level to provide standards and/or performance specifications for mailbox supports. Tests have shown that simple, safe, and economical support systems are attainable. The U.S. Postal Service, with assistance from FHWA, appears to be the logical agency to promulgate standards and specifications for mailbox supports. It seems reasonable to require that mailbox installations meet the same performance specifications now applied to structures such as signs and lightpoles.

2. Where possible, mailbox owners should be encouraged to place their installations on a side road, along a driveway, or a safe distance from the main roadway.

3. Multiple-box installations that include a beam or support member running parallel to the roadway are extremely hazardous and should be avoided. In our opinion, an acceptable alternative to multiple supports would be an individual, crashworthy support for each box. Impact should then cause a "domino effect". Tests are needed, however, to substantiate this hypothesis.

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Crash Tests of Construction-Zone Traffic Barriers

KENNETH C. HAHN AND JAMES E. BRYDEN

Tests conducted by the New York State Department of Transportation to determine the performance of various types of traffic barriers for construction zones are described. A 30.5-cm (12-in) timber curb with steel splice plates between sections and steel pins driven into the subbase was unable to redirect vehicles in minor impacts. A 40.6-cm (16-in) high timber curb with a W-beam steel rail bolted to the face was successfully tested at 76 km/h (47 miles/h) and 17° and at 61 km/h (38 miles/h) and 14°. Steel washers welded atop the anchor pins reduced barrier movement at impact. This barrier is suitable for use where moderate impacts may occur [64 km/h (40 miles/h) and 15°] and requires only a few inches of deflection distance. New York's standard portable concrete median barrier with pin-connected joints, which contained an impacting vehicle at 89 km/h (55 miles/h) and 25° without any connection to the pavement except the two terminal sections, appears to be suitable for use in high-speed work zones. Pulling the joints tight when it was installed and grouting the bottom corners reduced barrier deflection and damage. Deflection of as much as 38.1 cm (15 in) may be produced by 97-km/h (60-mile/h) impacts where anchorage to the pavement is not provided, but it would be less where conditions do not permit such severe impacts.

Timber curbs have been widely used as construction-zone barriers to provide delineation to guide traffic through work areas and redirect errant vehicles that leave the travel lanes. Several design variations have been used; most include timber sections from 25.4 to 30.5 cm (10-12 in) square and about 3.66 m (12 ft) long. In some states, vertical posts with horizontal rail elements are attached to the curb. Anchorage is generally minimal--often only a metal clip to join adjacent sections but no anchorage to the pavement.

These barriers, which are relatively inexpensive and easy to install, are so narrow as to detract little from the narrow pavement widths frequently encountered in work zones, and they generally provide good delineation. Unfortunately, they provide little redirection to impacting vehicles. A recent Virginia study (1) reported that 73.5 percent of vehicles impacting a 25.4-cm (10-in) square timber curb with timber railing penetrated or straddled the barrier. What is possibly even more serious is that barrier sections were frequently dislodged on impact and became additional hazards to oncoming traffic and workers in the area. Tests conducted by Southwest Research Institute (2) confirmed these problems.

When the hazards associated with timber curbs were recognized, their use on federal-aid projects was restricted by Federal Highway Administration (FHWA) Notice N5160.27. Because this federal action left no simple, inexpensive barrier available for construction-zone use, several research efforts were initiated to develop suitable barriers. These efforts can be grouped in three categories:

1. Modifications of timber curbs,

2. Portable concrete median barriers (CMBs), and
3. Other concepts, particularly W-beam rail on 208-L (55-gal) drums.

Two variations of the timber-curb concept were tested by Southwest Research Institute (2). A type X concrete curb--basically the lower section of a safety-shape CMB--was not successful in redirecting a full-sized passenger car in a 56-km/h (35-mile/h), 8° impact. The second type, two 30.5-cm (12-in) square timber curbs stacked vertically and bolted through a bridge deck, was developed by the Structures Design and Construction Subdivision of the New York State Department of Transportation (NYSDOT) for use as a temporary bridge railing. It performed well on impact, successfully redirecting a 1986-kg (4378-lb) vehicle in an 83-km/h (51.5-mile/h), 13° impact, but it was not practical for highway use because it required rigid connection to the deck.

Good results were also obtained for W-beam rail mounted on 208-L drums. In both tests by Southwest Research Institute (2), this system achieved successful redirection in a 72-km/h (45-mile/h), 13° impact with a full-sized car. However, the 1.04-m (3.4-ft) deflection of the barrier, coupled with tipping of the barrels, might be a problem in narrow work zones.

Considerable effort was also expended on portable CMBs for use in construction zones. Several tests in California (3-5) underscored the difficulty of providing a simple, easily erected portable CMB system that is capable of resisting overturning or penetration on severe impact. One proprietary precast CMB system tested at Southwest Research Institute performed well in a 99-km/h (61.7-mile/h), 24° impact (6). That barrier included a very strong connection between 9.14-m (30-ft) sections and used steel dowels to pin some sections to the pavement.

In a major CMB study by Southwest Research Institute (7-8), the authors have cautioned that "portable concrete median barriers require either large permissible translations during standard strength test impacts, or considerable joint resistance to rotation unless the free-standing barriers are restrained by some foundation." The authors point out, however, that it was difficult to design barriers that would perform adequately because "barrier strength and stability theoretical investigations were complicated by interactions [that] made analysis very difficult."

In brief, few practical construction-zone barrier systems were available when the research reported here was initiated. W-beam steel rail on 208-L drums was available but required about 1.07 m (3.5 ft) of deflection space for 72-km/h (45-mile/h), 15° impacts. Stacked 30.5x30.5-cm (12x12-in) timbers worked well on bridges where anchorage could be developed but would be difficult to use on pavement. One proprietary precast CMB had been tested successfully as a free-standing barrier, although it was pinned to the pavement. Other tests on precast CMBs had not been successful in developing a free-standing, easily transported barrier capable of withstanding 97-km/h (60-mile/h), 25° impacts.

PURPOSE AND SCOPE OF THE STUDY

In 1977, New York initiated research to develop work-zone barriers that would provide adequate traffic protection and yet be easy to install and remove. This effort was directed toward two specific objectives:

1. It was desirable to develop a simple, low-cost barrier for moderate [72-km/h (45-mile/h), 15°] impact conditions that could be used in lower-speed work zones. It was hoped that this system could be based on the previously used timber-curb barrier.
2. A portable CMB capable of containing vehicles in 97-km/h (60-mile/h), 25° impacts was desired for higher-speed work zones. NYSDOT had developed a standard design that included 6.10-m (20-ft) sections with pin-connected joints. Although the joint detail appeared sufficiently strong to withstand the design impact, testing was needed for confirmation. In addition, some barrier deflection on impact was expected. This could be determined from a full-scale test so that deflection limitations for the barrier could be established. Testing could also identify any deficiencies in the CMB joint and anchorage system.

Testing began in 1977 with six low-speed, low-angle impacts on a 30.5-cm (12-in) timber curb pinned to the pavement and joined with steel splice plates at the joints. That barrier was unsuccessful in redirecting the vehicle, so the design was modified and in 1978 two more tests were conducted. In addition, two tests on free-standing 6.10-m (20-ft) CMB sections were run in 1978. The three barrier systems tested are described here, and the tests results are summarized.

METHODOLOGY AND DESCRIPTION OF BARRIERS

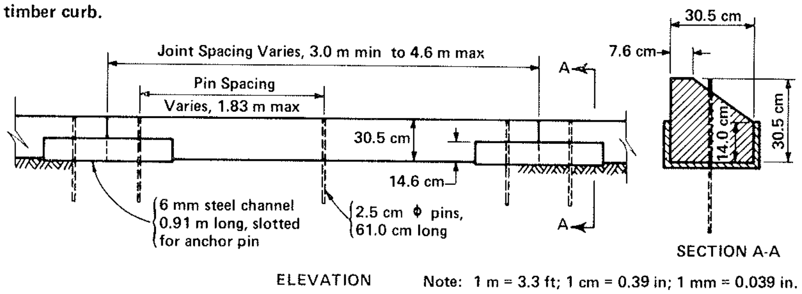
This study consisted of 10 full-scale crash tests to determine the performance of three construction-zone barriers. Testing details were taken from NCHRP Report 153 (9) and its successor, Transportation Research Circular 191 (10).

The first barrier tested was a 30.5-cm (12-in) vertical-face timber curb donated for testing purposes by a local contractor (see Figure 1). The original intention was to test the performance of this curb with an X-shape on the traffic face, but tests at Southwest Research Institute completed in early summer of 1977 confirmed that the X-shape did not redirect impacting vehicles. By the time those results were received, the X-shape had already been cut on the timber. Rather than scrap this material, therefore, it was decided to test the 30.5-cm vertical face with the X-face rotated 180° away from traffic.

Before 1977, NYSDOT standards called for 3.66-m (12-ft) sections of 30.5-cm square timber joined by steel splice plates across each joint. Sections were not pinned to the pavement. Field experience showed, however, that this barrier was dislodged on impact, and individual sections then became hazards to other traffic and workers. Two modifications thus were made to the timber curb for the 1977 test series. A 0.91-m (3-ft) long steel channel, bent from 9.5-mm (0.375-in) steel plate, was added at each joint. Adjoining timber ends were set inside the channel, which was 14 cm (5.5 in) deep. Slotted holes were provided in the channel to allow steel pins to be driven through each timber. Steel pins 2.5 cm (1 in) in diameter and 61 cm (24 in) in length were driven 30.5 cm into the ground on each side of the joint and at a maximum 1.83-m (6.0-ft) spacing along each curb section, which varied with timber length. The splice plates and pins were intended to anchor the curb section firmly in place during impact.

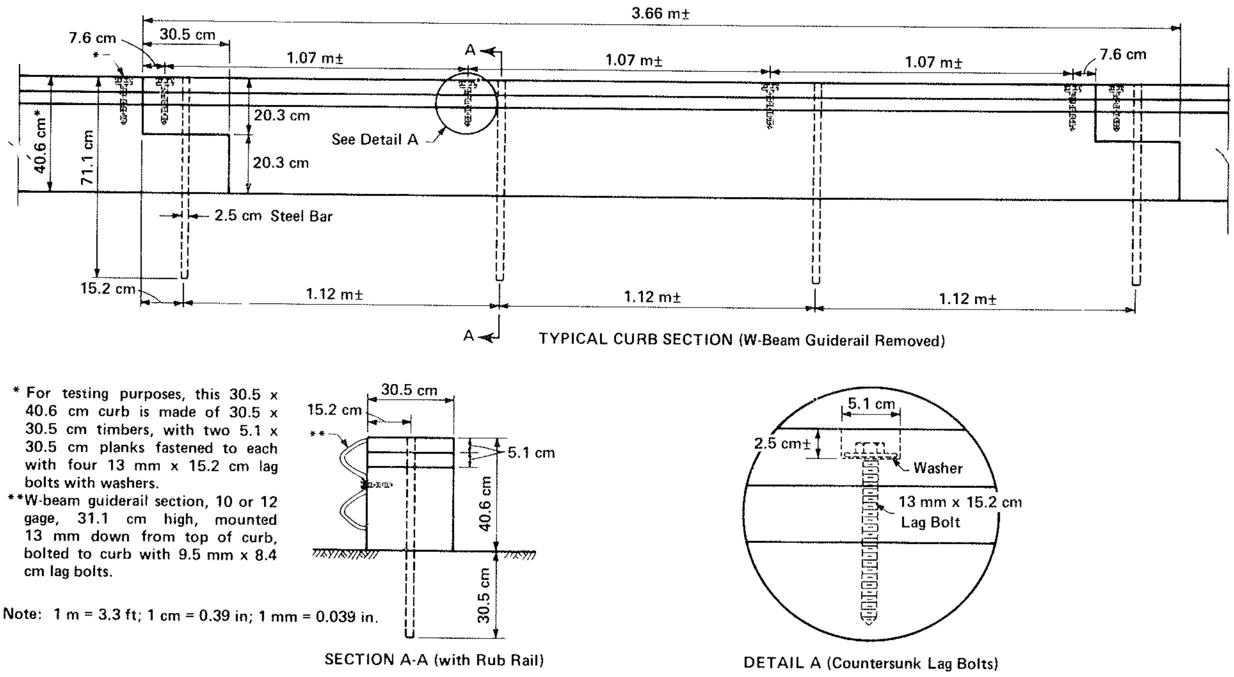
The total length of timber curb installed for the series of six tests was 44.81 m (147 ft) and consisted of 11 sections that varied from 3.05 to 4.57 m (10-15 ft) each. For the first three tests, the curb was installed at an angle of 3° to the vehicle path. The barrier was then removed and reset at 7.5° for the next three tests. Damaged

Figure 1. Details of 30.5x30.5-cm timber curb.



Note: 1 m = 3.3 ft; 1 cm = 0.39 in; 1 mm = 0.039 in.

Figure 2. Details of W-beam timber curb.



* For testing purposes, this 30.5 x 40.6 cm curb is made of 30.5 x 30.5 cm timbers, with two 5.1 x 30.5 cm planks fastened to each with four 13 mm x 15.2 cm lag bolts with washers.

**W-beam guiderail section, 10 or 12 gage, 31.1 cm high, mounted 13 mm down from top of curb, bolted to curb with 9.5 mm x 8.4 cm lag bolts.

Note: 1 m = 3.3 ft; 1 cm = 0.39 in; 1 mm = 0.039 in.

curb sections were replaced between individual tests. All six tests were run on a compacted gravel surface.

Because the 30.5-cm (12-in) vertical-face timber curb did not redirect vehicles during three of the first six tests, a second barrier was designed for testing in 1978. Early California research on curbs (11) pointed out the importance of providing an undercut and a smooth curb face to reduce tire climb, neither of which was provided by the 30.5-cm timber curb. In addition, the researchers believed additional curb height would reduce the possibility of vaulting by placing the top of the curb above the midheight of passenger-car tires (midheight is approximately the normal contact point of the tire on the curb).

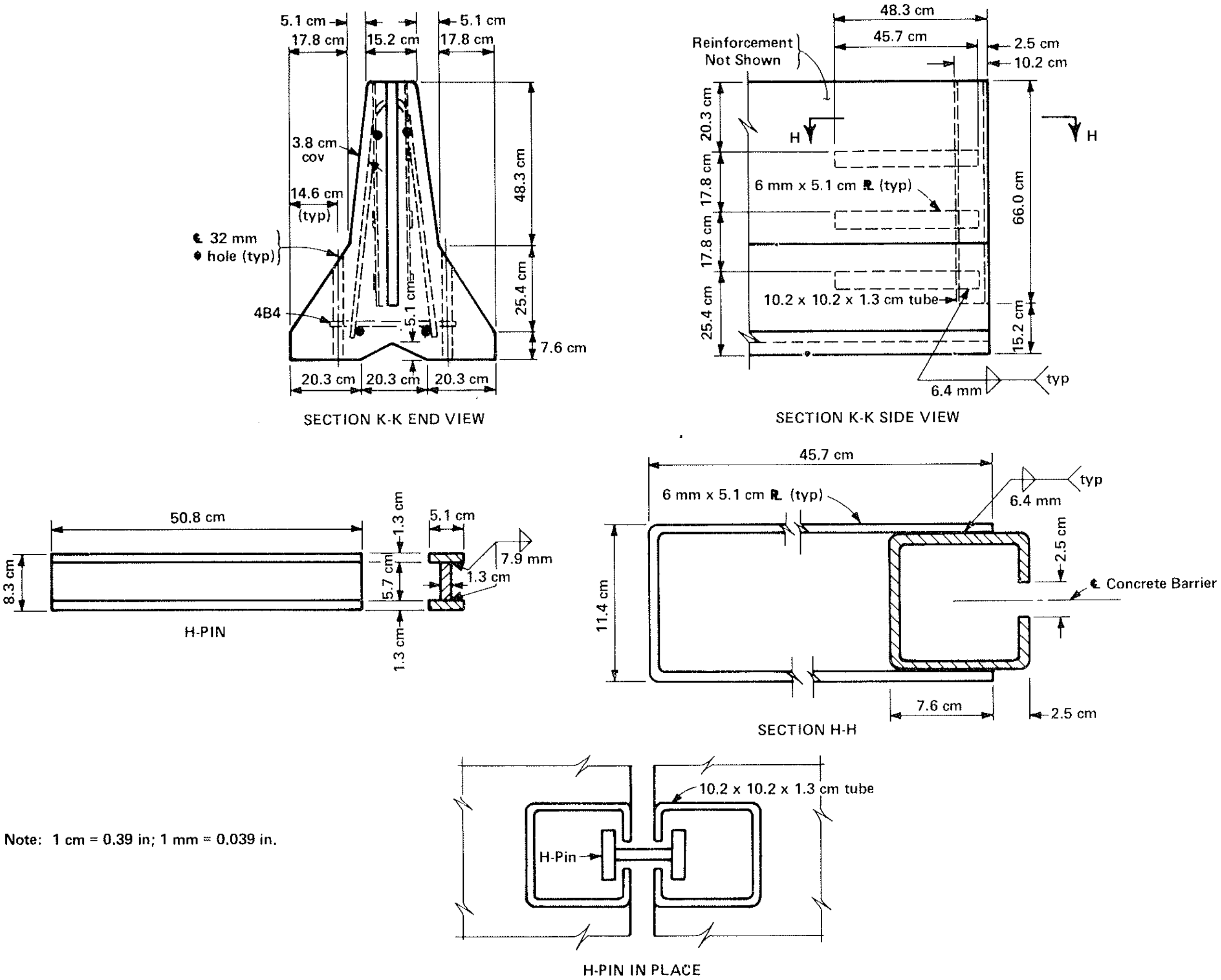
Thus, two modifications were made to the timber curb: Height was increased to 40.6 cm (16 in), well above the midheight of passenger-car tires, and a standard W-beam steel rail element was bolted to the traffic face of the curb to provide a smooth curb face and an undercut to prevent tire climb. To allow simpler field installation and to eliminate tire damage on the steel joint-splice plate, joint details were also changed. Details of the barrier are shown in Figure 2.

The timber curb was constructed of 30.5x30.5-cm (12x12-in) timbers with two 5.1x30.5-cm (2x12-in) planks spiked on the top. This would permit configuration changes if they were determined to be necessary after the initial tests. Overlapping joints 30.5 cm (12 in) long and 20.3 cm (8 in) deep were cut with a chain saw, and steel anchor pins 2.5 cm (1 in) in diameter and 71.1 cm (28 in) in length were driven flush with the top of the timber. The pins were placed at the center of each overlapping joint and at the one-third points of each timber section. For the 3.66-m (12-ft) timbers used, the distance between joints was 3.35 m (11 ft), which resulted in a pin spacing of 1.12 m (3 ft 8 in). The W-beam was spliced in the usual manner with eight 16-mm (0.625-in) bolts and connected to the timber curb with 9.5x64-mm (0.375x2.5-in) lag bolts at the one-third points between the rail splices. Splices on the W-beam did not coincide with the curb joints. Ten sections of curb with a total length of 34.14 m (112 ft) were installed on the compacted gravel test pad. This system is referred to here as the W-beam timber curb.

Details of the portable CMB are shown in Figure 3. Basically, this barrier consisted of 6.10-m (20-ft) precast sections of New Jersey-shape concrete barrier. The longitudinal reinforcing consisted of four No. 6 bars along with stirrups and other steel near the joints. Joint detail consisted of 10.2x10.2x6.4-mm (4x4x0.25-in) slotted steel tubes cast into each end of each barrier section. A steel H-pin made from 12.7-mm (0.5-in) thick plate connected adjoining sections.

For these two tests, eight sections of barrier

Figure 3. Details of portable CMB.



Note: 1 cm = 0.39 in; 1 mm = 0.039 in.

were set on the asphalt pavement. In the first test, sections 1 and 7 were pinned to the pavement; in the second test, only section 1 was pinned. The sections used in the test differed from those shown in Figure 3 in that the anchor pin holes were placed in the center of the barrier rather than on the sides. Steel pins 2.5 cm (1 in) in diameter and 1.42 m (4 ft 8 in) in length were driven 0.61 m (2 ft) into the asphalt pavement and gravel subbase. Nine pins were used for each anchored section.

In the first test, the adjoining sections were simply set on the pavement and the H-pin was slipped into place as the second section was lowered. No special effort was made to pull the sections tight. In the second test, two specific steps were taken to reduce barrier deflection: First, each barrier section was pulled as tight as possible against the adjacent section as it was set in place, and then stiff concrete mortar was packed into the bottom 15.2 cm (6 in) of each joint on both sides of the barrier to provide continuous bearing across the joint.

TEST RESULTS

30.5x30.5-cm Timber Curb

The results of six full-scale crash tests of 30.5x30.5-cm (12x12-in) timber curb performed in 1977 are summarized in Table 1. These were the first tests performed under this research project, and many equipment problems were encountered. Malfunction of the oscillograph recorder caused a loss of data on acceleration and event duration for these tests. However, because of the failure of this curb design to redirect the vehicle, the loss of these data is not critical. For the first three tests, the impact angle was 3°, speeds were 16, 32, and 48 km/h (10, 20, and 30 miles/h), consecutively, and the instrumented vehicle--a 1969 Ford Fairlane 500 sedan--weighed 1515 kg (3340 lb). The first test (test 1A) resulted in vehicle redirection parallel to the curb and only minor vehicle damage. The right front (impacting) tire was blown out by a protruding splice plate corner and the front bumper, right front fender, door, and rocker panel sustained some scratches and shallow dents. The vehicle was in contact with the barrier for 16.46 m (54 ft). Although it did not mount the curb, tire marks on the curb face indicated that the vehicle started to climb. The curb was undamaged and deflected only 5.1 cm (2 in).

The damage from the first test was painted over, and the same vehicle was used for the 32-km/h (20-mile/h) test (test 1B). Again, the vehicle was redirected parallel to the curb, and there was minor sheet-metal damage and a punctured right front tire. Tire marks on the curb indicated wheel climb

Table 1. Test results for 30.5x30.5-cm timber curb.

Item	Test 1A	1B	1C	2A	2B	2C
Impact condition						
Speed (km/h)	16	32	48	16	32	48
Angle (°)	−3	−3	−3	−7.5	−7.5	−7.5
Vehicle weight (kg)	1515	1515	1515	1533	1533	1533
Curb length (m)	44.81	44.81	44.81	44.81	44.81	44.81
Contact distance (m)	16.46	12.19	15.24	2.59	6.86	14.02
Curb deflection (cm)						
Dynamic	10.2	5.1	12.7	2.5	7.6	10.2
Permanent	5.1	2.5	5.1	0	2.5	5.1
Exit angle (°)	0	0	−12.6[a]	+5.0	−29.8[a]	−21.0[b]

Note: 1 km = 0.62 mile; 1 kg = 2.2 lb; 1 m = 3.3 ft; 1 cm = 0.39 in.
[a] No exit; vehicle stopped on curb.
[b] Vehicle stopped behind curb.

to the top of the curb face at three locations during 12.19 m (40 ft) of contact, but it did not mount or vault the curb. There was no curb damage and only 2.5 cm (1 in) of deflection.

The same vehicle was used for the 48-km/h (30-mile/h) test (test 1C). At impact, the right front wheel climbed and mounted the curb. The vehicle slid along the curb top, dragging the right rear tire along the curb face. The anchor pins, which were left protruding 2.5 to 5.1 cm (1 to 2 in) above the curb to facilitate removal, severely dented the right front wheel and damaged the suspension. The vehicle came to rest straddling the curb at a 12.6° angle; only the right front wheel was over the curb after 15.24 m (50 ft) of contact.

For the next three tests, the impact angle was increased to 7.5°, and successive speeds again were 16, 32, and 48 km/h (10, 20, and 30 miles/h). The instrumented vehicle, a 1970 Ford Fairlane sedan, weighed 1533 kg (3380 lb). In the first 7.5° test, the vehicle was smoothly redirected and exited the curb at a 5° angle after only 2.59 m (8.5 ft) of contact. There was no measurable barrier deflection or damage, and vehicle damage was limited to minor sheet-metal scratches on the stone shield and a flattened right front tire caused, as before, by a protruding splice.

In the second 7.5° test, the right front wheel climbed and vaulted the curb on impact. The vehicle ran 6.86 m (22.5 ft) along the curb top and came to rest on the curb, in much the same attitude as in test 1C, at an angle of 29.8°. The vehicle gouged the curb top badly in two locations, and the splintered wood wedged between the tire and wheel, damaging both. However, the wood was somewhat deteriorated before these tests. Vehicle damage included badly bent tie rods, minor sheet-metal dents, and scratches on the bumper, stone shield, lower right front fender, and rocker panel. Curb damage was limited to the splintering and gouging just mentioned. Permanent deflection was only 2.5 cm (1 in).

In the final test of 30.5x30.5-cm timber curb, the vehicle's right front wheel climbed and vaulted the curb on impact. As it ran along the curb top for 14.02 m (46 ft), the rest of the vehicle also climbed over the curb, finally coming to rest perpendicular to the curb and 6.10 m (20 ft) behind it. Curb damage included some minor gouging along the top front edge and a 1.52-m (5-ft) long, 12.7-cm (5-in) wide splinter that remained in front of the curb, extending about 1.22 m (4 ft) into the traveled way. Vehicle damage was limited to the undercarriage--large splinters in the suspension, slightly bent tie rods, a badly dented gas tank, and a torn and bent left rear body panel from below the rear bumper--and minor sheet-metal damage to the right front bumper, stone shield, and fender.

W-Beam Timber Curb

The results of two full-scale 1978 tests of W-beam timber curbs are summarized in Table 2. In the first test (test 11A), a 1746-kg (3850-lb) 1973 American Motors Corporation Matador sedan impacted the curb at 76 km/h (47.3 miles/h) and 17°. Impact occurred on the stone shield below the front bumper and on the right front wheel. The vehicle climbed about 25.4 cm (10 in) up the W-beam, deflecting the barrier back 27.9 cm (11 in). Both front wheels were airborne--about 15.2 cm (6 in) on the left and 25.4 cm on the right--for about 3.05 m (10 ft) of travel on the barrier and 3.05 m after leaving the barrier. Redirection parallel to the barrier occurred after only 6.10 m (20 ft) of contact. The vehicle then yawed 5° left as it exited the curb, but the flattened right front tire, after recontacting the ground, caused the car to swerve to the right, finally coming to rest some 76.2 m (250 ft) from impact.

Vehicle damage was minor and included a flat tire, a bent stone shield, and minor scratches and dents to the right side. Barrier damage was also minor. The impacting vehicle deflected the curb 27.9 cm (11 in) at the timber joint 1.22 m (4 ft) downstream from the impact point and tilted it back some 30°. No timbers were damaged, although several sections rode up the steel anchor pins, spreading but not separating several joints. Curb-section deflections at each joint are given below (1 cm = 0.39 in; impact between joints 3 and 4):

Joint	Deflection from Original Position (cm) Test 11A	Test 11B
1	2.5	0
2	10.2	2.5
3	26.7	7.6
4	17.8	5.1
5	8.9	3.8
6	3.8	2.5
7	0	0
8	0	0
9	0	0

One section of W-beam was dented slightly and was replaced before the next test.

For the second test (test 11B), 38-mm (1.5-in) diameter steel washers were welded to the top of each anchor pin to reduce the tendency of the timbers to slide up the pins. Except for this difference, the barrier was unchanged. A 1751-kg (3860-lb) Matador sedan impacted the curb at 61 km/h (38.0 miles/h) and 14°.

Impact again occurred on the stone shield and right front tire. The front of the vehicle rose slightly--7.6-10.2 cm (3-4 in) on the right and 10.2-15.2 cm (4-6 in) on the left--after deflecting the barrier back 7.6 cm. Redirection to 6° away from the curb occurred within 4.88 m (16 ft) of contact. The vehicle ran some 73.2 m (240 ft) from impact to rest, sustaining only minor damage including a bent stone shield and some scratches to the right side doors and lower rear fender.

Maximum barrier deflection occurred at the joint 1.22 m (4 ft) downstream from impact, where it was tilted back 5°. None of the timbers or W-beams was damaged and the retaining washers appeared to help significantly to reduce barrier movement and in turn reduced rise on the pins and vehicle jump during impact.

Portable Concrete Median Barrier

The results of the two 1978 full-scale crash tests of portable CMBs are summarized in Table 3. Both test installations consisted of eight 6.1-m (20-ft) long sections of precast barrier set on an asphalt pavement. For the first test, the first and seventh sections of barrier were anchored with nine 2.5-cm (1-in) diameter steel pins, 1.42 m (4 ft 8 in) long. The pins were inserted through precast holes in the barrier top and driven about 0.61 m (2 ft) into the pavement and gravel subbase until flush with the top of the barrier.

In the first CMB test (test 17), a 1928-kg (4250-lb) instrumented vehicle, a 1975 Plymouth sedan, impacted the barrier at 85 km/h (52.8 miles/h) and 25°. On impact it climbed to the top of the barrier and within 4.57 m (15 ft) was redirected parallel to the barrier. During initial redirection, while the right-side tires were up on the barrier, the left side was airborne. When the vehicle left the barrier, the front end pitched forward, dragging on the pavement, while the rear was still airborne for some time. Impact occurred at the center of the fourth section, and the vehicle remained in contact with the barrier for 10.36 m (34 ft), leaving it just beyond the joint between the fifth and sixth sections. Because its right front suspension was severely damaged and that tire flattened, the vehicle turned back into the barrier, again striking the bottom 7.6-cm (3-in) high vertical barrier face about 1.83 m (6 ft) into the seventh section. The bumper rode about halfway up the sloped barrier face, and the vehicle's right side was in contact with the barrier for the entire length of the eighth section. The vehicle, which came to rest about 12.19 m (40 ft) beyond and perpendicular to the barrier, sustained heavy damage to the front-end sheet metal, right front suspension, and along the entire right side.

Barrier damage was minor, and the maximum deflection was 40.6 cm (16 in). The third, fourth, and fifth sections were displaced laterally (Table 4), but examination of the test films revealed that there was no barrier rotation. The displacement was the result of the barrier simply sliding to the right on impact. Section 4, where impact occurred, sustained three vertical hairline cracks on the backside. Corners on the barrier base were spalled slightly at joints 2, 3, and 6 on the front, moderately at joint 4 on the front, and extensively [more than 30.5 cm (1 ft) long] on the back at joints 2 and 5.

For the second test (test 18), only the first section was pinned to approximate an upstream terminus. During installation, care was taken to ensure that each joint was pulled tight against the connecting H-pins. To further stiffen the barrier, each joint was packed with a stiff portland cement mortar to a height of 15.2 cm (6 in) and about 15.2 cm into the joint.

The 1919-kg (4230-lb) instrumented vehicle, a 1973 Matador station wagon, impacted the CMB at 88 km/h (54.8 miles/h) and 25°. The right-side tires quickly climbed to the barrier top and, on redirection, both tires were well above the top of the barrier. At 7.92 m (26 ft) after impact, the vehicle had rolled 36° to the left and was airborne--the left side some 20.3 cm (8 in) off the ground and the right side about 1.52 m (5 ft) off the ground. The vehicle's rear yawed right so that the right rear wheel was about 0.91 m (3 ft) above and 0.61 m (2 ft) behind the barrier. The vehicle recontacted the barrier 19.20 m (63 ft) downstream of impact with the right rear wheel atop the CMB, the right front and left rear wheels on the CMB

Table 2. Test results for W-beam timber curb.

Item	Test		Item	Test	
	11A	11B		11A	11B
Impact condition			Acceleration (g)		
Speed (km/h)	76	61	50-ms average		
Angle (°)	−17	−14	Longitudinal	1.81	1.81
Vehicle weight (kg)	1746	1751	Lateral	3.35	1.95
Curb length (m)	34.14	34.14	Maximum peak		
Contact			Longitudinal	–	9.97
Distance (m)	6.10	4.88	Lateral	14.76	14.16
Time (ms)	304	288	Average continuous		
Curb deflection (cm)			Longitudinal	1.19[a]	0.36
Dynamic	33.0	15.2	Lateral	2.70	1.33
Permanent	27.9	7.6	Exit angle (°)	+5	+6

Note: 1 km = 0.62 mile; 1 kg = 2.2 lb; 1 m = 3.3 ft; 1 cm = 0.39 in.
[a] For 75 ms only; recorder failed at this point.

Table 3. Test results for portable CMB.

Item	Test		Item	Test	
	17	18		17	18
Impact condition			Acceleration (g)		
Speed (km/h)	85	88	50-ms average		
Angle (°)	−25	−25	Longitudinal	–	4.89
Vehicle weight (kg)	1928	1919	Lateral	5.99	11.52
Barrier length (m)	48.77	48.77	Maximum peak		
Contact			Longitudinal	–	15.14
Distance (m)	10.36	21.64[a]	Lateral	14.30	26.35
Time (ms)	528	968[b]	Average continuous		
Deflection (cm)			Longitudinal	–	0.69[c]
Dynamic	40.6	27.9	Lateral	1.37	1.03[c]
Permanent	40.6	27.9	Exit angle (°)	+5	+15

Note: 1 km = 0.62 mile; 1 kg = 2.2 lb; 1 m = 3.3 ft; 1 cm = 0.39 in.
[a] Includes 10.97-ms airborne travel.
[b] Includes 510-ms airborne travel.
[c] For 272 ms only; vehicle airborne beyond this point.

Table 4. Lateral movement in CMB.

	Base Movement (cm)				Top Movement, Test 18 (cm)	
	Test 17		Test 18			
Joint	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream
1	0	0	0	0	0	0
2	0	1.3	0	0	1.3	0
3	12.7	10.2	21.6	21.6	27.9	25.4
4	40.6	40.6	25.4	25.4	24.1	27.9
5	1.3	3.8	6.4	6.4	6.4	6.4
6	0	0	0	0	0	0
7	0	0	0	0	0	0

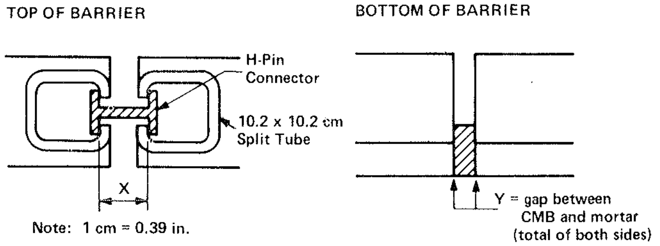
Notes: 1 cm = 0.39 in.
Impact between joints 3 and 4. Movement is displacement from original position, in this case away from traffic. All measurements to base made from reference marks of original position on pavement. All measurements to top made from reference markers erected behind barrier. Discrepancies between top and base movements (test 18) caused by pavement irregularities and barrier moving atop spalled concrete.

Table 5. Joint movement in CMB (test 18).

	X (cm)			Y (cm)		
Joint	Before	After	ΔX (cm)	Before	After	Location
1	5.7	5.7	0	0	0	–
2	5.7	5.7	0	0	1.0	Front
3	4.6	5.4	+0.8	0	1.0	Rear
4	5.2	5.6	+0.4	0	1.3	Rear
5	5.6	5.7	+0.2	0	0.6	Front
6	5.4	5.6	+0.2	0	0.3	Front
7	5.4	5.6	+0.2	0	0	–

Notes: 1 cm = 0.39 in.
Impact between joints 3 and 4.

Figure 4. Joint movement in CMB.



Note: 1 cm = 0.39 in.

face, and the left front wheel and bumper dug into the pavement. When it returned to the pavement 21.64 m (71 ft) after impact, the rear of the vehicle yawed sharply right and it rolled over, coming to rest on its wheels about 18.29 m (60 ft) beyond and perpendicular to the barrier.

The vehicle suffered extensive damage during both impact and rollover. Before rollover, it sustained heavy damage to all front-end and right-side sheet metal and to all right-side wheels and suspension parts. In addition, the frame was bent and the windshield broken. The rollover popped out the windshield, dented the roof, and crushed the engine compartment.

The barrier moved laterally a maximum of 27.9 cm (11 in) at the downstream end of the impacted (fourth) section, and there was less movement of the second, third, and fifth sections. Again, no barrier tipping or additional dynamic deflections were detected in the test films. Lateral movements at each joint, measured at both the top and bottom of the barrier, are summarized in Table 4. Widths of joint gaps, measured before and after impact to detect longitudinal movement, are given in Table 5 and shown in Figure 4. The unpinned seventh and eighth sections did not move.

The only significant barrier damage was confined, as in the previous test, to some base corner spalling and some cracks in the impacted section ranging from hairline fractures to cracks 3.2 mm (0.125 in) wide. Joint spalling in this test was noticeably less than in the first because the mortar helped to transfer impact forces across the joints more uniformly.

DISCUSSION AND FINDINGS

Results of the first six tests clearly indicate that the 30.5-cm (12-in) vertical-face timber curb is unable to redirect vehicles even in moderate impacts, although the anchorage system was able to prevent barrier misalignment. In addition, damage to the gasoline tank presents a severe fire hazard. At 3° and 48 km/h (30 miles/h), the vehicle completely vaulted the curb. Use of this curb as a positive barrier, even at very flat angles, thus cannot be justified at speeds above 16 km/h (10 miles/h). In addition, the risk of damage to vehicle sheet metal and suspension damage is great, even for moderate impacts. Gouging and splintering of the curb in several tests emphasize the importance of using only wood that is structurally sound. Tire damage caused by protruding splices indicates the importance of installing these plates flush with the curb face.

The W-beam timber curb, intended to prevent vehicle climb by increasing the curb height to 40.6 cm (16 in) and adding a W-beam to trap the impacting tire, was designed with overlapping joints to eliminate splice plates. The results of two crash tests at 15° indicates that the new design is a significant improvement over 30.5x30.5-cm (12x12-in) curbs. Vehicle climb was greatly reduced by addition of the W-beam rail. Redirection was achieved, and the exit trajectories of 5° and 6° were acceptably shallow. Vehicle decelerations (peak 50 ms) were below 2 *g* longitudinally in both tests and below 3.4 and 2.0 *g* laterally in tests 11A and 11B, respectively. Curb damage was minor: several bent anchor pins and one dented rail section. The overlapped, pinned joints proved adequate in test 11A; when a retainer washer was added on each pin in test 11B, deflections were reduced from 27.9 to 7.6 cm (11-3 in), vehicle jump from 25.4 to 10.2 cm (10-4 in), and curb tilt from 30° to 5°.

This design was intended to provide a simple, economical barrier for use in construction zones. It is made up from readily available components and is relatively easy to install and remove. Since the completion of these tests, it has been slightly modified. Timber lengths have been increased to 4.11 m (13 ft 6 in) so that the W-beam and timber joints coincide to allow for removal of one or several sections to provide access through the curb line. This modified design has been standardized by NYSDOT and is now available for use as a physical barrier on contracts where the anticipated operating speed is 64 km/h (40 miles/h) or less.

Where anticipated speeds are higher than 64 km/h or where more positive protection is required, a stronger barrier is needed. For this reason, a portable CMB was tested to determine its resistance to severe impacts. These two 25° tests were intended as tests of penetration resistance, and lack of satisfactory redirection is not indicative of unsatisfactory performance. It has been established by many testing agencies that CMBs can successfully redirect vehicles impacting at angles up to 15°. At steeper angles, proper redirection is not assured. Although the highest speed attained in the CMB tests was 89 km/h (55 miles/h), it appears that this barrier had sufficient reserve strength to withstand 97-km/h (60-mile/h) impacts, especially with the joints pulled tight and grouted. The low barrier deflection of 27.9 cm (11 in), the lack of barrier roll, and the movement of only four barrier sections on impact, combined with the very light damage to the joint system, all support this conclusion.

The vehicle rollover observed in test 18 is not surprising, because similar reactions have been reported in other such tests. However, both tests confirm that the current NYSDOT design for portable CMBs is sufficiently strong to resist these severe impacts. Results indicate that anchoring the CMB in midstream is unnecessary, because only a very few sections are disturbed even during severe impacts. Joint grouting reduced both joint deflection and corner spalling by stiffening the H-pin joints. Based on the 27.9-cm (11-in) deflection observed in the final test [1919-kg (4230-lb) vehicle at 89 km/h (55 miles/h) and 25°], a maximum barrier deflection of about 38.1 cm (15 in) can be expected for a 2041-kg (4500-lb) vehicle at 97 km/h (60 miles/h) and 25° when the joints are pulled tight and grouted. For ungrouted joints, the maximum deflection would be almost 0.61 m (2 ft). However, where conditions are not likely to result in impact speeds or angles this severe, smaller deflections would result for both the grouted and ungrouted designs. Vehicle decelerations (peak 50 ms) were below 5 g longitudinally for test 18 (test 17 data were not available) and below 12 and 6 g laterally in tests 17 and 18, respectively.

CONCLUSIONS

Based on these tests, the following conclusions appear to be warranted:

1. The 30.5x30.5-cm (12x12-in) timber curb did not redirect vehicles in moderate impacts and cannot be used as a positive barrier. However, the anchorage system tested did prevent barrier movement on impact.
2. The W-beam timber-curb barrier provides satisfactory redirection for impacts at speeds up to 64 km/h (40 miles/h) and 15°.
3. Deflection, joint separation, and curb roll were reduced by adding retaining washers to the top of the steel pins used to anchor the W-beam timber curb.
4. The portable CMB, incorporating NYSDOT's pin-connected joints, is an effective positive barrier for impacts at speeds up to 97 km/h (60 miles/h) and 25°, although satisfactory vehicle redirection cannot be ensured above 15° impact angles.
5. Barrier rotation during impact was effectively eliminated by the H-pin connectors.
6. CMB deflection and corner spalling were reduced by pulling the joints tight and grouting the lower 15.2 cm (6 in) of each joint, front and rear.
7. The portable CMB that uses the NYSDOT design with grouted joints will deflect only 38.1 cm (15 in) for 97-km/h (60-mile/h), 25° impacts. For less severe impact conditions, this deflection will be less.
8. Except for the terminal sections, this CMB design does not require pinning to the pavement or a wedge of asphalt pavement behind the barrier to provide resistance to severe impacts.

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Portable Concrete Median Barriers: Structural Design and Dynamic Performance

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Types of portable concrete median barriers (CMBs) in use in the United States are described primarily in terms of structural details and the load-bearing characteristics of their end connections. Twelve end-connection designs are analyzed to produce estimates of their resistance to loads in four test conditions: simple tension, shear, yaw moment, and torsion. Rotational connection slack is estimated from the geometric properties of the different end connections. Nine crash tests conducted by four research agencies are examined. These tests cover a range of barrier lengths from 3.81 to 9.14 m (12.5-30 ft) and a range of connection details that vary from low to significant load capacity. The crash tests vary in intensity from a 7° test at 104.6 km/h (65 miles/h) to a 25° test at 99.8 km/h (62 miles/h). Analysis of these tests yields specific conclusions on the performance of CMBs. An energy analysis of portable CMBs during vehicle impacts is presented. Estimates of barrier deflection derived from this analysis check closely with deflections observed during crash tests. A parametric study of the influence of various barrier characteristics, including barrier length and mass, connection slack and strength, and support media static and sliding friction, is also presented. Based on this analysis, portable CMBs can now be designed to provide specific performance characteristics.

The most widely used class of construction-zone barriers with positive redirection characteristics is the portable concrete median barrier (CMB). There are at least as many variations in CMB design as there are states in which it is used. The CMB usually has no mechanical fastening to the ground but relies on mass and sliding friction for translational stability. It is always segmented, and segment lengths vary from 3.05 to 9.14 m (10-30 ft). Segment lengths of 3.05, 3.66, 3.81, 6.10, and 9.14 m (10, 12, 12.5, 15, 20, and 30 ft) have been used. It is in the method of joining these segments that there is the greatest variation.

Figures 1 and 2 show applications of the portable CMB in Virginia and Texas, respectively. In Virginia, the barrier segments are 3.66 m long with a vertical concrete shear key connection design. In Texas, the segments are 9.14 m long, and three no. 8 reinforcing bar dowels form the connection. These two connections and four other representative connections are shown in Figures 3-8. Although only 6 connection designs are shown, 12 have been identified. Of these 12, 5 are variations of the California vertical pin connection shown in Figure 7.

The evolution of the portable CMB was straightforward. The CMB was first produced by forming the barrier in place for a permanent installation. Then, in an effort to reduce costs, precast fabrication was used. This made it necessary to move barrier segments from place to place. It became obvious that barrier segments could be placed temporarily in construction zones before final placement as permanent barriers. Once this was recognized, the use of portable CMBs became widespread. In early applications, the functional characteristics of the barrier were assumed to be adequate, an assumption that has generally been borne out by field experience.

TEST RESULTS

As the use of the CMB became more widespread, it was subjected to testing by at least four organizations: Southwest Research Institute (SwRI) (1), the Texas Transportation Institute (TTI) (2), the New York Department of Transportation (NYSDOT), and the California Department of Transportation (Caltrans) (3).

Currently, a total of nine tests have been conducted on barriers that may be considered portable. The results of these tests are summarized in Table 1. In six of the tests, the results were successful at least from the consideration of structural capacity [it must be noted that the test of a 2041-kg (4500-lb) vehicle at 96.5 km/h (60 miles/h) and 25° is a test of structural adequacy, not a test of vehicle reaction from a safety standpoint]. At least three designs have been shown to perform adequately in regard to structural integrity under vehicle collisions at the 96.5-km/h, 25°, 2041-kg energy level. This performance is illustrated in SwRI test CMB-24, TTI test CMB-2, and New York test NY-1. Barrier-segment lengths were 6.10 m (20 ft) for the New York and SwRI tests and 9.14 m (30 ft) for the TTI test. Structural failures occurred in SwRI test CMB-18, where the longitudinal reinforcement of the main section was insufficient to prevent a large portion of one segment from being dislodged; Caltrans test 292, where a main barrier segment was broken; and Caltrans test 293, where one barrier segment was knocked over. As a result of these latter two tests, Caltrans upgraded the design to the one shown in Figure 5 and described in Table 2.

Although many of these tests showed adequate barrier performance, there are a variety of untested designs in use. Some of these are of significantly