DYNAMIC TESTS OF METAL BEAM GUARDRAIL

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The results of four vehicle impact tests into metal beam guardrail using three types of posts and blocks are reported. The then current (1971) California standard plans for metal beam guardrail required 8 by 8-in. (203 by 203-mm) nominal douglas fir posts and blocks. We wanted to determine whether smaller sized wood posts and blocks could be used and whether steel posts and blocks could be used in place of the 8 by 8-in. (203 by 203-mm) blocks to reduce guardrail costs. We also wanted to obtain another permissible post material besides wood. It was concluded that 6 by 8-in. (152 by 203-mm) nominal douglas fir wood posts and blocks were an acceptable substitute and that wide-flange 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) steel posts and blocks could be used provided W-section backup plates were used at alternate posts where no beam splice occurred and a positive connection was used at the end-anchor cable in place of cable clips. All four tests conducted used 4,960-lb (2250-kg) passenger vehicles with nominal impact speeds and angles of 65 mph (105 km/h) and 25 deg respectively.

•IN 1964, the California Division of Highways performed a series of full-scale impact tests on the metal beam guardrail. Those tests (1) resulted in the adoption of a design that featured a 12-gauge (2.66-mm) W-section steel beam mounted on 8 by 8-in. (203 by 203-mm) douglas fir (DF) wood posts and blockout blocks that were spaced 6.25 ft (1.9 m) on center. The height at the top of the rail was 2.25 ft (0.7 m). Later tests between 1965 and 1968 on short sections of guardrail (2) established the need for a positive anchor at the ends of guardrail installations. As a result, end anchors became a part of the standard guardrail design. Operational experience has proved this barrier to be effective in California. This design was designated G4W (4).

In 1971, consideration was given to further changes in California's standard guardrail design that would decrease costs without impairing the effectiveness of the barrier. Other states were using 6 by 8-in. (152 by 203-mm) DF wood posts and wide flange (W) 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) steel posts. The Southwest Research Institute had conducted successful tests on the steel post design (3). Previously, steel posts were not economically competitive in California, but fluctuations in the price and supply of wood posts in 1972 made consideration of alternative post materials desirable.

This report describes the results of four full-scale dynamic impact tests on guardrails that incorporated either 8 by 8-in. (203 by 203-mm) or 6 by 8-in. (152 by 203-mm) wood posts and blocks or W 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) steel posts and blocks. These comparative tests were deemed necessary for three main reasons:

1. Guardrails with 6 by 8-in. (152 by 203-mm) wood posts and blocks or steel posts had never been tested under the more severe conditions considered representative of California freeways; therefore, they were used in California guardrail tests [±4,960-lb (2250-kg) vehicle, 65-mph (105-km/h) impact velocity, and 25-deg angle of impact].
2. Guardrails with the three types of posts had never been compared under identical test conditions.
3. Good accelerometer data had not been obtained in previous California guardrail tests.

Shortages of the W 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) steel post have developed since the tests were conducted. It is felt, however, that the tests still have value for comparative purposes with other guardrail designs, for verification of the integrity of steel post barriers in place on highways, and for illustration of the value of positive end anchorage connections and backup plates between posts and beams.

TEST CONDITIONS

Guardrail Design and Construction

Figure 1 shows the guardrail design details. Each 75-ft-long (22.9-m) test guardrail was built approximately 1.5 ft (0.46 m) in front of the previous guardrail tested with posts staggered midway between the post location of the previous guardrail. This procedure ensured that soil conditions would be nearly identical for all test guardrails, that posts for each guardrail would be placed in undisturbed soil, and that post resistance in the soil would not be affected by post holes from previous guardrails that were staggered out of the way.

Wood posts were installed in accordance with common practice in California. The 8 by 8-in. (203 by 203-mm) posts were driven into 9-in.-diameter (228-mm) predrilled holes. To simulate the same soil condition, the 6 by 8-in. (152 by 203-mm) wood posts were driven into 8-in.-diameter (203-mm) pilot holes. Steel W 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) posts were driven into the ground rather than into predrilled holes.

Figure 2 shows the cable-end anchor with a swaged fitting (replacing the cable clips) that was used in test 276. Note the strain gauges that were used on the anchor for test 276. The test equipment and procedure are given elsewhere (9).

Test 272

Test 272 was a control test on the metal beam guardrail using 8 by 8-in. (203 by 203-mm) wood posts and blocks (Figure 1). A 1970 Mercury sedan weighing 4,960 lb (2250 kg) impacted the barrier between posts 5 and 6 at 66 mph (106 km/h) and 26 deg. (Posts are numbered from the upstream end.)

There was little rise or roll imparted to the vehicle during impact until it was nearly parallel to the barrier. Then the vehicle rolled about 15 deg away from the barrier, and the right front end rose about 0.9 ft (0.27 m). The vehicle traveled smoothly through impact, had an exit angle of the vehicle's center of gravity (c.g.) of about 6 deg, and an exit heading angle of 0 deg so that the vehicle stayed close to the barrier and almost parallel to it. Figure 3 shows sequential photographs of the impact. The right front portion of the vehicle was so severely damaged that it could not be driven away. There was no intrusion of vehicle parts or barrier components into the passenger compartment. On impact, the dummy, restrained in the driver's position by a lap belt, was thrown sideways and downward toward the right passenger's seat. There were no apparent abrasions incurred by the dummy, and there was no damage to the interior of the vehicle caused by the dummy.

Two guardrail posts near the point of impact were destroyed, and pieces of the posts and their blocks were splintered and broken and thrown behind the barrier. Two other posts and their blocks were split. The metal beam was partially flattened and raised near the area of impact. Maximum displacement of the posts at ground level was 1 ft (0.3 m).

Test 273

Test 273 was performed on a guardrail identical to the guardrail in test 272 except that 6 by 8-in. (152 by 203-mm) wood posts and blocks were used in place of 8 by 8-in. (203 by 203-mm) wood posts and blocks. A 1970 Mercury sedan weighing 4,960 lb (2250 kg)

Figure 1. Test barrier details.

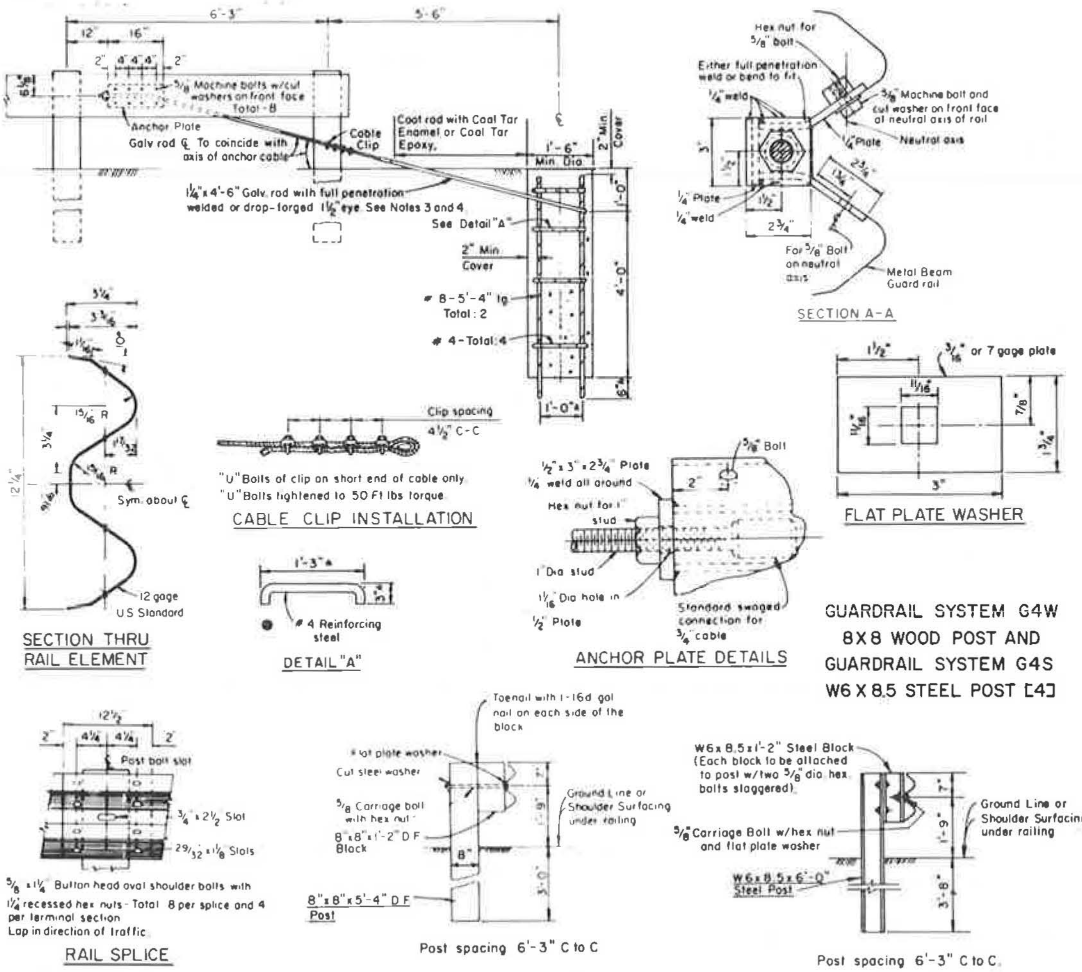


Figure 2. Cable-end anchor used on barrier for test 276.

impacted the barrier slightly downstream of post 4 at 68 mph (109 km/h) and 24 deg.

Vehicle behavior was similar to that in test 272. There was little rise or roll imparted to the vehicle during impact until it was nearly parallel to the barrier. Then the vehicle rolled about 17 deg away from the guardrail, and the right front end rose about 0.8 ft (0.24 m). The vehicle traveled smoothly through the impact. The exit angle of the vehicle's c.g. was 14 deg, which was the same as the exit heading angle of the vehicle. This angle gradually increased as the vehicle moved away from the guardrail. Figure 4 shows sequential photographs of the impact. Damage to the right front area of the vehicle was severe, and the car could not be driven away. There was no intrusion of vehicle parts or barrier components into the passenger compartment. Dummy behavior was the same as in test 272.

Two guardrail posts near the point of impact were destroyed. A third adjacent post was splintered, and one post near each end of the barrier was split. Three blocks were broken and thrown behind the barrier along with some of the splintered post debris. The beam was partially flattened and raised near the area of impact. Maximum displacement of the posts at ground level was 1.65 ft (0.5 m) perpendicular to the barrier at post 5.

Test 274

Steel W 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) posts and blocks were used in the guardrail for test 274 (Figure 1) in place of wood posts and blocks. A 1970 Mercury sedan weighing 4,960 lb (2250 kg) impacted the guardrail between posts 4 and 5 at 63 mph (101 km/h) and 24 deg.

The vehicle penetrated the guardrail with little change in direction and spun around 180 deg as it slid to a stop. Vehicle forestructure damage was severe, and the car could not be driven away. There was no intrusion of vehicle parts or guardrail components into the passenger compartment. Figure 5 shows sequential photographs of the impact.

Shearing of the W-section beam occurred at the downstream edge of post 6. The beam was detached from post 6 and bent back around post 5. Downstream, the beam segment was bent where post 7 had been attached and at the upstream edge of post 8. All 13 posts were twisted and displaced; the top of post 1 was displaced 1.5 ft (0.46 m) downstream, and the top of post 13 was displaced 1.25 ft (0.38 m) downstream. Posts 5, 6, and 7 were twisted and bent down near the ground about their minor axes with virtually no displacement of the posts in the ground. Slippage of the cable through five cable clips occurred at the upstream anchorage. These clips had been torqued to 50 ft-lbf (67.8 J) twice, including once on the day before the test. The bolt between the beam and block pulled through the beam at posts 5, 6, 7, and 8. The block at post 6 was buckled flat, and local buckling of block flanges occurred at several posts near impact.

Test 276

The guardrail for test 276 also incorporated steel W 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) posts and blocks and was the same as that for test 274 with two exceptions: (a) One-ft-long (0.3-m) steel W-section backup plates were placed behind the continuous guardrail beam at alternate steel posts where there were no beam splices, and (b) the cable clips at the cable-end anchors were replaced by a swaged fitting and clevis that connected to the standard eyerod that is embedded in the concrete footing at the ends of the barrier. A 1970 Mercury sedan weighing 4,960 lb (2250 kg) impacted the guardrail between posts 4 and 5 at 66 mph (106 km/h) and 25 deg.

Vehicle behavior was very stable during impact; there was virtually no vehicular roll or rise as redirection occurred. The exit angle of the vehicle's c.g. was about 16 deg and was the same as the exit heading angle of the vehicle. This angle decreased as the car skidded clockwise to a stop and came back toward the guardrail. Figure 6

Figure 3. Sequential views of test 272.

Impact　+0.370 Sec.　+0.538 Sec.　+1.075 Sec.

Figure 4. Sequential views of test 273.

Impact +0.032 Sec.　+0.204 Sec.　+0.418 Sec.　+0.776 Sec.

Figure 5. Sequential views of test 274.

Impact +0.052 Sec.　+0.134 Sec.　+0.296 Sec.　+0.550 Sec.

Figure 6. Sequential views of test 276.

Impact +0.025 Sec.　+0.174 Sec.　+0.273 Sec.　+0.673 Sec.

Figure 7. Barrier damage, test 276.

shows sequential photographs of the impact. Vehicle damage was similar to that in tests 272 and 273. During impact, the dummy was thrown to the right and downward into the right passenger's seat, apparently without striking the dashboard. The dummy immediately bounced back into an upright position, struck the back of its head on the left door post, and came to rest against the left door.

Guardrail damage consisted mainly of moderate twisting and bending of posts 5, 6, and 7 although none of the posts was bent to the ground. Separation of the metal beam from the steel post block occurred only at post 6. Severe buckling of the blocks occurred at posts 5, 6, and 7. A maximum $^3/_8$-in. (9.5-mm) slippage of a beam splice occurred at post 5. Barrier damage is shown in Figure 7.

TEST RESULTS

The test results were weighed against the service requirements and performance criteria for longitudinal barriers (4) as follows:

> The order of emphasis for service requirements is first to safety, second to economics, and third to aesthetics.... If the barrier system contains the moving vehicle (i.e., structural strength), the vehicle decelerations are judged to be within human tolerance levels, and the vehicle post impact trajectory is acceptable; the candidate barrier is considered acceptably safe for in-service experimental use. After the system has been carefully monitored and evaluated in service and its effectiveness has been established, the system is judged to be operational.

Dynamic Performance Criteria for Safety

Structural Integrity of Barrier

The guardrails impacted in tests 272, 273, and 276 all met the requirements of containment. There were no indications that they were on the brink of failure. The guardrail impacted in test 274 was penetrated, and this was unacceptable. An analysis of that failure is described later. Figure 7 shows close-up views of posts near the impact area for test 276. The backup plates at posts 4 and 8 clearly resisted excessive bending of the W-section beams at the posts.

Sample borings were taken of the soil at the test site. The soil consisted of a layer of stiff, overconsolidated clay in the top 1.5 ft (0.46 m) and a layer of sandy clay with gravel and clayey sand with gravel (commonly called hardpan) for 1.5 to 4.5 ft (0.46 to 1.37 m) of depth. This stiff soil probably gave the barrier added apparent stiffness and forced the wood posts near impact to shear and the steel posts to bend rather than to yield in the soil. However, the major restraining force in the barrier appears to come from the W-section beam as evidenced by test 274 during which the cable anchor slipped and the W-section tensile strength could not be developed.

Vehicle Deceleration

Guideline values for maximum vehicle decelerations (at the center of mass) are given in Table 1 (6). The limits of deceleration given are not nominal limits for no injury but rather are maximum limits beyond which disabling injury or fatality may be expected. Detailed explanation of reasons for using the 50-msec time interval is given elsewhere (7).

Table 2 indicates, in accordance with the values given in Table 1, that, for all tests, values of vehicle deceleration in the longitudinal direction were well below the 10-*g* recommended limit for lap-belted passengers and slightly over the 5-*g* recommended limit for unrestrained passengers. The values of vehicle deceleration in the lateral direction, which are more critical for impacts into guardrail, slightly exceeded the recommended limit of 5 *g* for lap-belted passengers but were well below the 15-*g* limit

Table 1. Maximum vehicle decelerations.

Barrier Performance Rating	Maximum Vehicle Decelerations[a] (g) Lateral	Longitudinal	Total
Limits for unrestrained passenger	3	5	6[b]
Limits for passenger restrained by lap belt	5	10	12
Limits for passenger restrained by lap and shoulder belts	15	25	25

[a]For vehicle rigid body; maximum 500-g/sec onset rate; highest 50 msec average.
[b]Preferred range.

Table 2. Test parameters and results.

Test Series	Test No.	Vehicle Weight (lb)	Vehicle Speed (mph)	Kinetic Energy (ft-kips)	Impact Angle (deg)	Vehicle Deceleration[a] (g) Lateral	Longitudinal	Gadd Severity Index	Maximum Permanent Guardrail Deflection[b] (ft)	Exit Angle[c] (deg)
Nordlin, Stoker, and Stoughton	272(G4W)	4,960	66	725	26	5.45	5.55	883	2.22	6
	273(G4W)[d]	4,960	68	770	24	6.95	6.75	1,130	2.33	14
	274(G4S)	4,960	63	661	24	4.75	5.80	279	Failure	–
	276(G4S)[e]	4,960	66	725	25	6.85	3.78	371	1.76	16
California Division of Highways, previous tests (1, 2)	107(G4W)	4,570	60	552	25	–	–	–	1.5	17
	108(G4W)[f]	4,570	59	534	25	–	–	–	1.5	19
	133(G4W)	4,540	56	477	30	–	–	–	2.8	7
	135(G4W)	4,540	59	534	28	–	–	–	1.6	24
Southwest Research Institute (3, 4)	101(G4W)	4,042	55.3	414	30.5	4.6	4.6	–	2.60	11.7
	103(G4W)	4,123	60.1	500	22.2	6.1	3.0	–	2.40	15.0
	119(G4S)[g]	4,169	53.4	400	30.2	4.4[h]	4.6[h]	–	2.67	19.8
	120(G4S)	3,813	56.8	413	28.4	6.6	3.9	–	2.90	8.0
	121(G4S)[i]	4,478	56.2	475	27.4	6.8[h]	3.7[h]	–	2.10	9.3
	122(G4S)[i]	4,570	62.9	607	25.3	7.8[h]	3.9[h]	–	2.90	9.0

Note: 1 lb = 0.45 kg. 1 mph = 1.6 km/h. 1 ft-lbf = 1.36 J. 1 ft = 0.3 m. G4W and G4S are defined elsewhere (4).
[a]Maximum averaged over a period of 50 msec. Values for guardrail tests 273(G4W) computed from high-speed movie film; other values computed from accelerometer data.
[b]Measured at top edge of rail.
[c]Direction that vehicle's c.g. was moving immediately following final vehicle contact with barrier.
[d]6 by 8 in. (152 by 203-mm) posts and blocks.
[e]Modified with backplates and clevis in anchorage.
[f]2 ft (0.6 m) beam height.
[g]No blockout.
[h]Peak decelerations.
[i]Double blockout.

Table 3. Vehicle rise and roll.

Test No.	Rise[a] (ft)	Roll[b] (deg) Front of Vehicle	Rear of Vehicle
272	0.9	15	12
273	0.8	17	–
276	–	0	-1

Note: 1 ft = 0.3 m.
[a]Measured at target on right front fender.
[b]Measured at top of front and rear windshields in degrees away from a horizontal plane.

for passengers wearing shoulder and lap belts.

Table 2 also gives the results of other test series involving similar vehicle weights, impact speeds, and angles of impact (4). The number of tests for which 50-msec values of deceleration have been reported in the literature are rather limited. Southwest Research Institute recently reported results of tests on guardrail and median barrier terminals. Eight side-angle tests into these barriers have yielded 50-msec values of longitudinal deceleration ranging from 4.6 to 8.5 g and values of lateral deceleration ranging from 2.5 to 7.6 g, given test parameters similar to those in Table 2.

Values of the Gadd severity index (similar to the head-injury criterion now more commonly used) were computed and are also given in Table 2. In test 273 only, the index slightly exceeded the threshold value of 1,000, above which serious injury or death might be expected because of a concussion. This value is not reliable as a sole indicator of the chance of passenger injuries because of the large number of variables related to the dummy and the vehicle interior.

Notwithstanding these limitations, it can be surmised that in these severe proof tests of the guardrails vehicle passengers had a fair chance of survival. Hence, in the large majority of actual highway accidents involving these guardrail systems, it can be predicted that passengers would sustain something less than serious injuries. The degree of injury would, of course, depend greatly on the type of passenger restraints.

Vehicle Post-Impact Trajectory

Barrier Deflection

The deflection of the rail in test 276 is less than that in tests 272 and 273. This may account for the relatively low longitudinal vehicle deceleration measured in this test. Table 2 indicates that the permanent barrier rail deflections recorded in this series were in the same range as those recorded for previous test series. It should be noted that the vehicle kinetic energy at impact for tests 272, 273, and 276 was appreciably higher than that for other tests shown in Table 2. Barrier damage in tests 272 and 273 was similar, and this indicates that the anchored metal beam, rather than the wood posts, was the critical restraining element.

Vehicle Crush

In a comparison of tests 272, 273, and 276, the damage to the right front portion of the vehicle was quite severe, was roughly similar for all tests, and was typical of that for other high-speed, oblique-angle guardrail crash tests. The right front wheel was disabled in all three tests.

Vehicle Rise and Roll

Analysis of the high-speed movie film produced the values of vehicle rise and roll given in Table 3. These values and the movie film demonstrate the stable condition of the test vehicles as they progressed through impact. The most stable condition occurred with the steel post guardrail.

Final Vehicle Position

Figure 8 shows the paths of the test vehicle after it impacted the test guardrails. There is no easy answer to explain the variance in post-impact trajectories. Various factors having an effect may include guardrail deflection, vehicle crush and damage to the wheel, time when brakes are actuated by remote control, amount of rise and roll, and paving surface conditions.

Barrier Debris

The steel post guardrail appears to have an advantage over wood post guardrail in that no barrier parts were dislodged in test 276. In tests 272 and 273, pieces of wood posts and blocks were thrown behind the barrier. Therefore, when guardrail is placed in narrow median or gore areas it may be preferable, from the debris standpoint, to use the steel post type of guardrail.

Cost

In the past, only wood posts were approved for use in guardrails in California. The use of steel posts had not been seriously considered because they were not cost competitive and the wood post type of guardrail had proved fully effective in full-scale tests and in operation. However, about the time this latest test series was conducted, the cost of wood posts and blocks was rising rapidly, and there was an apparent shortage. These rapid changes in supply and cost made it desirable to investigate the alternative use of steel posts in guardrails. The steel post guardrail used in test 276 was as effective as the wood post guardrail.

It does not appear that there would be any difference in maintenance and repair labor costs for the guardrail types tested in tests 272, 273, and 276. Cost and availability of replacement components are difficult to predict because of the current shortages of highway construction materials; this situation may continue into the future.

Aesthetics

Guardrails with 6 by 8-in. (152 by 203-mm) wood posts and blocks and W 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) steel posts and blocks do not appear to offer any substantial improvement or downgrading of the appearance of guardrails using 8 by 8-in. (203 by 203-mm) wood posts and blocks. The steel post guardrail is slightly more streamlined and has uniformity of materials (all steel); the wood post guardrail may have a blockier, more substantial appearance, and perhaps a more rustic appearance that may be desirable in rural areas or other selected locations. However, bare steel posts made of any of the weathering steels could also be used to provide a rustic appearance.

Analysis of Test 274

The guardrail used in test 274 incorporated W 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) steel posts and blocks. Penetration of the rail resulted when the vehicle impacted the barrier. The failure that led to the successfully revised barrier design used in test 276 is as follows:

1. The steel posts have about 90 times less torsional rigidity than wood posts, hence they absorbed little of the tensile load developed in the beam. Instead, they twisted and transmitted a large load almost instantly to the cable-end anchors.
2. Because of this large dynamic load (jerk), the cable slipped through the five cable clips at the upstream anchor.
3. Slipping of the cable relaxed the tension in the steel W-section beam and permitted severe pocketing, cold-working, and weakening of the metal beam.

To correct this condition, two changes were made to the barrier design for test 276: (a) A swaged fitting and clevis were used to replace the five cable clips on the cable-end anchorage to provide a positive anchorage and (b) twelve 1-ft-long (0.3-m) backup sections of W-section beam were placed behind the beam at alternate posts where beam splices did not occur. These backup sections reduced the tendency of the rail to hinge or tear along the hard sharp edge of the steel blocks and posts. The results of test 276 proved the effectiveness of these modifications.

Figure 9 shows the loads on the anchorage cables during impact and indicates more rapid load initiation times for tests 274 and 276 for which steel posts were used. Figure 9 also shows that the cables are not overdesigned.

The Southwest Research Institute also has conducted several successful tests on guardrail systems with W 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) steel posts and blocks. Results of test 141 at the Southwest Research Institute seem to confirm the effectiveness of backup plates on a steel post guardrail system (8).

Figure 8. Vehicle trajectories.

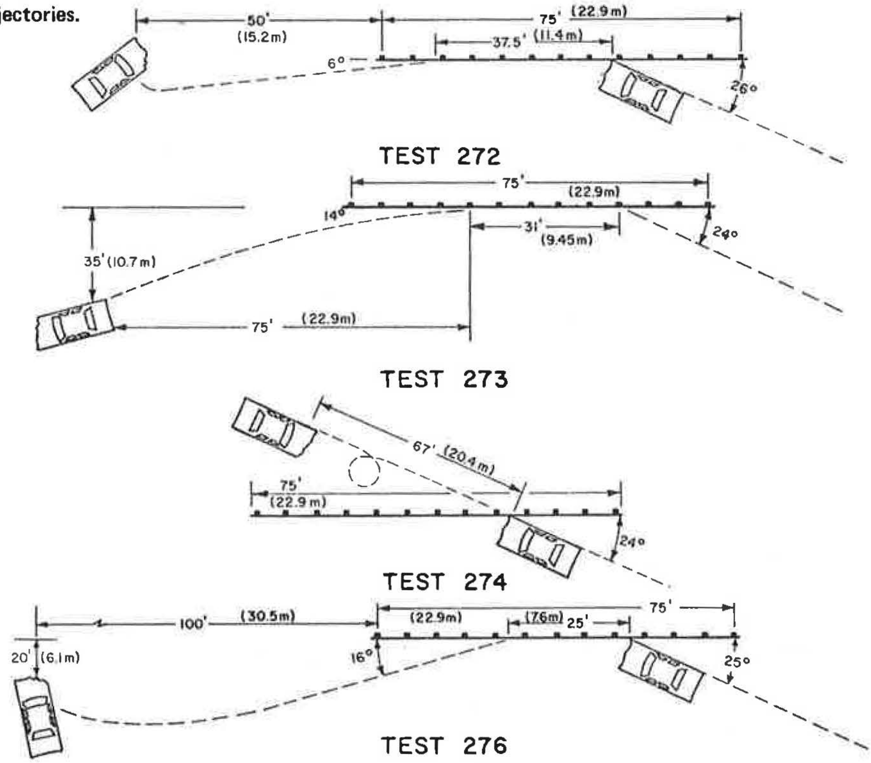
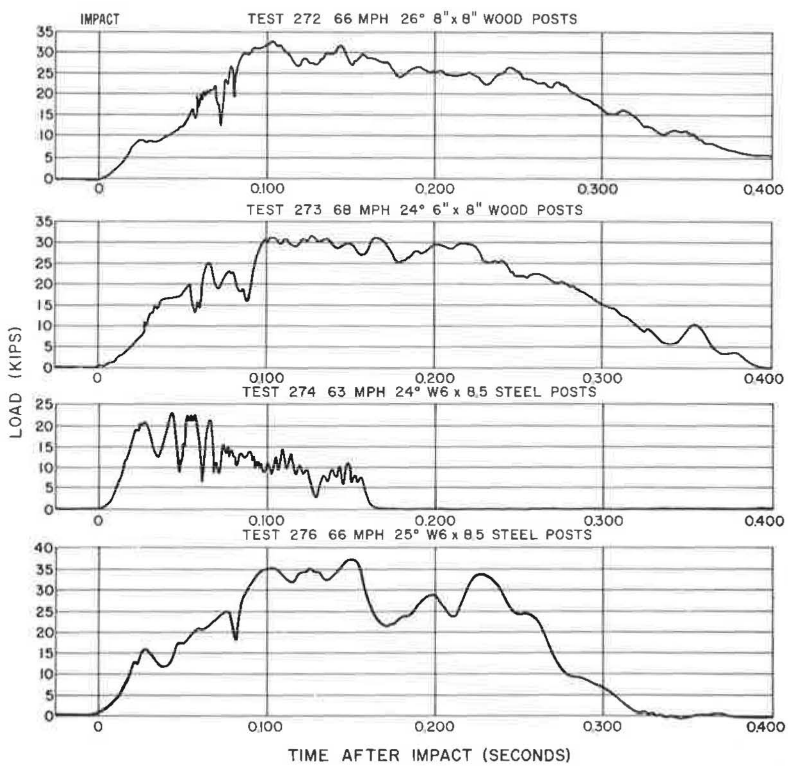


Figure 9. Upstream anchorage.



CONCLUSIONS

1. Metal beam guardrail using 6 by 8-in. (152 by 203-mm) DF wood posts and blocks effectively redirected a 4,960-lb (2250-kg) vehicle impacting the barrier at 68 mph (109 km/h) and 24 deg.
2. Metal beam guardrail using W 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) steel posts and blocks effectively redirected a 4,960-lb (2250-kg) vehicle impacting the barrier at 66 mph (106 km/h) and 25 deg. However, the following two modifications of the standard wood post design were necessary: (a) a 1-ft-long (0.3-m), 12 gauge (2.66-mm) W-section backup plate was placed between the beam and block at alternate posts where beam splices did not occur, and (b) the cable clips at the standard end-anchor connection were replaced with a swaged fitting and clevis, and this resulted in a positive cable connection.
3. Guardrails using either 6 by 8-in. (152 by 203-mm) wood posts and blocks or W 6-in. by 8.5-lb/ft (152-mm by 12.7-kg/m) steel posts and blocks (as modified in test 276) were as effective as the guardrails using 8 by 8-in. (203 by 203-mm) DF wood posts and blocks, which were also tested using a 4,960-lb (2250-kg) vehicle impacting the barrier at 66 mph (106 km/h) and 26 deg.

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