SAFETY PERFORMANCE EVALUATION OF MISSOURI'S SELF-DRIVING TEMPORARY SIGN STANDS

Submitted by

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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 unique 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 portable sign supports through full-scale crash testing. A total of two full-scale crash tests were conducted on various portable sign supports to determine their safety performance according to the Test Level 3 (TL-3) criteria set forth in the NCHRP Report No. 350. Neither of the impacts on the portable sign supports resulted in acceptable safety performances. 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.

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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 nor 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 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 unique 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 (8-17). These previous studies have provided some useful information. However, there remains unanswered questions regarding the performances of many work-zone traffic control devices, which vary from those crash tested previously.

1.2 Objective

The objective of the research project was to evaluate the safety performance of existing portable sign supports 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, two full-scale vehicle crash tests were performed on two work-zone traffic control devices. The two crash tests were completed in two runs with a centerline point impact in each run, resulting in a total of two crashes. Both of the full-scale tests were performed using a small car, weighing approximately 820 kg, with target impact speed and angle of 100.0 km/hr and 0 degrees, respectively. Next, a bogie test on a retrofit design was performed. The crash test was performed using a bogie vehicle, weighing approximately 895 kg, with target impact speed and angle of 80.5 km/hr and 0 degrees, respectively. Finally, the test results were analyzed, evaluated, and documented. Conclusions and recommendations were then made that pertain to the safety performance of the existing portable sign supports.

2 TEST REQUIREMENTS AND EVALUATION CRITERIA

2.1 Test Requirements

Work-zone traffic control devices, such as portable sign supports, 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* (18), work-zone traffic control devices are Category 2 devices, which are not expected to produce significant change in vehicular velocity, but may 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 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.

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

3 WORK-ZONE PORTABLE SIGN SUPPORTS

3.1 General Descriptions

A total of two existing work-zone traffic control devices were crash tested under this study and are described below. Both of the crash tests were conducted on portable sign supports. All materials for the traffic control devices were supplied by the sponsor.

The two different portable sign supports tested were:

1. (System No. 1) a self-driving, single-post sign support with a 1,196-mm x 1,216-mm vinyl flexible roll-up sign mounted at a height of 276 mm from the ground to the bottom of the sign panel and with the top of the single-post at a height of 2,136 mm from the ground to the top of the support system; and

2. (System No. 2) a self-driving, single-post sign support with a 1,220-mm x 1,220-mm rigid aluminum sign mounted at a height of 288 mm from the ground to the bottom of the sign panel and with the top of the single-post at a height of 2,136 mm from the ground to the top of the support system.

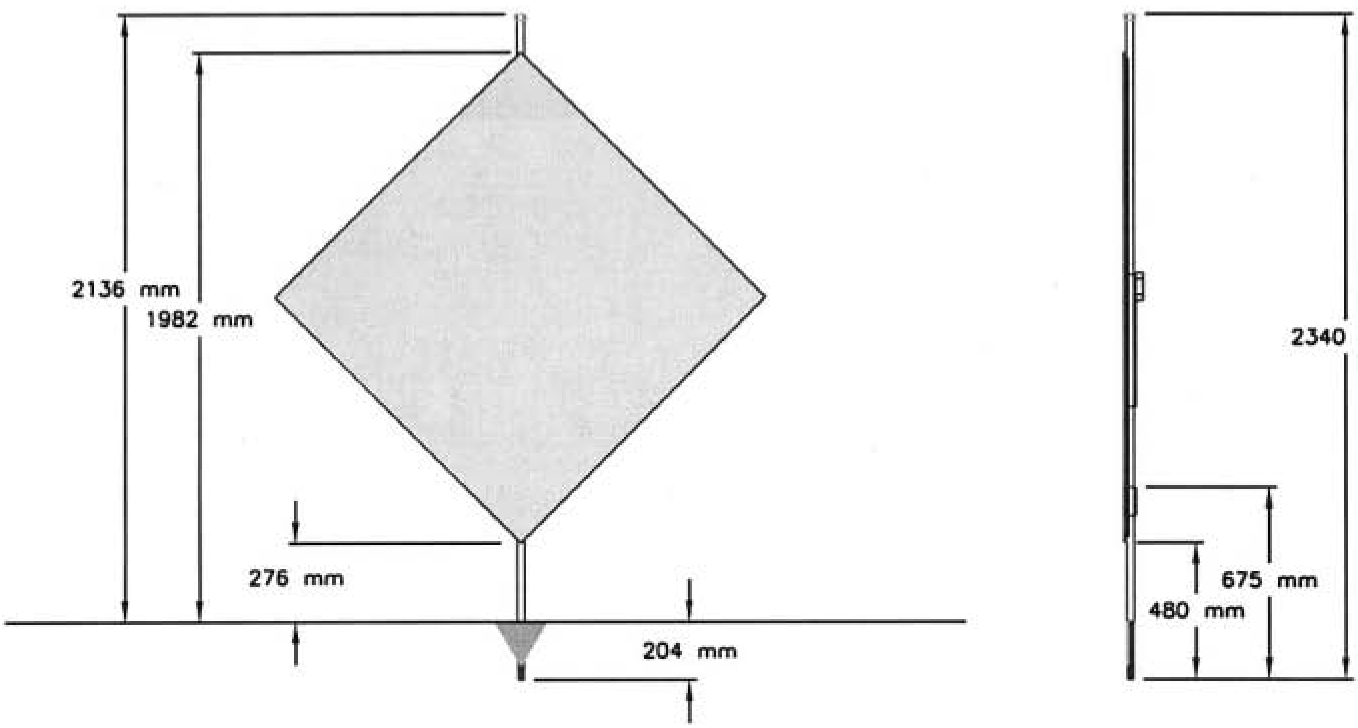
A list of the two crash tests are summarized in Table 3.

Table 3. List of Crash Tests Conducted

WORK-ZONE TRAFFIC CONTROL DEVICES		
PORTABLE SIGN SUPPORTS		
Test M-1	System No. 1	Self-Driving, Single-Post Sign Support, Vinyl Sign Panel, Head-on Impact (0 degrees)
Test M-2	System No. 2	Self-Driving, Single-Post Sign Support, Rigid Sign Panel, Head-on Impact (90 degrees)

3.2 Portable Sign Supports

The details of the portable sign support systems are shown in Figures 1 through 4. The dimensional measurements of the portable sign support systems are found in Appendix A. A detailed drawing of the self-driving, single-post, sign support system is found in Appendix B.



SELF-DRIVING, SINGLE-POST SIGN STAND

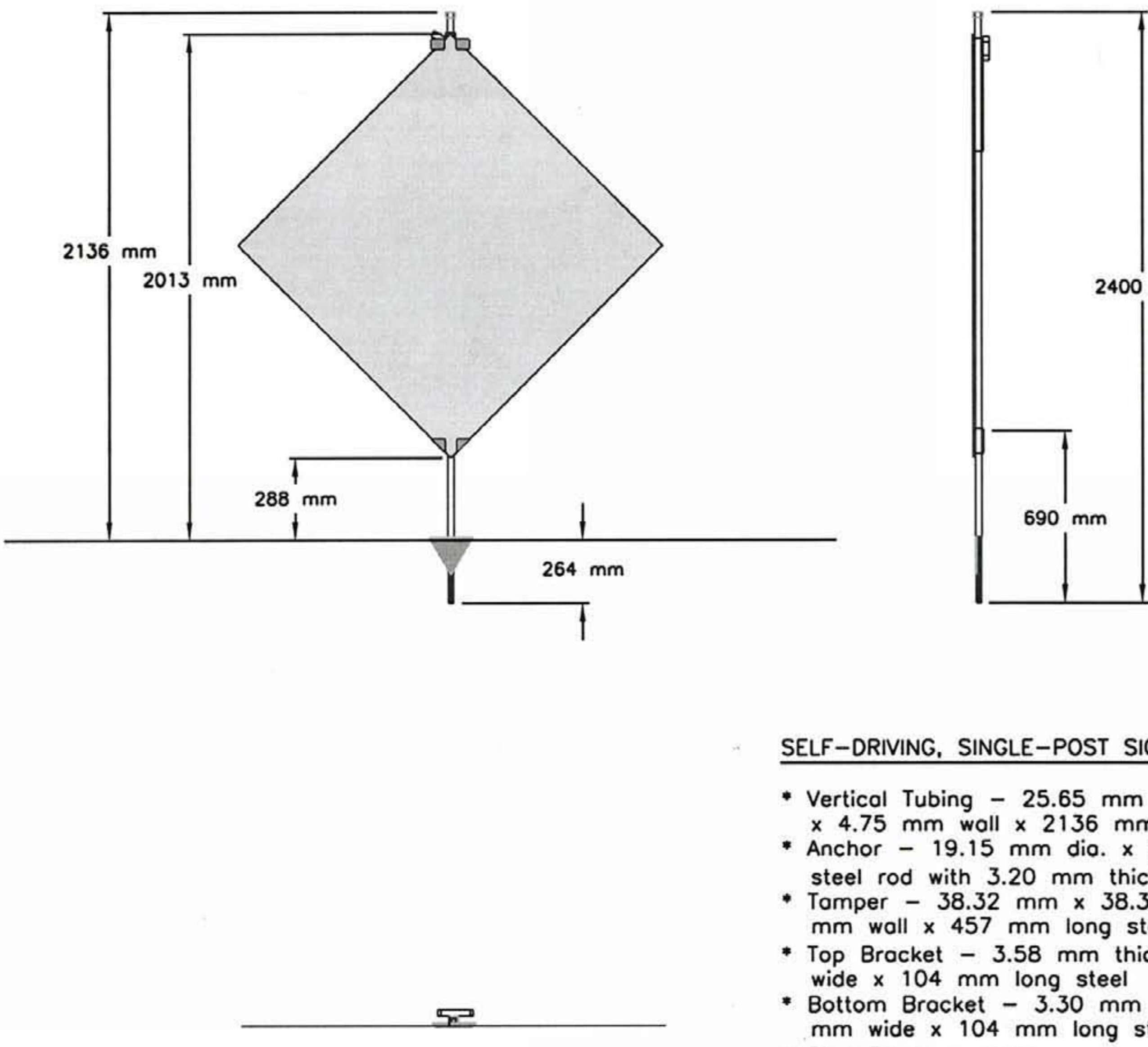
* Vertical Tubing – 25.35 mm x 25.80 mm x 4.45 mm wall x 2136 mm long steel
* Anchor – 19.10 mm dia. x 204 mm long steel rod with 3.10 mm thick triangles
* Tamper – 38.00 mm x 38.83 mm x 5.05 mm wall x 462 mm long steel
* Top Bracket – 2.56 mm thick x 153 mm wide x 73 mm long steel
* Bottom Bracket – 3.40 mm thick x 153 mm wide x 100 mm long steel
* Sign Perch – Triangular plate
* All material is ASTM Steel Grade A513 Mechanical Tubing

FLEXIBLE SIGN

* Panel – Fold & Roll style, reflective vinyl, 1196 mm x 1216 mm
* Crossbrace – Vertical member is 9.55 mm thick x 31.15 mm wide x 1680 mm long fiberglass
* Crossbrace – Horizontal member is 5.05 mm thick x 30.77 mm wide x 1685 mm long fiberglass

Figure 1. System No. 1 Sign Support Details, Test M-1

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



SELF-DRIVING, SINGLE-POST SIGN STAND

* Vertical Tubing – 25.65 mm x 25.85 mm x 4.75 mm wall x 2136 mm long steel
* Anchor – 19.15 mm dia. x 270 mm long steel rod with 3.20 mm thick triangles
* Tamper – 38.32 mm x 38.38 mm x 5.01 mm wall x 457 mm long steel
* Top Bracket – 3.58 mm thick x 152 mm wide x 104 mm long steel
* Bottom Bracket – 3.30 mm thick x 153 mm wide x 104 mm long steel
* Sign Perch – None
* All material is ASTM Steel Grade A513 Mechanical Tubing

RIGID SIGN

* Panel – Reflective aluminum, 1220 mm x 1220 mm with 2.80 mm thickness

Figure 3. System No. 2 Sign Support Details, Test M-2

Figure 4. System No. 2 Sign, Test M-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 work-zone traffic control device. A digital speedometer was located on the tow vehicle to increase the accuracy of the test vehicle impact speed.

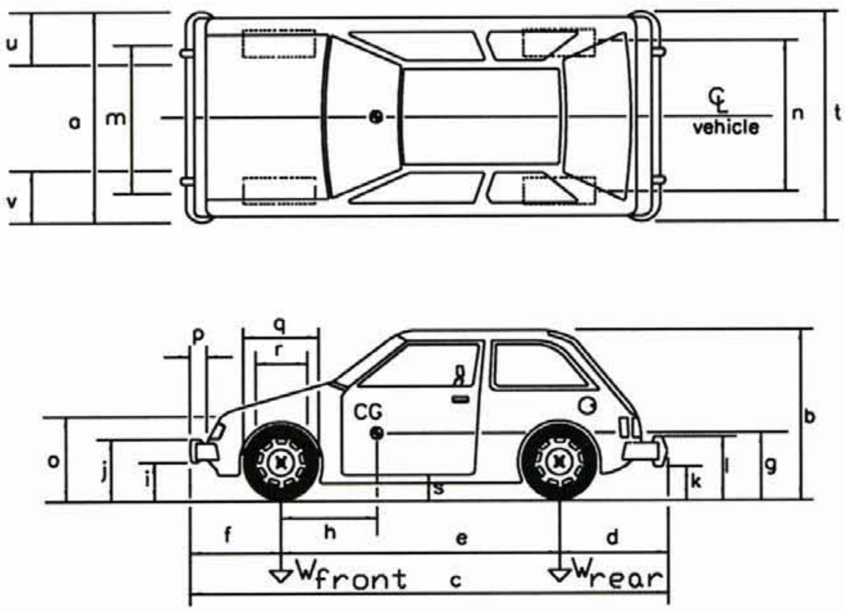
A vehicle guidance system developed by Hinch (19) was used to steer the test vehicle. A guide-flag, attached to the front-left wheel and the guide cable, was sheared off before impact with the work-zone traffic control device. The 9.5-mm diameter guide cable was tensioned to approximately 13.3 kN, and 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 304.8-m long.

4.3 Test Vehicles

For test M-1, a 1994 Geo Metro was used as the test vehicle. The test inertial and gross static weights were 811 kg and 887 kg, respectively. The test vehicle is shown in Figure 5, and vehicle dimensions are shown in Figure 6.

Figure 5. Test Vehicle, Test M-1

Dates:	11/15/99	Test Numbers:	M-1	Model:	Metro
Make:	GEO	Vehicle I.D.#:	2C1MR6468R6785054		
Tire Size:	155R12	Year:	1994	Odometer:	148,072



Vehicle Geometry - mm

a	1524	b	1346
c	3848	d	399
e	2369	f	832
g	546	h	946
i	375	j	489
k	279	l	552
m	1353	n	1353
o	533	p	89
q	527	r	330
s	267	t	1524
u	381	v	381

height of wheel center 254

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}	464	487	524
W_{rear}	297	324	363
W_{total}	761	811	887

Damage prior to test: ______________________

Figure 6. Vehicle Dimensions, Test M-1

For test M-2, a 1994 Geo Metro was used as the test vehicle. The test inertial and gross static weights were 823 kg and 898 kg, respectively. The test vehicle is shown in Figure 7, and vehicle dimensions are shown in Figure 8.

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 5 through 8.

Square, black and white-checkered targets were placed on the vehicle to aid in the analysis of the high-speed film, as shown in Figures 9 through 10. One target was place directly above each of the wheels on the driver and passenger sides. A target was place at the centerline 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 the right-quarter point of the vehicle's roof to pinpoint the time of impact with the work-zone traffic control device on the high-speed film. The flash bulbs were fired by a pressure tape switch mounted at the centerline point 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

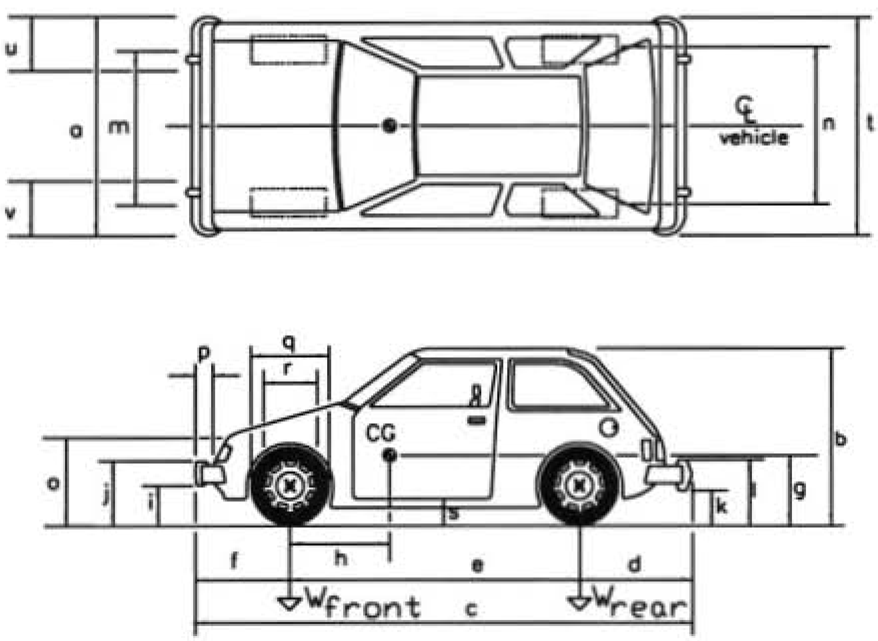
For tests M-1and M-2, one high-speed 16-mm Red Lake Locam camera, with operating speed of approximately 500 frames/sec, was used to film the crash test. One high-speed Red Lake E/cam video camera, with an operating speed of 500 frames/sec, was also used to film the crash test. A SVHS video camera and a 35-mm still camera were placed downstream and offset to the left from the impact point and had an angled view of the impact. A Locam, with a 16 to 64-mm zoom lens,

Figure 7. Test Vehicle, Test M-2

Dates: 11/15/99 Test Numbers: M-2 Model: Metro

Make: GEO Vehicle I.D.#: 2C1MR6467R6724522

Tire Size: P145/80 R12 Year: 1994 Odometer: 91,736



Vehicle Geometry - mm

a	1524	b	1359
c	3848	d	699
e	2369	f	749
g	546	h	914
i	368	j	451
k	279	l	533
m	1346	n	1340
o	521	p	95
q	521	r	330
s	273	t	1524
u	381	v	381

height of wheel center 241

Engine Type 3 cyl. gas

Engine size 1.0 L

Transmission Type:

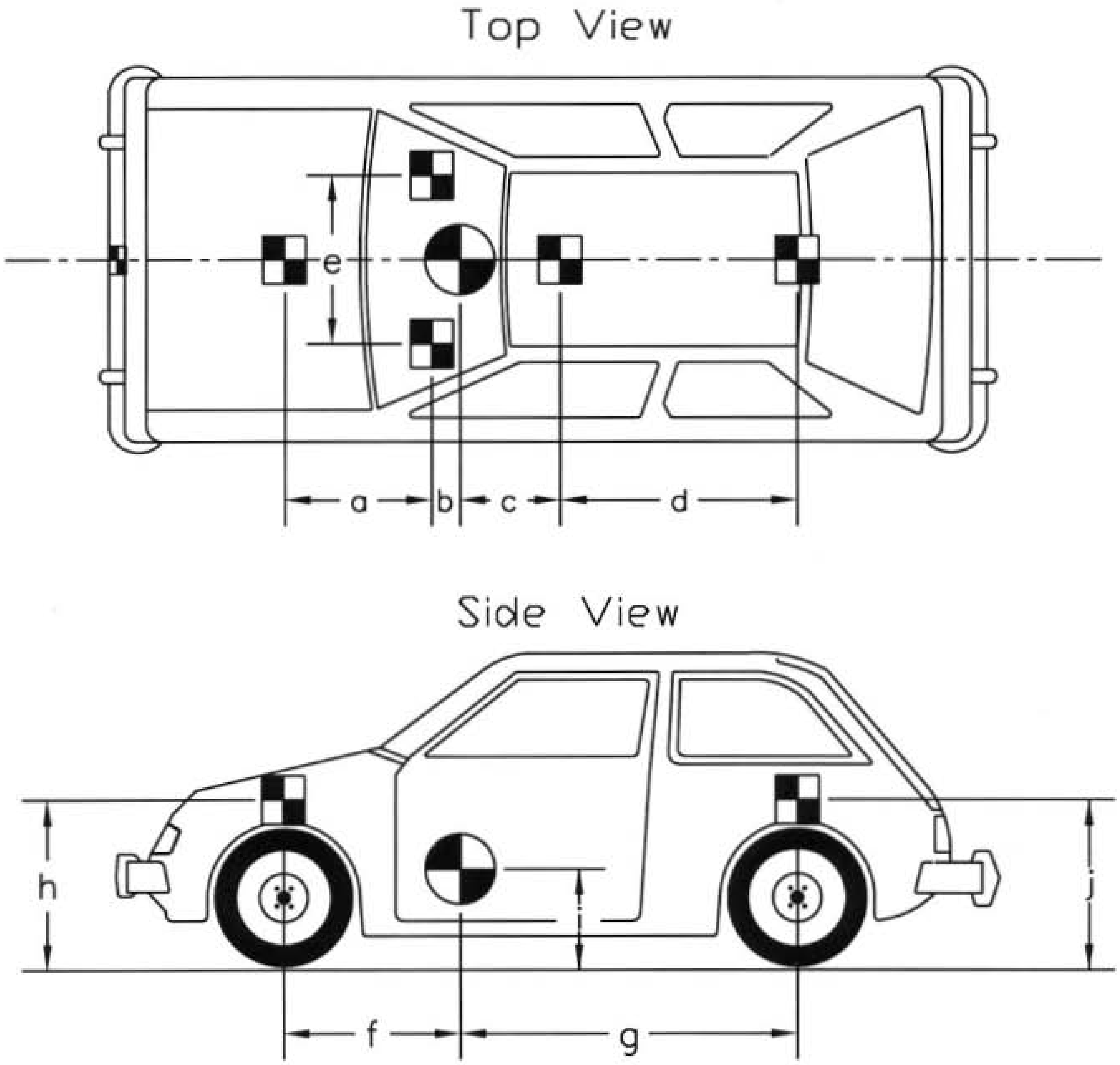
(Automatic) or Manual

(FWD) or RWD or 4WD

Weight - kg	Curb	Test Inertial	Gross Static
W_{front}	496	505	542
W_{rear}	309	318	356
W_{total}	805	823	898

Damage prior to test: ______________________

Figure 8. Vehicle Dimensions, Test M-2

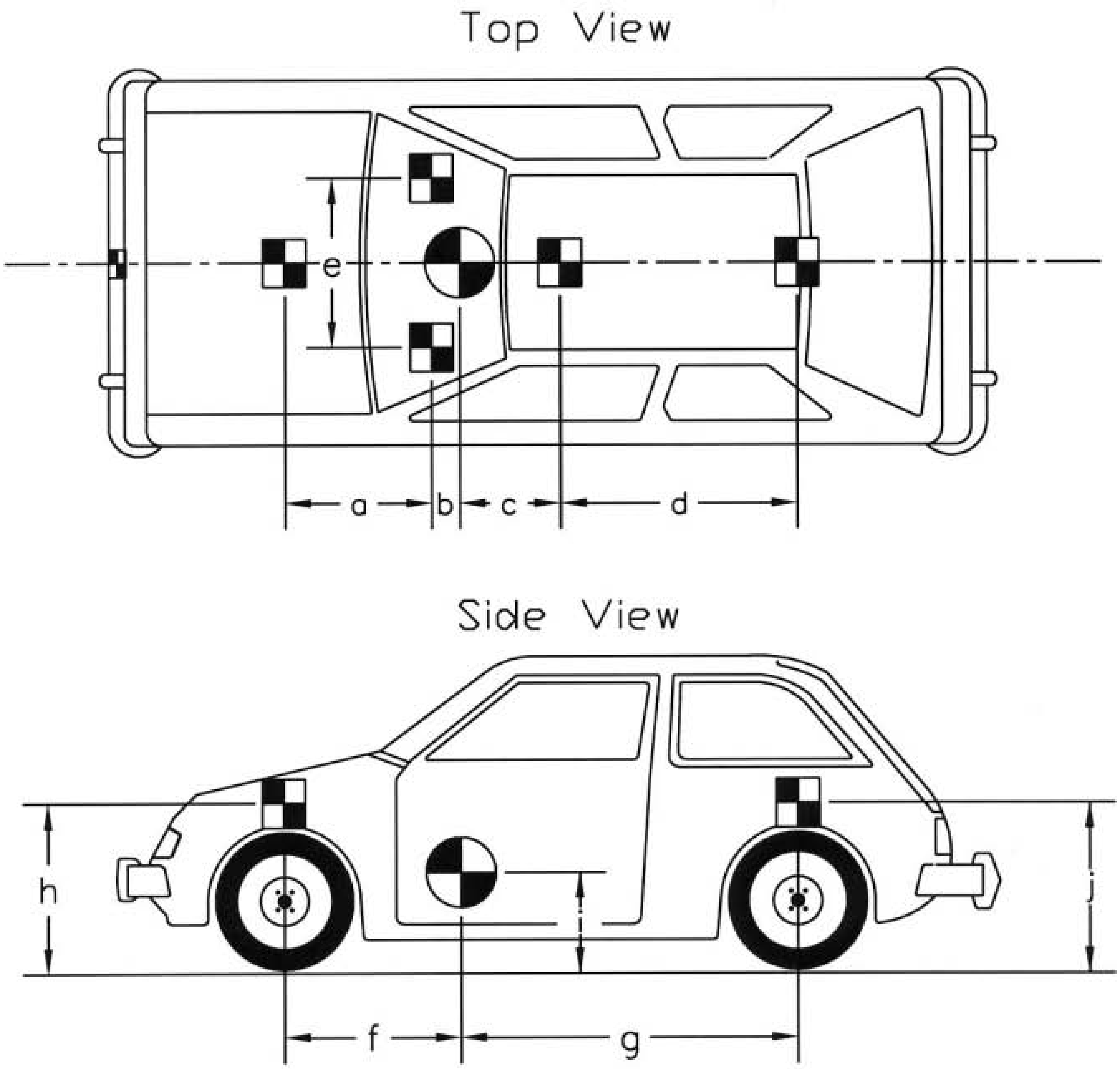


TEST #: M-1

TARGET GEOMETRY (mm)

a	---	b	---	c	---	d	---
e	---	f + g	2370			h	749
		i	---	j	730		

Figure 9. Vehicle Target Locations, Test M-1



TEST #: M-2

TARGET GEOMETRY (mm)

a	---	b	---	c	---	d	---
e	---	f + g	2370			h	699
		i	---	j	737		

Figure 10. Vehicle Target Locations, Test M-2

a Red Lake E/cam high-speed video camera and a SVHS video camera were placed on the left-side of the impact orientation and had a field of view perpendicular to the impact of the device. A SVHS video camera was placed on the right-side of the impact orientation and had an angled view of the impact. A schematic of all six camera locations for tests M-1 and M-2 is shown in Figure 11. The film was analyzed using the Vanguard Motion Analyzer. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed film.

4.4.2 Pressure Tape Switches

For tests M-1 and M-2, five pressure-activated tape switches, spaced at 2-m intervals, were used to determine the speed of the vehicle before impact with the device. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the left-front tire of the test vehicle passed over the 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.

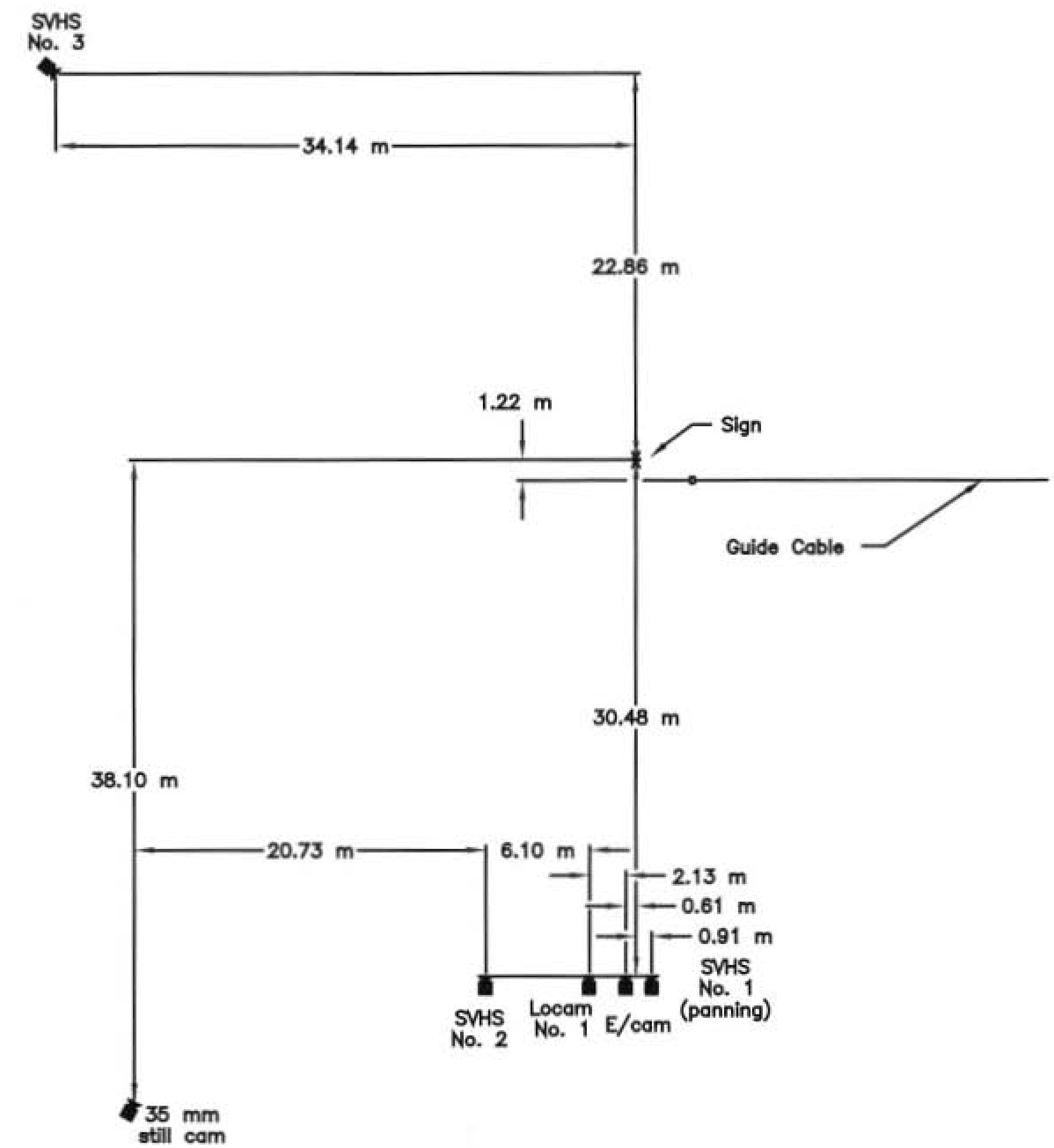


Figure 11. Location of High-Speed Cameras, Tests M-1 and M-2

5 CRASH TEST NO. 1 (SYSTEM NO. 1)

5.1 Test M-1

The 887-kg small car impacted System No. 1, a sign support oriented head-on to the vehicle (perpendicular to the vehicle's path), at a speed of 100.1 km/hr and an angle of 0 degrees. A summary of the test results and the sequential photographs are shown in Figure 12. Additional sequential photographs are shown in Figure 13.

5.2 Test Description

The test vehicle impacted System No. 1 with the centerline point of the vehicle's bumper aligned with the centerline of the sign support, as shown in Figure 14. At 0.004 sec after initial impact, the sign post deformed around the front of the vehicle. At 0.008 sec, the sign post began to pull out of the ground and continued to deform. At this same time, the bottom of the sign panel flexed and deformed around the vehicle's front nose. At 0.014 sec, the sign post continued to bend about the vehicle's contact point, and the bottom half of the sign panel rested on the hood of the vehicle. At 0.020 sec, the anchor pulled completely out of the ground. At this same time, the top of the sign post rotated toward the vehicle while the horizontal crossbraces flexed toward the vehicle. At 0.030 sec, the sign post deformed to approximately a 90-degree angle, and the sign panel traveled along with the vehicle with the sign post wrapped around the vehicle's front nose. At this same time, the ends of the horizontal crossbrace contacted the vehicle. At 0.045 sec, the top of the sign post impacted the center of the windshield as the sign panel rested across the vehicle's hood. At 0.057 sec, the bottom of the sign post rotated upward and was no longer under the front of the vehicle. At 0.075 sec, the sign post continued to rotate about the windshield contact point. At this same time, the anchor portion of the stand was perpendicular to the ground. At 0.109 sec, the sign post was embedded in the windshield and was positioned nearly parallel to the ground except for the fractured anchor portion. At this same time, the sign post continued to rotate upward. The self-driving sign post support came to rest 49.68 m-downstream from the original position. The sign panel was located 47.24-m downstream from the initial position. The vehicle subsequently came to rest 112.17-m downstream from the midpoint of the impact point and 7.62-m left from the centerline of the vehicle's original path. The final positions of the vehicle and the sign support are shown in Figures 12 and 15.

5.3 System and Component Damage

Damage to System No. 1 is shown in Figures 15 through 18. System No. 1 encountered moderate damage. The sign panel was removed from the horizontal and vertical crossbraces, except for the top of the vertical crossbrace. The velcro straps were removed from the sign support and the sign panel. The self-driving sign post fractured above the bottom sign panel bracket. The self-driving sign post also pulled completely out of the ground. The vinyl sign panel and the fiberglass crossbraces remained undamaged.

5.4 Vehicle Damage

Exterior vehicle damage is shown in Figures 19 and 20. The front bumper and lower plastic shield encountered light contact marks near the center. Contact and scrape marks were also found on the hood. The left-front quarter panel was dented above the tire. The center of the windshield sustained extensive "spider web" cracking of both layers of the glass, causing weak spots. This region of the windshield was also deformed toward the interior of the vehicle with a concentrated indentation. The middle region of the windshield had a hole in the glass. A significant amount of windshield glass had fractured off and was found in the interior of the vehicle. No damage was found to have occurred to the roof, parking lights, headlights, and fog lights.

5.5 Discussion

Following test M-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 extensive “spider web” cracking, hole, and indentation in the windshield which resulted in obstructed driver visibility and loss of structure of both glass layers. Detached elements and debris from System No. 1 penetrated the central region of the windshield. Deformations of, or intrusion into, the occupant compartment did occur. The vehicle’s trajectory did not intrude into adjacent traffic lanes.

0.000 sec | 0.008 sec | 0.020 sec | 0.045 sec | 0.075 sec

- Test Number M-1
- System Number 1
- Date 11/15/99
- Test Article
  - Type .... Traffic Control Device – Self-Driving, Single-Post, Sign Support System
  - Stand Name SH-96-2
  - Sign Panel Name .... Flexible Panel
  - Key Elements
    - Size and/or dimension . 2.2 m high after installation
    - Material .... ASTM Steel Grade A513 Mechanical Tubing
  - Orientation .... Head-on with centerline point
- Soil Type .... Grading B - AASHTO M 147-65 (1990)
- Vehicle Model .... 1994 Geo Metro
  - Curb .... 761 kg
  - Test Inertial .... 811 kg
  - Gross Static .... 887 kg
- Vehicle Speed
  - Impact .... 100.1 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 .... Severe windshield cracking, indentation, and penetration
  - TAD[20] 12-FC-1
  - SAE[21] 12-FCAW6
- Vehicle Stopping Distance .... 112.17 m downstream 7.62 m left
- Test Article Damage .... Moderate – Broke apart

Figure 12. Summary of Test Results and Sequential Photographs, Test M-1

0.000 sec

0.004 sec

0.008 sec

0.014 sec

0.020 sec

0.030 sec

0.045 sec

0.057 sec

0.075 sec

0.109 sec

Figure 13. Additional Sequential Photographs, Test M-1

Figure 14. Impact Locations, Test M-1

Figure 15. Overall Damage and Final Positions, Test M-1

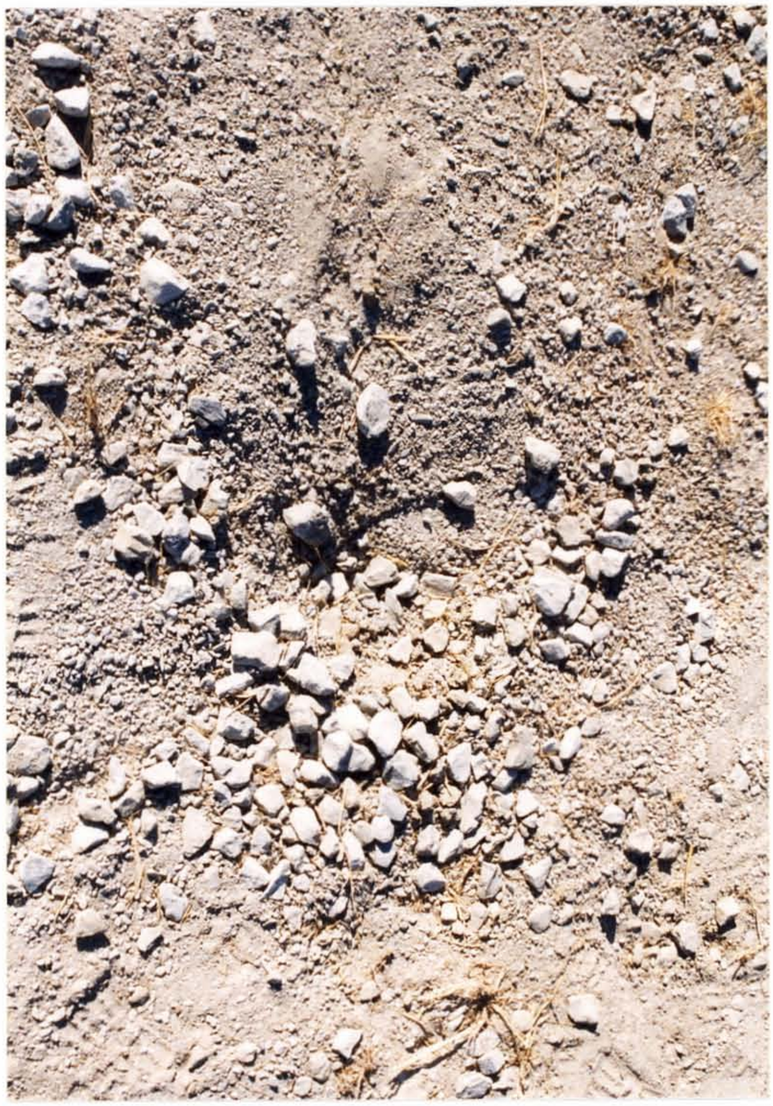


Figure 16. Final Soil Conditions at Embedment Point, Test M-1

Figure 17. System No. 1 Damage, Test M-1

Figure 18. System No. 1 Single-Post Sign Holder Damage, Test M-1

Figure 19. Vehicle Damage, Test M-1

Figure 20. Windshield Damage, Test M-1

6 CRASH TEST NO. 2 (SYSTEM NO. 2)

6.1 Test M-2

The 898-kg small car impacted System No. 2, a sign support oriented head-on to the vehicle, at a speed of 99.0 km/hr and an angle of 0 degrees. A summary of the test results and the sequential photographs are shown in Figure 21. Additional sequential photographs are shown in Figure 22.

6.2 Test Description

The test vehicle impacted System No. 2 with the centerline point of the vehicle's bumper aligned with the centerline of the sign support, as shown in Figure 23. At 0.004 sec after initial impact, the sign post deformed around the front nose of the vehicle. At this same time, the sign panel flexed away from the sign post. At 0.010 sec, the sign post continued to deform about the front nose of the vehicle. At this same time, the top of the sign post and the sign panel rotated toward the vehicle about the contact point with the vehicle. At 0.022 sec, the embedded anchor pulled completely out of the ground. At 0.036 sec, the bottom of the sign post deformed to nearly a 90-degree angle as the top of the sign post and the sign panel continued to rotate toward the vehicle. At this same time, the sign panel released from the top sign bracket. At 0.048 sec, the sign panel impacted and fractured the windshield. At this same time, the sign post was positioned nearly parallel with the windshield. At 0.065 sec, the top of the sign post impacted the center of the sign panel which was resting on the windshield, thus causing additional glass to fracture off of the windshield. At 0.083 sec, the sign panel deformed and rested on the windshield. At this same time, the sign post rested across the hood and the windshield. At 0.111 sec, the top of the sign post rebounded off of the vehicle's front end with the bottom portion of the sign post deformed to a 90-degree angle. At 0.176 sec, the sign post rotated away from the vehicle. At this same time, the sign panel rebounded off of the windshield with the sign panel still positioned in the bottom sign bracket. The self-driving sign post came to rest 69.80-m downstream and 1.52-m left from the original position. The sign panel was located 22.86-m downstream and 11.58-m left from the initial position. The vehicle subsequently came to rest 51.82-m downstream from the midpoint of the impact point and 0.0-m laterally from the centerline of the vehicle's original path. The final positions of the vehicle and the sign support are shown in Figures 21 and 24.

6.3 System and Component Damage

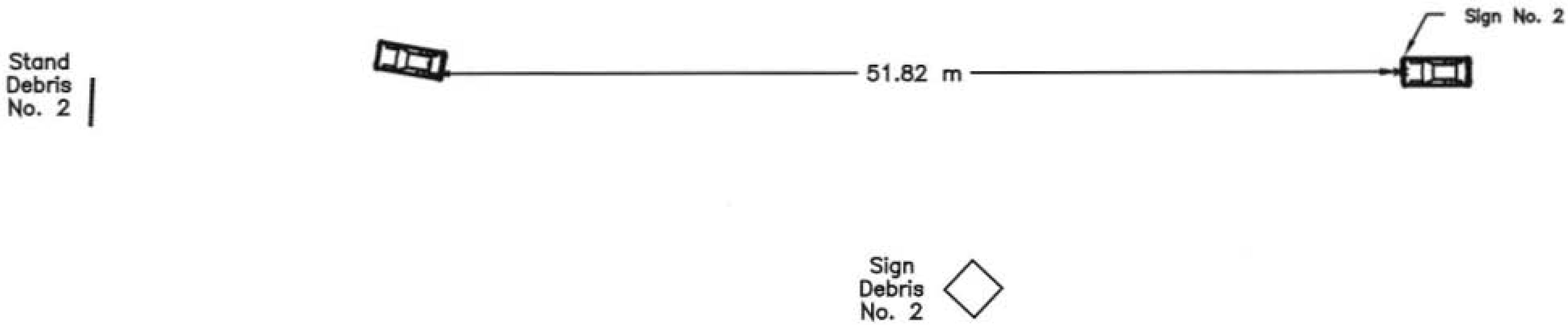
Damage to System No. 2 is shown in Figures 24 through 26. System No. 2 encountered moderate damage. The aluminum sign panel encountered slight deformations. Light scuff marks were found on the front side of the sign panel. The sign panel also disengaged from the sign panel locking brackets. The self-driving sign post fractured above the bottom sign panel bracket. The self-driving sign post also pulled completely out of the ground.

6.4 Vehicle Damage

Exterior vehicle damage is shown in Figures 27 and 28. The front bumper and lower plastic shield encountered light contact marks near the center. Contact and scrape marks were also found on the hood. The front-central region of the roof encountered scrape marks and dents. The center of the windshield sustained extensive "spider web" cracking of both layers of the glass, causing weak spots. This region of the windshield was also deformed toward the interior of the vehicle with a concentrated indentation. The upper-middle region of the windshield had a large hole in the glass. A significant amount of windshield glass had fractured off and was found in the interior of the vehicle. No damage was found to have occurred to the parking lights, headlights, and fog lights.

6.5 Discussion

Following test M-2, a safety performance evaluation was conducted, and the work-zone traffic control device, System No. 2, was determined to be unacceptable according to the NCHRP Report No. 350 criteria. It was deemed unacceptable due to the extensive "spider web" cracking, hole, and indentations in the windshield which resulted in obstructed driver visibility and loss of structure of both glass layers. Detached elements and debris from System No. 2 penetrated the upper-central region of the windshield. Deformations of, or intrusion into, the occupant compartment did occur. The vehicle's trajectory did not intrude into adjacent traffic lanes.



- Test Number M-2
- System Number 2
- Date 11/15/99
- Test Article
    - Type . . . . Traffic Control Device – Self-Driving, Single-Post, Sign Support System
    - Stand Name SH-96-2
    - Sign Panel Name . . . . Rigid Panel
    - Key Elements
        - Size and/or dimension . 2.2 m high after installation
        - Material . . . . ASTM Steel Grade A513 Mechanical Tubing
    - Orientation . . . . Head-on with centerline point
- Soil Type . . . . Grading B - AASHTO M 147-65 (1990)
- Vehicle Model . . . . 1994 Geo Metro
    - Curb . . . . 805 kg
    - Test Inertial . . . . 823 kg
    - Gross Static . . . . 898 kg
- Vehicle Speed
    - Impact . . . . 99.1 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 . . . . Severe windshield cracking, indentation, and penetration
    - TAD[20] 12-FC-1
    - SAE[21] 12-FCAW7
- Vehicle Stopping Distance . . . . 51.82 m downstream, 0.0 m laterally
- Test Article Damage . . . . Moderate – Broke apart

Figure 21. Summary of Test Results and Sequential Photographs, Test M-2

0.000 sec

0.004 sec

0.010 sec

0.022 sec

0.036 sec

0.048 sec

0.065 sec

0.083 sec

0.111 sec

0.176 sec

Figure 22. Additional Sequential Photographs, Test M-2

Figure 23. Impact Locations, Test M-2

Figure 24. Overall Damage and Final Positions, Test M-2

Figure 25. Final Soil Conditions at Embedment Point, Test M-2

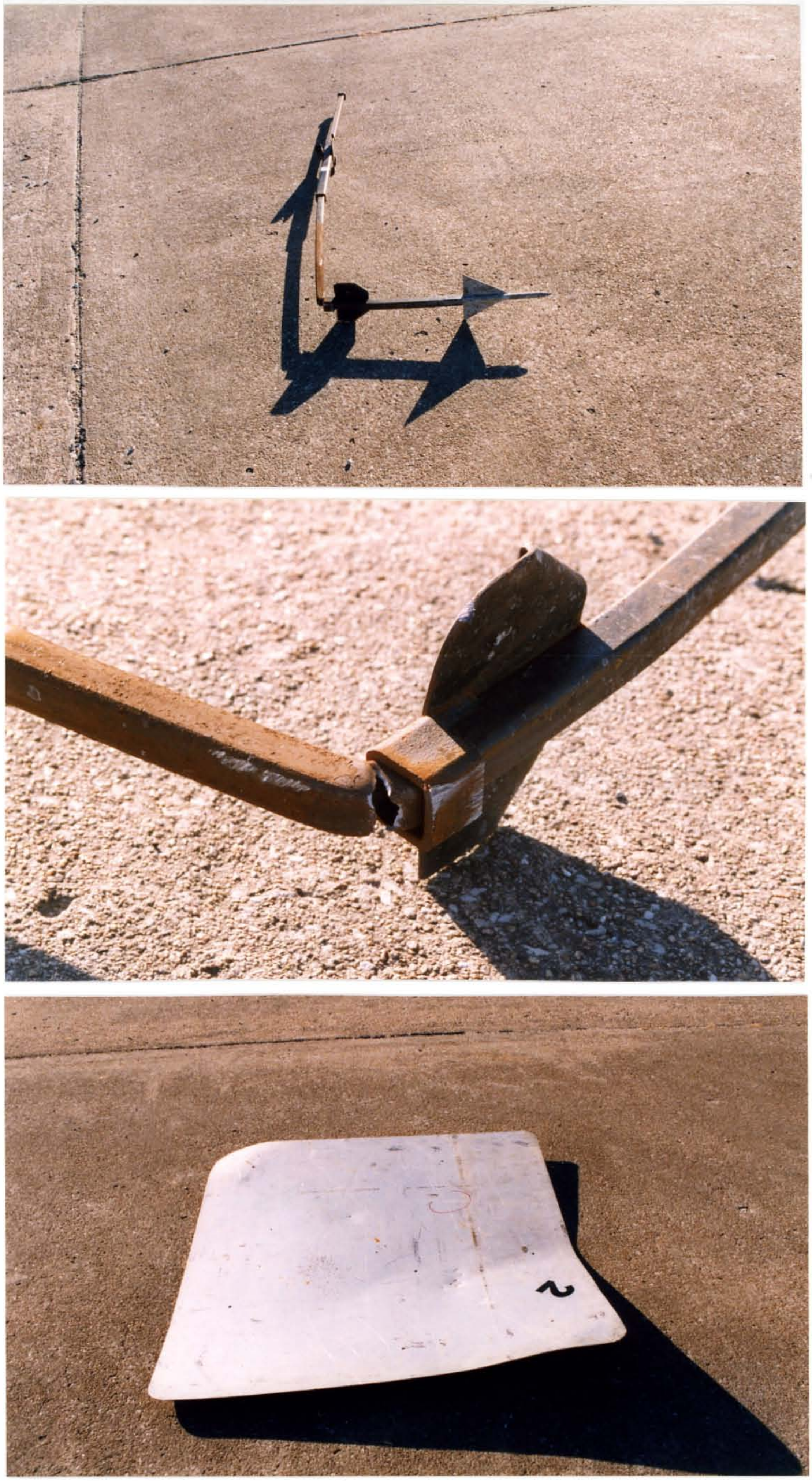


Figure 26. System No. 2 Damage, Test M-2

Figure 27. Vehicle Damage, Test M-2

Figure 28. Windshield Damage, Test M-2

7 DISCUSSION

Following tests M-1 and M-2, a safety performance evaluation was conducted, and both work-zone safety device systems were determined to be unacceptable according to the NCHRP Report No. 350 criteria. Due to the unsuccessful crash tests of both systems, it was necessary to determine the cause of the temporary sign support's poor performance so that design modifications potentially could be incorporated into the sign support systems. Although these temporary sign support systems could remain in use through their normal service life, the Missouri Department of Transportation (MoDOT) wished to utilize these devices with modifications. Design modifications would be made to improve safety of existing systems as well as to allow their continued purchase after October 1, 2000.

Following an analysis of the test results, the researchers believe that the partial post fracture versus a quick, clean fracture significantly lead to both system failures. As a result, the delayed post fracture caused the deformed system to be pushed by the vehicle's front end, thus causing the sign panel and support to be pulled down toward the windshield. For the crash test with a flexible roll-up sign panel, test no. M-1, the top of the support post caused the windshield damage. For the crash test with a rigid, aluminum sign panel, test no. M-2, the sign panel and the top of the post caused the windshield damage. From these crash tests, in both cases, the entire support post began to pull out of the soil before partial post fracture occurred.

Following this investigation, Midwest Roadside Safety Facility (MwRSF) researchers determined that there may be an opportunity to improve the safety performance of the self-driving, single-post support systems. The modifications included drilling two holes in the post near the top bumper height of the small car and through both directions – one at 0 degrees and one at 90 degrees.

These holes would help to activate the fracture of the sign post system, thus reducing the delayed post fracture, forward movement, and the downward post/panel motion toward the windshield. It was believed that these modifications would reduce the potential for severe windshield contact and fracture. However, the improvement in the safety performance due to these modifications are highly dependent on how well the post stub remains in place in the soil.

The final design modification consisted of moving the handle of the self-driver from the top of the moveable tube to the bottom of the moveable tube. This change would move the center of mass of the upper sign post stub and panel farther upward, thus reducing the potential for rapid post rotation in the air and windshield contact.

8 DEVELOPMENTAL TESTING – BOGIE TEST

8.1 Background and Design Modifications

One modification to the sign post system involved drilling a 12.7-mm diameter hole through all four sides of the sign post. These holes were drilled 495 mm from the end of the anchor tip or above the top of the collar of the driveable post. For the second modification, the top sign panel holder was moved from the top of the sliding, driver tube assembly to the bottom of the driver. This modification shifted the driver higher, and in turn, moved the system's center of mass upward. The modified sign support system is shown in Figure 29.

Prior to performing a full-scale crash test on the modified self-driving, single sign post system, MwRSF researchers deemed it necessary to conduct a preliminary evaluation using a bogie vehicle test. Therefore, one bogie test on the modified sign post was conducted. Although the sign post was placed in a rigid base versus a soil foundation, the engineers believed this testing would provide an accurate indication of the potential for windshield contact. This assessment would be based on post stub rotation and stub position relative to the simulated windshield located on the bogie vehicle.

8.2 Test Description

8.2.1 Bogie Vehicle

A rigid frame bogie, constructed from FHWA specifications (22), was used to impact the retrofitted design. The bogie was modified by adding a wooden frame which simulated the bumper, front clip, hood, windshield, A-pillars, and roof of a 1994 Geo Metro, as shown in Figures 30 and 31.

Figure 29. System Design Modifications, Bogie Test MOBOG1

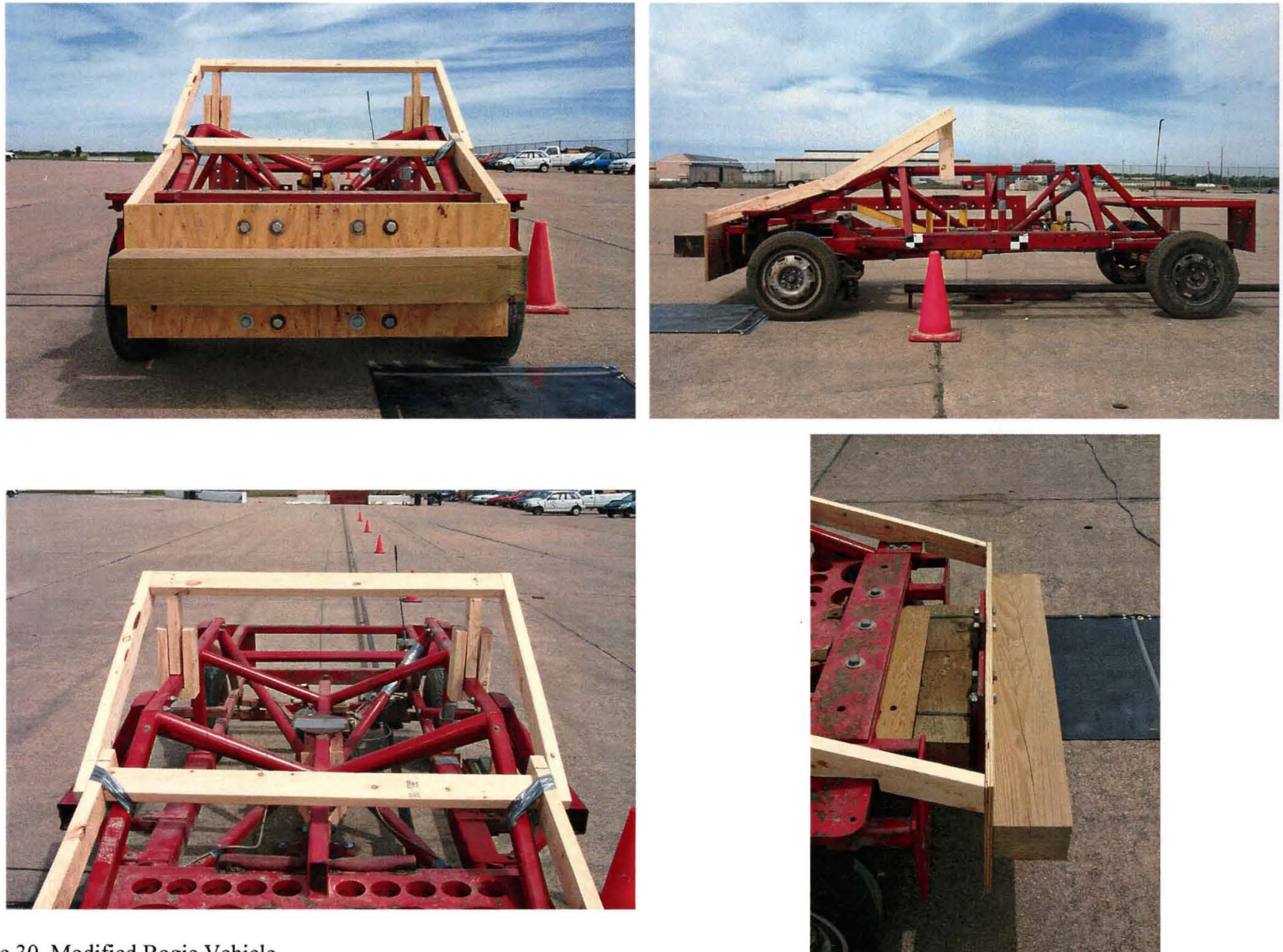


Figure 30. Modified Bogie Vehicle

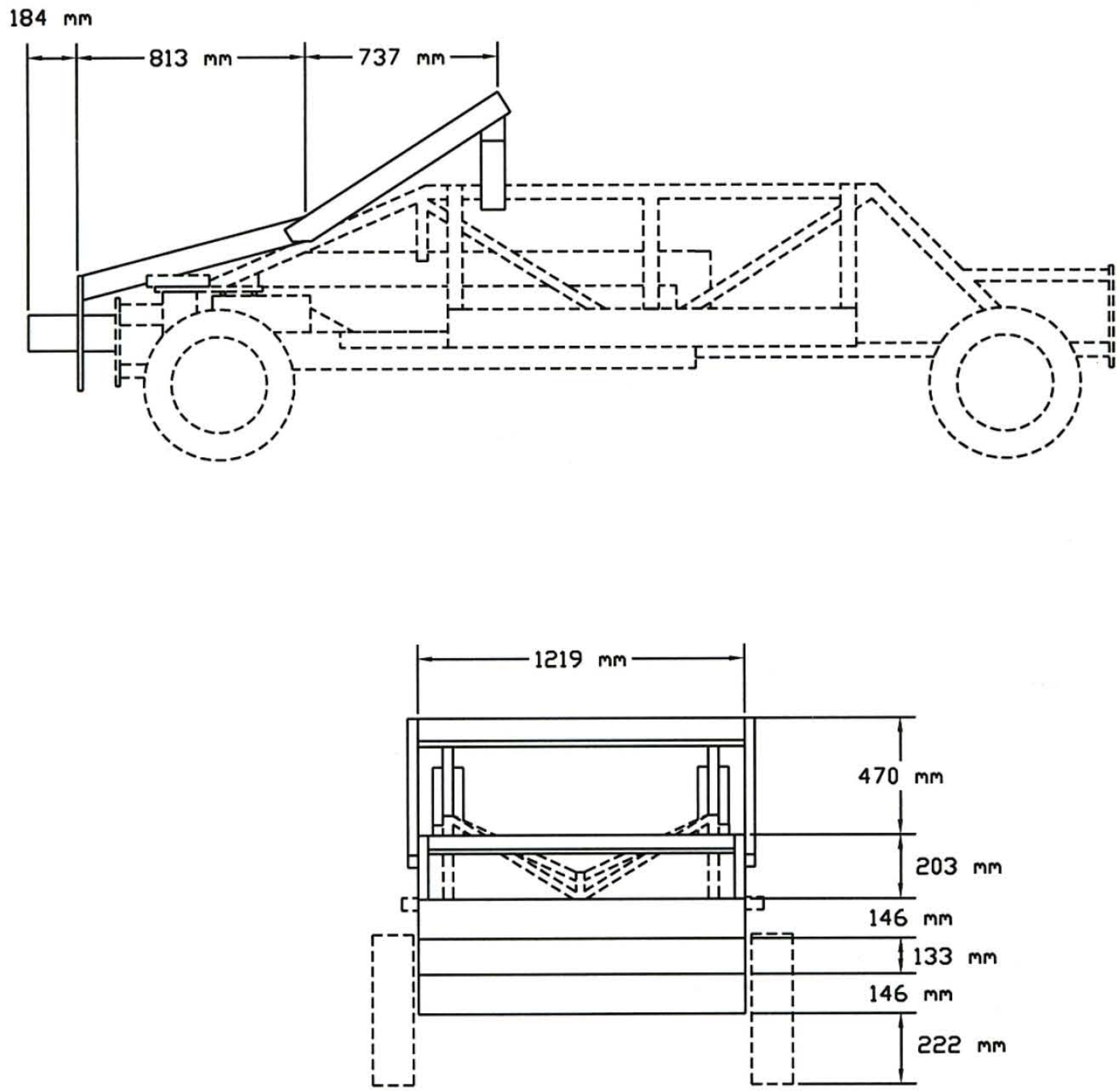


Figure 31. Modified Bogie Vehicle Dimensions

8.2.2 Bogie Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the bogie vehicle. The distance traveled and the speed of the tow vehicle were one-half that of the bogie vehicle. The bogie guide track was 51.8-m long. The guide track was constructed with 57-mm diameter steel pipes, with wall thicknesses and lengths of 4.76 mm and 2,965 mm, respectively. The pipes were supported every 3,048 mm by steel stanchions. The bogie vehicle was released from the tow cable and the bogie guide track before impact with the work-zone traffic control device, allowing the bogie to become a free projectile as it came off the bogie guide track.

8.2.3 System Installation

The system was installed in a fixed base. The fixed base was provided with the placement of plywood shims in the front and rear of the sign stand anchor plate. The anchor point rested on a 152-mm wide x 203-mm deep wooden post which was place inside a steel sleeve, as shown in Figure 32.

8.2.4 Data Acquisition Systems

8.2.4.1 High-Speed Photography

For the bogie test MOBOG1, a high-speed Red Lake E/cam video camera, with an operating speed of 500 frames/sec, was placed slightly downstream and on the left side of the modified system and had a slightly angled view of the retrofit system and impact. Another high-speed Red Lake E/cam video camera, with an operating speed of 250 frames/sec, was placed on the left side of the retrofit system and had a field of view perpendicular to the post. A Canon digital video camera was also place upstream and on the left side of the system and had an angled view of the system and impact.

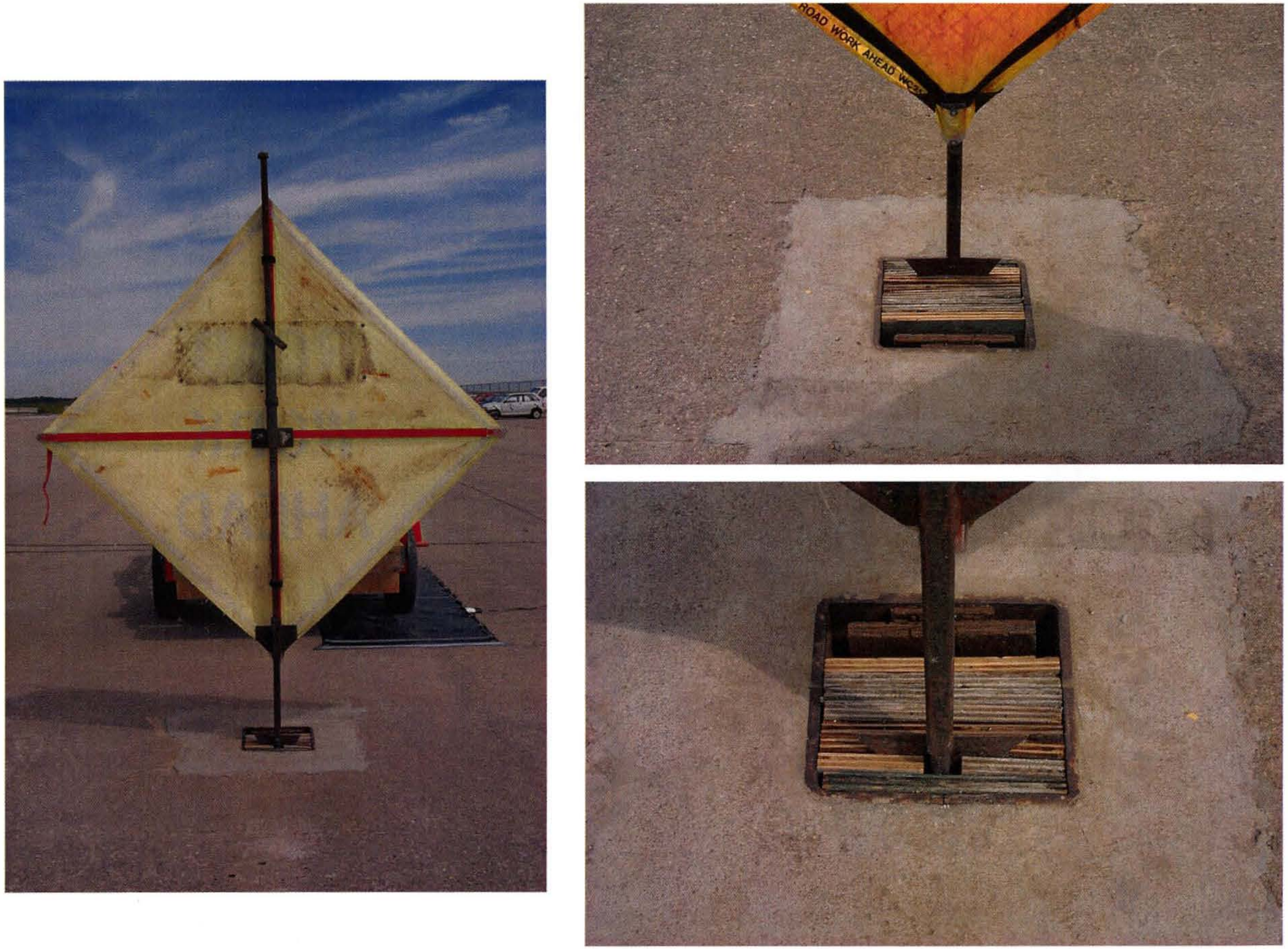


Figure 32. Modified System Installation, Bogie Test MOBOG1

8.2.4.2 Pressure Tape Switches

One set of three pressure-activated tape switches, spaced at 1-m intervals, were used to determine the speed of the bogie vehicle before impact with the device. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the left-front tire of the bogie vehicle passed over the set of tape switches. Test bogie vehicle speed was determined from electronic timing mark data recorded using the "Test Point" software.

8.3 Test Results

8.3.1 Test MOBOG1

The 895-kg bogie vehicle impacted the modified sign support system oriented head-on the to the vehicle at a speed of 68.2 km/hr and an angle of 0 degrees. Sequential photographs are shown in Figures 33 and 34.

8.3.2 Test Description

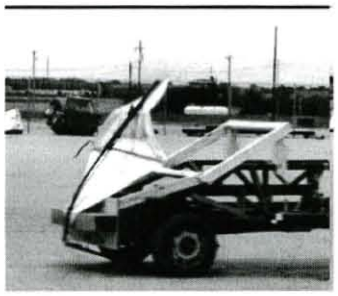
The bogie vehicle impacted the modified system with the centerline point of the vehicle's bumper aligned with the centerline of the sign support, as shown in Figure 35. At 0.006 sec initial impact, the sign post deformed around the bumper while the top of the sign post remained perpendicular to the ground. At 0.008 sec, the sign post continued to deform around the bumper, and the top of the sign post dropped down due to the deformation of the sign post. At 0.016 sec, the top of the sign post and sign panel rotated toward the simulated windshield. At this same time, the lower portion of the sign post rotated away from the bogie toward the ground. At 0.028 sec, the sign panel flexed toward the bogie windshield frame while the sign post partially fractured at the stress concentration points. At 0.040 sec, the sign post began to pull out of the fixed base with the lower section of the sign post parallel to the ground. At this same time, the sign panel flexed toward the

0.000 sec

0.006 sec

0.010 sec

0.018 sec



0.030 sec

0.034 sec

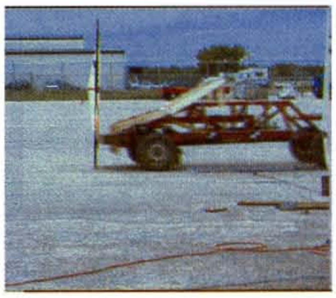
0.040 sec

0.052 sec

0.066 sec

0.070 sec

Figure 33. Additional Sequential Photographs, Bogie Test MOBOG1

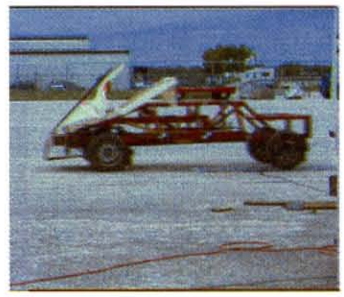


0.000 sec

0.006 sec

0.016 sec

0.028 sec



0.040 sec

0.056 sec

0.072 sec

Figure 34. Additional Sequential Photographs, Bogie Test MOBOG1

bogie, and the ends of the fiberglass crossbraces contacted the outsides of the windshield frame. At 0.056 sec, the sign post pulled completely out of the fixed base while the top of the sign post and the sign panel continued to rotate toward the simulated windshield. At 0.066 sec, the top of the sign post impacted the simulated windshield area. At this same time, the anchor portion of the sign post was still attached and drug along under the vehicle. At 0.072 sec, the system traveled along at the front of the vehicle. At this same time, the plywood shims popped out of the fixed base and up into the air.

8.3.3 System Damage

Damage to the modified system is shown in Figures 36 and 37. The system encountered moderate damage. The self-driving sign post fractured at the location of the drilled holes. The remaining stub of the self-driving sign post also pulled completely out of the fixed base, as seen in Figure 36. A few of the plywood shims came out of the fixed base, as shown in Figure 37. Deformations in the self-driving sign post were very prominent near the impact area of the bumper, as seen in Figure 36. The vinyl sign panel and fiberglass crossbraces remained undamaged and attached to the self-driving sign post.

8.3.4 Bogie Vehicle Damage

The bogie vehicle damage is shown in Figure 38. The center of the wooden simulated bumper was dented. The simulated windshield frame was fractured in the center of the lower frame section. No other damage was found to have occurred to the rest of the bogie vehicle.

8.3.5 Discussion

Following bogie test MOBOG1, an evaluation was conducted, and the modified work-zone traffic control device performed unacceptably in the bogie crash test. The modified system did not perform as expected, since the sign post did not break cleanly through all of the drilled, post-weakening holes. If a small car would have been used in place of the bogie vehicle, the system would have deformed around the bumper at the front of the small car. Along with the deformation around the front of the small car, the top of the sign post would have impacted and severely punctured the center region of the windshield.

Figure 35. Impact Location, Bogie Test MOBOG1

Figure 36. System Damage, Bogie Test MOBOG1

Figure 37. System Damage, Bogie Test MOBOG1

Figure 38. Bogie Vehicle Damage, Bogie Test MOBOG1

9 SUMMARY AND CONCLUSIONS

A total of two full-scale crash tests and one bogie vehicle test were conducted on the various portable sign supports. Both of the full-scale crash tests on the work-zone traffic control devices failed to satisfactorily meet 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. The bogie vehicle test on a modified sign support system also did not provide promising results.

For portable sign supports, the performance of these sign supports is based on the behavior of many sign features, such as the vertical distribution of the system's mass, stiffness and strength of the mast and stand, crossbrace member sizes and strength, ans sign material. Consequently, slight differences in system design details can potentially lead to very different results.

Table 4. Summary of Safety Performance Evaluation Results

Evaluation Factors	Evaluation Criteria	Test M-1	Test M-2
		#1	#2
		PS[1]	PS[1]
Structural Adequacy	B	S	S
Occupant Risk	D	U	U
	E	U	U
	F	S	S
	H	NA	NA
	I	NA	NA
Vehicle Trajectory	K	S	S
	N	S	S
NCHRP Test Level[2]		TL-3	TL-3
Method of Failure[3]		1,2,3,4	1,2,3,4
Pass/Fail		Fail	Fail

[1] Hardware Type: PS – Portable Sign
[2] NCHRP Report 350 Test Level: TL-3 – Test Level 3
[3] 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 - 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

10 RECOMMENDATIONS

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

- Test No. M-1, System No. 1 – Self-driving, single-post, sign support SH-96-2 stand with a vinyl flexible sign panel oriented head-on.
- Test No. M-2, System No. 2 – Self-driving, single-post, sign support SH-96-2 stand with an aluminum rigid sign panel oriented head-on.

Although the self-driving, single-post, sign supports did not perform in an acceptable manner, there still exists the potential for a self-driving work-zone traffic control device to meet the TL-3 safety standards. It is likely that simple modifications will greatly improve the work-zone traffic control device's performance. Examples of these design modifications include the following and/or combinations thereof: (1) using a more brittle vertical sign post material; (2) increasing the stub embedment depth in the ground; (3) reducing the vertical mast height; (4) increasing the vertical mast height to allow the system to bridge the windshield and incorporate multiple sign heights; and (5) incorporating a breakaway mechanism. However, any design modifications made to the work-zone traffic control device can only be verified through the use of full-scale vehicle crash testing.

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12 APPENDICES

APPENDIX A

Dimensional Measurements of Portable Sign Support Systems

Table A-1. Portable Sign Support System Dimensional Measurements

System Number	Test Number	STAND		SIGN		
		Type [1]	Weight (kg)	Type [2]	Material [3]	Weight (kg)
1	M-1	Self-Driving	8.618	Flexible	1	2.722
2	M-1	Self-Driving	9.072	Rigid	6	10.433

[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)

Table A-2. Portable Sign Support System Dimensional Measurements

System Number	HEIGHTS TO		
	Bottom of Sign Panel (mm)	Top of Sign Panel (mm)	Top of Sign Post (mm)
1	276	1982	2136
2	288	2013	2136

Table A-3. Portable Sign Support System Dimensional Measurements

Stand Type	VERTICAL TUBING					TAMPER TUBING				
	Material	Dimension #1 (mm)	Dimension #2 (mm)	Length (mm)	Thickness (mm)	Material	Dimension #1 (mm)	Dimension #2 (mm)	Length (mm)	Thickness (mm)
Self-Driving	ASTM Steel Grade A513 Mechanical Tubing	25.35	25.80	2136	4.45	ASTM Steel Grade A513 Mechanical Tubing	38.00	38.83	462	5.05
Self-Driving	ASTM Steel Grade A513 Mechanical Tubing	25.65	25.85	2136	4.75	ASTM Steel Grade A513 Mechanical Tubing	38.32	38.38	457	5.01

Table A-4. Portable Sign Support System Dimensional Measurements

Stand Type	UPPER SIGN BRACKET				LOWER SIGN BRACKET			
	Material	Width (mm)	Height (mm)	Thickness (mm)	Material	Width (mm)	Height (mm)	Thickness (mm)
Self-Driving	ASTM Steel Grade A513 Mechanical Tubing	153	73	2.56	ASTM Steel Grade A513 Mechanical Tubing	153	100	3.40
Self-Driving	ASTM Steel Grade A513 Mechanical Tubing	152	104	3.58	ASTM Steel Grade A513 Mechanical Tubing	153	104	3.30

Table A-5. Portable Sign Support System Dimensional Measurements

Stand Type	TYPE OF SIGN PERCH			ANCHOR				LENGTHS		
	Triangle Plate	Flat Plate	None	Material	Triangle Thickness (mm)	Bar Tubing Diameter (mm)	Length (mm)	Anchor end to bottom of sign perch (mm)	Anchor end to top of bottom sign bracket (mm)	Anchor end to top of sign post (mm)
Self-Driving	XXX			ASTM Steel Grade A513 Mechanical Tubing	3.10	19.10	204	480	675	2340
Self-Driving			XXX	ASTM Steel Grade A513 Mechanical Tubing	3.20	19.15	270	---	690	2400

Table A-6. Portable Sign Support System Dimensional Measurements

Sign Type	CROSSBRACE – VERTICAL MEMBER						CENTER HUB			
	Material	Square Dimension (mm sqr.)	Wall Thickness (mm)	Thickness (mm)	Width (mm)	Length (mm)	Material	Leg Length (mm)	Square Dimension (mm sqr.)	Shape
Flexible	Fiberglass	---	---	9.55	31.15	1680	---	---	---	---
Rigid	---	---	---	---	---	---	---	---	---	---

Table A-7. Portable Sign Support System Dimensional Measurements

Sign Type	CROSSBRACE – HORIZONTAL MEMBER					
	Material	Square Dimension (mm sqr.)	Wall Thickness (mm)	Thickness (mm)	Width (mm)	Length (mm)
Flexible	Fiberglass	---	---	5.05	30.77	1685
Rigid	---	---	---	---	---	---

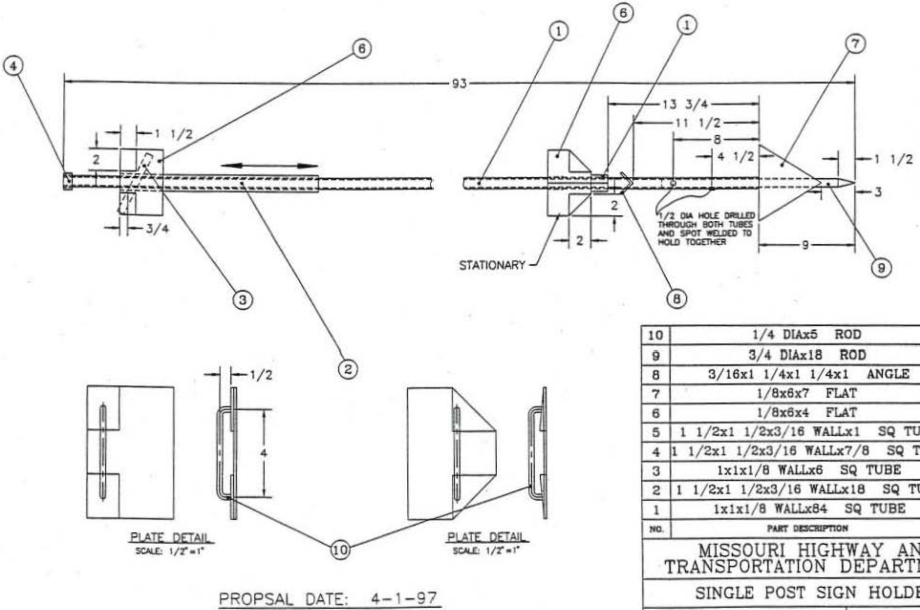
Table A-8. Portable Sign Support System Dimensional Measurements

Sign Type	SIGN PANEL				
	Material	Thickness		Length (mm)	Width (mm)
		Across Seam (mm)	At Seam (mm)		
Flexible	Reflective Vinyl	0.85	0.65	1216	1196
Rigid	Aluminum	2.80	---	1220	1220

APPENDIX B

Single Post Sign Holder System Details

Figure B-1. Single Post Sign Holder System Details



NO.	PART DESCRIPTION	REQ.
10	1/4 DIAx5 ROD	2
9	3/4 DIAx18 ROD	1
8	3/16x1 1/4x1 1/4x1 ANGLE	1
7	1/8x6x7 FLAT	1
6	1/8x6x4 FLAT	2
5	1 1/2x1 1/2x3/16 WALLx1 SQ TUBE	1
4	1 1/2x1 1/2x3/16 WALLx7/8 SQ TUBE	1
3	1x1x1/8 WALLx6 SQ TUBE	1
2	1 1/2x1 1/2x3/16 WALLx18 SQ TUBE	1
1	1x1x1/8 WALLx84 SQ TUBE	1

MISSOURI HIGHWAY AND TRANSPORTATION DEPARTMENT

SINGLE POST SIGN HOLDER

PART NAME	SIGN HOLDER	PART NUMBER	SH-96-2
DRAWN BY	B. COLE	APPROVED BY	________
SCALE 1/4" = 1"	DATE MARCH 27, 1997	PAGE 1 OF 1	

NOTES:
1. LOCATED ON DISK #11

Figure B-1. Single Post Sign Holder System Details