# New Highway Barriers: The Practical Application of Theoretical Design

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A six-year research program resulted in the complete revision of the standard barrier designs for roadsides, medians, and bridges specified by the New York State Department of Public Works. The study included a comprehensive theoretical analysis of the forces generated between vehicle and barrier during impact. This produced four mathematical models used to predict the trajectory of a vehicle in collision with a given barrier. These models have been programmed for computer solution. Three provide the force deflection curve of the barrier in the case of (a) a pure tension rail (cable), (b) a combination of tension and bending (W beam) and (c) pure bending (box beam). The fourth model gives the trajectory of the vehicle using the appropriate force-deflection curve as input.

Forty-eight full-scale collisions between standard-size passenger cars and various barrier configurations were carried out. Speeds of up to 60 mph and impact angles of up to 35 deg were selected as representing the most severe conditions expected on a highway. Also included were numerous dynamic tests on various guide rail posts embedded in different types of soil. The contribution of the post to the strength of the barrier system was determined and it was possible to optimize post size and embedment conditions.

This research led to the development of a new design, termed the box beam barrier. In this approach, a commercially available hollow structural rail section of considerable beam strength is supported by relatively weak posts; such a barrier deflects and absorbs impact forces while decelerating and redirecting the vehicle. By using box beams of different strengths and by varying the spacing of posts, barrier deflection can be controlled, thus making this type of barrier suitable for a guide rail, median barrier, or bridge railing.

A method of guide rail and median barrier selection is presented based on the amount of deflection which can be tolerated in any given situation. This criterion, used in conjunction with the improved barrier designs developed in this program, will insure that the minimum practicable decelerations will be imposed on a colliding vehicle.

•WHILE only about 10 percent of the highway accidents in New York State are classified as "fixed object" or "ran off road," this type of accident accounts for approximately 30 percent of the fatalities. Each year between 700 and 800 people lose their lives on

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New York State highways as a result of striking a fixed object such as a guide rail, median barrier, bridge rail, bridge pier, sign support, light pole or tree (1). It is readily apparent then that any improvement which can appreciably reduce the severity of such accidents can make a tremendous contribution to highway safety.

There are several ways in which the number or seriousness of "fixed object" collisions could be reduced. The object might be removed completely or moved far enough from the highway pavement so as to no longer be a hazard; however, this is possible in only a relatively few situations. Another approach is to reduce the size of the objects or use special collapsible designs which lessen the deceleration during impact to a level which is tolerable to vehicle occupants. Much progress has been shown in this area recently in the case of sign supports and light poles. However, about one-fourth of the fixed object collisions involve highway barriers; consequently, their improvement offers the greatest potential for increased highway safety. Barriers are placed along the roadway to prevent a vehicle from entering a dangerous area or striking an obstruction, but barriers should also be designed to redirect the vehicle parallel to the roadway while keeping decelerations to a level which will prevent the serious injury or death of the occupants.

Another major source of highway fatalities is cross-median collisions. A survey of accidents on divided highways in New York State during 1961 showed that only 8 percent were the result of vehicles crossing the median. However, this 8 percent comprised 62 percent of the deaths due to accidents on divided highways (2). Installation of any structurally adequate median barrier can certainly reduce cross-median accidents, but to effectively reduce fatalities the barrier must redirect vehicles so as to permit survival of the occupants and minimize the danger to adjacent and following traffic. In recognition of the major improvement in highway safety possible through the development of better highway barriers, the New York State Department of Public Works, in cooperation with the U. S. Bureau of Public Roads, six years ago undertook a comprehensive research program on guide rail, median barriers and bridge railings.

Investigations made by other organizations on this subject, as discussed in a report by the New York State Department of Public Works (3), have been concerned with static and dynamic full-scale testing of barriers and mathematical studies using scale models. There has been no investigation which could predict vehicle reaction during collision with a barrier; nor has there been research which could establish, theoretically, optimum characteristics for barriers to be used in different applications. Previous investigations have been limited primarily to qualitative and subjective judgments after observing high-speed movie films of full-scale tests.

## PURPOSE AND SCOPE

The objective of this investigation was threefold: to determine the effectiveness of existing barriers, to develop analytical procedures for predicting vehicle and barrier reactions, and to design highway barriers that would fulfill the following requirements.

1. Prevent a vehicle from crossing a median strip and from penetrating guide rails and bridge railings.
2. Decelerate a vehicle so that its occupants can survive the impact.
3. Redirect a vehicle parallel to the traffic flow, thereby minimizing danger to following and adjacent traffic.
4. Minimize vehicle damage so that it can be maneuvered after impact and redirection.
5. Satisfy the requirement of economical construction, installation and maintenance.
6. Have a pleasing appearance.

When this program was initiated early in 1960, the primary purpose was to develop a method for evaluating barriers and to establish a design for barriers to be installed on narrow medians separating heavily traveled highways. However, as the program evolved, the need for a design of other barrier types became apparent. The investigation has been conducted in three phases as follows:

Phase 1 (February 1960-May 1963). Under contract with the Department, the Cornell Aeronautical Laboratory, Inc., Buffalo, New York, was engaged to perform both the mathematical analysis and the dynamic testing. They developed a mathematical model to compute vehicle trajectory and three other mathematical models to describe the load deflection characteristics for three general classes of barriers. Nine full-scale tests were performed at the Niagara Falls airport to evaluate existing barriers and to verify analytical predictions.

Phase 2 (June 1963-December 1963). This phase of the investigation consisted of ten full-scale tests conducted by Cornell Laboratory to evaluate bridge railings and design concepts established during Phase 1. During this time the Bureau of Physical Research conducted static and dynamic tests to determine the action of posts, and used the mathematical analysis to design experimental barriers.

Phase 3 (January 1964-December 1966). The final phase of this investigation was conducted by the Bureau of Physical Research, and included 29 full-scale dynamic tests of barriers, post tests, completion of the mathematical analysis, and verification of the mathematical models. During this phase, new guide rails, median barriers and bridge railings were developed and have been adopted as standards by the Department.

## ESTABLISHING IMPACT CONDITIONS

Physically, there is a minimum radius of curvature a given vehicle can negotiate at any given speed. A sharper turn than this minimum radius cannot be held because the tires will not develop enough centripetal force to provide the necessary radial acceleration. If a vehicle is traveling parallel to a barrier and is suddenly turned toward it, the maximum angle of impact cannot exceed a value determined by the minimum radius of turn of the vehicle (at a given speed) and the initial distance between the vehicle and the barrier.

For any given speed, the impact angle may vary from nearly zero to a maximum of 90 deg; however, the 90-deg impact could occur only under two conditions: if the roadway is very wide and the vehicle moves slowly enough to make such a sharp turn, or if the vehicle collides with (sideswipes) another vehicle and is pushed toward the barrier. Such barrier collisions probably occur less frequently than those involving a single vehicle where distractions, inattention or trying to avoid another vehicle cause a driver to overcorrect and collide with a barrier. In computing the maximum probable impact conditions, the following assumptions were made:

1. The vehicle is initially at a known lateral distance from the barrier and is moving parallel to the barrier with no initial turning rate.
2. The front wheels of the vehicle are moved to maximum effective steer during zero time.
3. No prior collision with another vehicle or object occurs.
4. The maximum curvature (i. e., minimum radius) is reached immediately after the front wheels are turned.
5. The minimum radius of turn is determined by the friction developed between a dry pavement and a tire experiencing incipient skidding.
6. The speed of the vehicle is constant during the turning maneuver.
7. The sideslip of the vehicle is neglected.

Based on these assumptions and using a sliding wheel coefficient of friction which has been measured between tires and dry pavement (0. 7), maximum probable impact angles were computed. The results of the computations are shown in Table 1 for speeds of 30, 40, 50 and 60 mph on highways of various widths.

On a 2-lane highway, the vehicle might go to the right, traverse 3 ft of the lane it occupies, and then cross a 10-ft shoulder (13 ft laterally) before striking the barrier. It might also go to the left, cross the adjacent lane and then shoulder (25 ft). On a 3-lane highway (6-lane divided), the vehicle might cross an additional 12-ft lane and travel as much as 37 ft laterally. Thus, as shown in Table 1, impact angles between 15 and 35 deg represent the more severe conditions which might be encountered on a majority of highways. Computations for low speeds and wide roads were not made because these conditions are normally encountered only on a few rural, 2-lane roads. For the testing and analysis conducted during this study, a combination of 60 mph and 25 deg was

TABLE 1

COMPUTED IMPACT ANGLES IN DEGREES

| Speed (mph) | Lateral Distance From Car to Barrier (ft) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Straight Road | | | | Curved Road (5 deg) | | | |
| | 10 | 20 | 30 | 40 | 10 | 20 | 30 | 40 |
| 30 | 28 | 40 | | | 29 | 41 | | |
| 40 | 21 | 29 | 37 | | 22 | 31 | 39 | |
| 50 | 17 | 24 | 28 | 34 | 18 | 26 | 32 | 37 |
| 60 | 14 | 20 | 24 | 28 | 16 | 22 | 27 | 32 |

TABLE 2

LIMITS OF TOLERABLE DECELERATION (Tentative)

| Restraint | Maximum Deceleration (g's) | | |
|---|---|---|---|
| | Lateral | Longitudinal | Total |
| Unrestrained occupant | 3 | 5 | 6 |
| Occupant restrained by lap belt | 5 | 10 | 12 |
| Occupant restrained by lap belt and shoulder harness | 15 | 25 | 25 |

selected as the primary maximum probable impact. A second maximum probable impact condition of 45 mph and 35 deg was selected as this combination is also highly likely on many divided highways and primary state routes.

## ALLOWABLE VEHICLE DECELERATIONS

Generally, a highway barrier is considered to serve its purpose when it prevents a vehicle from crossing into an opposing lane of traffic or from leaving the highway or bridge. However, equally as important, a barrier should protect the occupants of a vehicle and keep the car from interfering with other traffic. Under optimum conditions it would be desirable to have a vehicle which strikes a barrier remain against it while being gently redirected parallel to the original barrier centerline with no change in speed or damage to the vehicle running gear. This would require a barrier which "gives" laterally so that it would not impart a lateral deceleration to the vehicle which would seriously injure the occupants. To evaluate barrier performance it was first necessary to establish some guides, no matter how tentative, as to the levels of vehicle deceleration which might produce injury to the occupants.

Investigations have been performed by various agencies in an attempt to determine human tolerance to deceleration. These studies have been primarily concerned with longitudinal deceleration and have revealed that the ability of a person to withstand deceleration depends on (a) method and degree of restraint; (b) duration of deceleration; (c) magnitude of deceleration; and (d) rate of onset of deceleration. Other factors such as age of the subject, environment, and emotional state also affect human tolerance to deceleration.

Stapp (4) performed longitudinal deceleration tests on voluntary subjects. He found that a human, restrained by a lap belt and shoulder harness, can survive 25-g deceleration forces for a period of 0.2 sec provided that the rate of onset is less than 500 g per sec.

Crash tests performed by Severy (5) indicated that an automobile crashing into a rigid barrier at 25 to 30 mph experienced a peak deceleration of 14 to 19 g's occurring in the primary structure of the vehicle with acceleration onset rates of 500 to 800 g's per sec. He also reported that photographic data of anthropomorphic dummies in the vehicle indicated that occupants of a vehicle undergoing this deceleration could survive the crash if they were restrained by lap belts and a shoulder harness. Unrestrained occupants or those protected only by a lap belt would probably have been killed.

In the case of an automobile collision, if the occupants were restrained by a lap belt and shoulder harness, they would be more likely to experience decelerations similar to those of the vehicle. However, in a similar accident involving unrestrained occupants the deceleration force of the occupants may be of entirely different magnitude than that of the vehicle. To illustrate the different decelerations of an unrestrained occupant and the vehicle consider the following case. A vehicle containing several unrestrained occupants and traveling at high speed leaves the roadway and strikes a large tree. Two collisions result. The first is the vehicle with the tree; the second and more critical is the occupant with the vehicle. As the vehicle decelerates the occupants continue to travel at the vehicle speed prior to impact until they collide with the interior of the car.

This collision between occupant and vehicle usually results in higher decelerations than that of the vehicle because stopping distances of the occupants are limited to only a few inches.

The work listed above all deals with longitudinal deceleration. However, during collision with a highway barrier occupants of the vehicle are subjected to simultaneous lateral and longitudinal decelerations. Little work has been done on the effects of lateral decelerations and even less is known about the effects of combined lateral and longitudinal decelerations.

In 1961, after reviewing the available literature concerning human tolerance to deceleration, Cornell Aeronautical Laboratory suggested tentative limits (Table 2) of combined lateral and longitudinal decelerations where the duration did not exceed 0.2 sec and the rate of onset did not exceed 500 g's per sec. However, laboratory engineers reported that further work with anthropomorphic dummies subjected to known decelerations are required to better establish these limits.

Although there is no relationship between the decelerations of a vehicle and an unrestrained occupant, one can reasonably assume that low decelerations of a vehicle would mean that the probable chances of severe injury to the occupants would be less. During this study a total deceleration of 10 g's for more than 0.05 sec (50 millisec) at the vehicle center of gravity has been considered as probably capable of producing serious injuries and perhaps even fatal injuries. Every effort has been made therefore to keep vehicle decelerations below this level during collision with the barriers developed during this study.

## MATHEMATICAL ANALYSES

Mathematical analyses were undertaken to develop calculation procedures for simulating vehicle trajectory during impact with various barrier configurations. The majority of previous investigations had been limited to full-scale tests because of the complex computations required to simulate vehicle response. Another limiting factor was the lack of knowledge of the dynamic characteristics of the items involved, such as vehicle structures, lateral force developed as a barrier deflected, and yield strength of posts embedded in soil. For these reasons, simulation of a vehicle collision with a barrier required a critical study of the interaction of barrier components with one another and with the impacting vehicle.

Basically, the steps required to analyze mathematically vehicle reaction during a barrier collision are (a) derive equations of vehicle motion in terms of the moments and forces being applied to it; (b) determine these forces and moments as a function of barrier characteristics and deflection; and (c) compare the solution of the equations with the desired barrier deflection, vehicle path, and vehicle decelerations.

### Model Development

To analyze highway barriers, two types of mathematical models were constructed. One type of model is used to calculate the barrier resistance during impact and another class of model is used to solve the vehicle responses. There are many physical characteristics of the vehicle and the barriers, and numerous forces that act during a collision. To have refined all of these would have been impractical, not only because of the complex mathematics involved, but because of the difficulty of working out a computer program. After considering the forces acting during a collision, it was decided to simplify the mathematical models, and then to verify and expand these models with experimental data obtained from dynamic testing.

The characteristics of a given barrier are first used to compute a series of force-deflection curves which represent that barrier. The data required include post strength, post spacing, rail bending strength, and rail strength in tension. These force-deflection curves, along with the characteristics of the vehicle and additional post strength data, are then used to calculate vehicle responses for given impact conditions.

Vehicle responses are calculated by a repetitive process programmed for solution on an electronic computer. During each millisecond of the collision, this process recalculates the vehicle position until the corresponding barrier deflections successively

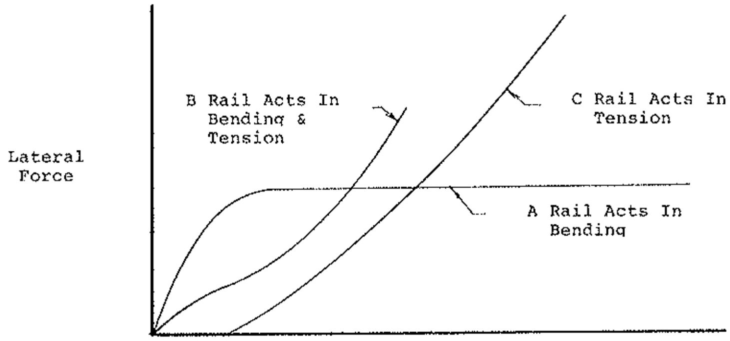



Figure 1. Barrier force-deflection characteristics.

agree within specified limits (usually 0.01 in.). The computer then prints out the vehicle position, velocity, deceleration, and barrier deflection.

Barrier Models

Preliminary studies of barrier configurations indicated that a barrier should present a continuous medium (surface or railing) to the impacting vehicle, and that impact forces on this continuous medium would have to be transmitted to the ground. A full concrete wall, for example, fulfills both conditions uniformly and continuously along the barrier, while a post and railing barrier transmits impact forces to the ground at discrete points. The concrete wall, however, is rigid and can produce severe, and sometimes fatal, deceleration forces, while a yielding barrier can deflect to absorb impact forces and re-uce deceleration.

If lateral vehicle deceleration is to be limited to 10 g's, the lateral resisting force developed by the barrier should not exceed 10 times the weight of the vehicle (40,000 lb for a 4,000-lb car). Also, during impact, a yielding barrier must absorb the lateral kinetic energy of the car not dissipated in crushing the car. If a 4,000-lb car is assumed to be initially 25 ft from the barrier and turns toward it as sharply as possible, the lateral kinetic energy of the vehicle at impact varies from about 60,000 ft-lb at 30 mph travel speed (45 deg impact angle) to 68,000 ft-lb at 60 mph (22 deg impact angle). The primary impact conditions selected for this study (60 mph, 25 deg and 45 mph, 35 deg) would result in a lateral kinetic energy of 86,000 and 89,000 ft-lb for a 4,000-lb car. As can be seen, the range of energy is not very great even though the speed range is quite large. This has occurred because the maximum probable impact angle decreases as speed increases for the same lateral distance. During the most severe vehicle collisions with a barrier it would appear that not more than 100,000 ft-lb of energy remain after the car is crushed. If the barrier develops 40,000 lb lateral restraint immediately upon impact and maintains this force as it deflects, the barrier would deflect $2\frac{1}{2}$ ft

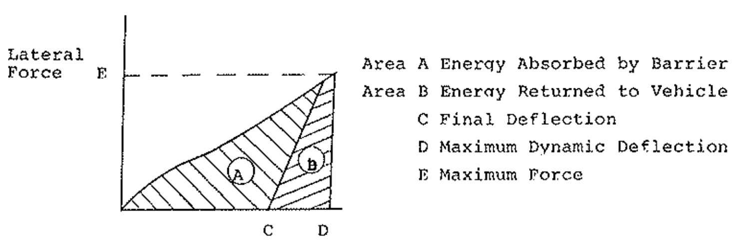
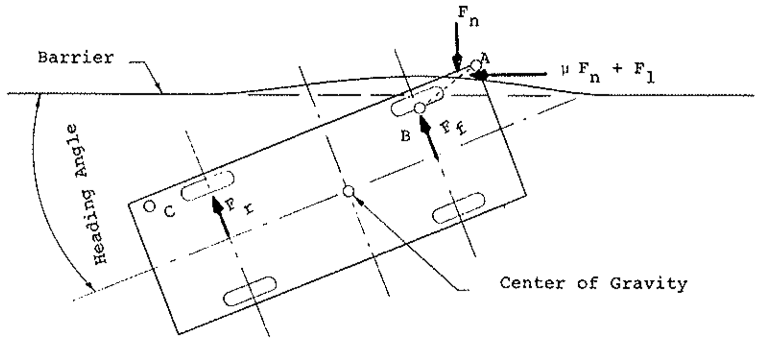



Figure 2. Barrier loading and unloading.




A. Initial position of concentration load point on vehicle (primary collision).

B. Position of concentrated load point on vehicle for maximum vehicle deformation (primary collision).

C. Position of concentrated load point on vehicle for secondary collision.

Figure 3. The vehicle model.

to absorb this energy. If the lateral resistance of the barrier is proportional to deflection and the maximum force does not exceed 40,000 lb, about 5 ft of deflection would be required to absorb the lateral kinetic energy of the car.

Figure 1 shows typical force-deflection curves for three different types of barriers: (a) a barrier that produces a nearly constant lateral force by yielding in the structural members such as a strong beam; (b) a barrier that produces lateral forces from both bending and tension; and (c) a barrier that produces lateral force through tension in a structural member, such as a cable. Although the specific values of force and deflection may be varied by changing the spacing, shape and size of components in the barrier, the shape of the curves will remain essentially the same. These lateral force-deflection characteristics indicate that different barriers can be used to advantage where different amounts of deflection can be allowed, as, for instance, the greater allowable deflection on an open highway fill than on a bridge.

If some plastic flow (yielding of a metal barrier) has occurred before maximum deflection has been reached, the load-deflection curve for unloading the barrier will differ from the curve representing the loading of the barrier. Plastic flow or yielding is desirable because in this way only a portion of the vehicle's lateral kinetic energy is returned to it, thus decreasing the lateral velocity as it leaves the barrier. The force deflection curve in Figure 2 approximates the maximum and final deflections as they would represent the loading and unloading of a yielding barrier. Of the total lateral kinetic energy of the car, a small part is dissipated by crushing the car, area A is dissipated in straining the components of the barrier, and area B is returned to the vehicle.

These preliminary considerations of vehicle/barrier reactions formed the basis for analyzing data for the mathematical models. The objective in mathematically describing the force-deflection characteristics of a barrier has been to develop the least complicated mathematical models that would correlate with experimental data. Therefore, certain assumptions were made as discussed in the following sections.

Vehicle Barrier Force—This force is known to be distributed over a finite area. However, the difficulties involved in simulating a distributed force with varying distribution and contact-area, in conjunction with the lack of vehicle structural data, led to the use of a point-load approximation of the resultant force.

Barrier Inertia—The mass of the highway barrier moving during impact is relatively small compared with the vehicle mass. During initial deflections of the barrier, when inertia effects would presumably be at maximum, the deformation of the vehicle reduces

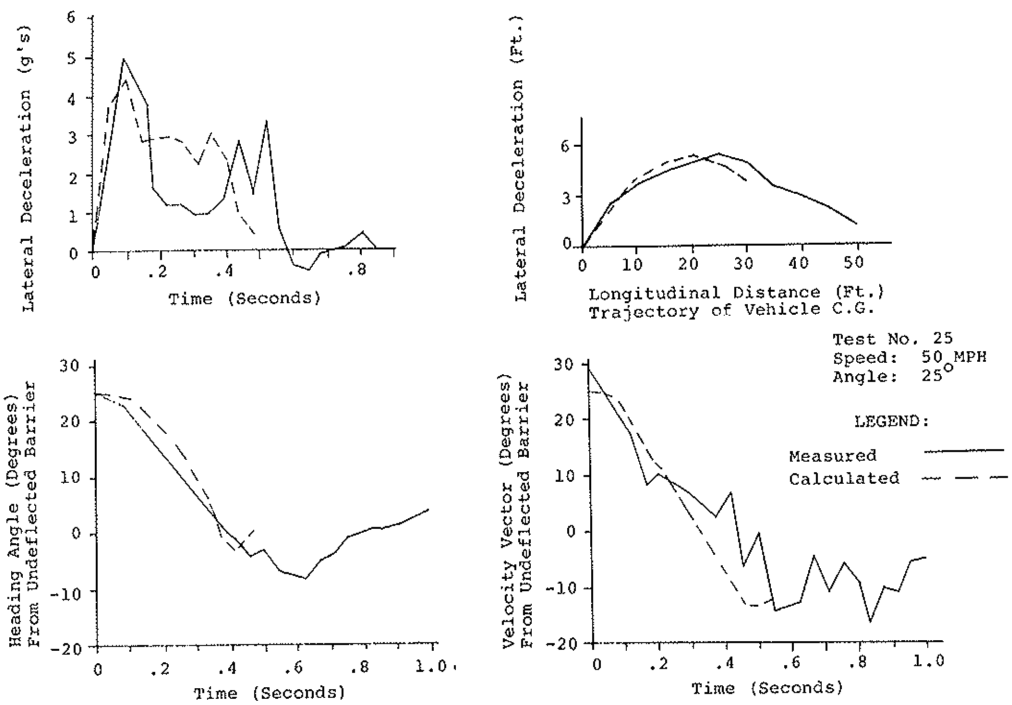



Figure 4. Measured and calculated vehicle reactions—box-beam guide rail.

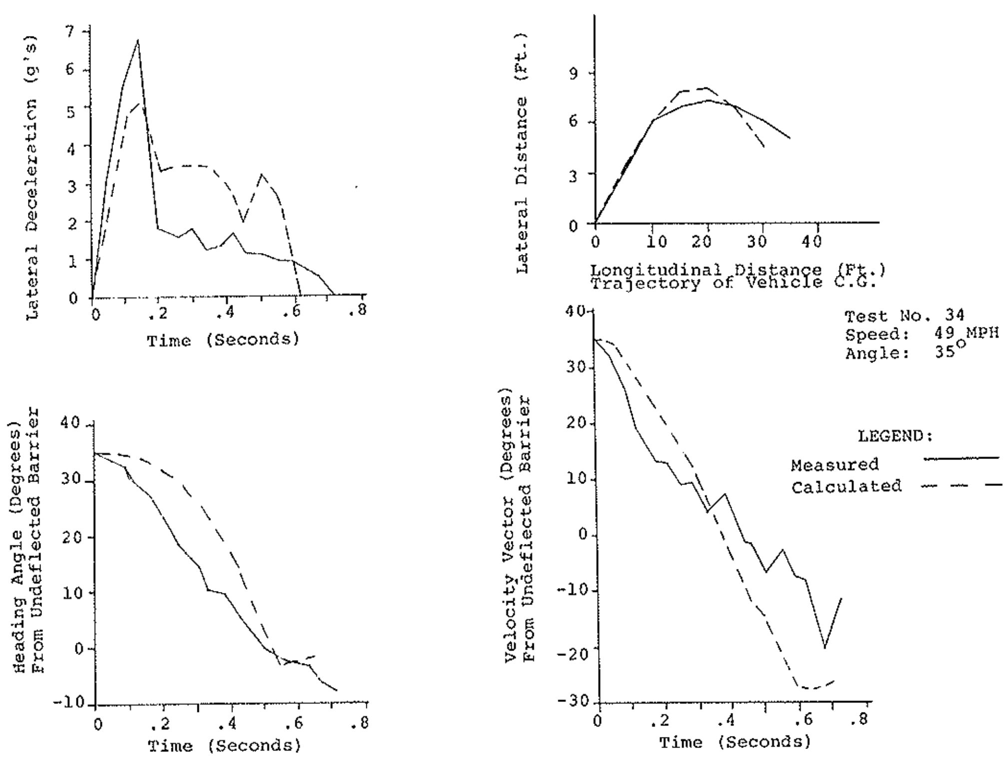



Figure 5. Measured and calculated vehicle reactions—box-beam guide rail.

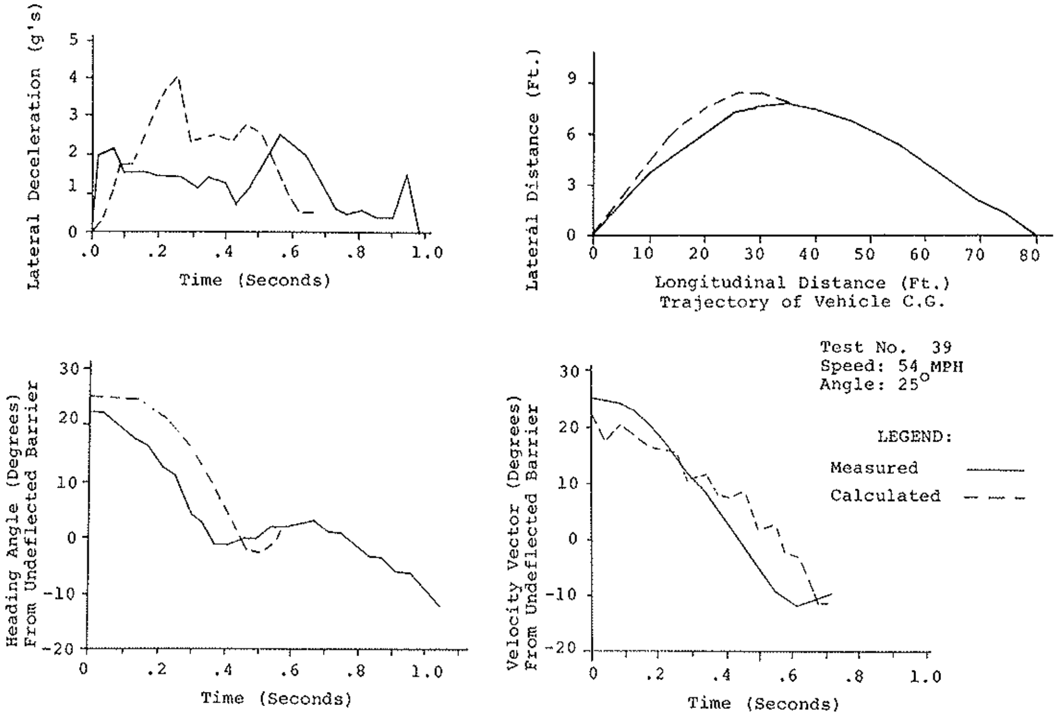



Figure 6. Measured and calculated vehicle reactions—W guide rail.

the accelerations imposed on the barrier. The resulting inertia forces are therefore considered to be of secondary importance and are omitted.

Bending Moments—Except when there is tension in the rail, bending moments in the rail and posts are assumed to saturate and remain constant when the dynamic yield stress is reached. This assumption is based on the concept of a plastic section modulus and an idealized stress-strain curve for plastic deformations, in which both the upper yield point and the effect of strain hardening are omitted. Thus stress is proportional to strain up to dynamic yield and constant thereafter as strain increases. When tension is present in the rail, the bending moment is reduced as a polynomial function of the axial tension. The plastic-yield hinge (saturated bending moment) in the rail is assumed to travel with the concentrated load-point. In effect, this treatment restores elastic properties to the rail after passage of the load whenever the stresses are reduced to a level below dynamic yield.

Barrier Unloading—Experimental data from full-scale tests indicated only the maximum and the permanent barrier deflections. Thus, for simplicity, the assumption has been made that the unloading curve is linear between these two points.

Length of Barrier Deflected—The deflected portion of a barrier on both sides of the region of yielded posts is represented by a limited number of spans supported by elastic posts. For a rail subjected to bending only, or combined bending and axial tension, a three-span section is included on each side of the yielded-post portion of the barrier. In these three spans, the rail bending moment is assumed to decrease to zero. The selection of three spans for this approximation was based on the complexity of the derivation (particularly with axial tension) rather than on a logical justification. Observation of full-scale test data film and barrier damage has verified this in most cases.

For a rail subjected to axial tension only, a five-span section with elastic posts is included. In these five spans deflection is assumed to decrease to zero. Where the rail element acts only in tension the lateral deflection decreases progressively at successiv

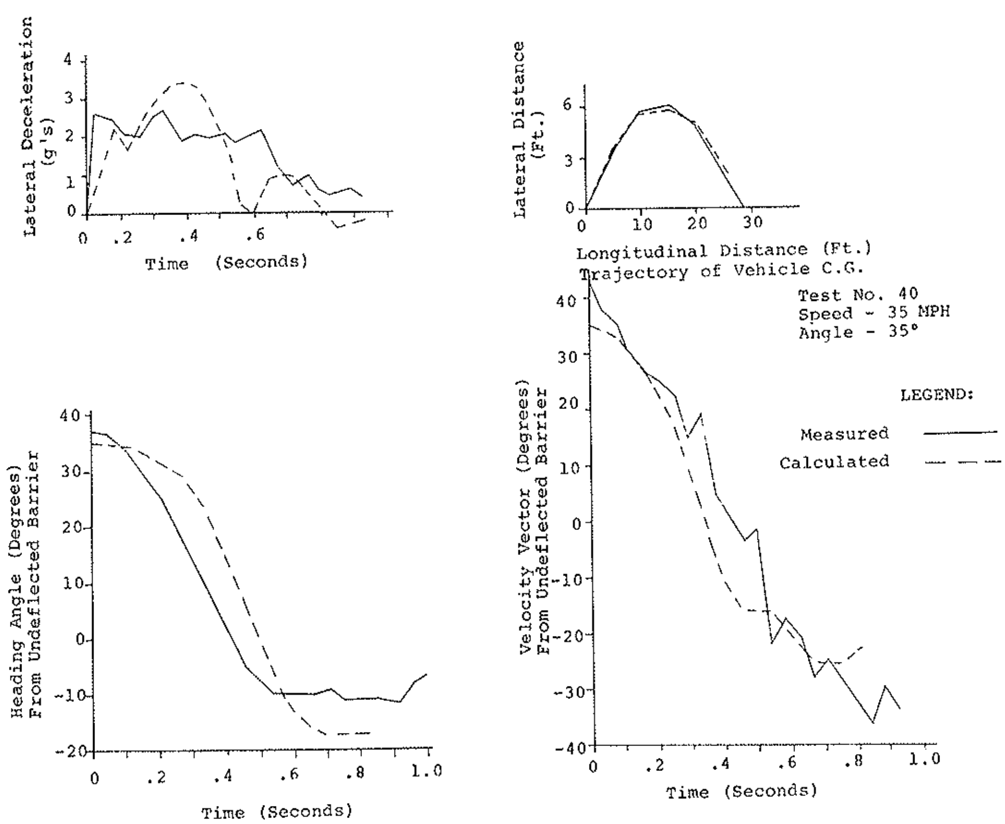



Figure 7. Measured and calculated vehicle reactions—W guide rail.

posts away from the applied load, without theoretically ever becoming equal to zero. However, the effects of the deflection on lateral load will become negligible in the first two or three spans beyond the outermost yielded post. The assumption of zero deflection at the end of five spans therefore introduces a negligible error in the calculated lateral load. The results of calculations for a typical cable-type barrier validate this assumption by indicating a negligible deflection at the end of two spans beyond the outermost yielded post.

Lateral Post Deflection—Failure of posts due to excessive lateral deflection by the rail has not been included in the analytical treatment. Also, failure of the rail element due to excessive strain in bending has not been included.

## Vehicle Model

Vehicle trajectory was obtained by inserting the barrier and ground forces acting on the vehicle into a set of equations stating Newton's laws of motion. To achieve a high degree of accuracy, equations should be used to represent the six degrees of vehicle motion: lateral, longitudinal and vertical linear motions, and roll, pitch and yaw angular motions. Simultaneous solution of these equations to describe vehicle motion under impact conditions is time-consuming and would have severely complicated computer programming. The horizontal motions provide nearly all the information that is required to determine the trajectory of a car during the time it is in contact with the barrier provided there is no significant vertical motion. Appreciable roll or pitch of the vehicle during impact is undesirable and if the barrier provides the desired horizontal trajectory it is unlikely that the vehicle will pitch or roll in a vertical plane. Therefore, only horizontal motion was used in the models.

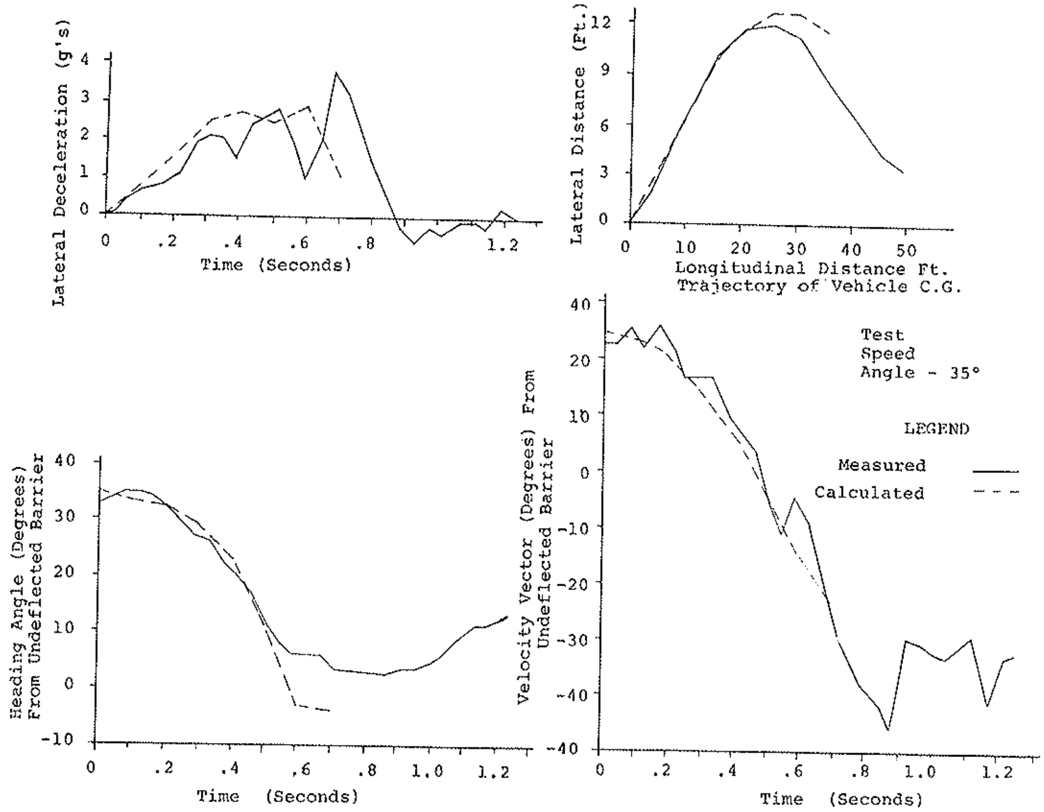



Figure 8. Measured and calculated vehicle reactions—cable guide rail.

To account for the many important physical characteristics of vehicle and barrier and the forces which act during a collision, it was necessary to make several simplifying assumptions. The fact that good verification was obtained with full-scale tests appears to justify these simplifications. The relatively small portion of the total mass in the deformed part of the vehicle permits the vehicle to be regarded as a single rigid body. All forces on the vehicle are assumed to act in the same horizontal plane and vehicle roll and pitch are neglected. In the primary (front-end) barrier impact, a given amount of energy is assumed to be dissipated within the vehicle as it is crushed. During crushing, the force between vehicle and barrier is assumed to increase linearly as it moves along a straight line (A-B, Fig. 3). A secondary (rear-end) collision is assumed to occur and the barrier force is instantly moved from point B to point C when the line drawn from B to C becomes parallel to the original barrier centerline. The forces between tires and pavement ($F_r$ and $F_f$, Fig. 3) are applied along the axles at the intersection of the car centerline. The coefficient of friction ($\mu$) between vehicle and barrier and tires and ground are assumed to be constant during the collision. The longitudinal force on the vehicle caused by each post ($F_l$) is assumed to be constant and active for a given distance.

In the original planning for this project, both the analytical investigations for deriving mathematical models and the dynamic, full-scale tests were considered necessary, so that one might serve to verify the other. This process of analysis and verification has been continued throughout the project. As the full-scale tests verified analytical predictions and assumptions, the computer procedures were revised to obtain more exact simulation of vehicle/barrier response.

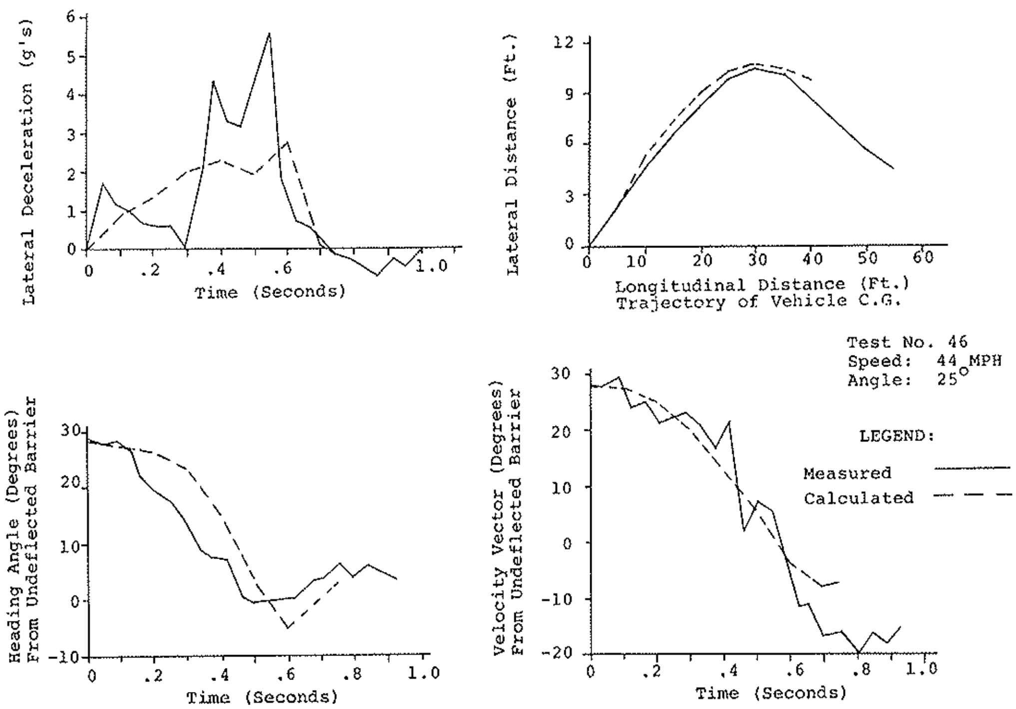



Figure 9. Measured and calculated vehicle reactions—cable guide rail.

## Model Verification

The mathematical models may be considered as tools to be used in evaluating a barrier for a particular purpose or in evaluating the effect of changing the strength or placement of a component of a barrier. The confidence one has in a model depends on how precisely the model simulates an actual condition or reaction. This precision depends not only on the construction of the model but also on the accuracy of the parameters that are used as input.

The only way to verify the models, and the estimated parameters, is to compare calculated vehicle reactions with measured reactions. To do this it was necessary to perform successful full-scale tests, establish the actual impact conditions, measure the actual vehicle reactions and then calculate the vehicle reactions using the mathematical models. This was done with 6 of the last 29 tests performed on the three basic types of barriers studied during this project (tension, bending and combination tension and bending). High-speed data cameras recorded the vehicle center of gravity location, heading angle and barrier deflection during the collision. The velocity and deceleration of the car were then measured by obtaining the first and second derivatives of the center of gravity locations. Vehicle reactions for these tests were calculated several times using various estimates of the uncertain input parameters until it appeared that no further improvement in agreement between measured and calculated reactions was likely.

The best agreement would be obtained between the measured and calculated vehicle locations (trajectories). However, the vehicle deceleration, heading angle, and direction of velocity vector are more sensitive to error. Any small difference in trajectory is magnified in the decelerations, heading angles and velocity vectors which are derived from the trajectory. Therefore these parameters and vehicle trajectory are used to compare calculated and measured vehicle reactions.

Since there are three force-deflection models, one for each type of barrier, the vehicle model was verified for each type. The estimated input parameters are likely to vary depending on the type of barrier. Therefore, comparisons were made for each

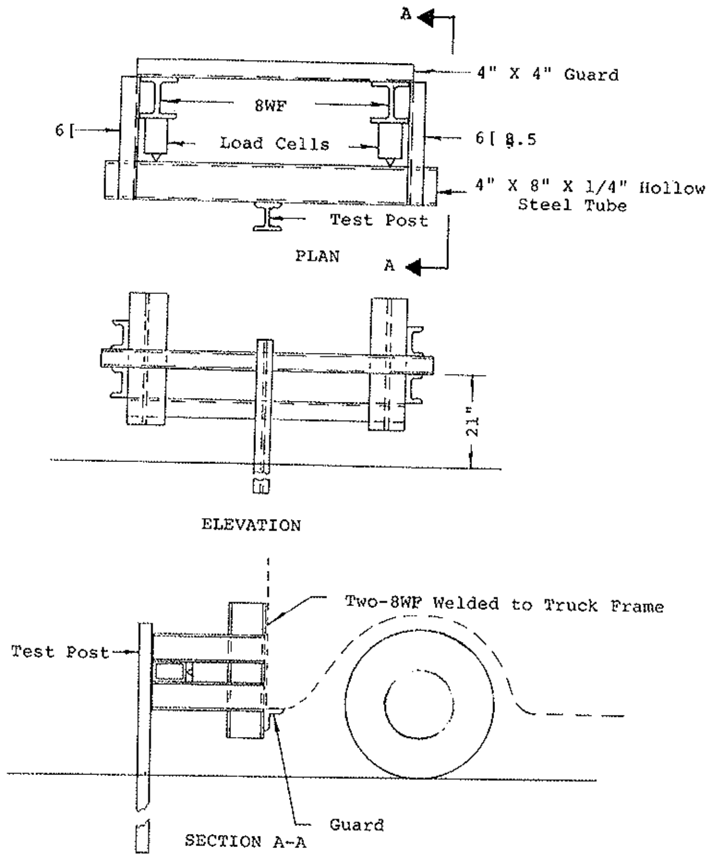



Figure 10. Post testing device.

type. To avoid any coincidence, comparisons were made for each class of barrier for both 25- and 35-deg angles of impact.

No comparisons were made for rigid barriers because the model programming is based on barriers which are intended to deflect more than a few inches.

The vehicle model was validated by Cornell Aeronautical Laboratory with barriers which deflected less than 3 ft. Under this condition the rear of the car does not drift away from the barrier after the rear-end collision. When the barrier deflects several feet, the rear end does move rapidly away from the rail, and the front end again contacts the barrier. This action is not accounted for in the vehicle model.

Figures 4-9 show graphical comparisons of measured and calculated vehicle decelerations (lateral and longitudinal), heading angles and direction of velocity vectors for six tests. A test at an impact angle of 25 deg and one at 35 deg are included for each type of barrier—box-beam guide rail (bending), W-section guide rail (combination bending and tension) and cable guide rail (tension). It is significant that the simplifications and assumptions used in calculating vehicle responses are verified by the close agreement with measured vehicle responses. With this agreement, it is possible to study the effects on vehicle responses caused by changing rail strength, post strength, post spacing, and impact conditions.

## FULL-SCALE POST TESTS

It was evident from the first barrier tests just how important post strength was to the proper functioning of a barrier. To begin refining barrier designs with the mathematical models it was necessary to acquire data on the dynamic strength in soil of many commonly used posts. To do this, it was decided to perform dynamic tests. It was also decided that, as much as possible, the factor of soil resistance on post strength should be eliminated. In this way, the post could be depended upon to provide the same reaction in all locations all year round.

## Test Procedure

If a vehicle impacts a barrier rail at 60 mph and an angle of 25 deg, a post located at or near the point of initial contact will be moved laterally at a speed of about 20 mph. As the vehicle is redirected, the lateral velocity it imparts to the posts decreases depending on the action of the rail in front of the vehicle. While the posts are moved laterally at speeds probably not exceeding 20 mph, they may be moved longitudinally at higher speeds when impacted directly by the vehicle. For these reasons, nearly all posts were tested at speeds of 10 and 20 mph on the lateral (major) axis and a few posts were tested at 30 mph on the longitudinal (minor) axis.

A 12, 500-lb truck was used for the tests because the large mass minimized deceleration during contact with the post. A special bumper was mounted on the truck which was guided between greased channel sections so that it could not move vertically but it was free to move horizontally. The horizontal movement rearward was restricted by two load cells and thereby horizontal loads were transmitted to the load cells. Small bolts through slots in the guide angles and bumper prevented excessive lateral movement of the bumper (Fig. 10). The load cells were wired so that total horizontal load was recorded independent of the lateral location of the load applied on the bumper. A light-beam galvanometer recorder was borrowed from the U. S. Bureau of Public Roads to record the dynamic loads.

The post test program was set up to include most of the posts then used by the department. A 3I5. 7, a 3 by 2-in. tube, and a 2 by 2-in. fence post were also included because they appeared to have desirable features. Each post was positioned so that the top was 27 in. above ground and the bottom 39 in. below ground. The standard posts were driven or set in the ground as required. The other posts were placed in concrete to assure that they would bend at ground level. An aluminum post was included to determine the dynamic strength of aluminum.

## Results

The posts were tested in three types of soil. In all cases the post strength in gravel was intermediate between the loose, fine sand and the glacial till, and the post reaction in gravel was generally not repeatable. Therefore, the gravel test results have been omitted. The results of tests in fine sand and glacial till are listed in Table 3.

The basis for comparison, since it had worked well in early barrier tests, was the right-of-way fence post ($2\frac{1}{4}$ by 2 by 4. 1-lb). All other posts had greater lateral resistance (except 3 by 2 steel tube) but the 3I5. 7 post appeared to have the most desirable properties. It had adequate resistance to lateral force and low resistance to longitudinal force (even less than the right-of-way $2\frac{1}{4}$ by 2). The right-of-way fence post was not considered practical for a barrier post when it was learned that it is produced from merchant quality steel with the result that extreme variations in yield stress are allowed and the steel is very difficult to weld.

A second series of tests was performed using only the 3I5. 7 post since it is not always convenient or economical to set a post in concrete, and a more practical soil anchor was required. Because only lateral strength was needed, a plate welded to the post was a logical substitute for the concrete. Furthermore, the plate did not prevent driving the post into the ground. There was no way to calculate the size of plate required to assure uniform strength in any soil, so several plate sizes were arbitrarily selected for full-scale tests (Table 4). When compared to the concrete embedment, it is apparent that all of the plates performed nearly as well in glacial till. The 8 by 39-in. plate performed best in fine sand. However, a depth greater than 24 in. did not appreciably increase lateral resistance, nor did it decrease the distance over which the post was active, indicating that it was preventing knifing through the soil. Therefore,

TABLE 3

DYNAMIC POST STRENGTH

| Post | Force | Maximum Resistance in lb at 20 mph | | | Inches Over Which Resistance Was Maintained | | |
|---|---|---|---|---|---|---|---|
| | | Fine Sand | Glacial Till | Concrete | Fine Sand | Glacial Till | Concrete |
| 3I5.7 | Lateral | | | 5,800 | | | 21 |
| | | | | 5,400[a] | | | 19 |
| | Longitudinal | | | 1,500 | | | 19 |
| | | | | 2,000[a] | | | 18 |
| 3 by 2 Tube | Lateral | | | 3,700 | | | 20 |
| | | | | 4,100[a] | | | 21 |
| | Longitudinal | | | 2,500 | | | 20 |
| | | | | 2,900[a] | | | 21 |
| R.O.W. | Lateral | | | 4,700[a] | | | 24 |
| 2¼ by 2 by 4.1 | Longitudinal | | | 2,100[b] | | | 20 |
| | | | | 2,400[b] | | | 22 |
| 6B8.5 | Lateral | 5,500 | 13,100 | | 34 | 22 | |
| | | 3,800[a] | 10,200 | | 30 | 23 | |
| | | 6,200[a] | 7,800[a] | | 31 | 28 | |
| | Longitudinal | 3,800 | 4,500 | | 26 | 25 | |
| | | 3,000 | 4,500 | | 25 | 21 | |
| | | 3,800 | 4,600 | | 27 | 23 | |
| | | 3,600[a] | 3,800[a] | | 26 | 21 | |
| $S_L$ | Lateral | 4,300 | 5,400 | | 31 | 30 | |
| | | 4,300[a] | 6,500[a] | | 29 | 24 | |
| | | 4,100[a] | | | 26 | | |
| | Longitudinal | 4,800 | 5,200 | | 30 | 28 | |
| | | 4,400[a] | 5,500[a] | | 31 | 21 | |
| | | | 5,700[a] | | | 18 | |
| Cedar (8 by 6) | Lateral | 5,800 | 10,400 | | 43 | 13 | |
| | | 4,800[a] | 7,100 | | 43 | 24 | |
| | | | 8,400[a] | | | 55 | |
| | Longitudinal | 5,800 | 9,500[a] | | 47 | 5 | |
| | | 6,600 | 7,000[a] | | 46 | 4 | |
| | | 5,200[a] | 6,700[b] | | 51 | 6 | |
| 3 by 5 Tube Aluminum | Lateral | | | 7,100[a] | | | 16 |

[a]10 mph.
[b]30 mph.

the 8 by 24-in. plate was selected because it appeared to be a good compromise among lateral strength, lateral distance the post was active and area of steel plate required. It was not considered economical to use other than a rectangular shape for the soil anchor.

## FULL-SCALE BARRIER TESTS

It was recognized at the outset of this research program that full-scale testing of selected barrier configurations would be required to supplement the mathematical analysis. Because of the complexity of the problem as well as the number and indeterminate nature of some of the parameters involved, it was essential that certain values be measured in order for equations to be derived which would describe mathematically a vehicle colliding with a barrier. Further, full-scale tests were required to verify these models by comparing the predicted performance of a given barrier under impact conditions with an actual collision under the same conditions of impact. Finally, full-scale testing was performed to obtain photographic evidence that would demonstrate the performance of the various types of barriers.

### Test Procedures

Vehicles—All vehicles for the dynamic tests were obtained from State surplus and returned for disposal on completion of the tests. Standard models of the popular makes were selected to provide results which could be taken as typical of those that might actually occur in barrier crashes.

Automobiles for Tests 1-9 (1960-1961) were 1957 4-door Ford sedans weighing 3,800 lb, with a wheelbase of 116 in., and equipped with interceptor engines, power brakes and

TABLE 4
DYNAMIC STRENGTH 315.7 POST WITH ANCHOR PLATES

| Plate Size, in. (Area, in.$^2$) | Lateral Axis | | | | Longitudinal Axis | | | |
|---|---|---|---|---|---|---|---|---|
| | Fine Sand | | Glacial Till | | Fine Sand | | Glacial Till | |
| | Lb | In. | Lb | In. | Lb | In. | Lb | In. |
| Concrete 12-in. diameter | | | 5, 800 | 21 | | | 1, 500 | 19 |
| | | | 5, 400[a] | 19 | | | 2, 000[a] | 18 |
| 4 by 24 (96) | 3, 900 | 34 | 4, 000 | 19 | | | 1, 500[a] | 10 |
| | | | 5, 200[a] | 24 | | | | |
| 6 by 24 (144) | 4, 100 | 31 | 5, 700 | 20 | | | | |
| | 4, 000[a] | 30 | 5, 200 | 19 | | | | |
| | | | 5, 000 | 17 | | | | |
| | | | 4, 200 | 22 | | | | |
| | | | 3, 700 | 20 | | | | |
| 8 by 24 (192) | 4, 500 | 31 | 4, 900[a] | 22 | | | 1, 900 | 20 |
| | 4, 300[a] | 25 | 4, 700[a] | 18 | | | | |
| 4 by 39 (156) | 4, 200 | 32 | | | 1, 600[a] | 20 | 2, 100[a] | 20 |
| | 4, 300[a] | 29 | | | | | 1, 600[a] | 16 |
| 6 by 39 (234) | 4, 400[a] | 27 | 5, 700 | 21 | 1, 600 | 21 | 1, 900[a] | 20 |
| | | | 5, 900[a] | 17 | 1, 600[a] | 18 | | |
| 8 by 39 (312) | 4, 800 | 23 | 5, 600 | 18 | | | 2, 000 | 19 |
| | 4, 700[a] | 21 | 5, 700[a] | 19 | | | | |

[a]10 mph.

standard shifts. The center of gravity was 22 in. above the pavement and 51. 3 in. aft of the front axle. One of the vehicles was used as a control car, and another to push test cars up to starting speeds.

Crash vehicles for Tests 10-19 (1963) were 1960 Plymouth 2-door sedans weighing 3, 900 lb, with a wheelbase of 118 in., and equipped with power steering, power brakes, and automatic transmissions. The center of gravity was 22 in. above the pavement and 53 in. aft of the front axle. One vehicle was used as the control car. A 1955 60-passenger Ford school bus, weighing approximately 14, 000 lb, was used for Test 16. The bus was 32 ft long, and its center of gravity was 42 in. above the pavement and 13 ft aft of the front axle.

Vehicles for Tests 20-24 (1965) were 1961 Plymouth 2-door sedans weighing 3500 lb, with a wheelbase of 119 in., and equipped with 6-cylinder engines, automatic transmissions, standard steering and brakes. The center of gravity was 22 in. above the pavement and 53 in. aft of the front axle.

Control Equipment—Three remote control systems were used during the investigation, with the final system providing the most precise control over impact angle. Before each full-scale test, the crash vehicle was driven through a series of preliminary runs to establish the line of approach and the length of run necessary to accelerate the vehicle to impact speed. After each test, remote control equipment was removed and placed in the next vehicle to be tested.

Radio Control—For the initial series of tests, equipment to control test vehicles was borrowed from the Materials and Research Section of the California Division of Highways, which also generously provided assistance in installation of the equipment.

Tether Cable Control—Because of interference on transmitting frequencies and difficulty in steering, the remote radio equipment was replaced with a system designed by Cornell Aeronautical Laboratory for Tests 8-19.

Guide Track Control—In both radio-controlled cars and the tethered cars the remote driver tended to oversteer because he had no feel for the car motion. In Tests 20-48 precise control of angle of impact was desired. Therefore, the cars were guided by placing the wheels on one side in a long steel channel (track) nailed to the runway along the predetermined approach to the impact point (Fig. 11). The channel, connected in 40-ft sections, was easily moved for the next test. Signals for ignition cut-off and braking were transmitted through a tether cable by opening a single switch controlled by a man located in good view of the approaching car and the barrier.

Figure 11. Test car in steel channel track.

Test Sites—Two test sites were used. Tests 1-19 (1961-1963) were conducted at Niagara Falls Municipal Airport. A wide concrete ramp provided an approach to an area suitable for erecting a barrier up to 200 ft long. Tests 20-48 (1965) were conducted at Schenectady County Airport. Two unused landing strips and flat areas between them provided room for erecting several barriers at the same time and permitted up to three tests in a week.

Barrier Construction—The first nine barriers were erected by Cornell Aeronautical Laboratory. Barriers for Tests 10-48 were fabricated and erected by O. W. Hubbell and Sons, Inc., under contract with New York State Department of Public Works. Barriers for Tests 10-19 were erected at Niagara Falls Airport under supervision of Department personnel from the Buffalo District office. Repair and maintenance of the test barriers was provided by Department maintenance personnel from Niagara County. Barriers for Tests 20-48 were erected at the Schenectady County Airport.

Photographic Coverage—Photographic coverage of all tests was provided by three types of cameras: (a) high-speed movie cameras (500 or 1000 fps) to provide data on vehicle motion; (b) documentary cameras (16 to 64 fps) to provide copy for reports and to document the tests; and (c) normal movies and still photographs taken after the tests to show vehicle and barrier damage.

In the first 19 tests, four high-speed cameras (1000 fps) were used as shown in Figure 12. One was placed at each end of the barrier, one on a line at right angles to the barrier intersecting the impact point and one on a mast 38 ft over the impact point. The cameras at each end of the barrier provided a duplication of data and the overhead camera provided a partial duplication due to a small field of view.

Documentary cameras were usually placed on the ground in these same positions but they were not always used in all locations depending on the barrier being tested. The duplication of coverage was justified because of the difficulty in maintaining a clear view (impact raised dust around the test cars), the probability of some mechanical failure, and the restricted impressions often rendered by a single view of a subject.

For Tests 20-48 the number of cameras was reduced. Only two high-speed cameras were needed for data. Since a large number of tests were scheduled and many were similar, it was felt that it would be easier to re-run a test if a camera failed than to provide duplicate coverage. In addition, a rigorous check-out and countdown system was developed to insure that all cameras would function for a test.

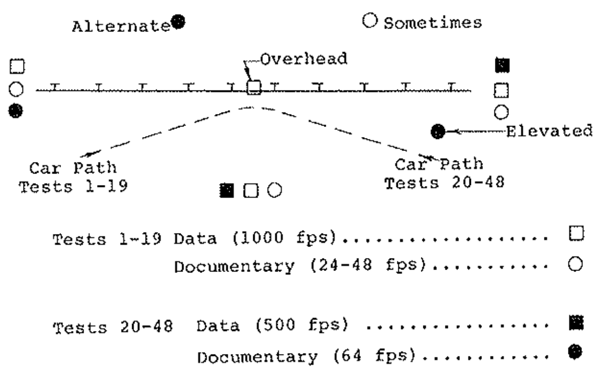



Figure 12. Camera locations.

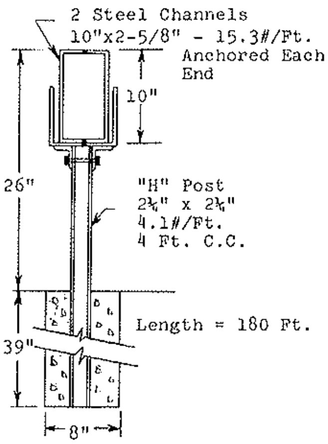
## DEVELOPMENT OF NEW BARRIERS

It would be desirable to have one "all-purpose" highway barrier for guide rail, median barrier or bridge railing. However, a primary function of any barrier is to minimize the loss of human life by keeping vehicle deceleration as low as possible during a collision. This can best be accomplished by a system that yields as it deflects since in doing so it absorbs energy and cushions the impact. Unfortunately, large deflections are not always permissible. There are many obstructions such as retaining walls, overhead sign supports, and bridge piers which cannot be removed from the roadside or median. Many existing medians are very narrow and may not economically be widened. For these locations some type of barrier is needed which will restrict deflection to a predetermined value and at the same time minimize vehicle deceleration.

A system relying primarily on rail bending was selected for situations where deflection must be restricted because it appeared the only practical way to develop a nearly constant restraining force with controlled magnitude. A cable guide rail design was modified for use where large deflections are tolerable and where a clear view is desirable or where other types might act as a snow fence. A modified W or corrugated rail design was also developed since it has certain advantages in that it is less affected by minor collisions than the cable, it provides better delineation than cable, and, as it turned out, provides very low vehicle deceleration during major collisions. On bridges, rail deflection must be kept at a very low value. Therefore, a relatively rigid bridge rail was developed. To keep vehicle decelerations as low as possible by permitting as much deflection as the situation will allow it is necessary to change from one system to another. This is most difficult where it is required to have a transition from guide rail to rigid bridge rail. Therefore, this type of transition was included in the test program.

### Box Beam Median Barrier

The first barrier rail designed to act primarily as a beam was a prototype median barrier built and tested by Cornell Aeronautical Laboratory for New York State (Fig. 13). It consisted of a box section rail mounted on lightweight posts. The posts were spaced close together so that several posts would be deflected at the same time during a collision. The rail rested in saddles fastened to the top of each post. The rail tended to stay at the same elevation during collision so that a car would not go over or under it. The small posts were considered expendable during major collisions. The rail and post strength were balanced to limit deceleration to less than 10 g's during a maximum impact by a 4, 000-lb car. For the first test on this prototype barrier the rail ends were anchored. This barrier redirected the car but the steering system was damaged by contact with the posts (Fig. 14) and the saddles were torn off the impacted posts during the collision. During a second test (Fig. 15) the rail ends were not anchored.




Impact Conditions:
Speed: 58 MPH
Angle: 18°

Maximum Dynamic
Deflection: 1.1 Ft.

Exit Conditions:
Speed: 41 MPH
Angle: 7°

Length of Barrier
Contact: 17 Ft.

Number of Posts
Damaged: 4

Average Deceleration:
During Highest Period
7.1 g's (0.05 sec.)
During Barrier Contact
4.6 g's (0.360 sec.)

Permanent Set: 0.2 Ft.

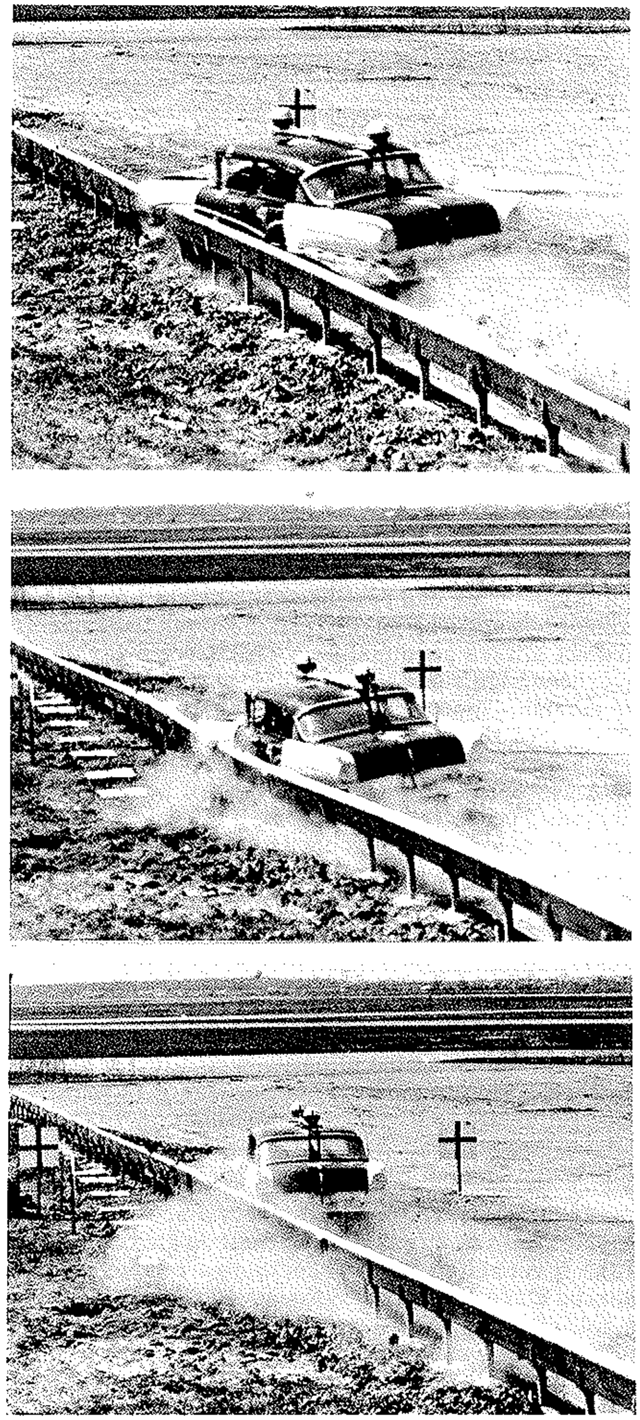


Figure 13. Box beam median barrier (Test 4).

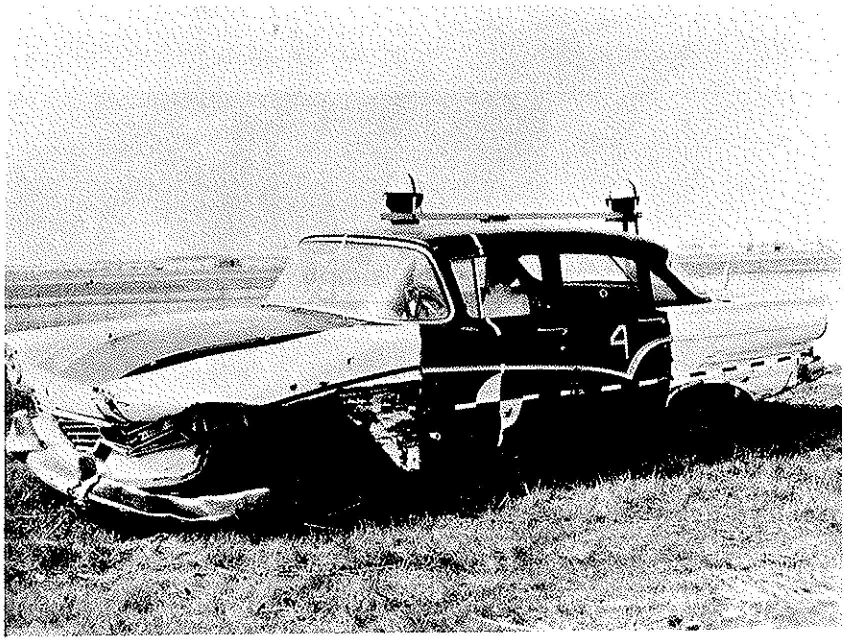


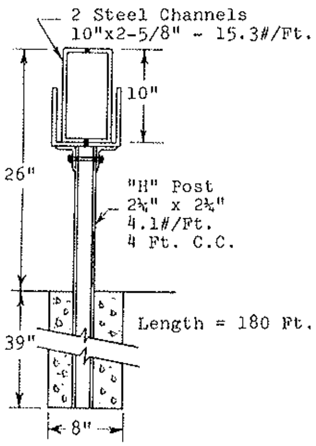
Figure 14. Car after Test 4.

The speed and angle of impact were nearly the same as the previous test and the car and barrier reactions were similar. The calculated increase in rail strength due to end anchors was only six percent at maximum anticipated rail deflection.

The two tests demonstrated that a barrier which controlled deflection without producing intolerable decelerations could be constructed. They also showed that the design concept was practical without providing rail tension with end anchors. The hollow steel tube had a neat appearance along with good performance and it was decided to use this basic concept in developing a median barrier, bridge rail and guide rail. Because of the hollow rectangular steel tube used as a rail this type of barrier became known as a box beam.

Although the first two tests on the prototype box-beam median barrier were highly successful, there were five features which needed improvement:

1. A wider rail was needed to help prevent wheels from contacting the posts in low angle collisions. It was also practical to use a more economical rail section which had the required lateral strength with somewhat less vertical strength. Only a modest vertical strength is required to prevent the rail from sagging between posts even after several have been eliminated during collision.
2. The saddles used to support the rail broke off and would have been a hazard to oncoming traffic.
3. Welded splices are not practical in the field particularly where sections of rail must be replaced by maintenance crews.
4. In tests of the prototype median barrier, posts were spaced at 4 ft. Greater post spacing was desirable in the interest of economy.
5. A post embedded in concrete is expensive and inconvenient to replace. A driven post is, therefore, more desirable.
6. The $2\frac{1}{4}$ by 2-in. fence posts used in Tests 4 and 5 were only available in merchant quality steel which does not have uniform strength or good welding properties. It was necessary to adopt a post with predictable structural characteristics.




Impact Conditions:
Speed: 52 MPH
Angle: 24°

Maximum Dynamic
Deflection: 0.8 Ft.

Exit Conditions:
Speed: 47 MPH
Angle 7°

Length of Barrier
Contact: 14 Ft.

Number of Posts
Damaged: 3

Average Deceleration:
During Highest Period
10.2 g's (0.05 sec.)
During Barrier Contact
4.5 g's (0.350 sec.)

Permanent Set: 0.2 Ft.

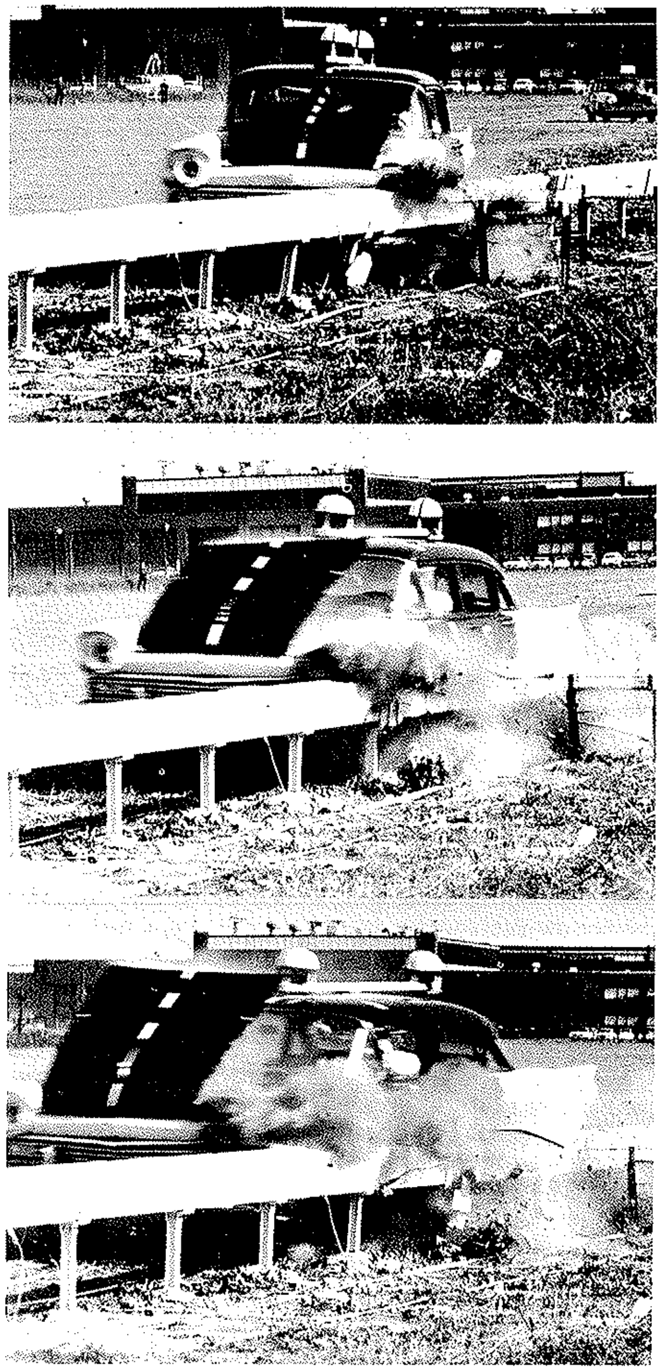


Figure 15. Box beam median barrier (Test 5).

TABLE 5

LATERAL BARRIER RESISTANCE AT 12-INCH DEFLECTION

| Rail Type | Wt/Ft | Sect. Mod. | Resistance (kips) at Post Spacing | | |
|---|---|---|---|---|---|
| | | | 8 Ft | 6 Ft | 4 Ft |
| 5 1/4 by 10 (Test 5) | 30.6 | 17.5 | — | — | 24.5[a] |
| 6 by 6 by 3/16 | 14.4 | 7.8 | 16.6 | 20.0 | 25.2√ |
| 6 by 6 by 1/4 | 18.8 | 9.9 | 17.6 | 22.4 | 28.0 |
| 6 by 6 by 5/16 | 23.0 | 11.8 | 19.6 | 23.6 | 30.0 |
| 6 by 6 by 3/8 | 27.0 | 13.5 | 21.6 | 24.6√ | 31.4 |
| 6 by 6 by 1/2 | 34.4 | 16.1 | 22.2 | 26.4√ | 33.6 |
| 8 by 6 by 3/16 | 16.8 | 11.4 | 20.2 | 24.0 | 30.0 |
| 8 by 6 by 1/4 | 22.0 | 14.6 | 22.8 | 26.0√ | 33.0 |
| 8 by 6 by 5/16 | 27.0 | 17.4 | 23.4 | 28.6 | 35.0 |
| 8 by 6 by 3/8 | 31.7 | 19.9 | 24.2 | 30.0 | 37.0 |
| 8 by 6 by 1/2 | 40.6 | 24.0 | 26.6√ | 31.6 | 40.0 |
| 10 by 6 by 1/4 | 25.4 | 20.1 | 25.4√ | 31.0 | 37.8 |
| 10 by 6 by 5/16 | 31.2 | 24.1 | 28.3 | 32.4 | 40.6 |
| 10 by 6 by 3/8 | 36.8 | 27.7 | 29.6 | 35.0 | 41.4 |
| 10 by 6 by 1/2 | 47.3 | 33.9 | 30.4 | 36.8 | 46.2 |

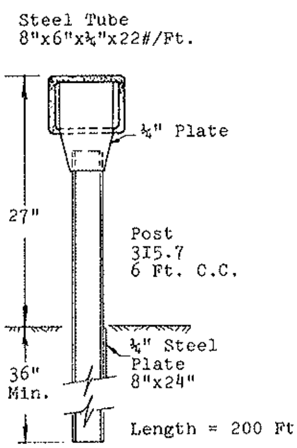
[a]Post strength for Test 5 was 3,000 lb, all others 4,100 lb.

Calculated barrier reactions for the design used in Tests 4 and 5 showed that the rail would deflect about 2 ft when hit by a 4,000-lb car traveling 60 mph and at an angle of 25 deg to the barrier. This would make the rail effective in a median 4 ft wide. It was therefore decided to select a post and rail combination that would have nearly the same characteristics as the one used in Tests 4 and 5.

Table 5 shows the force at 12-in. deflection for several rail and post combinations onsidered. This table includes, on the first line, the results of calculations performed for the prototype barrier. Following down the table it can be seen that the first rail section, tried on posts spaced at 4 ft, developed adequate lateral resistance (check marked). Lateral resistance was also suitable when the heavy wall 6 by 6 tubes and 8 by 6 tubes were mounted on posts spaced at 6 ft. Finally, another acceptable combination appeared to be the heavy wall 8 by 6 or 10 by 6 tubes on posts spaced at 8 ft. Since it was desirable to obtain a minimum weight of rail and a maximum offset between face of rail and post, the 8 by 6 by 1/4 rail on posts spaced at 6 ft was selected for further development.

Hollow steel tubes were selected for a rail because the tubes had good torsional stability, neat appearance and they are commercially available. The rectangular shape allowed maximum dynamic stress in the flanges with little danger of local buckling because of the two webs. An 8 by 6 by 3/16-in. tube with posts spaced at 6 ft had a resisting force almost the same as the CAL prototype, but an 8 by 6 by 1/4-in. tube was selected because it was necessary to cut holes in the tube to make post connections and it was felt that extreme bending would produce stress concentrations at ends of splice plates. The post selected first was a 3 by 2 by 3/16-in. hollow steel tube, but later the 3I5.7 post was found to have nearly the same lateral strength, less longitudinal strength and was more economical. The 3I5.7 post was substituted for the 3 by 2-in. tube without recalculating the force deflection curves or a vehicle trajectory.

Considerable difficulty was encountered in developing a satisfactory rail-post connection. The connection shown in Figure 16 was designed to sustain a 4,000-lb lateral load under plastic deformation. It will resist a longitudinal load of about 1,000 lb which is as little as could be obtained while maintaining a 4,000-lb lateral strength. The plate was designed to allow the rail to deflect laterally with little change in elevation. When a post is bent over by direct contact with a car bumper, the post is free to pull out of the rail so as not to pull the rail down. The tendency for the rail to lie down when hit by a car is resisted by the vertical stiffness of the rail and by undisturbed posts outside the impact area. There was no positive connection between rail and post. It was




Impact Conditions:
  Speed: 56 MPH
  Angle: 25°

Maximum Dynamic
  Deflection: 5.5 Ft.

Exit Conditions:
  Speed: 34 MPH
  Angle: 9°

Length of Barrier
  Contact: 30 Ft.

Number of Posts
  Damaged: 10

Average Decelerations:
  During Highest Period
  5.3 g's (0.05 sec.)
  During Barrier Contact
  1.6 g's (0.900 sec.)

Permanent Set: 3.0 Ft.


Figure 16. Box beam median barrier (Test 24).

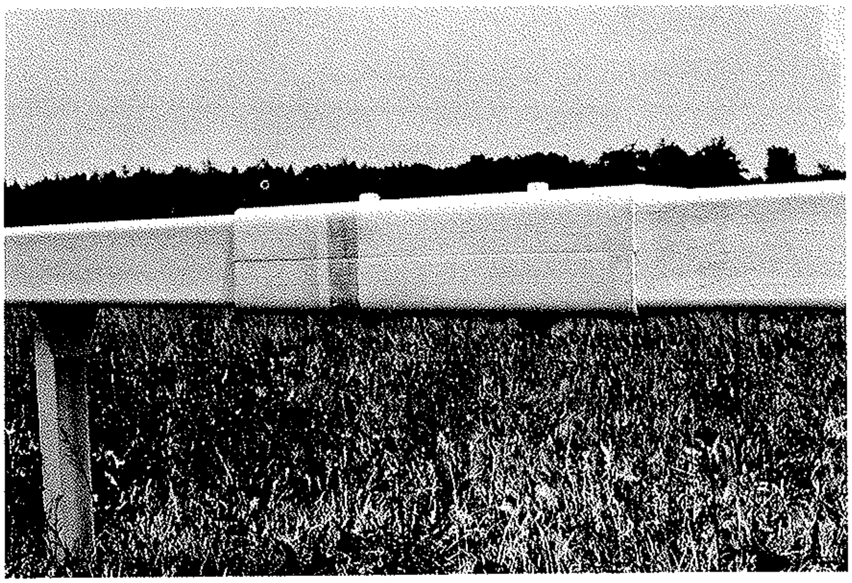


Figure 17. Box beam median barrier splice.

felt that any positive connection would make it more hazardous for a car to get by a post while the rail was deflected. It was also hoped that the rail denting into the car /ould help prevent rail uplift.

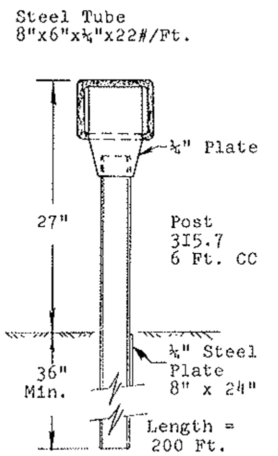
The splice illustrated in Figure 17 was designed to resist lateral bending. Since very little tension is developed in the rail, it was not necessary to design the splice to transmit high tensile stresses. The bolts serve first to hold the bent plates in place and second to develop a nominal amount of rail tension when the rail is loaded beyond design capacity. An internal splice would present a more pleasing appearance but would make rail replacement much more difficult. It is also difficult to develop an internal splice which is snug fitting and easily installed. A lateral snug fit is essential if lateral bending strength is to be maintained. Several internal and external splices were tested in the laboratory. The one shown in Figure 17 seemed like the simplest to fabricate and developed the lateral strength of the rail in laboratory tests.

The two major testing impact conditions, 60 mph at a 25-deg angle and 45 mph at a 35-deg angle were selected for the steel box beam median barrier because they represented the most severe impacts expected on this barrier. A shallow angle impact was not planned; however, one occurred following a major impact and it clearly demonstrated the favorable results of a shallow angle impact. A third test was performed at 60 mph with a 25-deg angle on an aluminum rail placed on the same posts used for the steel rail tests.

Results of the two tests on steel box beam median barrier are shown in Figures 17 and 18.

The vehicle reactions for these two tests were very satisfactory. Maximum vehicle decelerations were 5 g's and 10 g's as shown in Figures 16 and 18. In Test 24 the steering system was damaged when one wheel struck one or more posts (see Fig. 19). In Test 26 the deceleration was greater but the steering was not damaged. The car was driven away after the test (Fig. 20). Vehicle redirection was very good. In Test 24 the car collided with the barrier a second time and slid along the barrier until it stopped.

The barrier performance was not as good as desired. Rail deflections of 5.5 ft for Test 24 and 5.6 ft for Test 26 were greater than the 2 ft expected. The high-speed movies showed that the rail moved vertically up along the post as the post inclined




Impact Conditions:
Speed: 43 MPH
Angle: 35°

Maximum Dynamic
Deflection: 5.6 Ft.

Exit Conditions:
Speed: 22 MPH
Angle: 18°

Length of Barrier
Contact: 24 Ft.

Number of Posts
Damaged: 7

Average Deceleration:
During Highest Period
10.2 g's (0.05 sec.)
During Barrier Contact
2.4 g's (0.740 sec.)

Permanent Set: 2.5 Ft.

Figure 18. Box beam median barrier (Test 26).

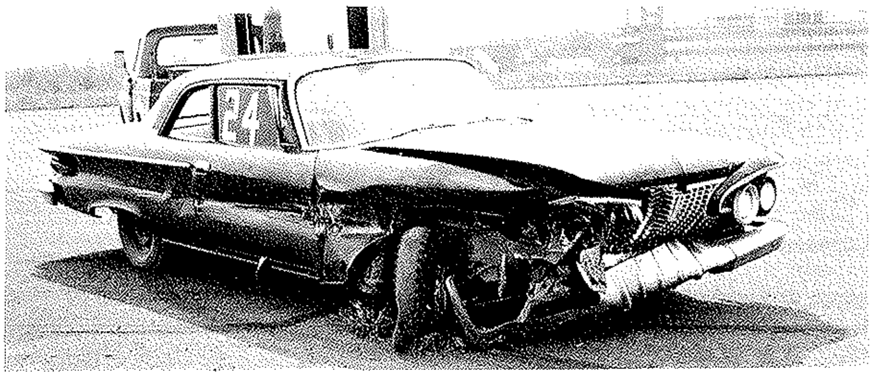



Figure 19. Car after Test 24.

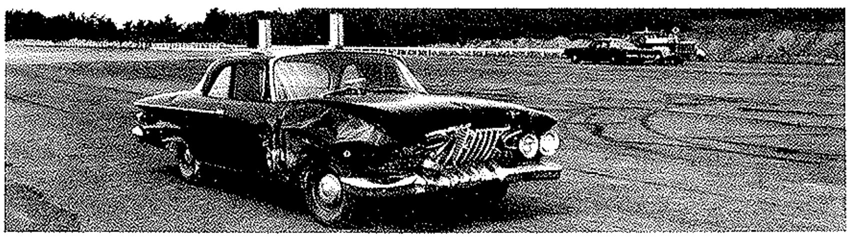


Figure 20. Car after Test 26.

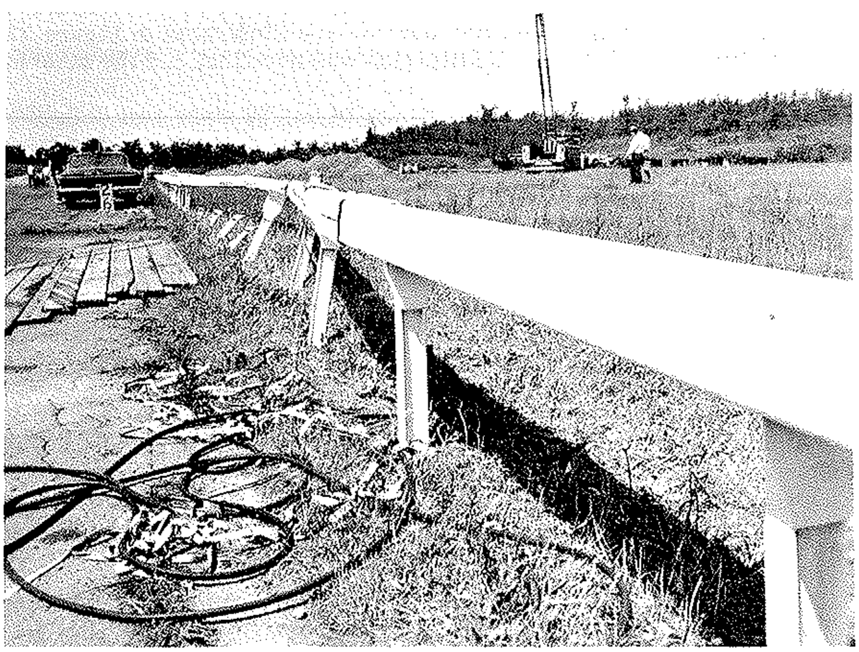


Figure 21. Box beam median barrier after Test 26.

laterally. When the rail lost contact with the post sooner than expected it was relatively free to deflect laterally. The extra deflection resulted in long vehicle contact with rail and several posts were bent over by the car (Fig. 21). The most noticeable rail bends occurred at the splices. There was about ⅛-in. lateral clearance between rail and splices which allowed the rail to deflect easily at the splices after the rail lost contact with the posts.

The test on a median barrier using an aluminum rail was planned for 60 mph and 25 deg, the same as for the steel rail, to provide data on the effects of rail mass and the dynamic strength of aluminum.

To evaluate the influence of rail inertia on a colliding vehicle it was assumed that an 18-ft section of steel box-beam rail (400 lb) attains a lateral velocity of 21 mph when impacted by a 3800-lb car at 60 mph and 25 deg (car's lateral velocity = 25 mph). Using the principle of conservation of momentum ($M_1 \times \Delta V_1 = M_2 \times \Delta V_2$), it was computed that lateral velocity of the car would decrease by 2 mph. An aluminum rail of the same cross-sectional area would weigh approximately one-third as much as the steel rail and the lateral velocity of the car would decrease about 0. 7 mph.

The change in lateral kinetic energy of the car due to the change in lateral velocity is about 530 ft-lb when impacting the steel rail and about 59 ft-lb when impacting the aluminum rail. Since the car has nearly 80, 000 ft-lb of lateral energy, it was concluded that rail inertia should not significantly affect the ability of the barrier to absorb the impact.

The dynamic yield strength of steel is about 20 percent greater than the static yield strength (6). The dynamic yield strength of 6061T6 aluminum alloy was found to be slightly less than the static yield strength in one dynamic post test. The aluminum rail had the same cross-sectional area as the steel tube used in Tests 24 and 26 but the wall thickness was varied to get a larger section modulus which compensated for the reduced dynamic yield strength.

The objective of a full-scale test on aluminum rail was to find out if the aluminum would perform in a manner similar to steel and if the difference in mass had any noticeable effect on reactions. However, the adverse effects of rail uplift in Tests 24 and 26 made it necessary to revise the rail-post connection so that some resistance to rail uplift was developed. This was accomplished by cutting the plate as shown in Figure 22. The ¼-in. "ear" provided a mechanical interlock with the lip on the bottom side of the rail.

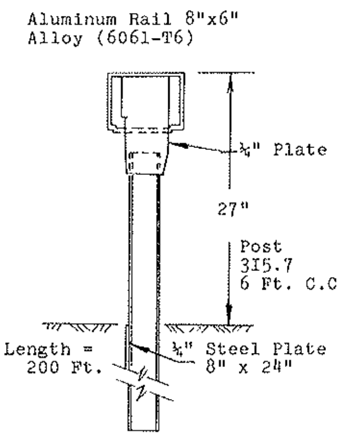
Results of the test on aluminum median barrier are illustrated in Figure 22. Vehicle deceleration was limited to 5. 5 g's. Redirection was excellent and the steering system was not badly damaged.

Barrier performance was better than in Tests 24 and 26 since rail deflection was limited to 3 ft and there was very little rail uplift. Some posts were lifted slightly which indicated that the "ear" on top of the post helped keep the rail down. The 3-ft rail deflection was still greater than was desired. The internal splices were loose as shown in Figure 23 and this may account for some of the dynamic deflection. During the collision one post was pulled completely out of the ground, bounced up, and drove up through the rear floor pan and into the right side of the car. The post was located where the rail deflected excessively and the plate on top of the post was bent about 90 deg. No other posts in the three tests were bent in this manner. It is assumed that this post action is due partly to excessive rail deflection. Damage to the aluminum rail was about the same as for the steel rails (Fig. 24).

The barrier details shown in Figure 25 have been accepted by the New York State Department of Public Works and are being used in medians up to 14 ft wide. Where necessary, shims are used at the splices to assure a snug lateral fit and minimum rail deflection. The paddle is bolted to the top of the post rather than welded for easier post driving. Holes 1 in. in diameter are used at splices for ¾-in. bolts to provide for temperature expansion and contraction. At bridge expansion joints the hole in the rail is slotted.

## Box Beam Bridge Railing

The box beam concept also appeared to be applicable in the design of bridge rails and it was decided to develop a bridge rail with the same force-deflection characteristics a




Impact Conditions:
  Speed: 50± MPH
  Angle: 25°

Maximum Dynamic
  Deflection: 3.0 Ft.

Exit Conditions:
  Speed: 40± MPH
  Angle: 0°±

Length of Barrier
  Contact: 30 Ft.

Number of Posts
  Damaged: 7

Average Deceleration:
  During Highest Period
  5.2 g's (0.05 sec.)
  During Barrier Contact
  1.6 g's (0.90 sec.)

Permanent Set: 2.0 Ft.

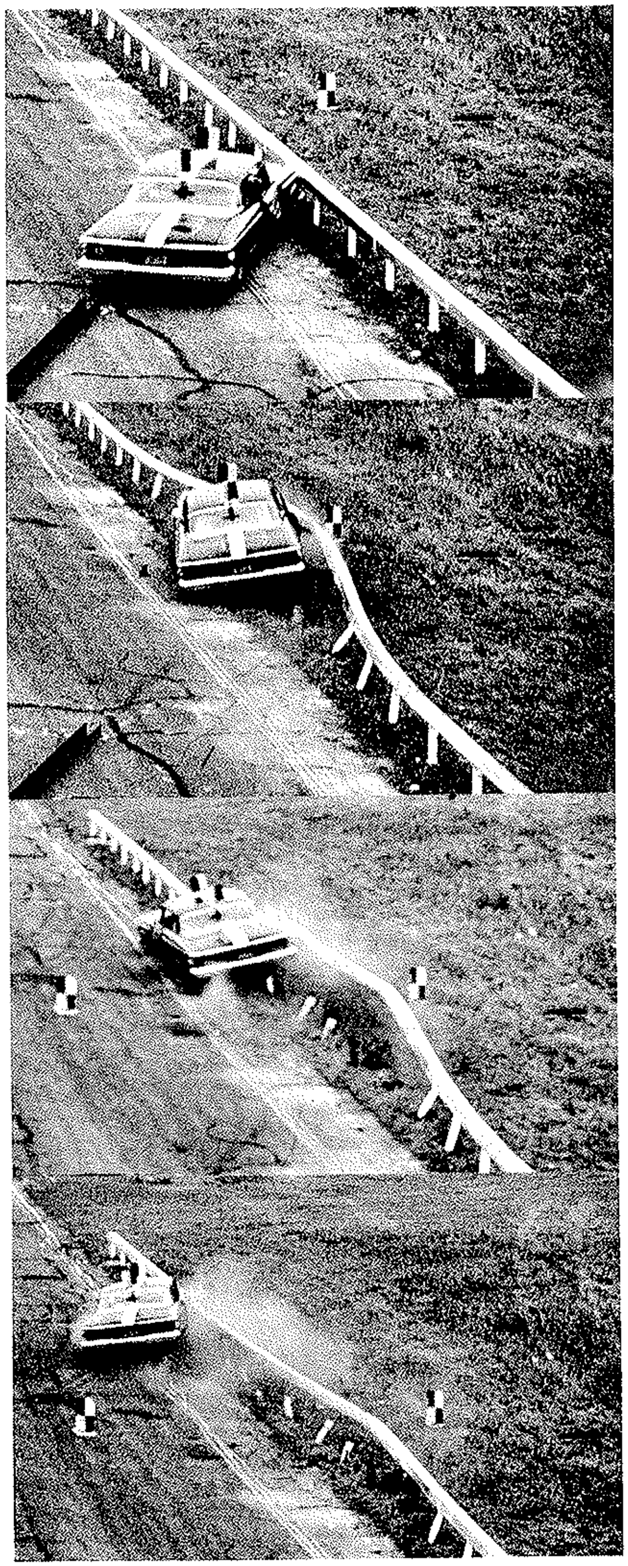


Figure 22. Box beam median barrier (Test 43).

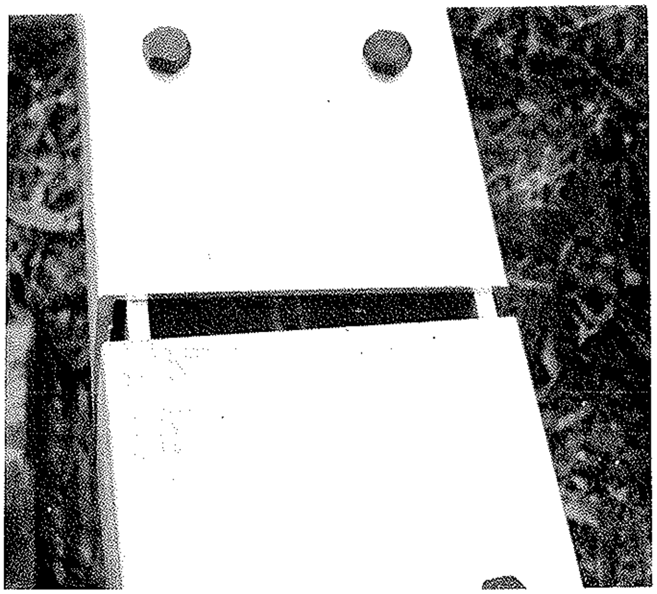


Figure 23. Splice after Test 43.

the box beam median barrier. There are several differences between the two systems. The median barrier posts are usually driven into soil, but on a bridge the posts are anchored to concrete or steel. On bridges the railing often serves as a pedestrian handrail and many times a curb is desirable to control drainage and provide a walkway for pedestrians. The box beam bridge rail was designed to meet all of these conditions along with the six normal functions of a highway barrier.

The first two box beam bridge rail tests are shown in Figures 26 and 27. Tests performed by the California Division of Highways (7) indicated that a curb could cause a car to jump appreciably. To provide for this possibility, the railing was first tested behind a 10-in. curb with a 5-ft sidewalk. The second test was performed on a rail mounted behind a 20-in. safety walk. The top rail in the first test and the bottom rail in the second test were placed at the elevation anticipated for the car center of gravity. It was thought that a passenger vehicle would contact only one rail and leave the other rail relatively free. Trucks, of course, would likely bear on both rails. Therefore each rail (considering post height and spacing) was designed to provide the same strength as the prototype box beam median barrier. The top rail had a larger section modulus in order to distribute the load over more posts because each post would act as a longer cantilever with the top rail than it would with the lower rail. A curb 10 in. high was used since this is accepted practice on New York State bridges. A 3 by 2-in. hollow steel tube post was selected because it had a pleasing appearance and the desired lateral strength.

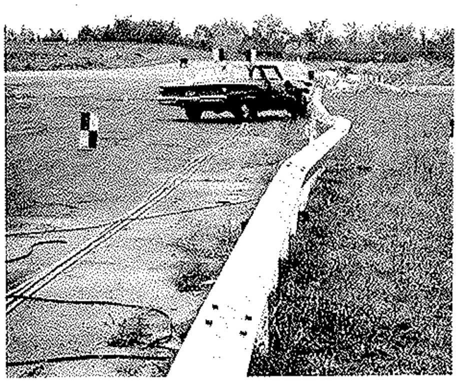


Figure 24. Barrier after Test 43.

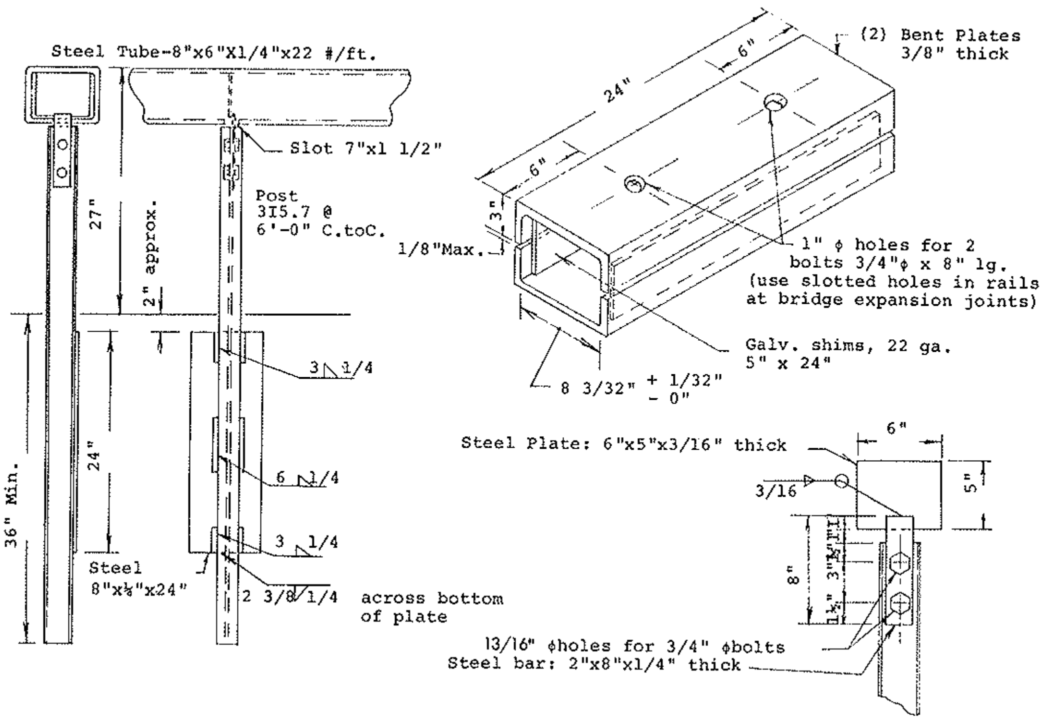


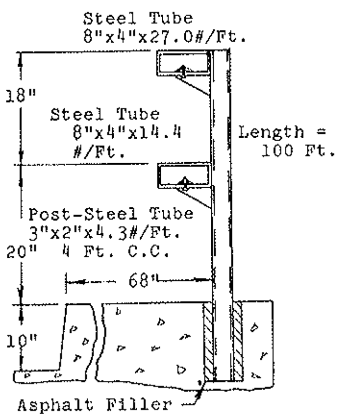

Figure 25. Box beam median barrier details.

The barriers were impacted at approximately 60 mph and 25 deg (Figs. 26 and 27). When the cars traversed the 5-ft wide sidewalk it did not jump. However, the car body was raised so that at impact it was at normal height above the sidewalk surface. To minimize longitudinal post strength, toggle bolts were tried in the first test. The particular size and style used proved to be too weak to retain the rails and while they did not influence the test results they were not used again. In both of these tests, the lateral rail deflection was much less than desired and accordingly the vehicle deceleration was much higher. Review of the high-speed data films showed that both rails were active in restraining the car. The 10-in. high curb damaged the steering system. Evidence of rail and curb action are shown in Figure 28 along with pictures of the bridge railing before and after test.

A third test was performed on this same box beam bridge rail design constructed of aluminum (Fig. 29). The car was partially redirected when the welded portion of the posts at the base plates began to tear. Successive failure of nearly every post allowed the car to carry off the rails. The high-speed films indicate that the barrier was performing as expected until the posts failed and correction of this deficiency might have provided an acceptable design.

A final test of this box beam design was performed using a 14,000-lb school bus (Fig. 30). The front wheel mounted the curb, the bus impacted the railing and was smoothly redirected. Neither the bus nor the rail were extensively damaged and vehicle deceleration was moderate. In addition to visually studying the problems which might be associated with high center of gravity and large wheels, this test provided data which could be used to verify the vehicle trajectory model with large vehicles.

As a result of the initial tests and analyses, a modified box beam bridge rail design was developed. This design had lighter rails which were assumed to act in unison to provide the lateral resisting force and deflect about 2 ft during a severe impact. The calculated force-deflection curve was nearly the same as for the prototype box beam median barrier.




Impact Conditions:
Speed: 61 MPH
Angle: 27°

Maximum Dynamic
Deflection: 0.9 Ft.

Exit Conditions:
Speed: 43 MPH
Angle: 6°

Length of Barrier
Contact: 16 Ft.

Number of Posts
Damaged: 4

Average Deceleration
During Highest Period
10.9 g's (0.05 sec.)
During Barrier Contact
5.2 g's (0.265 sec.)

Permanent Set: Not
measurable

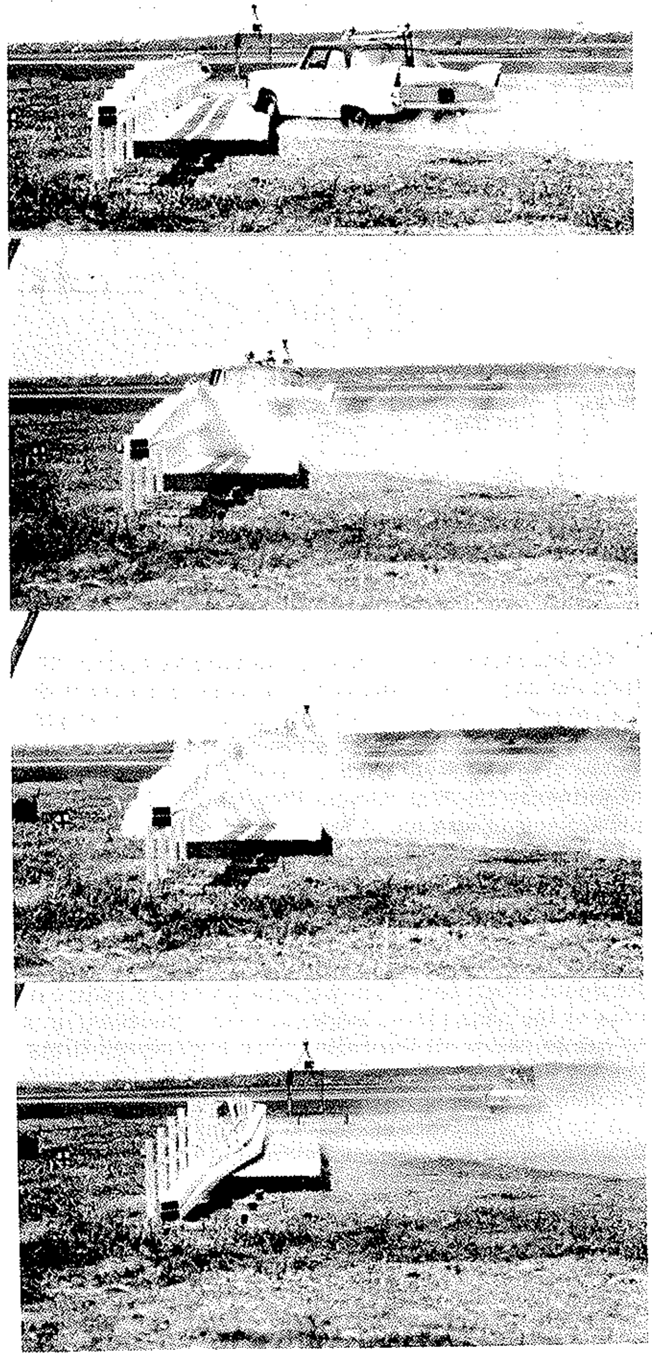
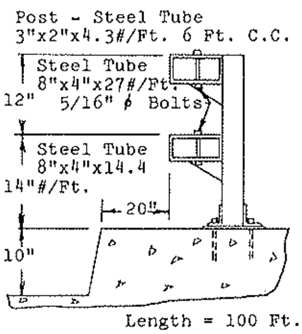


Figure 26. Box beam bridge rail (Test 10).




Impact Conditions:
Speed: 51 MPH
Angle: 28°

Maximum Dynamic
Deflection: 0.5 Ft.

Exit Conditions:
Speed: 38 MPH
Angle: 5°

Length of Barrier
Contact: 10 Ft.

Number of Posts
Damaged: 6

Average Deceleration:
During Highest Period
14.4 g's (0.05 sec.)
During Barrier Contact
3.7 g's (0.365 sec.)

Permanent Set: 0.1 Ft.

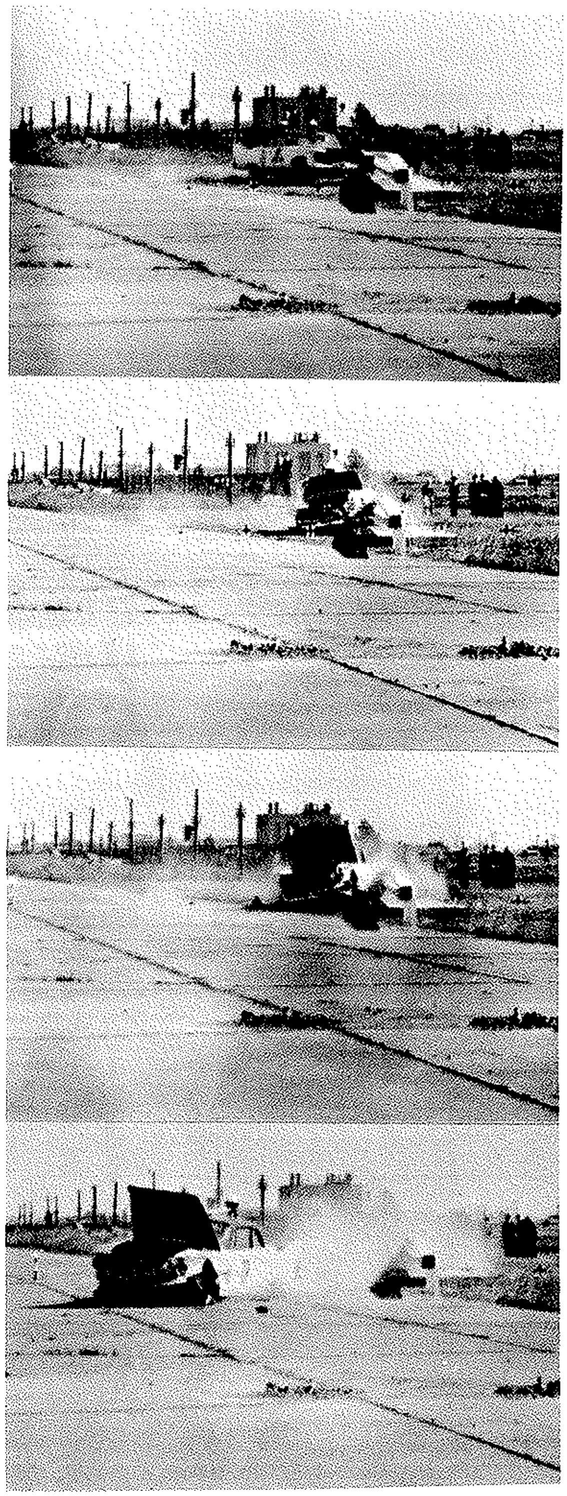


Figure 27. Box beam bridge rail (Test 11).

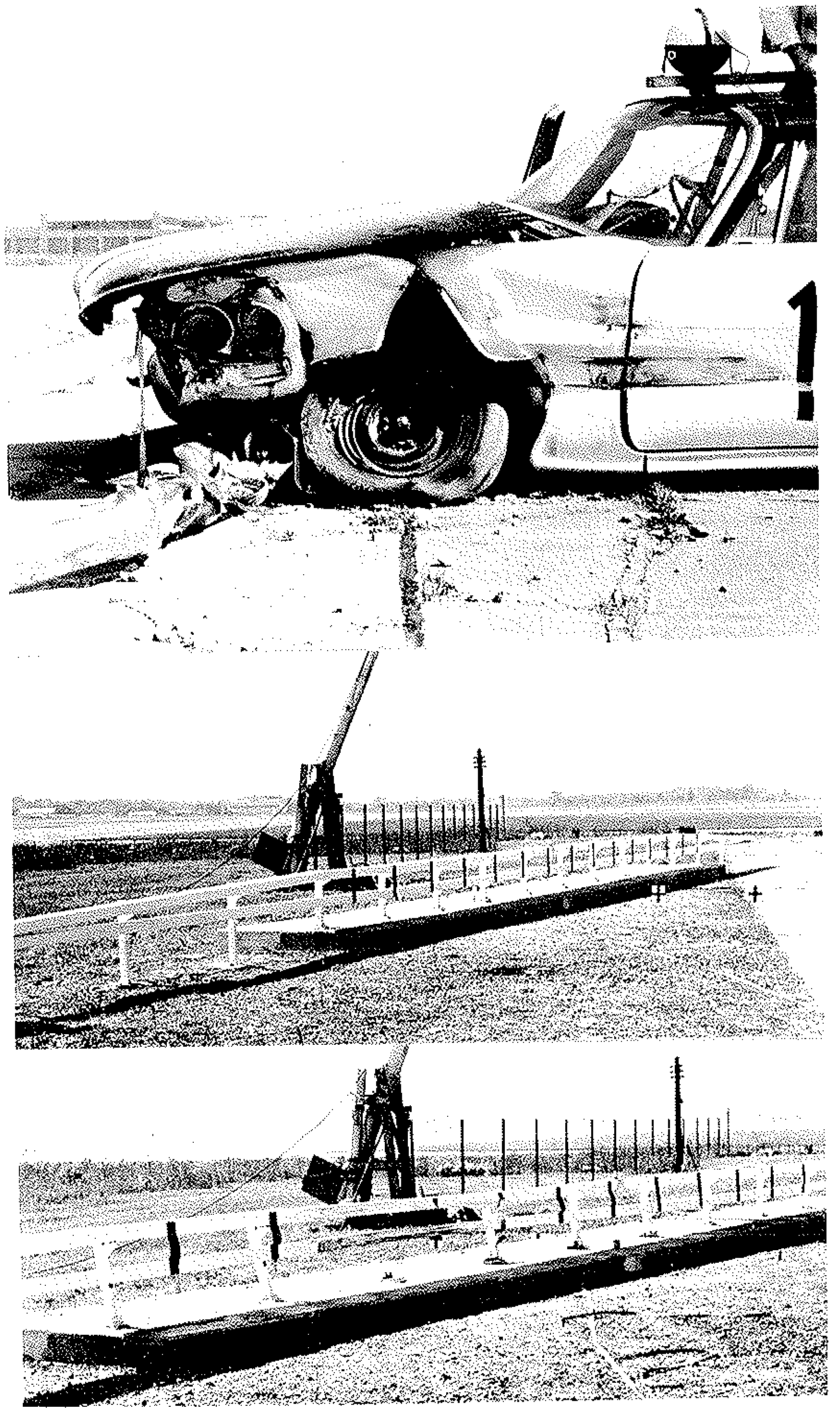
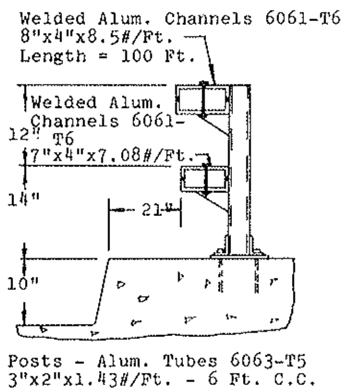


Figure 28. Car and barrier damage (Test 11).




mpact Conditions:
Speed: 57 MPH
Angle: 30°

Maximum Dynamic
Deflection: + 10 ft.

Exit Conditions:
Speed: Not applicable
Angle: Not applicable

Length of Barrier
Contact: +50 ft.

Number of Posts
Damaged: All

Average Deceleration:
During Highest Period
Not determined
During Barrier Contact
Not determined

Permanent Set:
None in rails

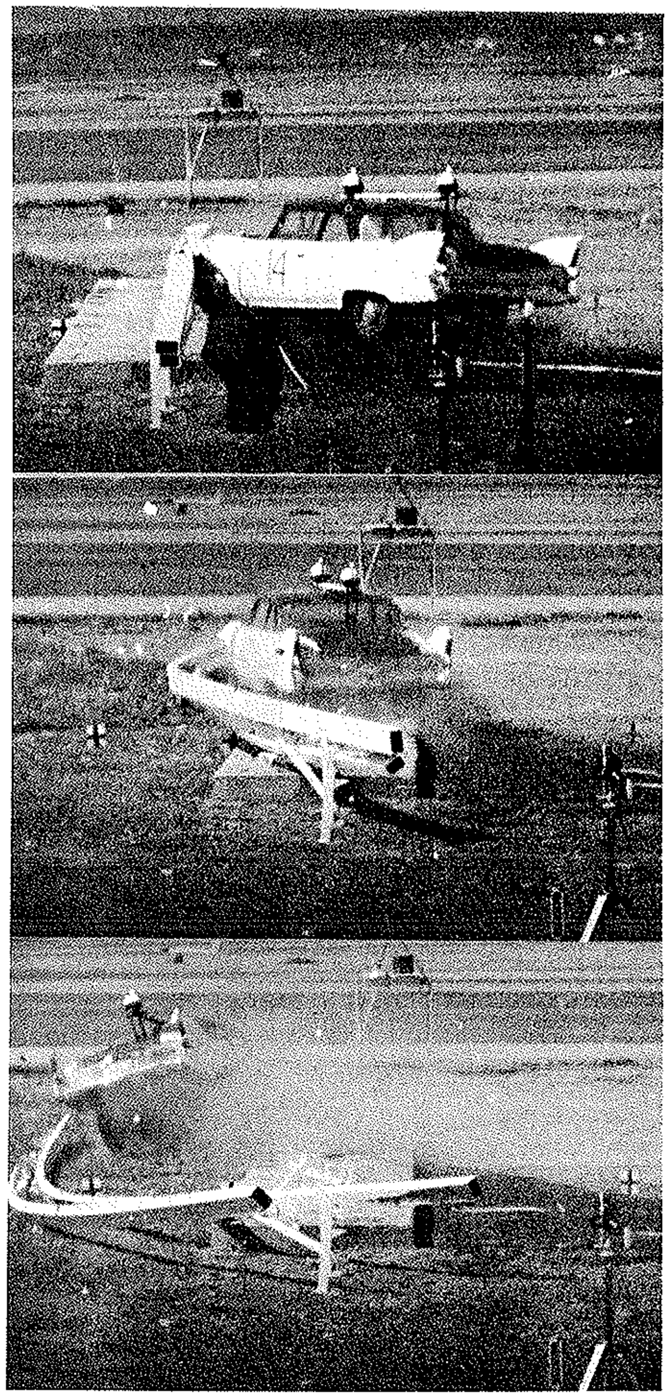
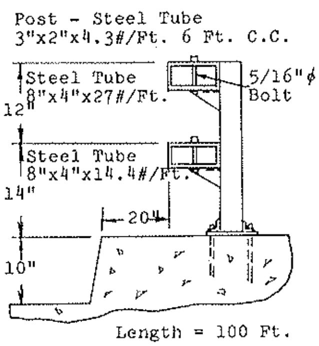


Figure 29. Box beam bridge rail (Test 14).




Impact Conditions:
  Speed: 29 MPH
  Angle: 22°

Maximum Dynamic
  Deflection: 0.3 Ft.

Exit Conditions:
  Speed: 25 MPH
  Angle: 6°

Length of Barrier
  Contact: 10 Ft.

Number of Posts
  Damaged: 6

Average Deceleration:
  During Highest Period
  3.7 g's (0.05 sec.)
  During Barrier Contact
  0.8 g's (1.000 sec.)

Permanent Set: 0.1 Ft.

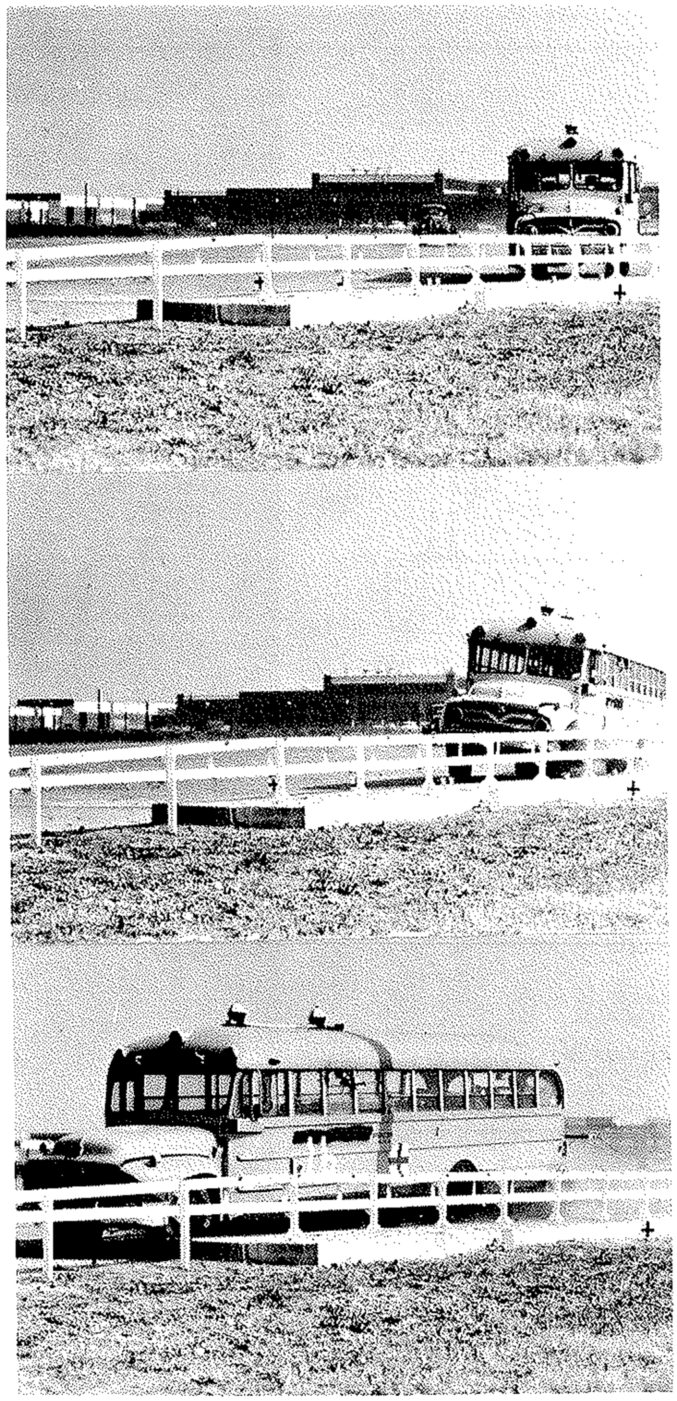
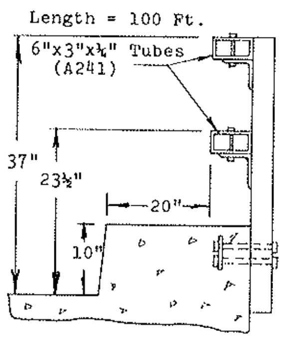


Figure 30. Box beam bridge rail (Test 16).




Post - 3"x2"x3/16" Tube
(A36)
6 Ft. C.C.

Impact Conditions:
Speed: 40 MPH
Angle: 25°

Maximum Dynamic
Deflection: 0.3 Ft.

Exit Conditions:
Speed: 12 MPH
Angle: 3°

Length of Barrier
Contact: 24 Ft.

Number of Posts
Damaged: 4

Average Deceleration:
During Highest Period
5.6 g's (0.05 sec.)
During Barrier Contact
2.4 g's (0.605 sec.)

Permanent Set: 0.2 Ft.

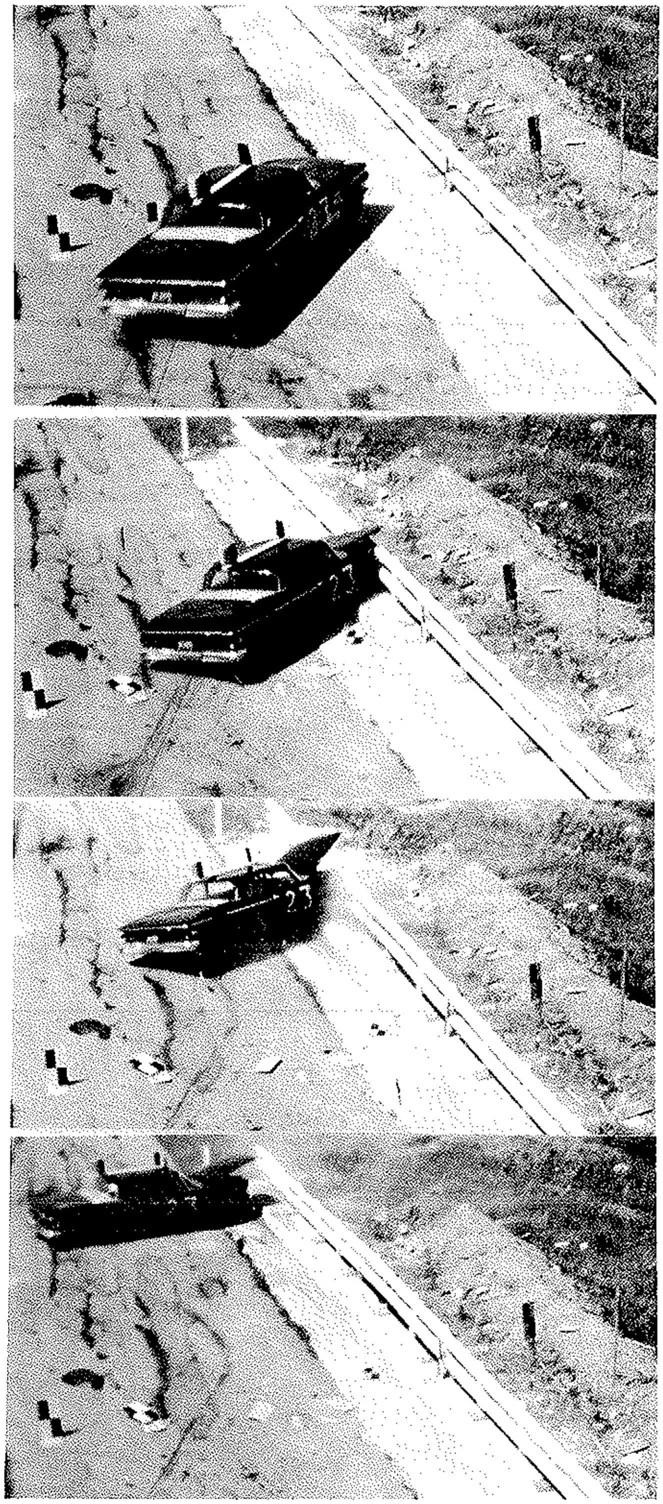
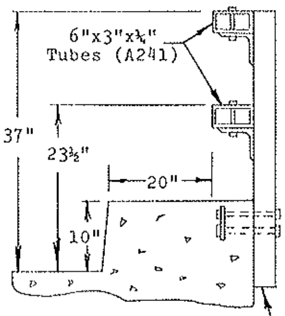


Figure 31. Box beam bridge rail (Test 23).




Length = 100 Ft.

Impact Conditions:
  Speed: 60 MPH
  Angle: 25°

Maximum Dynamic
  Deflection: No Data

Exit Conditions:
  Speed: No Data
  Angle: No Data

Length of Barrier
  Contact: 24 Ft.

Number of Posts
  Damaged: 4

Average Deceleration
  During Highest Period
    No Data
  During Barrier Contact
    No Data

Permanent Set: 0.4 Ft.

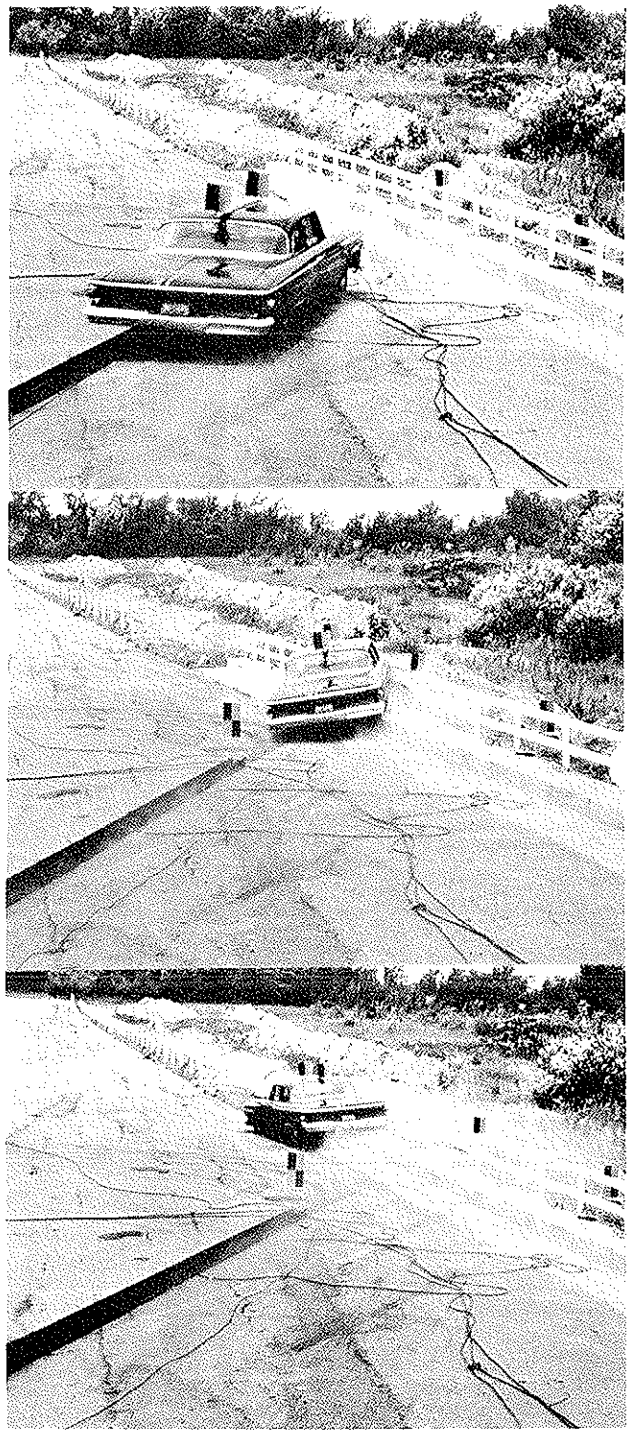
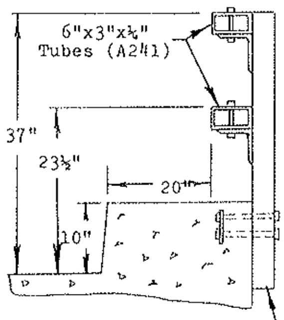


Figure 32. Box beam bridge rail (Test 31).




Post - 3"x2"x3/16" Tube (A36) 6 Ft. CC

Length = 100 Ft.

Impact Conditions:
Speed: 61 MPH
Angle: 25°

Maximum Dynamic
Deflection: 0.9 Ft.

Exit Conditions:
Speed: 52 MPH
Angle: 7°

Length of Barrier
Contact: 18 Ft.

Number of Posts
Damaged: 5

Average Deceleration
During Highest Period
9.5 g's (0.05 sec.)
During Barrier Contact
2.8 g's (0.570 sec.)

Permanent Set: 0.5 Ft.

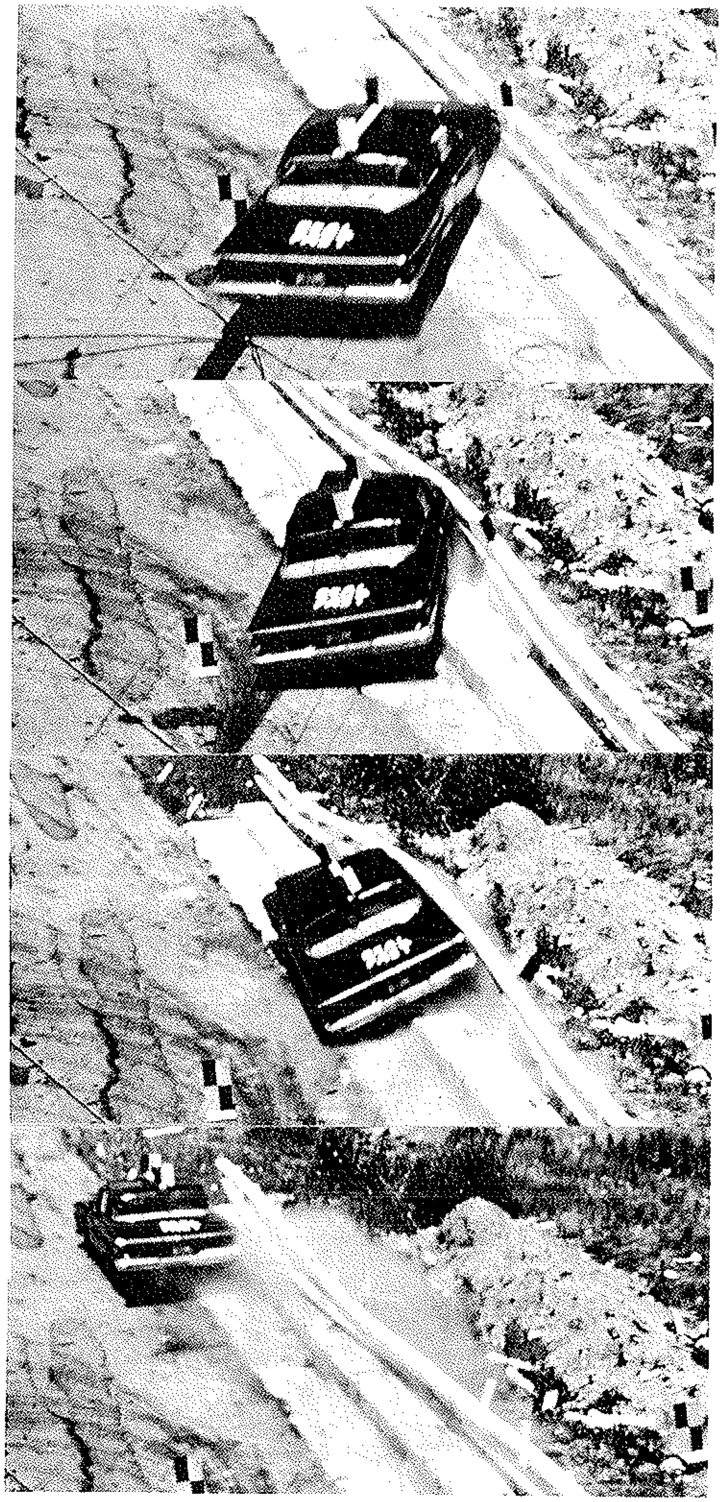


Figure 33. Box beam bridge rail (Test 32).

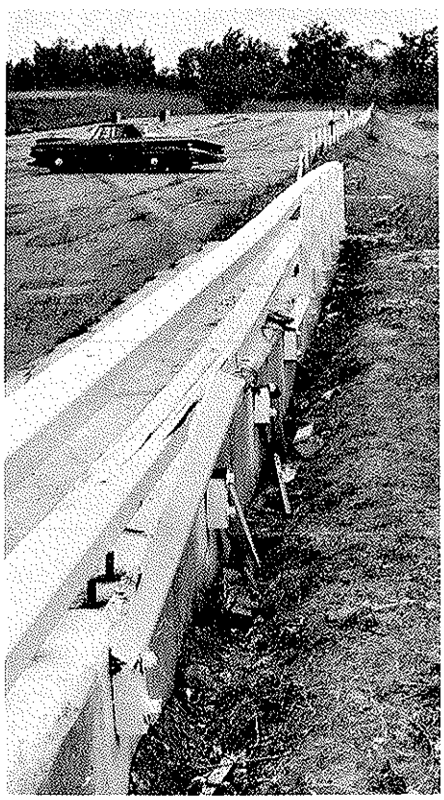


Figure 34. Car and rail after Test 31.

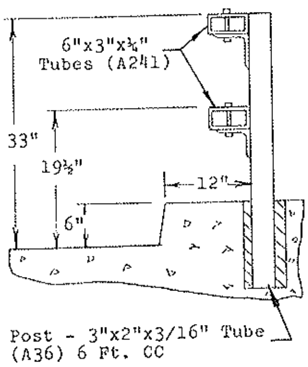

Figure 35. Car and rail after Test 32.

An impact at 45 mph and 35 deg was planned for the first test on this modified box beam bridge rail at Schenectady County Airport. To attain the high angle of impact the guide track was curved. On the approach run the car jumped the track too close to the barrier to avoid an impact and the results are shown in Figure 31. The car brakes were set before impact and the car drifted into the barrier at 40 mph. The drift was such that the velocity vector was about 25 deg but the heading angle was much larger. The barrier successfully retained the car but since the car was spinning it was unable to rotate it so that it could exit with the car axis nearly parallel to the rail.

A second test was planned at 60 mph and 25 deg. However, the data cameras did not work in Test 31 necessitating a rerun. The pictures obtained by the documentary cameras are shown in Figure 32. During the retest the barrier deflected about 11 in., lateral deceleration reached a peak of 9. 5 g's, and the car left the barrier at a shallow angle (Fig. 33). The high-speed movies showed that the car had no tendency to roll over the rail or drop off the edge of the structure.

The vehicle deceleration graphs indicated that occupants of the car would be subject to less than fatal injuries. The damage to the front wheel caused the car to veer away from the rail in Test 31 and toward the rail in Test 32 after the car left the rail (Figures 34 and 35).

In both Tests 31 and 32 the bridge rail sustained a 60 mph, 25-deg impact by a 3500-lb car. Up to five posts required replacement after each test. The system was still serviceable, and the rail splices held, having no noticeable effects on the rail or vehicle action (Figs. 34 and 35). Maximum dynamic deflection for Test 32 was 11 in. —at




Length = 100 Ft.

Impact Conditions:
Speed: 31 MPH
Angle: 7°

Maximum Dynamic
Deflection: 0.2 Ft.

Exit Conditions:
Speed: No Data Cameras
Angle: No Data Cameras

Length of Barrier
Contact: 6 Ft.

Number of Posts
Damaged: None

Average Deceleration:
During Highest Period
No Data Cameras
During Barrier Contact
No Data Cameras

Permanent Set: None

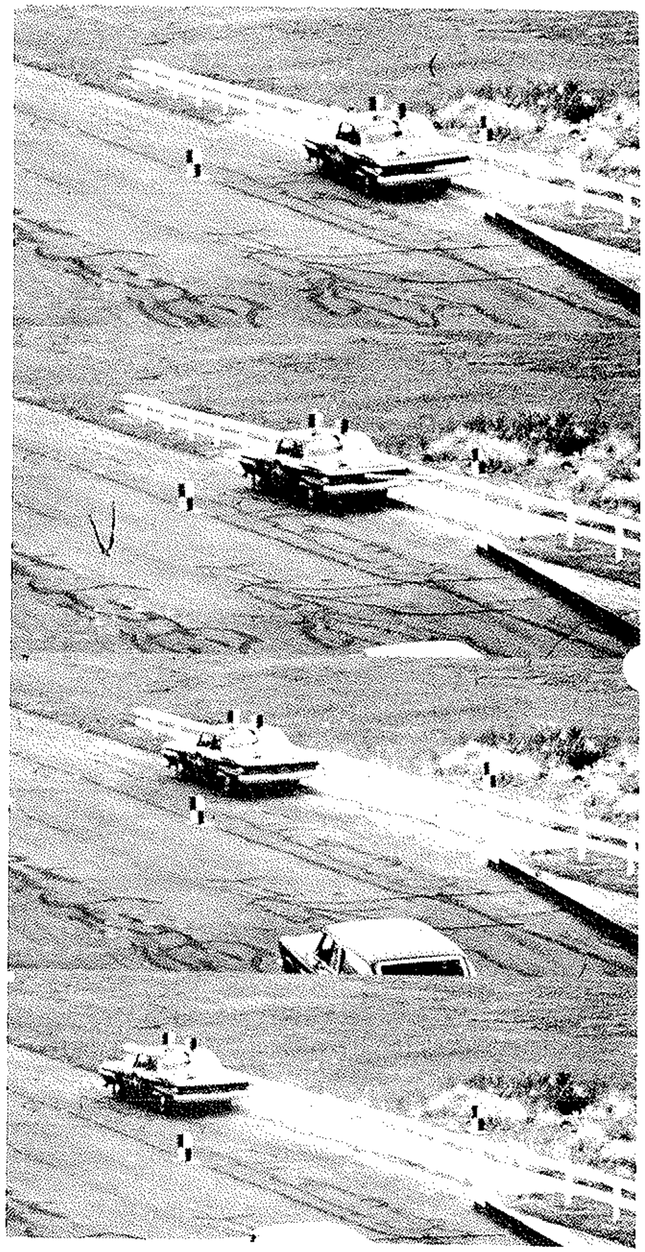
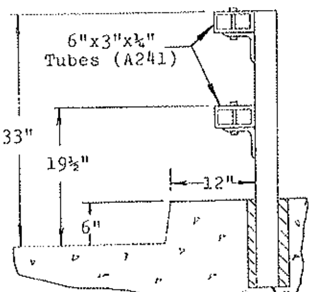


Figure 36. Box beam bridge rail (Test 44).




Post - 3"x2"x3/16" Tube
(A36) 6 Ft. CC

Length = 100 Ft.

Impact Conditions:
Speed: 53 MPH
Angle: 7°

Maximum Dynamic
Deflection: 0.7 Ft.

Exit Conditions:
Speed: No Data
Angle: No Data

Length of Barrier
Contact: 8 Ft.

Number of Posts
Damaged: None

Average Deceleration:
During Highest Period
2.0 g's (0.05 sec.)
During Barrier Contact
0.7 g's (0.680 sec.)

Permanent Set: None

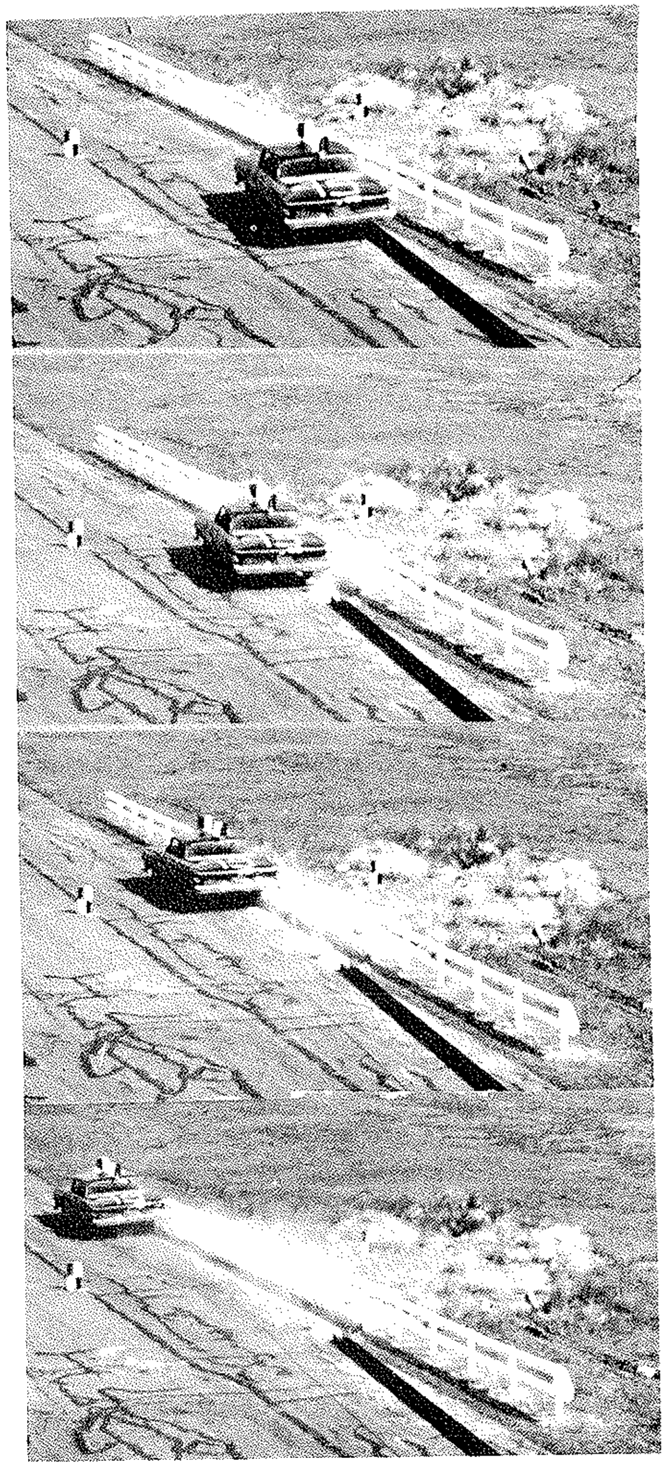


Figure 37. Box beam bridge rail (Test 45).

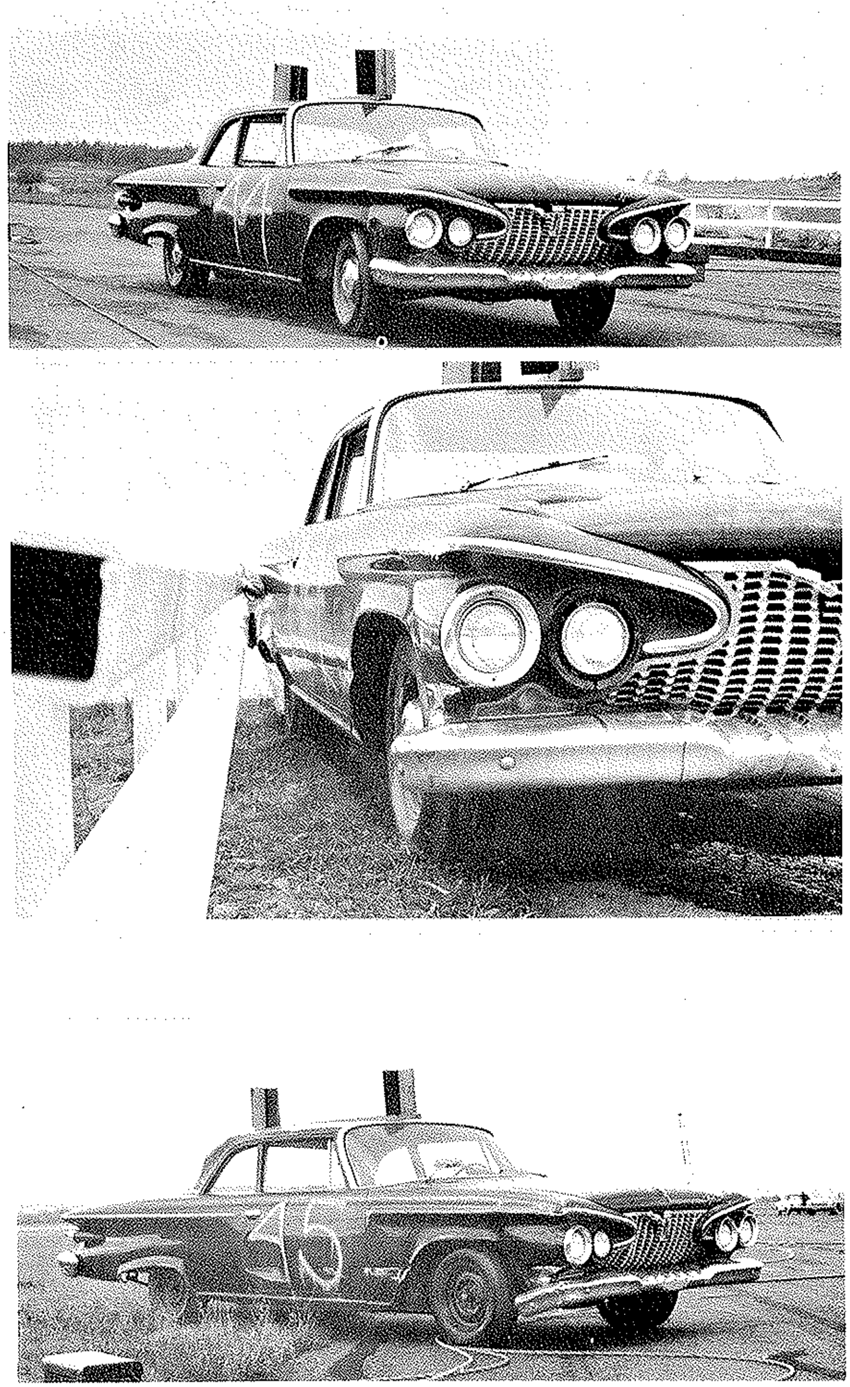
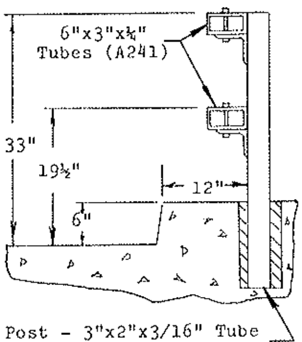


Figure 38. Car damage, box beam bridge rail (6-in. curb): top, before Test 44; center, after Test 44 and before Test 45; bottom, after Test 45.




Post - 3"x2"x3/16" Tube
(A36) 6 Ft. CC

Length = 100 Ft.

Impact Conditions:
Speed: 40 MPH
Angle: 25°

Maximum Dynamic
Deflection: 1.7 Ft.

Exit Conditions:
Speed: 32 MPH
Angle: 9°

Length of Barrier
Contact: 24 Ft.

Number of Posts
Damaged: 4

Average Deceleration:
During Highest Period
2.9 g's (0.05 sec.)
During Barrier Contact
1.5 g's (0.720 sec.)

Permanent Set: 0.2 Ft.

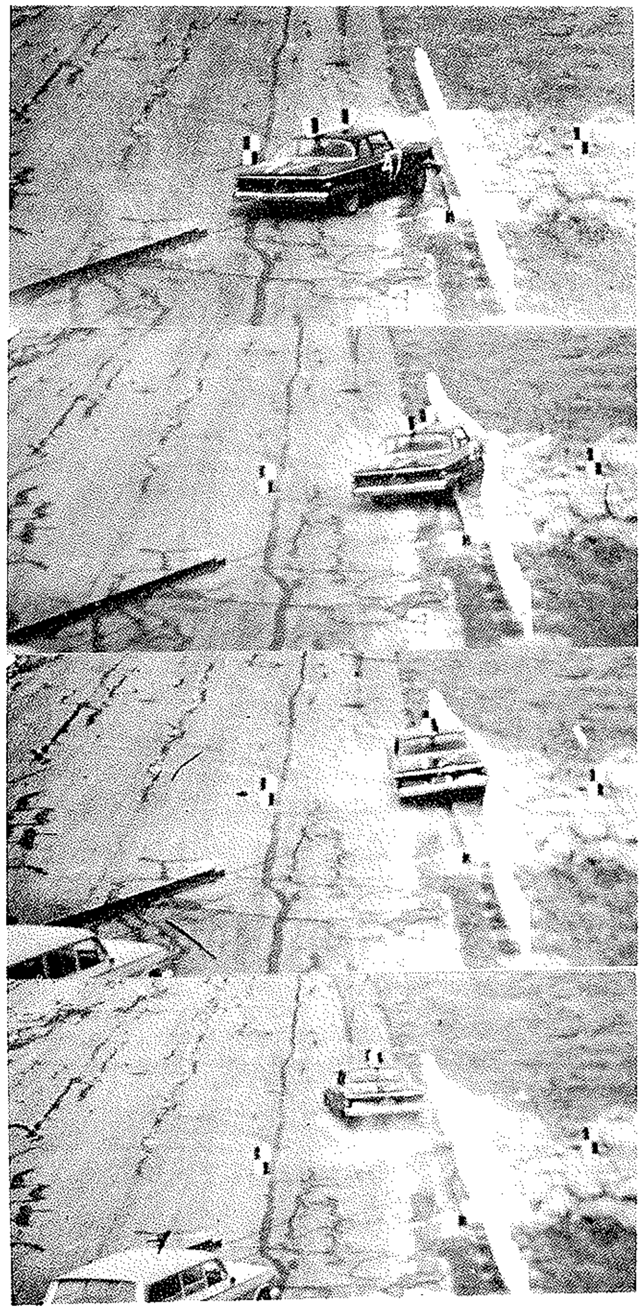
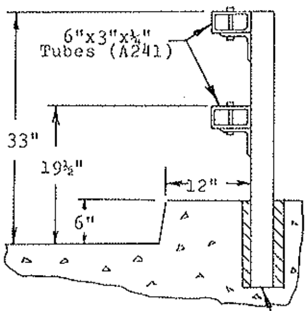


Figure 39. Box beam bridge rail (Test 47).




Post -3"x2"x3/16" Tube (A36) 6 Ft. CC

Length = 100 Ft.

Impact Conditions:
  Speed: 45 MPH
  Angle: 35°

Maximum Dynamic
  Deflection: 3.6 Ft.

Exit Conditions:
  Speed: 25 MPH
  Angle: 14°

Length of Barrier
  Contact: 30 Ft.

Number of Posts
  Damaged: 9

Average Deceleration:
  During Highest Period
  8.9 g's (0.05 sec.)
  During Barrier Contact
  4.1 g's (0.890 sec.)

Permanent Set:
  Not measurable because
  rails sagged

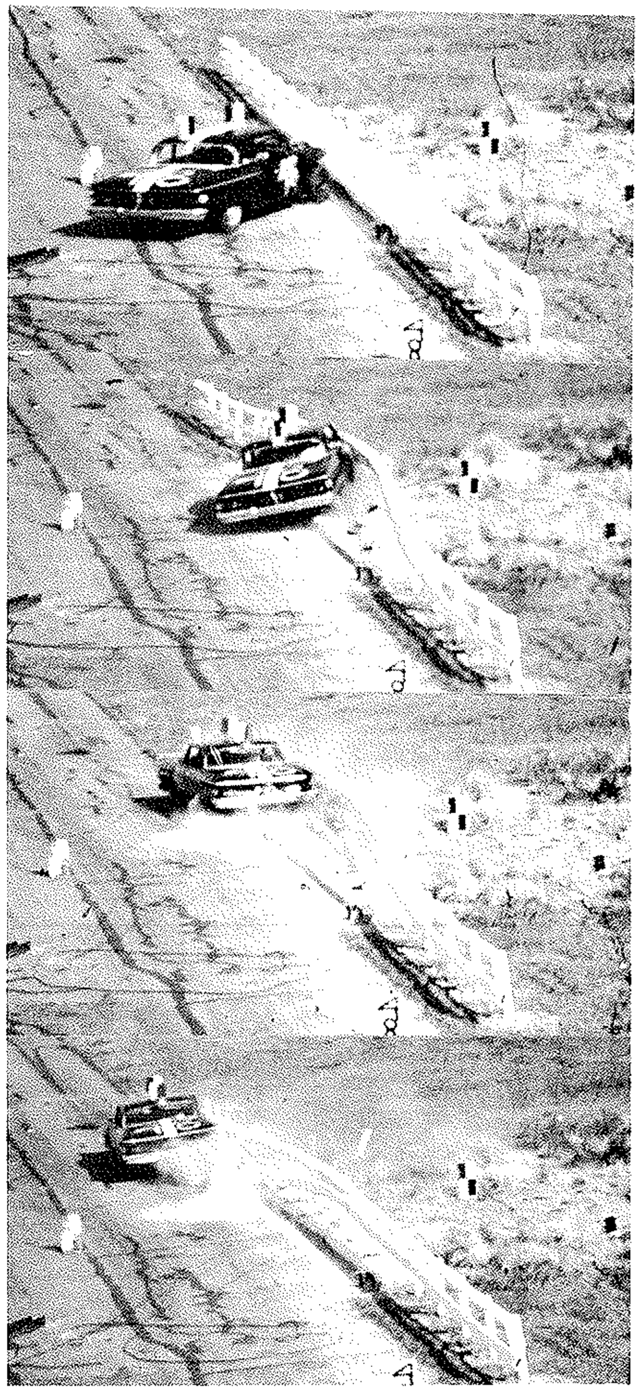
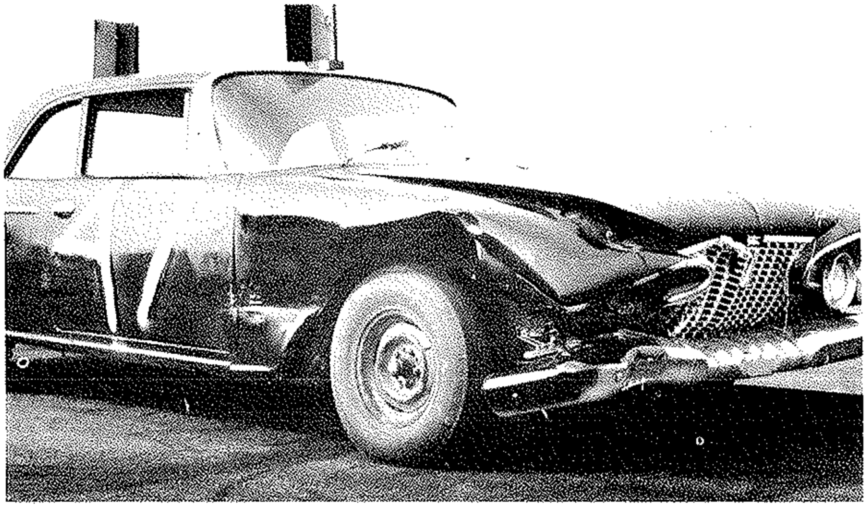


Figure 40. Box beam bridge rail (Test 48).



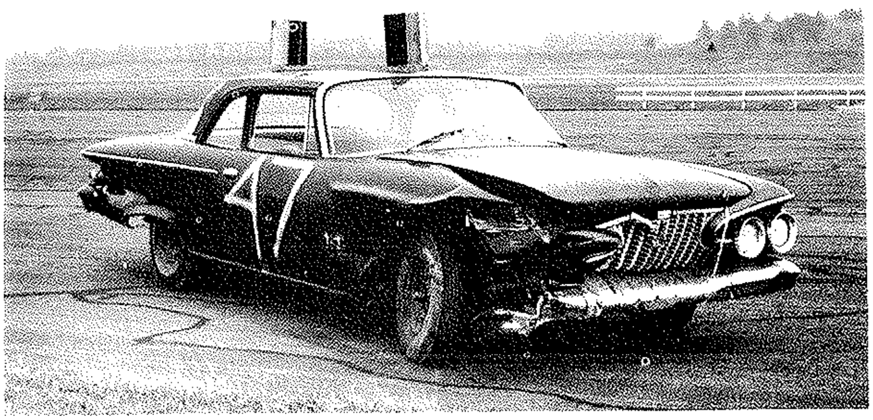


Figure 41. Car damage, box beam bridge rail (6-in. curb): top, before Test 47; bottom, after Test 47.

least 24 in. was expected. Had the rail deflected 24 in., the 9.5 g deceleration would have been considerably reduced.

It was apparent from the test results that the system was still too strong. The 10-in. high curb caused considerable steering damage and it was problematical where the car would stop after a severe collision with this height of curb. It was observed that car "jump" only occurred where the curb is offset from face of rail enough to allow the suspension system to recover before the car strikes the rail.

Impacts against a 6-in. curb without any railing were performed in a car controlled by a driver. These tests showed that a 6-in. high curb had almost no effect on the steering system. The 6-in. curb also had very little effect on the vehicle motion during several shallow-angle low-speed impacts. It was concluded that a 6-in. curb should not affect the motion of a car striking a box beam bridge rail if the rails were mounted close enough to the face of the curb to prevent car "jump" due to recovery of the suspension system. To verify this the bridge rail used in Tests 31 and 32 was erected on a curb 6 in. high for full-scale tests.

Four tests were performed. In the first two the car hit the rail at mild angles and speeds. Neither rail nor car was seriously damaged and the car was smoothly redirected (Figs. 36 and 37). Vehicle damage was slight enough so that the same car was


Impact Conditions:
Speed: 55 MPH
Angle: 26°

Maximum Dynamic
Deflection: Second Panel
Sheared Off

Exit Conditions:
Speed: None
Angle: None

Length of Barrier
Contact: Not applicable

Number of Posts
Damaged: 3

Average Deceleration:
During Highest Period
22.0 g's (0.05 sec.)
During Barrier Contact
2.8 g's (0.825 sec.)

Permanent Set:
Not applicable

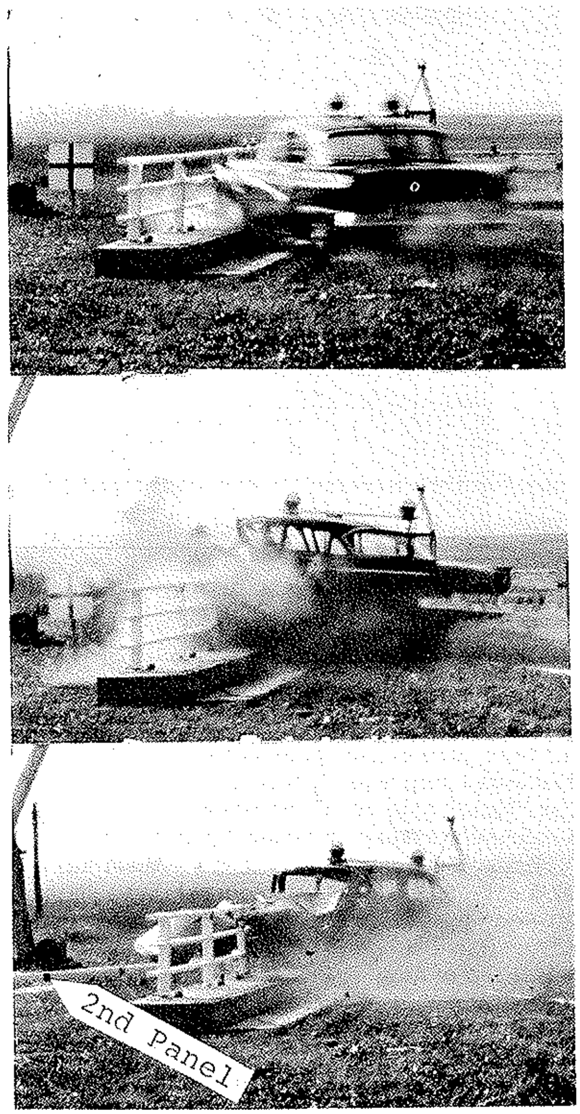
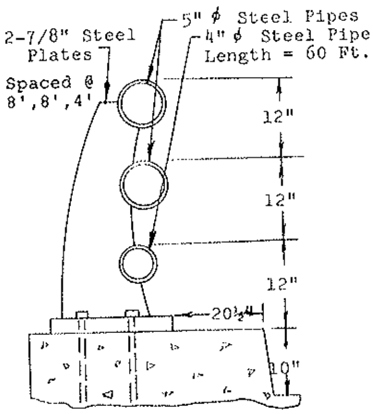



Figure 42. Rigid bridge rail (Test 9).




Impact Conditions:
Speed: 58 MPH
Angle: 27°

Maximum Dynamic
Deflection: 0.2 Ft.

Exit Conditions:
Speed: 46 MPH
Angle: 10°

Length of Barrier
Contact: 5 Ft.

Number of Posts
Damaged: None

Average Deceleration:
During Highest Period
10.1 g's (0.05 sec.)
During Barrier Contact
4.7 g's (0.300 sec.)

Permanent Set: 0.2 Ft.

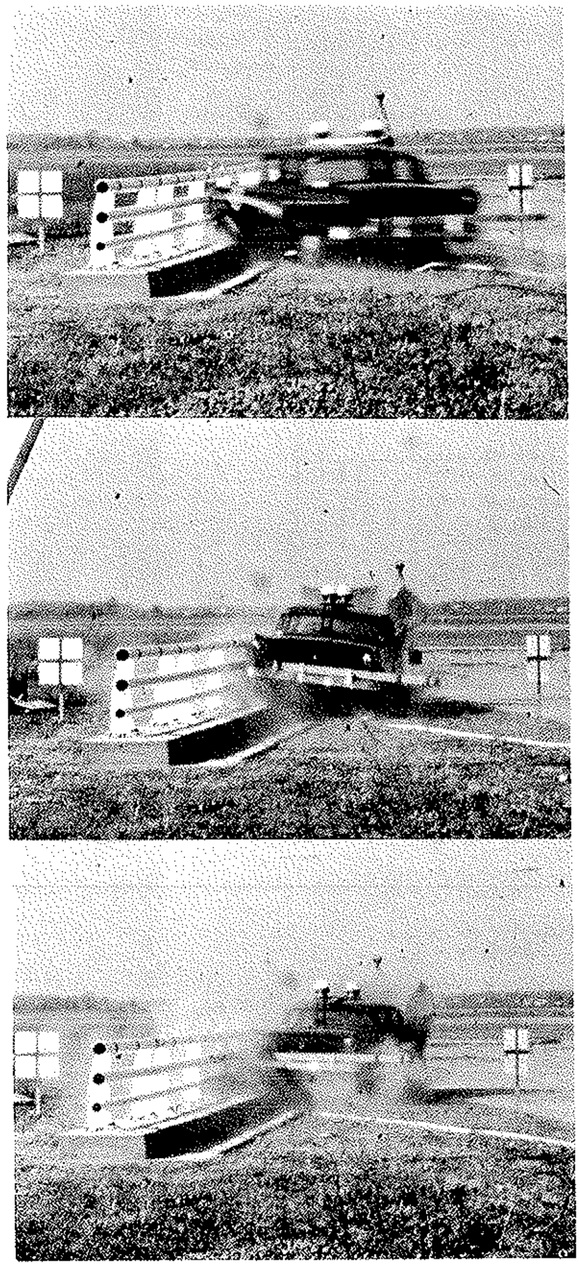
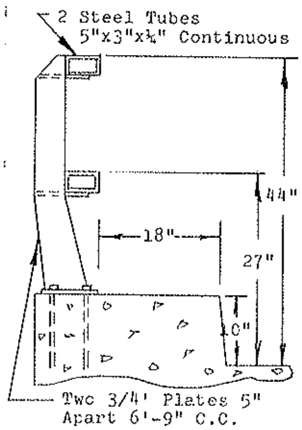


Figure 43. Rigid bridge rail (Test 8).




Length = 100 Ft.

Impact Conditions:
Speed: 45 MPH
Angle: 35°

Maximum Dynamic
Deflection: 0.3 Ft.

Exit Conditions:
Speed: Not Redirected
Angle: Not Redirected

Length of Barrier
Contact: 8 Ft.

Number of Posts
Damaged: 1

Average Deceleration:
During Highest Period
11.4 g's (0.05 sec.)
During Barrier Contact
2.2 g's (0.900 sec.)

Permanent Set:
Not applicable

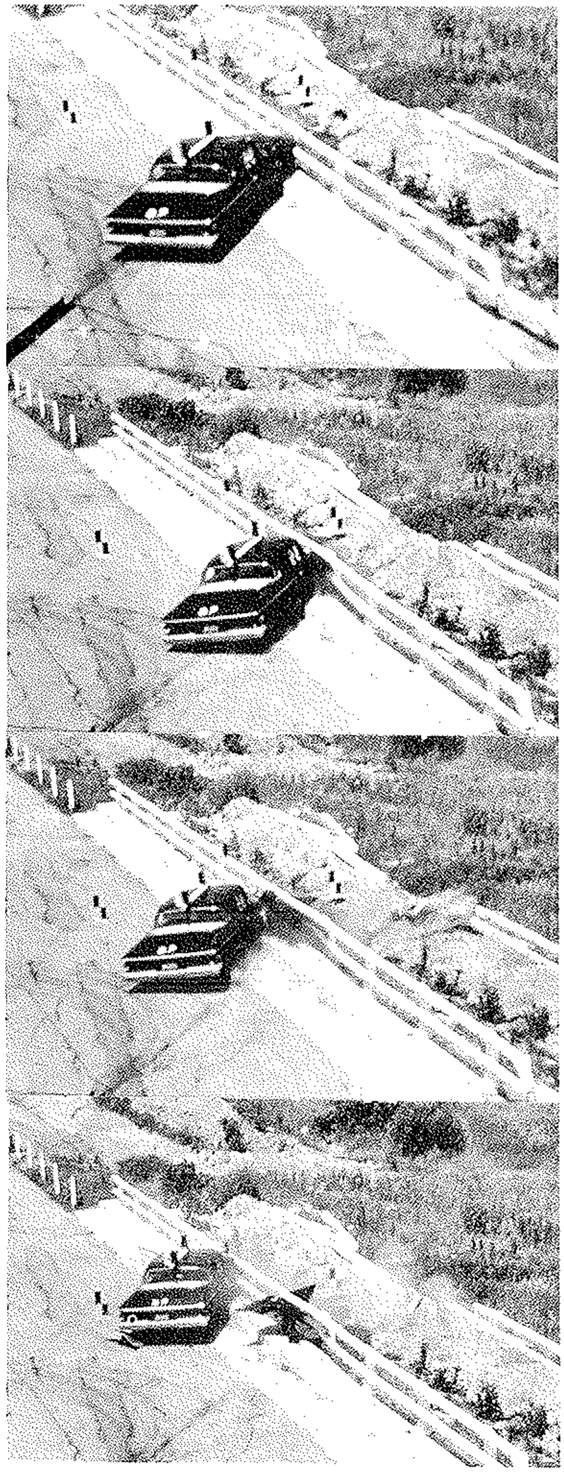
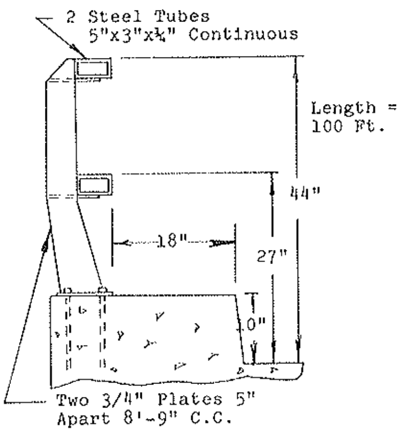


Figure 44. Rigid bridge rail (Test 29).




Impact Conditions:
  Speed: 55 MPH
  Angle: 25°

Maximum Dynamic
  Deflection: 0.0 Ft.

Exit Conditions:
  Speed: 37 MPH
  Angle: 1°

Length of Barrier
  Contact: 8 Ft.

Number of Posts Damaged:

Average Deceleration:
  During Highest Period
  12.3 g's (0.05 sec.)
  During Barrier Contact
  3.0 g's (0.440 sec.)

Permanent Set: 0.0 Ft.

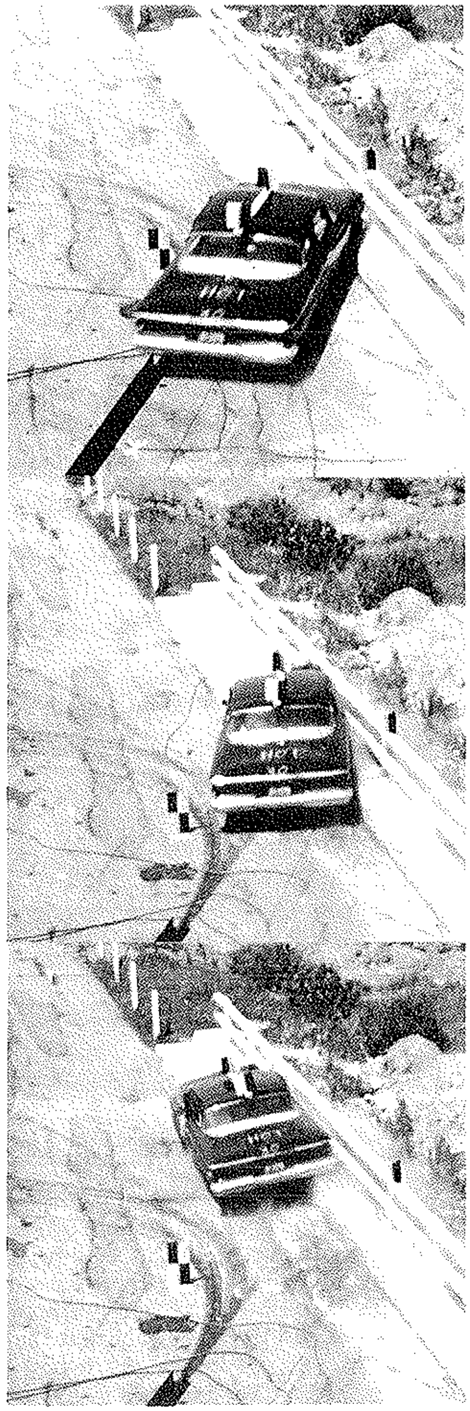


Figure 45. Rigid bridge rail (Test 30).


Figure 46. Vehicle damage, rigid bridge rails: top, after Test 29; bottom, after Test 30.

used for both tests and was driveable after the second test (Fig. 38). In the third and fourth tests the car hit the rail at 25 deg and 35 deg respectively (Figs. 39 and 40). In Test 47 a previously damaged car was used. However, the steering was not further damaged (Fig. 41) and the car was driven away after the test. In Test 48 a car with no bumper was used and the wheel nearest the barrier snagged on one or more posts and was snapped off. As predicted, the 6-in. -high curb had no noticeable effect on vehicle reactions.

Barrier damage for the shallow-angle tests was negligible and barrier damage for the 25-deg test was minimal since only four posts were damaged.

Tests 31 and 32 demonstrated that a 3500-lb car can be redirected by a box beam bridge rail under the most severe impact conditions. Tests 44 and 45 demonstrated that the box beam bridge rail can redirect a car as well as can a 10-in. high curb during mild impacts. Test 47 and several low-speed, low-angle tests showed that a car is not adversely affected by a curb 6 in. high.

## Rigid Bridge Railing

Four tests in the program were carried out to evaluate rigid bridge railings. In all four the barriers were mounted on curbs 10 in. high and offset 18 to 20 in. from the face of the curb. The 10-in. -high curb is used to prevent cars from rubbing a barrier during shallow-angle impacts which constitute the large percentage of collisions with bridge rails. The curb also serves as an elevated walkway for pedestrians or workmen.

Test 9 was performed on a bridge rail design consisting of three panels fabricated from thin-wall steel tubing (Fig. 42). The car struck near the end of the first panel, deflected the rails and hit the then-exposed end of the second panel "head on." The second panel was torn off the curb. Vehicle deceleration was very high. This test demonstrated the importance of continuous rails and the need for a generally stronger system.

Test 8 was performed on a proposed bridge rail designed to contain both large and small vehicles (Fig. 43). The car was redirected but vehicle deceleration was high. Only the lower rail was contacted by the car and the rail was bent slightly. The car made contact with the posts which added to the vehicle damage and the vehicle deceleration. This test showed that a 4-in. rail offset from the posts was not enough to prevent vehicle contact with a post, resulting in severe damage and longitudinal deceleration.

The bridge rail shown in Figures 44 and 45 meets current AASHO standards. Rails are offset from the posts 5 in. and rail and post strength are balanced to provide the required static design strength with minimum weight. Two tests were scheduled, one at 45 mph and 35 deg and one at 60 mph and 25 deg. A shallow-angle test was not planned because testing performed by the California Division of Highways indicated that a 10-in. curb would redirect a car at 60 mph and 7 deg. During the higher-angle impact the car was not redirected and decelerations were high (Fig. 44). The lower rail deflected 4 in. because a post failed at the base plate weld. Had the post held, the deceleration would have been slightly higher. For the higher-speed test, the welds on post bases were corrected and the test was run at 25 deg (Fig. 45). The car was redirected parallel to the rail for about 50 ft and then it left the roadway on the right. The steering system was badly damaged by the 10-in curb (Fig. 46). It is of interest to compare the vehicle damage which resulted during these tests with the damage which resulted from impacting a box beam bridge rail mounted on a 6-in. curb.

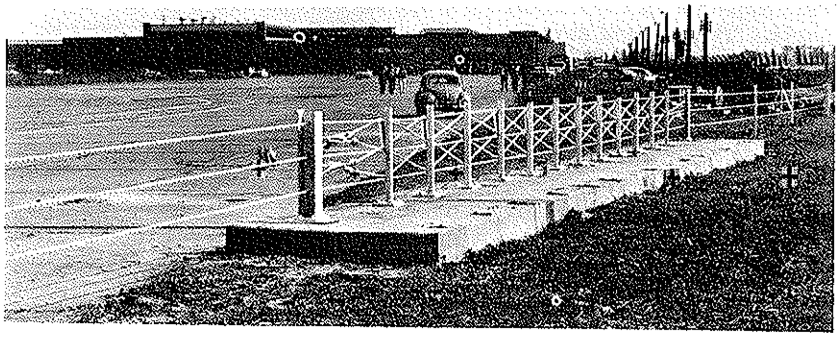
## Special Bridge Railing

The research on bridge railing conducted during this project was concerned primarily with analyzing and testing box beam bridge rails and testing rigid bridge rails. A small portion of the study (4 tests) was concerned with special railing configurations. These were proposed railings or modifications of existing types which the Department wished to evaluate. However, since they were structurally indeterminate and therefore did not lend themselves to analysis with the mathematical models, they were evaluated by reducing the movies of full-scale tests.

The first test on rails of this type was performed on a cable bridge rail (Fig. 47). The car impacted the barrier, was not redirected, broke nearly every one of the lightweight posts off near the base and came to rest with the cables across the windshield.

The second test was performed on a steel railing with continuous rails on the face of fairly heavy posts (Fig. 48). The car got off course on the approach and while attempting to turn away from the barrier the car drifted into the rail. The barrier reaction was acceptable in that the car was contained and continued on at about the same speed. However, the deceleration seemed rather high, considering the impact conditions, and this design was not considered further.

The third and fourth tests were conducted on a continuous aluminum bridge railing with a cable through the lower rail (Figs. 49 and 50). The third test was successful but the speed and angle of impact were not as severe as planned. Therefore, the test



Length = 200 Ft. Anchored
"H" Posts 2¼" x 2¼" 6 Ft. C.C.

Impact Conditions:
Speed: 52 MPH
Angle: 21°

Maximum Dynamic
Deflection: 4.0 Ft.

Exit Conditions:
Speed: Pocketed
Angle:

Length of Barrier
Contact: 42 Ft.

Number of Posts
Damaged: 12

Average Deceleration:
During Highest Period
12.2 g's (0.05 sec.)
During Barrier Contact
3.3 g's (0.650 sec.)

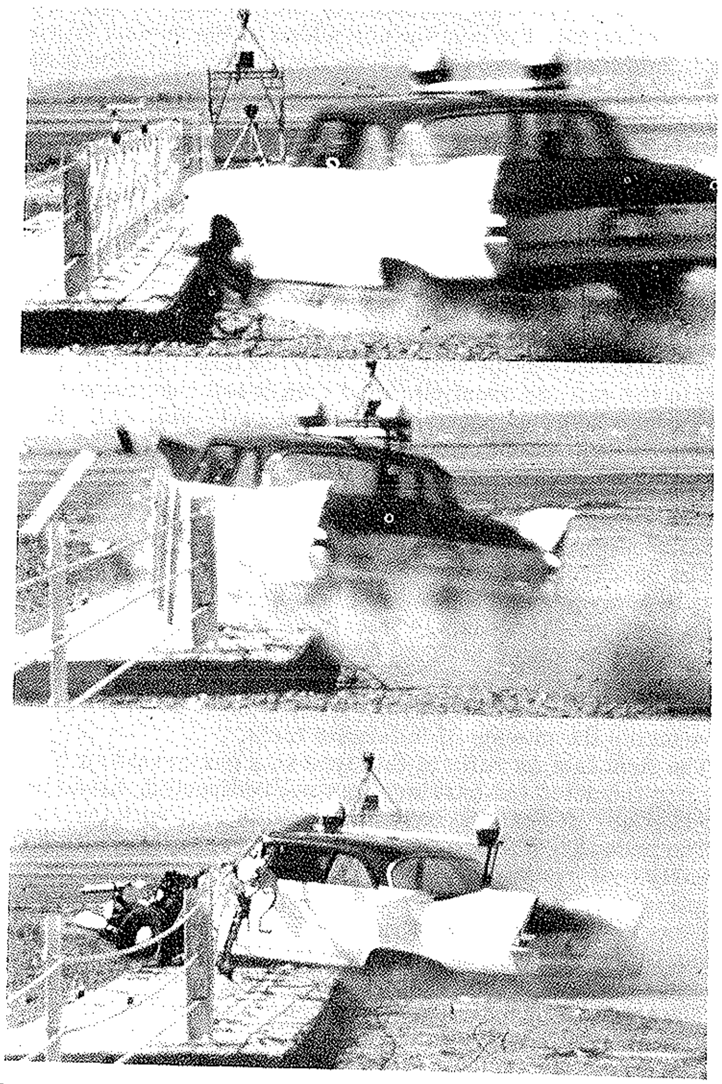
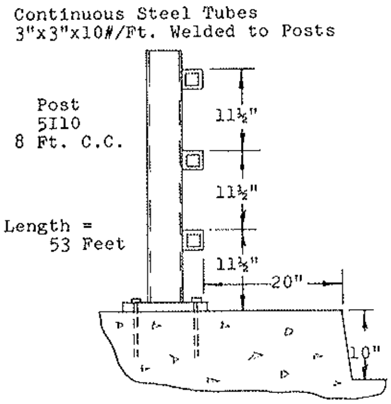


Figure 47. Cable bridge rail (Test 12).




Impact Conditions:
Speed: 55 MPH
Angle: 12°

Maximum Dynamic
Deflection: 0.2 Ft.

Exit Conditions:
Speed: Sideswipe
Angle: 4°

Length of Barrier
Contact: 15 Ft.

Number of Posts
Damaged: None

Average Deceleration:
During Highest Period
7.3 g's (0.05 sec.)
During Barrier Contact
2.3 g's (0.600 sec.)

Permanent Set: 0.2 Ft.

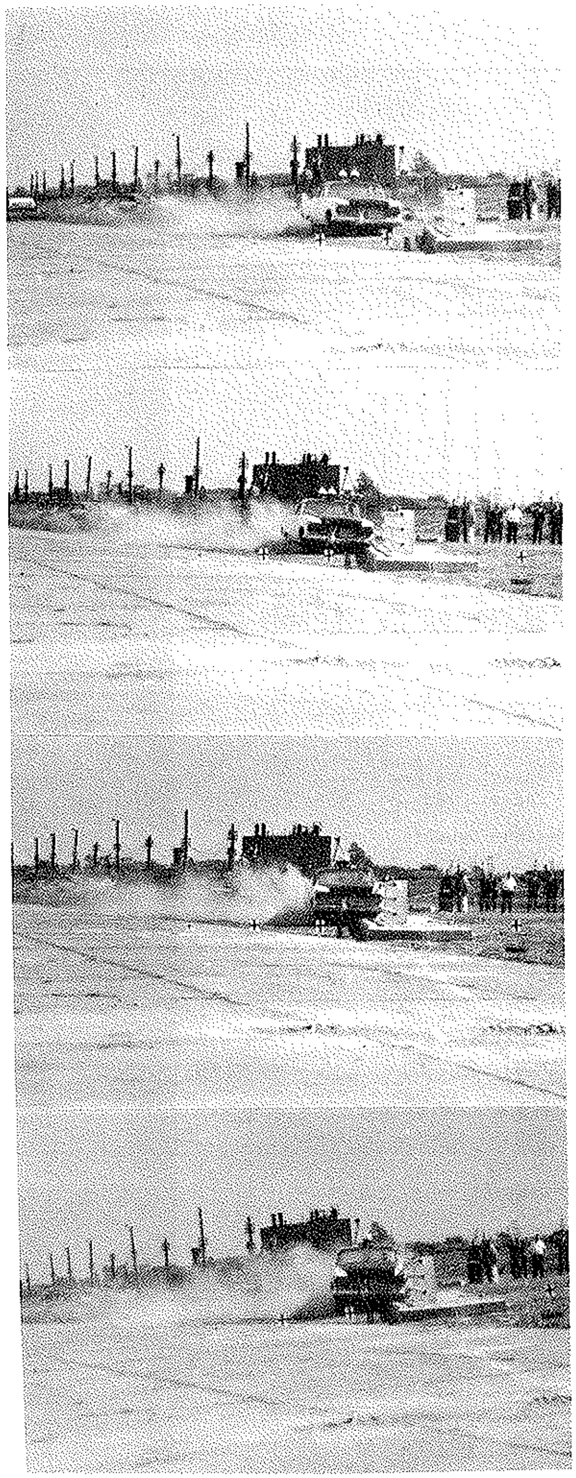
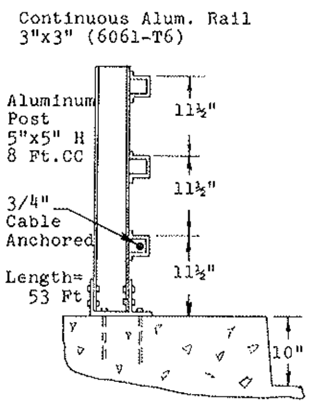


Figure 48. Continuous steel bridge rail (Test 13).




Impact Conditions:
  Speed: 53 MPH
  Angle: 15°

Maximum Dynamic
  Deflection: 0.1 Ft.

Exit Conditions:
  Speed: 52 MPH
  Angle: 4°

Length of Barrier
  Contact: 11 Ft.

Number of Posts
  Damaged: 1

Average Deceleration:
  During Highest Period
  4.4 g's (0.05 sec.)
  During Barrier Contact
  2.8 g's (0.725 sec.)

Permanent Set: 0.0 Ft.

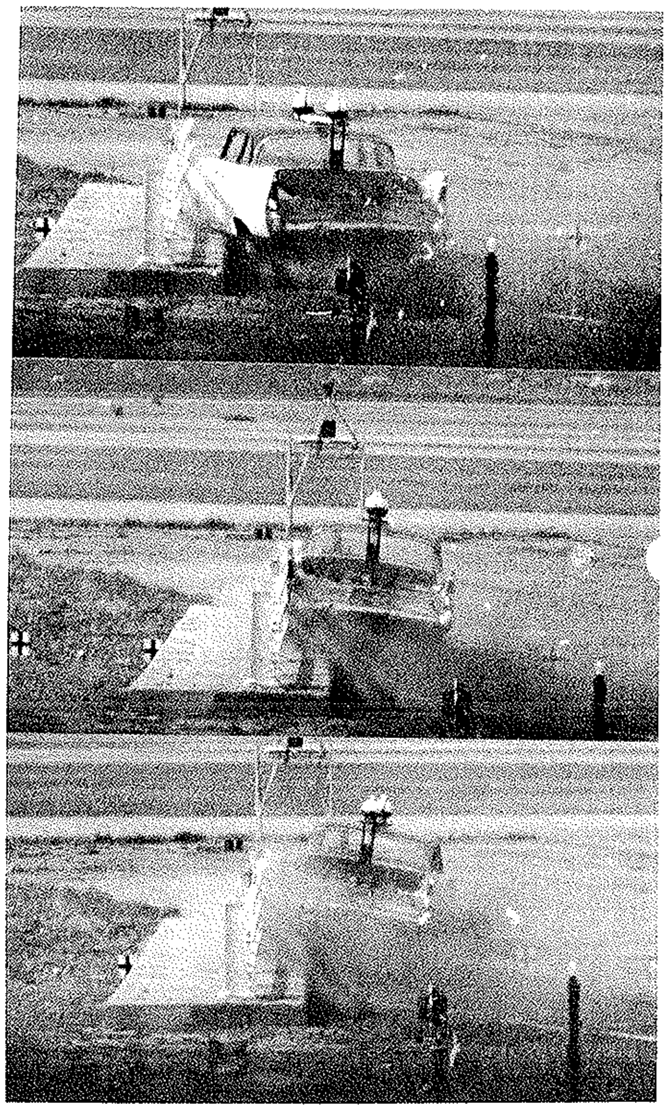
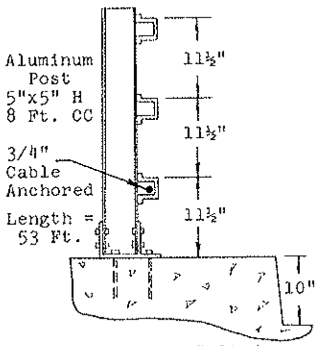


Figure 49. Continuous aluminum bridge rail (Test 15).




Impact Conditions:
Speed: 55 MPH
Angle: 28°

Maximum Dynamic
Deflection:

Exit Conditions:
Speed: Pocketed
Angle:

Length of Barrier
Contact:

Number of Posts
Damaged: 5

Average Deceleration:
During Highest Period
10.7 g's (0.05 sec.)
During Barrier Contact
5.3 g's (0.450 sec.)

Permanent Set: Rails
were bent and broken

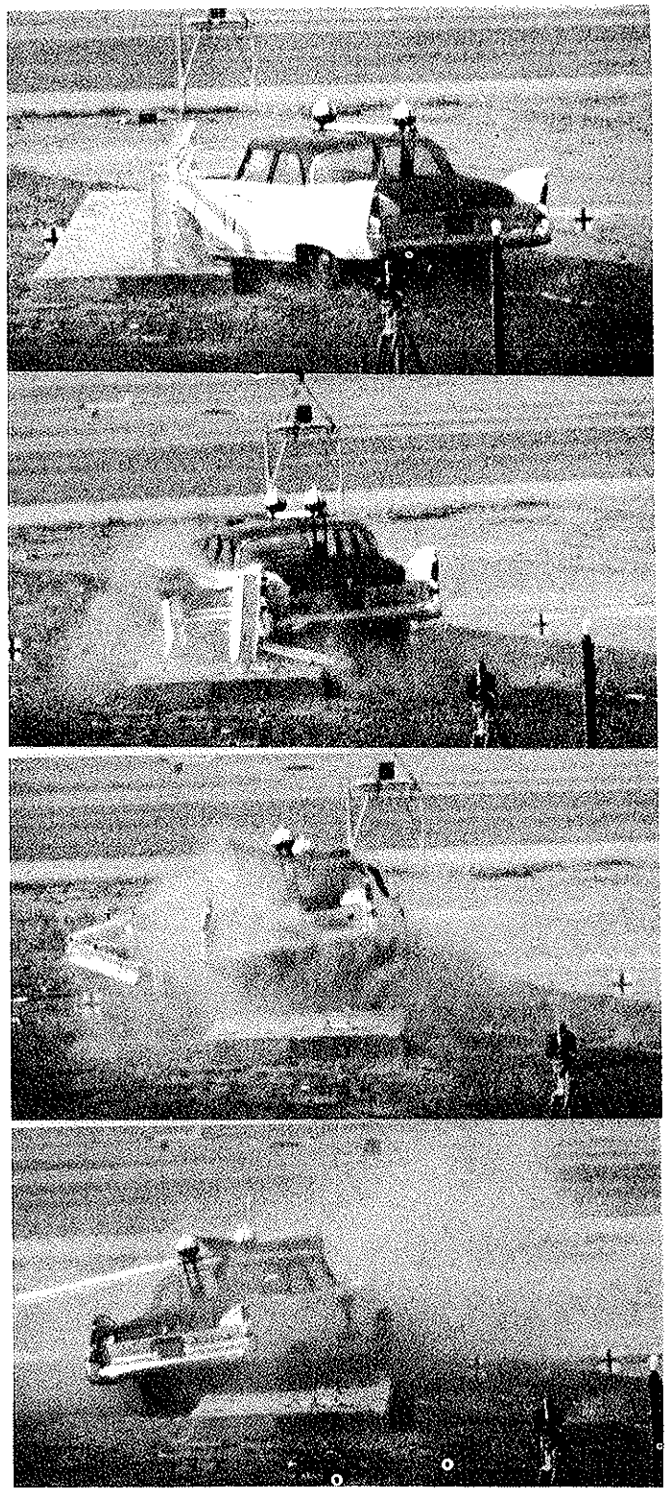
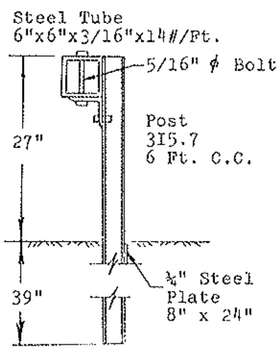


Figure 50. Continuous aluminum bridge rail (Test 17).




Length = 200 Ft.

Impact Conditions:
  Speed: 50 MPH
  Angle: 25°

Maximum Dynamic
  Deflection: 3.0 Ft.

Exit Conditions:
  Speed: 32 MPH
  Angle: 11°

Length of Barrier
  Contact: 24 Ft.

Number of Posts Damaged
  Damaged: 4

Average Decelerations:
  During Highest Period
  5.5 g's (0.05 sec.)
  During Barrier Contact
  1.6 g's (0.900 sec.)

Permanent Set: 1.0 Ft.

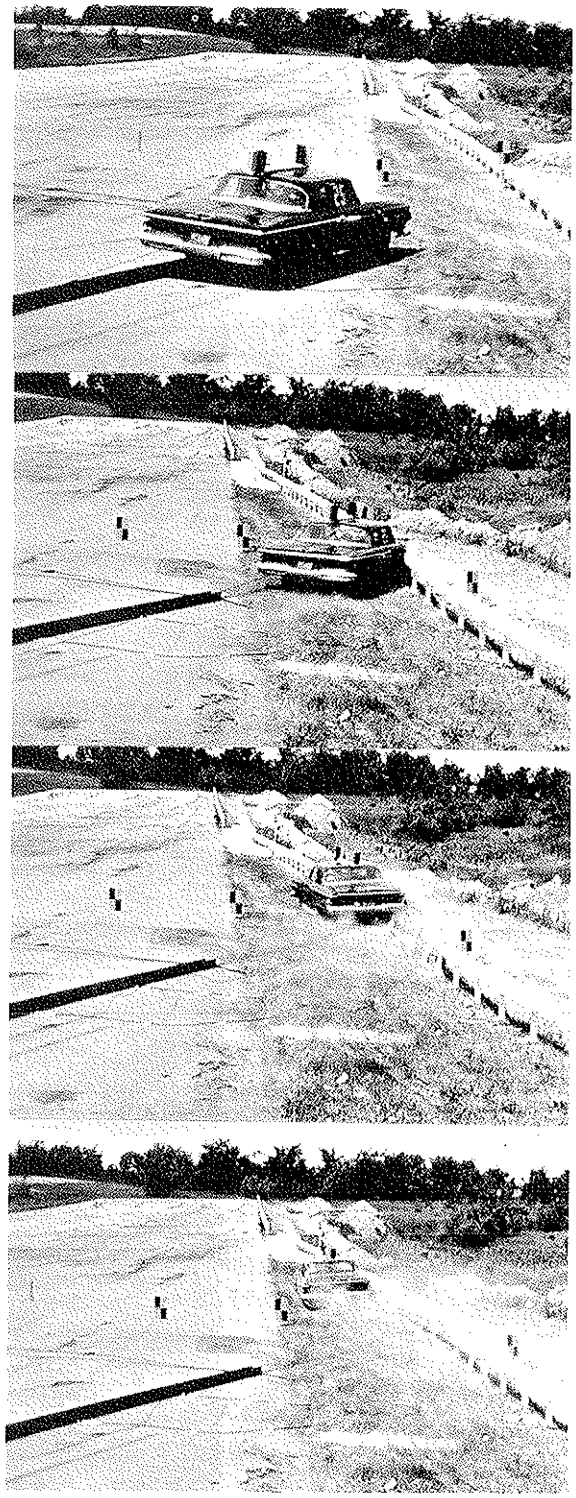
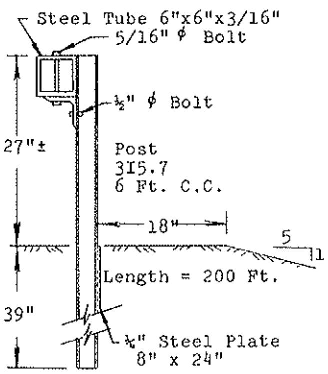


Figure 51. Box beam guide rail (Test 25).




ıpact Conditions:
Speed: 49 MPH
Angle: 35°

Maximum Dynamic
Deflection: 5.1 Ft.

Exit Conditions:
Speed: 24 MPH
Angle: 12°

Length of Barrier
Contact: 30 Ft.

Number of Posts
Damaged: 9

Average Deceleration:
During Highest Period
7.2 g's (0.05 sec.)
During Barrier Contact
2.5 g's (0.675 sec.)

Permanent Set: 3.0 Ft.

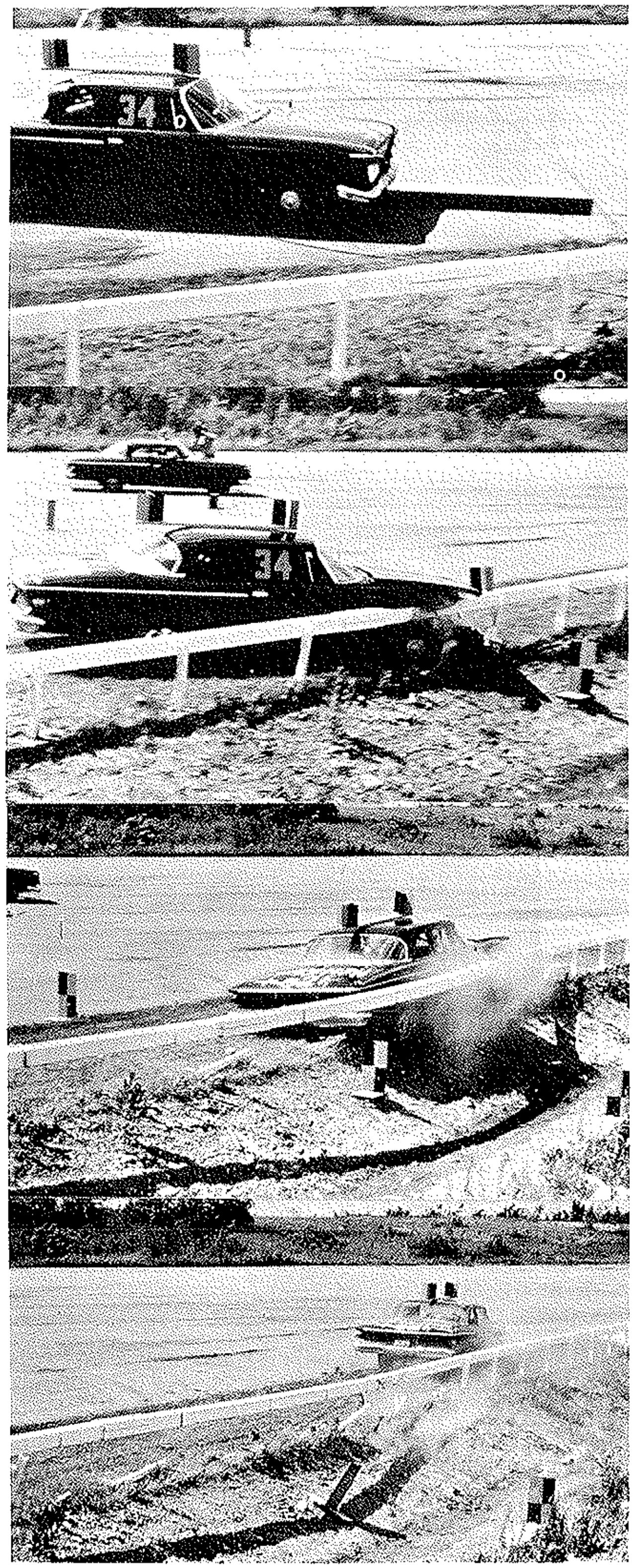



Figure 52. Box beam guide rail (Test 34).

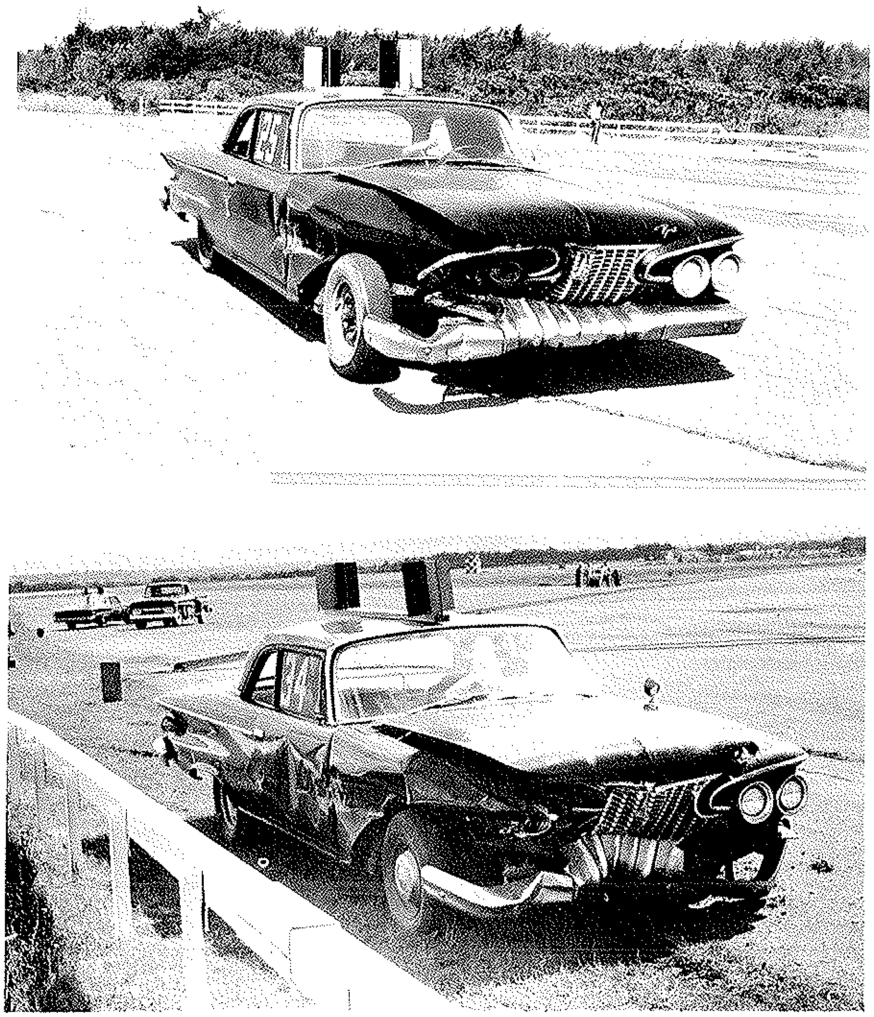


Figure 53. Vehicle damage, box beam guide rail: top, after Test 25; bottom, after Test 34.

was rerun. In the fourth test the railing failed, the cable broke the upstream end post, and the car destroyed about half of the railing. This type of railing was therefore abandoned as unsuitable.

## Box Beam Guide Rail

The box beam median barrier was designed to limit rail deflection to about 2 ft and vehicle deceleration to less than 10 g's. It was estimated that a cable or W-section system could limit deceleration to 2 or 3 g's with about 12 and 8 ft of deflection respectively. Since 8 to 12 ft of deflection is not always permissible because of the proximity to the roadway of sign posts and other fixed objects, a barrier was needed which would limit deflection to between 2 and 8 ft. The 6 by 8-in. tube used in the median barrier could be used if post spacing were made larger. However, a 6 by 6-in. rail was selected because it was more economical and since the rail would be mounted on the roadside face of the posts. The 6-in. width is enough to keep cars from contacting posts during ideswipes and the 6-in. height is about the minimum for adequate car contact and delineation. Figures in Table 5 show that the maximum decelerating force would be 20,000 lb, which could cause a 3500-lb car to decelerate about 5.7 g's if post spacing were 6 ft on centers. A vehicle trajectory was calculated which indicated that maximum displacement for the center of gravity of the car would be 48 in. and that maximum displacement would occur when the vehicle was parallel to the rail (vehicle heading angle = 0 deg). It also showed that the vehicle exit angle would be small (10 deg). Table 5 also shows that a 6 by 6 by $^3/_{16}$-in. rail with 4-ft post spacing will provide nearly the same bending resistance as the 8 by 6 by $^1/_4$-in. rail used in the box beam median barrier.

The 6 by 6 by $^3/_{16}$-in. rail appeared satisfactory and the rail-post arrangement shown in Figure 51 was scheduled for full-scale tests. A $^5/_{16}$-in. bolt was used to hold the rail to the posts because it had been successfully used in Test 11 to hold a similar bridge rail to posts. The clip angle was fastened to the post with a $^1/_2$-in. bolt which was the largest size that would fit the small flange (Fig. 51). The $^5/_{16}$-in. bolt was designed to break when a car made direct contact with a post.

An external splice was selected for the same reasons as with the median barrier. However, the splice bolts were placed through slots in the tube ends to prevent the rail from pulling all posts toward the colliding vehicle as the barrier deflected up to 4 ft under impact. This movement of the tube ends inside the splice plates does not reduce the ability of the splice to transmit the bending in the rail.

Two full-scale tests were completed and the results are shown in Figures 51, 52, and 53. In both tests the car followed a smooth path, deflected the barrier 3 to 5 ft and left the barrier traveling nearly parallel to it (Figs. 51 and 52). Lateral deceleration was limited to 5.5 g's and 7.2 g's. The 50-mph impact speed in Test 25 is less than the intended 60 mph and it follows that the deceleration is less than in Test 34.

After Test 25 the car was driven away from the test site with good steering control. After Test 34 the steering system was in excellent condition. Only a cracked ignition coil prevented the car from being driven away (Fig. 53).

These two tests show that the "sudden stop" occurring when a car hits a fixed object off the roadway can be prevented, the car can be redirected with minimal loss of control, and the barrier deflected within fixed limits.

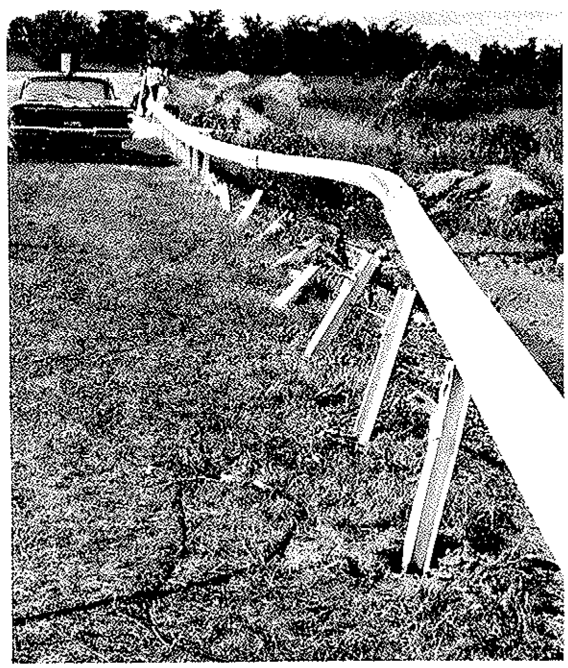


Figure 54. Box beam guide rail damage: left, after Test 25; right, after Test 34.

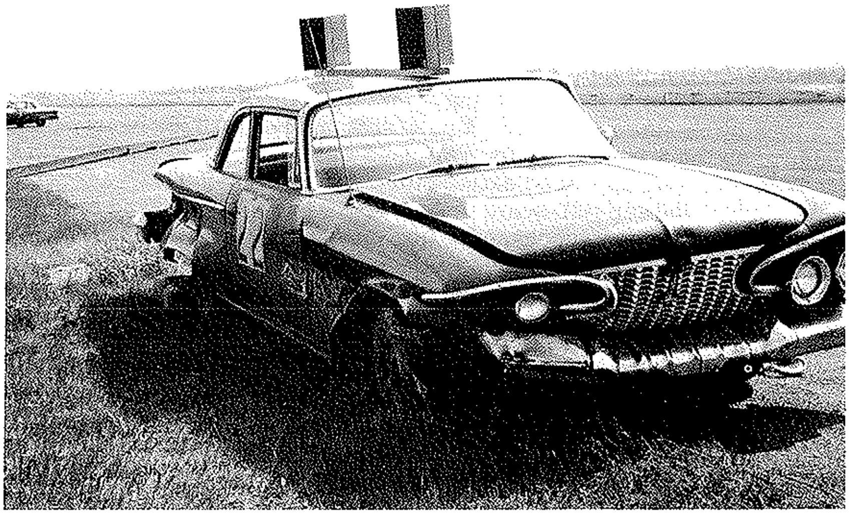


Figure 55. Vehicle damage, box beam end treatment.

In both Tests 25 and 34 the box beam guide rail performance was excellent but in Test 34 the impact speed was higher than expected and the rail deflected 5 ft instead of 4 ft as planned (Fig. 54). There was some uplift of the rail during impact as shown i Figure 54 but the effect is not considered significant. The $^5/_{16}$-in. bolt held the rail down to assure good barrier performance.

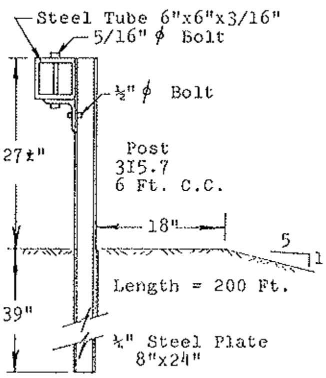
The rail splice was snug fitting and permitted no free lateral rail deflection. The splice plates were hammered onto the rails during erection. Where the fit is not snug, 22-gage sheet metal shims are inserted between rail and splices.

The rails expanded at the splice as provided for by the 4-in. slots in the end of each rail. The splice near the exit area in Test 34 would probably have to be replaced. One 24-ft section of rail in each test had to be replaced. The other splice in the impact area did not appear to be damaged.

Box Beam Ends and Transitions

The exposed end of a box beam rail, whether bridge, median or guide, would be a serious hazard which could be reduced by bending the rail down to the ground, or curving the rail away from the roadside to a point where the end is not likely to be hit by a car. Combining these two treatments incorporates the advantages of both, and therefore such a configuration was selected for a full-scale test at 60 mph and 25 deg. The car would leave the roadway and approach the normal tangent alignment of the barrier at 25 deg, but due to the curve in the rail the car would strike the barrier at about 35 deg. The curved portion was 78 ft long and the rail end was offset 18 ft from the tangent (32-deg curve). The car only attained a speed of 40 mph and was redirected with moderate deceleration and some body damage (Fig. 55). The test results are shown in Figure 56. A retest was made, the results of which are shown in Figure 57. In this test the vehicle speed was close to that desired and the rail failed to resist the impact.

These two tests show that the curved rail will resist a moderate collision but the end treatment should begin beyond the point of barrier need because of possible penetration. The curved rail could be stiffened by using closer post spacing or a stronger rail but this would result in higher vehicle decelerations. The curved rail is only a means of overcoming the danger of an exposed rail end.




Impact Conditions:
Speed: 40 MPH
Angle: 35±°

Maximum Dynamic
Deflection: 2.2 Ft.

Exit Conditions:
Speed: 25 MPH
Angle: 34°

Length of Barrier
Contact: 18 Ft.

Number of Posts
Damaged: 4

Average Deceleration:
During Highest Period
4.3 g's (0.05 sec.)
During Barrier Contact
2.7 g's (0.504 sec.)

Permanent Set: 1.0 Ft.

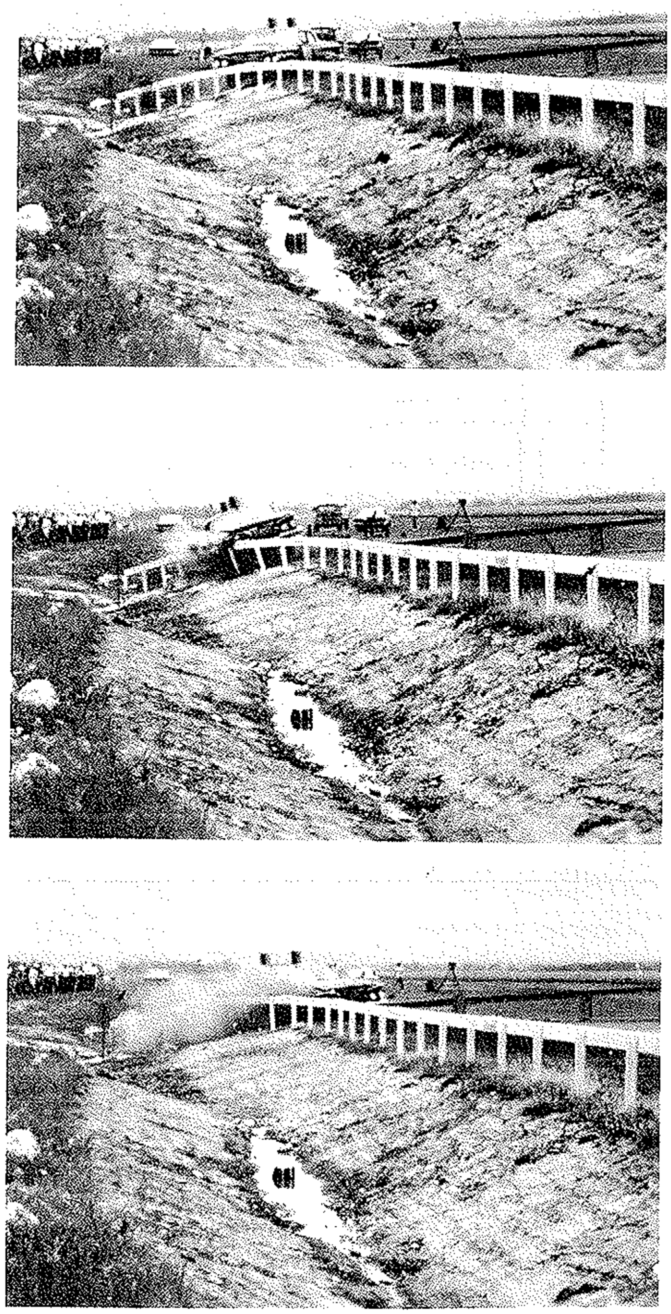
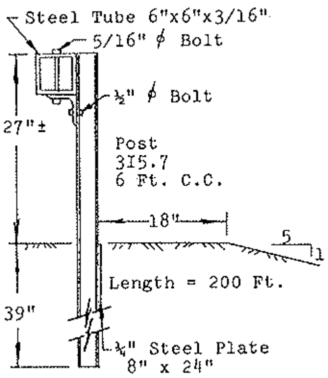


Figure 56. Box beam end treatment (Test 22).




Impact Conditions:
  Speed: 53 MPH
  Angle: 40° ±

Maximum Dynamic
  Deflection:

Exit Conditions:
  Speed: Barrier Failed
  Angle: Barrier Failed

Length of Barrier
  Contact: **Approx. 10 feet**

Number of Posts
  Damaged: 5

Average Deceleration:
  During Highest Period
  4.1 g's (0.05 sec.)
  During Barrier Contact
  2.0 g's (0.775 sec.)

Permanent Set:
  **Not applicable**

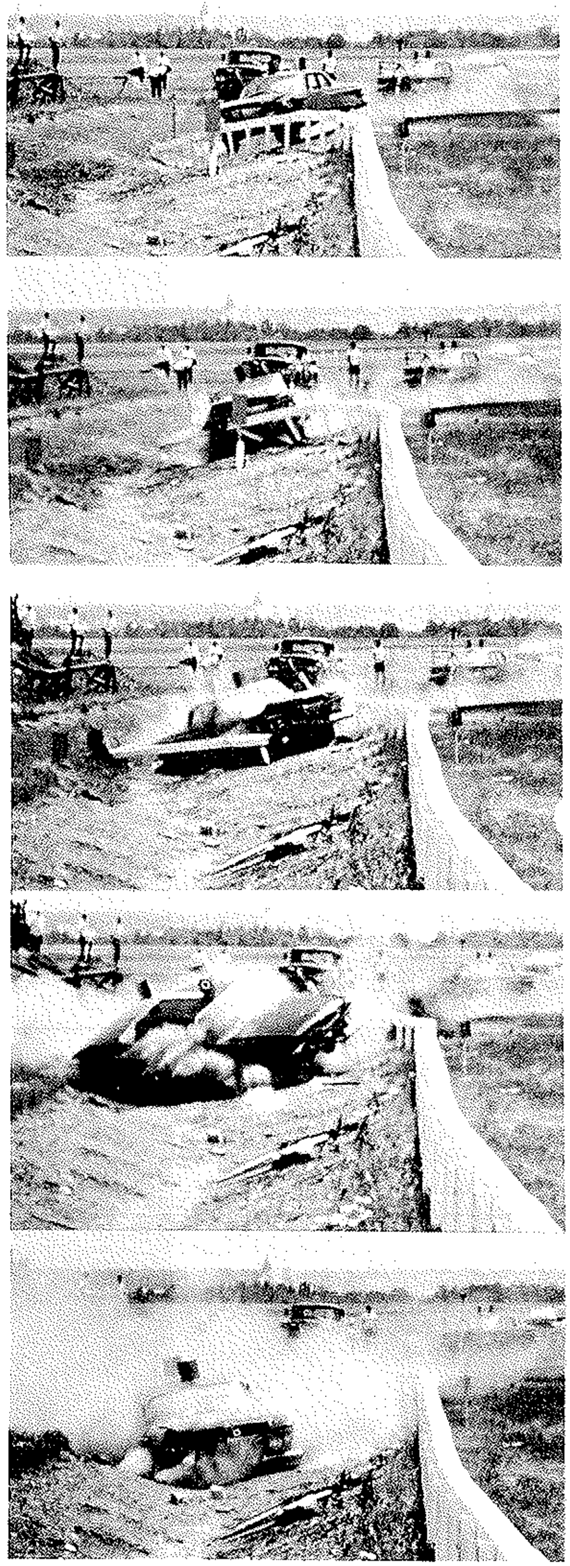


Figure 57. Box beam end treatment (Test 27).

Figure 58. Box beam transition to bridge rail.

It is not desirable to install a guide rail with little bending strength on a bridge approach adjacent to a pylon or stiff railing on the bridge itself. A collision with such an approach guide rail causes considerable deflection and serves to pocket the vehicle at the end of the bridge railing or pylon with disasterous results. The logical approach system to a relatively stiff bridge rail is a box beam guide rail with similar deflection ~operties. The 6 by 6 by $\frac{3}{16}$-in. rail with 4-ft post spacing has nearly the same force -eflection characteristics as the box beam bridge rail (Table 5) and was selected as a transition between bridge rail and normal box beam guide rail with posts spaced at 6 ft (Fig. 58).

Impacts at 25 and 35 deg were selected for the transition to box beam guide rail and a third test at 25 deg was scheduled for a similar transition to a rigid bridge railing.

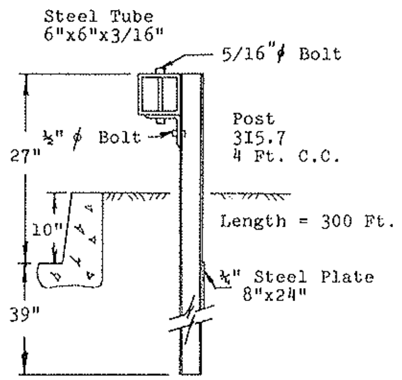
Results of the 25-deg test on the transition to box beam bridge rail are shown in Figure 59. The vehicle reaction was similar to the vehicle reaction in Test 32 on box beam bridge rail. The car was redirected but the deceleration was high and the steering was badly damaged. Barrier damage was more than expected for two reasons: (a) there was about 8 ft between the last bridge rail post and the first transition post (Fig. 58); and (b) a splice sleeve in the lower bridge rail was not properly installed and the far end of the lower bridge rail was relatively free to whip off the posts after the bolts connecting the rail to posts sheared off.

Results of the 35 deg test on transition to box beam bridge rail are shown in Figure 60. The car did not attain the desired speed before impact. It was not redirected and it is doubtful that it would have been redirected at an impact angle of 35 deg or greater considering the increased number of posts directly contacted and the longitudinal resistance provided by a 10-in. curb. However, decelerations were not extreme and the vehicle was retained.

The last test on a transition was performed at 25 deg (Fig. 61). In this test the bridge rail was a rigid system designed not to deflect during a collision. The transition details were the same as in the other two tests. The vehicle speed at impact could not be determined due to an error in selecting lenses for the data cameras. Judging by the vehicle and barrier damage, the speed probably exceeded 60 mph. The car was smoothly redirected and did not pocket at the end of the bridge rail.

## Cable Guide Rail

Cable guide rail has been used extensively in New York State and was considered "irst in the study since it appeared easy to analyze. A full-scale test was performed




Impact Conditions:
Speed: 54 MPH
Angle: 25°

Maximum Dynamic
Deflection: 4.6 Ft.

Exit Conditions:
Speed: 40 MPH
Angle: 2°

Length of Barrier
Contact: 32 Ft.

Number of Posts
Damaged: 5

Average Deceleration:
During Highest Period
9.4 g's (0.05 sec.)
During Barrier Contact
3.3 g's (0.360 sec.)

Permanent Set: 1.5 Ft.

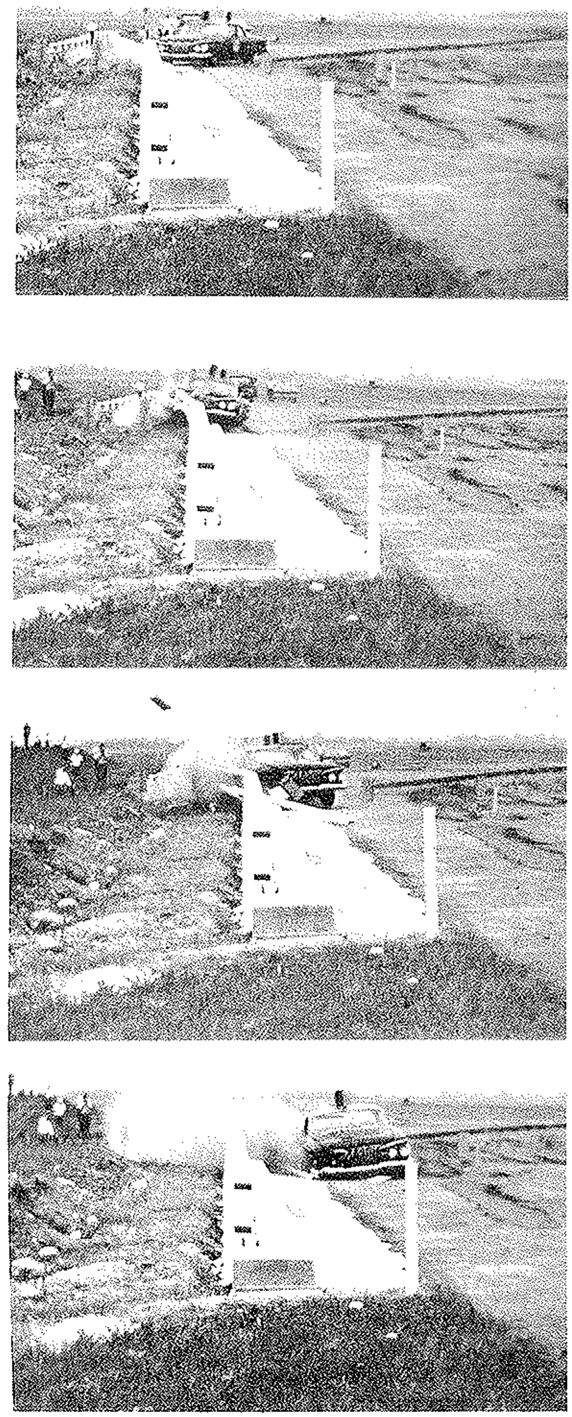
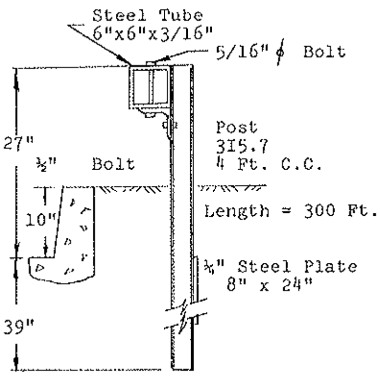


Figure 59. Box beam transition (Test 21).




Impact Conditions:
  Speed: 36 MPH
  Angle: 35°

Maximum Dynamic
  Deflection: 0.6 Ft.

Exit Conditions:
  Speed: Not Redirected
  Angle: Not Redirected

Length of Barrier
  Contact: 12 Ft.

Number of Posts
  Damaged: 3

Average Deceleration:
  During Highest Period
  3.9 g's (0.05 sec.)
  During Barrier Contact
  1.9 g's (0.825 sec.)

Permanent Set: 0.1 Ft.

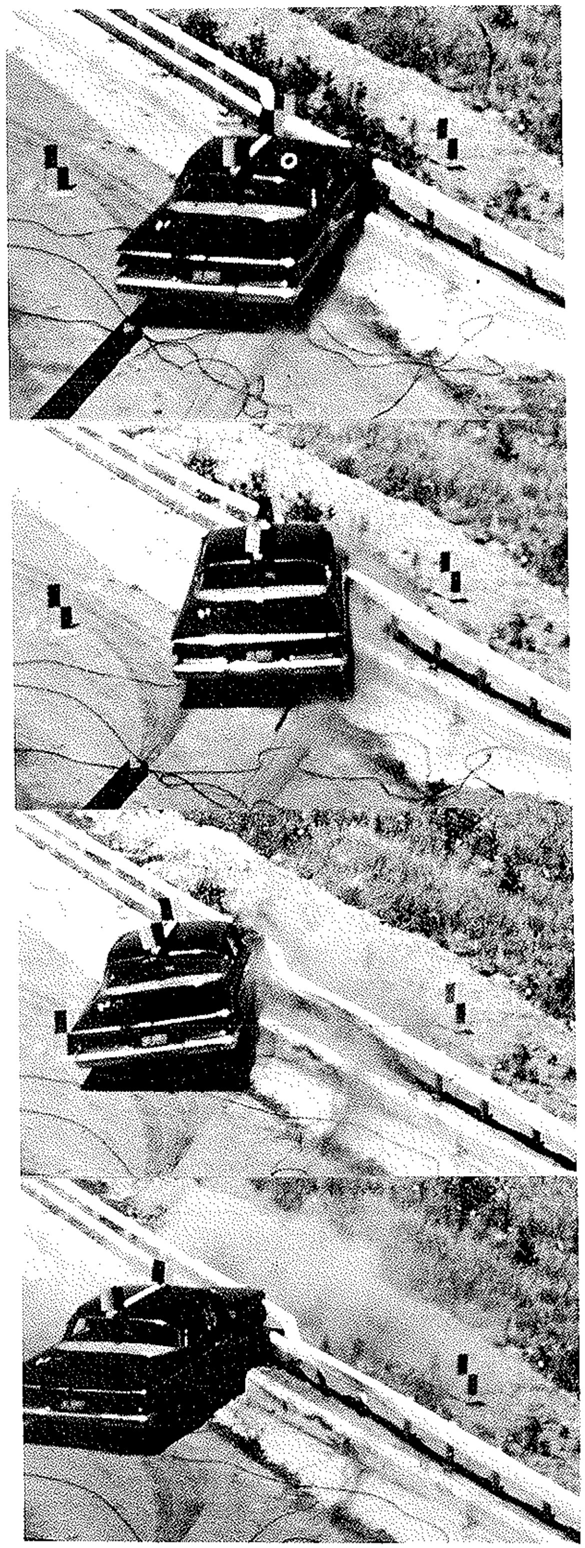
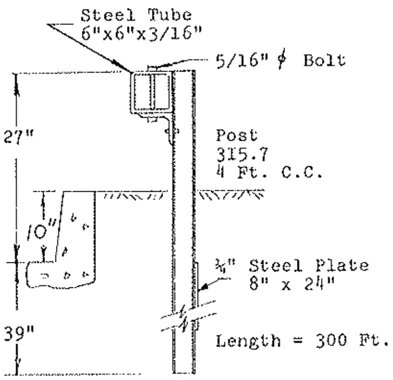


Figure 60. Box beam transition (Test 35).




Impact Conditions:
  Speed:
  Angle: 25°

Maximum Dynamic
  Deflections: 2.5 Ft.

Exit Conditions:
  Speed: No Data
  Angle: No Data

Length of Barrier
  Contact: 18 Ft.

Number of Posts
  Damaged: 5

Average Deceleration:
  During Highest Period
  8.4 g's (0.05 sec.)
  During Barrier Contact
  3.5 g's (0.302 sec.)

Permanent Set: 2.0 Ft.

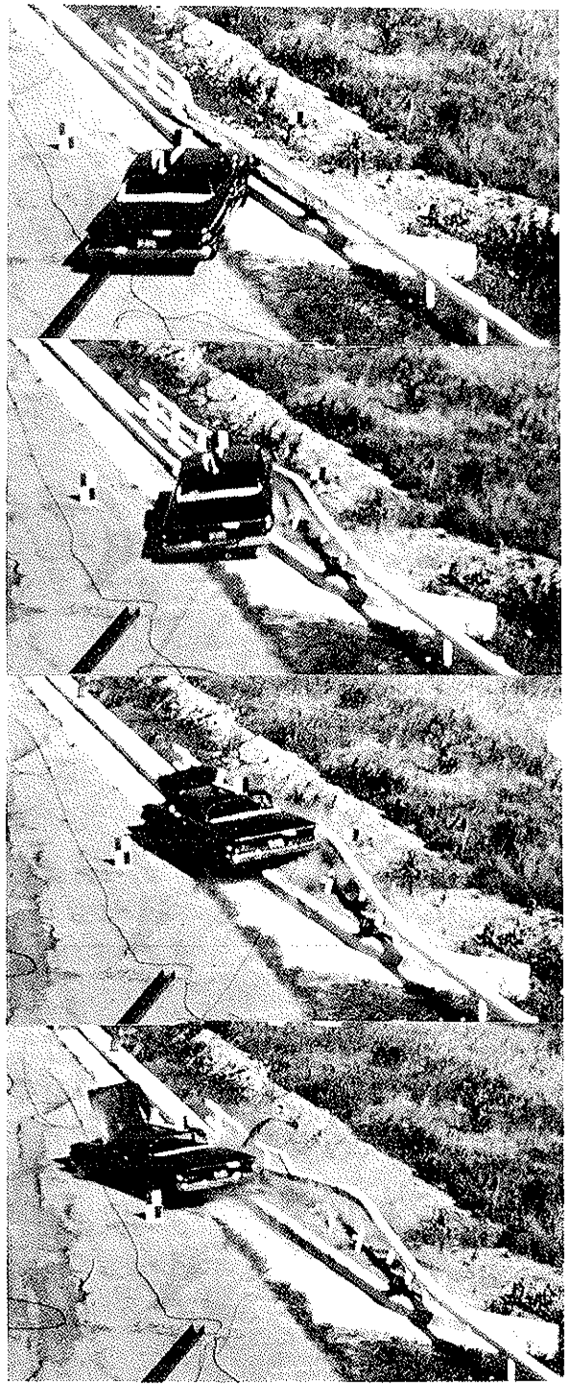
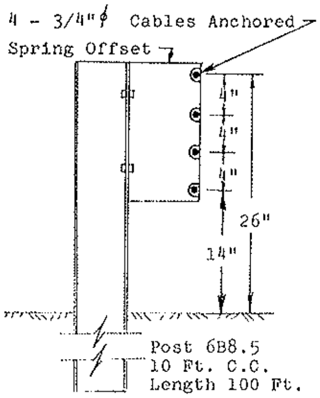


Figure 61. Box beam transition (Test 42).




Impact Conditions:
Speed: 41 MPH
Angle: 34°

Maximum Dynamic
Deflection: 12.0 Ft.

Exit Conditions:
Speed: None
Angle: None

Length of Barrier
Contact: 20 Ft.

Number of Posts
Damaged: 6

Average Deceleration:
During Highest Period
4.4 g's (0.05 sec.)
During Barrier Contact
2.4 g's (0.600 sec.)

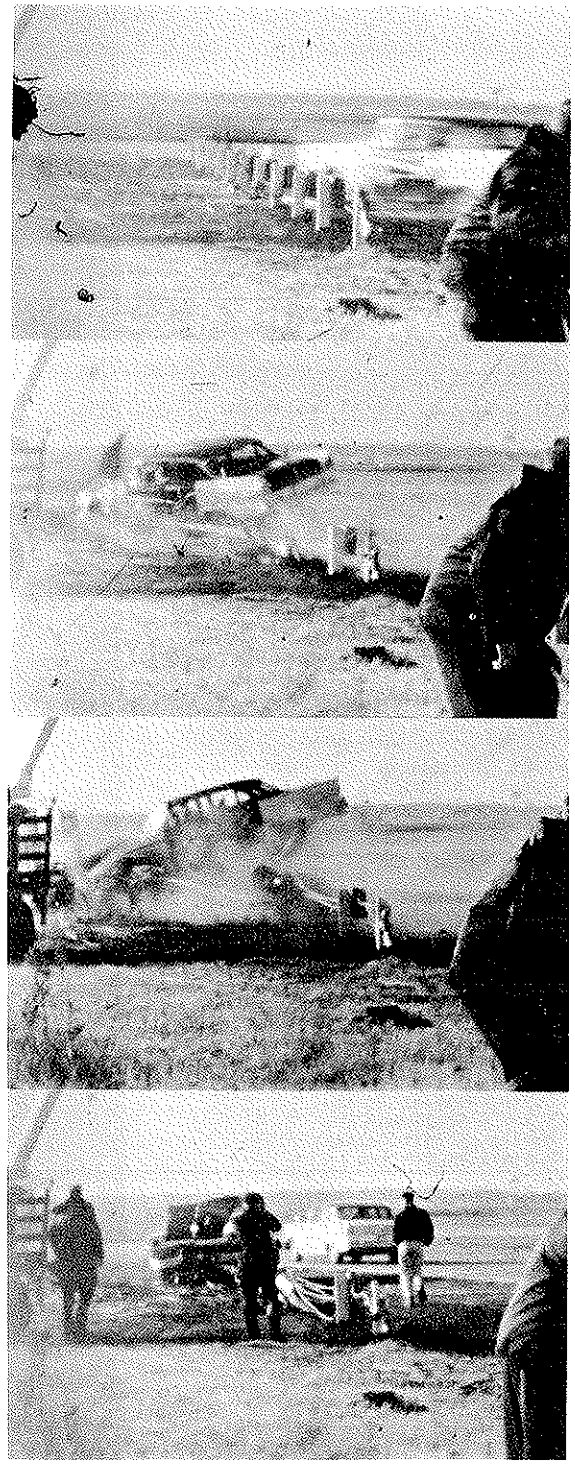
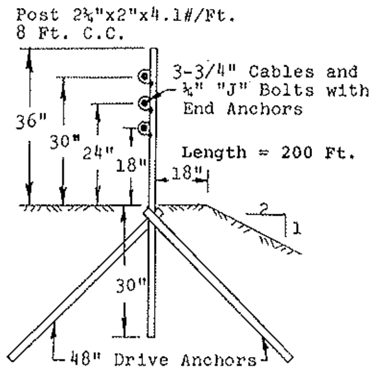


Figure 62. Cable guide rail (Test 1).




Impact Conditions:
Speed: 62 MPH
Angle: 32°

Maximum Dynamic
Deflections: 11 Ft.

Exit Conditions:
Speed: 37 MPH
Angle: 10°

Length of Barrier
Contact: 95 Ft.

Number of Posts
Damaged: All

Average Deceleration:
During Highest Period
5.2 g's (0.05 sec.)
During Barrier Contact
2.6 g's (0.725 sec.)

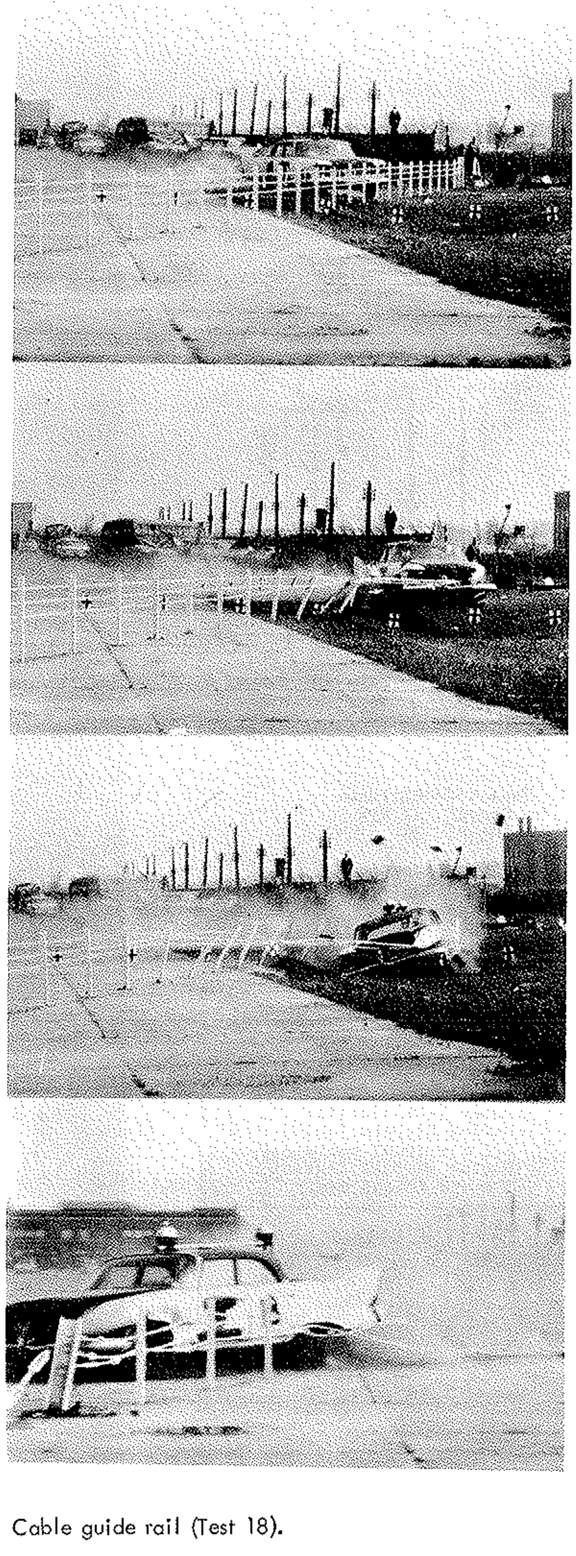
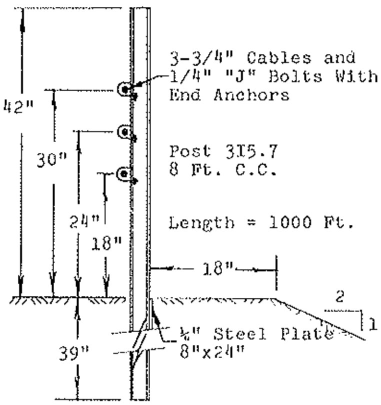


Figure 63. Cable guide rail (Test 18).




Impact Conditions:
Speed: 55 MPH
Angle: 25°

Maximum Dynamic
Deflection: 11 Ft.

Exit Conditions:
Speed: 42 MPH
Angle: 23°

Length of Barrier
Contact: 56 Ft.

Number of Posts
Damaged: 9

Average Deceleration:
During Highest Period
3.9 g's (0.05 sec.)
During Barrier Contact
2.0 g's (0.940 sec.)

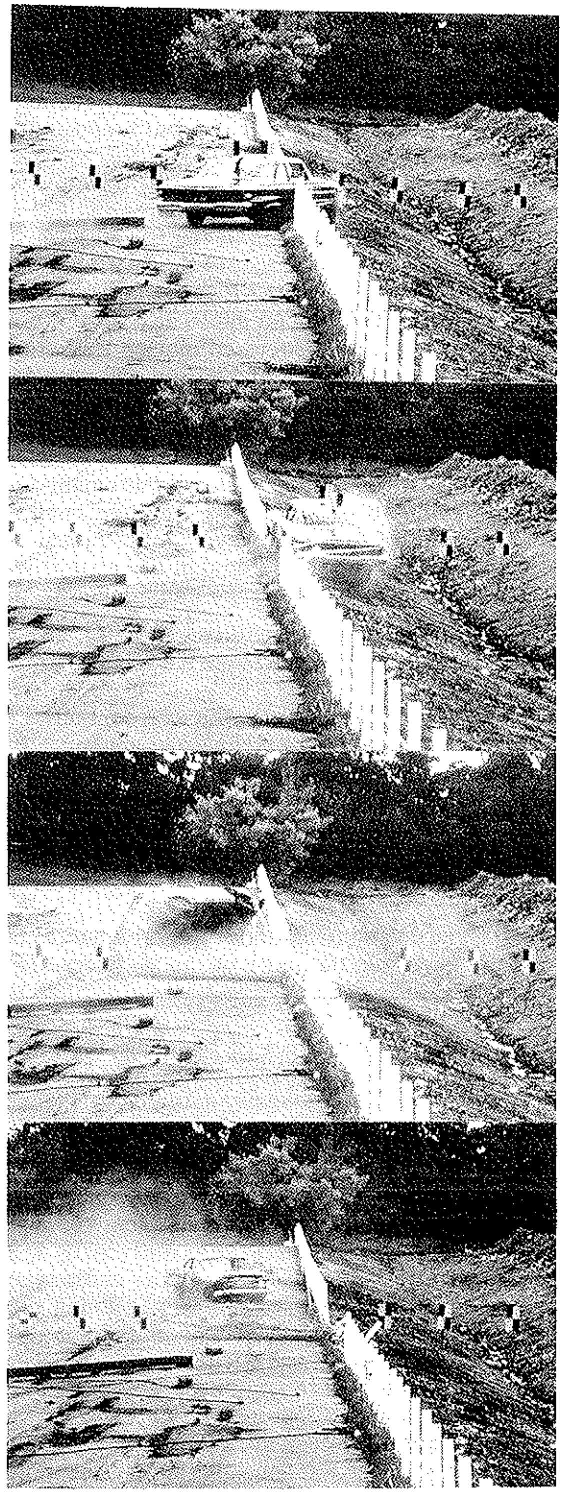


Figure 64. Cable guide rail (Test 20).

to compare the measured vehicle reaction with the computed vehicle reaction, thus establishing initial verification of the analytical approach. In addition, load cells and strain gages were placed on posts and anchor rods to validate assumptions made concerning their strength and elasticity in the soil. Furthermore, this system was an existing design and it was desirable to evaluate its performance over a range of impact conditions. Verification of the mathematical analysis would allow such an evaluation without further testing.

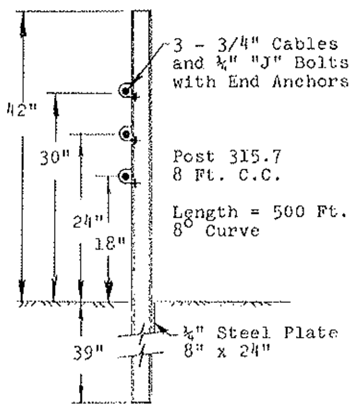
The test results shown in Figure 62 were disappointing in that the vehicle was not redirected and, therefore, the mathematical analysis could not be completely verified. In addition, some features of the barrier were found to be structurally inadequate. During the test, the car contacted the railing at 41 mph and 31 deg. It continued without appreciable redirection 12 ft into the barrier, knocking one post over, cutting one cable and separating the second cable at a splice. At this point the cable splice caught in a post offset, the car's forward motion was stopped and it was violently pitched about 17 deg, rolled up to 28 deg and yawed 150 deg, coming to rest on the barrier. Decelerations during the impact do not appear to be lethal, but the complete loss of forward velocity, lack of vehicle redirection and severe pitching would likely have thrown any occupants violently forward, resulting in serious injury.

Because of the disappointing performance of the first cable guide rail test and the desire to develop other barriers, further work on this type of barrier was delayed until later in the program. However, subsequent analysis and knowledge of the importance of post reaction led to the design of an improved cable guide rail.

The following factors were considered in modifying the cable guide rail design:

1. Cables elongate resulting in relatively large deflections.
2. Large deflections make it virtually impossible to prevent the vehicle from contacting posts.
3. A large number of posts are contacted at both shallow and large impact angles.
4. Cables require a strong end anchor. Existing anchors did not appear adequate for severe impacts.
5. Cable elevations might be critical—too low for big cars, too high for small cars.
6. Post height might be critical—too low is not effective in resisting large deflection, too high gets in the way of snowplows.
7. Effect of fill slope behind the barrier was not accounted for in mathematical models.
8. The optimum number of cables had to be established. (There appeared no reason to change the diameter of the $\frac{3}{4}$-in. cable commonly used.)
9. Cable is not very large and provides little roadway delineation compared with other rails.
10. Cables should not be securely fastened to posts to prevent posts from pulling cables down during impacts.
11. Temperature compensators are needed to minimize cable sag between posts during all seasons of the year.

After analyzing the data obtained, the following cable guide rail design was selected. It consisted of three $\frac{3}{4}$-in. cables mounted on lighter posts. The $2\frac{1}{4}$ by 2-in. by 4.1 lb/ft fence post was used with drive anchors, because the drive anchors provided a restraint to lateral post and cable movement and very little resistance to longitudinal movement. It was expected that the cable would deflect several feet and several posts would be bent over while the car was being redirected. The cable elevations were selected to cover the range of fender and hood elevations on both small and large cars. The posts were extended 6 in. above the top cable so as to provide resistance to large lateral movement of the cables when deflected by a car. Early loss of contact with the posts would permit larger cable deflections. Cables 200 ft long were selected primarily because the test area only had room for about 200 ft of barrier. It was felt that if a test was successful the mathematical models could be used to calculate the effects of using longer cables. Post spacing of 8 ft was selected which appeared reasonable since calculations showed that a deflection of 10 ft would result from an impact of 60 mph and 25 deg. The deflection could not be significantly reduced by closer post




Impact Conditions:
Speed: 53 MPH
Angle: 25°

Maximum Dynamic
Deflection: 8.5 Ft.

Exit Conditions:
Speed: 45± MPH
Angle: Large

Length of Barrier
Contact: 56 Ft.

Number of Posts
Damaged: 7

Average Deceleration:
During Highest Period
3.5 g's (0.05 sec.)
During Barrier Contact
1.2 g's (1.067 sec.)

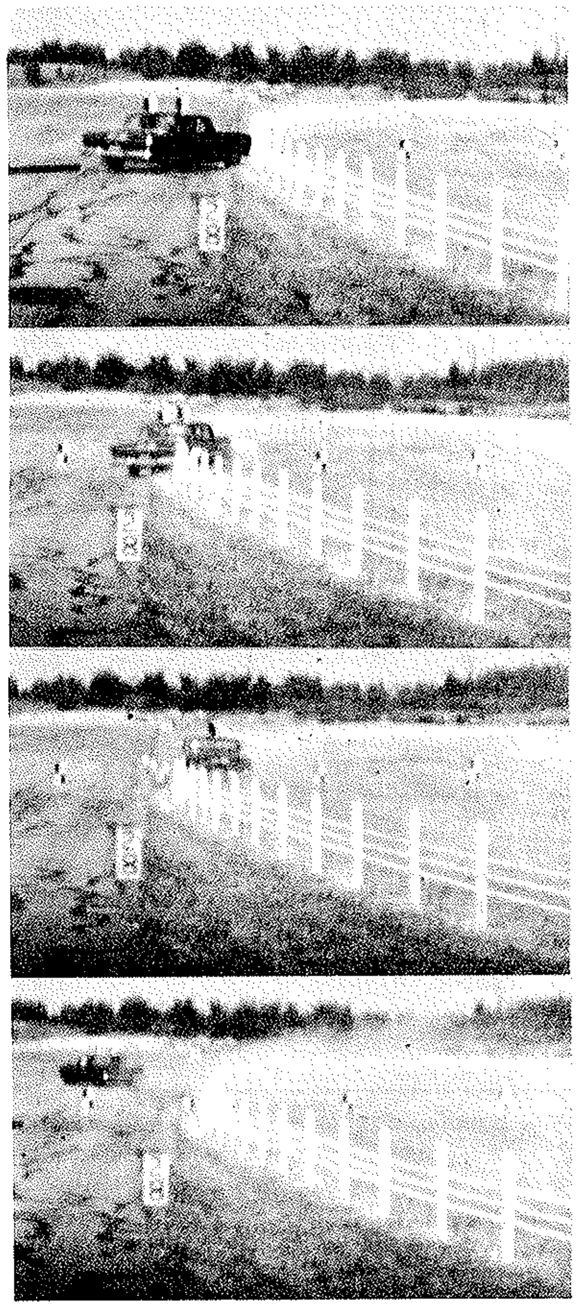
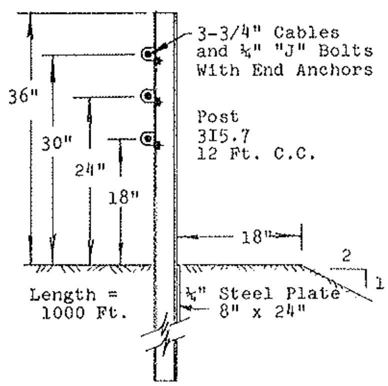


Figure 65. Cable guide rail (Test 28).




Impact Conditions:
  Speed: 54 MPH
  Angle: 25°

Maximum Dynamic
  Deflection: 8.7 Ft.

Exit Conditions:
  Speed: 33 MPH
  Angle: 12°

Length of Barrier
  Contact: 60 Ft.

Number of Posts
  Damaged: 6

Average Deceleration:
  During Highest Period
  2.4 g's (0.05 sec.)
  During Barrier Contact
  1.2 g's (1.280 sec.)

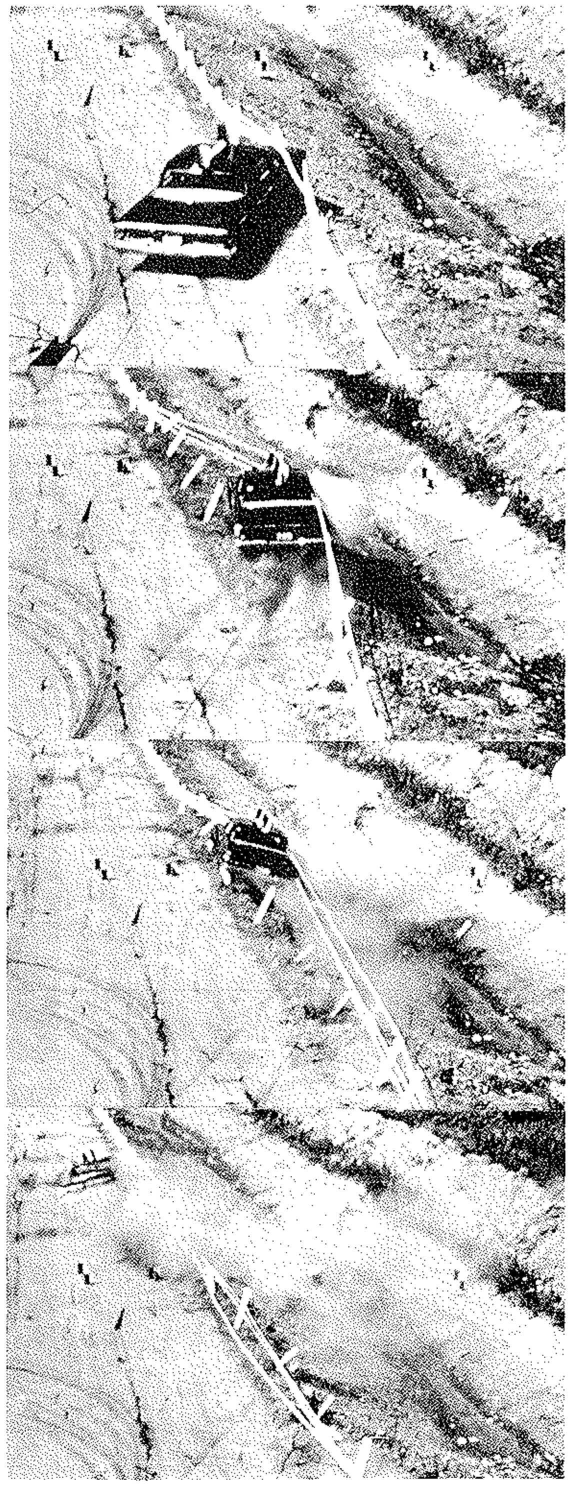
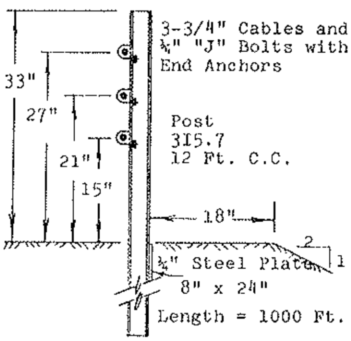


Figure 66. Cable guide rail (Test 33).




Impact Conditions:
Speed: 43 MPH
Angle: 35°

Maximum Dynamic
Deflection: 9.3 Ft.

Exit Conditions:
Speed: Not Redirected
Angle: Not Redirected

Length of Barrier
Contact: 72 Ft.

Number of Posts
Damaged: 6

Average Deceleration:
During Highest Period
5.2 g's (0.05 sec.)
During Barrier Contact
1.7 g's (1.140 sec.)

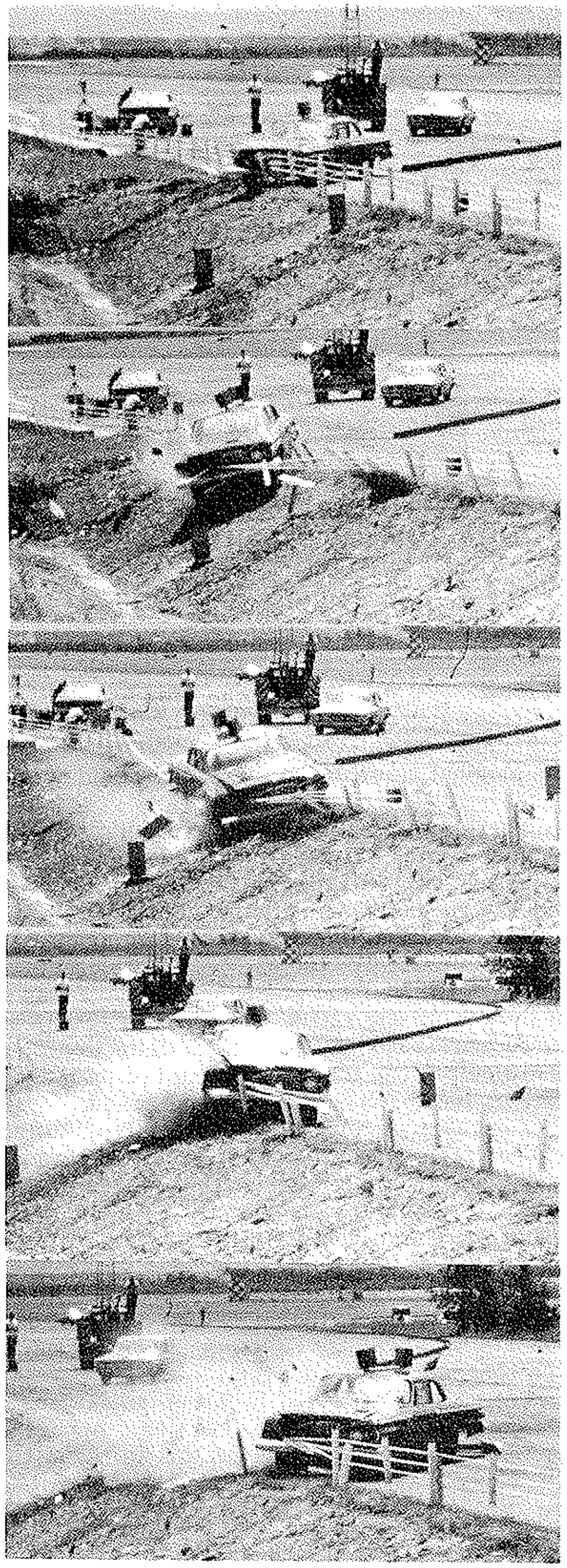


Figure 67. Cable guide rail (Test 36).

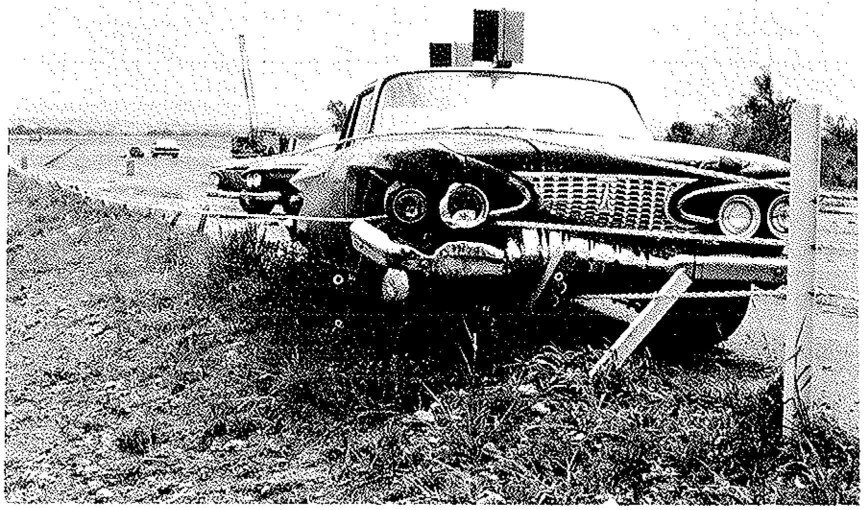


Figure 68. Car after Test 37.

spacing. A J bolt fastner was used to hold the cables to the post until the posts were deflected appreciably by lateral load or impacted directly by the car. When the post deflected, the relatively weak J bolt would open and allow the cable to stay at nearly the original elevation so that a car would not climb up on the cable. The cables were anchored at an end post.

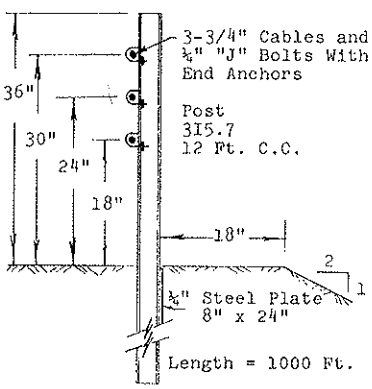
There was concern about the possibility that the car might roll over and down a fill slope. A ditch 3 ft deep with a 2:1 slope was dug behind the test barrier in order to permit visual evaluation of this factor. The vertical motions of the car are not considered in the mathematical analysis.

The results of the first test on the modified cable barrier are shown in Figure 63. The car was redirected with moderate decelerations and little steering damage, but the barrier deflected and was damaged more than expected partly because of the high angle of impact (30 deg rather than 25 deg). Tests showed that a cable system would redirect a car as desired but lateral deflection would be large. Large deflection could make it difficult to use the cable on the inside of sharp curves because the cables might not develop tension until the curve reversed.

The cable system was subsequently modified again and retested. As described elsewhere in this report it was desirable to change from a $2\frac{1}{4}$ by 2-in. by 4.1 lb/ft post to a 3I5.7 lb/ft. To minimize the use of intermediate anchors it was desirable to see if longer lengths were satisfactory. Finally, it was important to see how the system would react on relatively sharp curves.

A 1,000-ft barrier was tested as shown in Figure 64. The top of the posts was 12 in. above the top cable instead of 6 in. as in Test 18 to provide more resistance to cable deflections as the posts bent over. A 6-ft deep ditch with a 2:1 slope was provided to help evaluate the tendency for the car to roll over. The end post was anchored to a concrete deadman.

The barrier deflected 11 ft and the car was redirected but it rolled over onto the pavement as the car left the barrier. Apparently some of the energy absorbed by the cables was not dissipated, but was stored and returned to the car as it left the barrier. The cables "shoved" the rear end of the car back onto the pavement too fast causing the car to roll completely over and rotate nearly 180 deg. In the mathematical models the car was assumed to have contact with the ground at all times. The friction between tires and ground helped dissipate the lateral energy of the car in Test 18. In Test 20, the ground contact was not maintained as long as in Test 18.




Impact Conditions:
Speed: 53 MPH
Angle: 5°

Maximum Dynamic
Deflection: 1.0 Ft.

Exit Conditions:
Speed: None
Angle: None

Length of Barrier
Contact: 200 Ft.

Number of Posts
Damaged: 20

Average Deceleration:
During Highest Period
0.8 g's (0.05 sec.)
During Barrier Contact
0.4 g's (1.10 sec.)

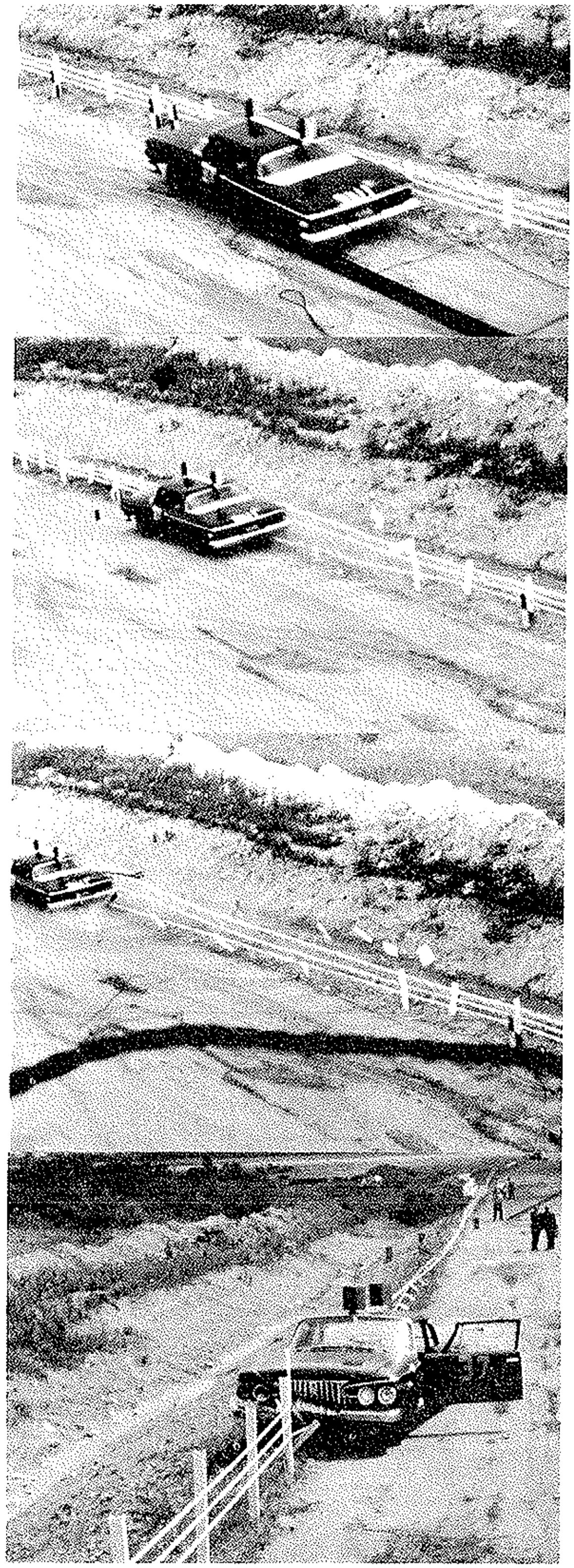
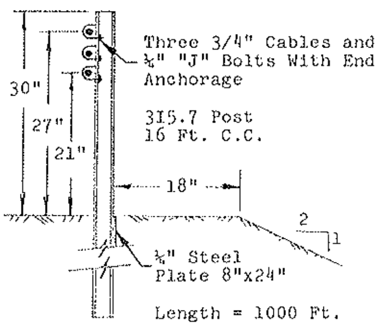


Figure 69. Cable guide rail (Test 37).




Impact Conditions:
Speed: 44 MPH
Angle: 25°

Maximum Dynamic
Deflection: 11 Ft.

Exit Conditions:
Speed: 32 MPH
Angle: 15°

Length of Barrier
Contact: 96 Ft.

Number of Posts
Damaged: 6

Average Deceleration:
During Highest Period
6.1 g's (0.05 sec.)
During Barrier Contact
1.7 g's (1.025 sec.)

Permanent Set:
Not Applicable

Figure 70. Cable guide rail (Test 46).

The 500-ft cable on an 8-deg curve was tested and the results are shown in Figure 65. In this test the ground behind the barrier was flat and the car was redirected as desired.

The basic difference in vehicle reaction between Tests 20 and 28 was the contact with the ground. It was apparent that the system should be weakened to permit larger deflection and more time for the car to settle into the ditch. The system could be weakened by using two cables instead of three or by increasing the post spacing. The increase in post spacing appeared to be more desirable and was tested at a 25-deg and a 35-deg impact angle. In both Tests 33 and 36 the cable performed acceptably.

The barrier details for Test 33 were the same as in Test 20 except that post spacing was 12 ft center-to-center and the top of the post was only 6 in. above the top cable to further weaken the system by allowing the cable to lose post contact easier.

The use of 3I5.7-lb posts instead of the 6B8.5-lb posts with offset brackets (Test 1) considerably reduced the visibility of the cable barrier. In Test 33, 3 by 3 by 24-in. angles were fastened to the cables between posts with J bolts to help increase visibility of the barrier.

Test results are shown in Figure 66 (note 3 by 3-in. angles before impact and after). The car was redirected as desired but the reaction was very similar to Test 20 and the car nearly rolled over again. In this test the top cable slid over the hood and cracked the windshield.

On the day of testing, the vehicle tendency to roll over was not noticed and the next test (35 deg) was scheduled before the data films were viewed. For the 35-deg test all three cables were lowered 3 in. to prevent the recurrence of a shattered windshield. Results are shown in Figure 67. The rear end of the car was again "shoved" out too fast and this, combined with the larger impact angle, caused the front end to snag on the cables.

In both Tests 33 and 36, the 3-in. angle delineators flew off the cables during impact and could have been a serious hazard. The use of angles was therefore discontinued.

Since the snagging in Test 36 appeared to be partly due to the large impact angle and post spacing rather than cable elevation, the 5-deg test was performed with the cables at the same elevations used in Test 36. Results are shown in Figures 68 and 69.

When the high-speed movies of Tests 33 and 36 were reviewed, it appeared that the system was still too stiff and that post spacing could be increased and post height above cables decreased. It also was decided to raise the lower cables to prevent them from sliding under the car as in Test 37 and to reduce the chance of snagging as in Test 36.

In Tests 20, 28, 33 and 36, very little movement of the end anchors was observed and it was felt that a lighter post with a flush deadman might work. A wide flange section was set in 1 cu yd of concrete placed flush with the ground. The 3I end post had a 6 by 6-in. plate welded to the bottom to prevent vertical settlement due to dynamic and residual cable loads. This end anchor along with 16-ft post spacing and cables at elevation shown in Figure 70 were used in Test 46. This time the car reacted very much as desired.

The details shown in Figure 71 have been adopted by New York as a standard. The end anchor consists of approximately 1 cu yd of concrete which has smooth sloping sides to help prevent frost from lifting the concrete. The top of concrete is flush with the ground. Cable lengths up to 2,000 ft between end anchors are allowed. Cable splices are permitted but their use is discouraged because of the observations made by the California Division of Highways and at the General Motors Proving Grounds that they tend to snag on the car during a collision. A slight tension is maintained in the cables at all times to prevent unsightly sag. A spring temperature compensator with an 8-in. take-up is provided on one end of each cable where the installation is less than 500 ft long. On longer installations a spring compensator is provided at both ends of each cable. The original $\frac{1}{4}$-in. J bolt has been replaced with a $\frac{5}{16}$-in. bolt which will resist shearing when the rail is rubbed by a snow plow and is less subject to vandalism.

## W Section Guide Rail

Like cable guide rail, the W-shape or corrugated metal rail has been used extensively in New York and other states. It was also used back-to-back as a median barrier. An

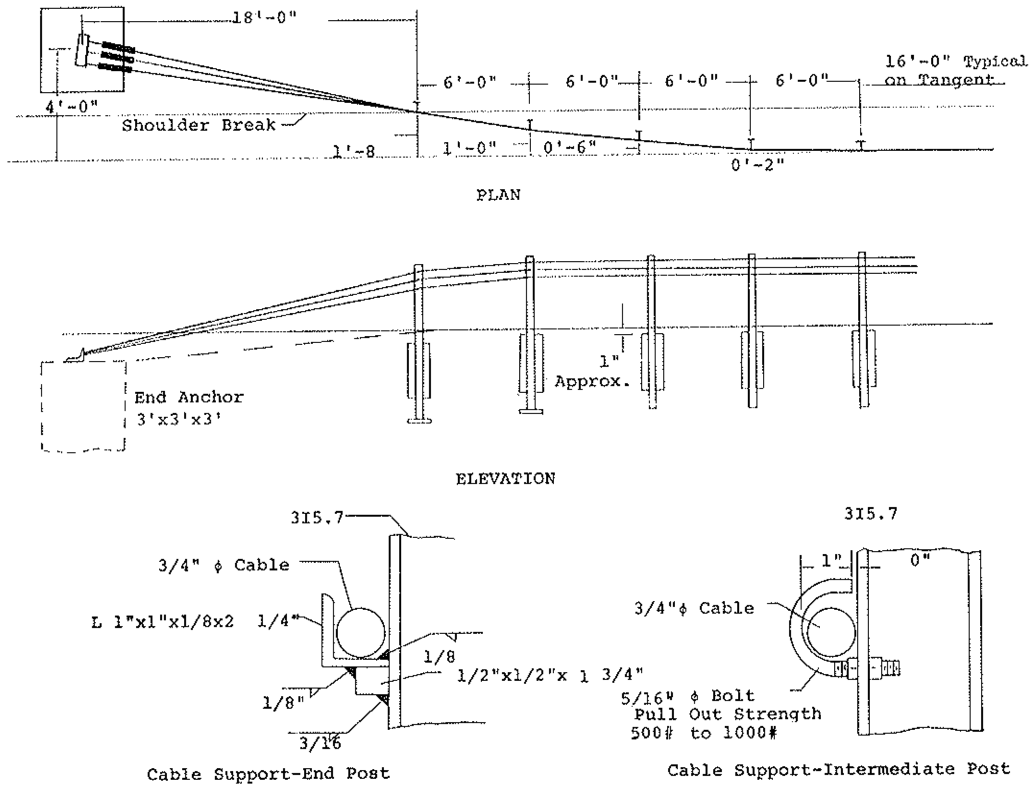



Figure 71. Details of modified cable guide rail.

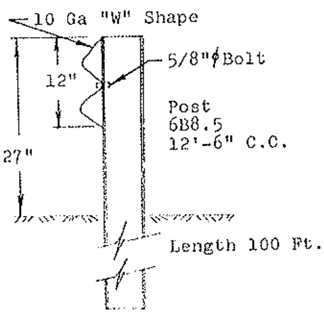
evaluation of the existing W-section guide rail began with a full-scale test so that the mathematical models could be verified and used in completing the evaluation. Test 2 (Fig. 72) provided an abrupt evaluation without the use of mathematical models. It was obvious that the posts were too strong and the rail had too little beam strength to span the 12 ft 6 in. post spacing.

It seemed logical that the system could be improved by using closer post spacing to increase beam strength, placing spacers between rail and post to help prevent the car from snagging on posts, and anchoring the ends to prevent rail tension from pulling posts over. Also, two rails as used in a median barrier would provide some truss action. Therefore, a median barrier with these features was tested in a second effort to provide a complete vehicle trajectory for the mathematical models. In Test 3 the impact was less severe than in Test 2 and the car was redirected (Fig. 73).

Although the car steering was damaged the barrier did perform well and was recommended to the Department as an interim solution to the median barrier problem.

The success of the prototype box beam median impacted in Tests 4 and 5 gave rise to speculation about a similar rail under tension. As conceived, this rail would have less bending strength than a median barrier and be anchored to develop rail tension. It would be mounted on posts in the same manner as the median barrier. The tops of the posts would have saddles in which the rail would rest freely. Such a barrier was constructed and tested twice. In the first test (Fig. 74) the cable clamps on the end anchorage failed, necessitating a re-test. The second test was successful and demonstrated the desirability of the light post (Fig. 75). The concept was sound, but with the anticipated vehicle and barrier damage during brushing accidents and difficulty of maintenance, the design was laid aside.

It was still desirable to use the W-shape rail and to find a way to modify the existing guide rails to get better performance. A full-scale test was scheduled for the barrier




Impact Conditions:
Speed: 54 MPH
Angle: 19°

Maximum Dynamic
Deflection: 6.0 Ft.

Exit Conditions:
Speed: None
Angle: None

Length of Barrier
Contact: 20 Ft.

Number of Posts
Damaged: 5

Average Deceleration:
During Highest Period
9.0 g's (0.05 sec.)
During Barrier Contact
4.0 g's (0.610 sec.)

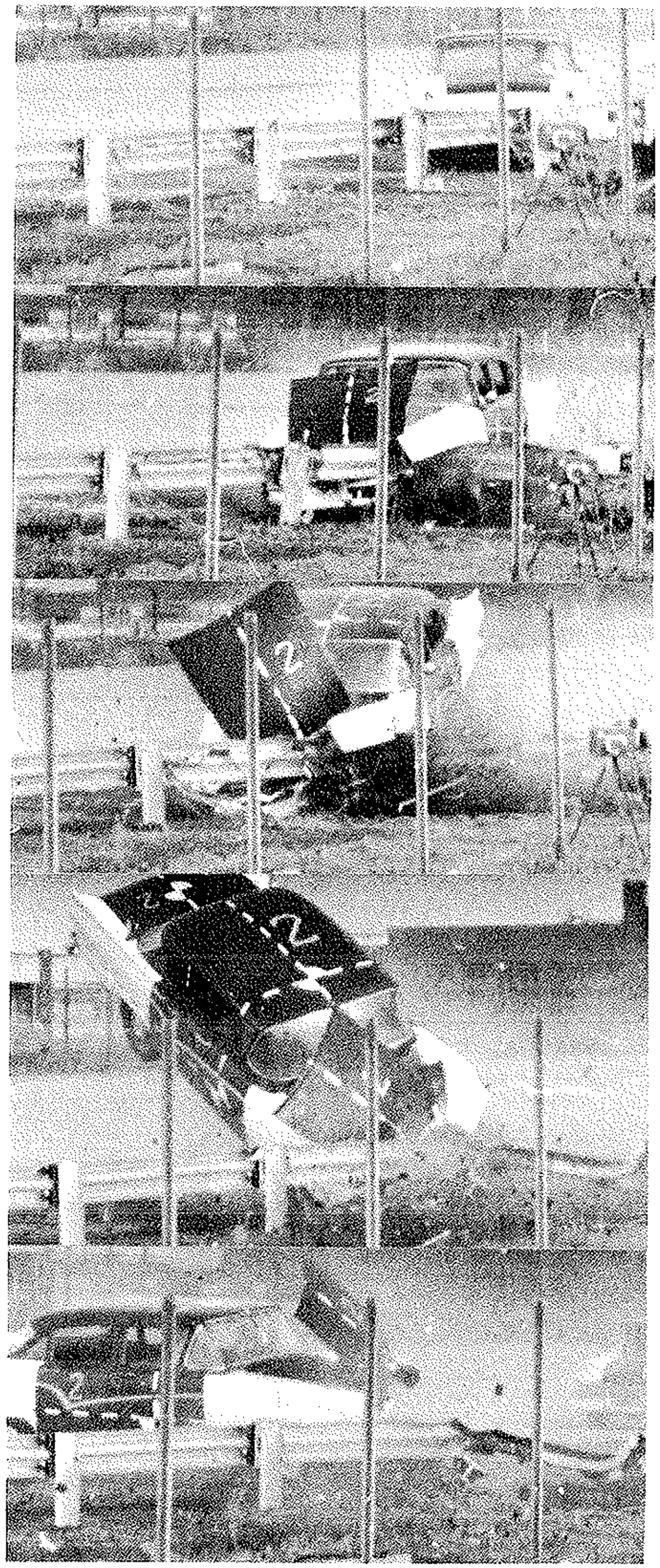
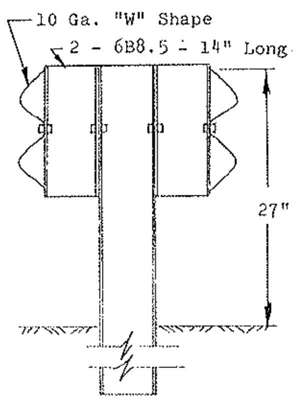


Figure 72. W-section guide rail (Test 2).




Post 6B8.5 6'-3" C.C.
Barrier Anchored Each End

Impact Conditions:
Speed: 67 MPH
Angle: 16°

Maximum Dynamic
Deflection: 1.5 Ft.

Exit Conditions:
Speed: 48 MPH
Angle: 9°

Length of Barrier
Contact: 25 Ft.

Number of Posts
Damaged: 2

Average Deceleration:
During Highest Period
5.7 g's (0.05 sec.)
During Barrier Contact
3.0 g's (0.450 sec.)

Permanent Set: 1.1 Ft.

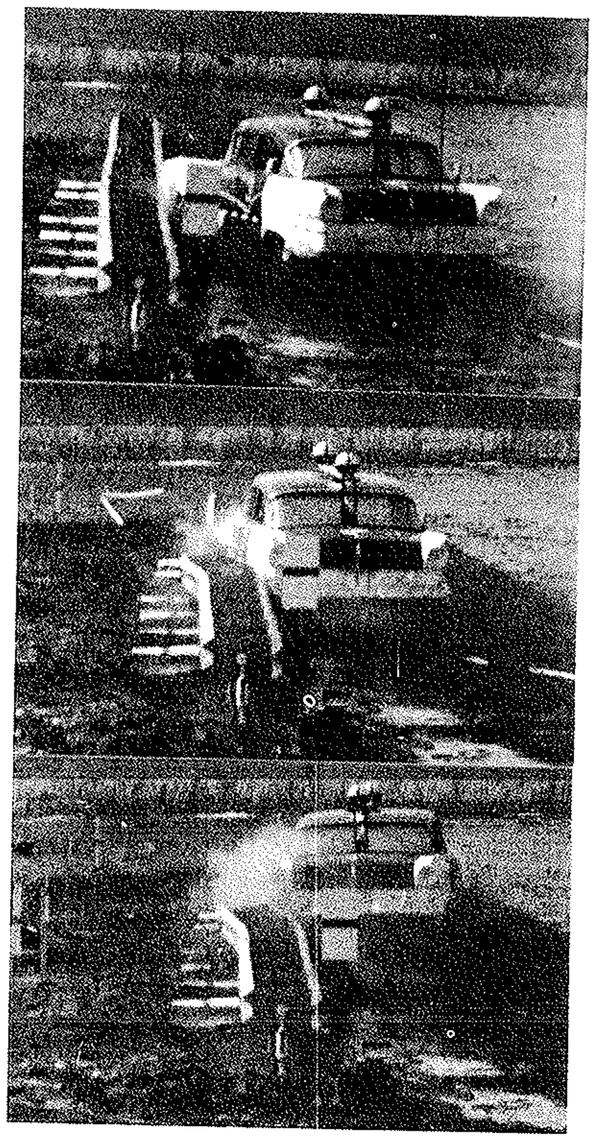
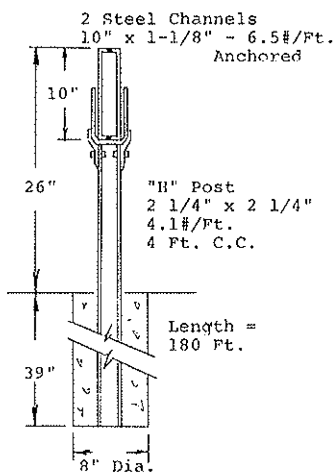


Figure 73. W-section median barrier (Test 3).




Impact Conditions:
Speed: 52 MPH
Angle: 18°

Faulty End Anchor Allowed
Excessive Rail Deflection.
See Test No. 7 for Barrier
Performance.

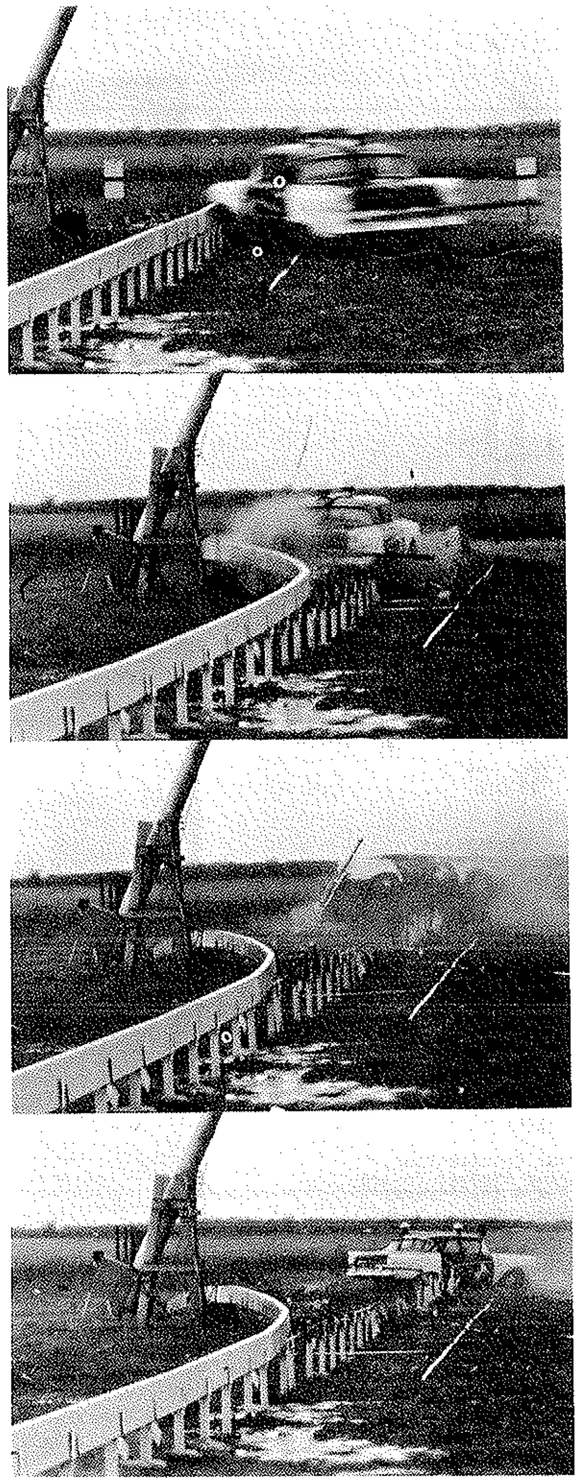
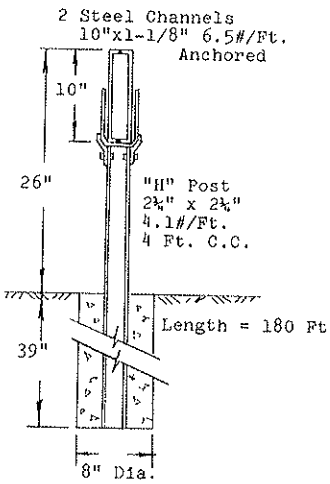


Figure 74. Tension box rail (Test 6).




Impact Conditions:
Speed: 55 MPH
Angle: 20°

Maximum Dynamic
Deflection: 2.5 Ft.

Exit Conditions:
Speed: 37 MPH
Angle: 9°

Length of Barrier
Contact: 28 Ft.

Number of Posts
Damaged: 7

Average Deceleration:
During Highest Period
4.9 g's (0.05 sec.)
During Barrier Contact
2.7 g's (0.550 sec.)

Permanent Set: 1.1 Ft.

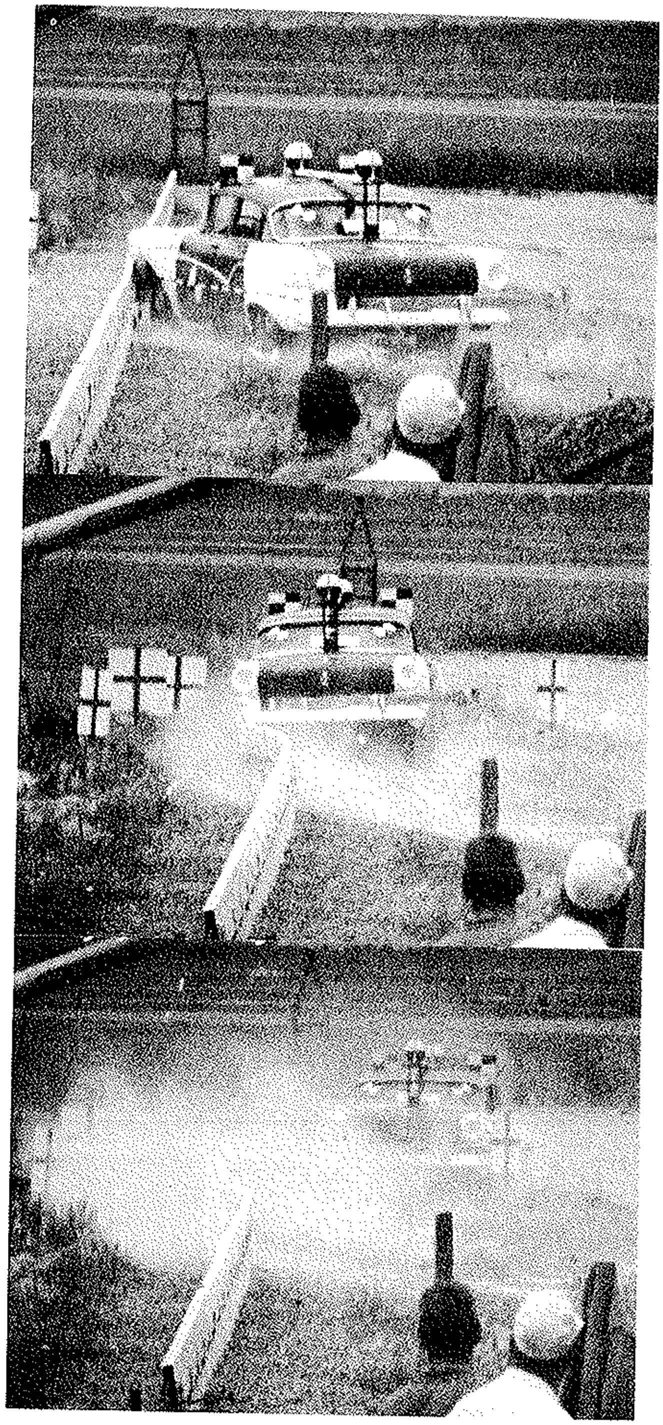
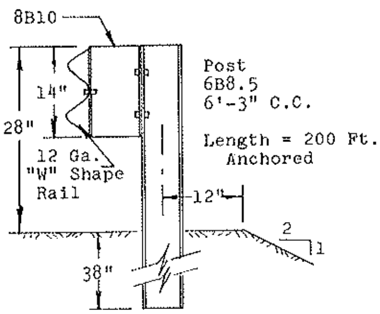


Figure 75. Tension box rail (Test 7).




Impact Conditions:
  Speed: 59 MPH
  Angle: 25°

Maximum Dynamic
  Deflection:

Exit Conditions:
  Speed: Pocketed
  Angle: Pocketed

Length of Barrier
  Contact: 25 Ft.

Number of Posts
  Damaged: 5

Average Deceleration:
  During Highest Period
  11.2 g's (0.05 sec.)
  During Barrier Contact
  4.0 g's (0.383 sec.)

Permanent Set:
Rail tore and separated

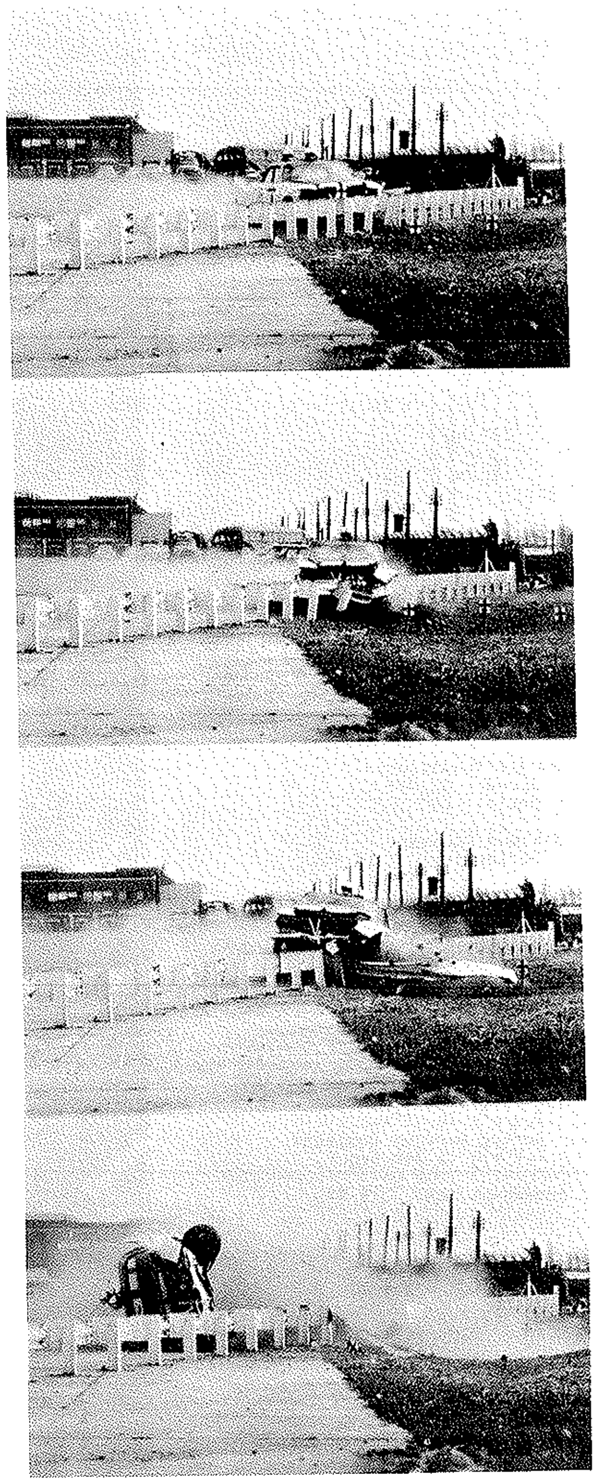
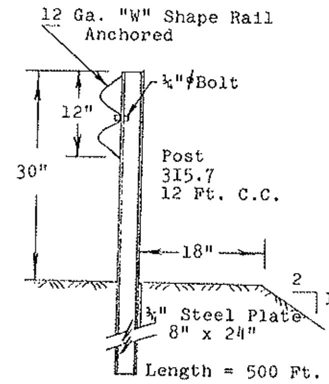


Figure 76. W-section guide rail (Test 19).




Impact Conditions:
Speed: 51 MPH
Angle: 25°

Maximum Dynamic
Deflection: 10.7 Ft.

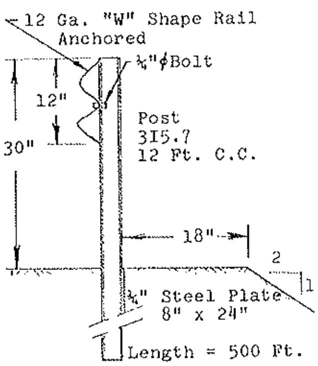
Exit Conditions:
Speed: None
Angle: None

Length of Barrier
Contact: 75 Ft.
End Anchor Failed
Number of Posts
Damaged: 6

Average Deceleration:
During Highest Period
8.1 g's (0.05 sec.)
During Barrier Contact
2.1 g's (1.240 sec.)

Permanent Set: 8 Ft.

Figure 77. W-section guide rail (Test 38).




mpact Conditions:
Speed: 54 MPH
Angle: 25°

Maximum Dynamic
Deflection: 6.8 Ft.

Exit Conditions:
Speed: 36 MPH
Angle: 14°

Length of Barrier
Contact: 60 Ft.

Number of Posts
Damaged: 6

Average Deceleration:
During Highest Period
2.7 g's (0.05 sec.)
During Barrier Contact
1.2 g's (1.450 sec.)

Permanent Set: 4.0 Ft.

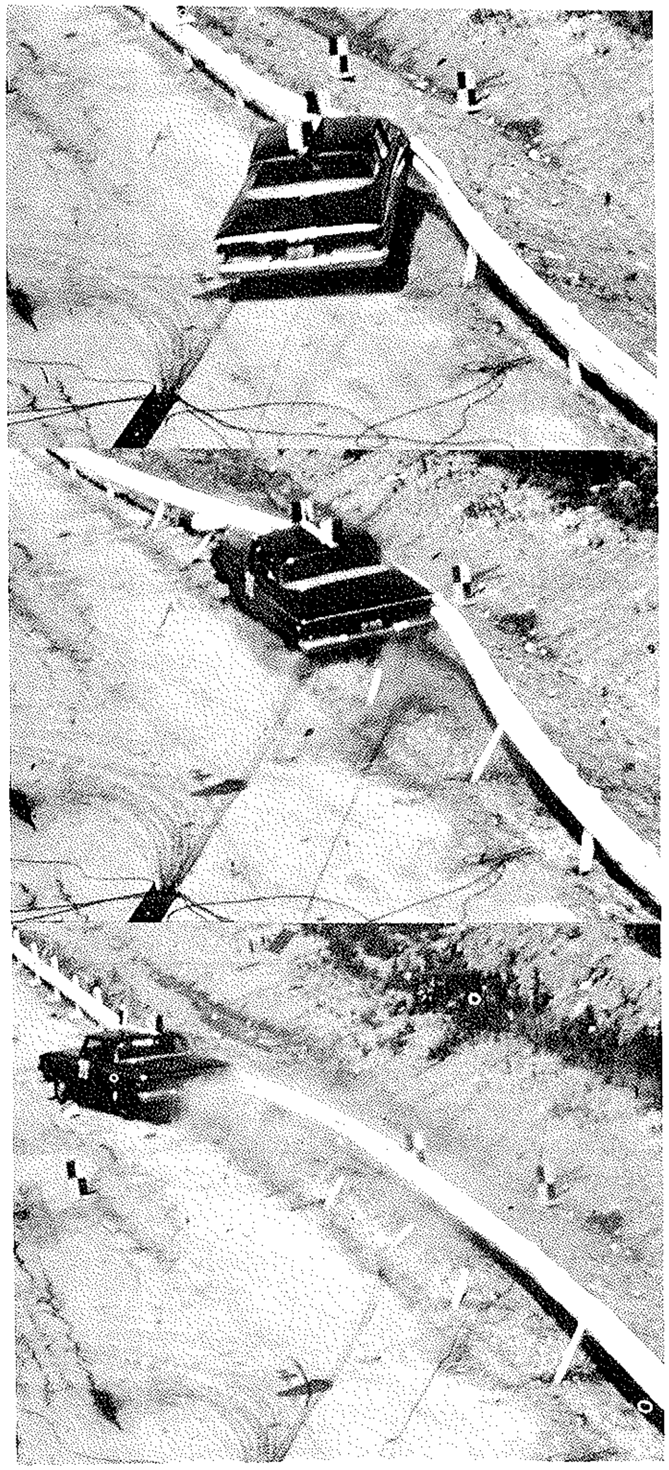
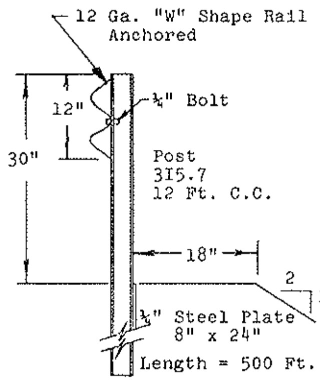


Figure 78. W-section guide rail (Test 39).




Impact Conditions:
Speed: 35 MPH
Angle: 35°

Maximum Dynamic
Deflection: 9.0 Ft.

Exit Conditions:
Speed: None
Angle: None

Length of Barrier
Contact: 40 Ft.

Number of Posts
Damaged: 5

Average Deceleration:
During Highest Period
2.8 g's (0.05 sec.)
During Barrier Contact
2.1 g's (0.805 sec.)

Permanent Set: 4.0 Ft.

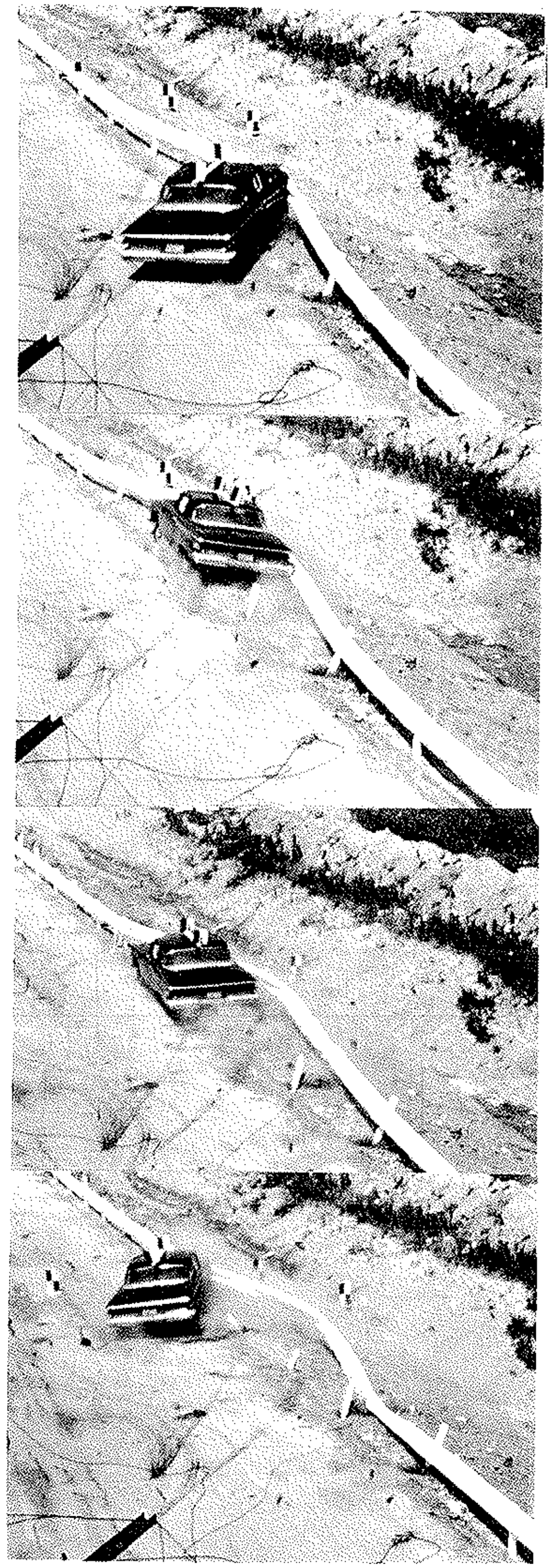
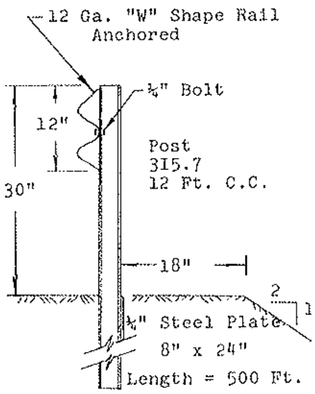


Figure 79. W-section guide rail (Test 40).




pact Conditions:
Speed: 57 MPH
Angle: 6°

Maximum Dynamic
Deflection: 0.0 Ft.

Exit Conditions:
Speed: 55 MPH
Angle: 1°

Length of Barrier
Contact: 12 Ft.

Number of Posts
Damaged: 2

Average Deceleration:
During Highest Period
1.0 g's (0.05 sec.)
During Barrier Contact
0.7 g's (0.320 sec.)

Permanent Set: 0.0 Ft.

Figure 80. W-section guide rail (Test 41).

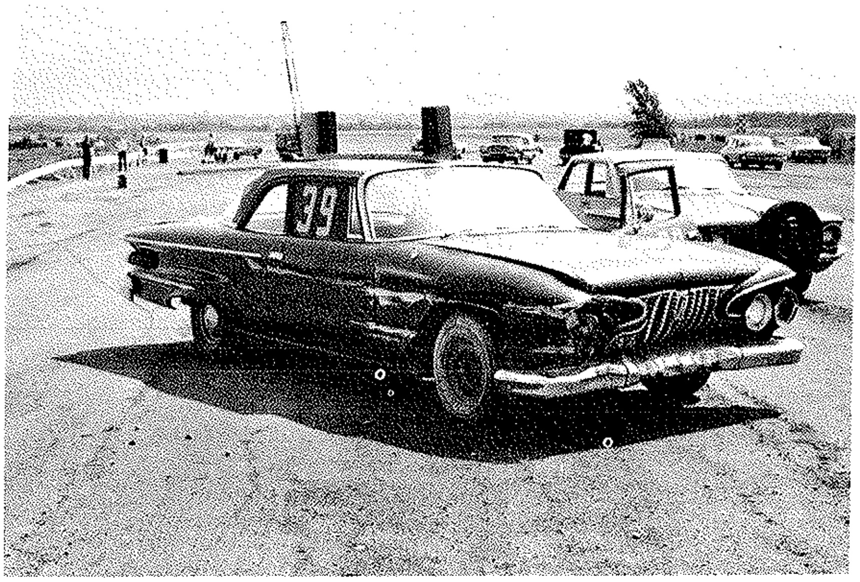



Figure 81. Car after Test 39.

shown in Figure 76. Post spacing was reduced from the normal 12 ft 6 in. to 6 ft 3 in. to increase beam strength of the rail and reduce lateral deflection. Spacers 8 in. wide were used to keep the car wheel away from the post as far as possible, and the rails were connected directly to end anchors to develop maximum rail tension during impact A 50-mph, 25-deg test was selected as the minimum impact which the system could re sist without exceeding the tensile strength of the rail. In the full-scale test the car attained a speed greater than planned and the rail failed as expected under a 60-mph impact (Fig. 76).

After Test 19 it was apparent that if the W-shape rail was to be used it would act primarily in tension, much as the cable rail. Therefore, provision would have to be made for large deflection. Further work was delayed until development of the modified cable barrier was completed.

Since the cable performed satisfactorily in Test 33 and the W rail was expected to react in a similar manner, the mathematical models were not used to evaluate the proposed system before the full-scale tests. The W-shape rail was erected on the same posts used for the cable tests except that only 500 ft of W rail was used. The centerline of rail was placed 24 in. above ground which is about 2 in. above the center of gravity of the car. The rail was fastened to each post with one $\frac{1}{4}$-in. bolt. A $\frac{5}{16}$-in. bolt is needed to support the rail under transient loads during erection or subsequent snow plowing but will fail when the post is struck by a car bumper. The rail will remain in contact with the car at the same elevation and not be pulled down with the post. The bolts outside the impact area prevent the rail from rising during a collision. The end anchors used in the full-scale tests were designed to develop the tensile strength of the rail. After the flush cable anchor proved successful in Test 46, it was adopted for use with W rail.

Tests at 60 mph and 25 deg and at 45 mph and 35 deg were scheduled to determine the ability of the system to absorb energy and redirect the car. In addition, a 50-mph, 5-deg test was scheduled to determine the barrier damage to be expected from sideswipes and shallow-angle impacts.

The vehicle trajectories and decelerations for four tests are shown in Figures 77 through 80. In Test 38 (Fig. 77), a faulty end anchor failed and the test is not considered to be significant. There was no significant deceleration in Test 41 (Fig. 80). In Tests 39 and 41 the car was redirected but in Test 40 the car was redirected until the


Figure 82. Barrier re-assembled after Test 39.

front end snagged on the rail and was forced to stop on the rail. None of the decelerations were high enough to preclude human survival but the exit angle for Test 39 was large enough to cause an oncoming traffic problem. In all three tests the steering system of the car was not damaged. The cars could be controlled after leaving the barrier, thus reducing the probability of interfering with traffic (Fig. 81).

During the high-angle tests the barrier deflected approximately 8 ft. This deflection limits the use of the barrier to areas where there are no solid objects within about 8 ft of the barrier. The rail did not spring back toward its original alignment, which indicates that the rail and posts absorbed most of the lateral kinetic energy of the car. However, the car left the barrier at an angle of 14 deg in Test 39. This was probably caused by the tendency of the car to follow the rail, which was deflected and therefore was at an angle to the roadway as the car left the barrier.

In the 5-deg test only two posts were damaged beyond simple realignment. In the test conducted at 54 mph and 25 deg, no rails were seriously damaged. The same rails were re-erected the day following the test. The only repairs required were new posts, new ¼-in. bolts and the pounding out of a few "scallops" on the rail edges (Fig. 82).

In Tests 39 and 40 the top of the rail was set at 30 in. above grade. During maximum rail deflection in Test 40 the front wheel dropped down on the fill slope while the frame of the car did not. The rail slid between the wheel and the frame and when the wheel returned to normal position the rail was caught between the wheel and the frame (Fig. 83). This prevented the front end of the car from leaving the barrier. Lowering the top of the rail to 27 in. above ground should prevent this type of snag.

During the 5-deg test a few of the ¼-in. bolts which hold the rail to the posts failed; however, the rail stayed at the proper elevation. Although two posts were bent over the system still was serviceable and repairs could be made at some later date with little loss of barrier protection before repairs.

Later experiences have shown that the ¼-in. bolts will shear when the rail is rubbed by a snowplow; $\frac{5}{16}$-in. bolts were substituted and held when the rail was severely rubbed by a large snowplow. Since the standard rail used in the United States has slots for $\frac{5}{8}$-in. bolts the washer detail shown in Figure 84 is used with the $\frac{5}{16}$-in. bolts.

The standard rail splice detail was used in all tests and appears to be entirely satisfactory.

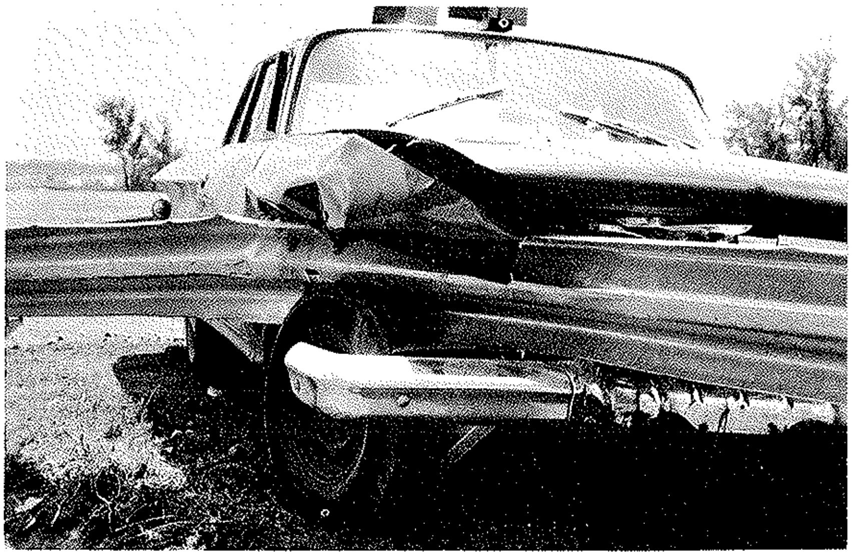


Figure 83. Car snagged on rail in Test 40.

The heavy anchor post with a rod to a deadman used in the tests is not considered satisfactory because the large post could cause severe deceleration to a car. The flush end anchor for cable proved successful and there seems to be no reason why a flush anchor cannot be used with the W-type rail. Vertical thrust on the end post or posts would only occur during an impact and would be minimal if the rail had a low-angle vertical bend.

Both cable and W-type barriers are used primarily as guide rail and are expected to resist impacts up to 60 mph and 25 deg by a 4,000-lb car. When these barriers are carried around an intersection on short radii it is possible for a car to strike the barrier at a 90-deg angle on a tangent to a short radius curve. The barrier was not designed to redirect a car under these conditions. The problem of protecting vehicle occupants in this situation has not been completely resolved. However, it is highly desirable to have an effective barrier near these intersections. If the barrier is carried around the curve it is necessary to insure that the rail will not pull over all the posts on the curve and that rail tension will be transmitted around the curve and ultimately to the end anchor. This can be assured by reducing post spacing on short-radius curves (Tables 6 and 7).

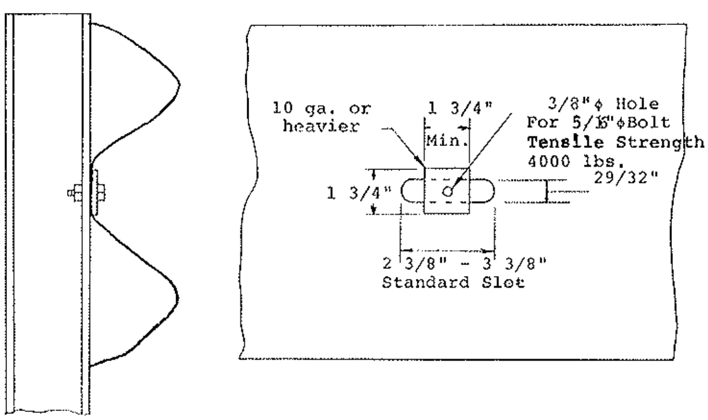



Figure 84. Suggested rail-post connection detail for W-shape guide rail.

TABLE 6

POST SPACING FOR CABLE GUIDE RAIL ON CURVES

| Curvature (Degree or Radius) | Post Spacing (ft) |
|---|---|
| 8 deg or less | 16 |
| More than 8 deg to 26 deg (220 ft radius) | 12 |
| 219 ft to 111 ft | 6 |
| 110 ft to 76 ft | 4 |
| 75 ft to 50 ft | 3 |
| Less than 50 ft | Use not recommended |

TABLE 7

POST SPACING FOR W RAIL ON CURVES

| Radius of Curvature | Post Spacing |
|---|---|
| More than 220 ft radius | 12 ft 6 in. |
| 219 ft to 111 ft | 6 ft 3 in. |
| 110 ft to 76 ft | 4 ft 2 in. |
| 75 ft to 50 ft | 3 ft 1½ in. |
| Less than 50 ft | Use not recommended |

The W or beam-type guide rail (Fig. 85) mounted on 3I5.7 posts and anchored at each end satisfied nearly all requirements for a guide rail. Vehicle deceleration for the most severe impacts is limited to less than 3 g's, which is lower than those for any other barrier tested, and a car can be brought under control when leaving the barrier. The rails are not subject to frequent replacement and they can be easily re-erected. The only problem is that a clear distance of at least 8 ft is required behind the rail to permit rail deflection during a collision. If the rail is painted a bright color the edge of the roadway can be delineated. Of course, delineation can easily be provided by erecting reflectors in several different ways.

The W-shape rail may also be used as a median barrier simply by adding a second rail to the other side of the posts. The ends of the second rail can be bolted to the first rail so that tension can be developed in the second rail. Since the rail on the back side of the posts from an impact can transfer very little load to posts the system should act very much the same as a single rail system with slightly less deflection. Because of the close similarity between the guide rail and median barrier no tests were considered necessary on the median barrier. The top of the rail can be kept at 30 in. above ground where the median is relatively flat.

## INSTALLATION AND PERFORMANCE OF NEW BARRIERS

The maximum dynamic deflections exhibited by the new standard guide rails and median barriers under impact condition of 60 mph and 25 deg are as follows:

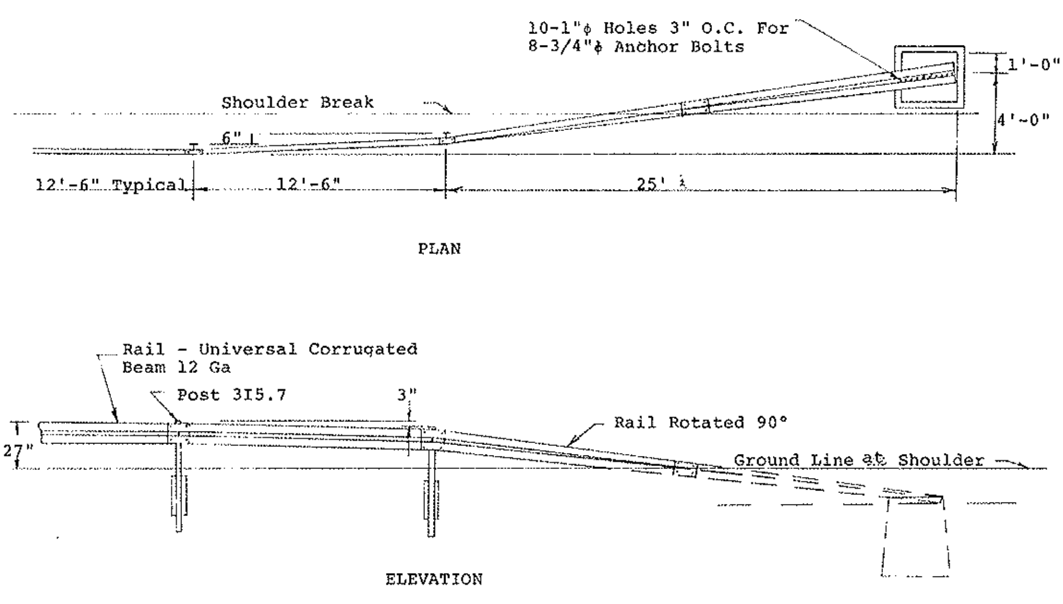



Figure 85. W or corrugated beam type guide rail.

Figure 86. Modified cable guide rail.

1. Cable guide rail—12 ft
2. W-section guide rail—8 ft
3. W-section median barrier—7 ft
4. Box beam guide rail—4 ft (posts spaced 6 ft c. c.)
5. Box beam guide rail—2 ft (posts spaced 4 ft c. c.)
6. Box beam median barrier—2 ft

Considering that the more deflection permitted, the lower the anticipated deceleration upon impact, it is logical to consider the use of this criterion in selecting the appropriate barrier type for a given situation. This procedure has the additional advantage of maximum economy, since the cost of the installation decreases as the deflection increases; that is, in order of increasing installation cost, the above barriers would be ranked 1, 2, 3, 4, 5, and 6. The amount of deflection allowed in any situation calling for a barrier has become a major factor in the choice of type by designers of the New York State Department of Public Works.

New barrier designs adopted by the Department have been installed on a number of highways throughout New York State, and are currently being placed on all construction. The typical appearance of all five types of barriers is shown in Figures 86 through 90.

In the next phase of this research project, accident data will be collected in order to verify the expected reduction in the severity of collisions with guide railing, median barriers and bridge rails. This survey should also uncover any problems in the maintenance of the new barriers. A preliminary study of barrier performance has been made and is summarized below.

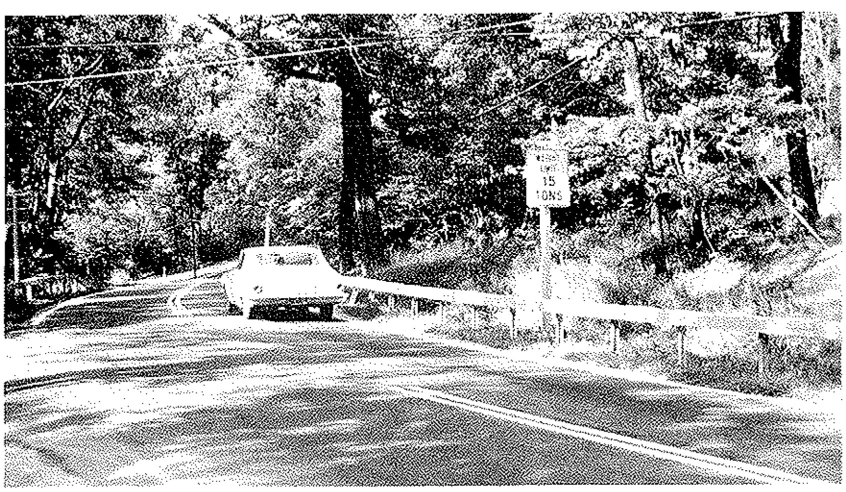


Figure 87. Box beam guide rail.

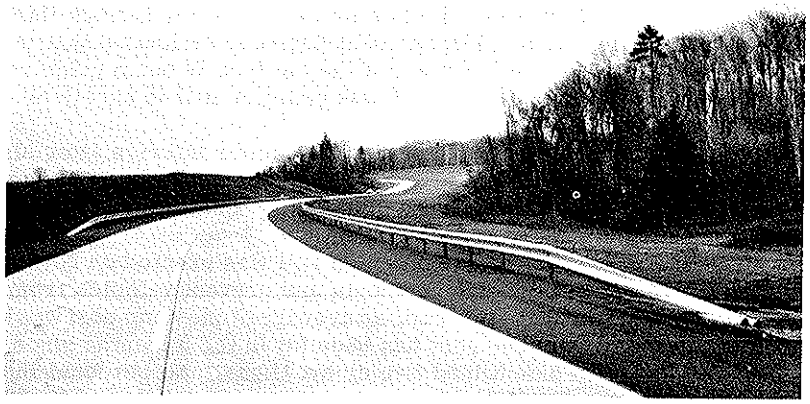


Figure 88. Modified W-shape guide rail.

Figure 89. Box beam median barrier.

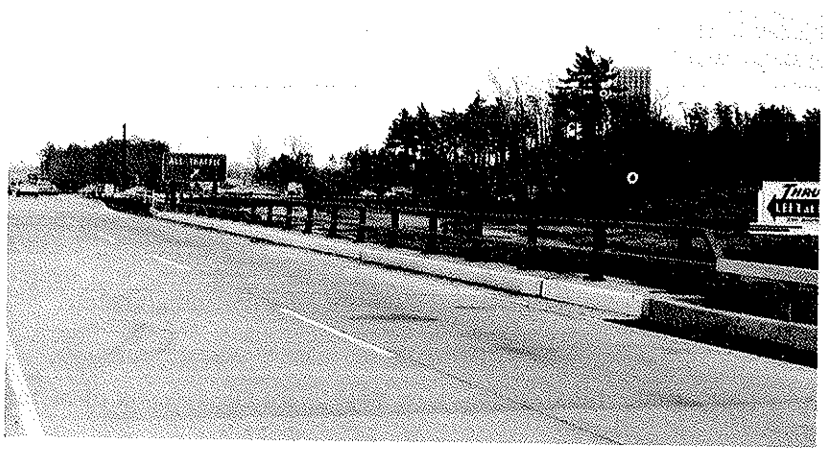


Figure 90. AASHO bridge rail.

Box Beam Guide Rail

In the 9 months since the rail was installed on Route 108, Cold Springs Harbor, Long Island, it has been hit several times. The resident engineer estimated that in each of the five most serious hits, at least one section of the old type W beam guide rail would have needed replacement. However, the 6 by 6 box beam is still in excellent condition and no posts have been damaged.

In one of the accidents, a man was hospitalized with minor injuries after his car hit the guide rail at a very high angle (about 70 deg). His car entered from a side road, crossed both lanes of Route 108 and struck the guide rail. In all other instances, the vehicles left the scene without reporting the accident.

On the Henry Hudson Parkway, a box beam guide rail was erected on both sides of a narrow median to prevent cross-median accidents and prevent vehicles from striking lamp posts. Prior to the installation of this rail, an average of one lamp post was knocked down or damaged each week. Only one post has been hit in the 5 months since the rail was erected. The rail has been sideswiped five or six times. No personal injuries have been reported. In the one accident where a light post was sheared off, 200 ft of rail each side of the median was dislodged from the posts. This was due to a lack of lateral restraint at rail ends near the point of impact and because a light pole close to the rail prevented the rail from deflecting more than a few inches. This can be corrected by anchoring the rail at the ends and by increasing the size of bolt used to hold the rail to the posts.

Box Beam Median Barrier

The median barrier on the Cross Bronx Expressway, New York City, has been hit on at least six occasions with one post being hit each time. Three posts were knocked out completely and three others were only bent. The bent posts were straightened and no rail has required replacement. The barrier has also been sideswiped several times but no maintenance was necessary. The original 6 by 8-in. box beam is still in very good condition. No injuries were reported in any of these accidents. All vehicles apparen drove away.

## CONCLUSIONS

As a result of this investigation, the New York State Department of Public Works has completely revised its specifications for highway barrers. New standards for guide rail, median barrier, and bridge railing based on research performed during this project are now being installed.

Mathematical models have been developed that permit the evaluation of many existing barriers, modifications to these barriers and proposed barrier designs. An electronic computer is employed to solve these mathematical models, which predict the reaction of a vehicle during impact.

The research led to the development of a new type of barrier design based on the concept of a strong beam and light post. In this approach, a rectangular rail section of considerable beam strength is supported by relatively weak posts; such a barrier deflects and absorbs impact forces over a large area while decelerating and redirecting the vehicle. By using box beams of different strengths and by varying the spacing of posts, barrier deflection can be controlled, thus making this type of barrier suitable for a guide rail, median barrier, or bridge railing.

A method of guide rail and median barrier selection is presented based on the amount of deflection which can be tolerated in any given situation. This criterion, used in conjunction with the improved barrier designs developed in this program, will insure that the minimum practicable decelerations will be imposed on a colliding vehicle.

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