Full Scale Tests of Concrete Bridge Rails Subjected to Automobile Impacts

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During the first half of 1955 the California Division of Highways conducted a series of full scale tests of concrete bridge barrier rails, a barrier rail and curb combination, and barrier curbs without rails. This is the second report completed concerning a series of tests of highway barriers which have been underway in California since 1953. The balance of the tests have concerned barrier curbs only. This report, supplemented by a motion picture record, covers the tests of the bridge rails, and the rail and curb combination. It was conducted by the Materials and Research Department at the request of the Bridge Department and Design Department of the California Division of Highways.

The object of this study was to investigate the performance of concrete bridge rails and barrier curbs when struck by cars traveling at high speeds. This report covers one phase of a three-part study of highway barriers and deals only with the performance of four trial designs of bridge rails and one trial design of a rail and curb combination. Other parts of the study deal with curbs only. The rail and curb combination is one which has been used on the San Francisco Division Street Interchange and several other structures in California. Of the bridge rail trial designs only one, Trial Design 2, has been actually constructed in California. A similar rail is in place on the Santa Maria River Bridge on California Route 1.

During 1953 the first phase of this study was made, involving full scale tests to determine the relative abilities of several trial designs of curbing to serve as physical barriers or deflectors to cars striking the curb. In this first series of tests the collision car was driven by a test driver at relatively low speeds; the maximum speed attained was 45 mph. The most recent series of tests include bridge railing and also a further test on curbing where the test cars were operated by remote radio control, and speeds between 50 and 60 mph. at time of collision were developed. Two of the collisions involved in this bridge rail study, which were made at oblique angles, were performed in cooperation with the Institute of Transportation and Traffic Engineering at the University of California at Los Angeles. The motion pictures of these two tests show two anthropometric dummies sitting in the front seats of the cars. The phase of the study involving effects on passengers represented by these dummies will be covered by the Institute of Transportation and Traffic Engineering, and no further reference will be included in this report.

Complete analyses and conclusions from the over-all investigation of bridge railings and barrier curbs will be made at a later date when an analysis and a correlation of the results from all three phases of this program are completed.

Many highway designers have raised the question as to the application of these test results to the steel guardrail which is used along the edge of many of our highways and in some cases is now being used as a barrier in median strips. It is not assumed that these data collected from tests of relatively rigid barriers are applicable to such steel guardrails.

● THE effectiveness of bridge railings to resist high speed impacts is increasingly important. This is due to the widespread need and use of bridge structures in the design of modern freeway facilities and the continued and unprecedented increase in volume of high speed traffic using such facilities. In many locations where a barrier railing is needed, such as in a traffic interchange structure, it is also necessary that as little obstruction as possible be placed in the driver's line of sight. The object of the test program reported by this paper is to provide certain facts concerning the dynamics involved in the design of "rigid" concrete barrier bridge railing and curbs so that such designs can more nearly serve the needs of present day traffic. It was considered especially necessary to obtain facts concerning the effect of curbs when combined with barrier rails and also to determine the minimum height at which a rigid rail would be effective as a barrier.

Figure 1. Test collision shortly after initial contact. Note recording movie camera in foreground.

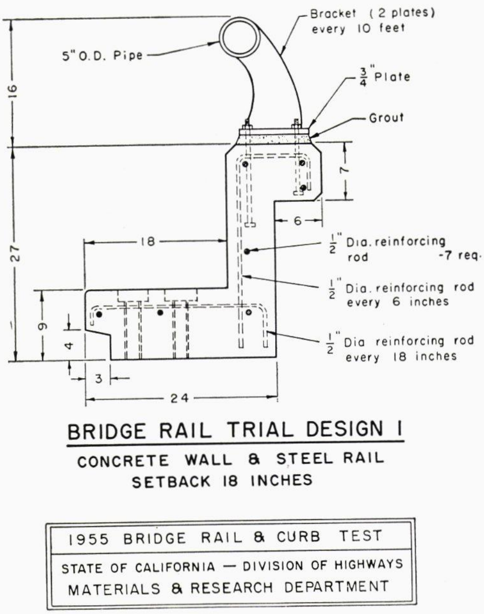

Figure 2.

This paper covers only one part of a three-part study which has been conducted by the California Division of Highways on the dynamics of highway bridge barriers. The first phase was completed in 1953, and involved the full scale testing of several designs of barrier curbing. In this first series of tests, the collision car was driven by a test driver at speeds up to 45 mph. at relatively low angles of collision. The object of this first series was to select the most effective of 11 types of curbing as a barrier and also to provide preliminary information so that refinement could be made in future tests.

Additional tests were needed to make specific recommendations for the design of more efficient barrier curbs. These additional studies were undertaken during the early part of 1955 and covered various shapes and heights of highway bridge barrier curbing constructed of concrete or steel and combinations of these two materials. This portion of the study has not yet been reported.

At the same time a study was made involving the testing of the five bridge rails (Figures 2 and 3) the results of which are covered by this paper. Of the five tests covered in this report, two were conducted in cooperation with the Institute of Transportation and Traffic Engineering of the University of California. The primary objective of the Division of Highways is to cover the effectiveness of these trial bridge railing designs in their action as barriers to automobile impacts. The effect of the collisions on the vehicles and the probable effect on the occupants of such vehicles as measured by the effects on anthropometric dummies will be reported separately by the University of California Institute of Transportation and Traffic Engineering. The five trial designs of bridge railings which were tested during this study were developed by the Bridge Department and Headquarters Design

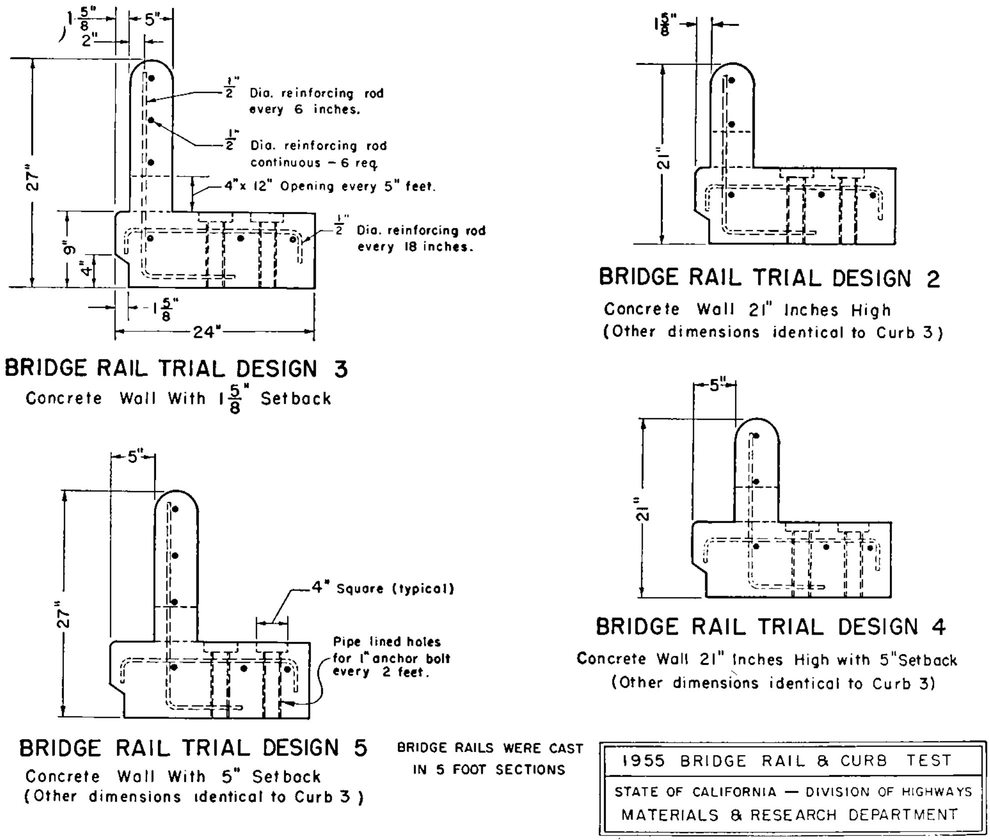

Figure 3.

Department of the California Division of Highways and recommended by the two departments for test. The tests were conducted by the Materials and Research Department. The collision cars used in this 1955 series of tests were driven by remote radio control. This was to avoid hazard to a test driver due to the heavy impact expected. The requirements of the test program were for speeds up to 60 mph. and for collision angles up to 30 degrees with the rail.

It is realized that five tests may be considered a small sampling on which to base decisions concerning the design of bridge railings. However, the selection of the number of tests and the procedures followed for each test were influenced by a background of 200 similar test collisions performed on barrier curbing, which assisted immeasurably in obtaining the maximum benefit from this phase of the study.

EXPERIMENTAL DETAIL

Test Units

Figures 2 and 3 show the cross-sectional details of the five trial designs of highway bridge rail units submitted for tests. The rails were designed by the California Bridge Department to conform to AASHO standard loadings.

Each trial design was prepared for a specific purpose. The purpose of Design 1 (Figure 2) was to check the dynamic performance of a barrier unit widely used by California Division of Highways especially in viaduct construction. The roadway curb had already been tested (*1*) and found efficient within the effective range of a 9-inch high curbing. It was therefore only necessary to study the over-all action of this rail and curb combination when subject to a high speed and angle collision.

The purposes of the four designs shown in

Figure 3 were to determine the minimum height at which a rail would be effective as a barrier and to determine the maximum distance a "top" rail could be set back from a "rubbing" curb without the curb acting as a dynamic lifting ramp.

Thirty feet of bridge railing were used in each test. This was rather a small target when viewed at an oblique angle by the driver located in the remote control car; nevertheless, it proved to be sufficient in all cases. This was due to the remarkable functioning of the remote control equipment and to the high degree of skill attained by the two operators of the control equipment.

The test rails were prefabricated to exact dimensions in 5-foot sections. Twenty-eight-day test cylinders indicated the concrete to vary in strength from 4700 to 5800 psi. for all test units. Intermediate grade reinforcing steel was used throughout.

During the test collision period the precast railing units were bolted securely to an anchor block. The anchor block was a continuous section of concrete 18 inches deep, 36 inches wide, and 30 feet long. Each railing unit was bolted to this anchor block by six 1-inch bolts spaced in pairs at two foot centers as indicated in Figures 2 and 3.

Test Site Layout

The layout of the test site and the position of various pieces of equipment used during the test are shown on Figure 4, titled, "Plan View of Test Site." The westerly runway of the Sacramento County Airport, located about 25 miles south of Sacramento, California, was used as a site for this experiment. The test was prepared by positioning the trial railings along the easterly edge of one of the airport runways about midway. This supplied about 1500 feet of runway approaching the rail from either direction. The remote control operator guided the crash car on its correct angle of collision by following a strip of white tape supplemented by a length of white sash cord fastened to the runway at the appropriate angle. A 15-foot by 90-foot grid of 5-foot squares was painted on the runway in front of and symmetrically about the test unit. This was to serve as a coordinate grid to observe the position of the car during the frame-by-frame analysis of the motion pictures of each

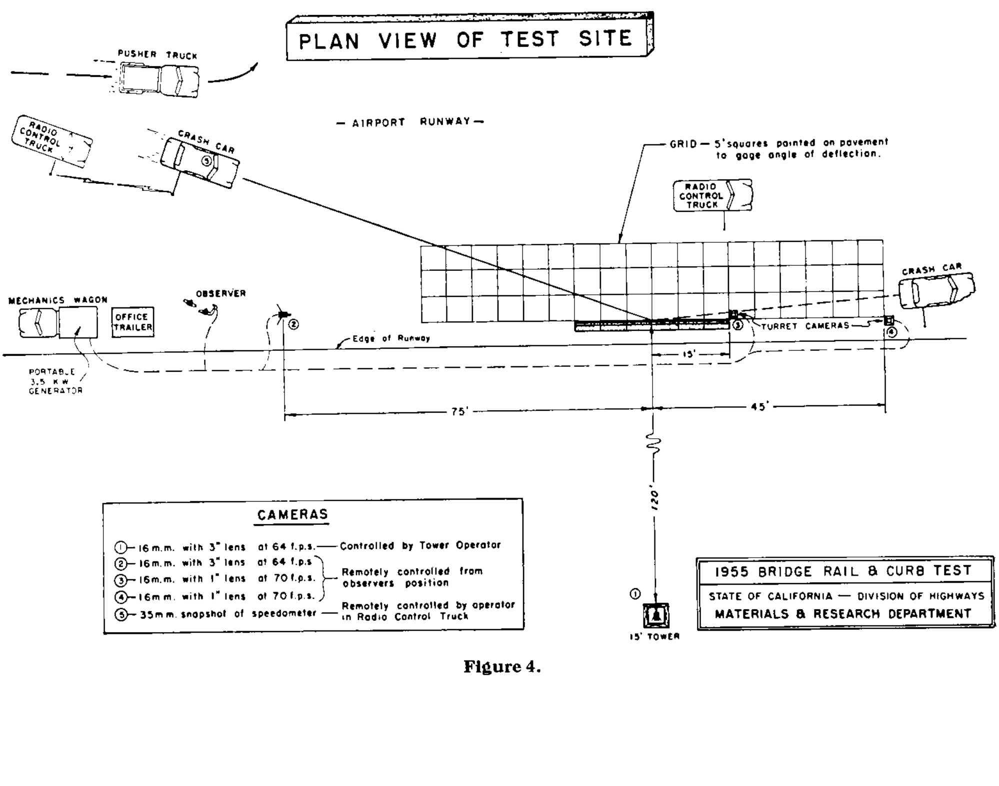

Figure 4.

test. Recording cameras and observers were strategically placed so as to picture all effects and motions pertinent to the program. The positioning of the cameras is shown on Figure 4.

TEST AUTOMOBILES

The following five automobiles were used as test cars: one 1949 Ford 4-door sedan, three 1949 Ford 2-door sedans, and one 1946 Buick 4-door sedan. The Fords were equipped with 6.00 by 16 tires, and the Buick with 7.60 by 15 tires.

Each of the cars was a standard stock model slightly modified in the following manner (most of the modifications were made so as to provide remote control):

1. An electric remote steering motor equipped with a gear box, shaft and pulley, was mounted to the frame in the front compartment as shown in Figure 5. Steering was accomplished through a V-belt drive to a larger pulley mounted directly on the steering shaft. The tension of the V belt was adjusted just to the point where the car could be controlled, but the belt still could slip and allow the steering wheel to be turned easily by hand. This adjustment was necessary so that on collision the wheel would jerk away from control as nearly as possible in the same manner as it might from a human driver.

2. The brakes were modified by disconnecting the front set and using only the rear wheel brakes. They were operated by remote control through a vacuum booster with the control valve connected to a rotary actuator.

3. The acceleration of the car was controlled remotely through a rotary actuator linked to the throttle. The top speed of the test car was preset and could be held within a one mile per hour tolerance by a flyball governor.

4. In order to provide power and action for the remote control devices in the automobile, the rear seat was removed and six storage batteries and appropriate electronic equipment were shock-mounted in the rear seat and trunk compartments of the car. Batteries were mounted in a row directly behind the front seat, and the electronic equipment was mounted in the trunk compartment. This positioning is shown by Figure 6.

5. Due to the fact that these cars were also used during the barrier curb testing portion of this investigation, miscellaneous minor structural alterations were made so as to minimize repairs during this portion of the program. These consisted of stiffening the front frame members by welding on additional ¼-inch side plates to the front 2 feet of the frame and also welding a 2- by 2-inch structural steel angle across the frame directly under the front seat. This latter was used primarily to protect the undercarriage from damage when the car slid over the curbs. In addition the engine was snubbed tightly to the frame with a cable so as to keep the clutch from disengaging when the car struck the curbs. A comparison of actions with and without this additional bracing during the barrier curb tests indicated that no appreciable external change in action occurred.

6. In order to attain the high speeds necessary for this test in the relatively short space

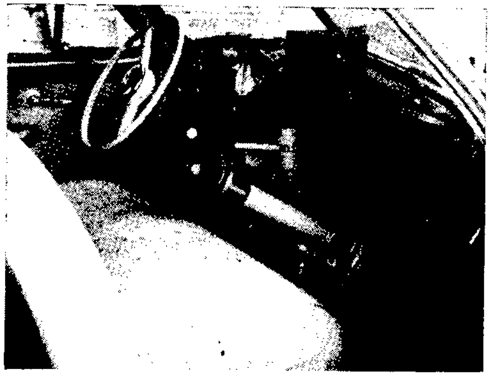

Figure 5. Driving compartment of crash car showing remote control apparatus

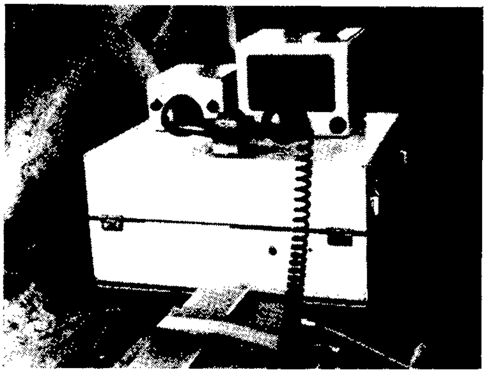

Figure 6. Remote control electronic equipment mounted in rear trunk of crash car.

of 1500 feet, the motor of each car was "souped up" as much as possible without adding any special equipment. This generally consisted of a complete tuneup and removal of muffler, air filter and fan.

7. In addition to the above modifications, the two cars used during the cooperative test program with the ITTE were further altered by removing the windshield glass and the door on the rider's side of the front compartment. These changes were made so that high speed motion pictures could be taken of the movements of the dummies during the collision period.

REMOTE CONTROL CAR

The radio control equipment was mounted in a Chevrolet Suburban. It consisted of a radio transmitter, tone oscillators, and a remote control panel (shown in Figure 7). Power was supplied through a gasoline-driven electric generator mounted in the rear of the Suburban. The remote control operator sat in the rider's seat of this control car and guided the test automobile from a position to the left and rear of the test car. This position was maintained by the driver of the remote control automobile. Remote operation was not used to start the crash car nor to engage the gears; therefore, a pusher truck was used to initiate the action. As soon as the car was underway, the remote driver took over operation and guided the car into its collision.

RADIO CONTROL

During 1952 this department performed a preliminary series of crash tests on barrier curbs (*1*). In this series of tests the crash cars were manned by an experienced test driver. To protect the driver these tests were limited to a top speed of 45 mph.

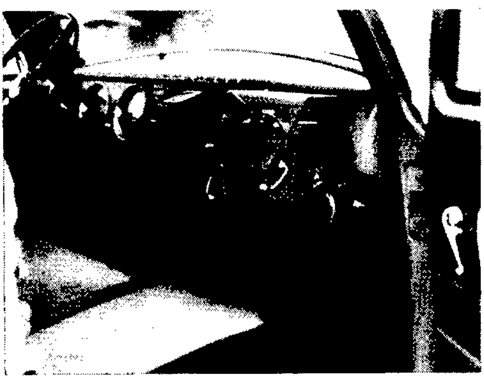

Figure 7. Remote control panel in remote control car.

For the present study, higher speeds were necessary in order to obtain the desired information and also to more closely simulate the actual highway conditions. For reasons of safety it was therefore necessary to eliminate the human driver and substitute some form of remote control. Several methods of remote control were considered. Essentially, however, they reduced to two methods: (1) an electrical connection, either by cable, fixed track or flexible trolley between the crash car and the control car or (2) radio remote control. All of the electrical connection methods posed certain practical limitations so it was decided to use radio control. This posed many difficult technical problems but solved the more complex operational problems. While the radio control of model boats or airplanes is rather commonplace, it was soon discovered that to control a series of stock cars with enough precision to reach and hold a predetermined speed on a straight course and strike a narrow target is something quite different. This equipment was completely developed and constructed by the Division of Highways Laboratory through the use of commercial component parts. The operational plan indicated that eight basic separate control functions were necessary. These were (1) ignition on; (2) ignition off; (3) accelerator on; (4) accelerator off; (5) brake on; (6) brake off; (7) steer right; and (8) steer left.

In order to conform with the Federal Communications Commission regulations, only one radio carrier frequency could be used; therefore, it was decided to use tone signals for controlling each action. A set of reed oscillator controls with a matching set of resonant reed relays was obtained to fulfill this requirement. These reeds operate in a manner similar to electrically driven tuning forks and are inherently more selective than tuned inductors. A paramount operation requirement was that the relays should never interact with one another. To do this it was necessary to alter the oscillators and reeds by retuning them to musical chord intervals.

The basic units of the over-all control system are shown by the block diagrams, Figures 8 and 9.

In addition to the electrical and mechanical

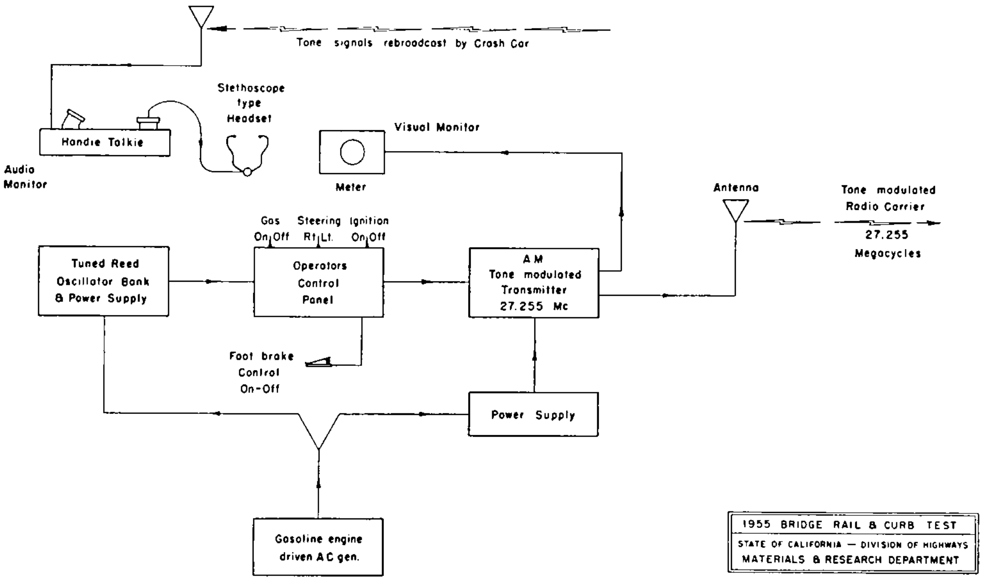

Figure 8. Remote control car radio control equipment.

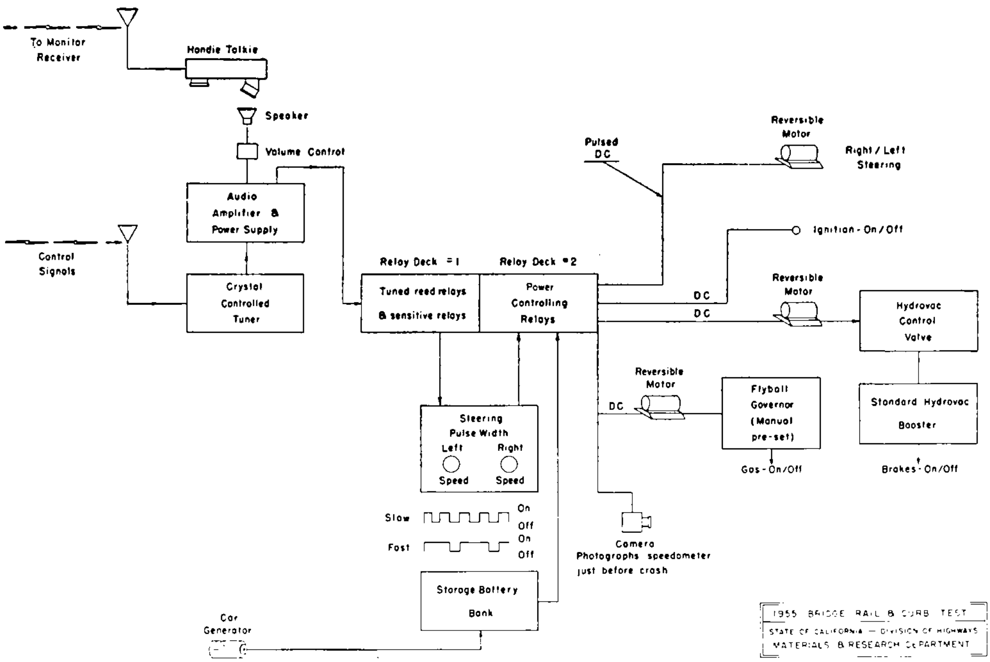

Figure 9. Crash car radio control equipment.

problems involved in the remote control of the crash car, it was necessary to solve the training problems involved in teaching a driver to operate an automobile from a remote position. There were two parts of this problem that were the most difficult to overcome. The first was learning that, because of the remote steering control mechanism, the car had lost the ability to come out of a turn by itself. Therefore, if it were turned in one direction, it was necessary that a counter-correction be made in the opposite direction to hold a straight course. The other problem resulted from the operator's having a feeling of motion from a car he was not operating rather than the car he was trying to operate. It was therefore necessary to create a closer contact between the operator and the crash car. This was done by mounting a very short range handi-talkie radio in the crash car and rebroadcasting the sounds within the collision automobile back to the operator. In this manner, he could hear what was going on and soon developed a new sensing technique. Two operators were used and each became exceptionally proficient.

All of the radio equipment was shock-mounted. This shock mounting was so efficient that the only difficulty encountered with the equipment during an entire series of 56 collisions (51 on barrier curbs) was one broken radio tube.

INSTRUMENTATION

Photographic and mechanical systems of instrumentation were used to record all actions and reactions during the high-speed collisions involved in this test program. Moving picture cameras were placed as shown and identified in Figure 4. Camera No. 1 was a 16-mm. moving picture camera with a 3-inch lens operating at slow motion speed of 64 frames per second. It was placed 120 feet in back of and normal to the test railing. A cameraman panned this camera from a 15-foot-high tower and picked up the crash car at a point about 100 feet before collision and followed the car on through to its final resting point. The purpose of this camera was to record the side view over-all action of the test car and also to show its exact position both approaching and leaving the collision point by reference to the coordinate grid painted on the pavement in front of the test railing.

Camera No. 2 was a 16-mm. moving picture camera, with a 3-inch lens, operating at a slow motion speed of 64 frames per second. This camera was operated from a fixed position about 3 feet above the pavement and 85 feet in back of the point of collision. Its picture angle was parallel to the test railing. The purpose of this camera was to record the various contacts of the crash car from a position in back of the car. Cameras No. 3 and 4 were 16-mm. moving picture cameras equipped with 1-inch lenses and operated at about 70 frames per second. These cameras were placed in the position shown on the site plan, (Figure 4), and were contained in welded steel turrets for protective purposes. They were both operated by remote control. Camera No. 3 was placed in a position flush with the ground and directly in front of the point of collision. Camera No. 4 was set at a point about 2 feet above the surface of the ground and pointed parallel to the test unit and directly into the point of collision. Its purpose was to complement Camera No. 2 by recording the front view of the over-all collision contacts. Camera No. 5 was a 35-mm. still camera placed inside the crash car and focused on a speedometer. This camera was operated by remote control from the radio control truck, and its purpose was to record the speed at the time of collision. So that there would be no disturbance to the speedometer by the collision, and also so that the changes due to acceleration could be minimized, this picture was actually taken at the last possible moment before contact. Additional cameras were used from time to time to record various physical facts during the post-collision surveys.

A special survey speedometer was installed in the car and calibrated. It was found to be accurate to ± 1 mile per hour in the range of speeds used for this test program. The outward sides of the tires on the collision side of the car were painted with cold water paint, the front tires red and the rear tires green. This paint readily rubbed off onto the railing showing the tire contact during the time of collision.

The above instrumentation was modified from time to time but as given is about the average used during the five tests. For the two tests made in cooperation with the ITTE, additional instrumentation was used. This consisted of two high-speed cameras, targets on the crash car, decelerometers mounted on the crash car to record both lateral and longitudinal deceleration during the crash period, and two completely instrumented anthropometric dummies.

TEST PROCEDURE

The same procedure was used for all five tests with the exception of the two that were performed in cooperation with the University of California Institute of Transportation and Traffic Engineering. In these two tests the same procedure was followed insofar as the objectives of the Division of Highways were concerned; the only modifications made were involved in preparing the crash car to accommodate and place the test dummies and to provide barrier protection for a high-speed camera that was located about 75 feet in front of the point of collision, in line with the probable path the crash car would take after collision. This modified procedure will not be covered in detail in this report.

Immediately before each test crash, the grid area in front of the test rail was cleaned of all debris, and the angle of approach of the crash car was delineated by fastening to the airport runway, from the proposed point of collision to the starting point of the crash car, a marker which consisted of white webbed belting for the first 160 feet from the rail with about 1100 feet of white sash cord from the end of the belting to the crash car. The settings and operation of each camera were then checked, and each camera was titled by identifying the proposed test. This being done, the test supervisor, observer, remote control camera operator, and the operator of the No. 1 camera located in the tower took their positions.

Meanwhile the crash car was being readied for the test by the operations crew. The first step was to adjust the governor to the desired test speed by a series of trials during which the operation of the car was also checked. The crash car then was manually driven into starting position and aimed along the approach line by the operator of the remote control equipment. He would then change over the operation of the car from manual to radio control by activating all of the electronic equipment. By cooperating with the driver of the radio control truck, each unit was checked for remote operation. Lastly, the shutter of the speedometer camera was cocked, and the crash car placed in high gear.

The remote control operator then took his position in the radio control truck, and the pusher truck was driven into position behind the crash car. When this preliminary work was completed, the remote control operator signalled the test supervisor that the car was ready. The test supervisor made a last minute check to see that the observers, cameras and operators were in appropriate position, and then signalled for the test to start. The cameras were started when the crash car reached a point 100 feet in advance of collision and were continued in operation until the crash car came to rest.

All physical data was recorded immediately after the collision. This consisted of damage to the test rail, damage to the test car, and measurements of contact prints of the front and rear wheels with the test railings, and a recording of the exit track or path taken by the crash car from the test unit after collision.

DISCUSSION OF RESULTS

The results peculiar to each individual test are discussed below. The damage to the car, however, is not repeated for each test as it was similar in every case. In general it consisted of:

1. Contact wheel crushed back into the frame from 1 to 2 feet out of position.
2. "A" frames damaged beyond repair.
3. Contact side of frame bent out of line 6 to 18 inches, opposite side bent 2 to 6 inches.
4. Engine shifted sideways and back away from contact side 4 to 12 inches.
5. Drive shaft misaligned.
6. Tie rod assembly distorted beyond repair.
7. Front fender, headlight, bumper, and hood on contact side crumpled beyond repair. Entire side of car on contact side creased and scratched.
8. Body frame sprung so that doors no longer worked properly.

Bridge Barrier Railing Trial Design No. 1

The details of this rail and curb design are shown in Figure 2. A schematic diagram showing the general results of the test of this trial design is shown in Figure 10.

Essentially this curb and rail combination consists of a 9-inch high undercut curb, the purpose of which is to serve as a barrier to low-speed, low-angle collision contacts. It has been shown by previous tests (*1*) to be the most efficient of 11 other designs of curbing as a barrier at relatively low speeds and flat angles of contact. Eighteen inches in back of this curb is placed a concrete wall surmounted by a steel pipe rail, together forming a barrier railing. It was the purpose of this test to observe the over-all dynamic phenomena resulting from a high-speed oblique collision.

The crash vehicle used in this test was a

1946 Buick sedan which approached the test unit at an angle of 20 degrees and at a speed just prior to collision of 50 mph. Physical measurements of the red and green marks left from the contacts of the wheels with the test unit showed that the car mounted the 9-inch-high curb with little or no sliding along the curb and then collided with and slid along the rail for 10 feet, then deflected off the rail and left the rail at about a 2-degree exit angle. The car came to rest at a point about 150 feet from the point of collision, at which spot it collided with a camera barricade. Had it not been for this barricade, it is probable that the car would have traveled on for at least another 100 feet, swinging slowly in the direction of the damaged front wheel. The only damage to this railing and curb combination was to the 5-foot section which bore the brunt of the collision. The concrete wall was pushed back out of plumb ½ inch and diagonal cracking occurred in the concrete running from the base of the concrete rail to the back heel of the curb block. This is shown in the "After" view titled "Damage to Bridge Rail" in Figure 10.

Of importance in any discussion of this railing and curb combination is a discussion of the motion picture analysis of another test of a car going over a similar curb without the railing. It was interesting that at about the same speed and angle of collision as used in this test the front contact wheel of the car appeared to collapse completely and the elevation of the car body remained unchanged until the car was about 2 feet (oblique distance) past the point of collision. Then the supposedly collapsed wheel regained its approximate original shape and position during which process the car sprang rapidly upward about 2 feet as it continued on in a forward direction.

As expected, analysis of the motion picture film for this rail test showed there was little immediate upward movement of the front of the car as it passed over the curb. However, just prior to collision with the rail, the front of the car started to rise rapidly. The maximum upward movement was about 6 inches.

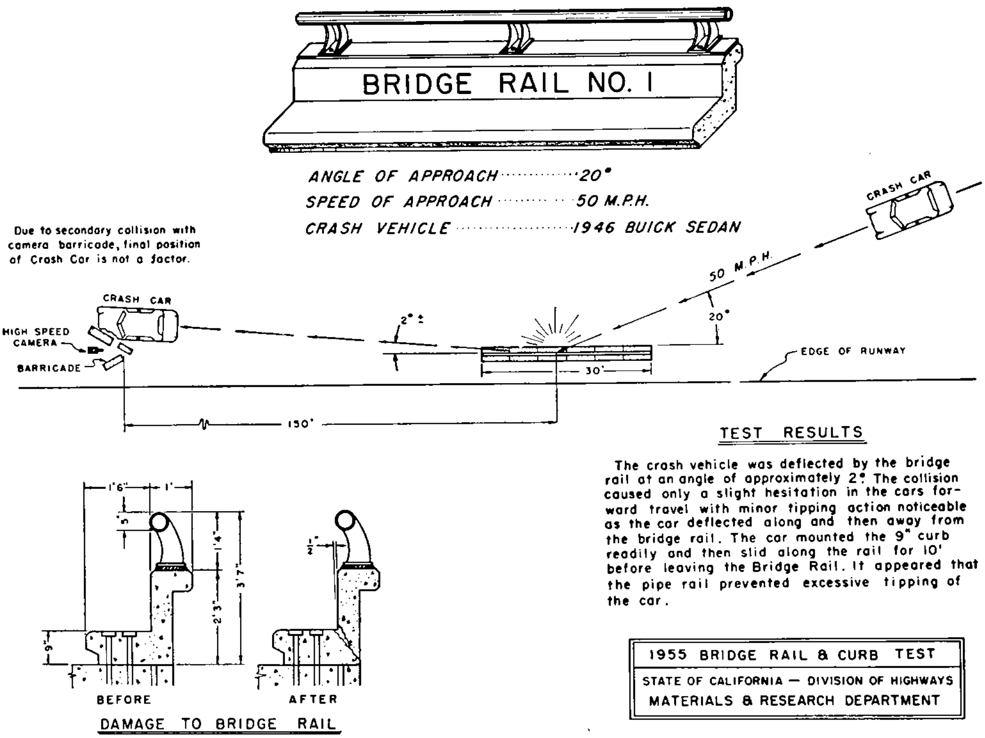

Figure 10.

Had the rail not been present, this upward movement probably would have continued as was witnessed in the test on the curb alone. Also had the railing been placed further in back of the curb than it was, the upward movement probably would have been more, perhaps enough to result in the car overtopping the rail. The resistance to excessive upward movement was probably offered by the forward pressure of the car against the railing. The pipe railing at the top of this unit seemed to serve as a slide after the complete car had been turned in a direction parallel to the rail. It also served to prevent excessive tipping of the car. The results of this test indicated that the curb at high speeds serves as a dynamic fulcrum for the crash car. However, the rail was close enough to the curb so that with a height of 33 inches it could "catch" the car before it attained enough elevation to go over the barrier.

Bridge Barrier Rail Trial Design No. 2

The physical details concerning the design of this railing are shown in Figure 3, and the general test results in Figure 11. The proposed use of this trial design was as one of four units to determine the minimum height to which a barrier rail could be built and still serve as a barrier when a barrier curb was not involved, and also to determine the maximum setback a "rubbing" curb could have without acting as a lifting fulcrum during high speed collisions. The specific use of this design was in the determination of the minimum barrier height by a comparison of its effect with that of Trial Design 3.

The physical facts concerning this test are that the crash vehicle was a 1949 2-door Ford sedan which collided with the test unit at an angle of 30 degrees and a speed of approach of 48 mph. The car crashed through the railing, demolishing a 9-ft. section. It then passed over the test unit, leaving the collision point at a −5-degree angle. It came to rest at a point 70 feet beyond the point of collision.

Analysis of the motion pictures shows that the most solid point of collision occurred when the front end of the crash car frame contacted the top edge of the rail. This caused an initial

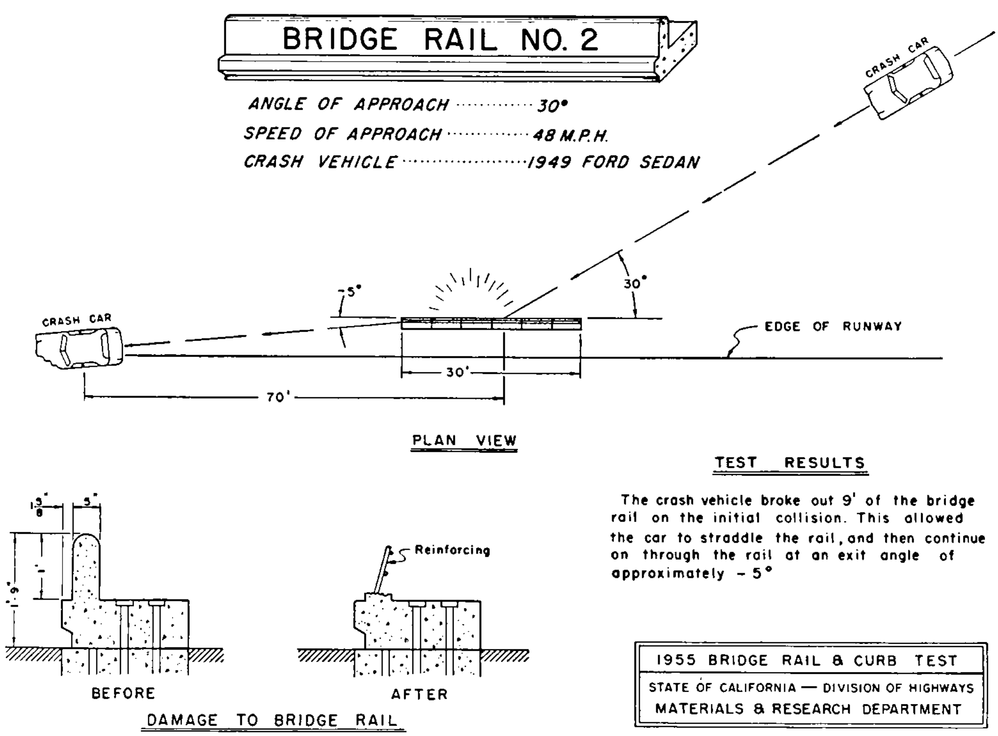

Figure 11.

failure of the concrete apparently in direct punching shear, probably highly concentrated due to the unsupported edge of the railing slab. From this point of beginning the failure seemed to progress rapidly as further pressure was applied by the moving crash car.

To check the possibility of weak concrete, cores were taken from the broken concrete specimens of this railing. They indicated the concrete to have had a compressive strength of approximately 4,800 psi. Test cores of the concrete taken of all of the bridge rails indicated this to be about the average strength of the concrete in all test units. This also checks the test cylinder data taken during fabrication.

Analysis of the post-collision travel of the automobile indicated that in passing through and over the rail the car jumped about 3 feet in the air and traveled through the air between 15 and 20 feet before again touching the ground. The results of this test seem to indicate that a bridge rail, to be effective as a barrier to high speed collisions, should be higher than 21 inches.

Bridge Barrier Rail Trial Design No. 3

The design details of this railing are shown in Figure 3. Two test collisions were made on this same unit, the general results of which are shown in Figures 12 and 13. The intent of these two tests was to provide tests for comparison with the 30-degree angle collision with Trial Design No. 2 and the 20-degree angle collision with Trial Design No. 5.

In this way the effect of height of a bridge railing could be tested by a comparison between Trial Designs 2 and 3, which were tested at the same angle, 30 degrees, and speed, 48 mph. Also the effect of setback between the face of the curb and the railing could be tested by a comparison between Trial Designs 3 and 5, which were tested at the same angle, 20 degrees, and reasonably close to the same speed, 55 and 50 mph., respectively. At the same time a common base for comparison of the over-all test results was provided by the two different tests being performed on this same trial design.

The crash car for the first test of this series was a 1949 2-door Ford sedan which collided with the test unit at an angle of 30 degrees and a speed of approach of 48 mph. The car glanced off the rail at an exit angle of about 5 degrees and came to rest about 125 feet from the point of collision. The car traveled in a straight line for about 70 feet after collision,

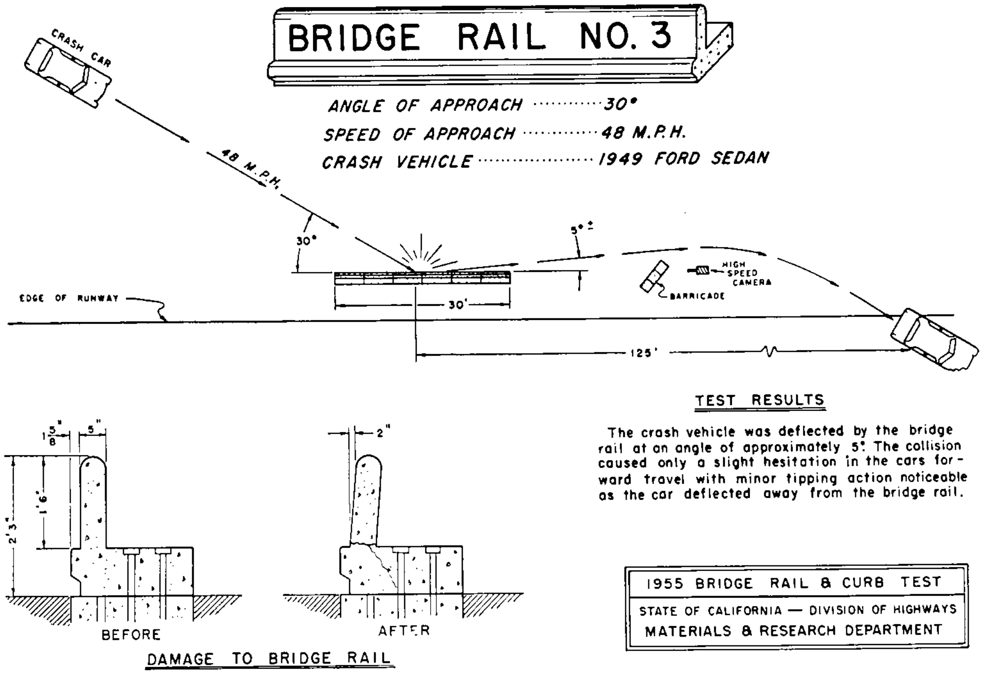

Figure 12.

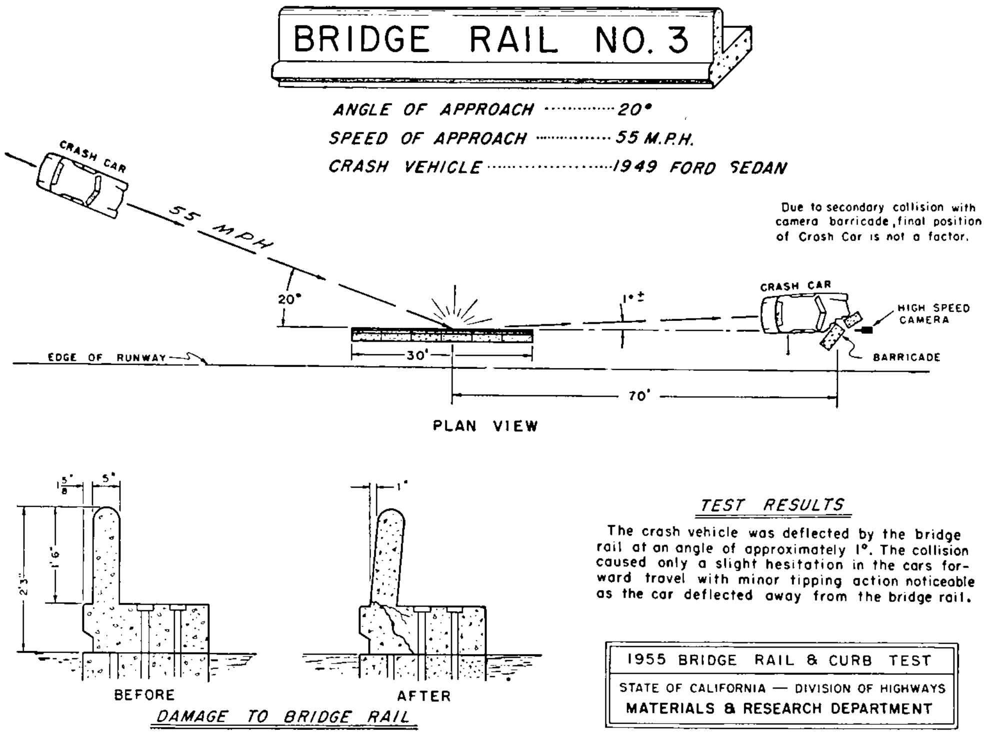

Figure 13.

then turned to the right. This turn was to the side of and caused by the front contact wheel, which had been badly damaged. This swing in the direction of the front damaged wheel was clearly shown only in this test because in the other four tests the crash car collided with a camera barricade before it had turned enough to be noticeable. It has been noted in other oblique collision tests (*1*) that this movement is typical.

Physical measurements of the red and green marks left from the contacts of the wheels with the test unit are given in Table 1.

Analysis of the motion picture film indicates, in general, that the over-all actions of the car as a result of the collision were about the same at both the 20-degree and 30-degree angle of approach. The contact wheels gave little indication of rising from the pavement, and only moderate tipping of the car was indicated.

At the 30-degree angle of collision, there was a slight lifting action of the front end of the body immediately upon collision, but no further upward movement as the car passed on through the collision. The tipping of the car was slightly greater for the 30-degree angle of contact in that the side of the car opposite from the collision rose about 1 foot from the pavement during the 30-degree angle contact and only about 9 inches for the 20-degree approach angle contact.

In addition to the normal instrumentation used for all of the tests, the cars for these two tests were also equipped with mechanical accelerometers, and high speed photography was used so as to aid in micro-motion analysis. The peak deceleration measured during these crashes are shown in Table 1.

As illustrated in Figures 12 and 13, the deformation remaining in the rail wall after collision amounted to 2 inches out of plumb for the 30-degree collision and 1 inch for the 20-degree collision. The results of these two tests indicate that a 27-inch high rail serves as an effective barrier to an ordinary car during high speed oblique collisions.

Bridge Barrier Railing Trial Design No. 4

The design details of this barrier railing trial design are shown on Figure 3. The planned purpose of this trial design was to study the effect of setback of the "rubbing" curb from the top rail by comparisons between it and Trial Design No. 2, providing it had been determined that a 21-inch over-all height of rail was sufficient to act as a barrier. The test on Trial Design No. 2 showed this height to be insufficient; therefore no tests were made of this Trial Design No. 4.

The effect of the additional setback, as noted by a comparison of the results of the tests on Trial Designs 3 and 5, would have been to raise the car slightly on impact. This would result in even greater tendency for a car to surmount this Trial Design No. 4 than Trial Design No. 2.

Bridge Barrier Railing Trial Design No. 5

The design details of this bridge railing are shown in Figure 3, and a schematic diagram of the over-all test results of this trial design is shown in Figure 14.

The purpose of this trial railing was to study the effect of distance of rail setback from a curb by comparison with Trial Design No. 3 and also to provide data to study the maximum possible setback that would not result in the curb serving as a lifting fulcrum for a car during high speed oblique collisions.

The crash vehicle used in this test was a 1949 2-door Ford sedan, which approached the test unit at an angle of 20 degrees, and a speed just prior to collision of 50 mph. Physical measurements of the markings left by the front and rear contact wheels of the test unit showed a tendency for the front wheel to mount the curb. However, the rear wheel did not show any such tendency. The length of contact of the front wheel with the test unit was about 9 feet. The crash car deflected off the rail, leaving it at an exit angle of about 2 degrees. The car came to rest about 200 feet from the point of collision. This after-travel, however, would probably have been about 250 feet if the car had not collided with a camera barricade, which was in its path of travel about 120 feet away from the point of collision. The car also would probably have turned in the direction of the damaged front wheel had it not been for this secondary collision. Typical dam-

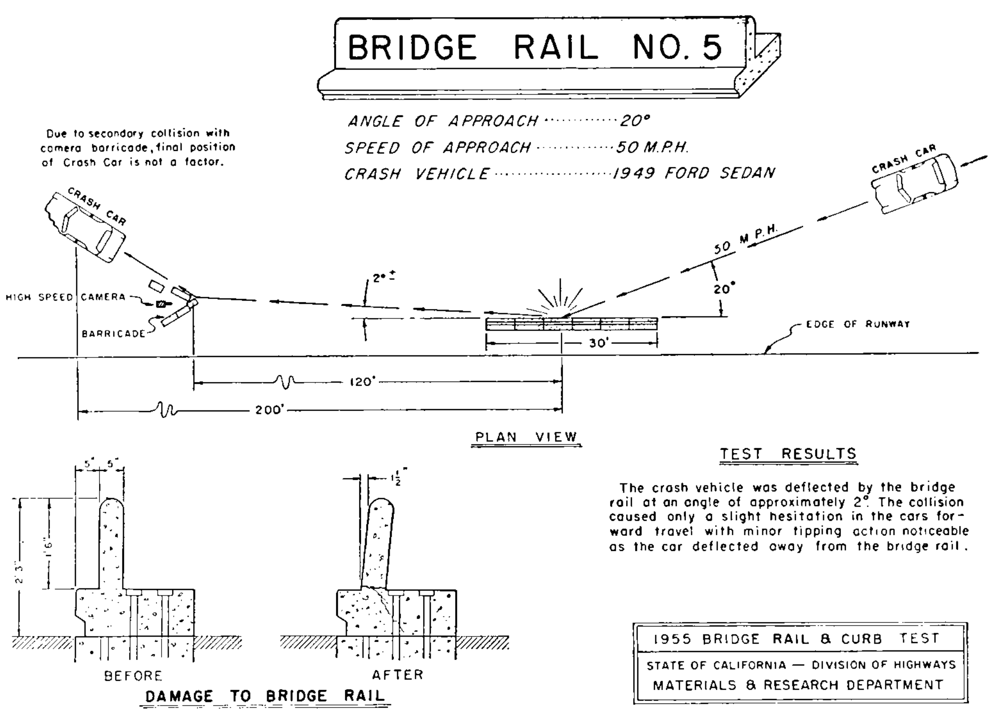

Figure 14.

age was done to the 18-inch wall setting above the curb. The test section that bore the brunt of the crash was deflected permanently 1½ inches out of plumb and typical diagonal cracking occurred at the base.

Analysis of the motion picture film showed that the front end of the car rose approximately 9 inches, but that there was little or no rising of the back end of the car. There was only a slight tipping action. The front wheel offside of the collision rose about 9 inches from the pavement, and the rear wheel about 1 inch. This test differed from the 20-degree oblique collision of Trial Design No. 3 in that there was little or no rising of the contact wheel during the collision contact with Trial Design No. 3. However, the tipping action of the car during contact with Trial Design No. 3 was more noticeable than during the contact with this Trial Design No. 5. This latter difference, of course, may also be due to the fact that this test of Bridge Railing No. 5 was conducted at 50 mph., whereas that on Bridge Railing No. 3 was conducted at 55 mph.

Motion picture analysis further reveals that the front contact wheel of this vehicle was completely torn off on collision with the curb. This was the only test unit on which this occurred. It appears to have been caused by the wheel bending over the curb. Lacking support from the wall, the wheel bent far enough to result in complete failure.

The results of this test indicate that 5 inches is about the maximum that a curb can project from a rail without the lifting effect of the curb affecting the over-all upward motion of the automobile during the collision period. In other words the lifting force created by the wheel rising is insufficient to overcome the resistance created by the pressure of the car against the concrete, and with the 5-inch setback this resistance is applied soon enough to prevent any upward motion.

General Observations

The following secondary observations were made during this series of tests. While these observations are not necessarily pertinent to the main objectives of the test program, they may be of some help in assisting the engineer more clearly to understand the dynamic phenomena involved during oblique automobile collisions with rigid barriers.

1. After each of these oblique collisions, the car left the barrier at a relatively flat exit angle. This angle varied primarily with the angle of collision.

2. The front wheel of each of the cars involved in an oblique collision with the barrier rail was damaged so badly as to be inoperable. The result of this was that the car turned or hooked in the direction of the barrier as soon as the vehicle slowed to the point where the effect of the drag of the damaged wheel made itself felt. This phenomenon could be impor

TABLE 1
1955 BRIDGE RAIL AND CURB TEST BARRIER RAIL TEST ANALYSIS SUMMARY

Item	Bridge Barrier Rail Trial Designs					
	1	2	3	3	4	5
Crash car	1946 Buick 4-door sedan	1949 Ford 2-door sedan	1949 Ford 2-door sedan	1949 Ford 4-door sedan	Analyzed but not tested	1949 Ford 2-door sedan
Approach speed, mph*	50	48	55	48		50
Approach angle, degrees	20	30	20	30		20
Wheel rise, inches						
Front contact	9 (0 curb)	40†	0	2		9¶
Rear contact	9 (0 curb)	24	2	4		0
Front offside	3	36	9	12		9
Rear offside	3	4	9	12		1
Rail contact, feet						
Front wheel	8.4	9.0†	7.0	7.0		8.6
Rear wheel	2.7	9.0	5.0	5.0		0
Peak longitudinal G‡	—	—	17	10		—
Average lateral G‡	—	—	>100 G§ for 8 ms.	90 G for 20 ms.		—

* Survey speedometer reading at instant before collision.
† Car broke through rail. Nine feet of railing were broken out.
‡ Furnished by Institute of Transportation and Traffic Engineering, University of California at Los Angeles, obtained from mechanical accelerometers and micromotion analysis.
§ Effect of force not too significant owing to extremely short duration.
¶ Wheel torn off car. This accounted for wheel rising to curb height. The car body only rose about six inches.

tant; for instance, if a relatively high traffic accident area were being protected by a barrier railing, and the barrier were not extended far enough so as to contain the car during its secondary hook.

3. While the essential purpose of this series of tests was to study the effect of the geometry of bridge railings, nevertheless all railing structural failures were recorded and have been reported. It is interesting to note that each of the rails failed to some degree, even though all were designed to AASHO loadings. Insufficient instrumentation was used during this test to accurately determine whether or not such design loadings are realistic. However, the failures do indicate that the speeds and weights of the present day automobile may justify a re-analysis of such design loadings, especially in areas where the needs of traffic indicate that a positive barrier is desirable.

SUMMARY

1. This report covers five full-scale tests of concrete bridge rails subjected to automobile impacts. These five tests were performed on four of the five bridge barrier rail trial designs shown on Figures 2 and 3. It was concluded that it was unnecessary to test Trial Design No. 4 as it was subject to analysis by application of the results on Trial Designs Nos. 2, 3 and 5. Table 1 is a summary of the physical facts as determined from an analysis of the field measurements combined with a frame-by-frame study of the moving pictures taken during each test.

2. The test units, angles of collision, and speeds of collision were selected only after a thorough analysis of some 200 full-scale tests performed on highway bridge curbing. It is therefore felt that while five tests may be considered a limited sample, the conclusions can be judged as significant.

3. Insofar as we can learn, this is the first series of full-scale tests in which remote radio control of an automobile has been used. The results of this test prove this system for conducting controlled automobile crashes to be adequate to yield reasonably accurate realistic engineering data with a minimum of hazard to test personnel.

CONCLUSIONS

An analysis of the data collected during the five impact tests of bridge barrier railing performed during this study warrant the following conclusions:

1. If a concrete barrier rail is constructed flush with the pavement and without a curb between it and the traveled way, then the rail should have a height of not less than 27 inches.

2. If a curb is placed at the base of a barrier rail and the primary function of the curb is to minimize the likelihood of scratching the casual car driven too closely to the rail, then such a "rubbing" curb should have a projection from the rail between 3 and 5 inches. If the curb projects more than 5 inches, it will probably act as a lifting fulcrum during high speed collisions.

3. Barrier rails which are used in combination with a curb, where the setback is greater than 5 inches, must be higher than when a curb is not present. Because of the many variables involved, the exact relationship between height of curb, setback of rail, and height of rail is difficult to determine. However, further analysis on this subject will be performed by the Division of Highways using the data collected in this series of tests performed on highway bridge curbing alone.

In this series of five railing tests only one rail and curb combination was used. It was Trial Design No. 1, which consisted of a 9-inch-high undercut curb, 34-inch-high rail, and an 18-inch setback. This combination gave excellent results. The 34-inch height (above the top of the curb) of the rail seemed about the minimum that should be used in this combination of dimensions.

4. Close observation of the moving pictures showing the dynamic actions and reactions between the crash car and the test railings indicates that the results of this test on relatively rigid barriers should not be considered as applicable to a flexible type of guardrail.

ACKNOWLEDGMENTS

These studies of highway bridge barriers of which this report covers only one portion are being conducted by the California Division of Highways. The program has been outlined and requested by the Bridge Department and Planning Department of the Division of Highways and conducted by the Operations Department.

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DISCUSSION

Robert S. Ayre, *Associate Professor of Civil Engineering, Structural Dynamics Laboratory, The Johns Hopkins University, Baltimore, Md.* —The full-scale tests conducted by the California Division of Highways and reported by Mr. Beaton are significant. The tests appear to have been well designed and well instrumented. It is highly desirable that equally well conducted tests be made, by some public agency, on impact between vehicles and guardrails (cable as well as steel beam type). In planning a series of tests on guardrails it should be noted that there are two variables which are very difficult to control; these are the ground surface condition adjacent to the guardrail and the soil foundation condition of the posts and end anchors.

John L. Beaton, *Closure.*—The author agrees with Mr. Ayer's discussion in general, and especially with his statement that some public agency should conduct a series of full-scale tests on the impact between vehicle and guardrails. It will be exceedingly difficult to segregate the significant factors involved in such a test, but it, nevertheless, would be well worthwhile.