Performance Evaluation of a Movable Concrete Barrier

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A series of crash tests and operational demonstrations of a precast movable concrete barrier (MCB) were performed. Four crash tests of the MCB showed that it can successfully redirect both light and heavy passenger cars at various angles of impact. The crash tests involved two large cars weighing 4,370 lb and 4,300 lb, traveling 59.3 and 59.4 mph, and striking at 24 degrees and 16 degrees, respectively; and two small cars weighing 2,000 lb and 1,895 lb, traveling 57.7 and 58.6 mph, and striking at 15½ degrees and 20½ degrees, respectively. The crash tests satisfied the requirements for structural adequacy and occupant risk in *NCHRP Report 230*. Vehicle trajectory requirements were not satisfied because of large exit angles. The demonstrations consisted of (a) a transfer vehicle straightening a deflected barrier after the last crash test; (b) a transfer vehicle transporting, assembling, and transferring a barrier on a 1,400-ft radius with a 12 percent cross-slope; (c) a transfer vehicle transferring a barrier on a 4 to 5 percent longitudinal grade; and (d) manual movement of the barrier to adjust minor misalignments. The MCB moves laterally under impact. The lateral movement is related to impact severity. Two equations are presented to predict lateral movement as a function of impact severity.

Traffic congestion has increased rapidly in recent years. At many highway and bridge locations there has not been room to add lanes or funds have been insufficient. At those locations where traffic is heavy in one direction in the morning and heavy in the opposite direction in the evening, a need has developed for a median barrier that can be moved easily from one lane boundary to another. With a movable barrier it would be possible to adjust the number of lanes available to peak traffic daily, while maintaining a positive barrier between opposing traffic lanes. The California Department of Transportation (Caltrans) has a pressing need for such a barrier on the Coronado Bridge in San Diego. The relocatable pylons used there now do nothing to retain out-of-control vehicles, and there have been severe head-on collisions. There are other locations where a movable barrier could be used to advantage. These include locations where a permanent system is needed and also construction and maintenance locations where a mobile barrier is needed that would provide greater protection to motorists and workers. Over the years several systems have been proposed to Caltrans. These systems have required an extensive and complicated mechanical installation within the roadbed, introducing a potential maintenance headache and precluding them from temporary use, or have demonstrated inferior performance as a barrier.

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DESCRIPTION OF BARRIER AND TRANSFER VEHICLE

A barrier that meets the criterion of simplicity and requires no roadbed modification has been developed. This barrier was conceived, developed, and tested in response to a continuing demand for a movable barrier from the United States and other countries. The Quickchange Movable Concrete Barrier System was invented by Quick-Steel Engineering Pty, Ltd., of Botany, New South Wales, Australia. Barrier Systems, Inc. (BSI), of Sausalito, California, is the North American licensee for the system. Hereafter this system will be referred to as a movable concrete barrier (MCB).

The MCB is a segmented concrete barrier formed similar to a Configuration F-shape modified with a narrowed neck and a T-shaped top (Figure 1). The segments are 3.28 ft (1 m) long, 2 ft (609 mm) wide at the base, and 32 in. (812 mm) high. They are joined together by a pin-and-link hinge.

The MCB is moved from one traffic lane line to another with a transfer vehicle (Figure 2). The vehicle is a mobile steel framework, which may be either self-propelled or towed, with an S-shaped conveyor assembly mounted on it. Closely spaced urethane conveyor wheels ride under the flanges of the T-shape of the stem (Figure 3). The segments are lifted off the pavement by the wheels, guided along the S-shaped conveyor to the new lane position, and lowered back down to the pavement. The barrier segments remain pinned together during the transfer operation. As the vehicle moves forward, the barrier is transferred from left to right (when used as a median barrier), minimizing the exposure of the transfer vehicle to traffic in both directions (Figure 2).

SCOPE OF RESEARCH

A series of crash tests and operational demonstrations of the MCB were performed. Two crash tests indicated a deficiency in the original design. After modification by the manufacturer, four additional tests demonstrated successful redirection of large and small cars. Four operational demonstrations indicated the maneuverability and maintainability of the MCB.

BARRIER DESIGN

Two tests were conducted on two versions of the original Australian design and are described in the full report (*1*). The tests were at impact angles of 15 degrees and 25 degrees with heavy vehicles at 60 mph (27 m/sec). The lateral deflections

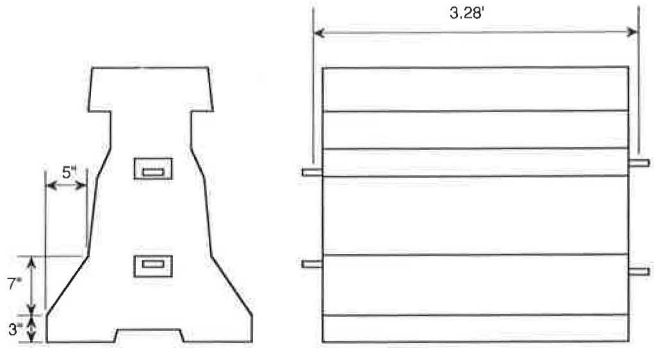


FIGURE 1 End view and elevation of MCB.

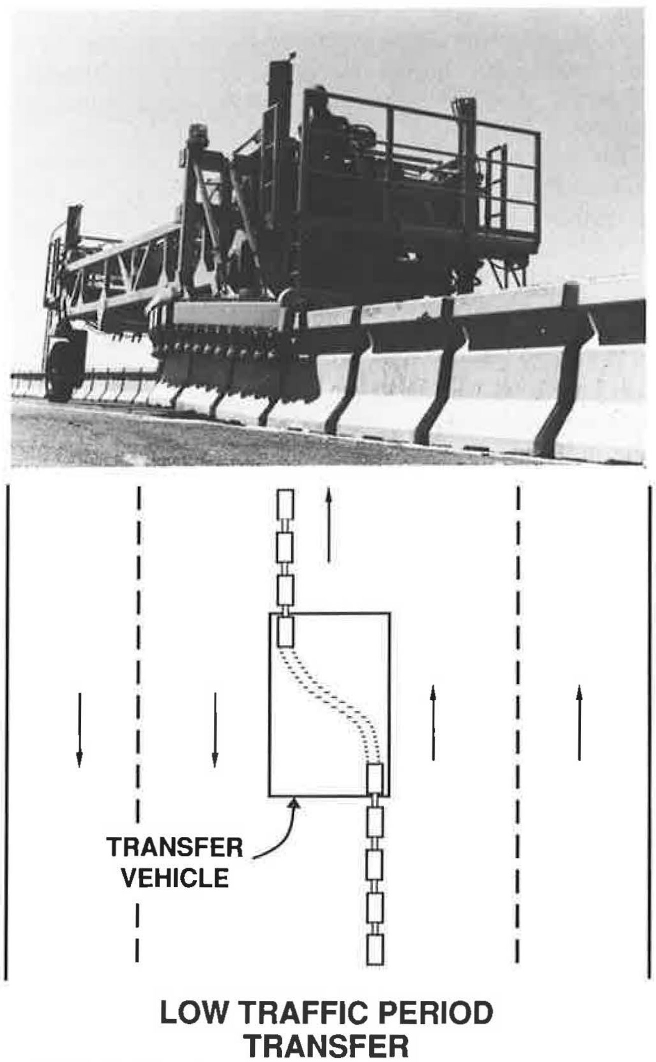


FIGURE 2 Transfer vehicle moves barrier one full lane width.

were 4.56 and 5.77 ft (1.4 and 1.8 m) for the two tests. The strength of the stem proved to be inadequate. Because this barrier was anticipated for use on a permanent installation, the lateral deflection was considered excessive.

The manufacturer, BSI, undertook a testing and development program to design a stronger stem and to determine what factors are important to lateral deflection. The stem was strengthened by thickening the narrow neck section, increasing it from 5⅛ in. (130 mm) to 8⅛ in. (206 mm) and increasing the reinforcement from 6 × 6–W5 × W5 welded wire fabric to two No. 4 reinforcing bars plus 4 × 4–W4 × W4 welded wire fabric. In addition, the wire fabric was bent outward into the top flange (Figure 4).

The method devised to limit the lateral deflection was to reduce the longitudinal clearance in the hinge assembly (Figure 5). The original design had a ±½ in. (12.7 mm) clearance to allow for barrier lengthening and shortening in changing radii and expansion joints on bridges. This clearance was reducted to ±³⁄₁₆ in. (4.8 mm). By reducing the clearance, more barrier segments (more mass) must be mobilized to effect a unit of lateral movement; thus more energy would be required per unit.

TEST RESULTS

Test 443 (4,370 lb, 59.3 mph, 24 degrees)

The left front bumper of the test vehicle struck the 100-segment barrier at the midpoint of Segment 62 at 59.3 mph (26.5 m/sec) and an angle of 24 degrees. The length of vehicle contact with the barrier was about 39 ft (12 m), from Segments 62 to 74. The car was smoothly redirected and lost contact with the barrier at an exit angle of 14¾ degrees. The car

FIGURE 3 Barrier is lifted by conveyor wheels under the MCB flange.

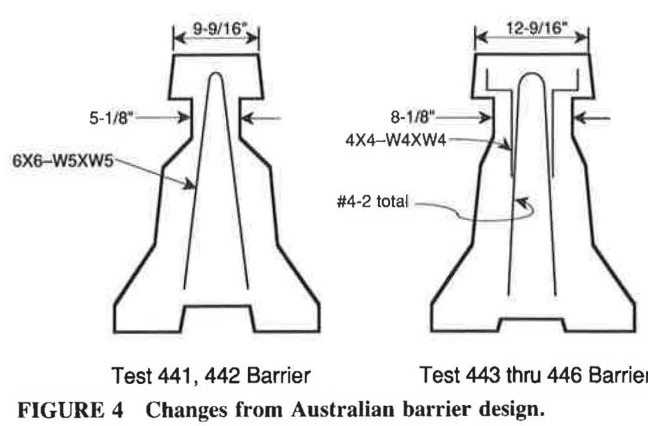


FIGURE 4 Changes from Australian barrier design.

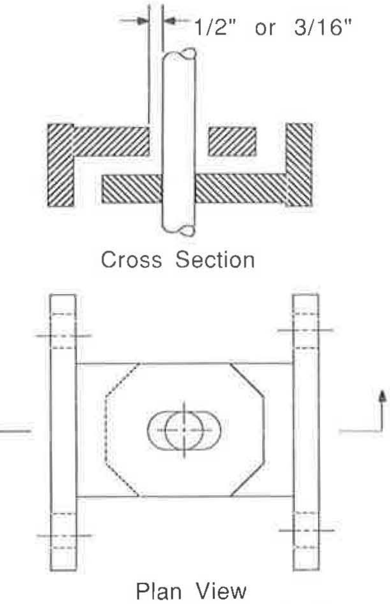


FIGURE 5 Simplified hinge detail.

experienced a maximum roll of −10¼ degrees. The maximum rise of the car was 4 in. (100 mm) 0.73 sec after impact, measured at the right rear corner of the roof. Figure 6 shows sequential photographs and a trajectory diagram.

The trajectory of the car after impact was back toward the line of the barrier. A second impact with the barrier occurred at Segment 93. The car came to rest about 30 ft (9.1 m) beyond the downstream end of the barrier and approximately in line with its face (Figure 7).

The barrier was displaced laterally along a distance of about 66 ft (20 m) (Segments 54 through 75). The maximum lateral displacement was 3.74 ft (1.3 m) at Segment 66 (Figure 8). There was longitudinal movement in the barrier from Segments 22 to 100. The maximum longitudinal displacement in the downstream direction was 0.5 ft (140 mm) at Segment 54. The maximum longitudinal displacement in the upstream direction was 0.15 ft (45 mm).

Test 444 (2,000 lb, 57.7 mph, 15½ degrees)

The left front bumper of the test vehicle struck the 100-segment barrier at the midpoint of Segment 48 at 57.7 mph (25.8 m/sec) and an angle of 15½ degrees. The length of vehicle contact with the barrier was about 16 ft (5 m), from Segments 48 to 52. The car was smoothly redirected and lost contact with the barrier at an exit angle of 10¼ degrees. The car experienced a maximum roll of −14½ degrees and a pitch of +10¼ degrees. The maximum rise of the car was 17 in. (430 mm) 0.36 sec after impact, measured on the right rear tire. Figure 9 shows sequential photographs and a trajectory diagram.

The trajectory of the car after impact was away from the barrier. The car came to rest off the paved area about 15 ft (4.6 m) beyond the downstream end of the barrier and 60 ft (18 m) from its face (Figure 10).

The barrier was displaced laterally along a distance of about 30 ft (9 m) (Segments 47 through 55) (Figure 11). The maximum lateral displacement was 1.78 ft (542 mm) at Segment 51. There was longitudinal movement in the barrier from Segments 36 to 65. The maximum longitudinal displacement in the downstream direction was 0.1 ft (30 mm) at Segment 47. The maximum longitudinal displacement in the upstream direction was 0.1 ft (31 mm) at Segment 55.

Test 445 (4,300 lb, 59.4 mph, 16 degrees)

The left front bumper of the test vehicle struck the 100-segment barrier at the midpoint of Segment 52 at 59.4 mph (26.6 m/sec) and an angle of 16 degrees. The length of vehicle contact with the barrier was about 33 ft (10 m), from Segments 52 to 61. The car was smoothly redirected and lost contact with the barrier at an exit angle of 16½ degrees. The car experienced a maximum roll of +6¼ degrees and a pitch of +5⅜ degrees. The maximum rise of the car was 19 in. (490 mm) 0.54 sec after impact, measured on the right rear bumper. Figure 12 shows sequence photographs and a trajectory diagram.

The trajectory of the car after impact was away from the barrier. The car came to rest off the paved area at the toe of an earth berm about 79 ft (24 m) beyond the downstream end of the barrier and 41 ft (12.5 mm) from its face (Figure 13).

The barrier was displaced laterally along a distance of about 59 ft (18 m) (Segments 47 through 65). The maximum lateral displacement was 2.85 ft (870 mm) at Segment 59 (Figure 14). There was longitudinal movement in the barrier from Segments 26 to 81. The maximum longitudinal displacement in the downstream direction was 0.4 ft (110 mm) at Segment 58. The maximum longitudinal displacement in the upstream direction was 0.1 ft (34 mm) at Segment 70.

Test 446 (1,895 lb, 58.6 mph, 20½ degrees)

The left front bumper of the test vehicle struck the 100-segment barrier at Segment 55 at 58.6 mph (26.2 m/sec) and an angle of 20½ degrees. The length of vehicle contact with the barrier was about 20 ft (6 m), from Segments 55 to 60. The car was smoothly redirected and lost contact with the barrier at an exit angle of 19½ degrees. The car experienced a maximum roll of −15 degrees and a pitch of +12½ degrees. The maximum rise of the car was 30 in. (760 mm) 0.44 sec after impact, measured on the right rear bumper. Figure 15 shows sequence photographs and a trajectory diagram.

The trajectory of the car after impact was away from the barrier. The car came to rest about even with the downstream end of the barrier 37 ft (11 m) away from its face (Figure 16).

The barrier was displaced laterally along a distance of about 42 ft (13 m) (Segments 52 through 64). The maximum lateral displacement was 2.24 ft (684 mm) at Segment 59 (Figure 17). There was longitudinal movement from Segments 37 to 84. The maximum longitudinal displacement in the downstream direction was 0.15 ft (48 mm) at Segment 55. The maximum longitudinal displacement in the upstream direction was 0.2 ft (54 mm) at Segment 64.

DISCUSSION OF TEST RESULTS

In Tests 443 through 446 the MCB demonstrated its ability to retain and redirect a vehicle under a variety of impact

Impact + 0.014 s

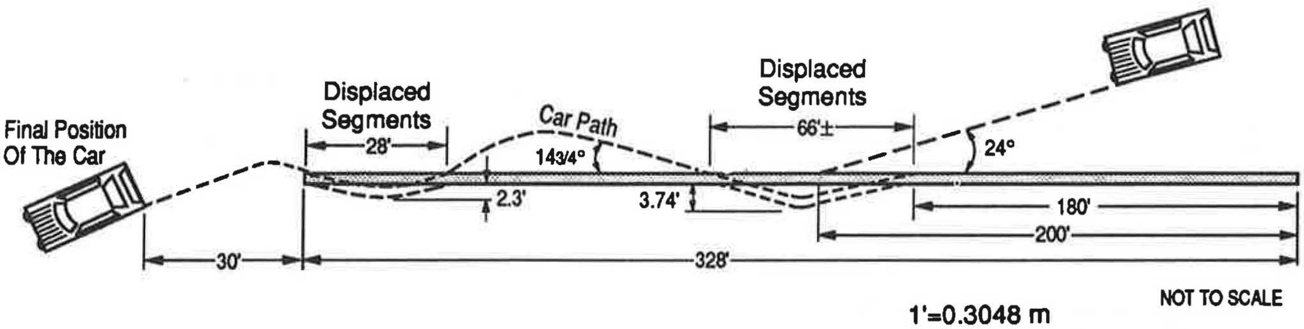
I + 0.074 s

I + 0.204 s

I + 0.674 s

I + 1.32 s

I + 1.68 s



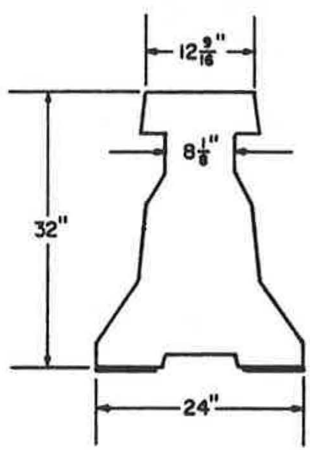
Test Barrier:
- Type: Movable Concrete Barrier (Simple Hinge Connections with Reduced Clearance)
- Length: 328 ft (100 m) - 100 segments

Test Date: November 18, 1987

TestVehicle:
- Model: 1982 Olds Station Wagon
- Inertial Mass: 4370 lb (1982 kg)
- Impact Velocity: 59.3 mph (26.5 m/s)
- Impact; Exit Angle: 24 deg; 14 3/4 deg

Test Dummy:
- Type: Part 572, 50th Percentile Male
- Weight / Restraint: 165 lb (75 kg)/ none
- Position: Driver's seat

Test Data:
- Occupant Impact Velocity (long): 27.0 fps. (8.2 m/s)
- Max 50 ms Avg Accel: long –8.3 g, lat -7.7 g, vert -2.0 g
- HIC / TAD / VDI: 121 / LFQ6 / 11LDEW2
- Max Roll;Pitch;Yaw : –10 1/4 deg; NA; NA
- Barrier Displacement: 3.74 ft (1.14 m) at segment 66
- Max Dynamic Deflection (film): 4.10 ft (1.25m)
- Barrier Damage: Minor scratches on 11 segments at the area of contact with test car



1"=0.0254 m

FIGURE 6 Summary of data for Test 443.

FIGURE 7 Car and barrier after impact, Test 443.

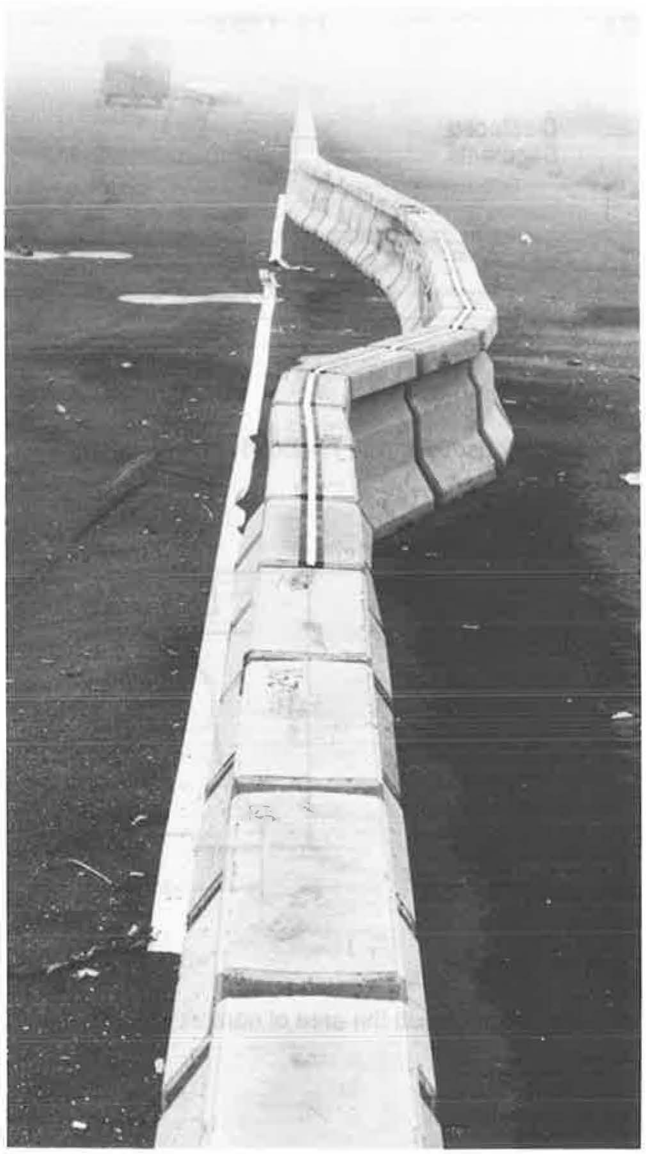


FIGURE 8 Deflected barrier after impact, Test 443.

conditions. Vehicle rederection was smooth in all these tests. There was no tendency for the barrier to pocket or trap the vehicles. There was no evidence of any structural distress of the barrier segments. All four tests were performed on the same set of barrier segments without replacing any segments, welded hinge plates, or steel hinge pins. Segments were shifted after each test so fresh segments would be located in the main impact zone.

There was significant lateral displacement of the test barrier during each test (Table 1). The barrier displacement was closely related to impact severity (IS). The data from these tests were statistically analyzed to obtain an equation for lateral displacement as a function of IS.

Two equations (Table 2) were found to fit the experimental data. These equations are represented in graphical form with the experimental data in Figure 18. The correlation is significant at the 5 percent level (*2*, pp. 462–463). Data from other tests were also used in deriving these equations (*1*; E. F. Nordlin, unpublished data).

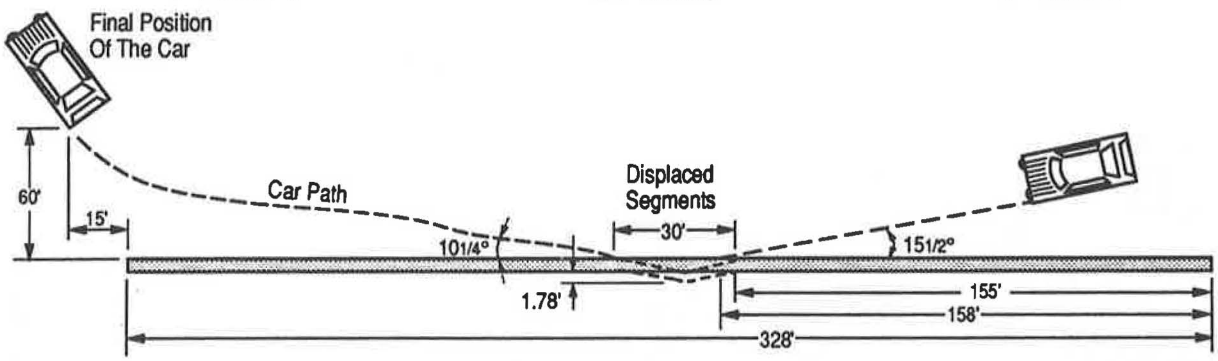
For very small values, up to 3.8 ft-kips (5.2 kJ), no deflection is predicted by Equation 1. Although the second equation approaches a zero displacement as IS approaches zero, it can be considered to evaluate to zero for IS less than 1 ft-kip (1.4 kJ).

For small impacts, up to 15 ft-kips (20 kJ), it is believed that Equation 1 understates the displacement that might be expected. Within this impact severity range, Equation 2 probably gives a better value of lateral displacement. The reason why the lateral displacement is probably larger than that predicted by Equation 1 lies in the action within the hinge during impact. In high-IS impacts, like those used to derive Equation 1, many of the barrier segments move. For each segment that moves, the entire longitudinal clearance in the hinge is taken up, effecting a lengthening of the barrier to allow lateral movement. During low-energy impacts many fewer segments are brought into the movement zone, down to the limiting case where only two segments move at all. In an impact when only two or three segments move, all the longitudinal clearance in the hinge may not be used, thus allowing movement with very low energy input.

In the range of 15 to 130 ft-kips (20 to 175 kJ), the two equations give the same answer within the accuracy that can be expected from such an estimator. Caution must be exercised when using these equations to extrapolate beyond 100 ft-kips (135 kJ), because that is beyond the value of any data used to derive the equations. At some unknown value of impact severity some structural elements of the barrier may fail, thus invalidating any attempt at predicting deflection.

Table 3 shows roll, pitch, and yaw values, maximum 50 msec average accelerations, occupant impact velocities, and ridedown accelerations. For comparison, Tests 443 through 446 are included with data from previous tests on continuous concrete safety shaped barriers done by Caltrans.

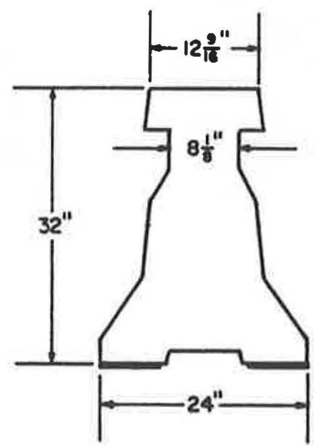
Note that the magnitude of roll in Tests 443 through 446 is generally lower than in other tests of concrete safety shaped barriers. The amount of roll and pitch is low to moderate in all MCB tests. None of the test cars showed any indication of being close to rollover. Scuff and rub marks on the face of the barrier indicated that the projecting cap of the MCB restricted the climb of the car, thereby minimizing the roll angle.



1'=0.3048 m NOT TO SCALE

Test Barrier:

Type:	Movable Concrete Barrier (Simple Hinge Connections with Reduced Clearance)
Length:	328 ft (100 m) - 100 segments
Test Date:	December 18, 1987
TestVehicle:	
Model:	1981 Honda Civic
Inertial Mass:	2000 lb (907 kg)
Impact Velocity:	57.7 mph (25.8 m/s)
Impact; Exit Angle:	15 1/2 deg; 10 1/4 deg
Test Dummy:	
Type:	Part 572, 50th Percentile Male
Weight / Restraint:	165 lb (75 kg)/ none
Position:	Driver's seat
Test Data:	
Occupant Impact Velocity (long):	15.1 fps. (4.6 m/s)
Max 50 ms Avg Accel:	long –4.6 g, lat –6.7 g, vert 1.7 g
HIC / TAD / VDI:	30 / LFQ4 / 12LDEE2
Max Roll;Pitch;Yaw :	–14 1/2 deg; 10 1/4 deg; NA
Barrier Displacement:	1.78 ft (0.54 m) at segment 51
Max Dynamic Deflection (film):	1.92 ft (0.58 m)
Barrier Damage:	Minor scratches at the area of contact with test car



1"=0.0254 m

FIGURE 9 Summary of data for Test 444.

FIGURE 10 Car and barrier after impact, Test 444.

FIGURE 11 Deflected barrier after impact, Test 444.

The longitudinal occupant impact velocity in Test 444 (see Table 3) was below the *NCHRP Report 230* (*3*) recommended maximum value and also smaller than in other Caltrans tests on permanent concrete median barriers. Although this was the only test required to meet Section F of the occupant risk requirements of *NCHRP Report 230*, the criterion was also met in Tests 443, 445, and 446.

In all four tests the exit angle exceeded 60 percent of the impact angle, the recommended limit in *NCHRP Report 230*, though only slightly in Tests 443 and 444 (Table 4). In Test 443 the velocity change also exceeded the recommended limit, 15 mph. In that test, the vehicle steered back toward the MCB and struck a second time. In Tests 444, 445, and 446 the vehicle speed change was 11 to 12 mph (4.9 to 5.3 m/sec), and the vehicles then crossed the traveled way and came to rest 40 to 60 ft (11 to 18 m) from the barrier face. The vehicles were disabled in all four tests and stopped 150 to 200 ft (45 to 62 m) from the impact point.

THE TRANSFER VEHICLE

The transfer vehicle is 49 ft (15 m) long and 8.2 ft (2.5 m) wide and weighs 30 tons (27 000 kg) (Figure 19). It is self-powered; a 200-hp (150-kW) diesel engine powers a hydraulic drive and steering. Each wheel can be independently raised and lowered. A barrier can be transferred onto or off a curb up to 12 in. high. The lateral move of the barrier can be varied from 6 ft to 16 ft. Up to 15 segments of the barrier can be carried and transported as a unit. The transfer vehicle operates in either direction and is operationally symmetrical. Each end of the vehicle is independently steered with its own steering wheel. Movement can be controlled from either end.

DEMONSTRATIONS OF TRANSFER VEHICLE

A prototype transfer vehicle was used for four demonstrations. The demonstrations consisted of (a) straightening a deflected barrier after the last crash test, (b) transporting and assembling a 10-segment length of barrier, (c) transferring a barrier on a 1,400-ft radius with a 12 percent cross slope, and (d) transferring a barrier on a 4 to 5 percent longitudinal grade.

The first demonstration showed the ability of the transfer vehicle to realign a deflected barrier. The barrier was deflected by Test 446 a maximum of 2.24 ft (683 mm). The barrier was back to a straight alignment in its original position after two passes (Figure 19). It appeared that with more experienced operators the barrier could have been made straight with only one pass. Realignment was accomplished without placing

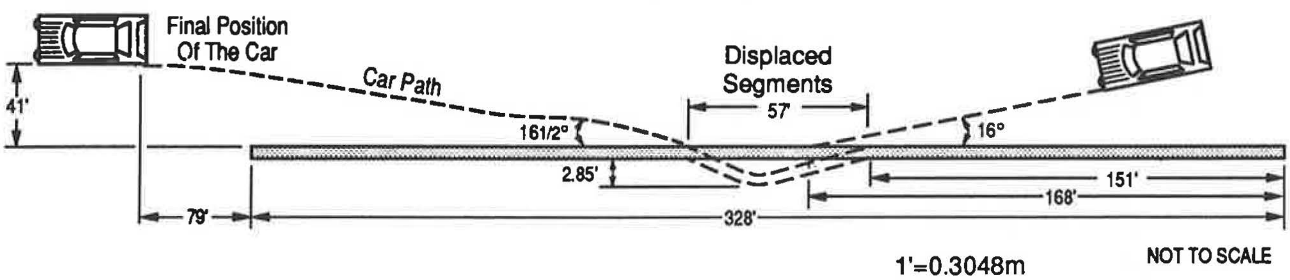
Impact

I + 0.118 s

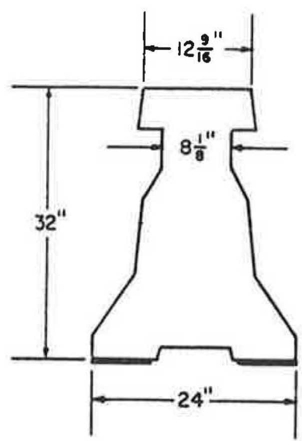
I + 0.238 s

I + 0.458 s

I + 0.71 s



Test Barrier:
Type: Movable Concrete Barrier (Simple Hinge Connections with Reduced Clearance)
Length: 328 ft (100 m) - 100 segments
Test Date: January 21, 1988
TestVehicle:
Model: 1982 Olds Station Wagon
Inertial Mass: 4300 lb (1950 kg)
Impact Velocity: 59.4 mph (26.6 m/s)
Impact; Exit Angle: 16 deg; 161/2 deg
Test Dummy:
Type: Part 572, 50th Percentile Male
Weight / Restraint: 165 lb (75 kg)/ none
Position: Driver's seat
Test Data:
Occupant Impact Velocity (long): 14.3 fps (4.4 m/s)
Max 50 ms Avg Accel: long −3.3 g, lat −5.9 g, vert −1.7 g
HIC / TAD / VDI: 45 / LFQ4 / 12LDEE2
Max Roll;Pitch;Yaw : 61/4 deg; 53/8 deg; NA
Barrier Displacement: 2.85 ft (0.87 m) at segment 59
Max Dynamic Deflection (film): 3.04 ft (0.93 m)
Barrier Damage: Minor scratches and spalling at the area of contact with test car



1"=0.0254m

FIGURE 12 Summary of data for Test 445.

FIGURE 13 Car after impact, Test 445.

FIGURE 14 Deflected barrier after impact, Test 445.

workers on the ground to manually adjust the barrier. Two additional passes were made over the barrier to demonstrate simple transfer operation. All the functions of the transfer vehicle—lifting, lateral transport, and deposit of the modules—were smooth and continuous, and the vehicle moved at about 6 mph (2.7 m/sec).

The second demonstration showed how lengths of barrier can be transported and reattached to a standing barrier. (Such an operation might be performed to move the lane closure zone of a progressing construction site.) A length of barrier, 10 segments, was loaded onto the conveyor of the transfer vehicle, carried to the location of the third demonstration, and reassembled (Figure 20). The transport distance was about 0.5 mi (800 m), and the travel speed on the paved road was about 10 mph (4.5 m/sec). To reassemble the MCB, the barrier on the ground was aligned with the barrier within the vehicle and a hinge pin was inserted. Alignment was accomplished by loading the portion on the ground partway into the conveyor (Figure 21) until it came in contact with the carried barrier. There was some difficulty inserting the pin because the joint to be connected was sometimes pushed too far into the vehicle, to a place that hampered insertion. Even with that problem, though, assembly of the barrier was much faster than if it had been set one segment at a time.

The third demonstration consisted of transferring a barrier plus and minus 6 ft (1.8 m) from its original position on a curve of radius 1,400-ft (426.7 m) with a 12 percent cross slope (Figure 22). Two reference lines were laid out for use by the vehicle operators to place the barrier on each transfer run. A total of 70 segments were used to compose a barrier 230 ft (70 m) long. Two four-movement cycles were performed. In each cycle, the barrier was first moved outward to a 1,406-ft (428.5-m) radius, then inward two times to a radius of 1,394 ft (424.9 m), then outward to its original position.

The last demonstration, transferring a barrier on a 5 percent longitudinal grade, was done in Lodi, California, at the BSI test site. The barrier consisted of 76 segments for a total length of 250 ft (76 m). The whole barrier was transferred laterally back and forth 6 ft (1.8 m) each time from the middle, initial position. The speed of the transfer vehicle was about 5 mph (2.2 m/sec) both uphill and downhill. The barrier segments were freestanding in the first eight transfers and tethered in the second set of eight transfers.

Measurements of the joint displacements were taken across a set of four joints located about 50 ft (15 m) from each barrier end. The measurements were taken after each lateral transfer. The net change in length was near zero after each complete transfer cycle. Stretching of the barrier apparently occurred during travel of the transfer vehicle uphill, and contraction occurred during downhill transfers. However, the number of transfers was too small for a definite pattern to be discerned.

The lateral transfers resulted in a gradual longitudinal movement of the barrier system downhill. Measurements of longitudinal movement were made at the downhill end of the barrier. The total longitudinal movement was 4¾ in. (120 mm) after eight lateral transfers. Because the length of the barrier did not change, as shown by the measurements above, the whole barrier must have moved longitudinally downhill.

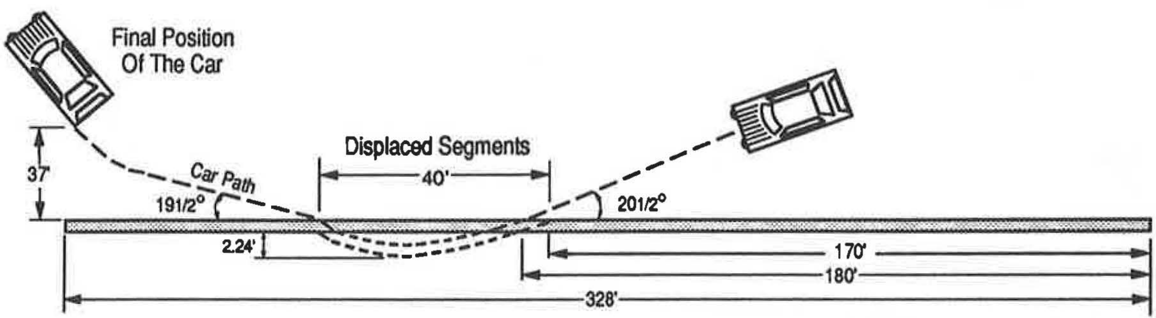
To counteract this tendency, the upstream end of the barrier was tethered with a cable tensioned to 1,000 lb (450 N) at the beginning of each downhill run (Figure 23). The same measurements as for the freestanding barrier were performed. The measurements indicated an apparent stretching of the barrier after each transfer cycle. The stretch was about 0.1 in. (2.5 mm) per joint. A total longitudinal movement of 3⅜ in. (84 mm) occurred after eight lateral transfers. Because the upstream end of the barrier was tethered, the downhill creep may be explained by the stretch in the barrier noted.

Although creep appeared to be restricted by pulling at the upstream end, it was not eliminated. A definite pattern or determination cannot be drawn from these data because the number of repetitions was limited.

Longitudinal creep has been reported in a similar barrier system installed in Paris, France (*4*). The total longitudinal movement of the French barrier 1.5 mi (2.4 km) long on a downhill grade of 1.5 to 2.0 percent was 3.3 to 6.6 ft (1 to 2 m) during the initial months of operation. The French solution to retard longitudinal creep was manual jacking of the uphill end of the barrier system before starting each daily barrier

Impact + 0.015 s | I + 0.098 s | I + 0.168 s

I + 0.303 s | I + 0.515 s | I + 1.208 s



Test Barrier:
- Type: Movable Concrete Barrier (Simple Hinge Connections with Reduced Clearance)
- Length: 328 ft (100 m) - 100 segments

Test Date: March 9, 1988

TestVehicle:
- Model: 1984 Nissan
- Inertial Mass: 1890 lb (857 kg)
- Impact Velocity: 58.6 mph (26.2 m/s)
- Impact; Exit Angle: 20 1/2 deg; 19 1/2 deg

Test Dummy:
- Type: Part 572, 50th Percentile Male
- Weight / Restraint: 165 lb (75 kg)/ none
- Position: Driver's seat

Test Data:
- Occupant Impact Velocity (long): 16.9 fps (5.2 m/s)
- Max 50 ms Avg Accel: long -7.6 g, lat –11.3 g, vert 2.8g
- HIC / TAD / VDI: 86 / LFQ4 / 11LDEE2
- Max Roll;Pitch;Yaw : –1.5 deg; 12 1/2 deg; NA
- Barrier Displacement: 2.24 ft (0.68 m) at segment 59
- Max Dynamic Deflection (film): 2.41 ft (0.73 m)
- Barrier Damage: Minor scratches on 2 segments at the area of contact with test car

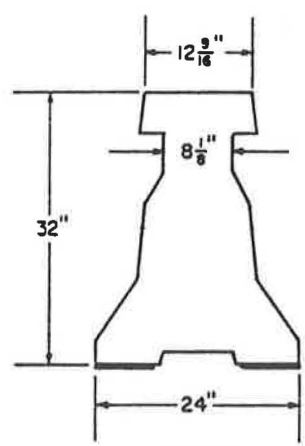


FIGURE 15 Summary of data for Test 446.

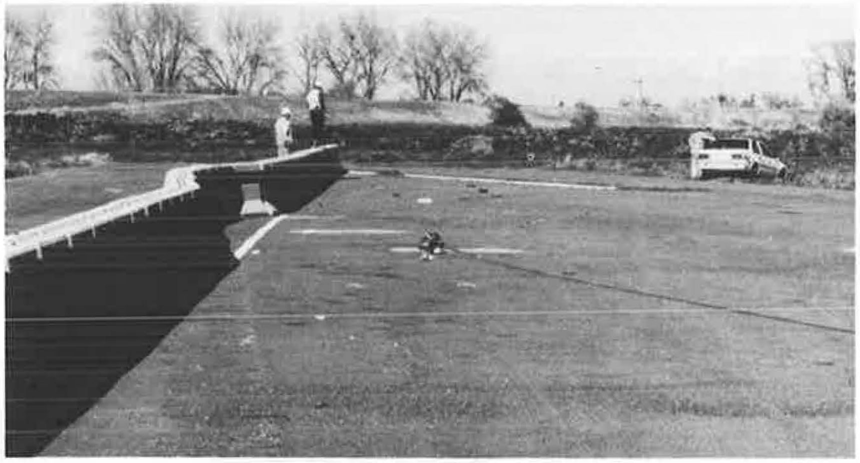


FIGURE 16 Car and barrier after impact, Test 446.

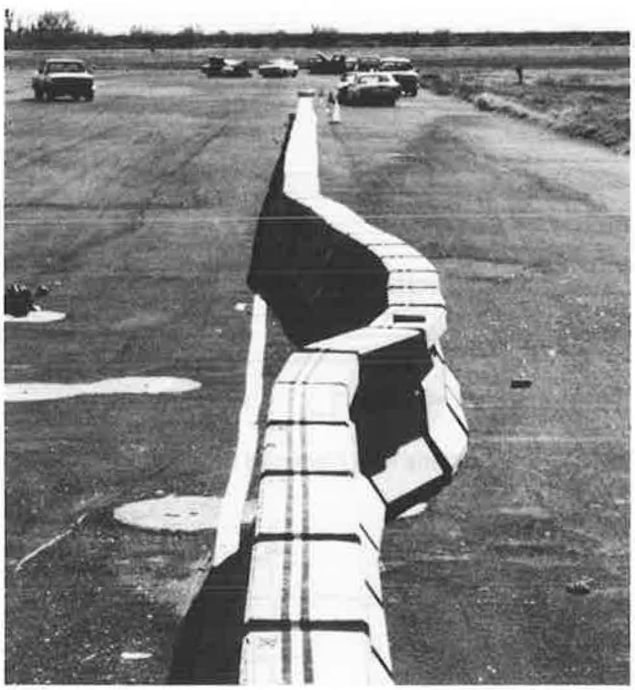


FIGURE 17 Deflected barrier after impact, Test 446.

transfer in the downhill direction, similar to what was done in this demonstration.

MANUAL MOVEMENT

Another method of moving the MCB is by hand. This would be useful in making minor alignment adjustments either while assembling the barrier or after an impact. Movement by hand was done by a single person using a pry bar 6 ft (2 m) long during installation of the test barrier. BSI also demonstrated that a vehicle access 9 ft (2.8 m) can be made by one person in 3 min (5).

CONCLUSIONS

Based on the results of impact tests on this movable concrete barrier, the following conclusions can be drawn: Small cars can be smoothly redirected by a MCB with satisfactory occupant risk factors. The MCB is strong enough to fully contain a 4,500-lb (2040-kg) vehicle, striking at 60 mph (26 m/sec) and 25 degrees with no structural failure and little debris generation. The vehicle exit angle tends to be slightly more than 60 percent of the impact angle. The flanged top that is

TABLE 1 LATERAL DISPLACEMENT OF BARRIER

TEST #	Vehicle Inertial Mass lbs (kg)	Impact Speed, mph (m/s)	Impact Angle, degrees	Impact Severity ft-kips (kJ)	Max. Permanent Lat. Displacement D, ft. (m)
443	4370 (1982)	59.3 (26.5)	24	85.0 (115)	3.74(1.14)
444	2000 (907)	57.7 (25.8)	15 1/2	15.9 (21.5)	1.78(0.54)
445	4300 (1950)	59.4 (26.6)	16	38.4 (50.8)	2.85(0.87)
446	1895 (857)	58.6 (26.2)	20 1/2	26.7 (36.1)	2.24(0.68)

TABLE 2 EQUATIONS TO PREDICT LATERAL DISPLACEMENT

Eq. #	Equation	Coefficients A	B	C	Applicable IS Range ft-kips (kJ)	r
1	$D = A + B \ln(IS)$	-1.62	1.21	-	15–130	.993
		(-0.592)	(0.365)		(20–175)	
2	$D = A + B^{(1/IS)}\, IS^{C}$	0.961	0.0125	0.319	1–130	.985
		(0.266)	(0.00263)	(0.319)	(1–175)	

For D in meters, use the coefficients in parentheses.

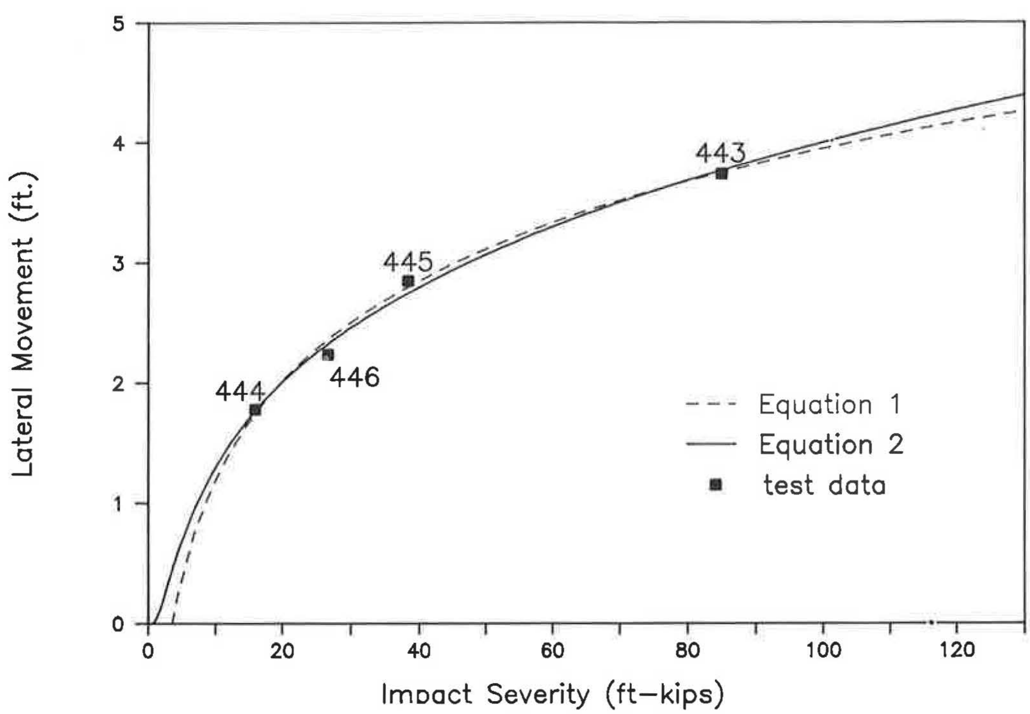


FIGURE 18 Plot of predictive equations and test data.

TABLE 3 TEST RESULTS

Test #	443	444	445	446	451(6)	431(7)	262(8)	264(8)	301(9)	321(10)
Concrete Barrier Type	MCB	MCB	MCB	MCB	New Jersey	New Jersey	Type 50	Type 50	Type 50	Type 50
Car Mass, lbs	4370	2000	4300	1895	3575	1860	4960	4860	4860	4700
(kg)	(1982)	(907)	(1950)	(857)	(1622)	(844)	(2250)	(2200)	(2200)	(2130)
Impact Angle,deg	24	15 1/2	16	20 1/2	45	52	25	25	27	26
Speed, mph	59.3	57.7	59.4	58.6	40.3	27.4	59.0	64.0	68.0	61.0
(m/s)	(26.5)	(25.8)	(26.6)	(26.2)	(18.0)	(12.2)	(26.4)	(28.6)	(30.4)	(27.3)
Roll, degrees	-10 1/2	-14 1/2	6 1/2	-15	7 1/2	71	>90	NA	27	48
Pitch, degrees	NA	10 1/4	5 3/8	12 1/2	NA	-2	NA	NA	NA	NA
Yaw, degrees	NA	NA	NA	NA	NA	-12	NA	NA	NA	NA
Maximum rise, in.	4.4	16.7	19.3	29.6	NA	NA	34	36	38	66
Max. 50 ms Average Acceleration, g										
Longitudinal[1]	8.3	-4.6	-3.3	-7.6	-11.2	-12.4	7.0	5.2	11.7	NA
Lateral[2]	-7.7	-6.7	-5.9	-11.3	-8.7	-5.5	11.6	13.0	13.8	NA
Occupant Impact Velocity Vlimit fps (m/s)										
Longitudinal[3]	27.0	15.1	14.3	16.9	28.6	32.9	NA	NA	NA	NA
	(8.2)	(4.6)	(4.4)	(5.2)	(8.7)	(10.0)				
Lateral (digital recorder)		18.0	NA	14.0	NA	NA	NA	NA	NA	NA
NA										
	(5.5)		(4.3)							
Ride down Accelerations, g										
Longitudinal	-5.6	-6	-3.9	-5	NA	-15	NA	NA	NA	NA
Lateral	7.6	-10	10.6	-13	NA	-10	NA	NA	NA	NA

1. TRC 191 recommended value: -5g (acceptable value: -10g)
2. TRC 191 recommended value: -3g (acceptable value: -5g)
3. NCHRP Report 230 1. recommended value: 30fps (9.1 m/s)

TABLE 4 IMPACT AND EXIT CONDITIONS

Test number	Impact Angle, deg.	60% of Impact Angle, deg.	Exit Angle, deg.	Impact Speed, V_I mph (m/s)	Exit Speed, V_E mph (m/s)	Speed Change, $V_I - V_E$ mph (m/s)
443	24	14 1/2	14 3/4	59.3 (26.5)	27.0 (12.1)	32.3 (14.4)
444	15 1/2	9 1/4	10 1/4	57.7 (25.8)	45.8 (20.5)	11.9 (5.3)
445	16	9 1/2	16 1/2	59.4 (26.6)	48.0 (21.5)	11.4 (5.1)
446	20 1/2	12 1/4	19 1/2	58.6 (26.2)	47.6 (21.3)	11.0 (4.9)

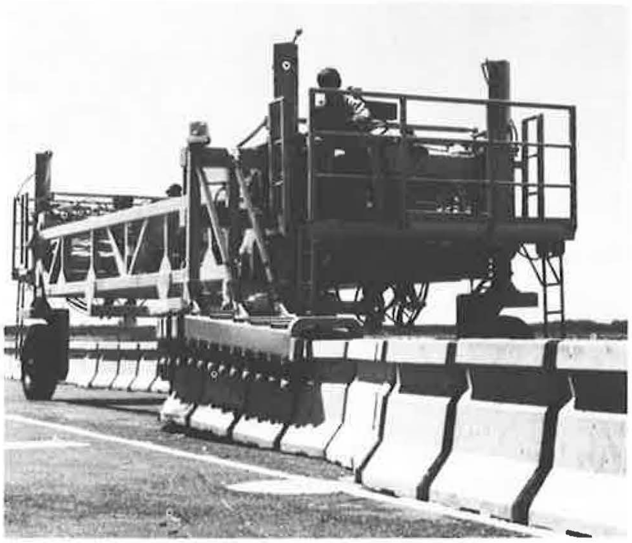


FIGURE 19 Transfer vehicle straightening deflected barrier.

FIGURE 20 Transfer vehicle carrying barrier.

FIGURE 21 Aligning barrier for connecting carried barrier and placed barrier.

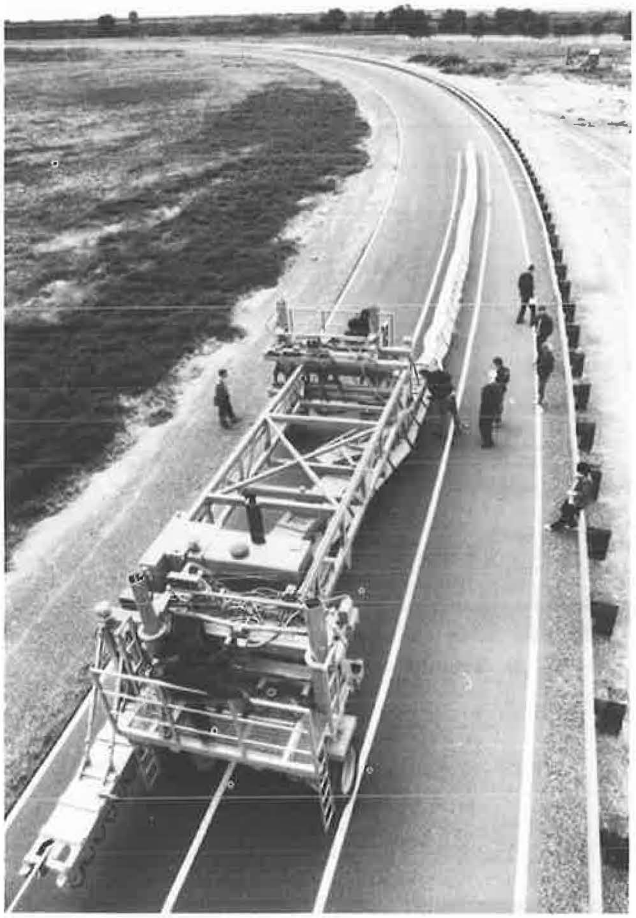


FIGURE 22 Transfer vehicle on curve with 1,400-ft radius.

used to lift the barrier appears to limit the distance a vehicle climbs the face of the barrier, thus limiting the roll angle of the vehicle. The MCB deflects laterally under impact. The lateral deflection of the MCB has a strong statistical relation to impact severity.

Based on the results of the demonstrations of moving the MCB both with a transfer vehicle and by hand, the following conclusions can be drawn: The transfer vehicle can easily and smoothly move the barrier one full lane width at speeds up to 6 mph (2.7 m/sec). Transporting, assembling, and transferring an MCB on a curve of radius 1,400 ft (427 m) with a 12 percent cross slope and transferring a barrier on a 5 percent longitudinal grade can be successfully performed by the transfer vehicle. And a barrier deflected as much as 2.24 ft (0.7 m) can be straightened by the transfer vehicle or can be pushed back into place with a pry bar by one person.

FIGURE 23 Tensioning the tether cable.

ACKNOWLEDGMENTS

This federally funded research project was initiated by Caltrans and was a joint effort of Caltrans and BSI. BSI supplied a test barrier in place and conducted demonstrations of the transfer vehicle. Caltrans conducted the crash tests, collected and analyzed data, and wrote the final research report (*1*).

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