from the sign post according to expectations and according to the prediction from the finite element analysis. The left quarter portion of the vehicle's front bumper was bent as was the front hood of the vehicle, again, according to expectations. The consequence of the expected separation of the sign panel was that, according to prediction, the sign panel cleared the top of the vehicle and did not come into contact with the any part of the vehicle. The event can be observed in Figure 36.

Figure 44. Impact point of 90-degree sign post.

The second sign post came into contact with the vehicle 2.5 inches to the right of the right-side quarter point of the vehicle, and buckled also. Again, the expected separation of the sign panel from the vertical sign post occurred on impact at the exactly predicted moment. The consequence of the expected separation of the sign panel was that, according to prediction, the sign panel cleared the top of the vehicle and did not come into contact with the any part of the vehicle. This post, since it was placed with the panel facing the approaching vehicle, did not cause damage to the windshield and roof, since the sign panel did not come into contact with the vehicle.

The behavior of both the 90-degree and 0-degree placed sign panels can be observed in Figure 45, where the panel crashed into first (the 90-degree panel) is already falling behind the traveling vehicle, while the second sign panel (the 0-degree panel) is above the vehicle's right side over the roof of the vehicle.

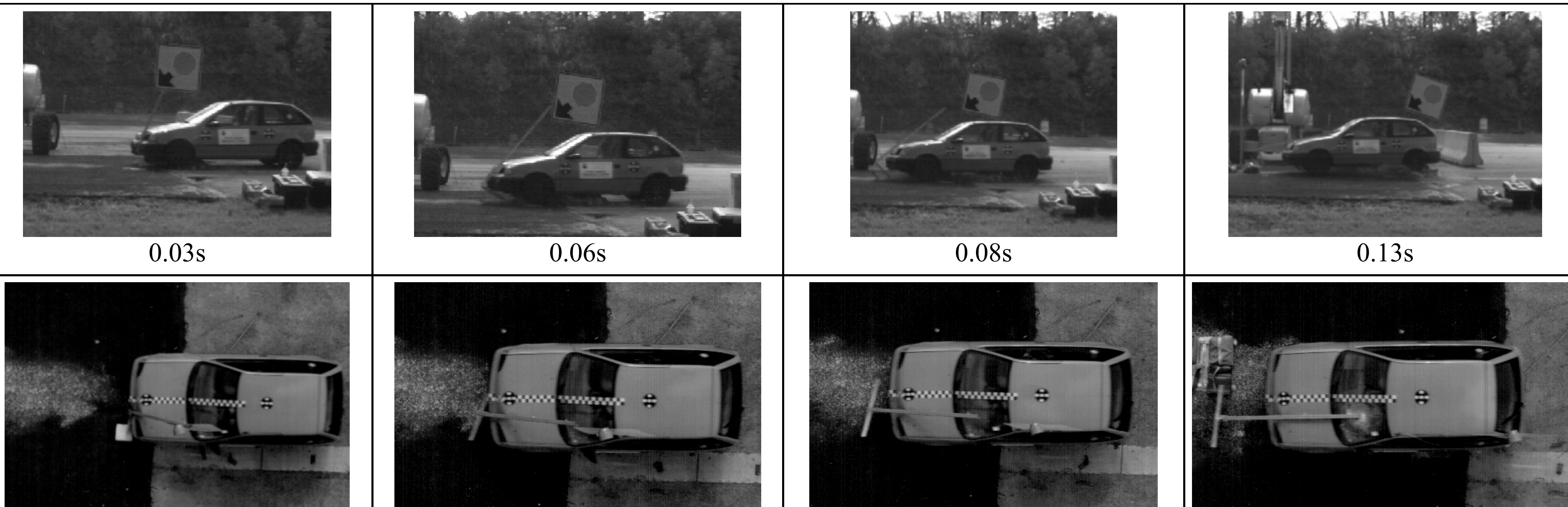
Figure 45. Sign panel separation and behavior.

The same behavior can be observed from the side view of the crash in Figure 46.

Figure 46. Side view of panel behavior.

Test results are summarized in

Figure 47 and in Figure 48.



0.03s | 0.06s | 0.08s | 0.13s

0.03s | 0.06s | 0.08s | 0.13s

General Information

Test Agency	Pennsylvania Transportation Institute
Test No.	PennDOT 02
Date	28 September 2007

Test Article

Type	PennDOT – H Portable Sign Post

Test Vehicle

Type	820C
Designation	
Model	Geo Metro
Mass (Kg)	
Test Inertial	1945 lbs (882 kg)
Gross Static	1780 lbs (807 kg)

Impact Conditions

Speed (km/h)	100.4 km/h (62.4 mi/h)
Angle (deg)	90 degrees

Test Article Deflections (m)

Dynamic	See Evaluation and Assessment of Test Results
Permanent	See Evaluation and Assessment of Test Results

Figure 47. Test summary sheet 90-degree sign post.

0.03s

0.06s

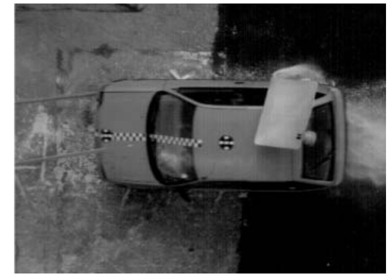
0.08s

0.13s

0.03s

0.06s

0.08s



0.13s

General Information

Test Agency .... Pennsylvania Transportation Institute
Test No. .... PennDOT 02
Date .... 28 September 2007

Test Article

Type .... PennDOT – H Portable Sign Post
....

Test Vehicle

Type 820C
Designation............
Model .... Geo Metro
Mass (Kg)
Test Inertial .... 1945 lbs (882 kg)
Gross Static .... 1780 lbs (807 kg)

Impact Conditions

Speed (km/h)............ 100.4 km/h (62.4 mi/h)
Angle (deg) .... 0 degrees

Test Article Deflections (m)

Dynamic .... See Evaluation and Assessment of Test Results
Permanent .... See Evaluation and Assessment of Test Results

Figure 48. Test summary sheet 0-degree sign post.

6.5.1.2 Evaluation and Assessment of Test Results

6.5.1.2.1 Test Article Damage and Vehicle Damage

Sign and vehicle crash performance were visually addressed through crash and post-crash images. In addition, crash performance from LS-DYNA simulations and full-scale crash testing were compared and assessed following evaluation criteria from NHCRP 350.

Post-crash performance photographs are shown in Figure 49. The pictures in Figure 49 show that both the 0- and 90-degree H-base structures were severely deformed approximately 43 cm (17 in) in height above the ground, which was approximately equal to the front bumper height. It can be seen that horizontal legs were also severely deformed at their connection joint. The deformations of the two signs were very similar. Both sign posts buckled at the point where the bumper of the crash vehicle came into contact with the vertical poles. One of the signs bent to almost 90 degrees, while the other suffered a similar but somewhat smaller deformation. Both of the signs show that the base structure, which carried all of the weight from the stabilizing sand bags, became fractured and separated from the sign posts. Figure 50 shows that the 820C vehicle was damaged mildly, according to expectations. The front bumper on both sides near the quarter points suffered small dents, and the hood of the vehicle was dented by the buckling sign posts to a small degree.

Figure 49. Crash performances for H-base sign structures.

Figure 50. Post-test photograph of test vehicle.

Actual crash performance was very well predicted from the LS-DYNA simulations, both qualitatively and quantitatively.

6.5.1.3 Conclusion

The crash testing performance of two H-base temporary sign support structures was examined using full-scale crash testing and performance acceptability according to NCHRP 350 criteria. Results showed that the H-base structures oriented both parallel and perpendicular to the vehicle satisfied the NCHRP Flail-Safe Model requirements with respect to occupant velocities and accelerations/decelerations. The calculated occupant risk factors, together with the required limitations from the NCHRP recommendations, are collected in Table 11.

Table 11. Aggregate occupant risk factors and NCHRP evaluation limits.

Sign Post Name	Vehicle Speed	Aggregate Occupant Impact Velocity, m/s (ft/s)	Occupant Ridedown Acceleration, m/s^2 (ft/s^2)
0 degree	100.4km/hr (62.4mph)	1.93 (6.33)	6.72 (22.05)
90 degree	100.4km/hr (62.4mph)	2.15 (7.05)	7.56 (24.8)
NCHRP Evaluation Limits		**Aggregate Occupant Impact Velocity, m/s (ft/s)**	**Occupant Ridedown Acceleration, m/s^2 (ft/s^2)**
Preferred		3(9.84)	5(16.4)
Maximum		15(49.2)	20(164.0)

6.5.1.4 Evaluation and performance expectation of "X-Base" sign post

The FHWA crash rating approval procedure for portable work zone devices allows that modifications to already crash-tested structures can be evaluated using best engineering practices. The design review of the modified structure should show with high confidence that the modifications will not cause the modified device to behave significantly differently in a similar crash situation to that of the already tested device. It was the agreed plan that, using the actual crash results from the "H-base" sign post structure and the performed FEA analysis of both structures, a request for approval of the "X-base" sign post be filed upon the received approval of the "H-base" sign post.

Since the actual dimensions, materials and construction of both sign posts were kept identical, the inertial and kinetic properties of the crash with regard to vehicle deceleration, vehicle trajectory and occupant aggregate risk factors caused by vehicle dynamics remained statistically the same. The performed FEA analysis that was validated by the actual crash test to a very high level of confidence provides a very solid platform for this request. The FEA analysis of the "X-base" structure (see section 6.4, "FEA Analysis of Modified Sign Structure") verifies that the different shape of the standing base of the sign post does not adversely affect the crash performance of the device, and therefore a request letter with accompanying engineering drawings will be submitted to FHWA to request the crashworthiness approval of the "X-base" sign post upon the received approval of the "H-base" structure.

7 Report to FHWA

Please see the document of the FHWA report in “20 APPENDIX L – FHWA REPORT.”

8 REFERENCES

1 Ross, H. E., Jr., Sicking, D. L. and Zimmer, R. A. (1993), *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Highway Research Program Report 350, Texas Transportation Institute, Texas A&M University System, College Station, TX.

2 U.S. Department of Transportation (1998), "Crash Tested Work Zone Traffic Control Devices," Memorandum, Office of Engineering, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., August 28, 1998.

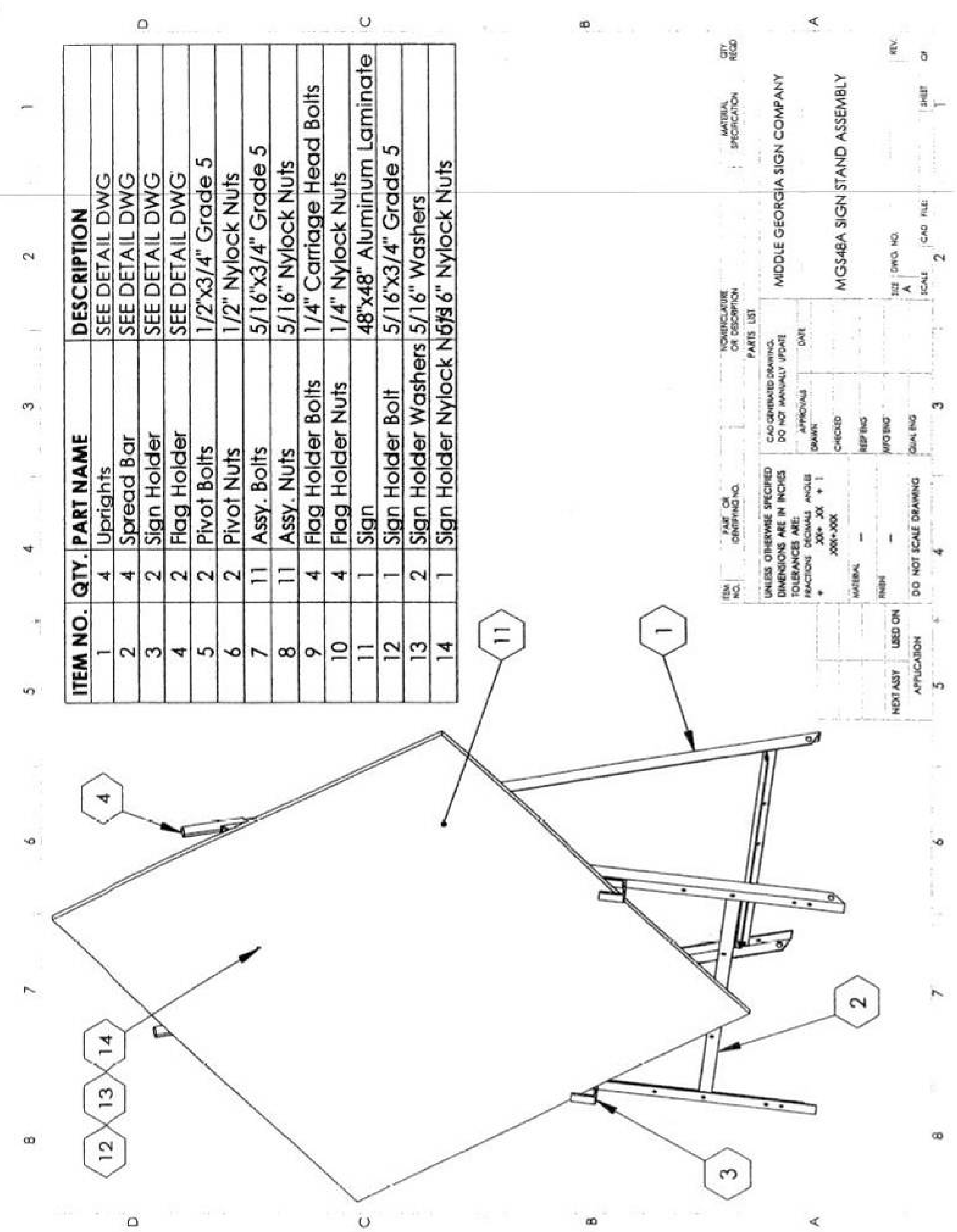
3 U.S. Department of Transportation (1997), "Identifying Acceptable Highway Safety Features," Memorandum, Office of Engineering, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., July 25, 1997.

4 Internet address: http://safety.fhwa.dot.gov/roadway_dept/road_hardware/listing.cfm?code=signs

5 Internet address: http://safety.fhwa.dot.gov/roadway_dept/road_hardware/listing.cfm?code=workzone

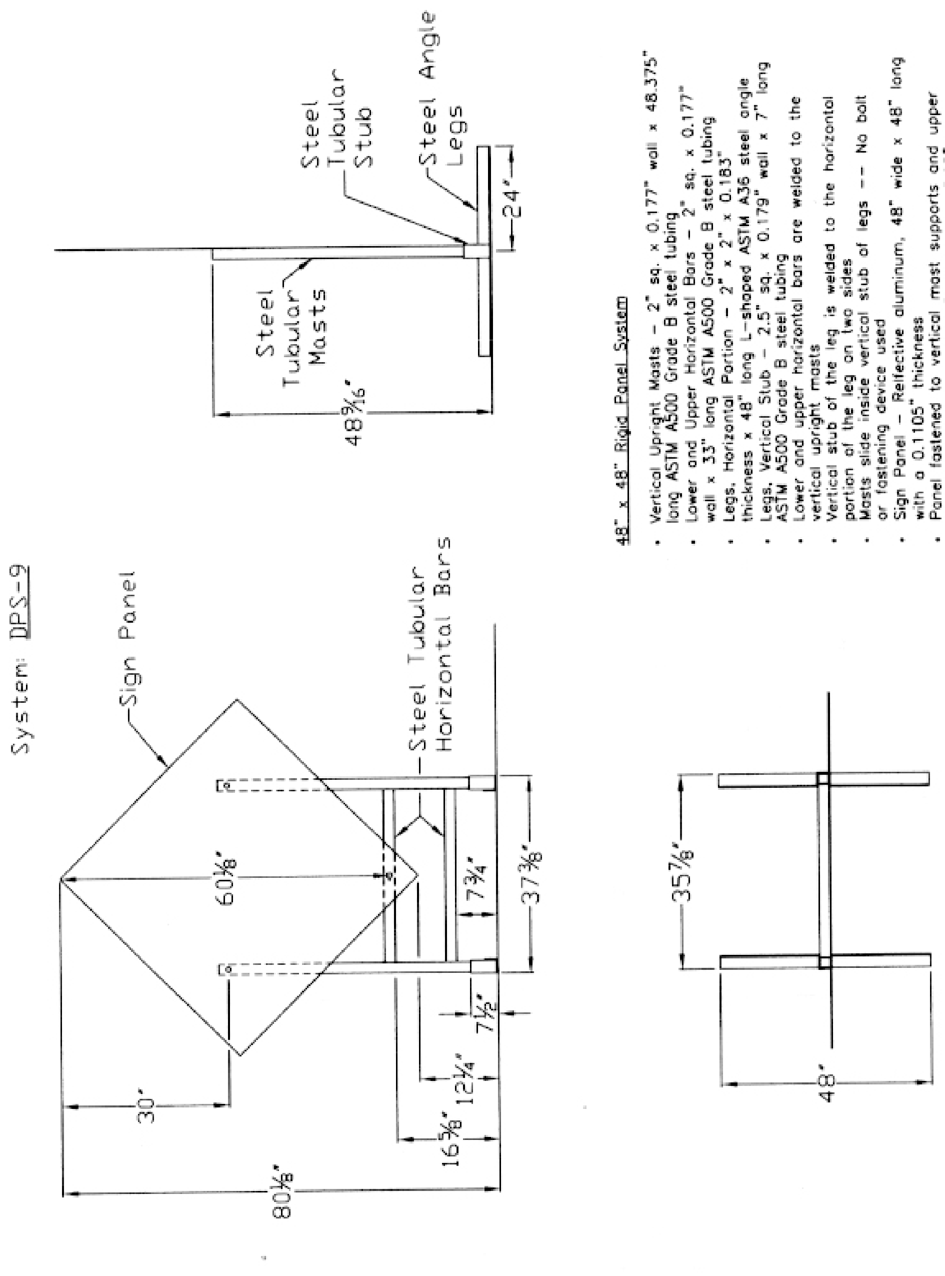
6 Conversation, N. Artimovich, FHWA Office of Safety Design, April 4, 2007.

9 APPENDIX A – Selected Easel Framed Structure (E)



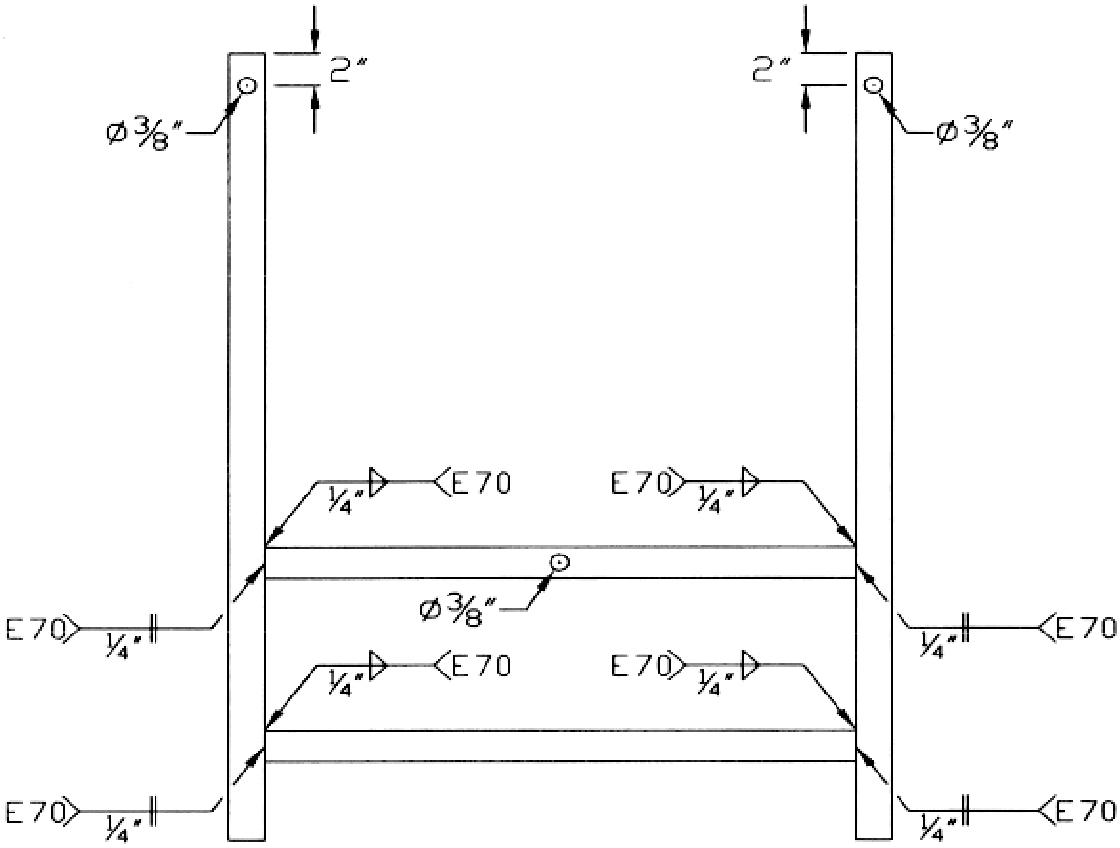
ITEM NO.	QTY.	PART NAME	DESCRIPTION
1	4	Uprights	SEE DETAIL DWG
2	4	Spread Bar	SEE DETAIL DWG
3	2	Sign Holder	SEE DETAIL DWG
4	2	Flag Holder	SEE DETAIL DWG
5	2	Pivot Bolts	1/2"x3/4" Grade 5
6	2	Pivot Nuts	1/2" Nylock Nuts
7	11	Assy. Bolts	5/16"x3/4" Grade 5
8	11	Assy. Nuts	5/16" Nylock Nuts
9	4	Flag Holder Bolts	1/4" Carriage Head Bolts
10	4	Flag Holder Nuts	1/4" Nylock Nuts
11	1	Sign	48"x48" Aluminum Laminate
12	1	Sign Holder Bolt	5/16"x3/4" Grade 5
13	2	Sign Holder Washers	5/16" Washers
14	1	Sign Holder Nylock Nuts	5/16" Nylock Nuts

10 APPENDIX B – Selected H-Shaped Base Structures (H)

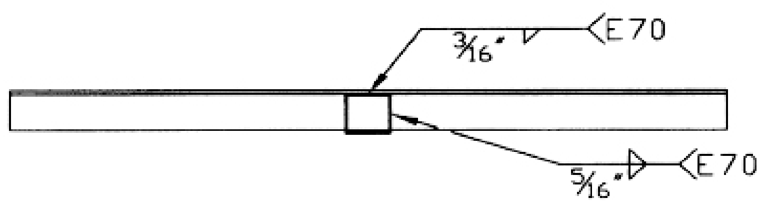


System: DPS-9

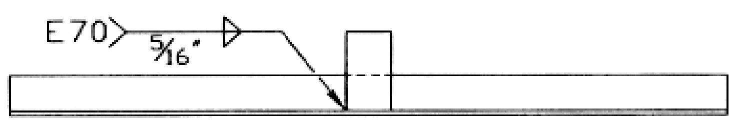
Front View
(Masts and Horizontal Bars)



Top View (Legs)



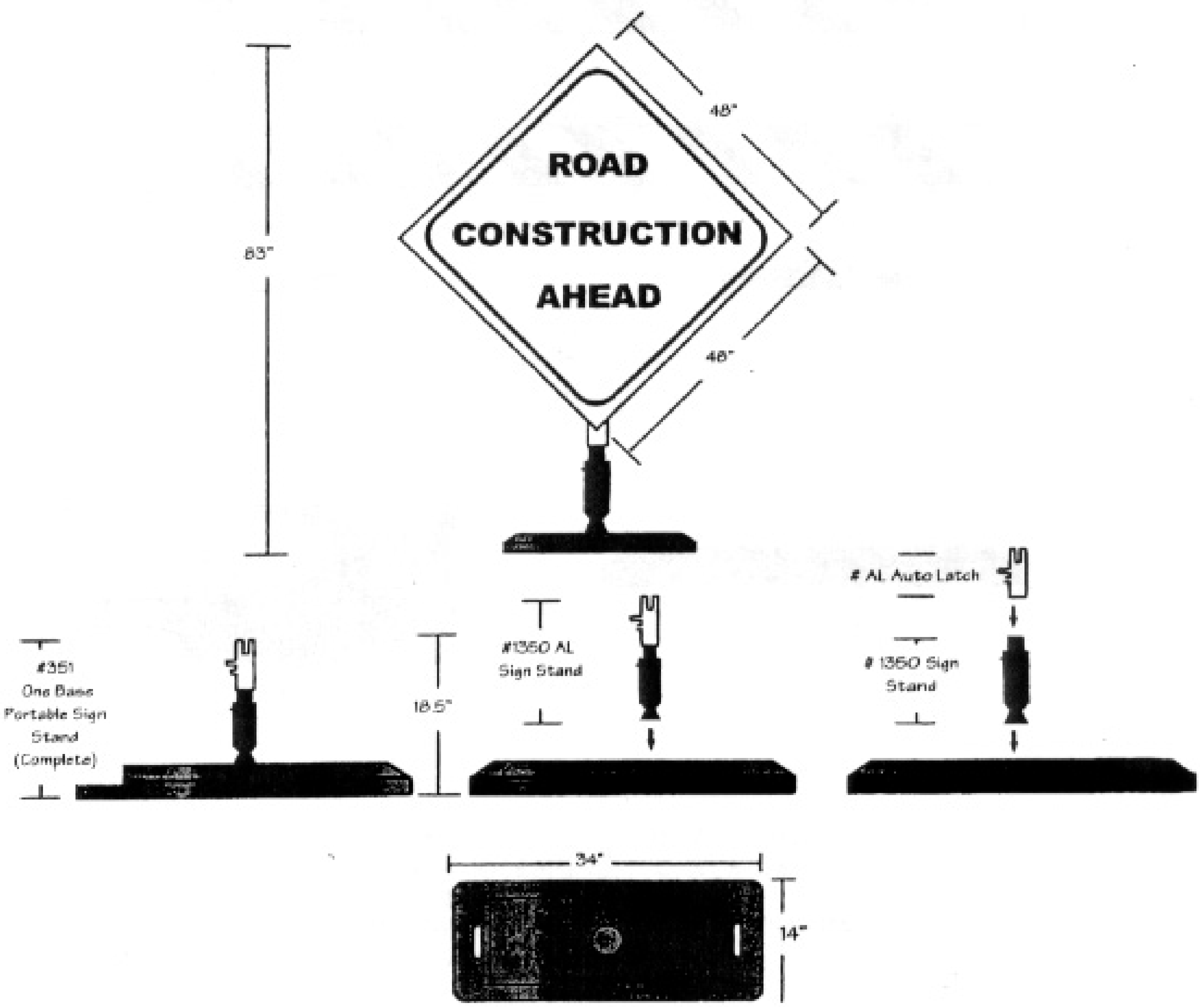
Side View (Legs)



11 APPENDIX C – Selected Rectangular Base Structure (R)

Part #351
One Base Portable Sign Stand with Auto Latch Bracket

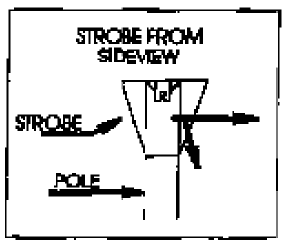
Component Parts Breakdown

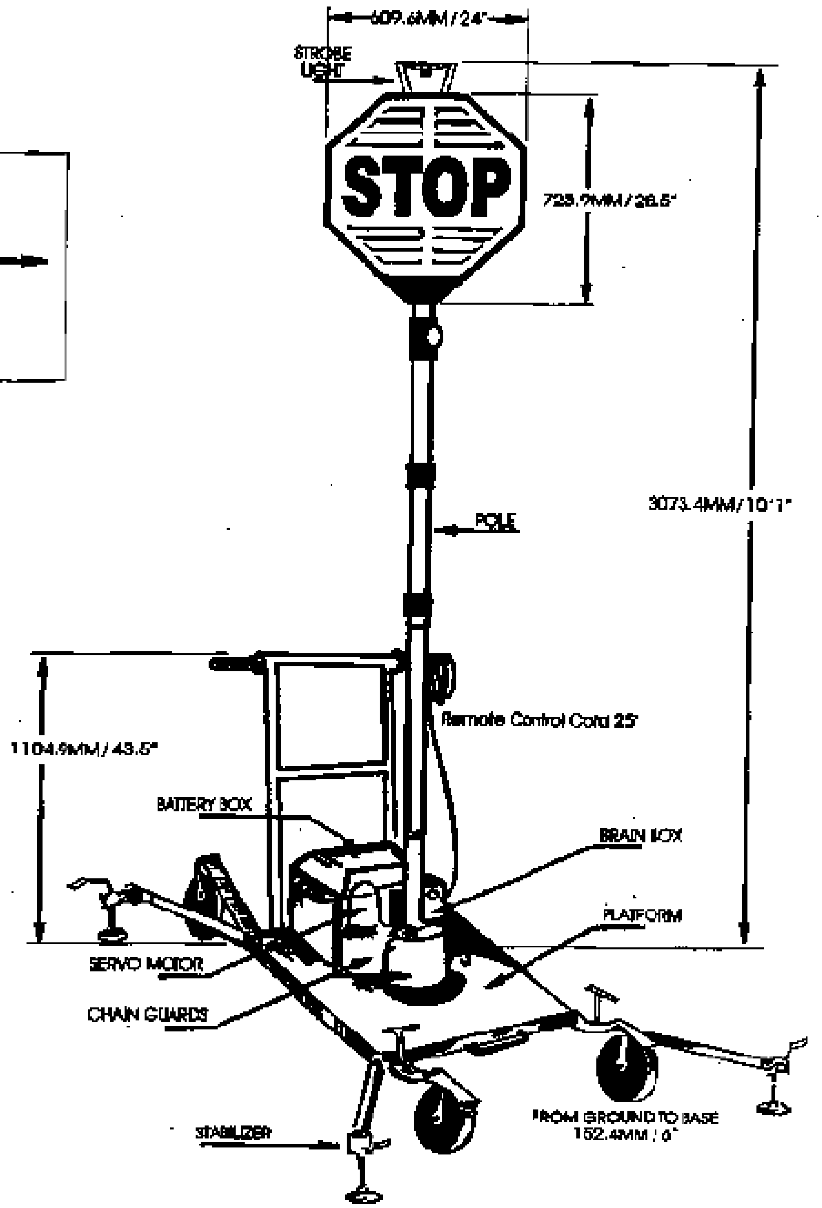


IMPACT RECOVERY SYSTEMS®, INC.
246 W. JOSEPHINE, P.O. BOX 12637
SAN ANTONIO, TX 78212
(210) 736-4IRS (4477) FAX (210) 734-6448
www.impactrecovery.com

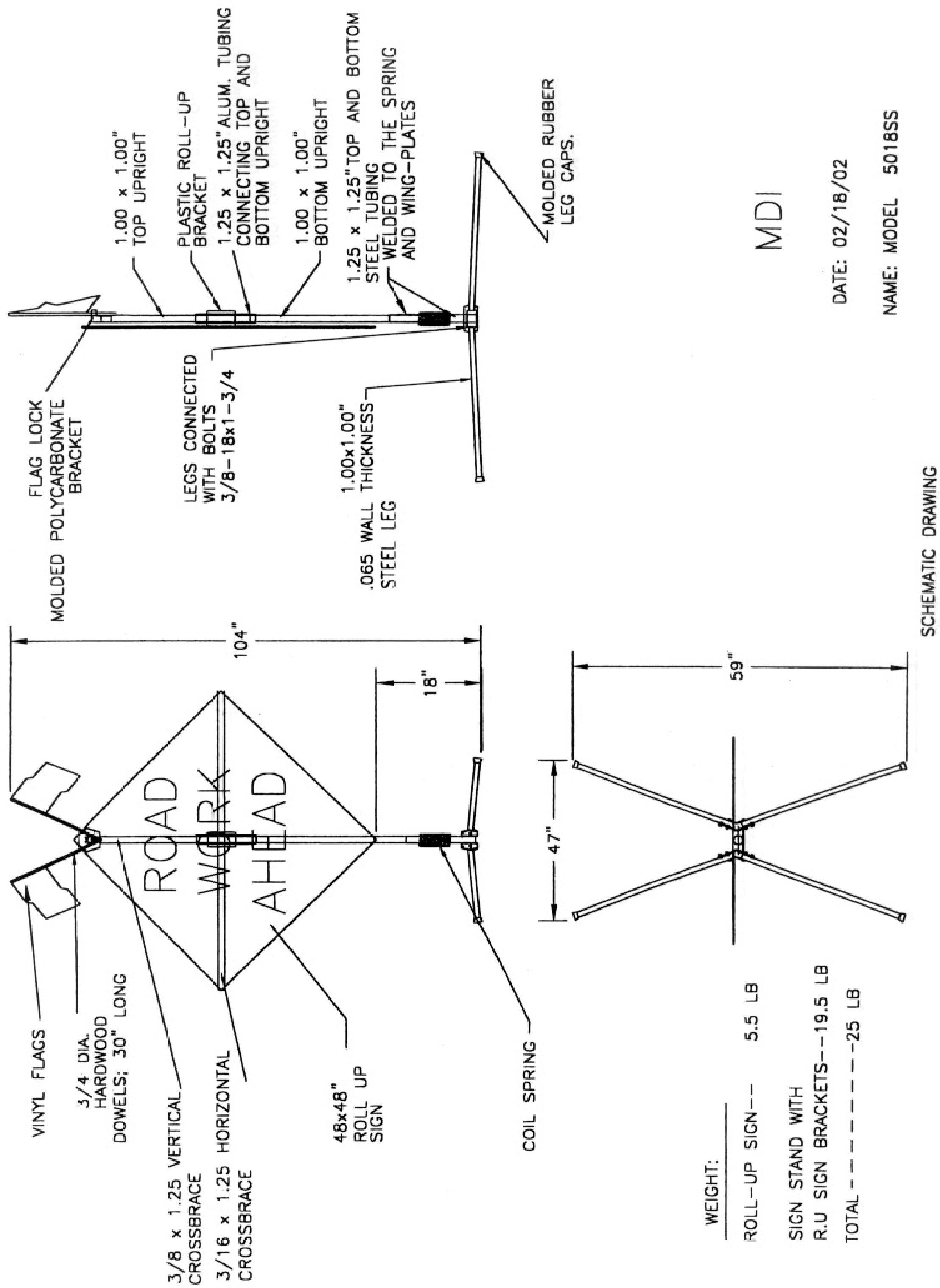
June 2001

12 APPENDIX D – Selected Wheeled Base Structure (W)

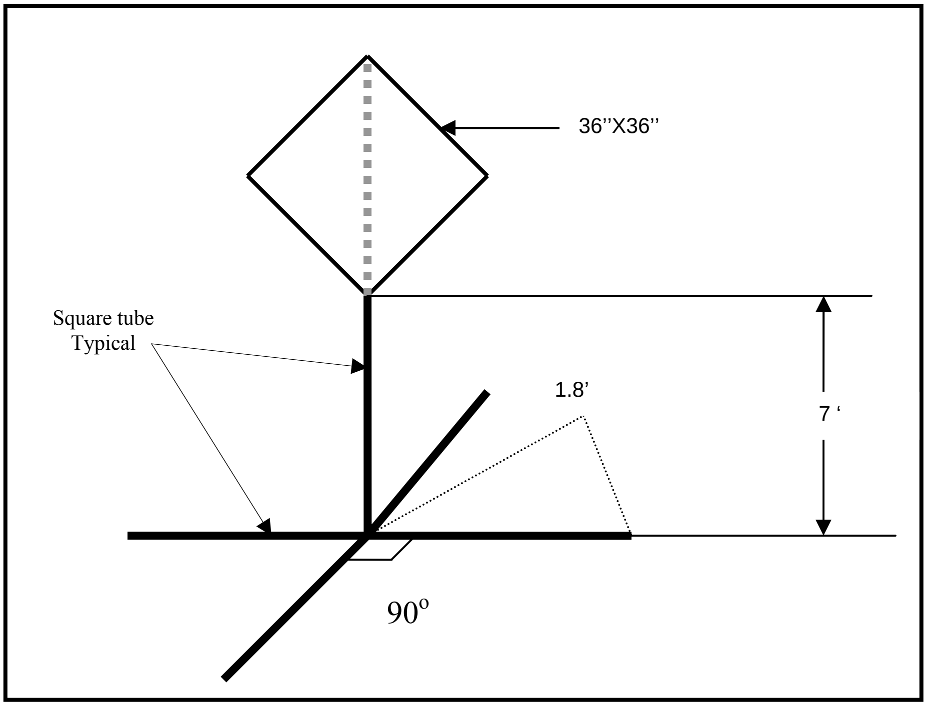




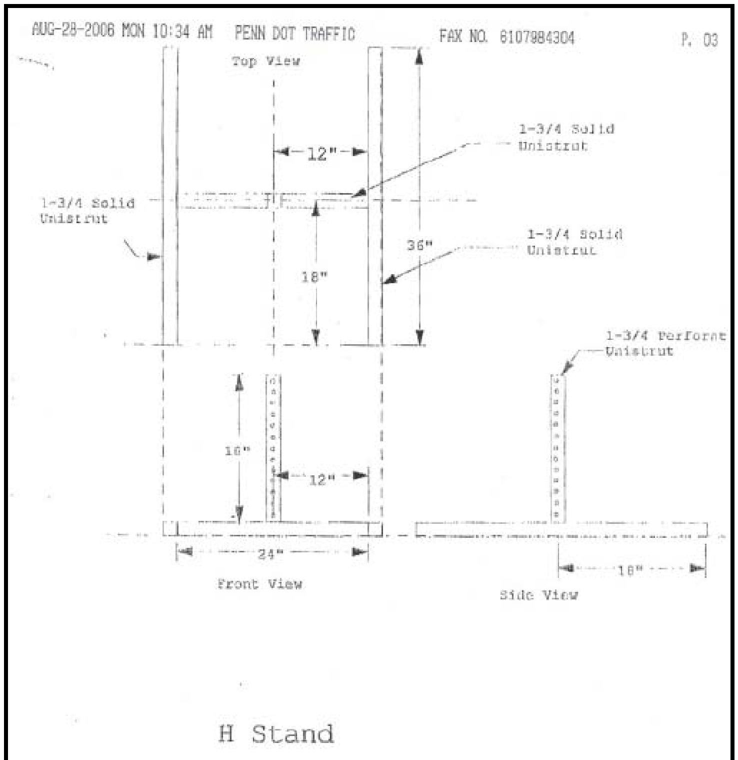
13 APPENDIX E – Selected X-Shaped Base Structure (X)

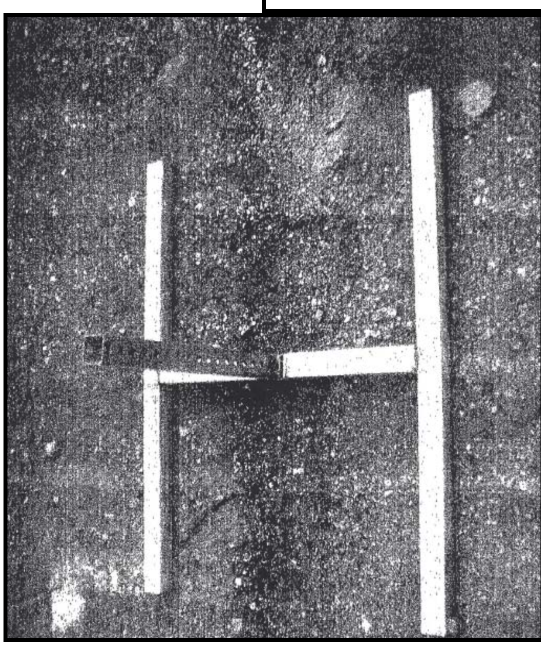


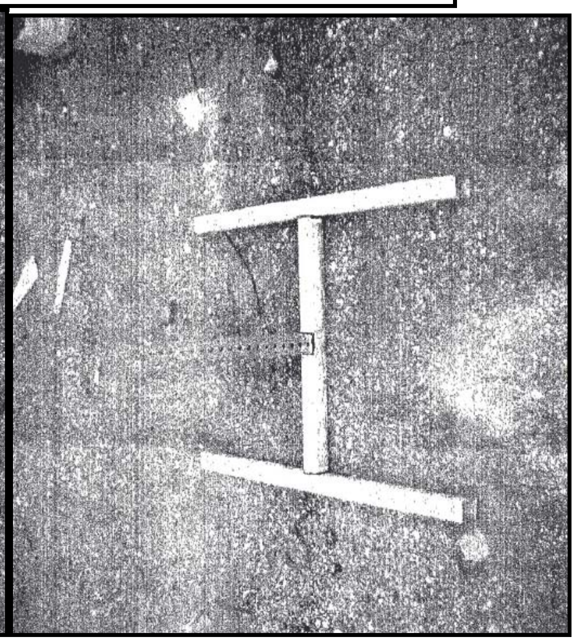
14 APPENDIX F - Pennsylvania structure – X-shape



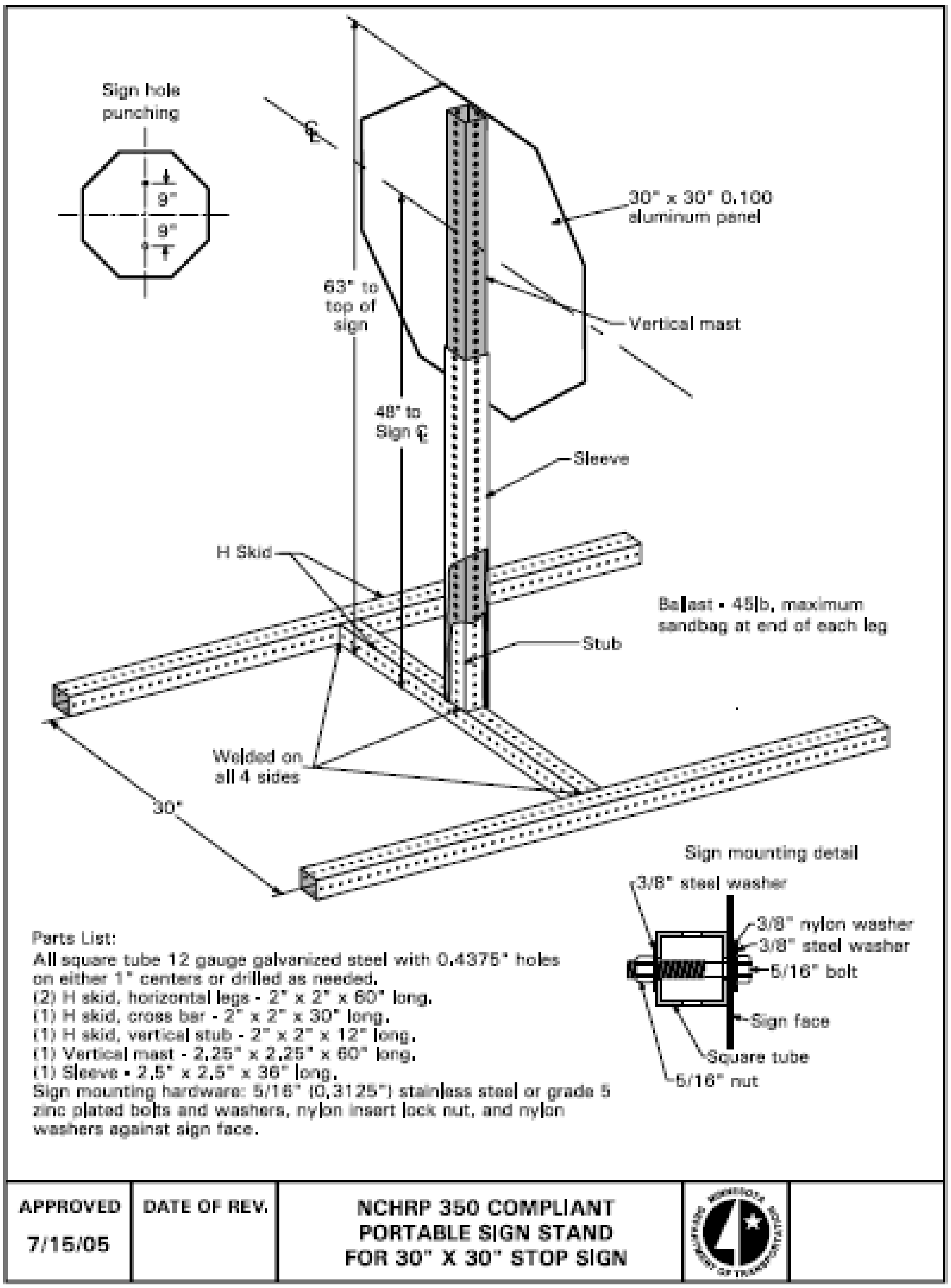
15 APPENDIX G - Pennsylvania structure – H-shape



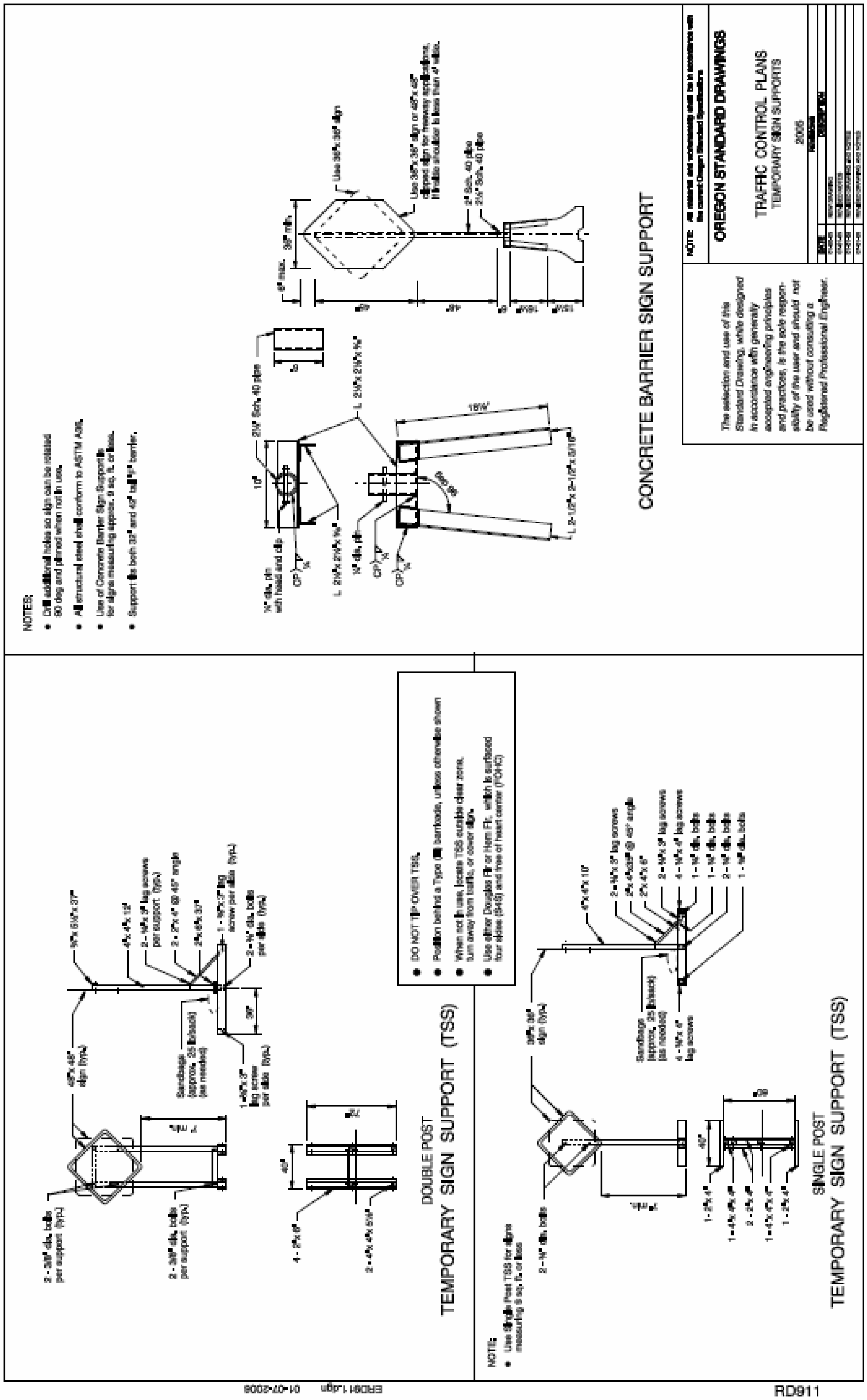




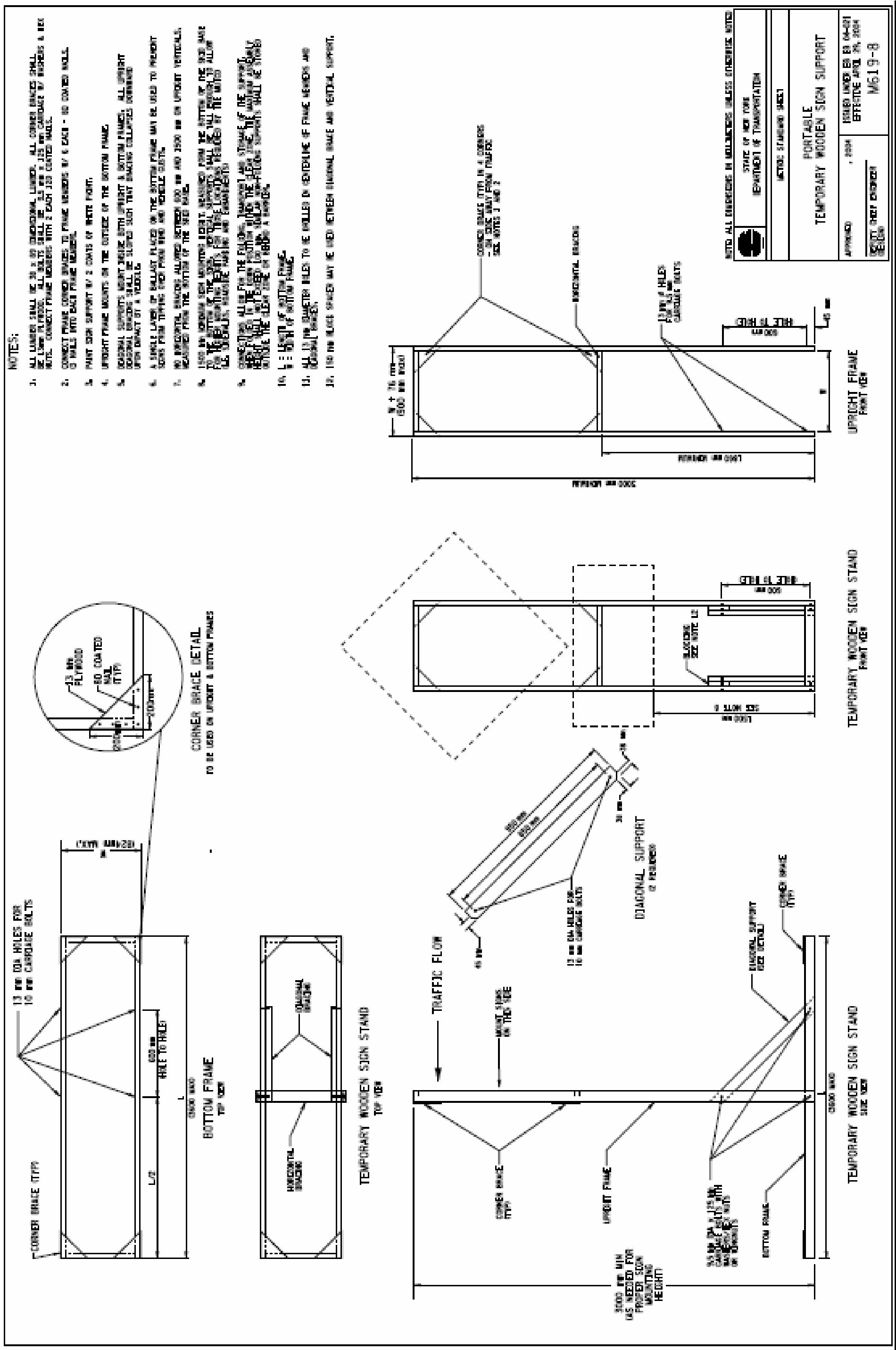
16 APPENDIX H - Minnesota structure



17 APPENDIX I - Oregon structure



18 APPENDIX J - New York structure



19 APPENDIX K - Test Vehicle Equipment and Guidance Methods

The Pennsylvania Transportation Institute (PTI) facility uses a rigid rail to provide vehicle guidance, a reverse towing system to accelerate the vehicle to the required test speed, and a release mechanism that disconnects the tow cable prior to impact (see Figure 51). The guidance systems currently being used by crash-testing facilities can be generally categorized into three types: remote control guidance, flexible cable guidance, and rigid rail guidance. Remote (radio) control systems have been used with limited success, largely due to problems caused by delays in reaction time and response of the control system and operator. Cable guidance systems are attractive because of their low set-up cost and versatility. However, the instability introduced by the lateral deflection of the guidance cable makes it difficult to reliably achieve the tolerances specified. The rigid rail guidance system effectively removes many of the lateral instability problems associated with cable-guided systems.

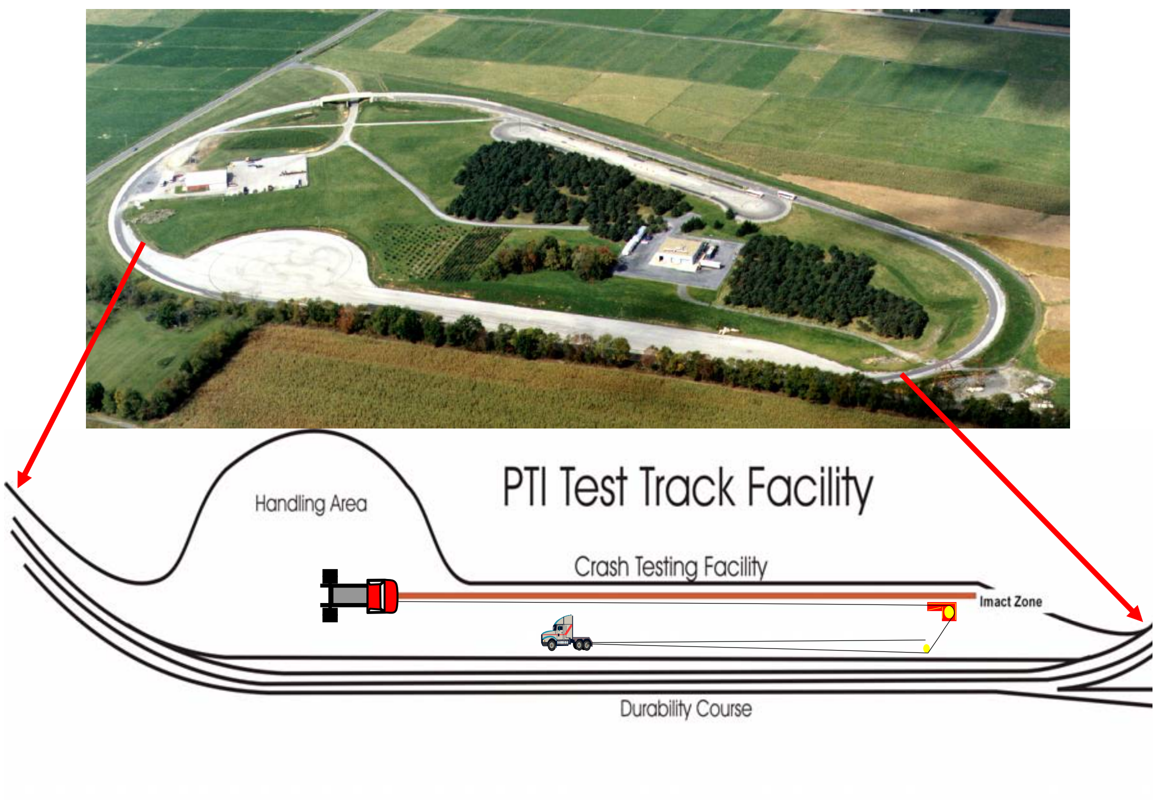


Figure 51. PTI's full-scale crash testing facility.

PTI's rail guidance system consists of a 1050-ft-long, 3.5-in-high I-beam (guide rail) and bogey assembly (see Figure 52 and Figure 53. The east end of the rail terminates into the impact zone where the bogey is detached from the vehicle. The rail is securely anchored to the pavement along the edge of the vehicle dynamics test pad, as is the bogey arresting device. When a truck (2000P or 8000S) is being used for testing, the bogey is attached underneath the vehicle to the steering arms. When the small car (820C) is being used, the bogey is attached to undercarriage of the vehicle from the side.

Figure 52. Impact area

Figure 53. Bogey assembly and its attachment to vehicles.

The towing system is used to bring the test vehicle up to the desired impact speed. This system consists of a tow vehicle, a tow cable, two anchored re-directional pulleys, a speed multiplier pulley attached to the towing vehicle, and a quick-release mechanism anchored to the pavement as shown in Figure 54 and Figure 55. This configuration results in a speed-doubling effect, in that the speed of the test vehicle is twice the speed of the towing vehicle.

Figure 54. PTI's towing system components.

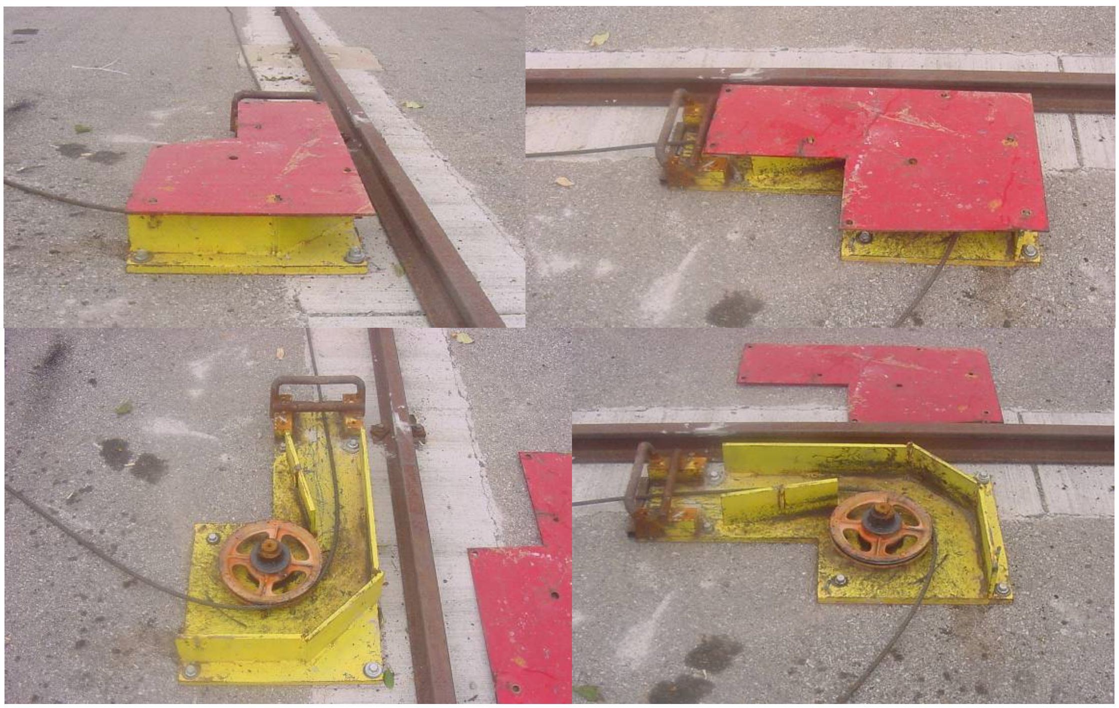


Figure 55. PTI's towing system components.

20 APPENDIX L – FHWA REPORT

PENNSTATE

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The Pennsylvania Transportation Institute
Vehicle Systems & Safety Program

The Pennsylvania State University
201 Research Office Building
University Park, PA 16802-4710

Federal Highway Administration
Office of Safety Design

Category 2 Work Zone Device Acceptance Letter

Letter Number: PennDOT PS-01
Date: 01 December 2007

CONTACT INFORMATION:	**Petioner / Developer Name:**	**Andrew Markunas, PE**
	Title:	**Manager, Work Zone Traffic Control Section**
	Company:	**Pennsylvania Department of Transportation Bureau of Highway Safety & Traffic Engineering Work Zone Traffic Control Section**
	Street:	**400 North Street, 6th Floor**
	City, State, and Zipcode:	**Harrisburg, PA 17120**
	I herby certify that the device(s) covered by this Acceptance Letter meet(s) the crash – worthiness test and evaluation requirements of the FHWA and NCHRP Report 350.	
	Signature:	
	Telephone Number:	**(717) 783-6080**
	E-mail Address:	**amarkunas@state.pa.us**
	Engineer Name:	**Dr. Zoltan Rado**
	Laboratory Name:	**The Pennsylvania Transportation Institute**
	Street:	**201 Transportation Research Bldg.**
	City, State, and Zipcode:	**University Park, PA, 16802**
	Check One:	
	☑	I hereby certify that the testing that supports this Acceptance Letter was conducted in accordance with NCHRP Report 350 guidelines, that the device(s) tested is/are accurately described on this form, and that the test results indicate that the device meets all applicable NCHRP Report 350 evaluation criteria.
		I have evaluated the requested modifications to these devices previously found acceptable by the FHWA in Acceptance Letter WZ-____, and hereby certify that, in my opinion, the modifications do not adversely affect the crash performance of the devices. I also certify that these devices are accurately described on this form.
	Signature:	[signature]
	Telephone Number:	**(814)-863-7925**
	E-mail Address:	**zxr100@psu.edu**

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KEYWORDS	**Please select from the following Keywords for "Type of Device":** Longitudinal Channelizing Barricade Curb (Curb channelizer system with or without road tubes or other channelizers) Drum H-Footprint Sign Stand X-Footprint Sign Stand Trailer Mounted Signs (Does not include arrow boards or variable message signs or other Category 4 trailer mounted devices.) Automated Flagger Device (not trailer mounted) Tripod Sign Stand Type I Barricade Type II Barricade Type III Barricade Vertical Panel Intrusion Detector Ballast (Action relates to ballast on one or more devices) Channelizer (Individual units unlike cones, road tubes, or drums) Other (Please describe on form)	**Type of Device:** **H-Footprint Sign Stand**
	Please Select from the following Keywords for Composition of Sign or Rail Substrate: Roll-up / Fabric (with fiberglass spreaders – aluminum or steel spreaders are not allowed.) Plywood Aluminum – Solid Aluminum – Laminate Corrugated Plastic Extruded Plastic Waffleboard Plastic Wood / Lumber	**Compositon of Sign or Rail Substrate:** **Aluminum - Solid**

	Thickness of substrate (inches):		
	Indicate the height of sign from the ground (inches), if applicable:		Low: 12 to 18 inches above the pavement Mid-A: 20 to 24 inches above the pavement Mid-B: 25 to 36 inches above the pavement Mid-C: 37 to 59 inches above the pavement Tall: 60 to 71 inches above the pavement Oversized: 72 inches and taller **Height of Sign:** **Oversized: 96 inches**
	Flags and or lights present during test? Indicate number of each:		
	# of flags: 0	# of lights: 1	Weight of lights: ea. 2lbs
DEVICE NAME:	Provide Detailed Description of Device, Materials, sizes, Fasteners, Substrates, Foundation, Aux. Features Ballast, etc. (May be attached on separate page(s)) Description: The sign's horizontal support legs consist of ASTM A500 Grade B steel tubes that are 44.5mm (1.75in) × 44.5mm (1.75in) × 2.78mm (0.11in) thick. The cross member used for the H-shaped base is 610mm (24in) in length. The two side members of the H-shaped base are both 914mm (36in) in legth. The aluminum sign panel fastened onto the vertical support beam is 914mm (36in) × 914mm (36in) square × 5.54mm (0.22in) thick. The sign panel is rigidly bolted to the vertical post made of ASTM A500 Grade B steel tubing. The vertical post is 50.8mm (2in) × 50.8mm (2in) square × 2.78mm (0.11in) thick and 2438mm (96in) in height. The sandbags used for temporary stabilization of portable sign structure are placed on the end of each of the four horizontal legs. Each sandbag is 406mm (16in) wide × 203 (8in) mm in height × 101mm (4in) in		

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length. The safety light has a radius of 187.3mm (7.4in) and is positioned on top of the sign. Bolts that attached the sign panel to the vertical post are made of nylon 6/6 material and are fully threaded. The diameter of each head and thread is 12mm (0.47in), and 7mm (0.28in).

Material list:

Part	Description	Dimensions	Material	Qty
1	Veritcal steel tubular stub	1.75" sq. x 0.109" wall x 16" long	ASTM A500 Grade B steel tubing	1
2	Legs cross member	1.75" sq. x 0.109" wall x 24" long	ASTM A500 Grade B steel tubing	1
3	Legs	1.75" sq. x 0.109" wall x 36" long	ASTM A500 Grade B steel tubing	2
4	Vertical upright mast	2.0" sq. x 0.109" wall x 96" long	ASTM A500 Grade B steel tubing	1

Mast slides outside vertical stub fastened with 5/16" (0.3125") diameter 2 1/4" (2.25") long stainless steel or grade 5 zinc plated bolts and nylon insert lock nuts. Use 3/8" steel and nylon washers under both the bolt and nut.

The sign panel is placed on the vertical sign post with top edge aligned with post top end and fastened with 5/16" (0.3125") diameter 2 1/4" (2.25") long nylon 6/6 fully threaded hex headed bolts and nylon insert lock nuts. Use 3/8" steel and nylon washers under both the bolt and nut.

Drawings:

The engineering drawings are attached separately.

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MANDATORY ATTACHMENTS:	**Please include those pages as separate electronic files as they will be posted on the FHWA website in lieu of the entire final report.**	
	Attachment #1: Test data summary page(s)	
	Attach. #1a	Test #: PennDOT 02
	Attach. #1b	Test #-
	Attach. #1c	Test #-
	Attach. #1d	Test #-
	Alternative	
	Attachment #1: Description and discussion of modification(s) to crash tested and/or accepted device.	
	Date:	
	Attachment # 2: PDF drawing(s) of device(s) - **Mandatory Attachments: Please include those pages as separate electronic files as they will be posted on the FHWA website in lieu of the entire final report.**	
	Attach. #2a	Drawing Title: H-Stand
		Drawing #: S-H-001
	Attach. #2b	Drawing Title:-
		Drawing #:-
	Attach. #2c	Drawing Title:-
		Drawing #:-
	Attach. #2d	Drawing Title:-
		Drawing #:-
	Attach. #2e	Drawing Title:-
		Drawing #:-
	Attach. #2f	Drawing Title:-
		Drawing #:-
	Attach. #2g	Drawing Title:-

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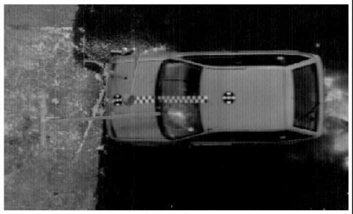
Attachment #1a: (a) Test summary sheet 0 degree Sign Post

0.03s

0.06s

0.08s

0.13s



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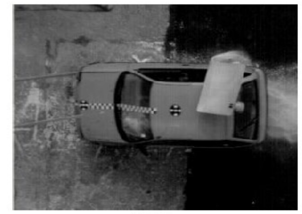

0.13s

General Information

Test Agency	Pennsylvania Transportation Institute
Test No.	PennDOT 02
Date	28 September 2007
Test Article	
Type	PennDOT – H Portable Sign Post
Test Vehicle	
Type	820C
Designation	
Model	Geo Metro
Mass (Kg)	
Test Inertial	1945 lbs (882 kg)
Gross Static	1780 lbs (807 kg)

Impact Conditions

Speed (km/h)	100.4 km/h (62.4 mi/h)
Angle (deg)	0 degrees
Test Article Deflections (m)	
Dynamic	See Evaluation and Assessment of Test Results
Permanent	See Evaluation and Assessment of Test Results

Attachment #1a: (b) Test summary sheet 90 degree Sign Post


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General Information

Test Agency	Pennsylvania Transportation Institute
Test No.	PennDOT 02
Date	28 September 2007
Test Article	
Type	PennDOT – H Portable Sign Post
Test Vehicle	
Type	820C
Designation	
Model	Geo Metro
Mass (Kg)	
Test Inertial	1945 lbs (882 kg)
Gross Static	1780 lbs (807 kg)

Impact Conditions

Speed (km/h)	100.4 km/h (62.4 mi/h)
Angle (deg)	90 degrees
Test Article Deflections (m)	
Dynamic	See Evaluation and Assessment of Test Results
Permanent	See Evaluation and Assessment of Test Results

Attachment #1a: (c) Evaluation and Assessment of Test Results

Test Article Damage and Vehicle Damage

Sign and vehicle crash performance was visually addressed through crash and post-crash images. In addition, crash performance from LS-DYNA simulations and full-scale crash testing were compared and assessed following evaluation criteria from NHCRP 350.
Post-crash performance photographs are shown in Figure 1. The pictures in Figure 1show that both the 0 and 90 degree H-base structures were severely deformed approximately 43 cm (17in) in height above the ground, which was approximately equal to the front bumper height. It can be seen that horizontal legs were also severely deformed at their connection joint. The deformations of the two signs were very similar. Both sign posts buckled at the point where the bumper of the crash vehicle came into contact with the vertical poles. One of the signs bent to almost 90 degrees while the other suffered a similar but somewhat smaller deformation. Both of the signs show that the base structure which carried all of the weights from the stabilizing sand bags became fractured and separated from the sign posts. Figure 2shows that the 820C vehicle was damaged mildly according to expectations. The front bumper on both sides near the quarter points suffered small dents and also the hood of the vehicle was dented by the buckling sign posts to a small degree.

Figure 1. Crash performances for H-base sign structures.

Figure 2. Post-test photographs of test vehicle.

Windshield Deformation and Damage Assessment

Windshield Damage Data Measured according to E-TECH Technique:

Location #	Vertical Ref. Dim.	Horizontal Ref. Dim.	Crash Vehicle Meas.	Ref. Vehicle Meas.	Deformation
1	14"	15 ¼"	5 ¾"	4 1/16"	1 2/16"

Windshield Damage Index according to WDI procedure:

Zone: **1** (Left 1/3 quadrant), Vertical Position: **C** (center horizontal slice),
Horizontal Position: **R** (Right side of slice), Shape: **E** (Elliptical)
Depth of Indentation: **3** (1<DI<1 ½"), Extent of Indentation: **3** (20<EI<50 in^2)

WDI: 441CRE33

Figure 3. Windshield Damage

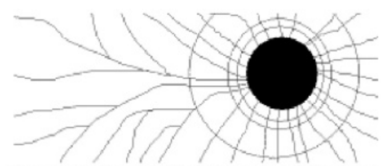

Figure 4. Case 5: Significant local damage

Attachment #2a