SAFETY PERFORMANCE EVALUATION OF MICHIGAN'S TEMPORARY TRAFFIC CONTROL DEVICES

Submitted by

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MwRSF Research Report No. TRP-03-128-02

January 27, 2003

Technical Report Documentation Page

1. Report No.	2.	3. Recipient's Accession No.
4. Title and Subtitle Safety Performance Evaluation of Michigan's Temporary Traffic Control Devices		5. Report Date January 27, 2003
		6.
7. Author(s) Polivka, K.A., Faller, R.K., Holloway, J.C., Rohde, J.R., and Sicking, D.L.		8. Performing Organization Report No. TRP-03-128-02
9. Performing Organization Name and Address Midwest Roadside Safety Facility (MwRSF) University of Nebraska-Lincoln 1901 Y St., Bldg. C Lincoln, NE 68588-0601		10. Project/Task/Work Unit No.
		11. Contract © or Grant (G) No.
12. Sponsoring Organization Name and Address Michigan Department of Transportation P.O. Box 30049 885 Ricks Road Lansing, Michigan 48909		13. Type of Report and Period Covered Final Report 2001-2003
		14. Sponsoring Agency Code
15. Supplementary Notes Prepared in cooperation with U.S. Department of Transportation, Federal Highway Administration		

16. Abstract (Limit: 200 words)

A wide variety of traffic controlling devices are used in work zones, some of which are not normally found on the roadside or in the traveled way outside of the work zones. These devices are used to enhance the safety of the work zones by controlling the traffic through these areas. Due to the placement of the traffic control devices, the devices themselves may be potentially hazardous to both workers and errant vehicles. The impact performance of many work-zone traffic control devices is mainly unknown and to date limited crash testing has been conducted, under the criteria of National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features*.

The objective of the study was to evaluate the safety performance of existing work-zone traffic control devices through full-scale crash testing. A total of six full-scale crash tests were conducted on various tall-mounted, rigid panel sign supports and Type III barricades with attached warning lights to determine their safety performance according to the Test Level 3 (TL-3) criteria set forth in the NCHRP Report No. 350. Three of the four impacts on the tall-mounted, rigid panel sign supports and one of the two impacts on the Type III barricades resulted in acceptable safety performances. Following the analysis of these crash tests as well as the test results from other testing programs, it has been found that slight variations in design features of the work-zone traffic control devices can lead to very different performance results. Therefore, extreme care should be taken in applying crash test results from one work-zone traffic control device to similar work-zone traffic control devices with slight variations. The results of the crash tests were documented, and conclusions and recommendations pertaining to the safety performance of the existing work-zone traffic control devices were made.

17. Document Analysis/Descriptors		18. Availability Statement	
Highway Safety, Rigid Panels, Barricade, Work Zone Safety, Roadside Appurtenances, Crash Test, Compliance Test		No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 127	22. Price

DISCLAIMER STATEMENT

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ACKNOWLEDGMENTS

The authors wish to acknowledge several sources that made a contribution to this project: (1) the Michigan Department of Transportation for donating the work-zone devices and for sponsoring this project; and (2) MwRSF personnel for conducting the crash tests.

A special thanks is also given to the following individuals who made a contribution to the completion of this research project.

<u>Midwest Roadside Safety Facility</u>

J.D. Reid, Ph.D., Associate Professor, Mechanical Engineering Department
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TABLE OF CONTENTS

List of Figures

Page

List of Tables

Page

1 INTRODUCTION

1.1 Problem Statement

A wide variety of traffic controlling devices are used in work zones, some of which are not normally found on the roadside or in the traveled way outside of the work zones. These devices are used to enhance the safety of the work zones by controlling the traffic through these areas. Due to the placement of the traffic control devices, the devices themselves may be potentially hazardous to both workers (or bystanders) and occupants of errant vehicles. Thus, the Federal Highway Administration (FHWA) and the *Manual on Uniform Traffic Control Devices (MUTCD)* (1) require that work-zone traffic control devices must demonstrate acceptable crashworthy performance in order to be used within the roadway on the National Highway System (NHS).

The impact performance of many work-zone traffic control devices is mainly unknown and limited crash testing has been conducted in accordance with the guidelines set forth in National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (2). The Texas Department of Transportation (TxDOT) has sponsored a number of studies at the Texas Transportation Institute (TTI) to assess the impact performance of various work-zone traffic control devices, including plastic drums, sign substrates, barricades, and temporary sign supports (3-7). Full-scale crash testing on plastic drums, barricades, portable sign supports, and tall-mounted, rigid panel sign supports has also been previously conducted at the University of Nebraska-Lincoln (8-23). The previous studies have provided some useful information, but there remains unanswered questions regarding the performances of many work-zone traffic control devices, which are slightly different from those crash tested.

1.2 Objective

The objective of the research project was to evaluate the safety performance of two of Michigan's existing temporary traffic control devices through full-scale crash testing. The safety performance evaluations were conducted according to the Test Level 3 (TL-3) criteria set forth in the NCHRP Report No. 350 (2).

1.3 Scope

The research objective was achieved by performing several tasks. First, six full-scale vehicle crash tests were performed on three work-zone traffic control devices. The six crash tests were completed in three runs with a right-side quarter-point and a centerline impact in the first and third runs. The second run had a left-side quarter-point and a right-side quarter-point impact, resulting in a total of six crashes. The full-scale crash tests were performed using a small car, weighing approximately 820 kg, with target impact speeds of 105.0 km/hr and 100.0 km/hr for the first and second impacts, respectively, and angles of 0 or 90 degrees for the impacts. Finally, the test results were analyzed, evaluated, and documented. Conclusions and recommendations were then made that pertain to the safety performance of the existing work-zone traffic control devices.

2 TEST REQUIREMENTS AND EVALUATION CRITERIA

2.1 Test Requirements

Work-zone traffic control devices, such as portable mounted traffic control signs and Type III barricades, must satisfy the requirements provided in NCHRP Report No. 350 to be accepted by FHWA for use on NHS construction projects or as a replacement for existing designs not meeting current safety standards. According to FHWA's Submission Guidelines attached to the July 1997 memorandum, *Action: Identifying Acceptable Highway Safety Features* (24), work-zone traffic control devices are Category 2 devices, which are not expected to produce significant change in vehicular velocity, but may otherwise be hazardous since they have the potential to penetrate a windshield, injure a worker, or cause vehicle instability when driven over or lodged under a vehicle.

According to Test Level 3 (TL-3) of NCHRP Report No. 350 and FHWA's Submission Guidelines for acceptable Category 2 devices, work-zone traffic control devices must be subjected to two full-scale vehicle crash tests: (1) an 820-kg small car impacting at a speed of 35.0 km/hr and at an angle of 0 degrees; and (2) an 820-kg small car impacting at a speed of 100.0 km/hr and at an angle of 0 degrees. The low-speed test is intended to evaluate the breakaway, fracture, or yielding mechanism of the device and occupant risk factors whereas the high-speed test is intended to evaluate vehicular stability, test article trajectory, and occupant risk factors. Since most work-zone traffic control devices have a relatively small mass (less than 45 kg), the high-speed crash test is more critical due to the propensity of the test article to penetrate into the occupant compartment. Therefore, the 820-kg small car crash test, impacting at a speed of 35.0 km/hr and at an angle of 0 degrees, was deemed unnecessary for this project. However, these devices are often situated on the roadway where an impact could occur at other angle orientations, such as at 90 degrees at an intersecting roadway. Thus, it has become generally recognized and endorsed by the FHWA as described in “Questions and Answers about Crash Testing of Work-Zone Safety Appurtenances” that an additional test should be performed on such devices at the target speed of 100 km/hr and at a target impact angle of 90 degrees (25).

2.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the work-zone traffic control device to break away, fracture, or yield in a predictable manner. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle, including windshield damage. Vehicle trajectory after collision is a measure of the potential for the post-impact trajectory of the vehicle to cause subsequent multi-vehicle accidents, thereby subjecting occupants of other vehicles to undue hazards or to subject the occupants of the impacting vehicle to secondary collisions with other fixed objects. These three evaluation criteria are defined in Table 1. The full-scale vehicle crash tests were conducted and reported in accordance with the procedures provided in NCHRP Report No. 350 and for Category 2 devices.

Windshield damage is a major area of concern when evaluating the safety performance of a work-zone traffic control device. The windshield should not be shattered nor damaged in a way that visibility is significantly obstructed. Minor chipping and cracking of the windshield is acceptable. Significant loss of visibility due to extensive “spider web” cracking at key regions of the windshield would deem the performance of the device unsatisfactory. Both layers of glass should not be fractured nor indented with the potential for the test article to penetrate the windshield. The five main failure criteria are defined in Table 2.

Table 1. NCHRP Report No. 350 Evaluation Criteria for 820C Small Car Crash Test (2)

Structural Adequacy	B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.
Occupant Risk	D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.
	E. Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.
	F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.
	H. Longitudinal occupant impact velocities should fall below the preferred value of 3 m/s, or at least below the maximum allowable value of 5 m/s.
	I. Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15 G's, or at least below the maximum allowable value of 20 G's.
Vehicle Trajectory	K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.
	N. Vehicle trajectory behind the test article is acceptable.

Table 2. Failure Criteria

METHOD OF FAILURE	
1	Severe windshield cracking and fracture
2	Windshield indentation
3	Obstruction of driver visibility
4	Windshield penetration
5	Occupant compartment penetration other than windshield penetration
6	Roof deformations greater than 152 mm

3 WORK-ZONE TRAFFIC CONTROL DEVICES

3.1 General Descriptions

A total of six existing work-zone traffic control devices were crash tested under this study and are described below. Four of the crash tests were conducted on tall-mounted, rigid panel sign supports with sandbags. The other two crash tests were conducted on Type III barricades with sandbags. All materials for the traffic control devices were supplied by the sponsor.

The two different tall-mounted, rigid panel sign support systems tested were:

1. (System Nos. 1 and 2) a 1,723-mm wide x 1,222-mm deep x 3,254-mm tall steel sign support with a 1,218-mm x 1,219-mm x 15.9-mm thick plywood diamond-shaped sign panel with reflective material mounted at a height of 1,530 mm from the ground to the bottom of the sign panel and a 609-mm x 610-mm x 15.9-mm thick square-shaped sign panel with reflective material mounted on one mast at a height of 911 mm from the ground to the bottom of the sign panel and with a "Work Safe Supply" Type A warning light mounted at a height of 2,794 mm from the ground to the top of the warning light and with 31.75 kg of sandbags at the end of each leg; and

2. (System Nos. 5 and 6) a 1,730-mm wide x 1,829-mm deep x 3,264-mm tall steel sign support with a 1,219-mm x 1,219-mm x 15.9-mm thick plywood diamond-shaped sign panel with reflective material mounted at a height of 1,540 mm from the ground to the bottom of the sign panel and with a lightweight "Empco-Lite" Type A warning light mounted at a height of 2,597 mm from the ground to the top of the warning light and with 15.88 kg of sandbags at the end of each leg.

The one barricade system tested was:

1. (System Nos. 3 and 4) a 3,662-mm wide x 1,222-mm deep x 1,759-mm tall wood and steel Type III barricade with three "Work Safe Supply" Type A warning lights mounted at a height of 1,759 mm from the ground to the top of the warning light and with 31.75 kg of sandbags at the end of each leg.

A list of the six crash tests are summarized in Table 3.

Table 3. List of Crash Tests Conducted

WORK-ZONE TRAFFIC CONTROL DEVICES		
<u>TALL-MOUNTED, RIGID PANEL SIGN SUPPORT</u>		
Test MI-1	System No. 1	Steel Sign Support with a Diamond-Shaped Wood Panel and a Smaller Square-Shaped Wood Panel, “Work Safe Supply” Type A Warning Light, Sandbags on Each Leg, End-on Impact (90 degrees)
Test MI-1	System No. 2	Steel Sign Support with a Diamond-Shaped Wood Panel and a Smaller Square Shaped Wood Panel, “Work Safe Supply” Type A Warning Light, Sandbags on Each Leg, Head-on Impact (0 degrees)
Test MI-3	System No. 5	Steel Sign Support with a Diamond-Shaped Wood Panel, lightweight “Empco-Lite” Type A Warning Light, Sandbag on Each Leg, End-on Impact (90 degrees)
Test MI-3	System No. 6	Steel Sign Support with a Diamond-Shaped Wood Panel, lightweight “Empco-Lite” Type A Warning Light, Sandbag on Each Leg, Head-on Impact (0 degrees)
<u>TYPE III BARRICADES</u>		
Test MI-2	System No. 3	Type III Wood and Steel Barricade, three “Work Safe Supply" Type A Warning Lights, Sandbags on Each Leg, Head-on Impact (0 degrees)
Test MI-2	System No. 4	Type III Wood and Steel Barricade, three “Work Safe Supply" Type A Warning Lights, Sandbags on Each Leg, End-on Impact (90 degrees)

3.2 Tall-Mounted, Rigid Panel Sign Supports

The details of the tall-mounted, rigid panel sign support systems are shown in Figures 1 through 7. The dimensional measurements of the tall-mounted, rigid panel sign support systems and warning lights are found in Appendix A. Additional system details are found in Appendix B.

3.3 Type III Barricades

The details of the Type III barricade systems are shown in Figures 8 through 10. The dimensional measurements of the Type III barricades and warning lights are found in Appendix C. Additional barricade details are found in Appendix D.

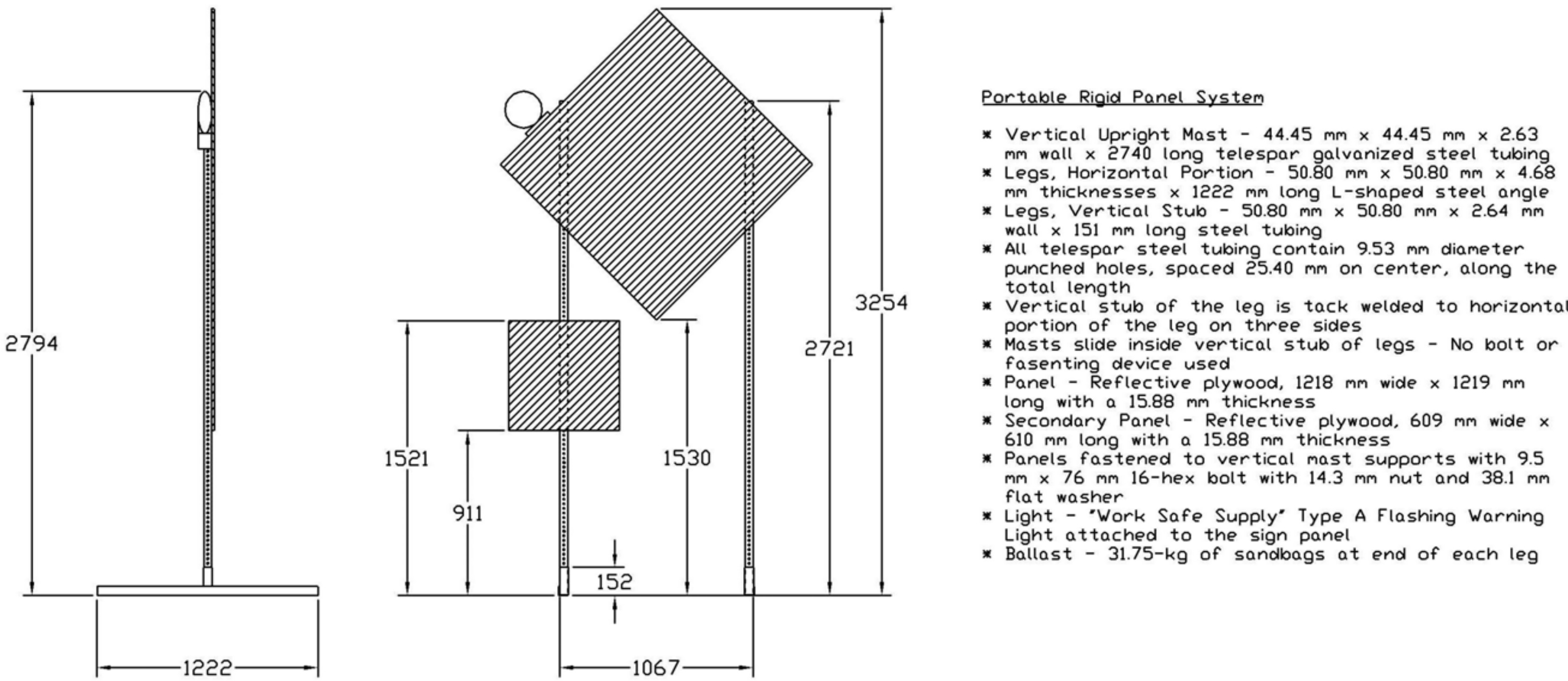
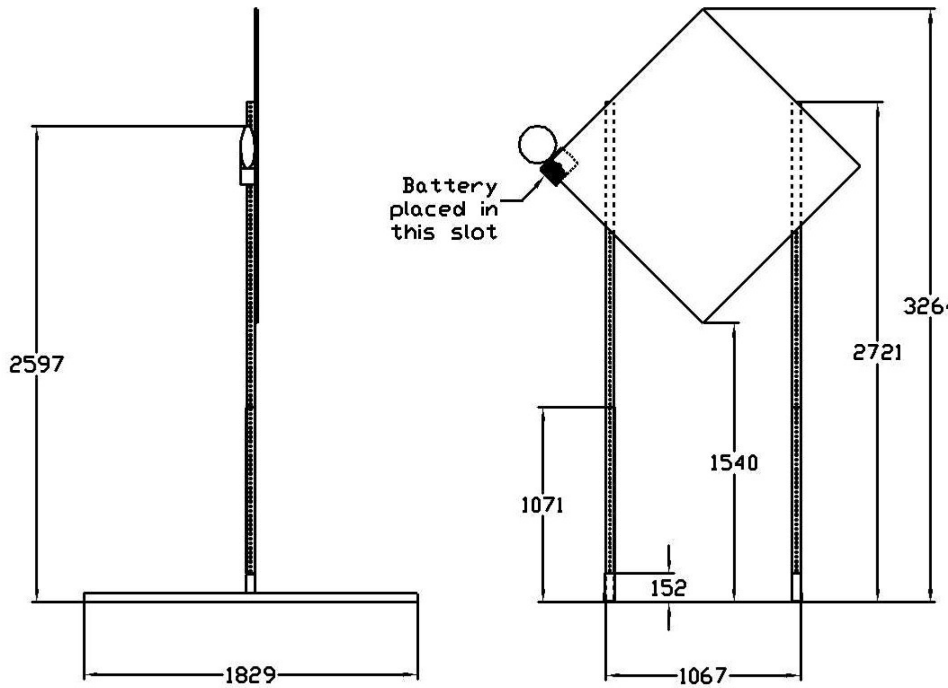


Figure 1. System Nos. 1 and 2 Sign Support Details, Test MI-1

Figure 2. System No. 1 Sign, Test MI-1

Figure 3. System No. 2 Sign, Test MI-1



Modified Portable Rigid Panel System

* Vertical Upright Mast - 44.45 mm x 44.45 mm x 2.16 mm wall x 2743 long galvanized telespar steel tubing
* Outside Vertical Upright Tubing - 50.00 mm x 50.00 mm x 2.77 mm wall x 912 mm long galvanized telespar steel tubing
* Legs, Horizontal Portion - 50.80 mm x 50.80 mm x 6.35 mm thicknesses x 1829 mm long L-shaped steel angle
* Legs, Vertical Stub - 50.80 mm x 50.80 mm x 2.67 mm wall x 152 mm long steel tubing
* All telespar steel tubing contain 9.53 mm diameter punched holes, spaced 25.40 mm on center, along the total length
* Vertical stub of the leg is tack welded to horizontal portion of the leg on three sides
* Outside stiffening tubes slide over the vertical upright masts and are bolted at the top and bottom of the stiffening tubes with 7.9 mm x 51 mm coarse bolts with nut and washer
* Masts slide inside vertical stub of legs - No bolt or fasenting device used
* Panel - Reflective plywood, 1219 mm wide x 1219 mm long with a 15.88 mm thickness
* Panel fastened to vertical mast supports with quick-release 9.5 mm x 76 mm - 16 zinc coated steel hex bolts with 14.3 mm nut and 38.1 mm x 1.6 mm thick flat washer
* Light - "Empco-Lite", model no. 400 Type A Flashing Warning Light attached to the corner of the sign panel with only one battery placed in the box at the outermost slot in the battery box
* Bolt for the warning light was placed 51 mm in from and perpendicular to each edge line of the panel or along the centerline drawn between the two side corners of the panel
* Ballast - 15.88-kg of sandbags at end of each leg

Figure 4. System Nos. 5 and 6 Sign Support Details, Test MI-3

Figure 5. System No. 5 Sign, Test MI-3

Figure 6. System No. 6 Sign, Test MI-3

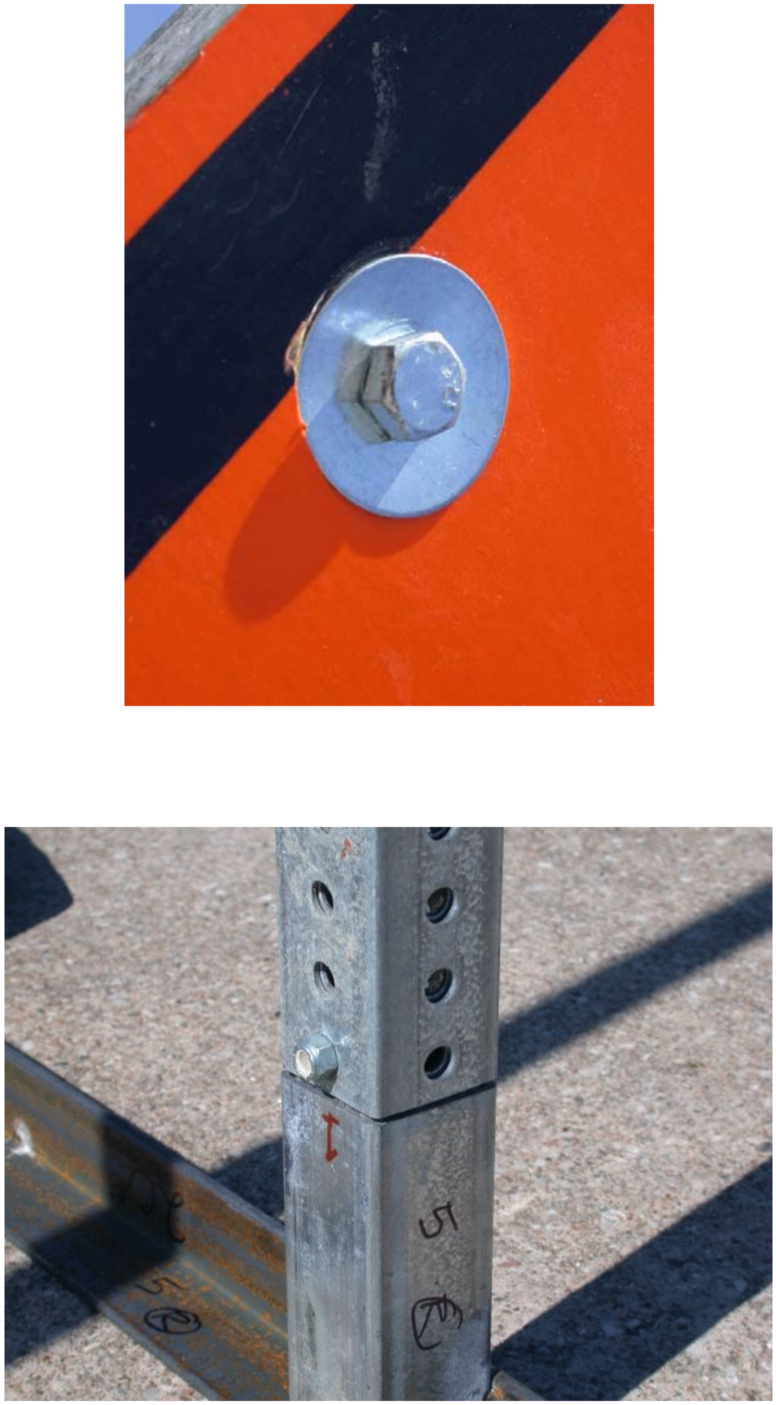
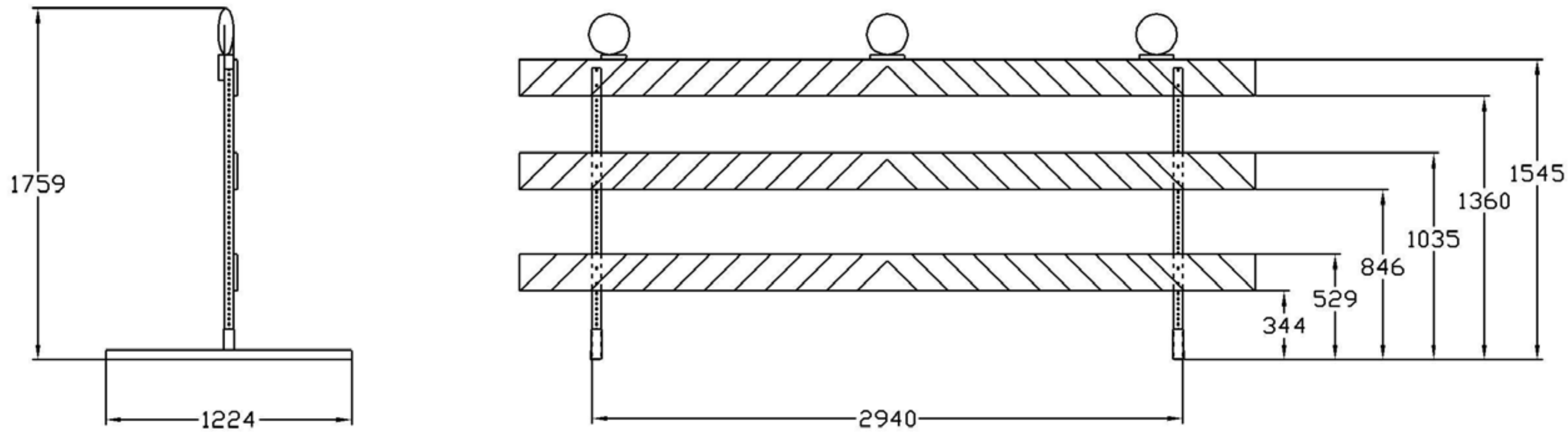


Figure 7. System No. 5 and 6 Sign Components, Test MI-3



<u>Type III Barricade System</u>

* Vertical Upright Mast - 44.70 mm x 44.96 mm x 2.59 mm wall x 2940 long telespar galvanized steel tubing
* Legs, Horizontal Portion - 50.80 mm x 50.80 mm x 4.69 mm thicknesses x 1222 mm long L-shaped steel angle
* Legs, Vertical Stub - 50.80 mm x 50.80 mm x 2.64 mm wall x 151 mm long steel tubing
* All telespar steel tubing contain 9.53 mm diameter punched holes, spaced 25.40 mm on center, along the total length
* Vertical stub of the leg is tack welded to horizontal portion of the leg on three sides
* Masts slide inside vertical stub of legs - No bolt or fasenting device used
* Top Barricade Panel - Reflective wood, 184 mm wide x 3662 mm long with a 19.05 mm thickness
* Middle Barricade Panel - Reflective wood, 183 mm wide x 3662 mm long with a 19.05 mm thickness
* Bottom Barricade Panel - Reflective wood, 184 mm wide x 3662 mm long with a 19.05 mm thickness
* Panels fastened to vertical mast supports with 9.5 mm x 76 mm 16-hex bolt with 14.3 mm nut and 38.1 mm flat washer
* Lights - Three 'Work Safe Supply' Type A Flashing Warning Light attached to the top barricade panel
* Ballast - 31.75-kg of sandbags at end of each leg

Figure 8. System Nos. 3 and 4 Barricade Details, Test MI-2

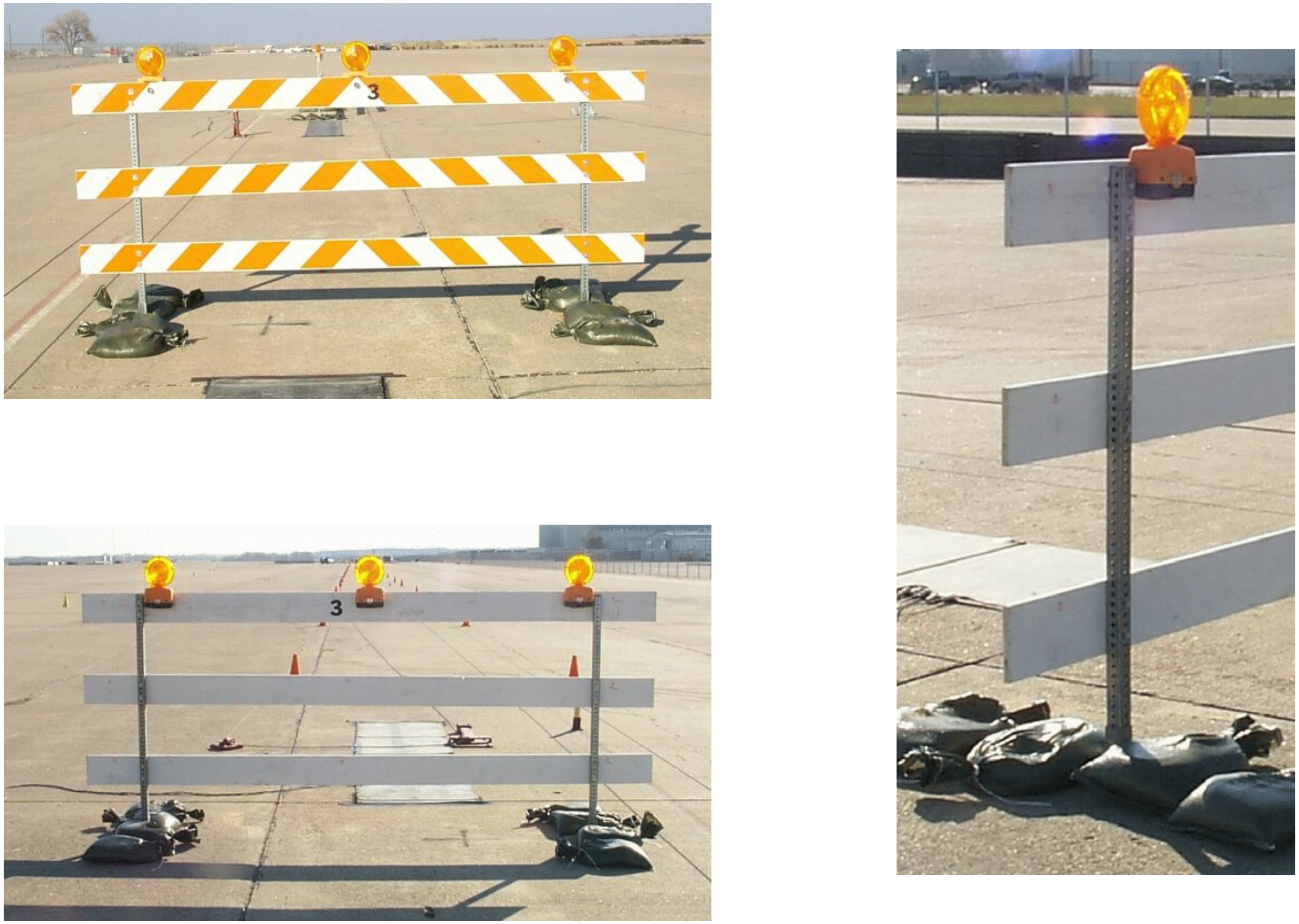


Figure 9. System No. 3 Barricade, Test MI-2

Figure 10. System No. 4 Barricade, Test MI-2

4 TEST CONDITIONS

4.1 Test Facility

The testing facility is located at the Lincoln Air-Park on the northwest (NW) side of the Lincoln Municipal Airport and is approximately 8.0 km NW of the University of Nebraska-Lincoln.

4.2 Vehicle Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the test vehicles. The distance traveled and the speed of the tow vehicle were one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the first work-zone traffic control device. A digital speedometer was located on the tow vehicle to increase the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch (26) was used to steer the test vehicle. A guide-flag, attached to the front-left wheel and the guide cable, was sheared off before impact with the second work-zone traffic control device. The 9.5-mm diameter guide cable was tensioned to approximately 13.3 kN, and supported laterally and vertically every 30.48 m by hinged stanchions. The hinged stanchions stood upright while holding up the guide cable, but as the vehicle was towed down the line, the guide-flag struck and knocked each stanchion to the ground. The vehicle guidance system was approximately 305-m long.

4.3 Test Vehicles

For test MI-1, a 1996 Geo Metro was used as the test vehicle. The test inertial and gross static weights were 813 kg and 888 kg, respectively. The test vehicle is shown in Figure 11, and vehicle dimensions are shown in Figure 12.

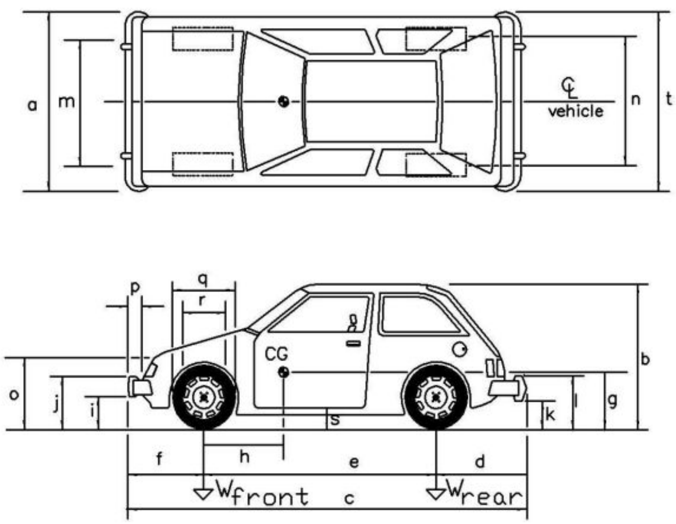
For test MI-2, a 1996 Geo Metro was used as the test vehicle. The test inertial and gross

Figure 11. Test Vehicle, Test MI-1

Dates: 11/6/01 Test Numbers: MI-1 Model: Metro 2-dr.

Make: GEO Vehicle I.D.#: 2C1MR22265T6753813

Tire Size: P175/70R13 Year: 1996 Odometer: 91314



Vehicle Geometry - mm

a	1537	b	1391
c	3785	d	635
e	2368	f	806
g	546	h	911
i	216	j	527
k	318	l	610
m	1384	n	1353
o	552	p	2743
q	572	r	362
s	311	t	1568

height of wheel center 264

Engine Type 3 cyl. gas

Engine size 1.0 L

Transmission Type:

Automatic or (Manual)

(FWD) or RWD or 4WD

Weight - kg	Curb	Test Inertial	Gross Static
W_{front}	439	498	534
W_{rear}	263	315	354
W_{total}	702	813	888

Damage prior to test: Right-side fender and rocker dents

Figure 12. Vehicle Dimensions, Test MI-1

static weights were 813 kg and 888 kg, respectively. The test vehicle is shown in Figure 13, and vehicle dimensions are shown in Figure 14.

For test MI-3, a 1996 Geo Metro was used as the test vehicle. The test inertial and gross static weights were 820 kg and 896 kg, respectively. The test vehicle is shown in Figure 15, and vehicle dimensions are shown in Figure 16.

The longitudinal component of the center of gravity was determined using the measured axle weights. The location of the final centers of gravity are shown in Figures 11 through 16.

Square, black and white-checkered targets were placed on the vehicle to aid in the analysis of the high-speed E/cam video, as shown in Figures 17 through 19. One target was placed directly above each of the wheels on the driver and passenger sides of the test vehicle. A target was placed at each quarter point on the front of the vehicle's hood.

The front wheels of the test vehicle were aligned for camber, caster, and toe-in values of zero so that the vehicle would track properly along the guide cable. Two 5B flash bulbs were mounted on both the left and right quarter points of the vehicle's roof to pinpoint the time of impact with each of the work-zone traffic control devices on the high-speed E/cam video. The flash bulbs were fired by a pressure tape switch mounted at each of the quarter points on the front face of the bumper. A remote controlled brake system was installed in the test vehicle so the vehicle could be brought safely to a stop after the test.

4.4 Data Acquisition Systems

4.4.1 High-Speed Photography

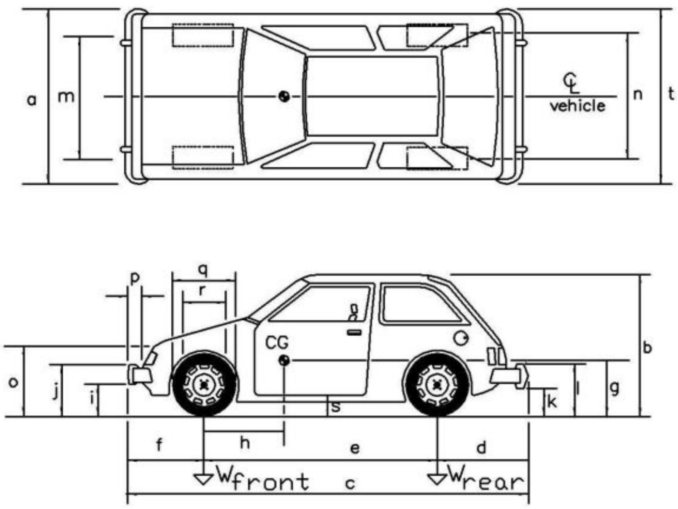
For tests MI-1, MI-2, and MI-3, two high-speed Red Lake E/cam video cameras, with operating speeds of 500 frames/sec, were used to film the crash test. Three Canon digital video

Figure 13. Test Vehicle, Test MI-2

Dates: 11/6/01 Test Numbers: MI-2 Model: Metro 2-dr.

Make: GEO Vehicle I.D.#: 2C1MR2268T6754860

Tire Size: P155/80R13 Year: 1996 Odometer: 129,533



Vehicle Geometry - mm.

a	1549	b	1416
c	3797	d	584
e	2375	f	838
g	546	h	921
i	435	j	549
k	575	l	667
m	1378	n	1353
o	578	p	95
q	572	r	365
s	324	t	1556

height of wheel center 264

Engine Type 3 cyl. gas

Engine size 1.0 L

Transmission Type:

Automatic or (Manual)

(FWD) or RWD or 4WD

Weight - kg.	Curb	Test Inertial	Gross Static
W_{front}	496	500	537
W_{rear}	298	313	351
W_{total}	794	813	888

Damage prior to test: None

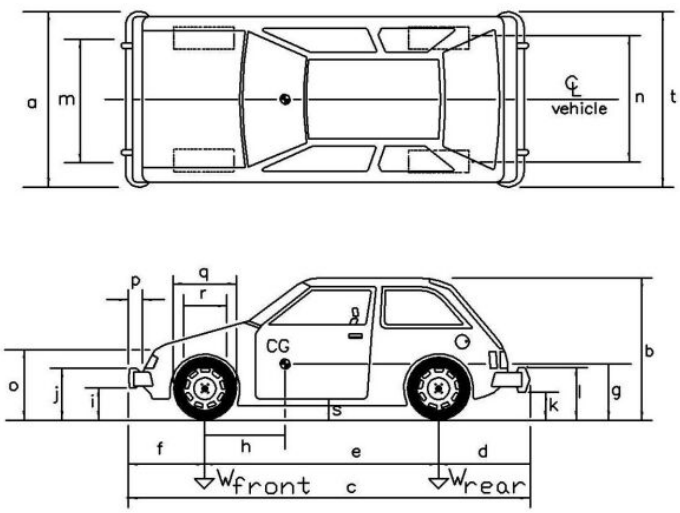
Figure 14. Vehicle Dimensions, Test MI-2

Figure 15. Test Vehicle, Test MI-3

Dates: 10/8/02 Test Numbers: MI-3 Model: Metro 2-dr.

Make: GEO Vehicle I.D.#: 2C1MR2262T6789541

Tire Size: P155/80R13 Year: 1996 Odometer: 93,055



Vehicle Geometry – mm

a	1556	b	1511
c	3785	d	686
e	2350	f	749
g	546	h	940
i	279	j	565
k	311	l	641
m	1378	n	1353
o	578	p	102
q	565	r	362
s	311	t	1549

height of wheel center 267

Engine Type 3 cyl. gas

Engine size 1.0 L

Transmission Type:

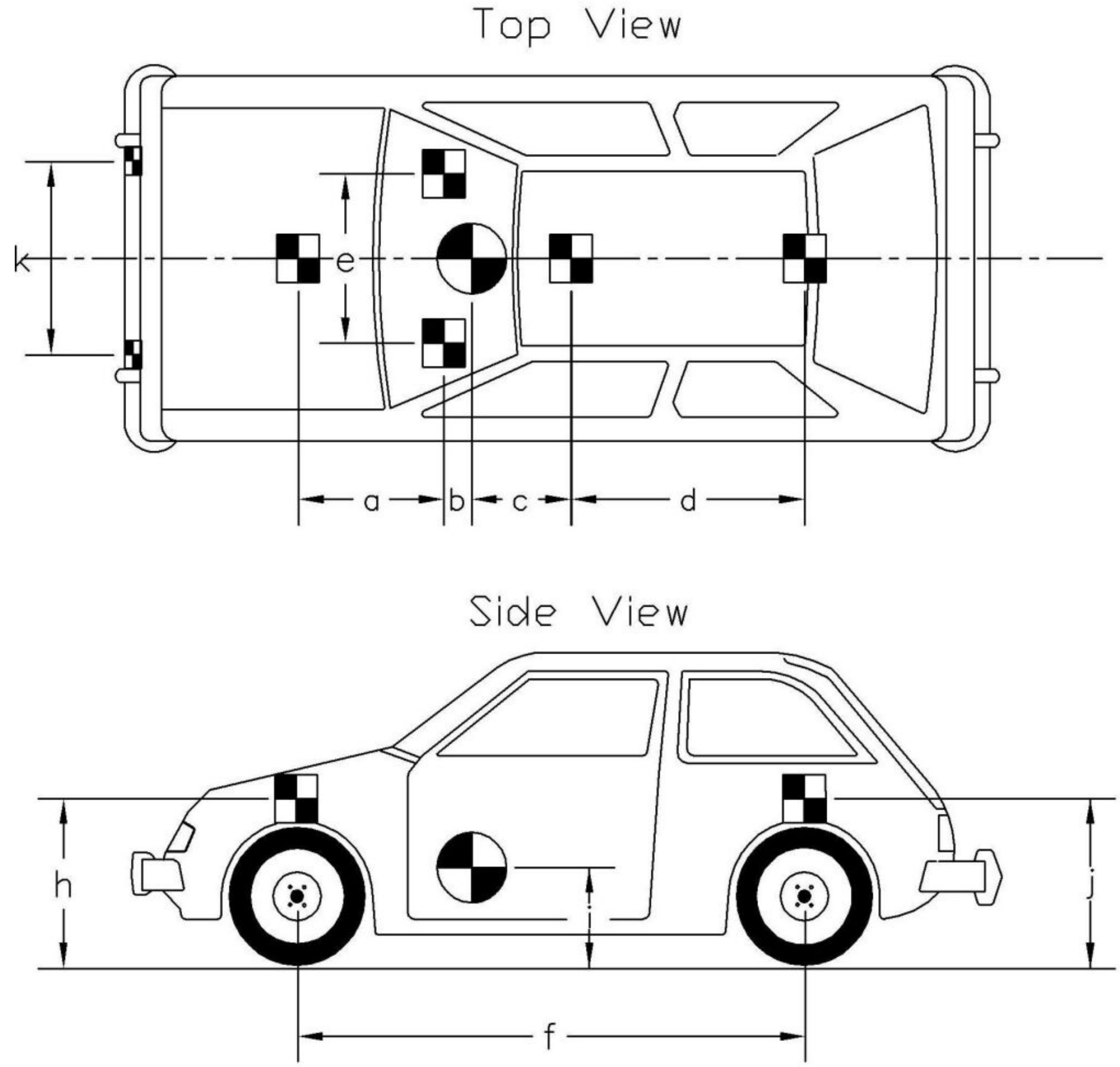
Automatic or (Manual)

(FWD) or RWD or 4WD

Weight – kg	Curb	Test Inertial	Gross Static
W_{front}	478	484	520
W_{rear}	336	336	376
W_{total}	814	820	896

Damage prior to test: None

Figure 16. Vehicle Dimensions, Test MI-3



TEST #: MI-1

TARGET GEOMETRY (mm)

a	---	b	---	c	---	d	---
e	---	f	987	g	1448	h	714
i	546	j	746	k	---		

Figure 17. Vehicle Target Locations, Test MI-1

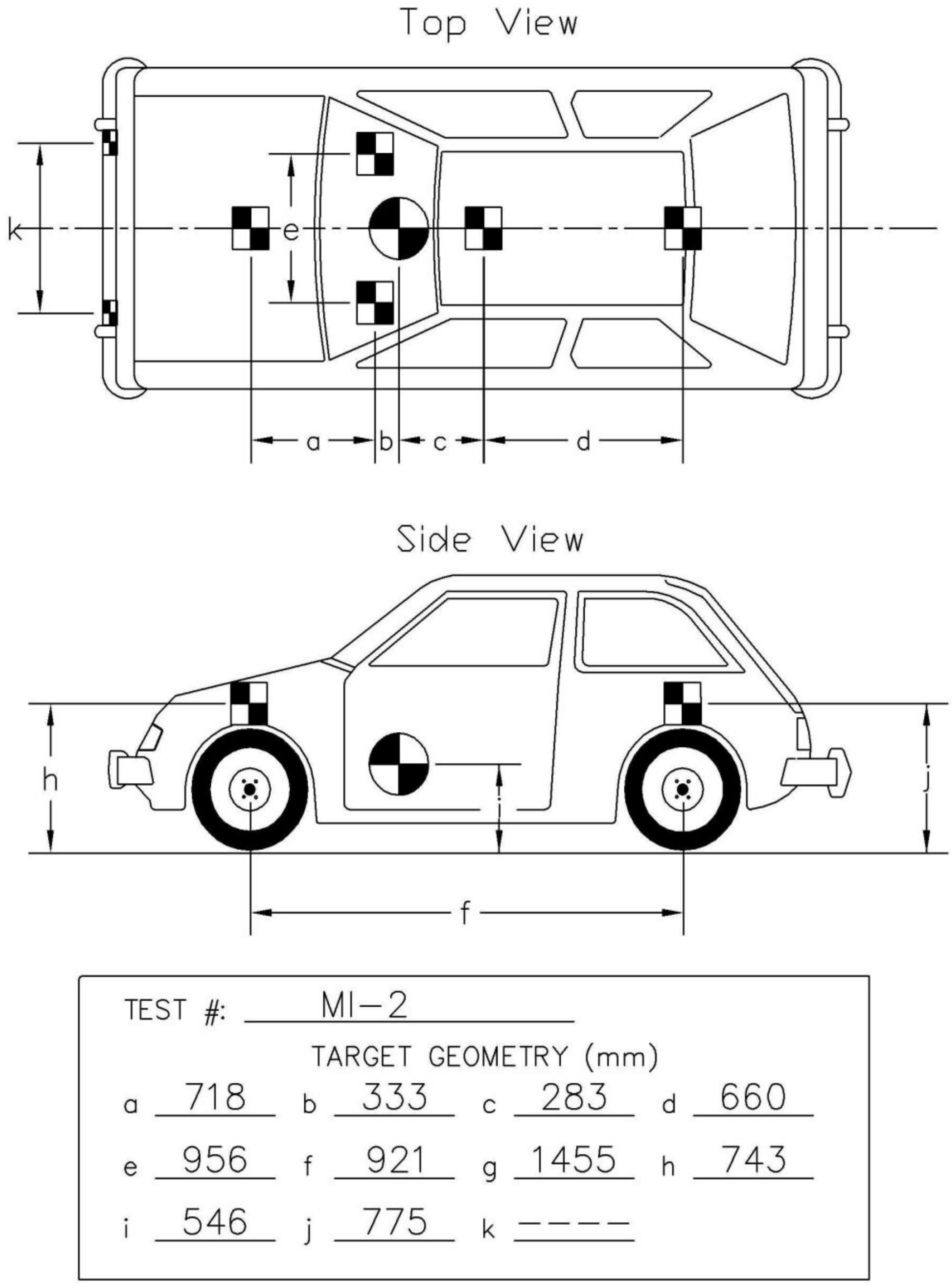


Figure 18. Vehicle Target Locations, Test MI-2

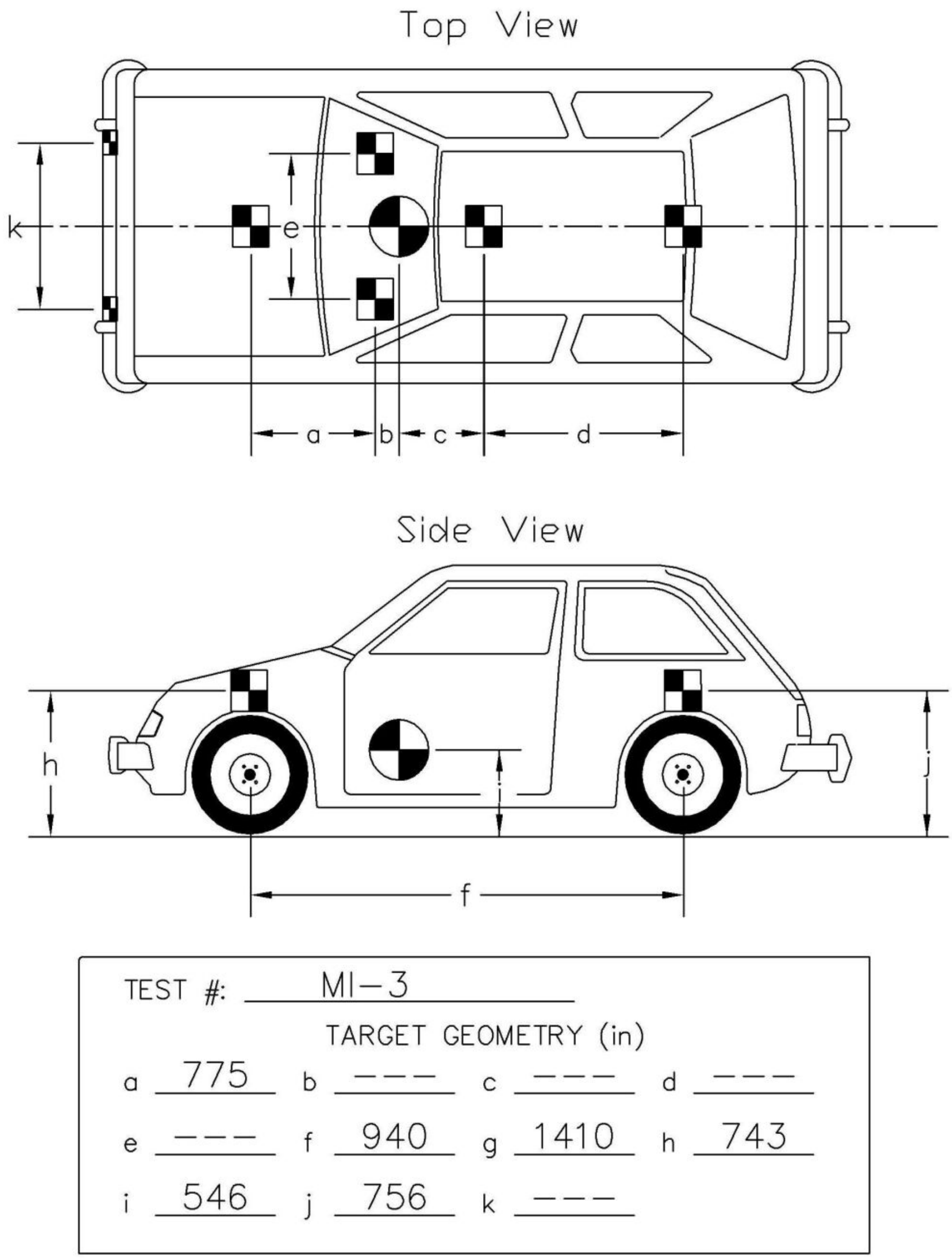


Figure 19. Vehicle Target Locations, Test MI-3

cameras, with a standard operating speed of 29.97 frames/sec, were also used to film the crash test. A high-speed E/cam video camera and a Canon digital video camera were placed on the right side of the impact orientation and had a field of view perpendicular to the impact of the first device. Another high-speed E/cam video camera and a Canon digital video camera were placed on the right side of the impact orientation and had a field of view perpendicular to the impact of the second device. Another Canon digital video camera was placed downstream and offset to the right from the second impact point and had an angled view of both impacts. A schematic of all five camera locations for tests MI-1 and MI-2 is shown in Figure 20. A schematic of all five camera locations for test MI-3 is shown in Figure 21. The film was analyzed using the Redlake Motion Scope software. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed and digital video.

4.4.2 Pressure Tape Switches

For tests MI-1, MI-2, and MI-3, two sets of three pressure-activated tape switches, spaced at 2-m intervals, were used to determine the speed of the vehicle before impact with each device. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the vehicle’s front tire passed over it. For tests MI-1 through MI-3, the right-front tire of the test vehicle passed over both sets of tape switches. Test vehicle speed was determined from electronic timing mark data recorded using the "Test Point" software. Strobe lights and high-speed film analysis are used only as a backup in the event that vehicle speed cannot be determined from the electronic data.

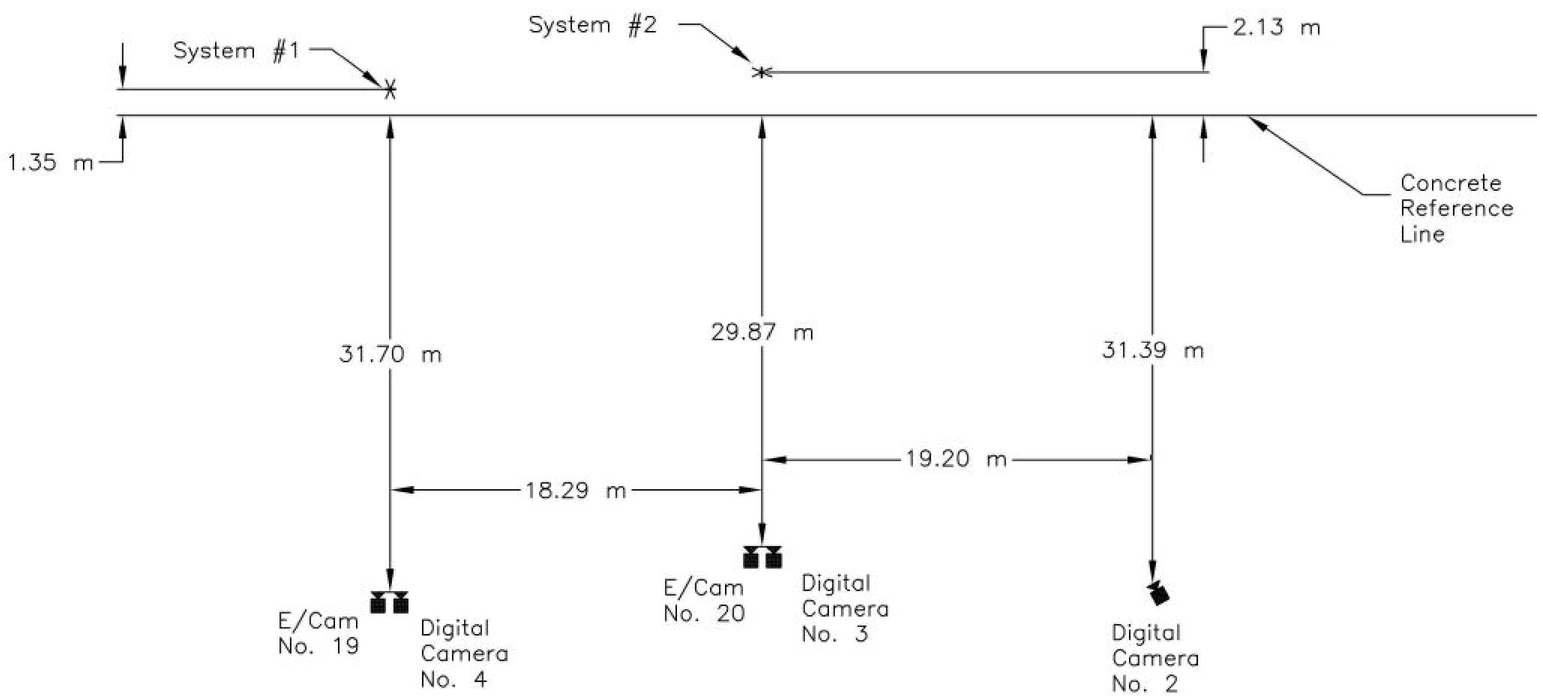


Figure 20. Location of High-Speed Cameras, Tests MI-1 and MI-2

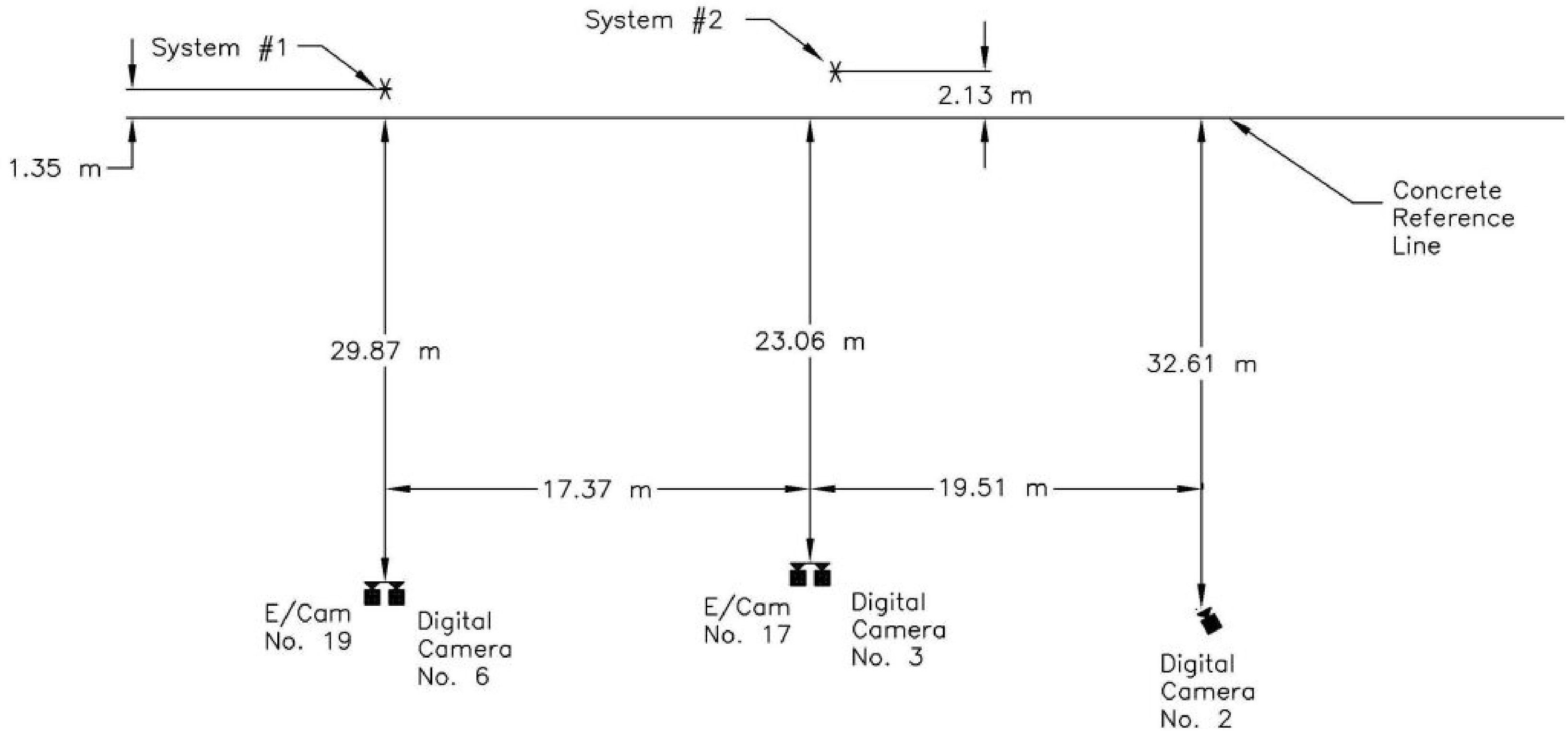


Figure 21. Location of High-Speed Cameras, Test MI-3

5 CRASH TEST NO. 1 (SYSTEM NOS. 1 AND 2)

5.1 Test MI-1

The 888-kg small car impacted System No. 1, a portable mounted traffic control sign (PMTCS) with a diamond-shaped plywood panel and a plywood speed advisory sign panel oriented end-on to the vehicle (parallel to the vehicle's path), at a speed of 102.9 km/hr and at an angle of 90 degrees. The small car then impacted System No. 2, a PMTCS with a diamond-shaped plywood panel and a plywood speed advisory sign panel oriented head-on to the vehicle (perpendicular to the vehicle's path), at a speed of 97.0 km/hr and at an angle of 0 degrees. A summary of the test results and the sequential photographs are shown in Figures 22 and 23. Additional sequential photographs are shown in Figure 24. Documentary photographs of the crash tests are shown in Figures 25 and 26.

5.2 Test Description

The test vehicle impacted System No. 1 with the right-front quarter point of the vehicle aligned with the centerline of the sign support, as shown in Figure 27. At 0.014 sec after initial impact, the impacted mast deformed around the front of the vehicle and moved toward the other mast. At this same time, the impacted mast disengaged from the impacted leg as the top of the sign panel rotated toward the vehicle. At 0.030 sec, the speed advisory sign panel impacted the hood of the vehicle. At 0.038 sec, the impacted mast and vehicle contacted the other mast. At 0.048 sec, the non-impacted mast disengaged from the corresponding leg. At 0.074 sec, the top corner of the speed advisory sign panel impacted the windshield as both sign panels and masts continue to rotate counter-clockwise (CCW) toward the vehicle. At 0.090 sec, the impact-side corner of the large sign panel impacted the roof as the masts were positioned above the vehicle's hood. At 0.128 sec, the large sign panel indented and penetrated the roof of the vehicle as it rotated to a position parallel with the ground. At 0.184 sec, the sign panel lost contact with the roof, continued to rotate CCW, and ascended into the air. At 0.384 sec, the system was airborne and rotating CCW. Both legs remained at their original positions. The sign panels, masts, and warning light box was located 56.39-m downstream and 4.09-m right from the original position. The light portion of the warning light was located 50.90-m downstream and scattered 6.27-m left and 8.97-m right from the original position of the sign support.

Approximately 0.67 sec after impact with System No. 1, the vehicle impacted System No. 2 with the centerline of the vehicle aligned with the centerline of the sign support, as shown in Figure 27. At 0.008 sec after initial impact, both masts deformed around the front of the vehicle and disengaged from their respective legs. At 0.028 sec, both masts were severely deformed at the bumper height. At this same time, the top of the sign panel rotated down toward the vehicle. At 0.048 sec, both masts lost contact with the vehicle and were positioned in front of the vehicle. At 0.092 sec, the sign panels and masts rotated to a position parallel with the ground. At 0.102 sec, the top-left portion of the sign panel contacted the roof. At 0.110 sec, the sign panel was creased at the top of the masts while the top of the sign panel remained flat against the roof. At this same time, the masts continued to rotate up and over the vehicle. At 0.150 sec, the right side of the sign panel lost contact with the vehicle as it began to rotate toward the left side of the vehicle. At 0.226 sec, the sign panel continued to rotate off the left side of the vehicle. At 0.350 sec, the sign panel was positioned perpendicular to the ground and behind the vehicle. Both legs remained at their original positions. The vertical upright of the right-side leg was located 6.10-m downstream and 1.68-m right from the original position. The vertical upright of the left-side leg was located 31.55-m downstream and

5.03-m right from the original position. The sign panels, masts, and warning light came to rest 42.98-m downstream and 4.27-m right from the original position. The bottom portion of the left mast came to rest 42.67-m downstream and 1.22-m left from the original position of the sign support. The vehicle subsequently came to rest 77.42-m downstream from the longitudinal midpoint of the two impact points and 1.28-m right from the centerline of the vehicle's original path. The final positions of the vehicle and the sign supports are shown in Figures 22, 23, and 28.

5.3 System and Component Damage

Damage to System Nos. 1 and 2 is shown in Figures 28 through 30. System No. 1 encountered moderate damage. Both legs disengaged from the masts but remained undamaged at their original positions. Both masts were deformed at the bumper height with the impacted mast encountering more significant damage. The light portion of the warning light broke off and was shattered, while the bottom box portion was still attached to the sign panel. The sign panel encountered moderate deformations on the impact side as well as scuff and scrape marks. Windshield glass was found embedded in the safety layer of the speed advisory sign panel. Scuff and scrape marks were also found on the speed advisory sign panel. The masts remained attached to the sign panel. Five of the sandbags were torn open with the sand scattered along the path of the vehicle, starting at the initial position of the first sign support. The other three sandbags remained undamaged.

System No. 2 encountered moderate damage. Both legs disengaged from the masts. The welds holding the vertical tubes to both legs fractured, resulting in both tubes disengaging from the angle legs. Both masts remained attached to both signs, but were deformed and bent at the bumper height. The mast without the attached speed advisory sign panel was also deformed at the bottom large sign panel bolt. The mast with the attached speed advisory sign panel was also slightly deformed at the top of the speed advisory sign panel. The large sign panel encountered a tear due to the flash bulb mechanism on the roof of the test vehicle. Both the large sign panel and speed advisory sign panel encountered minor scuff marks. The warning light remained intact and attached to the large sign panel. Six of the sandbags were torn open with the sand scattered along the path of the vehicle, starting at the initial position of the second sign support. The other two sandbags remained undamaged.

5.4 Vehicle Damage

Exterior vehicle damage is shown in Figures 31 through 33. The front bumper and lower plastic shield encountered minor dents and contact marks. Both sides of the bumper disengaged from the bumper clips. The right-front fender was dented and scratched. A small dent was located along the right-side quarter point of the engine hood. The right side of the roof encountered a major indentation and subsequent penetration. The left-rear of the roof encountered a minor dent. The entire roof also sustained scuff and scrape marks. Both fog lights broke. The right-side headlight was pushed inward toward the engine compartment but remained undamaged. The windshield sustained major "spider web" cracking on the right side, with both layers of the right-side windshield being cracked. Most of the structural integrity of the windshield on the right side was lost and the windshield indented inward toward the occupant compartment. A large hole (slice) through the windshield was located near the center region of the right side. No damage was found to have occurred to the left side, rear-end, left-side headlight, nor parking lights.

5.5 Discussion

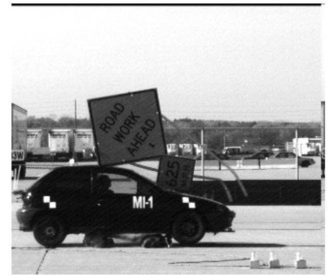
Following test MI-1, a safety performance evaluation was conducted, and the work-zone traffic control device, System No. 1 was determined to be unacceptable according to the NCHRP Report No. 350 criteria. It was deemed unacceptable due to the "spider web" cracking, indentation, and hole in the windshield, resulting in obstructed driver visibility and loss of structure of both glass layers. In addition, deformations of, or intrusion into, the occupant compartment did occur as detached elements and debris from System No. 1 penetrated the right region of the windshield and the right side of the roof.

System No. 2 was determined to be acceptable according to the NCHRP Report No. 350 criteria. Detached elements and debris from System No. 2 did not penetrate nor show potential for penetrating the occupant compartment. Deformations of, or intrusion into, the occupant compartment did occur as the roof was indented slightly downward toward the occupant compartment. However, the insignificant roof deformation was acceptable. The vehicle's trajectory did not intrude into adjacent traffic lanes.

0.000 sec

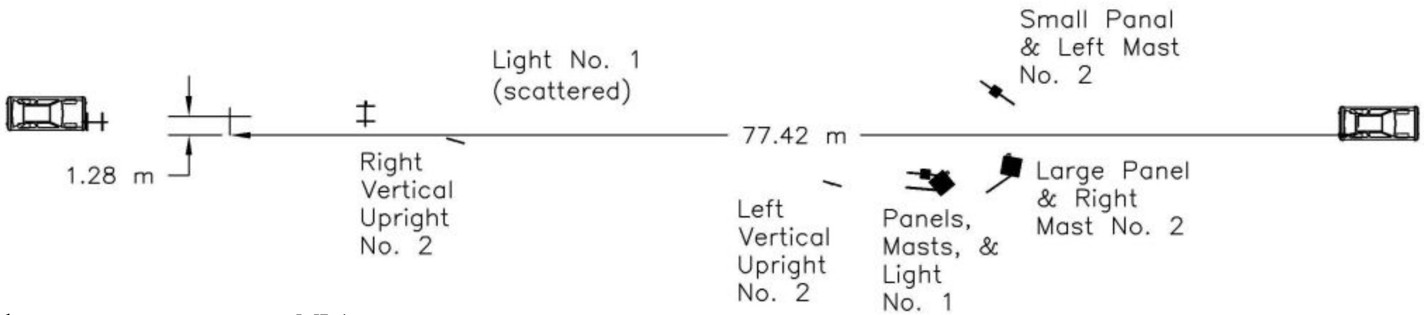
0.030 sec

0.048 sec



0.090 sec

0.128 sec

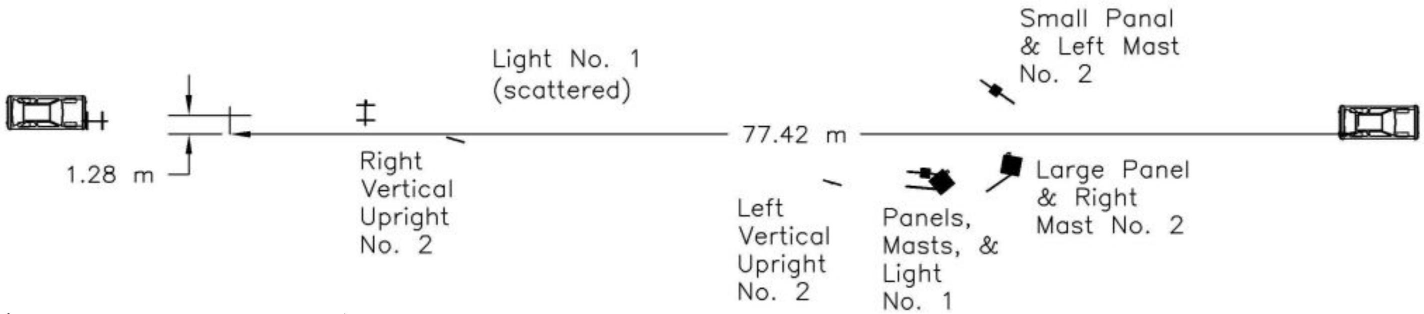


• Test Number	MI-1
• System Number	1
• Date	11/6/01
• Test Article	
Type	Traffic Control Device – Steel Sign Support With Two Wood Sign Panels and Warning Light
Stand	Portable Mounted Traffic Control Signs
Sign Panel	Rigid Plywood, 1218 x 1219 x 15.9-mm thick
Height above ground	1,530 mm to panel bottom
Speed Advisory Sign Panel	Rigid Plywood, 609 x 610 x15.9-mm thick
Height above ground	911 mm to panel bottom
Warning Light	"Work Safe Supply" Type A Light
Key Elements	
Size and/or dimension	3.3 m high
Material	Telespar Steel Tubing
Orientation	End-on with right quarter point
• Soil Type	On dry pavement
• Vehicle Model	1996 Geo Metro
Curb	702 kg
Test Inertial	813 kg
Gross Static	888 kg

• Vehicle Speed	
Impact	102.9 km/hr
Exit	NA
• Vehicle Angle	
Impact	90 deg
Exit	90 deg
• Vehicle Stability	Satisfactory
• Occupant Ridedown Deceleration (10 msec avg.)	
Longitudinal	NA
Lateral (not required)	NA
• Occupant Impact Velocity (Normalized)	
Longitudinal	NA
Lateral (not required)	NA
• Vehicle Damage	Roof and windshield penetration
TAD[27]	12-FR-1
SAE[28]	12-FRAN9
• Vehicle Stopping Distance	77.42 m downstream 1.28 m right
• Test Article Damage	Moderate – Broke apart

Figure 22. Summary of Test Results and Sequential Photographs, Test MI-1, Impact No. 1

0.000 sec 0.028 sec 0.048 sec 0.092 sec 0.110 sec



- Test Number MI-1
- System Number 2
- Date 11/6/01
- Test Article
    - Type . . . . Traffic Control Device – Steel Sign Support With Two Wood Sign Panels and Warning Light
    - Stand . . . . Portable Mounted Traffic Control Signs
    - Sign Panel . . . . Rigid Plywood, 1218 x 1219 x 15.9-mm thick
        - Height above ground . . . . 1,530 mm to panel bottom
    - Speed Advisory Sign Panel . . . Rigid Plywood, 609 x 610 x15.9-mm thick
        - Height above ground . . . . 911 mm to panel bottom
    - Warning Light . . . . “Work Safe Supply” Type A Light
    - Key Elements
        - Size and/or dimension . . . 3.3 m high
        - Material . . . . Telespar Steel Tubing
    - Orientation . . . . Head-on with centerline
- Soil Type . . . . On dry pavement
- Vehicle Model . . . . 1996 Geo Metro
    - Curb . . . . 702 kg
    - Test Inertial . . . . 813 kg
    - Gross Static . . . . 888 kg
- Vehicle Speed
    - Impact . . . . 97.0 km/hr
    - Exit . . . . NA
- Vehicle Angle
    - Impact . . . . 0 deg
    - Exit . . . . 0 deg
- Vehicle Stability . . . . Satisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
    - Longitudinal . . . . NA
    - Lateral (not required) . . . . . NA
- Occupant Impact Velocity (Normalized)
    - Longitudinal . . . . NA
    - Lateral (not required) . . . . . NA
- Vehicle Damage . . . . Minimal
    - TAD[27] 12-FC-1
    - SAE[28] 12-FCAW9
- Vehicle Stopping Distance . . . . 77.42 m downstream
  1.28 m right
- Test Article Damage . . . . Moderate – Broke apart

Figure 23. Summary of Test Results and Sequential Photographs, Test MI-1, Impact No. 2

-0.017 sec

-0.017 sec

0.050 sec

0.050 sec

0.083 sec

0.117 sec

0.117 sec

0.184 sec

0.184 sec

0.350 sec

Figure 24. Additional Sequential Photographs, Test MI-1

Figure 25. Documentary Photographs, Test MI-1

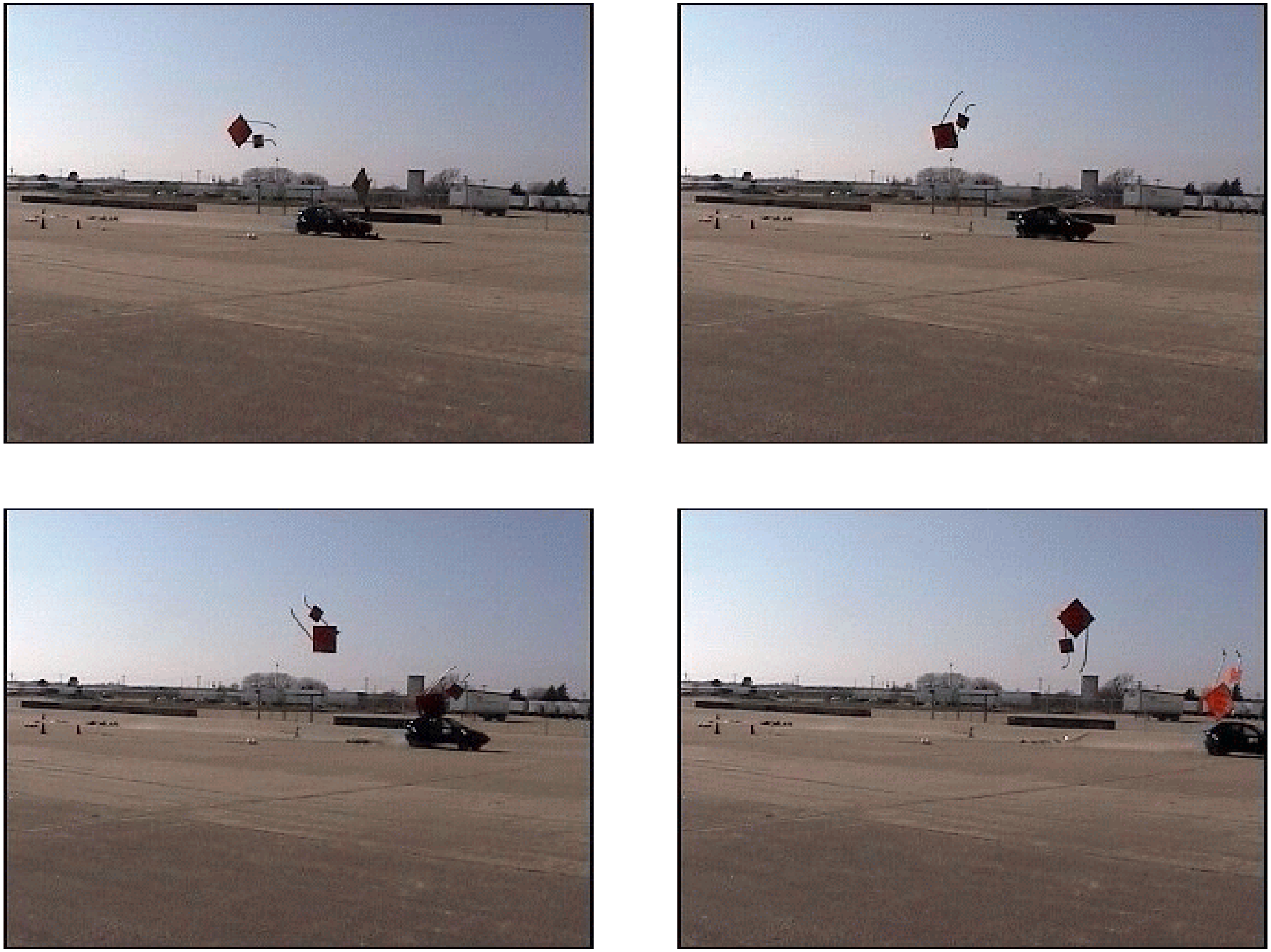


Figure 26. Documentary Photographs, Test MI-1

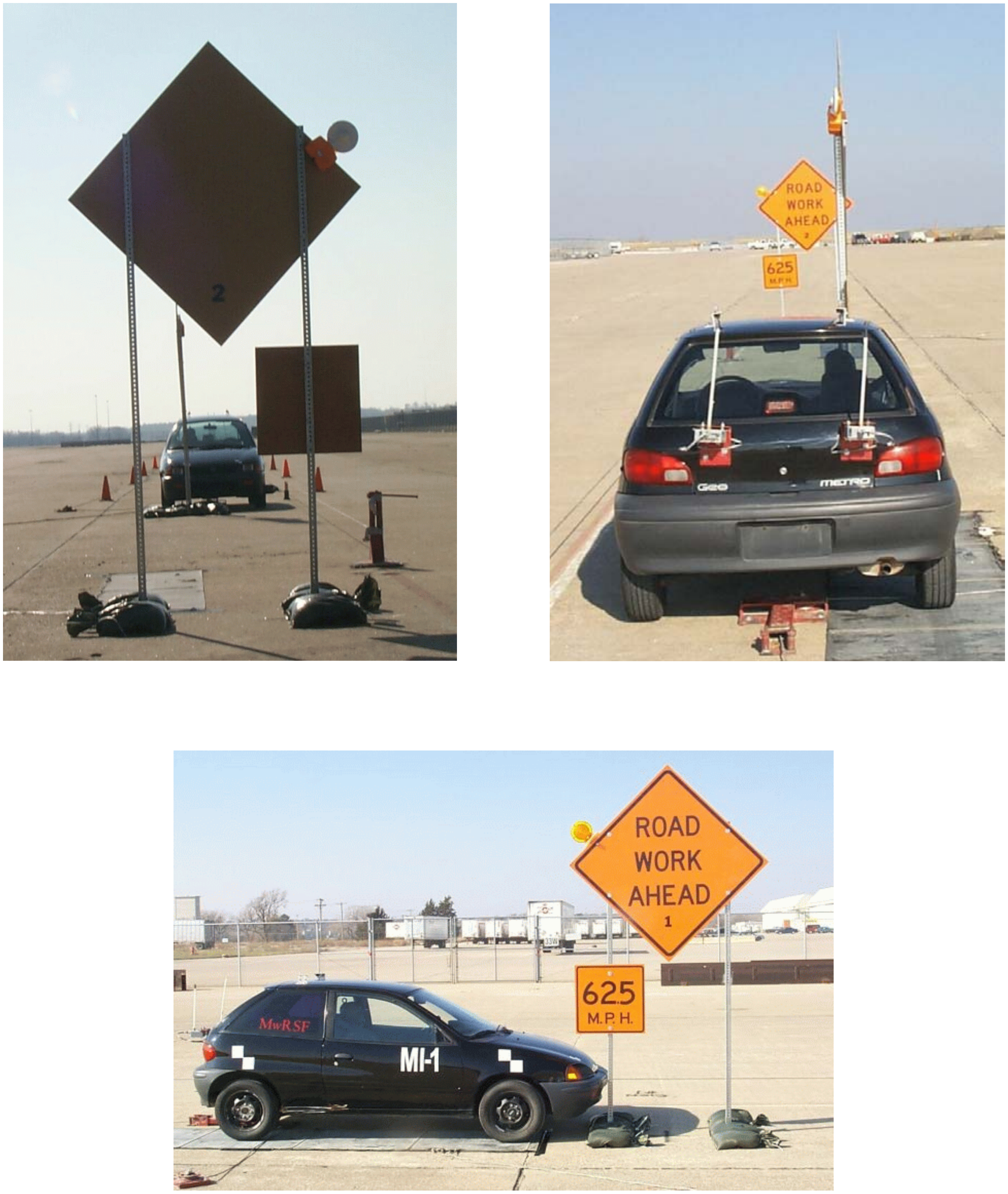


Figure 27. Impact Location, Test MI-1

Figure 28. Overall Damage and Final Positions, Test MI-1

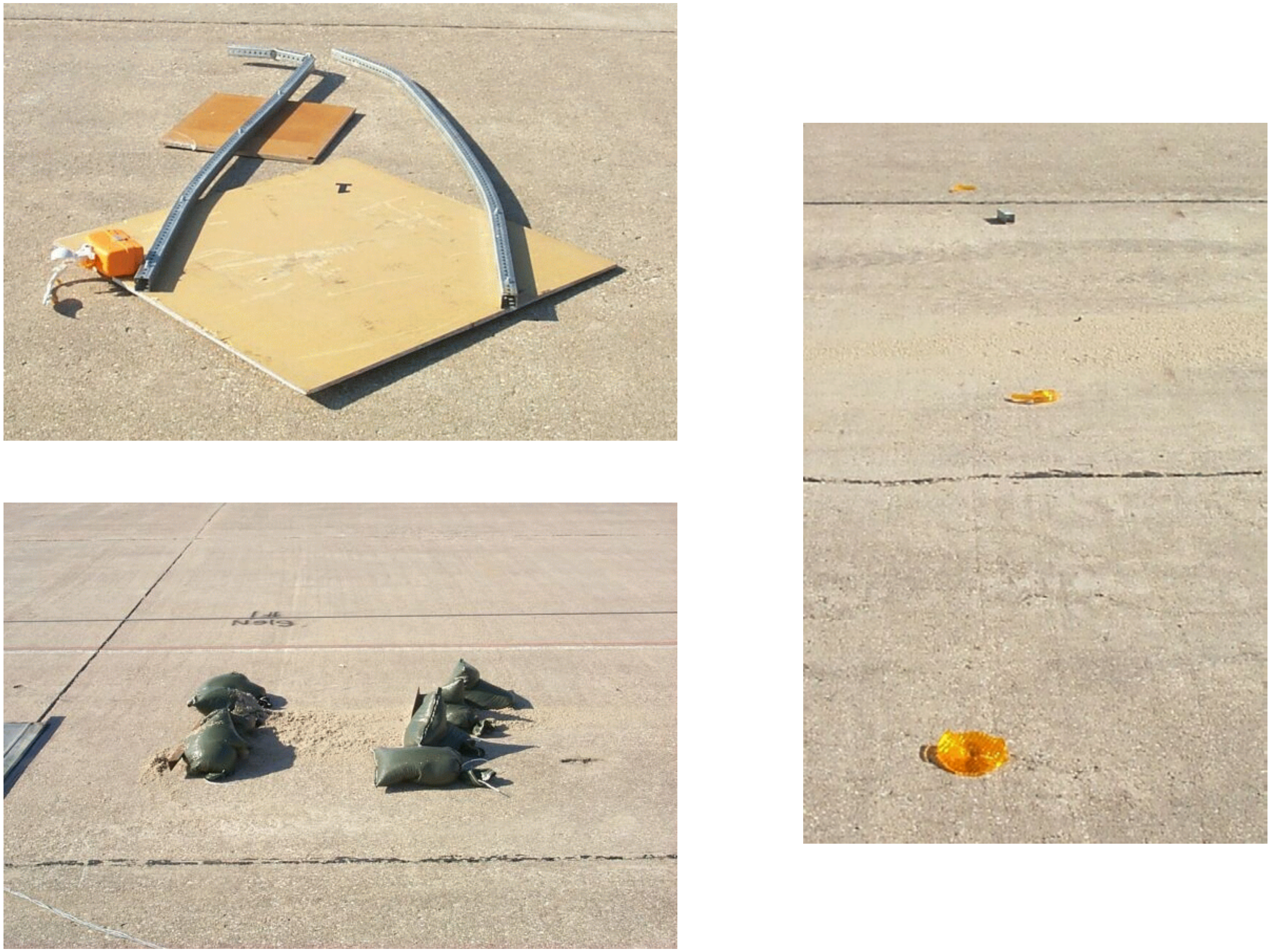


Figure 29. System No. 1 Damage, Test MI-1

Figure 30. System No. 2 Damage, Test MI-1

Figure 31. Vehicle Damage, Test MI-1

Figure 32. Vehicle Roof Damage, Test MI-1

Figure 33. Windshield and Front-End Damage, Test MI-1

6 CRASH TEST NO. 2 (SYSTEM NOS. 3 AND 4)

6.1 Test M-2

The 888-kg small car impacted System No. 3, a Type III barricade oriented head-on to the vehicle, at a speed of 103.2 km/hr and at an angle of 0 degrees. The small car then impacted System No. 4, a Type III barricade oriented end-on to the vehicle, at a speed of 100.1 km/hr and at an angle of 90 degrees. A summary of the test results and the sequential photographs are shown in Figures 34 and 35. Additional sequential photographs are shown in Figure 36. Documentary photographs of the crash tests are shown in Figures 37 and 38.

6.2 Test Description

The test vehicle impacted System No. 3 with the left-front quarter point of the vehicle aligned with the centerline of the barricade's left leg, as shown in Figure 39. At 0.006 sec after initial impact, the impacted mast disengaged from the impacted leg. At this same time, the bottom barricade panel fractured. At 0.018 sec, the impacted mast deformed around the front of the vehicle as the top of this same mast rotated down toward the vehicle. At 0.044 sec, the top of the impacted mast and light contacted the windshield. At this same time, the middle barricade panel was positioned on top of the vehicle's hood. At 0.062 sec, all three of the barricade boards fractured apart as the center warning light and barricade board impacted the rear right-side window. At this same time, the impacted mast remained in contact with the windshield and began to slide upward toward the vehicle's roof. At 0.134 sec, the fractured pieces of the system traveled along with the vehicle. At this same time, the non-impacted mast and leg remained unmoved and positioned behind and alongside the vehicle. At 0.162 sec, the fractured pieces of the system continued to travel in front of and with the vehicle. The non-impacted mast and leg with half the barricade's panels remained at its original position. The impacted leg also remained at its original position. The middle warning light was located 5.79-m downstream and 5.31-m right from the original position. The impacted mast was located 44.81-m downstream and 1.50-m right from the original position. The impact-side warning light came to rest 100.28-m downstream and 0.89-m right from the original position. The impacted leg's vertical upright was located 110.95-m downstream and 2.26-m right from the original position of the barricade system.

Approximately 0.63 sec after impact with System No. 3, the vehicle impacted System No. 4 with the right-front quarter point of the vehicle aligned with the centerline of the barricade, as shown in Figure 39. At 0.006 sec after initial impact, the bottom barricade panel moved away from the vehicle as the vehicle contacted it. At this same time, both masts deformed slightly. At 0.016 sec, the front of the vehicle contacted the impacted mast. At 0.032 sec, the entire system deformed as it traveled away from the vehicle. At 0.046 sec, both masts deformed extensively as the lower barricade panel fractured. At this same time, the impacted mast disengaged from the impacted leg. At 0.064 sec, the middle barricade panel fractured. At this same time, the impacted mast deformed extensively and moved toward the other mast. At 0.086 sec, the middle and top barricade panels contacted the hood and lower portion of the windshield, respectively. At 0.120 sec, the non-impacted mast rotated downward toward the ground. At this same time, the bottom barricade panel contacted the ground as the top barricade panel fractured. At 0.150 sec, the bottom of both masts contacted one another as the entire system encountered major deformation. At 0.188 sec, pieces of the system traveled along with the vehicle. At 0.217 sec, the impacted mast rotated and contacted the lower portion of the windshield. The impacted leg was located 0.91-m downstream and 0.30-m right from the original position. The non-impacted leg was located 14.63-m downstream and 0.61-m right from the original position. The impacted mast was located 43.28-m downstream and 2.13-m right from the original position. A piece of the middle barricade panel came to rest 81.99-m downstream and 7.92-m right from the original position. The top barricade panel, the non-impacted mast, the non-impact-side warning light, and the middle warning light still attached were located 91.14-m downstream and 6.71-m right from the original position. The impact-side warning light was located 97.69-m downstream and 2.29-m right from the original position of the barricade. Pieces of debris from both systems were scattered in a patterned bound by 13.72-m and 67.06-m downstream, 14.20-m left, and 22.07-m right from the original position of the first system. The vehicle subsequently came to rest 92.81-m downstream from the longitudinal midpoint of the two impact points and 6.92-m right from the centerline of the vehicle's original path. The final positions of the vehicle and the sign supports are shown in Figures 34, 35, and 40.

6.3 System and Component Damage

Damage to System Nos. 3 and 4 is shown in Figures 40 through 44. System No. 3 encountered moderate damage. The non-impacted mast, leg, and warning light remained intact with half of all three barricade panels and undamaged. The impacted leg disengaged from the mast. The welds holding the vertical tubes to the impacted leg fractured, causing the tube to be disengaged from the angle leg. The impacted mast was disengaged from the rest of the system and was deformed at the bumper height. The warning lights near the impacted mast and at the center of the barricade disengaged from the rest of the system. The barricade panels fractured into many small pieces and were scattered downstream. Two of the sandbags were torn open with the sand scattered along the path of the vehicle, starting at the initial position of the first barricade. The other six sandbags remained undamaged.

System No. 4 encountered moderate damage. Both legs disengaged from the masts. The impacted leg fractured at the bumper height and disengaged from the rest of the system. The non-impacted leg and a portion of the top barricade panel along with the middle and nonimpact-side warning lights remained attached. The impact-side warning light disengaged from the top barricade panel. The barricade panels fractured into many small pieces and were scattered downstream from the original position. All eight of the sandbags were torn open with the sand scattered along the path of the vehicle, starting at the initial position of the second barricade.

6.4 Vehicle Damage

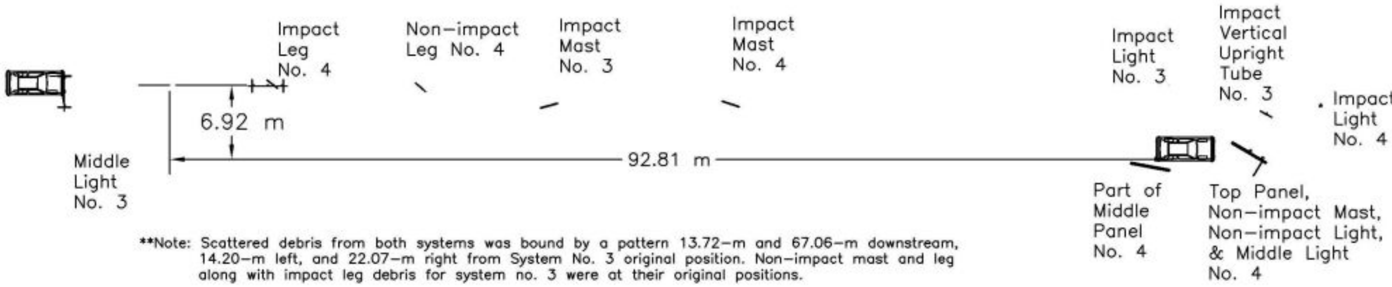
Exterior vehicle damage is shown in Figures 45 through 47. The vehicle sustained significant front-end damage. The bumper was deformed and pushed inward toward the radiator. The hood encountered dents and major scrape marks. The right-side quarter point of the hood also encountered a buckle point. The right-side fog light broke and the park light was removed from the light housing. The windshield sustained major "spider web" cracking throughout, with both layers of the windshield being cracked. Major indentation and penetration through the windshield was located near the central region of the left side. The right-rear window was shattered. Part of the lower barricade panel was embedded in the right-side of the engine compartment. No damage was found to have occurred to the roof, rear-end, headlights, nor the left-side fog and parking lights.

6.5 Discussion

Following test MI-2, a safety performance evaluation was conducted, and the work-zone traffic control device, System No. 3, was determined to be unacceptable according to the NCHRP Report No. 350 criteria. It was deemed unacceptable due to the "spider web" cracking, indentation, and hole in the windshield, resulting in obstructed drive visibility and loss of structure of both glass layers. In addition, deformation of, or intrusion into, the occupant compartment did occur as detached elements and debris from System No. 3 penetrated the left region of the windshield and the right-rear side window.

System No. 4 was determined to be acceptable according to the NCHRP Report No. 350 criteria. Detached elements and debris from System No. 4 did not penetrate nor show potential for penetrating the occupant compartment. Deformations of, or intrusion into, the occupant compartment did not occur. The vehicle’s trajectory did not intrude into adjacent traffic lanes.

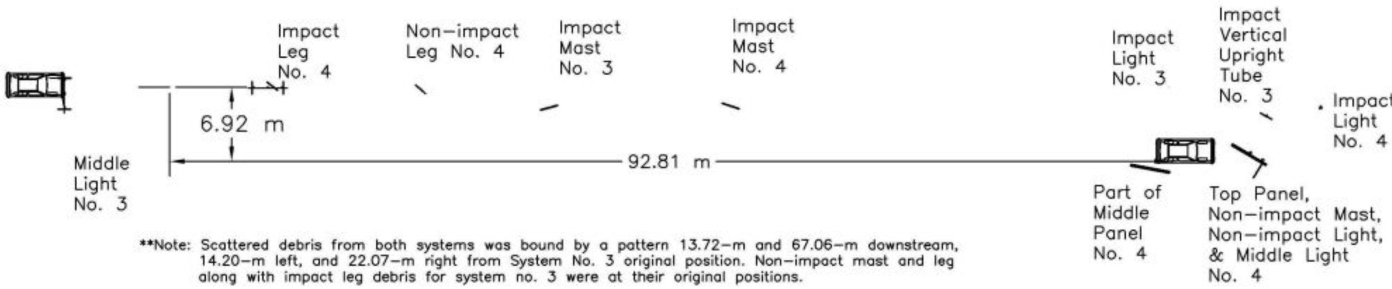
0.000 sec 0.018 sec 0.062 sec 0.106 sec 0.134 sec



- Test Number MI-2
- System Number 3
- Date 11/6/01
- Test Article
  - Type . . . . Traffic Control Device – Wood and Steel Type III Barricade with Warning Lights
  - Stand Name . . . . Michigan's Type III Barricade
  - Warning Lights . . . . "Work Safe Supply" Type A Light
  - Key Elements
    - Size and/or dimension . 1.8 m high
    - Material . . . . Telespar Steel Tubing; Wood Barricade Panels
  - Orientation . . . . Head-on with left quarter point
- Soil Type . . . . On dry pavement
- Vehicle Model . . . . 1996 Geo Metro
  - Curb . . . . 794 kg
  - Test Inertial . . . . 813 kg
  - Gross Static . . . . 888 kg
- Vehicle Speed
  - Impact . . . . 103.2 km/hr
  - Exit . . . . NA
- Vehicle Angle
  - Impact . . . . 0 deg
  - Exit . . . . 0 deg
- Vehicle Stability . . . . Satisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
  - Longitudinal . . . . NA
  - Lateral (not required) . . . . . . NA
- Occupant Impact Velocity (Normalized)
  - Longitudinal . . . . NA
  - Lateral (not required) . . . . . . NA
- Vehicle Damage . . . . Windshield and side window penetration
  - TAD[27] 12-FL-1
  - SAE[28] 12-FLEN5
- Vehicle Stopping Distance . . . . . 92.81 m downstream; 6.92 m right
- Test Article Damage . . . . Moderate – Broke apart

Figure 34. Summary of Test Results and Sequential Photographs, Test MI-2, Impact No. 1

0.000 sec | 0.046 sec | 0.086 sec | 0.120 sec | 0.150 sec



- Test Number MI-2
- System Number 4
- Date 11/6/01
- Test Article
  - Type . . . . Traffic Control Device – Wood and Steel Type III Barricade with Warning Lights
  - Stand Name . . . . Michigan's Type III Barricade
  - Warning Lights . . . . "Work Safe Supply" Type A Light
  - Key Elements
    - Size and/or dimension . 1.8 m high
    - Material . . . . Telespar Steel Tubing
Wood Barricade Panels
  - Orientation . . . . End-on with right quarter point
- Soil Type . . . . On dry pavement
- Vehicle Model . . . . 1996 Geo Metro
  - Curb . . . . 794 kg
  - Test Inertial . . . . 813 kg
  - Gross Static . . . . 888 kg
- Vehicle Speed
  - Impact . . . . 100.1 km/hr
  - Exit . . . . NA
- Vehicle Angle
  - Impact . . . . 90 deg
  - Exit . . . . 90 deg
- Vehicle Stability . . . . Satisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
  - Longitudinal . . . . NA
  - Lateral (not required) . . . . . . NA
- Occupant Impact Velocity (Normalized)
  - Longitudinal . . . . NA
  - Lateral (not required) . . . . . . NA
- Vehicle Damage . . . . Minimal
  - TAD[27] 12-FR-2
  - SAE[28] 12-FRAN6
- Vehicle Stopping Distance . . . . . 92.81 m downstream
6.92 m right
- Test Article Damage . . . . Moderate – Broke apart

Figure 35. Summary of Test Results and Sequential Photographs, Test MI-2, Impact No. 2

0.000 sec

0.017 sec

0.033 sec

0.050 sec

0.067 sec

0.117 sec

0.133 sec

0.184 sec

0.200 sec

0.250 sec

Figure 36. Additional Sequential Photographs, Test MI-2

Figure 37. Documentary Photographs, Test MI-2

Figure 38. Documentary Photographs, Test MI-2

Figure 39. Impact Locations, Test MI-2

Figure 40. Overall Damage and Final Positions, Test MI-2

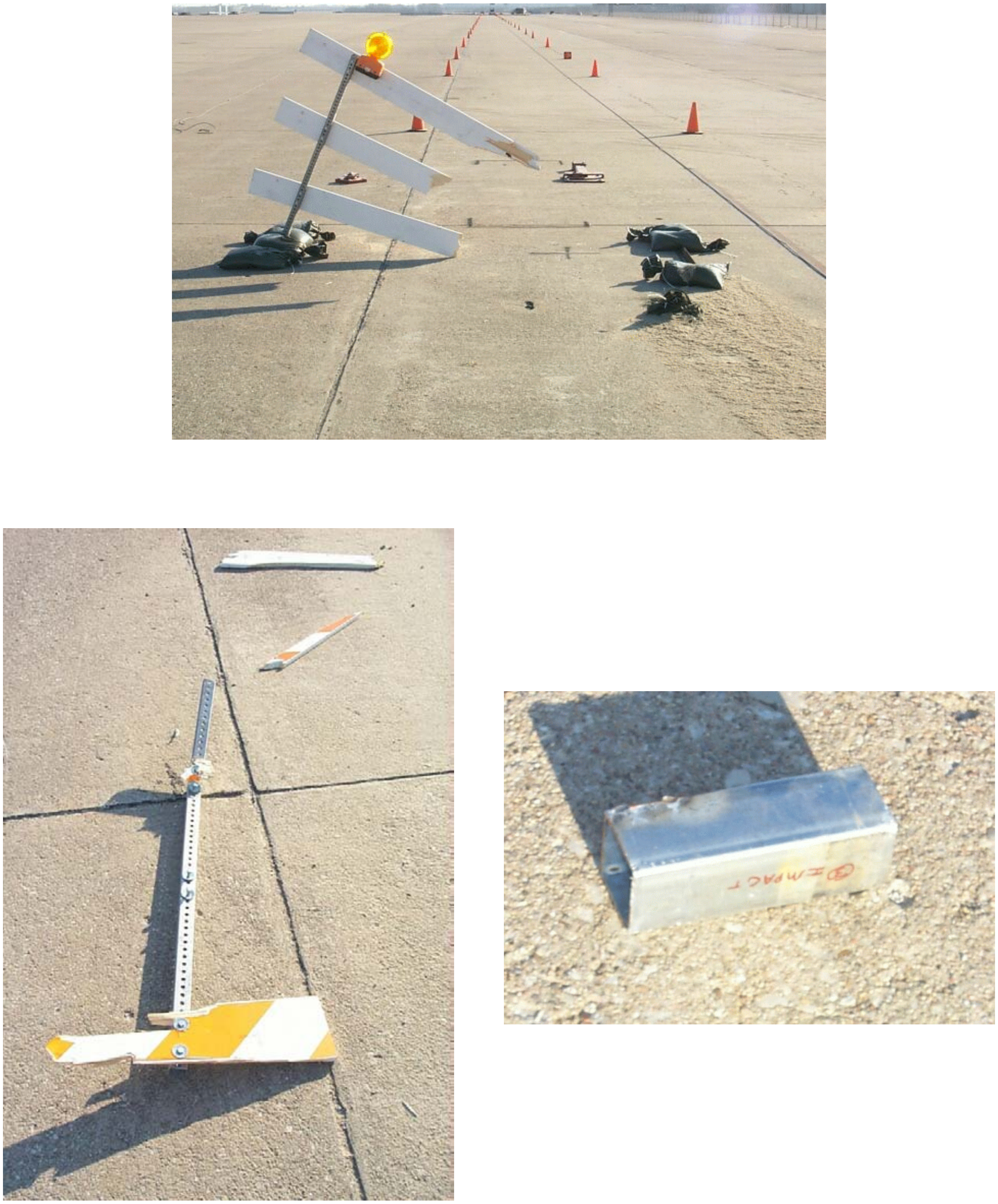


Figure 41. System No. 3 Damage, Test MI-2

Figure 42. System No. 3 Damage, Test MI-2

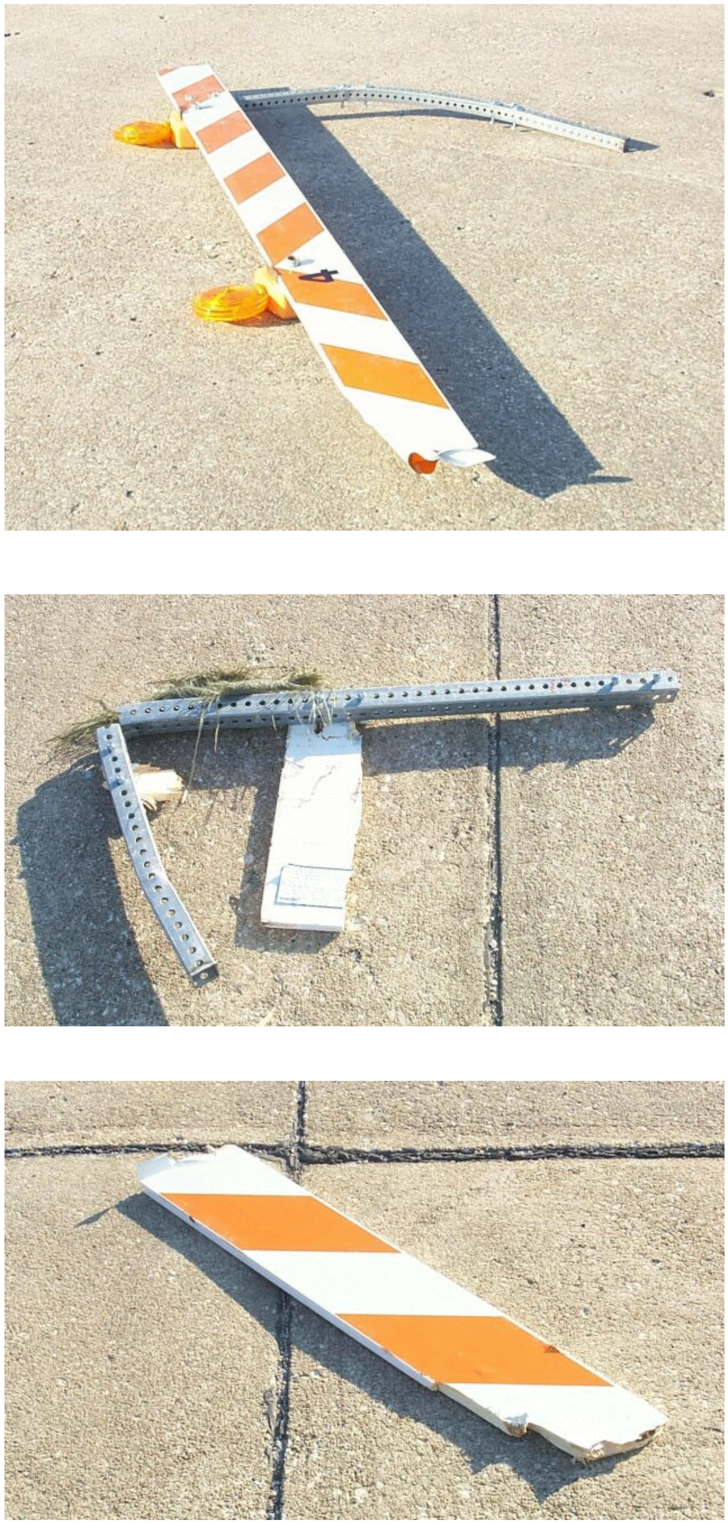


Figure 43. System No. 4 Damage, Test MI-2

Figure 44. System No. 4 Damage, Test MI-2

Figure 45. Vehicle Damage, Test MI-2

Figure 46. Vehicle Damage, Test MI-2

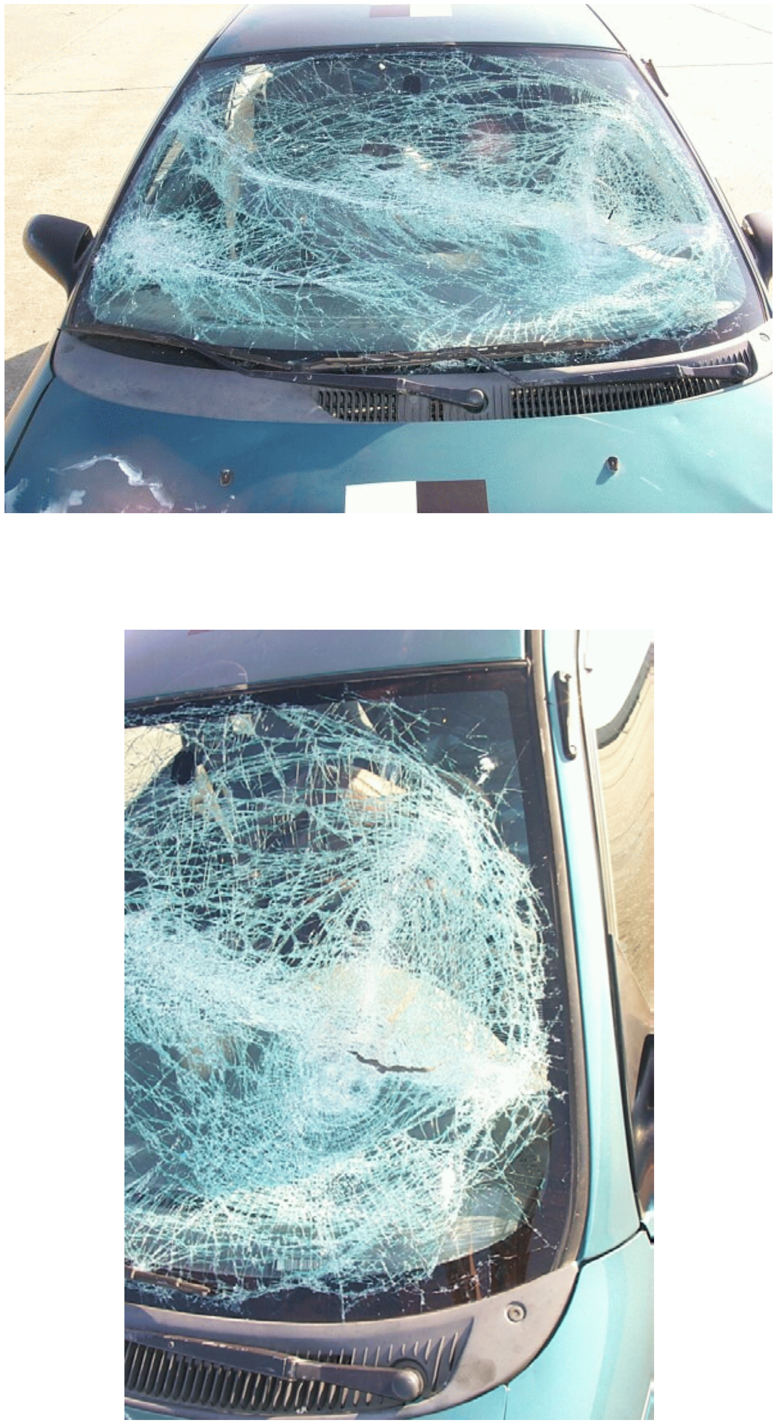


Figure 47. Windshield Damage, Test MI-2

7 DISCUSSION AND DESIGN MODIFICATIONS

7.1 Tall-Mounted, Rigid Panel Sign Support with Speed Advisory Panel and Warning Light

7.1.1 Test MI-1 Discussion and Proposed Design Modifications

A dual-mast, portable sign support system, which utilized wood panels and one warning light, was crash tested according to the NCHRP Report No. 350 safety standards. This system's safety performance was acceptable at the 0-degree orientation but unacceptable at the 90-degree orientation. Thus, any changes geared toward improving its performance for 90-degree impacts should consider their effects on the system at the 0-degree orientation. During the 90-degree impact event, the vehicle struck the left mast, causing it to deform around the vehicle's front-end before it released off of the leg support. This release did not occur quickly as its behavior was dependent upon significant mast deformation to allow it to lift up and off of the rotated lower stub. As a result, the upper and lower sign panels contacted and penetrated the roof and windshield, respectively. Additional discussion as well as recommended design changes are provided in two letters sent to Mr. Jeff Grossklaus of the Michigan Department of Transportation (MDOT) on November 12, 2001 and November 30, 2001, as provided in Appendix E.

7.2 Type III Barricades with Warning Lights

7.2.1 Test MI-2 Discussion and Proposed Design Modifications

A Type III barricade, which utilized 3.66-m long wood panels and three warning lights attached to the top panel, was crash tested according to the NCHRP Report No. 350 safety standards. This system's safety performance was acceptable at the 90-degree orientation but unacceptable at the 0-degree orientation. Thus, any changes geared toward improving its performance for 0-degree impacts should consider their effects on the system at the 90-degree orientation. During the 0-degree impact event, the vehicle struck the left mast, causing it to deform around the vehicle's front-end before it released off of the leg support. Once again, this release did not occur quickly as its behavior was dependent upon significant mast deformation before a sufficient load was transferred to the welded stub to cause it to fracture away from the leg. As a result, the left light assembly and upper part of the mast struck and penetrated the windshield.

In addition, there were two other phenomena that presented potential for increased safety performance. First, besides the windshield failure, the right-side rear window was also penetrated as the middle light assembly and upper panel's fractured end passed by and struck the window glass. The researchers felt that it was prudent to address the problems associated with the system's poor performance at the front windshield before addressing this issue. Secondly, the 90-degree impact condition exhibited a unique behavior that had not been observed in other testing scenarios. During the impact, the lower panel actually penetrated through the bumper and a panel fragment came to rest within the engine compartment. Although this penetration was observed, it is noted that this behavior does not constitute a failure at the 90-degree orientation. Any improvements in the breakaway or release of the mast from the base will decrease the potential for this behavior. Additional discussion as well as recommended design changes are provided in two letters sent to Mr. Jeff Grossklaus of the MDOT on November 12, 2001 and November 30, 2001, as provided in Appendix E.

8 CRASH TEST NO. 3 (SYSTEM NOS. 5 AND 6)

8.1 Test MI-3

The 896-kg small car impacted System No. 5, a sign support with a diamond-shaped plywood panel oriented end-on to the vehicle, at a speed of 101.0 km/hr and at an angle of 90 degrees. The small car then impacted System No. 6, a sign support with a diamond-shaped plywood panel oriented head-on to the vehicle, at a speed of 91.3 km/hr and at an angle of 0 degrees. A summary of the test results and the sequential photographs are shown in Figures 48 and 49. Additional sequential photographs are shown in Figure 50. Documentary photographs of the crash tests are shown in Figures 51 and 52.

8.2 Test Description

The test vehicle impacted System No. 5 with the right-front quarter point of the vehicle aligned with the centerline of the sign support, as shown in Figure 53. At 0.008 sec after initial impact, the impacted leg deformed and moved toward the non-impacted leg. At 0.036 sec, the impacted leg contacted the other leg which began to travel away from the vehicle. At this same time, the sign panel rotated CCW toward the vehicle. At 0.060 sec, both legs became airborne. At 0.084 sec, the sign panel rotated CCW approximately 45 degrees. At 0.090 sec, the warning light impacted the right side of the roof. At 0.148 sec, the system stopped rotating CCW with the deformed legs airborne and lodged under the bumper. Shortly after this time, the legs disengaged from the masts as the non-impact mast disengaged from the sign panel. At 0.256 sec, the sign panel lost contact with the roof. The warning light box was located 25.30-m downstream and 11.56-m right from the original position. The light portion of the warning light was located 28.04-m downstream and 2.62-m left from the original position. The sign panel came to rest 37.64-m downstream and 8.97-m right from the original position. The angle portion of the non-impacted leg was located 48.16-m downstream and 7.14-m right from the original position. The vertical upright tube of the non-impacted leg was located 67.97-m downstream and 5.77-m right from the original position. The non-impacted mast was located 76.50-m downstream and 2.41-m right from the original position. The impacted mast and leg were located 103.63-m downstream and 0.33-m left from the original position of the sign support.

Approximately 0.69 sec after impact with System No. 5, the vehicle impacted System No. 6 with the centerline of the vehicle aligned with the centerline of the sign support, as shown in Figure 53. At 0.006 sec after initial impact, the right-side mast deformed and the lower-right sign panel bolt pulled through the sign panel. At 0.018 sec, the upper-right sign panel bolt pulled through the sign panel and completely released the sign panel from the right mast. At 0.022 sec, the sign panel contacted the mast from the first system. At this same time, the right mast traveled along in front of the vehicle. At 0.050 sec, the sign panel rotated parallel to the vehicle as it impacted the other mast from the first system. At 0.134 sec, the sign panel and the left mast rotated down toward the left side near the rear of the vehicle. At this same time, the right mast and leg traveled along in front of the vehicle. At 0.254 sec, the sign panel descended toward the ground behind the vehicle. The sign panel, warning light, left mast, left outer tube, and vertical upright tube of the left leg, which were all still attached, were located 6.10-m downstream and 0.30-m left from the original position. The angle portion of the left leg was located 41.00-m downstream and 3.81-m left from the original position. The right mast, outer tube, and leg all intact were located 70.10-m downstream and 0.61-m left from the original position. The vehicle subsequently came to rest 93.42-m downstream from the longitudinal midpoint of the two impact points and 2.98-m left from the centerline of the vehicle's original path. The final positions of the vehicle and the sign supports are shown in Figures 48, 49, and 54.

8.3 System and Component Damage

Damage to System Nos. 5 and 6 is shown in Figures 54 through 59. System No. 5 encountered moderate damage. The impacted mast, outer tube, and leg remained attached, and the top of the mast encountered minor deformations. The legs' angles were deformed into approximate 90 degree angles. The non-impacted leg disengaged from the mast and outer tube. The non-impacted leg's vertical upright tube disengaged from the angle portion due to fracture of the welds. The sign panel disengaged from both masts. The sign panel encountered scuff and scrape marks as well as damage to the impact-side corner. The light portion of the warning light broke off and the bottom box portion disengaged from the sign panel. Two of the sandbags were torn open with the sand scattered along the path of the vehicle, starting at the initial position of the first sign support. The other two sandbag remained undamaged.

System No. 6 encountered moderate damage. The right mast, outer tube, and leg remained attached, and the mast encountered minor deformations. The left leg disengaged from the mast and outer tube. The left leg's vertical upright tube disengaged from the undeformed angle portion but remained attached to the mast. The sign panel disengaged from both masts and encountered minor scuff and scrape marks. The warning light remained intact and attached to the sign panel. The sandbags were torn open with the sand scattered along the path of the vehicle, starting at the initial position of the second sign support.

8.4 Vehicle Damage

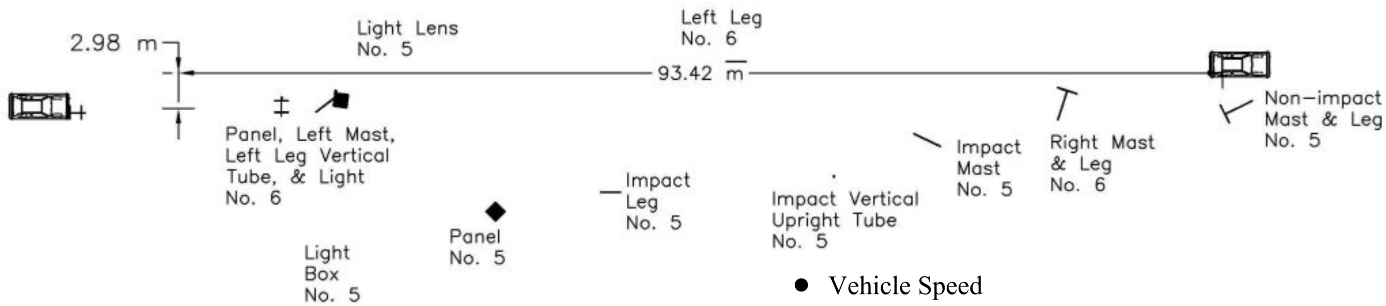
Exterior vehicle damage is shown in Figures 60 through 62. The vehicle sustained significant front-end damage. Light contact marks were found on the front bumper, the hood, the roof, and the left-side door. The bumper, grill, and radiator were deformed and pushed inward toward the engine compartment. The right-quarter point of the hood encountered a buckle point and major deformation. The front-right quarter point of the roof was indented near the roof/windshield interface. The right-side of the roof was indented a maximum of 95 mm at 445-mm back from the top of the windshield and 114-mm inward from the roof's right edge. The right-side mirror fractured off while the glass from the left-side mirror was disengaged. The upper-right region of the windshield sustained "spider web" cracking of the glass but without a concentrated impact point or indentation. However, the degree of cracking was judged insufficient to hinder visibility nor cause weak spots in both layers of glass. No damage was found to have occurred to the rear-end, headlights, fog lights, nor parking lights.

8.5 Discussion

Following test MI-3, a safety performance evaluation was conducted, and the work-zone traffic control devices, System Nos. 5 and 6, were determined to be acceptable according to the NCHRP Report No. 350 criteria. Detached elements and debris from the traffic control systems did not penetrate nor show potential for penetrating the occupant compartment. Deformations of, or intrusion into, the occupant compartment did occur as the roof was indented slightly downward toward the occupant compartment. However, the 95-mm roof deformation was acceptable since the vehicle can sustain roof deformations which are less than 152 mm (27). The vehicle's trajectory did not intrude into adjacent traffic lanes. Additional discussion was provided in a letter sent to Mr. Jeff Grossklaus of the MDOT on October 11, 2002, as shown in Appendix E.

It should be noted that the impact speed for System No. 6 was measured to be approximately 91.3 km/hr or 8.7 km/hr less than the 100.0 km/hr target speed. Although, this lower impact speed decreased the actual impact severity of the test, it is not believed that the system would have performed any differently with a higher impact speed. It is also believed that an increased potential for occupant compartment deformation or intrusion would not occur. Furthermore, the panel's dynamic behavior is not believed to be significantly different from that observed during a test of an almost identical system. In Test No. MI-1, System No. 2, the panel was not dislodged from the masts, and the masts deformed around the vehicle's front-end. This deformation and mast rotation resulted in the panel contacting the vehicle's roof but without any significant damage to the roof. Therefore, even with the reduced impact speed, the crash test results are believed to be a valid indicator of the system's safety performance.

0.000 sec | 0.036 sec | 0.060 sec | 0.090 sec | 0.148 sec



- Test Number MI-3
- System Number 5
- Date 10/8/02
- Test Article
  - Type . . . . Traffic Control Device – Steel Sign Support With Wood Sign Panel and Warning Light
  - Stand . . . . Modified Portable Mounted Traffic Control Sign
  - Sign Panel . . . . Rigid Plywood, 1219 x 1219 x 15.9-mm thick
    - Height above ground . . 1,540 mm to panel bottom
  - Warning Light . . . . "Empco-Lite", Model No. 400
  - Key Elements
    - Size and/or dimension . 3.3 m high
    - Material . . . . Telespar Steel Tubing
  - Orientation . . . . End-on with right quarter point
- Soil Type . . . . On dry pavement
- Vehicle Model . . . . 1996 Geo Metro
  - Curb . . . . 814 kg
  - Test Inertial . . . . 820 kg
  - Gross Static . . . . 896 kg
- Vehicle Speed
  - Impact . . . . 101.0 km/hr
  - Exit . . . . NA
- Vehicle Angle
  - Impact . . . . 90 deg
  - Exit . . . . 90 deg
- Vehicle Stability . . . . Satisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
  - Longitudinal . . . . NA
  - Lateral (not required) . . . . . NA
- Occupant Impact Velocity (Normalized)
  - Longitudinal . . . . NA
  - Lateral (not required) . . . . . NA
- Vehicle Damage . . . . Minor roof indentation
  - TAD[27] 12-FR-2
  - SAE[28] 12-FRAN9
- Vehicle Stopping Distance . . . . 93.42 m downstream, 2.98 m left
- Test Article Damage . . . . Moderate – Broke apart

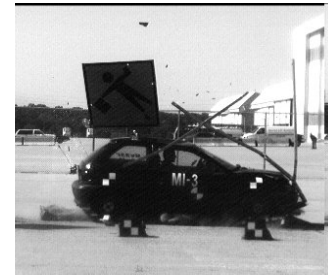
Figure 48. Summary of Test Results and Sequential Photographs, Test MI-3, Impact No. 1

0.000 sec

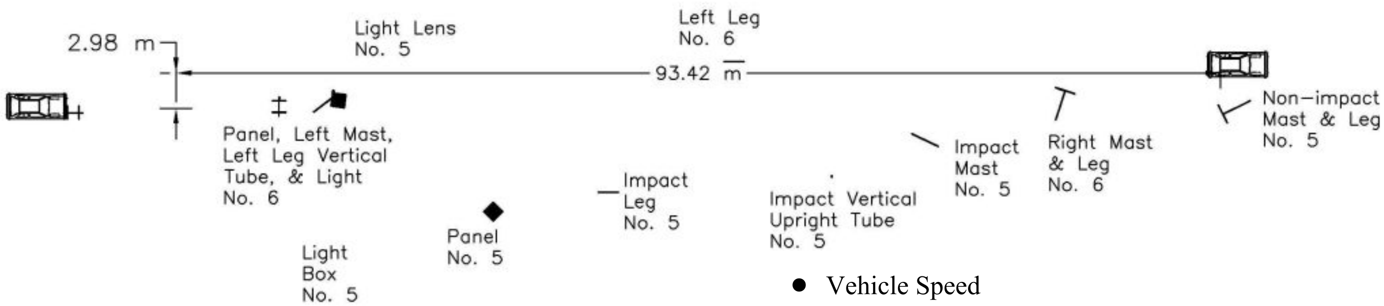
0.006 sec

0.018 sec

0.050 sec



0.134 sec



- Test Number MI-3
- System Number 6
- Date 10/8/02
- Test Article
  - Type . . . . Traffic Control Device – Steel Sign Support With Wood Sign Panel and Warning Light
  - Stand . . . . Modified Portable Mounted Traffic Control Sign
  - Sign Panel . . . . Rigid Plywood, 1219 x 1219 x 15.9-mm thick
    - Height above ground . . 1,540 mm to panel bottom
  - Warning Light . . . . “Empco-Lite”, Model No. 400
  - Key Elements
    - Size and/or dimension . 3.3 m high
    - Material . . . . Telespar Steel Tubing
  - Orientation . . . . Head-on with centerline
- Soil Type . . . . On dry pavement
- Vehicle Model . . . . 1996 Geo Metro
  - Curb . . . . 814 kg
  - Test Inertial . . . . 820 kg
  - Gross Static . . . . 896 kg
- Vehicle Speed
  - Impact . . . . 91.3 km/hr
  - Exit . . . . NA
- Vehicle Angle
  - Impact . . . . 0 deg
  - Exit . . . . 0 deg
- Vehicle Stability . . . . Satisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
  - Longitudinal . . . . NA
  - Lateral (not required) . . . . . NA
- Occupant Impact Velocity (Normalized)
  - Longitudinal . . . . NA
  - Lateral (not required) . . . . . NA
- Vehicle Damage . . . . Minimal
  - TAD[27] 12-FC-3
  - SAE[28] 12-FCEW5
- Vehicle Stopping Distance . . . . 93.42 m downstream, 2.98 m left
- Test Article Damage . . . . Moderate – Broke apart

Figure 49. Summary of Test Results and Sequential Photographs, Test MI-3, Impact No. 2

-0.017 sec

0.050 sec

0.083 sec

0.117 sec

0.184 sec

Figure 50. Additional Sequential Photographs, Test MI-3

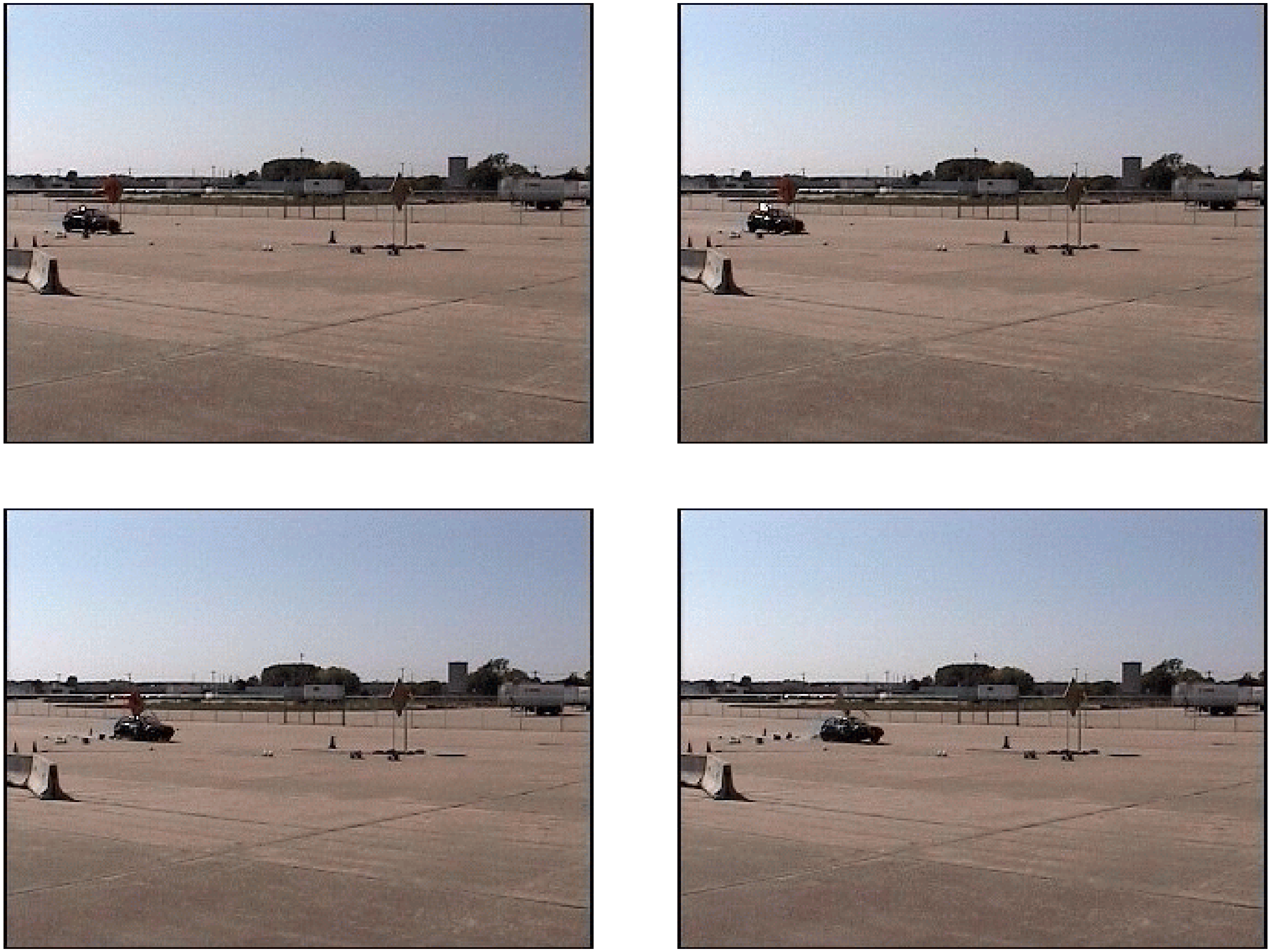


Figure 51. Documentary Photographs, Test MI-3

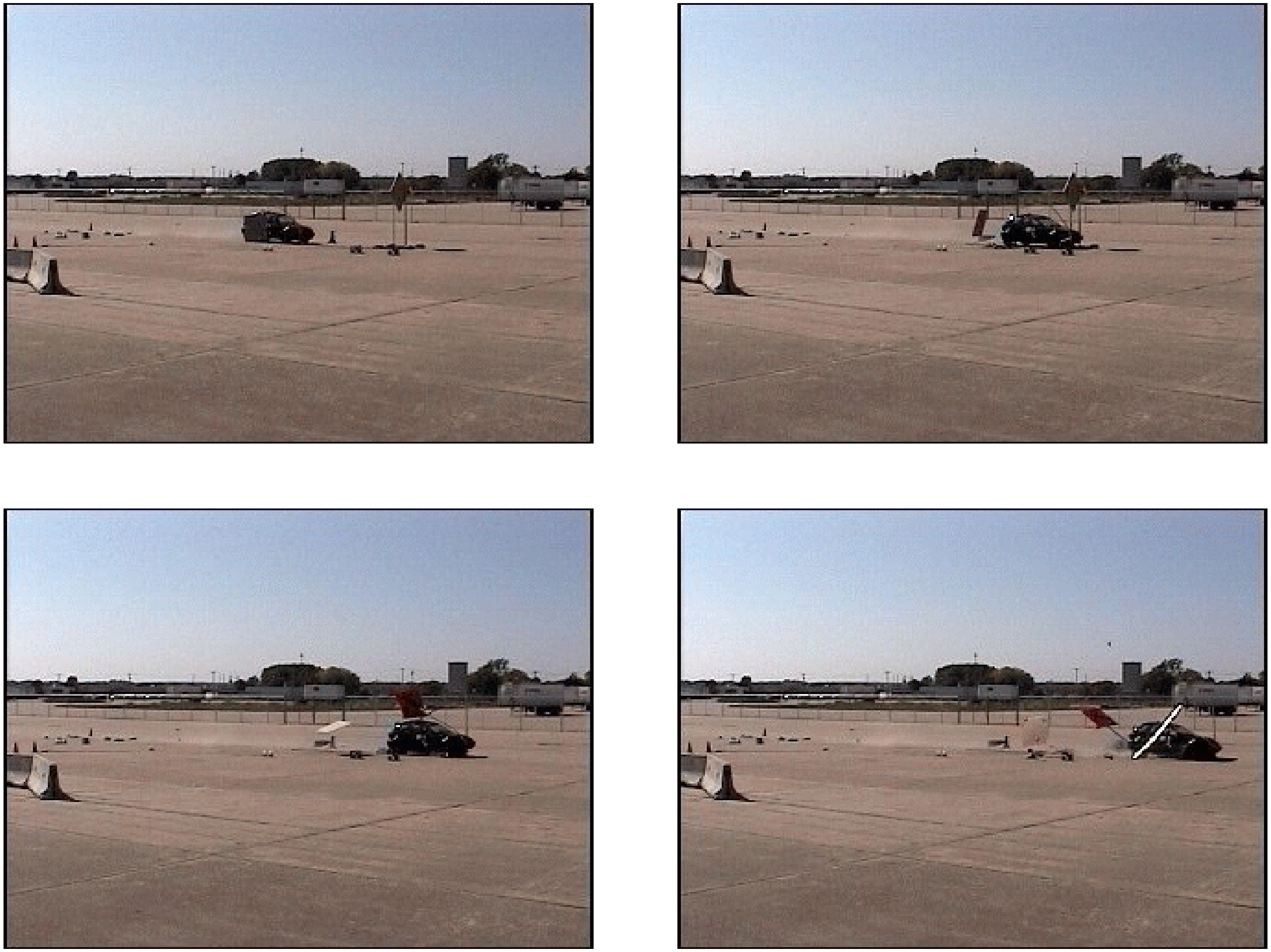


Figure 52. Documentary Photographs, Test MI-3

Figure 53. Impact Location, Test MI-3

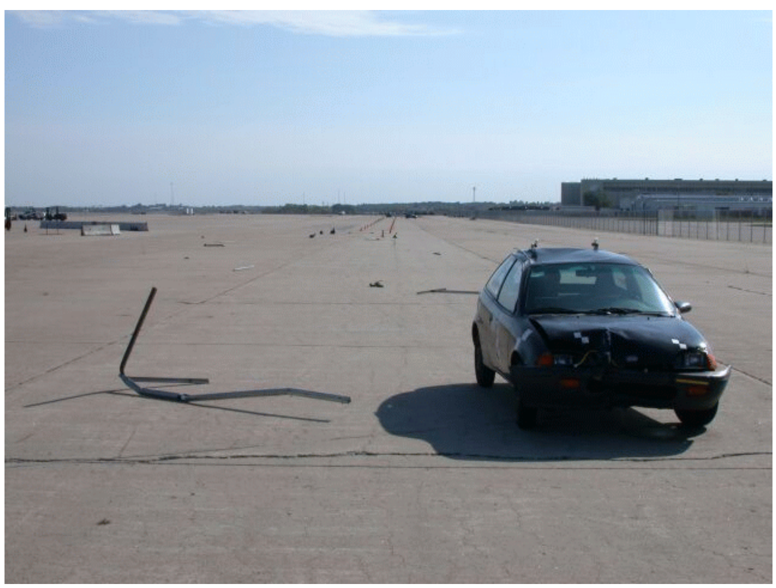


Figure 54. Overall Damage and Final Positions, Test MI-3

Figure 55. System No. 5 Damage, Test MI-3

Figure 56. System No. 5 Damage, Test MI-3

Figure 57. System No. 5 Damage, Test MI-3

Figure 58. System No. 6 Damage, Test MI-3

Figure 59. System No. 6 Damage, Test MI-3

Figure 60. Vehicle Damage, Test MI-3

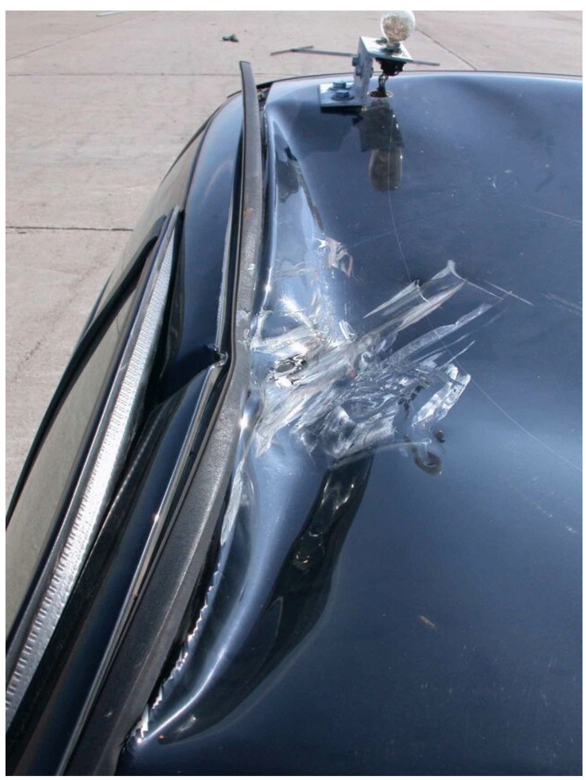


Figure 61. Vehicle Roof Damage, Test MI-3

Figure 62. Windshield and Front-End Damage, Test MI-3

9 DISCUSSION

Following a redesign phase, a full-scale crash test was conducted on Michigan's modified dual-mast, portable sign support system which utilized a wood panel and one warning light according to the NCHRP Report No. 350 safety standards. This system's safety performance was acceptable at both the 0-degree and 90-degree orientations.

During the 90-degree impact event, the vehicle struck the left mast, causing it to deform slightly near the vehicle's front-end as well as near the top of the outer stiffening sleeve. Deformation occurred to the impact-side leg angle as the lower part of the mast was pushed in front of the vehicle. The impact-side leg was held in place by two sandbags. As a result, the impact side of the panel rotated and was pulled down toward the vehicle. Following this, the impact-side corner of the panel with the attached warning light contacted the vehicle's roof. No roof penetration was observed, and the maximum roof crush was measured to be approximately 95 mm which is acceptable according to FHWA.

During the 0-degree impact event, the vehicle struck the right mast, causing it to separate from the sign panel with the panel supported in the air by the left mast. It should be noted that this impact was to have occurred with both masts impacted instead of only one. However, the researchers believe that satisfactory performance would have resulted had both masts been impacted simultaneously for the following reasons. First, the over-sized holes in the panel would have resulted in a similar quick release of both masts from the panel. This response would allow the panel to be temporarily suspended in mid-air with the vehicle traveling underneath the panel. In addition, this quick panel release produces a reduced potential for the panel to be pulled down onto the vehicle. Secondly, even if full release of the masts away from the panel would not occur, the panel's dynamic behavior is not believed to be significantly different from that observed during Test No. MI-1, System No. 2. In the earlier test, the panel was not dislodged from the masts, and the masts deformed around the vehicle's front-end. This deformation and mast rotation resulted in the panel contacting the vehicle's roof but without any significant damage to the roof. Therefore, the researchers believe that this impact event remains a valid indicator of the system's safety performance when installed in the 0-degree orientation.

Finally, following an analysis of the test results, it was evident that the debris from these work-zone traffic control devices tended to be thrown along the path of the impacting vehicle. The relative hazard posed to the traffic and work-zone crews located adjacent to the sign supports is somewhat subjective in nature. Depending on the specific site conditions at which these devices are being used, the system debris was determined to be less of a hazard to adjacent traffic and work-zone crews than the moving vehicle itself.

10 SUMMARY AND CONCLUSIONS

A total of six crash tests were conducted on various work-zone traffic control devices, including: (1) four tall-mounted, rigid panel sign supports with sandbags, and (2) two Type III barricades. Four out of the six crash tests on these work-zone traffic control devices satisfactorily met the TL-3 evaluation criteria set forth in NCHRP Report No. 350. A summary of the safety performance evaluation of each system is provided in Table 4.

From this testing and previous testing, slight differences in system design details can potentially lead to very different results. Therefore, extreme care should be taken when applying one crash test to variations in any design features without clearly understanding the complete work-zone traffic control device performance. Also, extreme care should be taken when attempting to catagorize various products for one or more manufacturers.

Table 4. Summary of Safety Performance Evaluation Results

Evaluation Factors	Evaluation Criteria	Test MI-1		Test MI-2		Test MI-3	
		#1	#2	#3	#4	#5	#6
		LSPL [1]	LSPL [1]	WBL [1]	WBL [1]	LSPL [1]	LSPL [1]
Structural Adequacy	B	U	S	U	S	S	S
Occupant Risk	D	U	S	U	S	S	S
	E	U	S	U	S	S	S
	F	S	S	S	S	S	S
	H	NA	NA	NA	NA	NA	NA
	I	NA	NA	NA	NA	NA	NA
Vehicle Trajectory	K	S	S	S	S	S	S
	N	S	S	S	S	S	S
NCHRP Report No. 350 Test Level		TL-3	TL-3	TL-3	TL-3	TL-3	TL-3
Method of Failure[2]		1,2,3,4,5	NA	1,2,3,4	NA	NA	NA
Pass/Fail		Fail	Pass	Fail	Pass	Pass	Pass

[1] Hardware Type: LSPL – Large Sign Support with Sign Panel(s) and Warning Light
WBL – Wood and Steel Barricade with Warning Light(s)

[2] Method of Failure:
1 - Severe windshield cracking and fracture
2 - Windshield indentation
3 - Obstruction of driver visibility
4 - Windshield penetration
5 - Occupant compartment penetration other than windshield penetration
6 - Roof deformations greater than 152 mm
7 - Test invalid due to flying debris from the first device contacting the second device before vehicle impact

S - Satisfactory
M - Marginal
U - Unsatisfactory
NA - Not Available

11 RECOMMENDATIONS

One work-zone traffic control device satisfactorily met the evaluation criteria set forth in NCHRP Report No. 350 and is recommended for field implementation. This work-zone traffic control device includes:

- Test No. MI-3, System Nos. 5 and 6 – Michigan's Portable Mounted Traffic Control Sign System – A steel sign support, with 15.9 kg of sand on each leg and 912-mm long 12-gauge stiffening tubes, and with a 1,219-mm wide x 1,219-mm tall x 15.9-mm thick, diamond-shaped plywood sign panel utilizing oversized holes, pull-through panel bolts, and cup washers and a specially-positioned attached lightweight warning light model no. 400 ("Empco-Lite") oriented end-on and head-on, respectively.

Following a review of the test results, the researcher's determined that the systems in Test No. MI-3 could also be fabricated using 12-gauge instead of 14-gauge steel tubes for the masts without affecting performance, as previously discussed in a letter dated October 11, 2002 and provided in Appendix E.

Two work-zone traffic control devices satisfactorily met the evaluation criteria set forth in NCHRP Report No. 350 in the direction the systems were oriented. These work-zone traffic control devices include:

- Test No. MI-1, System No. 2 – Michigan's Portable Mounted Traffic Control Sign System – A steel sign support, with 31.8 kg of sand on each leg, and with a 1,218-mm wide x 1,219-mm tall x 15.9-mm thick, diamond-shaped plywood sign panel, a 609-mm wide x 610-mm tall x 15.9-mm thick, square-shaped plywood speed advisory sign panel, and an attached warning light, model "Work Safe Supply" Type A oriented head-on.

- Test No. MI-2, System No. 4 – Michigan's Type III Barricade with wood panels and three attached warning lights, model "Work Safe Supply" Type A oriented end-on.

Two work-zone traffic control devices performed unsatisfactorily according to the test evaluation criteria set forth in NCHRP Report No. 350 in the direction the systems were oriented and are not recommended for field applications. These work-zone traffic control devices include:

- Test No. MI-1, System No. 1 – Michigan's Portable Mounted Traffic Control Sign System – A steel sign support, with 31.8 kg of sand on each leg, and with a 1,218-mm wide x 1,219-mm tall x 15.9-mm thick, diamond-shaped plywood sign panel, a 609-mm wide x 610-mm tall x 15.9-mm thick, square-shaped plywood speed advisory sign panel, and an attached warning light, model "Work Safe Supply" Type A oriented end-on. The same system performed satisfactorily when oriented head-on (Test No. MI-1, System No. 2).

- Test No. MI-2, System No. 3 – Michigan's Type III Barricade with wood panels and three attached warning lights, model "Work Safe Supply" Type A oriented head-on. The same system performed satisfactorily when oriented end-on (Test No. MI-2, System No. 4).

For work-zone traffic control devices, such as those presented herein, similar devices may be capable of meeting the performance requirements from NCHRP Report No. 350; however, it is noted that slight differences in design details can potentially lead to very different results. Therefore, it is suggested that the impact performance of tall-mounted, rigid panel sign supports and Type III barricades can only be verified through the use of full-scale vehicle crash testing. Thus, it is recommended that the research described herein be extended to determine the performance behavior of other similar work-zone traffic control devices.

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13 APPENDICES

APPENDIX A

Dimensional Measurements of Tall-Mounted, Rigid Panel Sign Support Systems

Table A-1. Tall-Mounted, Rigid Panel Sign Support System Dimensional Measurements

System Number	Test Number	STAND		SIGN		
		Type [1]	Weight (kg)	Type [2]	Material [3]	Weight (kg)
1, 2	MI-1	Steel Sign Stand (Legs & Two Masts)	26.308	Two Rigid Panels & Light	7	21.772
5, 6	MI-3	Steel Sign Stand (Legs, Two Masts, & Two Outer Tubes)	37.194	Rigid Panel & Light	7	16.329

[1] When more than one stand type is listed, they are different reference names for the same stand.
[2] When more than one sign type is listed, they are different reference names for the same sign.
[3] Description of material types:
1 - (Reflexite Superbright)
2 - (3M RS34)
3 - (3M Diamond Grade RS24)
4 - (Non-reflective Mesh)
5 - (Reflexite Non-reflective)
6 - (Aluminum)
7 - (Plywood)

Table A-2. Tall-Mounted, Rigid Panel Sign Support System Dimensional Measurements

System Number	HEIGHTS TO				
	Bottom of Bottom (or Only) Sign Panel (mm)	Top of Bottom (or Only) Sign Panel (mm)	Bottom of Top Sign Panel (mm)	Top of Top Sign Panel (mm)	Top of Light (mm)
1, 2	911	1521	1530	3254	2794
5, 6	1540	3264	----	----	2597

Table A-3. Tall-Mounted, Rigid Panel Sign Support System Dimensional Measurements

Stand Type	System Number	LEGS				
		Horizontal Portion				
		Material	Dimension #1 (mm)	Dimension #2 (mm)	Thickness (mm)	Length (mm)
Steel Sign Stand	1, 2	ASTM A-36 Steel	50.80	50.80	4.69	1222
Steel Sign Stand	5, 6	ASTM A-36 Steel	50.80	50.80	6.35	1829

Table A-4. Tall-Mounted, Rigid Panel Sign Support System Dimensional Measurements

Stand Type	System Number	LEGS				
		Vertical Portion				
		Material	Dimension #1 (mm)	Dimension #2 (mm)	Thickness (mm)	Length (mm)
Steel Sign Stand	1, 2	Steel Tubing	50.80	50.80	2.64	151
Steel Sign Stand	5, 6	Steel Tubing	50.80	50.80	2.67	152

Table A-5. Tall-Mounted, Rigid Panel Sign Support System Dimensional Measurements

Stand Type	System Number	MASTS (VERTICAL UPRIGHTS)					
		Number of Masts	Material	Dimension #1 (mm)	Dimension #2 (mm)	Thickness (mm)	Length (mm)
Steel Sign Stand	1, 2	2	Telespar Steel Tubing	44.45	44.45	2.63	2740
Steel Sign Stand	5, 6	2	Telespar Steel Tubing	44.45	44.45	2.16	2743

Table A-6. Tall-Mounted, Rigid Panel Sign Support System Dimensional Measurements

Stand Type	System Number	MASTS (OUTER VERTICAL TUBES)						
		Number of Outer Masts	Material	Dimension #1 (mm)	Dimension #2 (mm)	Thickness (mm)	Length (mm)	Space between masts (out to out) (mm)
Steel Sign Stand	1, 2	----	----	----	----	----	----	1067
Steel Sign Stand	5, 6	2	Telespar ASTM A-653 Grade 50 Steel	50.00	50.00	2.77	912	1067

Table A-7. Tall-Mounted, Rigid Panel Sign Support System Dimensional Measurements

Stand Type	System Number	HOLES		SMALL PANELS					
		Diameter of holes (mm)	Hole Spacings (center to center) (mm)	Number of Small Panels	BOTTOM PANEL				
					Material	Length (mm)	Width (mm)	Thickness	
								Thickest (mm)	Thinnest (mm)
Steel Sign Stand	1, 2	9.53	25.40	----	----	----	----	----	----
Steel Sign Stand	5, 6	9.53	25.40	----	----	----	----	----	----

Table A-8. Tall-Mounted, Rigid Panel Sign Support System Dimensional Measurements

Stand Type	System Number	SMALL PANELS									
		MIDDLE PANEL					TOP PANEL				
		Material	Length (mm)	Width (mm)	Thickness		Material	Length (mm)	Width (mm)	Thickness	
					Thickest (mm)	Thinnest (mm)				Thickest (mm)	Thinnest (mm)
Steel Sign Stand	1, 2	----	----	----	----	----	----	----	----	----	----
Steel Sign Stand	5, 6	----	----	----	----	----	----	----	----	----	----

Table A-9. Tall-Mounted, Rigid Panel Sign Support System Dimensional Measurements

Sign Type	System Number	SIGN PANELS						
		Material	Bottom (or Only) Panel			Top Panel		
			Thickness (mm)	Length (mm)	Width (mm)	Thickness (mm)	Length (mm)	Width (mm)
Two Rigid Panels	1, 2	Plywood	15.88	610	609	15.88	1219	1218
Rigid Panel	5, 6	Plywood	15.88	1219	1219	----	----	----

Table A-10. Warning Light Dimensional Measurements

System No.	Manufacturer	Model Number	Model Name	Dimensional Measurements						
				Box (mm)			Light Diameter (mm)	Overall Height (mm)	Weight (kg)	
				Length	Width	Depth			w/o batteries	w/ batteries
1, 2	Work Safe Supply	----	Work Safe Supply	170	127	76	187	270	0.91	2.27
5, 6	Empco-Lite	400	Empco-Lite	170	127	76	187	270	0.91	1.59

APPENDIX B

Tall-Mounted, Rigid Panel Sign Support System Details

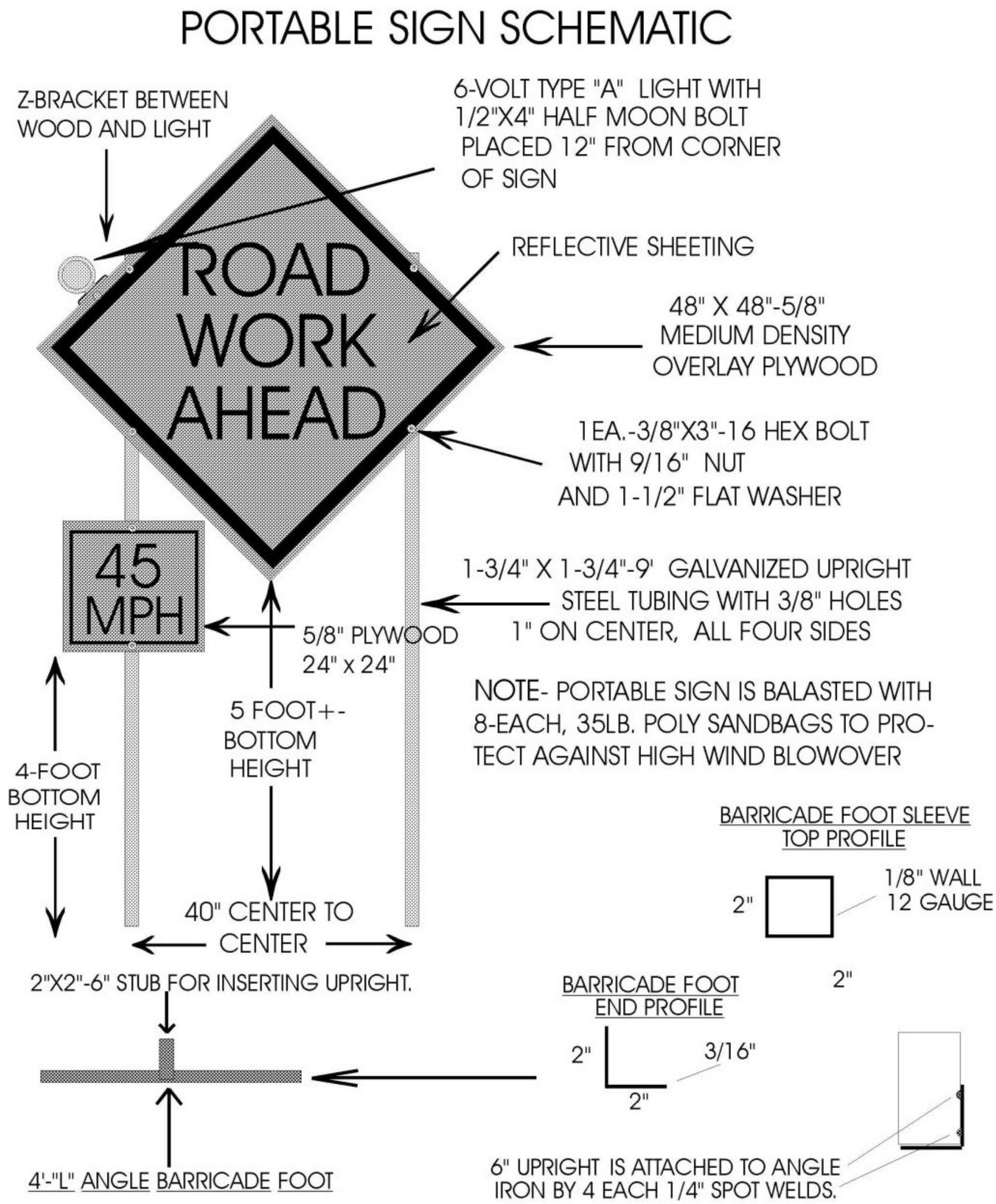

Figure B-1. Portable Mounted Rigid Panel System (Test MI-1)

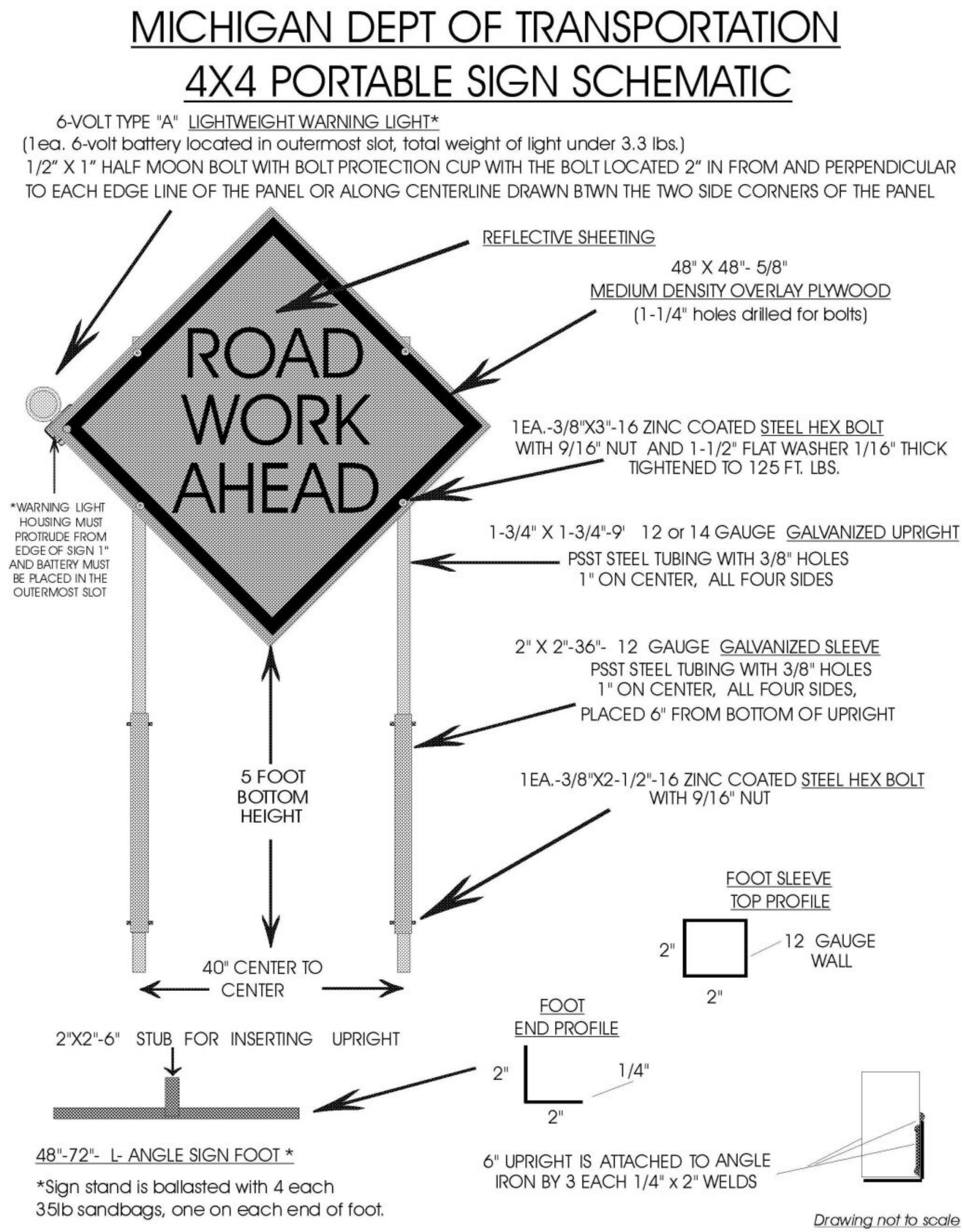

Figure B-2. Michigan's 4X4 Portable Mounted Rigid Panel System (Test MI-3)

APPENDIX C

Dimensional Measurements of Barricade Systems

Table C-1. Barricade System Dimensional Measurements

System Number	Test Number	STAND		SIGN		
		Type [1]	Weight (kg)	Type [2]	Material [3]	Weight (kg)
3, 4	MI-2	Type III Barricade	44.452	----	----	----

[1] When more than one stand type is listed, they are different reference names for the same stand.
[2] When more than one sign type is listed, they are different reference names for the same sign.
[3] Description of material types: 1 - (Reflexite Superbright)
2 - (3M RS34)
3 - (3M Diamond Grade RS24)
4 - (Non-reflective Mesh)
5 - (Reflexite Non-reflective)
6 - (Aluminum)
7 - (Plywood)

Table C-2. Barricade Dimensional Measurements

System Number	HEIGHTS TO				
	Bottom of Bottom Panel (mm)	Bottom of Middle Panel (mm)	Bottom of Top Panel (mm)	Top of Top Panel (mm)	Top of Light (mm)
3, 4	340	846	1360	1545	1759

Table C-3. Barricade Dimensional Measurements

Stand Type	LEGS				
	Horizontal Portion				
	Material	Dimension #1 (mm)	Dimension #2 (mm)	Thickness (mm)	Length (mm)
Type III Barricade	ASTM A-36 Steel	50.80	50.80	4.69	1222

Table C-4. Barricade Dimensional Measurements

Stand Type	LEGS				
	Vertical Portion				
	Material	Dimension #1 (mm)	Dimension #2 (mm)	Thickness (mm)	Length (mm)
Type III Barricade	Steel Tubing	50.80	50.80	2.64	151

Table C-5. Barricade Dimensional Measurements

Stand Type	MASTS (VERTICAL UPRIGHTS)						
	Number of Masts	Material	Dimension #1 (mm)	Dimension #2 (mm)	Thickness (mm)	Length (mm)	Space between masts (out to out) (mm)
Type III Barricade	2	Telespar Steel Tubing	44.70	44.96	2.59	1521	2940

Table C-6. Barricade Dimensional Measurements

Stand Type	HOLES		BARRICADE PANELS				
				BOTTOM PANEL			
	Diameter of holes (mm)	Hole Spacings (center to center) (mm)	Number of Small Panels	Material	Length (mm)	Width (mm)	Thickness (mm)
Type III Barricade	9.53	25.40	3	Wood	3662	184	19.05

Table C-7. Barricade Dimensional Measurements

Stand Type	BARRICADE PANELS							
	MIDDLE PANEL				TOP PANEL			
	Material	Length (mm)	Width (mm)	Thickness (mm)	Material	Length (mm)	Width (mm)	Thickness (mm)
Type III Barricade	Wood	3662	183	19.05	Wood	3662	184	19.05

Table C-8. Warning Light Dimensional Measurements

System No.	Manufacturer	Model Number	Model Name	Dimensional Measurements						
				Box (mm)			Light Diameter (mm)	Overall Height (mm)	Weight (kg)	
				Length	Width	Depth			w/o batteries	w/ batteries
3, 4	Work Safe Supply	----	Work Safe Supply	170	127	76	187	270	0.91	2.27

APPENDIX D

Type III Barricade Details

Figure D-1. Type III Barricade System (Test MI-2)

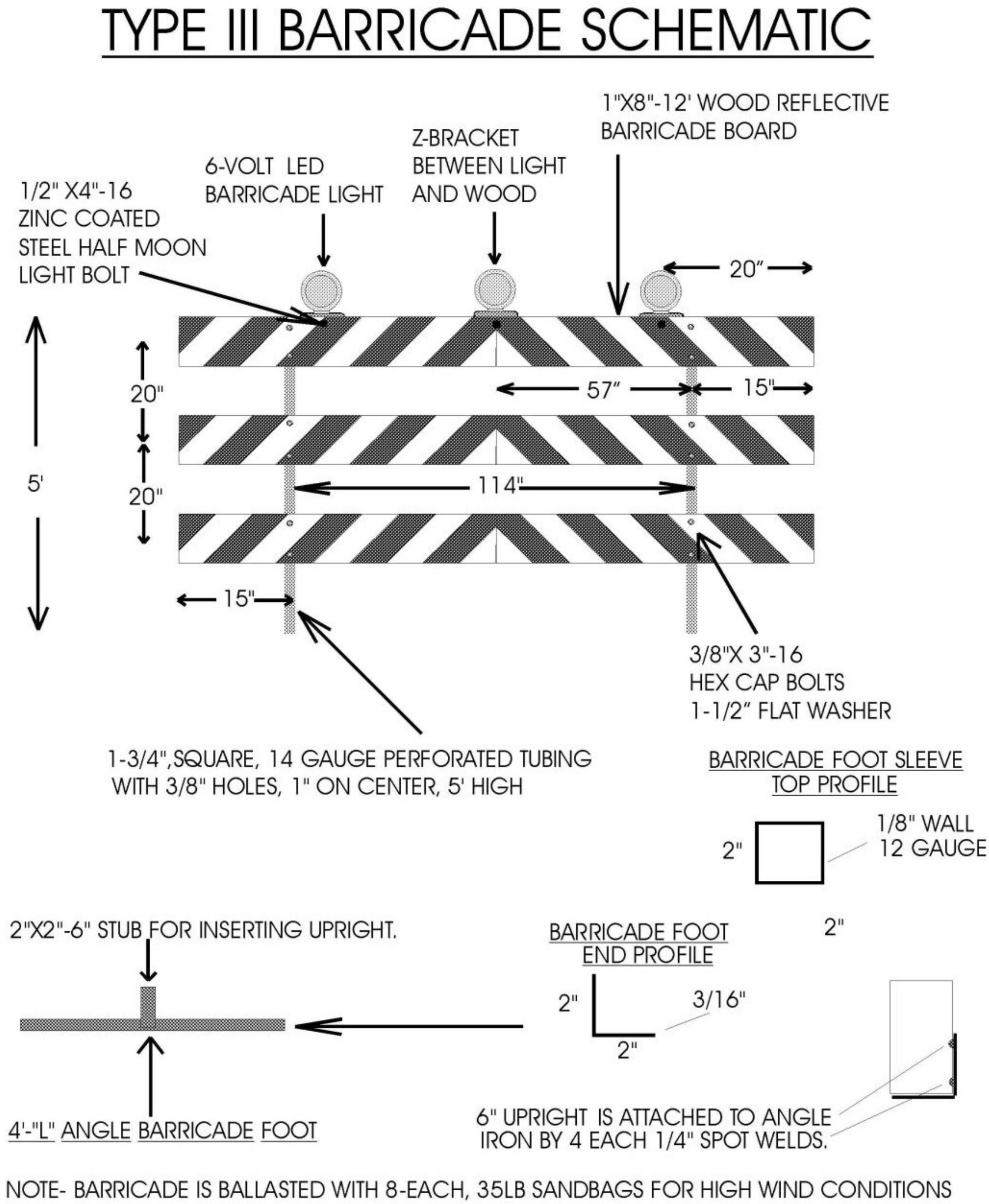

Figure D-1. Type III Barricade System (Test MI-2)

APPENDIX E

Relevant Correspondence

UNIVERSITY OF Nebraska Lincoln

MIDWEST ROADSIDE SAFETY FACILITY

November 12, 2001

Mr. Jeff Grossklaus, P.E.
Construction Staff Engineer
Michigan Department of Transportation
Research and Technology Section
Secondary Governmental Complex
P.O. Box 30049
Lansing, Michigan 48909

Subject: Discussion on recent crash testing of Michigan's work zone devices.

Dear Mr. Grossklaus:

On Tuesday, November 6, 2001, the Midwest Roadside Safety Facility (MwRSF) performed two full-scale vehicle crash tests on two of Michigan's work zone devices. The crash tests were performed in accordance with the requirements documented in the NCHRP Report No. 350 and included 100 km/hr impacts at both the 0 and 90 degree orientations. Following the completion of the two crash test runs (actually four impacts), I promised that we would review the test results and provide you with discussion and potential changes for each device by Monday or Tuesday of this week.

Portable Sign Support System

System no. 1 consisted of a dual-mast, portable sign support system which utilized wood panels and one warning light. A 4-ft by 4-ft sign panel was mounted 5-ft above the ground, as measured to its lowest position. A 2-ft by 2-ft secondary speed limit sign was also attached to the left mast at a location of 3-ft above the ground, as measured to the bottom surface. The centerline of the speed limit sign was attached to the centerline of the mast. Two 35-lb sandbags were placed on each leg. Following a review of the test results, it was determined that the portable sign support system's performance was acceptable at the 0-degree orientation but unacceptable at the 90-degree orientation.

It is noted that the sign stand's safety performance was acceptable at the 0-degree orientation. Thus, any changes geared toward improving its performance for 90-degrees impacts should consider their effect on the system at the 0-degree orientation. During the 90-degree impact event, the small car struck the left mast, causing it to deform around the vehicle's front end before its release off of the leg support. This release did not occur quickly as its behavior was dependent upon significant mast deformation to allow it to lift up and off of the rotated lower stub. As a result, the upper and lower sign panels contacted and penetrated the roof and windshield, respectively.

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One alternative would be to increase the bending capacity of the two masts in order to reduce mast deformation and implement a breakaway feature at the base of each support. A more rapid fracture, combined with minimal bending deformations of the masts, would reduce the tendency for the two signs to be pulled downward toward the windshield and roof during the system's rotation in the air. It may also be possible to use a horizontal bar between the lower region of the masts if dual mast fracture is needed. Another option would be to relocate the speed limit sign such that it cannot contact and penetrate the windshield. In this case, the smaller sign could be positioned between the masts without requiring an increase in sign height. This may occur by attaching the left side of the sign on the face of the left mast or adding a horizontal tube between the masts for mounting the speed limit sign. For the larger sign panel, the left-side corner of the panel rotated and penetrated the roof. If no other improvements are made to improve the system, one may consider increasing the edge surface area of the sign's corner or decreasing the sharpness of the corner in order to reduce the potential for occupant compartment penetration. As an alternative, it may be possible to use other materials for the sign panel, such as plastic core or vinyl roll-up panels. Finally, it may be advantageous to raise the height of the upper sign panel such that contact with the interior region of the roof in diminished. Consequently, raising sign height also requires consideration for increased instability of the sign support system for resisting wind loads. However, we believe that a combination of increased ballast and/or leg length can accommodate the increased wind-induced moments.

Type III Barricade

System no. 2 consisted of a Type III barricade which utilized 12-ft long wood panels and three warning lights attached to the top panel. Two 35-lb sandbags were placed on each leg. Following a review of the test results, it was determined that the Type III barricade's performance was unacceptable at the 0-degree orientation but acceptable at the 90-degree orientation.

It is noted that the barricade's safety performance was acceptable at the 90-degree orientation. Thus, any changes geared toward improving its performance for 0-degrees impacts should consider their effect on the system at the 90-degree orientation. During the 0-degree impact event, the small car struck the left mast, causing it to deform around the vehicle's front end before its release off of the leg support. Once gain, this release did not occur quickly as its behavior was dependent upon significant mast deformation before a sufficient load was transferred to the welded stub to cause it to fracture away from the leg. As a result, the left light assembly and upper part of the mast struck and penetrated the windshield.

One alternative would be to increase the bending capacity of the two masts in order to reduce mast deformation and possibly implement an improved breakaway feature at the base of each support. However, the existing base may be acceptable as is if a stronger mast is used. A more rapid fracture, combined with minimal bending deformations of the masts, would reduce the tendency for the light assembly and mast top to be pulled downward toward the windshield during the impact sequence. In addition, it may be helpful to raise the height of the light assembly and upper part of the mast in order to allow for them to contact the roof rather than the windshield. However, this option should be secondary to increasing the mast's bending strength. In addition to the windshield failure, the right-side rear window was also penetrated as the middle light assembly and upper panel's fractured end passed by and struck the window glass. At this time, we believe it prudent to first address the problems associated with the system's poor performance at the front windshield.

In addition, the 90-degree impact condition exhibited a unique behavior that had not been observed before at MwSRF. During the impact, the lower panel actually penetrated through the bumper, and a panel fragment came to a stop within the engine compartment. Although this penetration was observed, it is noted that this behavior does not constitute a failure at the 90-degree orientation. Any improvements in the breakaway or release of the mast from the base will decrease the potential for this behavior.

In summary, I have provided some discussion on the two recently crash tested systems. For each failure, proposed conceptual changes or modifications to the devices are noted but without detail. If you have any questions regarding this information, please feel free to call me to discuss at (402) 472-6864.

Sincerely,

Ronald K. Faller

Ronald K. Faller, Ph.D., P.E.
Research Assistant Professor

University of Nebraska Lincoln

MIDWEST ROADSIDE SAFETY FACILITY

November 30, 2001

Mr. Jeff Grossklaus, P.E.
Construction Staff Engineer
Michigan Department of Transportation
Research and Technology Section
Secondary Governmental Complex
P.O. Box 30049
Lansing, Michigan 48909

Subject: Proposed changes for Michigan's work zone devices.

Dear Mr. Grossklaus:

On November 12, 2001, I forwarded to you a letter which discussed the two full-scale vehicle crash tests that were performed on two of Michigan's work zone devices. The crash tests were performed on November 6, 2001 and were conducted in accordance with the requirements documented in the NCHRP Report No. 350. These tests included 100 km/hr impacts at both the 0 and 90 degree orientations. In addition, I included general discussion of the source of the system failures as well as provided information for potential design modifications. Subsequently, you further requested information on the costs for conducting dynamic bogie tests on work-zone prototypes.

Subsequently, a review of the previously-submitted information was made by Michigan Department of Transportation (MiDOT) personnel. As a result, MiDOT officials determined that bogie testing would not be used to evaluate design changes. In addition, design modifications, which allowed for the continued use of existing hardware, were desired. Once these design changes were implemented into each system, full-scale crash tests were to be performed according to the requirements contained in the original contractual agreement.

Based on this information, MwRSF engineers further reviewed the potential design modifications for the MiDOT work-zone devices. These changes are included in greater detail below.

Temporary Combination Work-Zone and Speed Advisory Panel System

In an effort to utilize the existing MiDOT materials, we have developed several ideas for modifying the system mentioned previously.

(1) Relocate the lower speed advisory panel to the interior of the two masts in order to eliminate its contact with the windshield. The panel may be either mounted to the inner side of a mast using a steel bracket or attached to a new horizontal member between the two masts. This horizontal

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member would likely be a steel tube (i.e., 1.75-in. square by 12-gauge) which is the same tubing used in the rest of the system.

(2) Increase the bending strength of the two masts over most of length below the warning sign panel. This may be done by: (a) adding a outer steel tube (2-in. square by 12-gauge); (b) increasing the outer stub height of the bases; ©) replacing the mast with a stronger steel tube (2.5-in. square by 12- or 10-gauge); or (d) using a combination of (a) through ©). We have had limited experience with (a) and (b) on other projects, but this seems like it would be viable and meet your general criteria for modifications.

(3) As the mast strength is increased, a breakaway mechanism or a quicker mast-to-base release may be necessary. These mechanisms are often just a modification of the cross-section of the upright. From previous experience, it has taken a few tries to balance wind capacity and break-away performance. We would be hesitant to try this idea for the first time in a full-scale test. Dynamic bogie testing is the preferred mode of testing for evaluating breakaway prototypes.

(4) Add some type of corner protector to the left- and right-side corners of the diamond-shaped warning panel. If we could triple the contact area of this corner on impact with the top of the vehicle, it likely would not penetrate the roof. Either a blunt-end tube extending on both sides to the edges of the sign or something to attach to the sign would be functional.

(5) Add a horizontal member between the two masts to help, if necessary, to activate their simultaneous movement and possible fracture in front of the moving vehicle. Maybe consider locating this near the bumper height. This horizontal member would likely be a steel tube (i.e., 1.75-in. square by 12-gauge) which is used in the entire system. Again this idea is a fundamental change of the sign structure that may negatively impact other performance aspects of the sign.

(6) One last alternative would be to use a plastic core panels in lieu of the wood panels. For both of the vehicle penetrations (windshield and top), these plastic core signs have shown much lower propensity for penetration.

In summary, the subset of changes that would directly impact the performance without fundamentally changing the existing performance of the sign are:

(a) Move the speed limit advisory sign to the center of the two masts and increase the contact area between the corner of the sign and the roof of the vehicle.

Type III 12-ft Wood Panel Barricade System

In an effort to utilize the existing MiDOT materials, we have developed several ideas for modifying the system mentioned previously.

(1) Decrease the number of sandbags per leg from two to one. This should allow the system to slide forward when impacted at the 90-degree orientation and reduce the propensity for the top of the mast and the light to whip into the windshield.

(2) In reviewing the MnDOT Type III barricade when tested at the 0-degree orientation, the top of the impacted mast never really contacted the windshield region or if it did, it was very gentle. Also, it appeared that the mast stayed in front of the car more than was observed for the MiDOT comparable test. The MnDOT Type III barricade utilized 1.5-in. square by 11-gauge steel tubing for the masts. Thus, one option is to better attach the mast to the base in order to help keep the device contained in front of the vehicle. To do this, consider changing the base to steel tubes versus angles and utilize a stub similar in height to the MnDOT barricade or sign support systems.

In recent bogie tests performed on the MnDOT's low-height, rigid panel signs, a steel collar tube was added to a mast in order to provide increased bending strength and stiffness. In this case, a 2-in. square by 12-gauge steel tube was placed around an existing 1.75-in. square by 12-gauge mast. In addition, the stronger masts were placed over the stubs extending vertically off of the base legs and then were bolted into placed. The combination of these modifications allowed for improved containment of the sign system near the front of the impacting vehicle, thus resulting in a reduced propensity for windshield contact and penetration.

(3) If (2) is not used, then consider changing the mast to a larger steel tube section in order to reduce mast deformations and/or their rotation around the vehicle's front end. It is noted that an improved base configuration would still need to be used, as identified in (2).

(4) Eliminate the light assembly. If that is not possible, add an insert tube to the top of the existing mast or replace it with a longer length mast in order to move the light assembly's location higher and away from a potential contact with the windshield.

(5) It may seem prudent to first address the front windshield region before making changes to eliminate the right-rear side window penetration. Possibly, those changes implemented above will eliminate this occurrence. Otherwise, it may be necessary to replace the wood panels with plastic or aluminum panels.

If you have any questions regarding this information, please feel free to call me to discuss it further. My phone number is (402) 472-6864. At this time, we are seeking your and MiDOT's input and guidance on the direction for which we are to proceed with the research project.

Sincerely,

Ronald K. Faller

Ronald K. Faller, Ph.D., P.E.
Research Assistant Professor

October 11, 2002

Mr. Jeff Grossklaus, P.E.
Construction Staff Engineer
Michigan Department of Transportation
Research and Technology Section
Secondary Governmental Complex
P.O. Box 30049
Lansing, Michigan 48909

Subject: Discussion on the recent crash testing of Michigan's work zone device.

Dear Mr. Grossklaus:

On Tuesday, October 8, 2002, the Midwest Roadside Safety Facility (MwRSF) performed one full-scale vehicle crash test on Michigan's modified temporary sign support system. The crash test was performed in accordance with the requirements documented in NCHRP Report No. 350 and included a 100 km/hr impact at both the 90 and 0 degree orientations. Following the completion of the crash test run (actually two impacts), I promised that we would review the test results and provide you with a letter documenting its overall safety performance prior to the completion of the draft research report.

Dual Mast, Rigid Panel Portable Sign Support System

The work-zone device used in Test No. MI-3 consisted of a dual-mast, portable sign support system which utilized a ⅝-in. thick, medium density plywood panel and one Type "A" lightweight warning light with a single 6-volt battery. A 4-ft x 4-ft sign panel was mounted 5-ft above the ground, as measured to its lowest position. Over-sized holes were drilled into the panel in order to facilitate its release from the two masts during impact. No secondary speed limit sign was used on this system. One 35-lb sandbag was used on each leg (a total of four) and was positioned toward each leg end. The vertical masts were configured with 1¾-in. x 1¾-in. x 14-gauge, square perforated steel tubing, each measuring 9-ft long. The vertical masts were inserted into 2-in. x 2-in. x 3/16-in. square tube sections, each measuring 6-in. long, and welded to the steel angle legs. The angle legs measured 6-ft in length.

For additional mast stiffening near the region of the vehicle's bumper, one 2-in. x 2-in. x 12-gauge by 36-in. long, square perforated steel tube section was placed over each mast section. The bottom end of the outer sleeve was positioned directly above the top of the 6-in. steel stub. The warning light assembly was also re-positioned near the side corner of the panel such that it would shield the corner and prevent it from penetrating into the small car's roof. The bolt hole for the warning light assembly was located 2-in. inward from and perpendicular to each edge line of the panel or along the centerline drawn between the two side corners of the panel. One battery was used in the two battery box and was positioned at the outer slot in order to provide additional crush stiffness in the box assembly that extended beyond the panel's corner.

Crash Test No. MI-3

As mentioned previously, Test No. MI-3 consisted of two impacts in the one crash test run. The second work-zone device was positioned approximately 60 ft downstream from the first device. The first impact was performed on the work-zone device (System No. 5) placed in the 90-degree orientation (end-on) and at the right-side quarter point of the vehicle's front end. The second impact was to be performed on the work-zone device (System No. 6) placed in the 0-degree orientation (head-on) and with the center of the device positioned along the centerline of the vehicle's front end. However, during the impact with the first device, debris from System No. 5 damaged the vehicle's steering components which resulted in the vehicle tracking and/or shifting slightly to the right. As a result of vehicle's lateral shift, only one vertical upright (right side) was struck during the second impact event. Additional discussion on this result will be included later.

System No. 5 Results (90 Degree)

Following a review of the test results, it was determined that the portable sign support system's safety performance was acceptable at the 90-degree impact orientation. During the crash event, the small car struck the left mast, causing it to deform slightly near the vehicle's front end as well as near the top of the outer stiffening sleeve. Deformations also occurred to the left-side (impact-side) ground support angle as the lower part of the mast was being pushed in front of the car. The left leg was held in place with two bags. As a result, the left side of the panel rotated and was pulled down toward the small car. Later, the left-side corner of the panel with the attached battery box contacted the roof of the vehicle. No penetration of the roof was observed. The maximum roof crush was measured to be approximately 3.75 in. Roof deformations equal to or less than 5 in. are deemed acceptable by the Federal Highway Administration.

System No. 6 Results (0 Degree)

Following a review of the test results, it was determined that the portable sign support system's safety performance was acceptable at the 0-degree impact orientation. During the crash event, the small car struck the right mast, causing it to separate from the sign panel with the panel supported in mid-air by the left-side mast. As mentioned previously, the second impact was to have occurred with both masts impacted instead of only one. However, we believe that satisfactory performance would have resulted had both masts been impacted simultaneously for two basic reasons. First, the over-sized holes would have resulted in a similar quick release of both masts away from the panel. This response would allow the panel to be temporarily suspended in mid-air with the car traveling underneath the panel. In addition, there exists a reduced potential for the panel to be pulled down onto the vehicle. Second, even if full release of the masts away from the panel would not occur, the panel's dynamic behavior is not believed to be significantly different from that observed during Test No. MI-1, System No. 2. For this earlier test, the panel was not dislodged from the masts, and the mast deformed around the vehicle's front end. This deformation and mast rotation resulted in the panel contacting the vehicle's roof but without any consequences. Therefore, we believe that the second impact event remains a valid indicator of the system's safety performance when installed in the 0-degree orientation.

In summary, I have provided you with the relevant discussion on the recently crash tested work-zone device. Based on our analysis of the test results, this work-zone sign support system meets the Test Level 3 (TL-3) requirements set forth in NCHRP Report No. 350. Finally, it is our opinion that this system could be fabricated using 12-gauge versus 14-gauge steel tubes for the actual masts without effecting the system's safety performance.

As stated in our contract, we will be preparing a draft research report which summarizes the results of all three tests. This report will be provided to you by early December 2002 for review and comment. In addition, ten VHS copies of the MI-3 crash test footage and two CD-ROM copies with photographic documentation will be provided to you by mid-November 2002. If you have any questions regarding this information, please feel free to call me to discuss at (402) 472-6864.

Sincerely,

Ronald K. Faller

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Research Assistant Professor

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