freeways. The barrier was used at several test sites after the study was completed, and it has performed well according to TSDHPT engineers.

The used car barrier can be used to protect highway construction and maintenance personnel at work sites where conventional positive construction zone barriers are impractical. It can be set up and removed quickly enough to be used when maintenance is scheduled to take only a few hours. The used car barrier should therefore reduce injury and fatality rates among highway construction and maintenance personnel.

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Crash Tests of Portable Concrete Median Barrier for Maintenance Zones

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An 8-ft version of New York's standard 20-ft portable barrier was evaluated through full-scale crash tests. The 8-ft barrier is both shorter and more portable than the standard concrete median. It employs the basic New Jersey shape and New York's pin-connected joints but is not connected to the pavement. Four full-scale crash tests were performed with 2,250- and 4,500-lb sedans at about 60 mph and 15- or 25-degree angles. Test results were generally good in terms of vehicle accelerations and occupant-vehicle impact velocities. Lateral barrier movement was similar to that experienced with the 20-ft barrier sections. Vehicle reactions were somewhat violent, especially in the 25-degree impacts, which demonstrates the severity of high-angle impacts with rigid barriers. Smooth barrier surface textures appear to be important for minimizing vehicle roll angles. Performance of 8-ft barriers appears comparable to that of the 20-ft lengths now in use.

Research reported by New York State in 1980 (1) demonstrated that a portable concrete barrier with 20-ft sections is suitable for use on construction projects. A similar use of portable concrete median barrier (CMB) by state maintenance forces could improve safety in work zone situations for both state forces and the motoring public. Some drawbacks of the standard 20-ft CMB, as noted by the New York State Department of Transportation's (NYSDOT) Highway Maintenance Division, are its size, weight, and requirements for handling equipment. A standard 20-ft long section weighs about 8,000 lb and must be set in place by a crane. Maintenance forces often have only light equipment available to move and set barriers, and the amount of heavy equipment that would be required to move and set a 20-ft CMB is unavailable. The Highway Maintenance Division suggested 8-ft sections, weighing about 3,200 lb each, for full-scale crash tests to determine the performance on impact of the shorter barrier. Verification of adequate performance of the shorter sections of temporary CMB would permit their use in an anticipated major bridge rehabilitation program during the next decade and in other maintenance work zones where a positive temporary barrier is warranted.

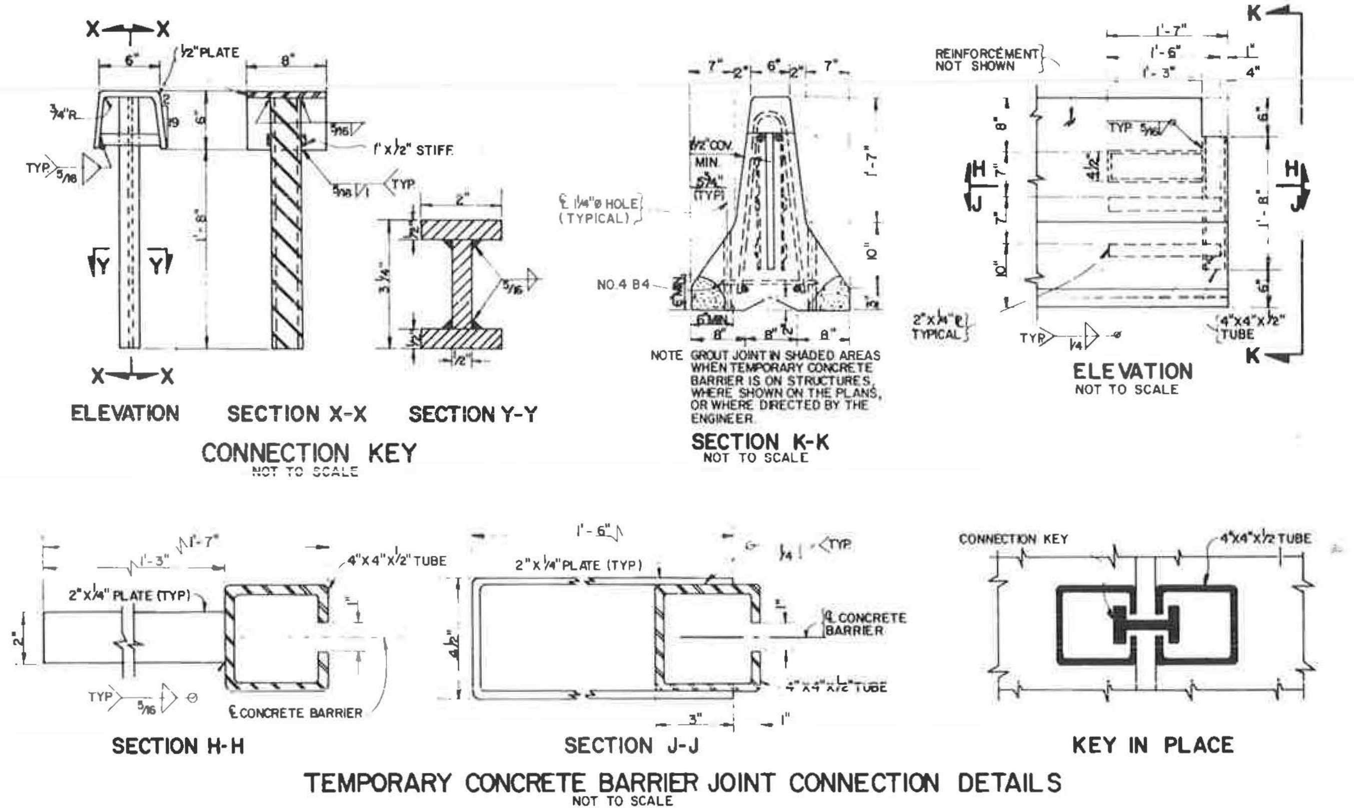
METHODOLOGY AND DESCRIPTION OF BARRIER

Four full-scale tests were conducted to determine the performance of 8-ft sections of portable CMB with New York State's standard pinned connection (Figure 1). Evaluation parameters included vehicle redirection and impact severity, barrier damage, and barrier movement. Testing details were taken from Transportation Research Circular 191 (2). Data analysis and reporting procedures were subsequently revised to reflect the requirements specified in NCHRP Report 230 (3).

The test matrix was composed of longitudinal barrier length-of-need tests designated in NCHRP Report 230 as nos. 10 and 11. Two strength tests were performed--one with and one without added joint restraints--and impact severity tests were performed on both smooth- and rough-textured barriers. This test matrix was sufficient to determine if the shortened version of the portable CMB would perform satisfactorily and to find any drawbacks because of the smaller mass of each unit.

In all tests the barrier was the basic New Jersey shape as used for the current standard New York barrier (standard sheet 619-3R2), following reinforcement recommendations by Southwest Research Institute (4). Except for section length and minor adjustments in reinforcing detail, the revision was identical to New York's current standard. The barrier installation consisted of 20 sections of 8-ft barriers, placed in a straight line and anchored by three steel pins into the pavement at the first and last section. Joints were secured by connection keys. For one of the four tests, sections were pulled to remove any slack in the joints, and portland-cement mortar was packed into the bottom of the joint to restrain movement during impact. The test sections were placed on an asphalt pavement to simulate typical field installations. The 8-ft sections were delivered with a rough-brushed surface texture which the fabricator had applied to cover minor air voids. For the final test, two 20-ft barrier sec-

Figure 1. Portable CMB details.



tions with a smooth surface texture were substituted in the impact zone to determine the effect of the rough surface on vehicle redirection. Because the first three tests on the 8-ft sections demonstrated that the 8- and 20-ft sections performed about the same in terms of lateral barrier deflection, differences in the fourth test could be attributed to surface texture.

RESULTS

Results of the four full-scale crash tests of the 8-ft-long portable CMB are summarized in Table 1. Lateral movement is summarized in Table 2. The total barrier joints affected by impacts in both lateral and longitudinal directions are summarized in the table below. Note that in test 44 the vehicle had post-impact contact with the barrier along the top edge; the barrier was anchored at the upstream and downstream ends. In test 46 the joints were grouted. In test 47 two 20-ft sections were in the impact zone.

	Total Joints Displaced	
Test	Longitudinal	Lateral
44	16	7
45	6	4
46	9	8
47	7	4

In the first test (no. 44), a 4,300-lb Plymouth sedan hit the CMB installation 58.0 ft from the beginning at 64.9 mph and 27.1 degrees. On impact the vehicle's right side immediately climbed to the CMB top, the hood opened, and the vehicle pitched up -8 degrees and deflected the barrier about 17.0 in. Peak g's were 14.2 longitudinal and 18.9 lateral, with peak 50-msec averages of 7.2-g longitudinal and 8.6-g lateral. The vehicle was redirected, but, because it was at a high roll angle of -54 degrees left and had its underside against the barrier, redirection was not smooth. The vehicle contacted the barrier a number of times and the right-rear tire caught behind the barrier top when its right side came down. The left-front tire directed the vehicle's front away from the barrier initially, with a 10-degree left exit angle, but, when the damaged right-front tire recontacted the ground, the front end pitched down to a maximum of +23 degrees and increased its deceleration. The rear end lifted and the vehicle rolled right 180 degrees, yawed 90 degrees left about its front end, and came to rest on its roof.

Vehicle damage was severe--the roof and hood were dented, front suspension was heavily damaged, the frame was damaged, the right-side sheet metal was damaged, and both right tires were blown. Roof crush was probably exaggerated because the targets concentrated the impact in the center of the roof. Barrier damage was moderate and consisted mostly of scratches and spalled areas. Section 7 had a cracked base and sections 8 and 9 had hairline cracks in the backside surfaces (Figure 2).

In the second test (no. 45), a 2,175-lb Vega impacted the CMB installation 54.0 ft from the beginning at 65.5 mph and 16.1 degrees. The vehicle's right side immediately climbed to the CMB top and pitched up -2 degrees. The barrier was deflected 2.75 in. The right-front tire blew out and the steering and suspension were damaged on impact. Peak g's were 11.4 longitudinal and 10.5 lateral with peak 50-msec averages of 5.6-g longitudinal and 6.8-g lateral. The vehicle was redirected with an exit angle of 5 degrees left and maximum pitch down of +8 degrees, with a maximum roll left of -64 de-

Table 1. Test results.

Item	Test 44	Test 45	Test 46	Test 47
Impact conditions				
Speed (mph)	64.9	65.5	61.1	61.4
Angle (nominal)	25.0	15.0	25.0	15.0
Angle (measured from film)	27.1	16.1	25.2	15.2
Vehicle weight (lb)	4300	2175	4350	2175
Point of impact[a]	58.0	54.0	54.5	53.0
Exit angle	10.0	5.0	8.0	5.0
Exit speed (mph)	30.8	55.4	45.3	53.2
Max roll (degree)	-54.0[b]	-64.0	-42.0	-11.0
Max pitch (degree)	+23.0	+8.0	+10.0	+3.0
Max yaw (degree)	+90.0	0.0	+270.0	0.0
Barrier length (ft)	160.0	160.0	160.0	160.0
Contact distance (ft)[c]	16.0	22.0	20.5	29.0
Initial total distance	80.0		70.0	
Time (msec)	1,458[d]	287	1,790[d]	206
Barrier deflection (in.)	17.00	2.75	6.75	3.50
Accelerations (*g*)				
50-msec avg				
Longitudinal	7.2	5.6	5.6	3.5
Lateral	8.6	6.8	6.1	7.5
Max peak				
Longitudinal	14.2	11.4	12.7	7.9
Lateral	18.9	10.5	10.5	11.1
Occupant impact velocity (ft/sec)				
Longitudinal, 2.0 ft	24.1	16.7	21.6	–[e]
Lateral, 1.0 ft	19.2	13.6	17.6	15.3
Occupant ridedown acceleration				
Longitudinal, 10-msec avg (*g*)	6.0	3.3	5.0	–[e]
Lateral, 10-msec avg (*g*)	7.4	7.9	5.7	6.0

Notes: Test 44–Ungrouted joints, Test 45–Ungrouted joints, Test 46–Grouted joints, and Test 47–Two smooth-faced 20-ft sections in impact zone, ungrouted joints.

[a] From beginning of installation.

[b] Vehicle rolled + 180 degrees after leaving barrier.

[c] Initial impact contact distance, not counting lateral contact.

[d] From first contact to last contact with barrier.

[e] Occupant impact did not occur; maximum occupant velocity relative to vehicle was 7.5 ft/sec.

Table 2. CMB lateral movement.

	Base Movement (in.)[a]							
	Test 44		Test 45		Test 46[b]		Test 47[c]	
Joint	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
1	–	–	–	–	–	–	–	–
2	–	–	–	–	–	–	–	–
3	–	–	–	–	–	–	–	–
4	–	–	–	–	-1.0	-0.5	–	+0.5
5	–	–	–	–	-2.5	-2.75	–	–
6	-6.0	-6.0	-1.75	-2.00	-4.5	-4.5	-2.0	-2.5
7	-13.5	-13.75	-2.75	-2.75	-6.75	-6.5	-3.5	-2.75
8	-17.0	-17.0	-1.75	-1.75	-6.75	-6.75	+0.5	–
9	-13.25	-12.5	-0.50	-0.50	-5.00	-5.00	–	–
10	-4.5	-4.5	–	–	-3.0	-3.0	–	–
11	+1.5	+1.0	–	–	-1.0	-1.50	–	–
12	+2.0	+2.0	–	–	–	–	–	–
13	–	–	–	–	–	–	–	–
14	–	–	–	–	–	–	–	–

Notes: In tests 45, 46, and 47 impact occurred between joints 6 and 7. In test 44 impact occurred between joints 7 and 8.

[a] Movement is displacement from original position: – means away from traffic, and + means toward traffic; all measurements to the base made from reference marks of original position on pavement.

[b] Grouted joints.

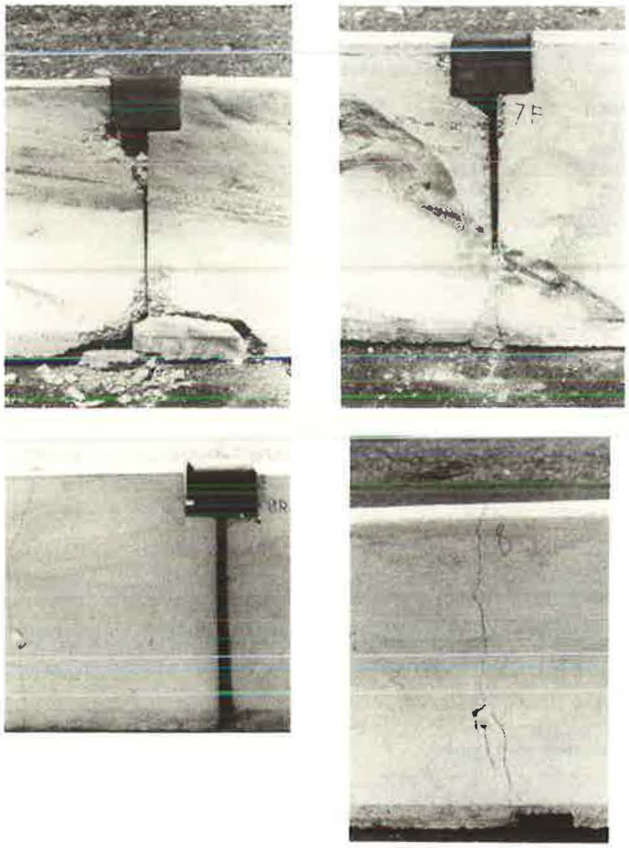
[c] Two 20-ft sections in impact zone.

grees. The vehicle would have rolled over had not the 1-in.^{2} data cable bar mounted on the rear contacted the ground and acted as a counterforce to its roll. After leaving the barrier, the full weight of the vehicle came down on the left side, the right side recontacted the ground, and the damaged front end caused the vehicle to swerve to the left, where it was stopped by a cable and safety fence.

Vehicle damage was moderate--the steering and front suspension were damaged, the right-front tire was blown, the front end and right side had sheet-metal damage, and the right-hand edge of the windshield was cracked. Barrier damage was only cosmetic, such as scratches and tire marks.

In the third test (no. 46), a 4,350-lb Chevrolet sedan impacted the CMB installation (with grouted joints) 54.5 ft from the beginning at 61.1 mph and 25 degrees. On impact its right side climbed to the

Figure 2. Barrier damage from test 44 (left) and test 46 (right).



CMB top, the vehicle pitched up -5 degrees, and the barrier was deflected 6.75 in. Peak g's were 12.7 longitudinal and 10.5 lateral, with peak 50-msec averages of 5.6-g longitudinal and 6.1-g lateral. The vehicle was redirected with an exit angle of 8 degrees left and a maximum roll of -42 degrees left. The right-rear tire caught behind the barrier as the vehicle lost roll angle, which caused its weight to be shifted to the left-front tire with a maximum pitch down of +10 degrees and yawed it to the left. The rear end of the vehicle remained on the barrier while yaw increased and the roll changed to the right. The damaged right-front tire and suspension were brought down to the ground, the vehicle decelerated further, and yaw increased. The rear end of the vehicle reached the end of the barrier installation and came off the barrier then bounced on the ground and continued to yaw until it was stopped by the cable and safety fence with a maximum yaw of +270 degrees left.

Vehicle damage was severe; the front and rear suspension were particularly affected. Both right tires were blown, the front sheet metal and bumper were damaged, and the windshield was cracked. Barrier damage (Figure 2) was moderate, including scratches, gouges, hairline cracks, and broken corners.

For the last test a smooth-finish barrier face was used instead of the rough hand-finished texture that was supplied by the precasting company and used in the first three tests. Because the 8-ft sections on hand had a rough-textured finish, two 20-ft CMB sections left over from previous tests were used for test 47 in the impact area to determine if surface texture affected vehicle roll. High roll angles were observed in the first three tests. The angles seemed to relate to the rapid front tire climb after barrier contact. Barrier deflections recorded in the first three tests were sufficient for evaluation of the 8-ft CMB sections, and lateral barrier deflection appeared similar to that of the 20-ft sections tested earlier.

In test 47 a 2,175-lb Vega impacted the CMB installation 53.0 ft from the beginning at 61.4 mph and 15.2 degrees. On impact the vehicle climbed the barrier, but this time only halfway up, and pitched up less than -3 degrees. Maximum roll was -11 degrees right, and it was redirected quite smoothly. Peak g's were 7.9 longitudinal and 11.1 lateral; peak 50-msec averages were 3.5-g longitudinal and 7.5-g lateral. A maximum pitch of +3 degrees down preceded its loss of contact with the barrier. The vehicle left the barrier 82 ft from the beginning at an exit angle of 5 degrees left. No yaw was observed and the vehicle continued its exit until stopped by safety cables.

Vehicle damage was moderate, mostly involving sheet metal and the front suspension and steering. The barrier was not damaged except for scratches and tire marks. Deflection was measured as 3.5-in. maximum.

DISCUSSION AND FINDINGS

Several advantages are offered by 8-ft barrier sections compared with the now-standard 20-ft sections. In addition to improved ease of handling because of shorter length and lighter weight, the 8-ft barrier sections can also provide better conformity with uneven pavement. However, before shorter sections could be used, it was necessary to ensure that barrier performance was not affected adversely by the shorter sections and to determine their deflection on impact.

Earlier work by Ivey (5) predicted that deflections would be similar for the two section lengths; however, the 20-ft sections were expected to deflect slightly more than shorter ones, provided that barrier unit weight remained constant. Table 3 compares lateral deflections for tests with both the 8- and 20-ft sections. In test 17 compared with test 44, with ungrouted joints, the 8-ft sections deflected only 1 in. more, although impact speed was 12 mph greater. In test 18 compared with 46, with grouted joints, the 8-ft sections deflected less than the 20-ft sections, although impact speed was 6 mph higher. Tests 44 and 46 also reconfirmed the value of pulling the joints tight and packing with grout to reduce joint deflection.

The current design deflection distances for 20-ft sections and impact conditions of 4,500-lb sedans at 60 mph and 25 degrees are 11 and 16 in. for grouted and ungrouted joints, respectively. Based on these

Table 3. Comparison of lateral barrier deflections for 20- and 8-ft section lengths.

	Impact Conditions				
Test	Vehicle Weight (lb)	Speed (mph)	Angle (°)	Barrier Length (ft)	Deflection (in.)
17[a]	4,250	53	25	20	16
18[a]	4,230	55	25	20[b]	11
44	4,300	65	27	8	17
46	4,350	61	25	8[b]	6.75
45	2,175	66	16	8	2.75
47	2,175	61	15	20	3.50

[a] From Hahn and Bryden (1). [b] Grouted.

tests, the use of the same design deflections for any section lengths between 8 and 20 ft appears to be conservative. Although some small refinement in these deflection values might be possible, any such change would probably be no more than a few inches and thus does not justify additional testing for such a small refinement. Finally, comparison of tests 45 and 47 confirms that substitution of the 20-ft sections in the final test had only a minimal effect on barrier deflection.

NCHRP Report 230 (3) provides the current evaluation criteria to which this barrier's performance was compared in Table 4. Portable CMB has generally met structural adequacy criteria when strong joint connections were used between sections, and these 8-ft sections also proved adequate. Criterion A, which requires vehicle redirection, and criterion D, which prohibits barrier fragments, were both met by this barrier, although redirection trajectory was not smooth for the two large-sedan tests. In addition, in both of the large car tests, the vehicles protruded behind the top of the barrier, which might result in a hazard if workers or equipment were located near the back of the barrier. However, these reactions are typical of other crash tests of concrete barrier, in terms of both vehicle trajectory and protrusion behind the barrier (4,6,7), and point out the desirability of limiting this barrier to locations where high-angle, high-speed impacts are unlikely.

In terms of occupant risk, CMB has also often resulted in marginal results for high-speed and high-angle collisions, and these tests are no exception. Criterion E limits vehicle roll, pitch, and yaw, but three of these four tests were marginal because of high roll or yaw. Only the fourth, which was a 15-degree impact against the smooth-faced barrier, resulted in a smooth vehicle trajectory.

Figure 3 compares the results of similar impacts in tests 45 and 47 by using nearly identical vehicles and impact conditions. In test 45 a -64-degree roll resulted on the rough barrier face, which appeared to promote severe wheel climb. On the smooth barrier face in test 47 roll was limited to only -11 degrees. In test 45 the impacting front wheel climbed at a 30-degree angle nearly to the top and then at a flatter angle to the top of the barrier. In test 47 the wheel climb angle was only 22 degrees and ended well below the top of the barrier.

Other possible causes have also been suggested for the difference in vehicle roll between these tests in addition to barrier surface texture. Although in test 45 speed and angles were slightly more severe than those in test 47, this difference would not seem to cause such a large increase in vehicle climb. Differential barrier tipping, which might vary with section length, could also be expected to influence vehicle climb. Close examination of the test films, however, revealed no measurable barrier rotation in the vertical plane in any

Table 4. Comparison of test results to evaluation criteria in NCHRP Report 230.

Evaluation Factor	Test 44	Test 45	Test 46	Test 47
Structural adequacy				
A	Marginal[a]	OK	Marginal[a]	OK
D	OK	OK	OK	OK
Occupant risk				
E	Not good	Marginal	Marginal	OK
F	Not good	Marginal	Marginal	OK
Occupant impact velocity				
Longitudinal	–[b]	OK	–[b]	OK
Lateral	–[b]	OK	–[b]	OK
Ridedown acceleration				
Longitudinal	–[b]	OK	–[b]	OK
Lateral	–[b]	OK	–[b]	OK
Vehicle trajectory				
H	OK	OK	OK	OK

[a] Vehicle was redirected, but trajectory was not smooth.

[b] These evaluation criteria were not evaluated for strength tests.

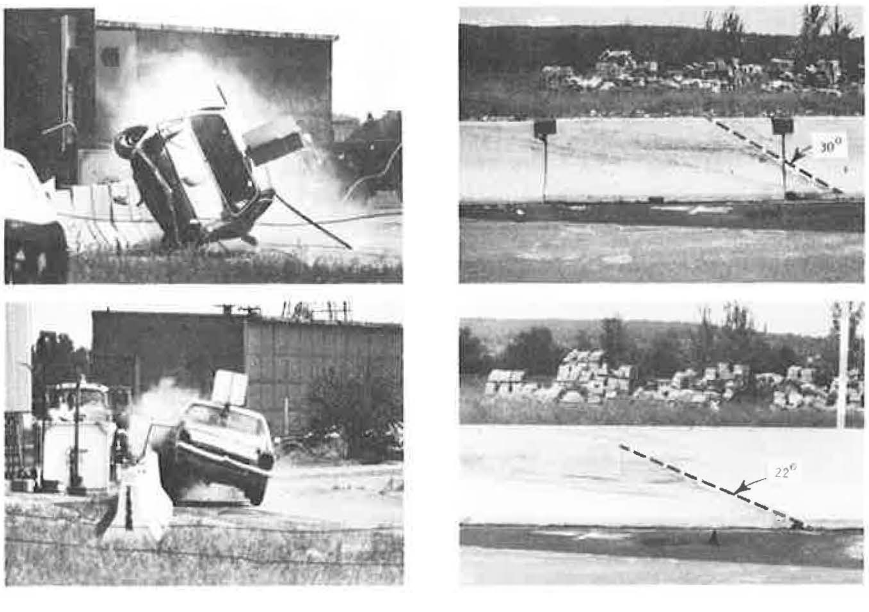


Figure 3. Vehicle roll and wheel climb in test 45, with rough surface texture (above) and test 47 with smooth surface texture (below).

of the four tests. Analysis of the geometry of this joint detail reveals that the maximum possible differential barrier rotation is about 2.5 degrees for this design. Thus, a smooth barrier face is desirable to limit wheel climb and resulting vehicle roll.

In Table 1 all four tests, even with the more severe 25-degree impacts, are within the recommended occupant impact velocities and ridedown decelerations in criterion F. However, lateral 50-msec average decelerations somewhat exceeded the recommended values from Circular 191 (2). For the 25-degree impacts, those criteria are not generally expected to apply because of the increased impact severity. For the 15-degree impacts, however, the values of 6.8 and 7.5 g exceeded the recommended 5.0 g. Although decelerations could be expected to be somewhat lower if impact speeds had not exceeded 60 mph, these tests still point out the severity of impacts with barriers as rigid as portable CMB.

NCHRP vehicle trajectory criteria were generally met by these tests. The vehicles remained close to the barrier after impact, thus satisfying criterion H. Because the vehicles did not intrude into adjacent lanes, criterion I, relating to velocity change and departure angle, does not apply.

Except for the upstream and downstream terminals, none of these barrier sections was connected to the pavement. The in-text table confirms that only a short barrier length was moved laterally (72 ft in the extreme cases), and only 120 ft experienced slight longitudinal movement. Thus, for installations where the design lateral deflections can be tolerated, the data in this table confirm that pinning the barrier to the pavement is not necessary even with 8-ft section lengths.

Based on the results of these full-scale tests, the following findings can be stated.

1. Portable CMB that meet New York's standard design criteria and use 8-ft section lengths provided performance comparable with that of 20-ft lengths.
2. Barrier surface texture should be as smooth as possible to reduce front-tire climb and resulting high roll angles.
3. Portable 8-ft CMB sections using New York's pinned connected joints are an effective positive barrier for impact conditions of 4,500 lb, 60 mph, and 25 degrees, although smooth redirection cannot be ensured for 60-mph, 25-degree impacts, and the vehicle may intrude behind the barrier during redirection in these severe impacts.
4. Lateral barrier deflections for the 8-ft sections were similar to those for the 20-ft sections; therefore, the same design deflections can be used for any section lengths between 8 and 20 ft.
5. Barrier deflection and corner damage were reduced by pulling the joints tight and grouting the lower 6 in. of joint, front and rear.
6. Pinning intermediate barrier sections to the pavement is not necessary unless small lateral deflections are required.

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