life expectancy of the unmodified configuration and that the modification used in the fifth fatigue test may approximate that of the unmodified base in the absence of weldments in or near the plane of saw cuts.

Impact Severity

The primary criterion for evaluation of breakaway supports is a maximum vehicle momentum change of 500 kg·s (1100 lb·s) with a desirable limit of 350 kg·s (750 lb·s). The momentum changes occurring in the five tests conducted are summarized below (1 kg·s = 2.2 lb·s):

Item	Test Number				
	1	2	3	4	5
Speed trap measurement	—	485	358	—	506
Integration of acceleration					
Tunnel	1145	504	351	338	457
Rear deck	1105	499	360	349	418
High-speed film reduction	1060	512	350	388	457

In test 1, there was no penetration in the speed trap measurement, and in test 4 the measurement was erroneous. Test 5 was biased due to secondary impacts.

As indicated in the above summary, the momentum change, resulting from test 2 with a modified transformer base cut so that 102 mm (4 in) of material remained on each side panel, comes close to meeting the maximum allowed momentum change at an impact speed of 9 m/s (20 mph) with a 1020-kg (2250-lb) vehicle.

The third and fourth tests employed a modified transformer base cut with 76 mm (3 in) of material remaining on each panel, and succeeded in nearly meeting the desirable momentum change limit of 350 kg·s (750 lb·s). These tests were conducted with nominal 1020-kg (2250-lb) vehicles at speeds of 9 and 18 m/s (20 and 40 mph) respectively.

The fifth impact test employed a transformer base cut so that 76 mm (3 in) of material remained at each corner. This further modification was made in an attempt to increase the fatigue life of the base and, in a 9-m/s (20-mph) impact with a 1020-kg (2250-lb) vehicle, successfully limited the momentum change to below 500 kg·s (1100 lb·s). However, as discussed in the complete report, the momentum transfer is believed to be approximately 91 kg·s (200 lb·s) too high as a result of secondary impacts with the base by both the towing attachment and the guide slipper.

The maximum 50-ms average deceleration computed for the five tests are as follows: Test 1, 16.8 g; test 2, 7.9 g; test 3, 6.2 g; test 4, 6.0 g; and test 5, 5.9 g.

Vehicle Trajectory Hazard

No substantial vehicle trajectory hazard exists with roadside appurtenances tested since they are not redirective devices. However, as noted previously, pole kinematics after impact could not be adequately defined because of the influence of the abort brake that did not allow the vehicle to clear the pole drop zone at exit velocity.

Pendulum Tests of Breakaway Wood Sign Supports Using Crushable Bumpers

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Ten pendulum impact tests of breakaway wood sign supports were conducted to evaluate safety performance. Two sizes of timber supports were tested per AASHTO impact conditions, i.e., 1020 kg (2250 lb) mass and 32 km/h (20 mph). Two crushable pendulum nose designs were also used to evaluate relative performance. The findings indicate that both support sizes can be modified by drilled holes to effect structures that safely break away with a pendulum mass momentum change of less than 3.36 kN·s (750 lb·s). The findings also indicate that the crushable nose design has an important effect on the breakaway performance. Sequential photographs illustrate that the fracture mechanism is similar for the ten tests.

at the Southwest Research Institute's (SwRI) pendulum facility to evaluate their performance as breakaway roadside structures. A total of eight tests were conducted on 100 × 150-mm (4 × 6-in) and 150 × 200-mm (6 × 8-in) timber sign supports with and without holes near grade level with a crushable pendulum nose design (1). Two additional tests were conducted with a recently developed crushable pendulum nose design (2). Details of the program, test procedures, results, and conclusions are summarized in the following sections.

Two sizes of timber sign supports were impact-tested

BACKGROUND

Evaluation Criterion

Patrick (3) and Blamey (4) concluded that head and chest impact injuries occur among vehicle occupants when the head velocity, measured relative to the vehicle, exceeds 18 km/h (11 mph). Edwards (5) stated that if the vehicle velocity change exceeds 10 km/h (6 mph), there is a possibility of minor passenger injury; velocity changes larger than 19 km/h (12 mph) should be avoided. Since vehicle velocity change imparted by a specific breakaway structure is an inverse function of the impacting vehicle mass, a more definitive performance criterion was established by coupling a 910-kg (2000-lb) vehicle with the 19-km/h (12-mph) velocity change to produce a 4.93-kN·s (1100-lb·s) impulse or change in momentum (9). For this same impulse and an 1820-kg (4010-lb) automobile, the velocity change is 10 km/h (6 mph) and, hence, the impact is less hazardous to vehicle occupants. In 1975, AASHTO (6) indicated that while the 4.93-kN·s (1100-lb·s) impulse is acceptable, a maximum 3.36 kN·s (750 lb·s) is preferred. Procedures for conducting vehicle crash tests of breakaway of yielding supports are de-scribed in NCHRP Report 153 (7).

Pendulum Test

Because of variation in crush characteristics of automobiles and the relative high cost for staging full-scale tests, effort has been devoted by the Federal Highway Administration (FHWA) (8) and others (2) to develop an "equivalent" nonautomobile test. In 1970, FHWA (9) permitted the use, with certain exceptions, of ballistic pendulum tests as a substitute for full-scale vehicle testing to determine acceptability of breakaway characteristics of luminaire supports. An interim acceptance level of a 1.79-kN·s (400-lb·s) change in momentum of the impacting mass was established when tested with a 910-kg (2000-lb) pendulum mass, a 32.2-km/h (20-mph) impact speed, and 0.51-m (20-in) striking height. This procedure implied that a pole that produced a 4.93-kN·s (1100-lb·s) change in vehicle momentum in a full-scale test would produce a 1.79-kN·s (400-lb·s) momentum change in the rigid-nose pendulum mass. The difference in momentum change was attributed to vehicle crush characteristics and other factors. Unfortunately, it has been shown that pole breakaway performance cannot be

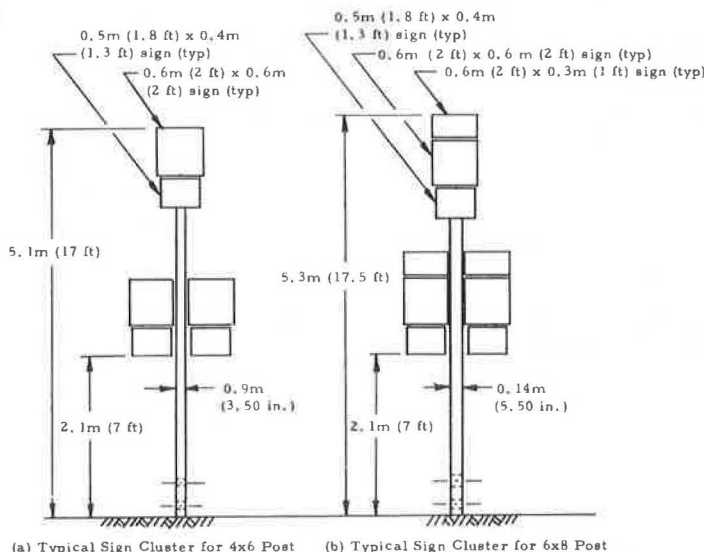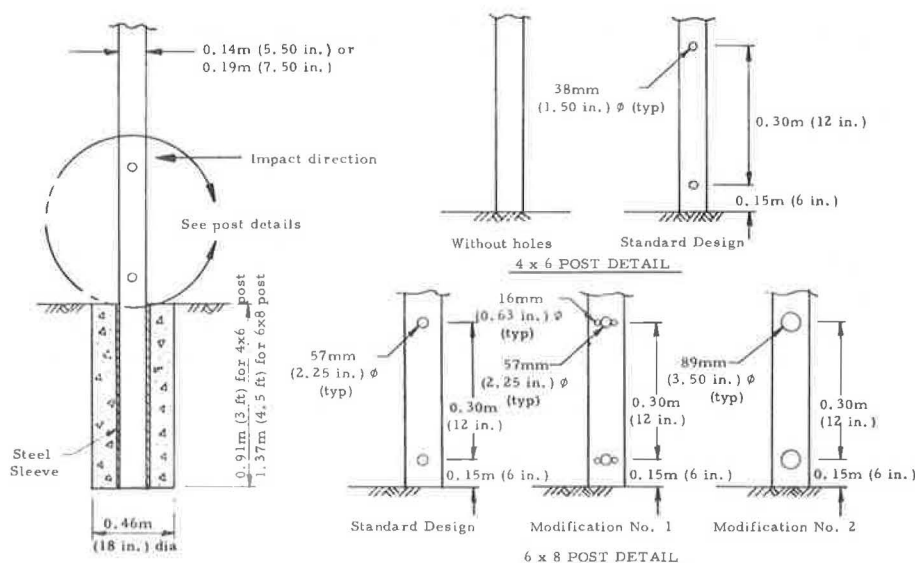Figure 1. Sign configuration for test specimen.

(a) Typical Sign Cluster for 4x6 Post　(b) Typical Sign Cluster for 6x8 Post

Figure 2. Specimen breakaway designs.

Figure 3. Crushable nose configurations.

(a) Per FHWA Notice N5040.20
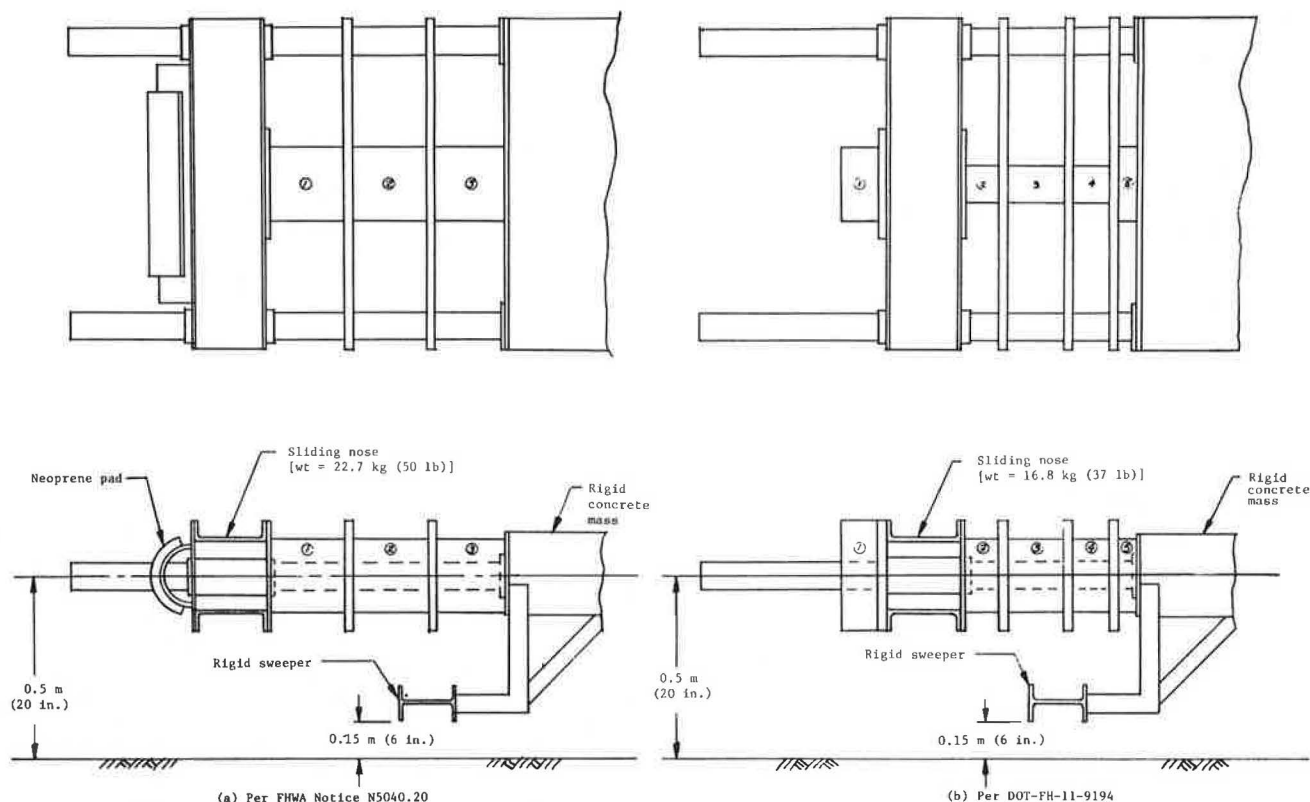
(b) Per DOT-FH-11-9194

Figure 4. Photographs of test setup.

(a) Specimen with Sign Cluster

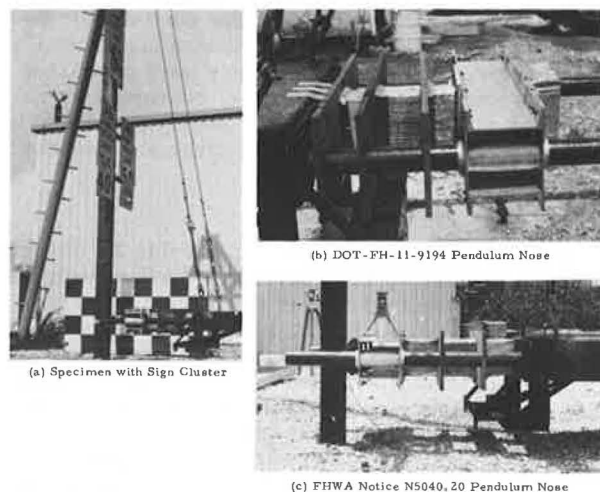(b) DOT-FH-11-9194 Pendulum Nose

(c) FHWA Notice N5040.20 Pendulum Nose

Table 1. Details of honeycomb configurations.

Nose Design	Stage No.	Height (m)	Width (m)	Thickness[a] (m)	Static Strength (kN)
FHWA Notice N5040.20	1	0.20	0.20	0.20	21
	2	0.20	0.20	0.20	37
	3	0.20	0.20	0.20	65
DOT-FH-11-9194	1	0.30	0.20	0.10	32
	2	0.20	0.10	0.10	11
	3	0.20	0.10	0.15	19
	4	0.20	0.10	0.10	33
	5	0.20	0.20	0.05	65

Note: 1 m = 3.3 ft and 1 kN = 0.225 kip.

[a]Thickness before 6.4-mm (0.25-in) precrush.

reliably projected from rigid-nose pendulum test results (8).

Crushable Pendulum Nose

In 1976, FHWA (1) presented details for a crushable nose for pendulum and bogies and stated that nonautomobile test procedures are considered equivalent for some types of hardware—luminaire supports, slip-base and load-concentrating sign supports, and, with a bogie only, single-post timber and base-bending sign supports. However, testing by FHWA in the fall of 1976 revealed that the pendulum tests using this nose setup failed to produce results correlating with full-scale test results obtained at the Texas Transportation Institute for certain support types. In particular, steel slip-base luminaire supports were severely deformed by the pendulum impact and, in some cases, momentum changes over 5.38 kN·s (1200 lb·s) were recorded. Full-scale test results for a subcompact vehicle striking a slip-base luminaire support at 32.2 km/h (20 mph) were in the 2.24-kN·s (500-lb·s) range.

A second-generation crushable pendulum nose has recently been developed by FHWA and Ensco (2). The nose has been configured to develop crush characteristics of a pre-1974 Chevrolet Vega. This vehicle was chosen because it is a typical 1020-kg (2250-lb) automobile. Although this nose design has not been endorsed by FHWA engineering as a replacement for design presented in FHWA Notice N5040.20, preliminary findings indicate the pendulum results compare favorably with full-scale crash test results (2).

Although the objective of the program reported here was to evaluate breakaway characteristics of timber sign supports with the pendulum nose presented in FHWA Notice N5040.20, two additional tests were performed using the second-generation crushable nose to provide

Table 2. Test matrix and data summary.

Test No.	Specimen Dimensions (m)	Breakaway Design[a]	Pendulum Nose Configuration[b]	Impact Velocity (m/s)	Pulse Duration (m/s)	Velocity Change (m/s)	Peak Force (kN)	Impulse (kN·s)	Energy (kJ)		
									Total Kinetic[c]	Nose Crush[d]	Specimen Fracture[e]
M1	0.10 x 0.15	Standard	A	9.03	50	0.73	34.7	0.75	6.46	0.40	6.06
M2	0.10 x 0.15	Standard	A	9.17	53	0.73	35.1	0.75	6.60	0.67	5.93
M3	0.10 x 0.15	Standard	B	9.10	84	1.77	60.5	1.81	14.84	8.39	6.45
M4	0.10 x 0.15	Without holes	A	8.90	30	0.62	34.7	0.63	5.44	1.24	4.20
M11	0.15 x 0.20	Standard	A	9.17	100	5.68	82.7	5.80	36.69	18.43	18.26
M12	0.15 x 0.20	Standard	A	8.96	95	3.13	64.1	3.19	23.62	10.59	13.03
M13	0.15 x 0.20	Mod. 1	A	8.96	55	1.23	35.6	1.26	10.48	6.92	3.56
M14	0.15 x 0.20	Mod. 1	A	8.96	40	0.91	45.4	0.93	7.90	2.79	5.11
M15	0.15 x 0.20	Mod. 2	A	9.24	42	1.21	49.8	1.23	10.66	4.01	6.65
M16	0.15 x 0.20	Mod. 1	B	8.84	77	2.39	81.0	2.44	18.56	9.92	8.73

Note: 1 m = 3.3 ft, 1 m/s = 3.28 ft/s, 1 kN = 0.225 kip, 1 kN·s = 223.1 lb·s, 1 kJ = 0.738 ft·kip.

[a]See Figure 2 for details.
[b]A, per FHWA Notice N5040.20; B, per DOT Contract FH-11-9194.
[c]KE = 0.5 m (V_f^2 - V_o^2).
[d]See Table 2.
[e]Specimen fracture energy = total KE - nose crush energy.

Table 3. Pendulum nose deformation and crush energy.

Test No.	Stage No.	Average Thickness (mm)			Compressive Strength (kN)	Crush Energy (kJ)
		Initial	Final	Crush		
M1	1	197	178	19	21	0.40
	2	197	197	0	37	0.00
	3	197	197	0	65	0.00
M2	1	197	165	32	21	0.67
	2	197	197	0	37	0.00
	3	197	197	0	65	0.00
M3	1	95	13	82	32	2.62
	2	95	13	82	11	0.90
	3	146	24	122	19	2.32
	4	95	20	75	33	2.48
	5	44	43	1	65	0.07
M4	1	197	133	159	21	1.24
	2	197	197	0	37	0.00
	3	197	197	0	65	0.00
M11	1	197	29	168	21	3.53
	2	197	35	162	37	5.99
	3	197	60	137	65	8.91
M12	1	197	37	160	21	3.36
	2	197	35	162	37	5.99
	3	197	178	19	65	1.24
M13	1	197	35	162	21	3.40
	2	197	102	95	37	3.52
	3	197	197	0	65	0.00
M14	1	197	64	133	21	2.79
	2	197	197	0	37	0.00
	3	197	197	0	65	0.00
M15	1	197	38	159	21	3.34
	2	197	179	18	37	0.67
	3	197	197	0	65	0.00
M16	1	95	25	70	32	2.24
	2	95	11	84	11	0.92
	3	146	19	129	19	2.43
	4	95	19	76	33	2.51
	5	44	16	28	65	1.82

Note: 1 mm = 0.039 in, 1 kN = 0.225 kip, 1 kJ = 0.738 ft·kip.

comparison and insight to their relative performance.

Test Specimens

Timber test specimens and signing hardware were supplied by the Michigan Department of State Highways and Transportation (MDSHT). The timber supports were Southern yellow pine with pentachlorophenol preservative. The test articles were assembled and erected according to MDSHT drawings S3.30, S9.20, and engineering sketches. Arrangement of signing is shown in Figure 1.

Test Procedures

The timber specimens were modified as shown in Figure 2 and inserted into a 0.46-m (18-in) round concrete footing that had been constructed with a sheet metal sleeve. Wood shims were used to ensure that the specimen was tightly fitted in the sleeve. Soil, specified and consolidated per recommendations of NCHRP Report 153, represented a relatively stiff support for the concrete footing.

A 1020-kg (2250-lb) reinforced concrete mass with a swing radius of 7.9 m (26 ft) impacted each specimen 0.5 m (20 in) above grade. The front of the 0.9 × 1.8 × 0.2-m (3 × 6 × 0.75-ft) mass was fitted with a crushable aluminum honeycomb nose to simulate vehicle crush or deformation. Details of the two types of nose configuration are shown in Figures 3 and 4 and Table 1.

To initiate a test, the pendulum mass was elevated to a predetermined height and released. Actual impact speed was determined from a photocell-operated speed trap.

Signals from an accelerometer, mounted at the rear of the concrete pendulum mass, were continuously recorded throughout the impact events by a high-speed magnetic tape recorder. These were later processed through an SAE J211 Class 60 filter, converted from analog to digital format, and subsequently processed by digital computer for kinematic and dynamic parameters.

FINDINGS

A summary of test results appears in Table 2. Velocity change and impulse are key parameters when evaluating performance of the break-away mechanism. Because nose crush energy is reflected in the impulse values and two different nose designs were used, fracture energy of the specimens was determined by subtracting the nose crush energy (i.e., honeycomb deformation × compressive strength) from the change in pendulum kinetic energy. A summary of nose crush findings is presented in Table 3. Typical impact sequence photographs are shown in Figure 5.

ANALYSIS OF TEST RESULTS

Performance

Of the ten tests, only test M11, the standard 150 × 200-mm (6 × 8-in) support, failed to pass the acceptable maximum 4.93-kN·s (1100-lb·s) or preferred maximum 3.36-kN·s (750-lb·s) change in momentum criteria. All other specimens broke away within the preferred maximum impulse limits. From these tests, it appears that all single support designs except that evaluated in test M11 should be accepted for in-service use, provided the designs satisfy environmental loadings.

Figure 5. Sequence photographs of fracture mechanism.

| Test M2 | Test M16 | Test M13 | Test M4 | Test M3 |
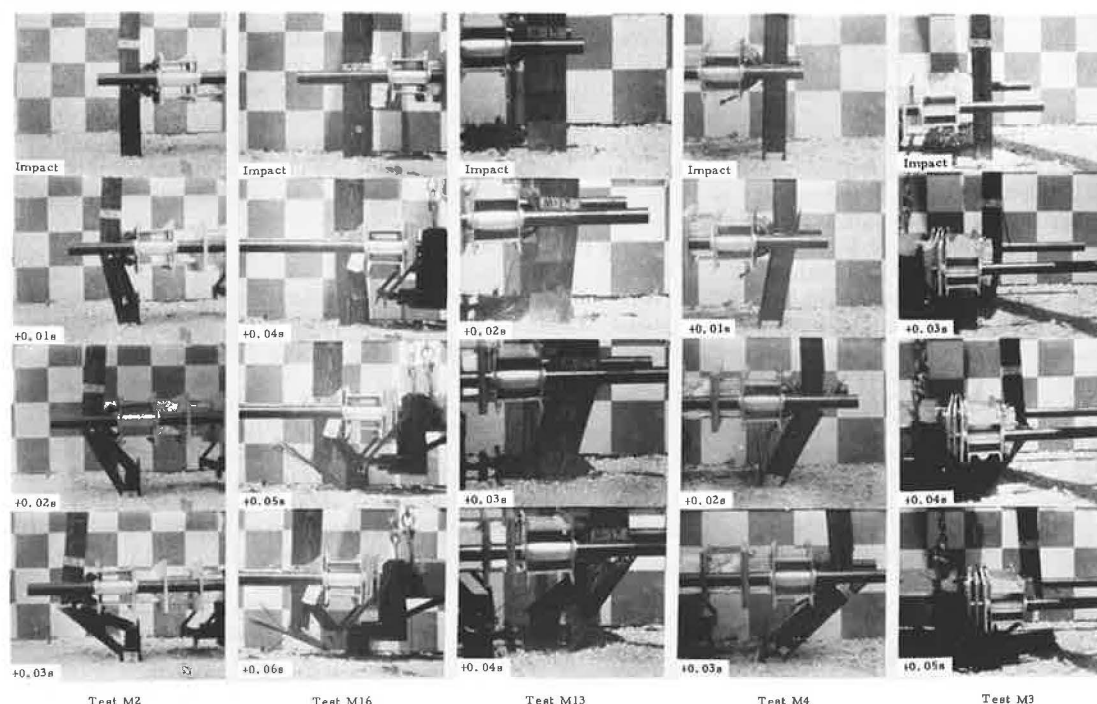
Stages of Support Fracture

Four stages of support fracture are shown in Figure 5 for tests M2, M3, M4, M13, and M16. These illustrations are also typical for tests M1, M11, M12, M14, and M16:

1. Stage 1. The first photograph in each test shows the support at instant of impact. No deformation of support or crushing of pendulum nose has occurred.
2. Stage 2. Between stages 1 and 2, practically all pendulum nose crush has occurred. A plastic hinge is forming in the support at the point of pendulum contact and a second hinge is forming at grade. The portion of the support above the pendulum remains essentially vertical. Peak resisting force of the support occurs at or about the time of this stage.
3. Stage 3. A vertical split in the support forms from grade up to the pendulum contact. The forward (away from the pendulum contact) segment of the partially severed support breaks in flexure at grade level and at the pendulum plane. For the rear segment, the break occurs at the lower hole pattern and at the pendulum plane. For test M4, no vertical fracture is evident; the support fractures at grade and at the pendulum plane.
4. Stage 4. Fracture of the support is completed.

Foundation

All tests were performed with the support mounted in a 0.46-m (18-in) diameter concrete footing. The footing minimized movement of the support during impact, although some movement was observed in high-speed cine for tests M11 and M12. The effect of this small movement is unknown but it is surmised to have caused a slight increase in momentum change. The soil is specified by NCHRP Report 153 and provides a high level of lateral support to the concrete foundation and specimen. Installation procedures for the sign supports should in-

clude guidelines that will assure a densely compacted soil around the concrete footing.

Michigan's standard practice is to cast the footing in place after making the hole with an auger. This could result in a more rigid foundation depending on soil conditions in the field. It follows, therefore, that actual field conditions could result in less momentum change than the laboratory tests indicate.

An important aspect of the concrete footing is the rigid flexure line or stress riser at grade level. All specimens were observed to ultimately break at this juncture. Without this stress riser, it is conjectured that a tougher, less brittle failure would occur at or below grade. Hence, to effect field performance corresponding to these test results, the concrete footing is required.

Crushable Nose Designs

Two crushable nose designs were used in the program. Although the eight tests with configuration A and two tests with configuration B are too few to draw statistically valid conclusions, the following observations are presented.

First, the two nose designs do not give similar results and therefore are not interchangeble. More of the pendulum kinetic energy is absorbed in crushing the softer nose. For example, 0.53-kJ (0.4-ft·kip) average energy was absorbed by the nose in tests M1 and M2 as opposed to 8.39-kJ (6.2-ft·kip) energy absorbed by the soft configuration B nose in test M3. Since essentially all nose crushing occurs prior to fracture of the support, the change in momentum attributed to the nose crush is calculated to be 0.061 kN·s (13.6 lb·s) for configuration A (average of M1 and M2) and 0.972 kN·s (217 lb·s) for configuration B in test M3. Similarly, more energy and momentum change is caused by configuration B in test M16 than for configuration A in tests M13 and M14.

A second consideration is that the contact force between the pendulum mass and the wood support builds up

more slowly for the soft-nose configuration B designs. Thus, the more sudden onset rate of loading for the harder nose design, which promotes a more brittle fracture of the wood, is attenuated. This action results in the specimen exhibiting tougher strength characteristics for the softer nose pendulum.

It is noted that configuration B is patterned to match the crush properties of a pre-1974 Chevrolet Vega. After 1974, a stiffer bumper and front end were produced to meet new U.S. Department of Transportation safety regulations. Hence, by using configuration B, the more conservative crushable nose is utilized in evaluating roadside appurtenances. At some time in the future, when most pre-1974 vehicles are no longer in service, a more rigid pendulum nose should be used.

To date, no full-scale vehicle tests have been performed on the Michigan sign support designs. Hence, a comparison between full-scale crash tests and pendulum test results cannot be made.

CONCLUSIONS

A number of conclusions can be made from the findings:

1. With the exception of test M11 on the 150 × 200-mm (6 × 8-in) support standard, all configurations produced less than the maximum preferred momentum change specified by FHWA (1). Although test M12, a replication of test M11, did produce less than the preferred momentum change, it would seem prudent to use modifications 1 or 2 to achieve a higher degree of safety performance.

2. The two crushable nose designs are not equivalent based on momentum change of the pendulum and fracture energy of the support. A major part of the difference is due to the energy absorbed in the nose crush. In addition, it appears the slower buildup of force in the soft nose tests may attenuate the tendency for low-energy brittle fracture of the wood and thereby produce a tougher breakaway phenomenon.

3. The fracture mechanisms of the modified supports were generally consistent with (a) a shear failure occurring between the upper hole, through the lower hole, and to grade, and (b) flexure fractures occurring at the

upper hole, at the lower hole, and at grade. Knots or other wood discontinuities located in these failure planes would probably affect the results.

4. Since all specimens were tested with a concrete footing, any operational design based on these findings should include a similar foundation. We believe that a less rigid foundation and stress riser at grade level would increase the toughness of the fracture mechanism, thereby effecting a less conservative breakaway support.

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Abridgment
Breakaway Sign Testing, Phase 1

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Because of the damage to people and vehicles when an errant vehicle hits a fixed object, the state of New Jersey developed a breakaway system for large ground-mounted sign supports. Testing was conducted under various controlled conditions and indicated that the system met the appropriate criteria for a breakaway support. Subsequent to the testing, some modifications were made to the system, including the components used to restrain the breakaway section of the post to the fixed post segment.

After several years of experience it was found that the system was not performing as desired, although no injuries or deaths were reported as a result of hitting the

breakaway structures. Frequently, the restraint components failed, permitting the struck post to separate completely from the remaining post. Other components also were found to fail on occasion, although the system continued to function sufficiently to prevent any reported injuries.

At this time a detailed review of the breakaway system, including the results of investigations of actual sign impacts, became appropriate. Personnel from the state transportation department's research, design, construction, and inspection units studied the system, suggested necessary modification, and assisted in de-