Development of an Analytical Procedure for Prediction of Highway Barrier Performance

GEORGE W. McALPIN, MALCOLM D. GRAHAM, WILLIAM C. BURNETT, and RAYMOND R. McHENRY

Respectively, Deputy Chief Engineer, Director, and Associate Civil Engineer, Bureau of Physical Research, New York State Department of Public Works; and Research Mechanical Engineer, Cornell Aeronautical Laboratory, Buffalo, New York

From 1960 to 1963, the New York State Department of Public Works, in cooperation with the U. S. Bureau of Public Roads, has sponsored and participated in a combined analysis and testing program on highway barriers at Cornell Aeronautical Laboratory. This program has included the full-scale dynamic testing of median barriers, guide rails and bridge rails to gain a fuller understanding of the forces involved between vehicle and barrier during collision. This work has resulted in the development of mathematical models for predicting the performance of current and proposed barrier designs. Barrier performance as predicted by computer solution of the mathematical model has been verified by subsequent full-scale crash tests.

Additional work is under way to evaluate more accurately some of the variables in the model and to refine the model accordingly. However, work to date has demonstrated the feasibility of predicting barrier performance by means of these equations and the development of a rational method of design of barrier systems based on dynamic principles.

•HIGHWAY BARRIERS are erected to delineate the roadway limits and physically restrain vehicles from entering areas they cannot safely traverse. Equally as important, impact with the barrier should not overturn the vehicle nor result in decelerations that would preclude human survival. The basic requirements of a highway barrier can be stated as follows:

1. Containment—The vehicle must not get beyond the barrier. If a barrier is required in an area, the consequences of penetration are presumably more serious than even a sudden stop on the barrier.
2. Minimum injury potential—To reduce the inherent hazards of a barrier collision, the vehicle must be decelerated at the lowest rate possible without exceeding the allowable barrier deflection.
3. Redirection—The barrier should not stop the vehicle abruptly or rebound it across the highway, thus presenting a hazard to following or adjacent traffic.

If highway barriers fulfill these requirements, the motoring public is assured the maximum possible protection. To provide this protection, the responsible highway department must determine the capabilities of existing, new, and modified barriers. The obvious approach has been to perform full-scale dynamic tests. A review of

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previous investigations revealed that a large number of tests had been performed. The resulting barrier designs were a significant improvement, but the tests appeared to be insufficient by themselves since at least one test was required for every factor evaluated. Research had also been conducted to analyze mathematically the reaction of a vehicle during a barrier collision. However, the mathematical analyses, without verification, were never demonstrated to be adequate because of the great number of simplifying assumptions required. Therefore, to achieve maximum benefit it was decided that this study would consist of two phases—a mathematical analysis of the reaction of a vehicle during collision with a barrier and a series of full-scale dynamic tests. This approach would permit the full-scale testing to serve as verification for the mathematical analysis and the mathematical analysis to prescribe the necessary changes in the barrier configuration.

The investigation was performed by Cornell Aeronautical Laboratory under contract with the New York State Department of Public Works, in cooperation with the U.S. Bureau of Public Roads. In all, 19 full-scale tests were performed—4 guide rail, 5 median barrier and 10 bridge rail tests. The theoretical analysis resulted in the development of four mathematical models programmed for solution by electronic computer. These models can successfully predict the performance of a highway barrier under a wide range of impact conditions.

GLOSSARY OF TERMS

"Snagging" of a vehicle wheel on a post is assumed to occur only when (a) the structural collapse of the vehicle has progressed to a point within the vehicle tread dimension, and (b) the corresponding deflection of the barrier rail (or cables) has progressed beyond the centerline of the undeflected posts. Since snagging occurs at a point on the post below the rail attachment, the yield force of a post can be considerably increased by the effect of rail tension if the individual posts are attached to the rail.

"Pocketing" of the vehicle is assumed to occur if the center of gravity of the vehicle passes the original centerline of the barrier while the vehicle is still headed into the barrier. The conditions for pocketing are considered to be similar to those for wheel snagging, except that the entire front of the vehicle, rather than only the impacting front wheel, is caught behind a post. If the vehicle were to pass through the barrier or be redirected out of the barrier, it would not be considered pocketed.

MATHEMATICAL MODELS

Mathematical models were constructed to compute the response of a vehicle during collision with a highway barrier. 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.

The characteristics of a given barrier are first used to compute a series of force-deflection curves representing 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.

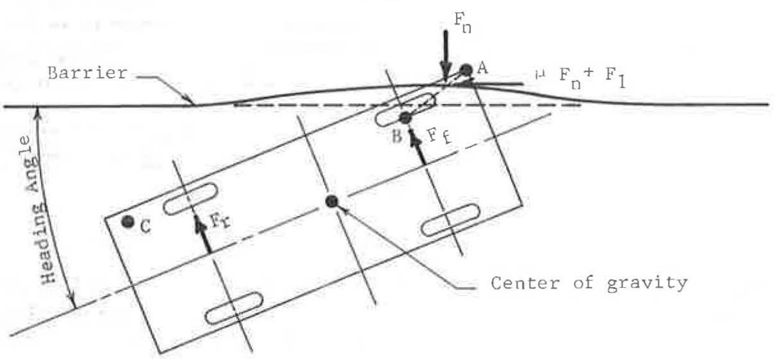
Vehicle responses are calculated by a repetitive process programmed for solution on an IBM 704 computer. During each millisecond of the collision, this process recalculates the vehicle position until the corresponding barrier deflections successively agree within specified limits (usually 0.01 inch). The computer than prints out the vehicle position, velocity, deceleration, and barrier deflection.

To account for the many important physical characteristics of vehicle and barrier and the forces which act during a collision, several simplifying assumptions must be made. 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. The horizontal force between vehicle and barrier is assumed to be a concentrated point load. 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. 1). 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. 1) are applied along the axles at the intersection of the car centerline. The coefficient of friction (μ) between vehicle and barrier is 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. The mass of the barrier is neglected.

Separate models were developed for three classes of barriers, depending on the way the rails resist impact. These classes correspond to the manner in which the rail acts as follows: (a) bending resistance only, (b) axial tension only, and (c) combined axial tension and bending resistance. Barriers not intended to deflect when impacted were not analyzed because they impart severe decelerations to the vehicle. The vehicle reaction during impact with a rigid barrier is also greatly influenced by the crushing characteristics of that particular vehicle.

A rail with bending resistance only is treated as a continuous beam which distributes the impact load over several posts. Progressing outward from the impact point, the posts provide increasing lateral support for the rail until they yield. Thereafter, each yielded post sustains a constant load until enough posts have yielded to resist the impact force completely. The rail is assumed to form a constant moment plastic hinge at the point of impact. It is this yielding of posts and rail that minimizes car deceleration and at the same time provides enough resistance to turn the car and redirect it.

A rail with axial tension only (e.g., cables) is represented by straight-line segments which intersect at post locations, starting at the applied load position and continuing to the original centerline of the barrier at a post location for which the lateral deflection is assumed negligible. Tension is calculated from the axial restraint at the end of the barrier and the total elongation of the cable. The following iterative method is applied: (a) an assumed tension is used to obtain a deflection profile for a given solution point; (b) the elongation of the cable is calculated from this deflection profile to determine the corresponding calculated tension; (c) the assumed and calculated tensions are then compared and an average is taken, if necessary, for a second assumed tension; and (d) this process is repeated at each solution point until agreement, within



A. Initial position of concentrated 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 1. Vehicle model.

specified limits, is obtained between the assumed and the calculated values of axial tension. The axial restraint at the ends of the cable caused by end anchorages is treated as a linear tension spring.

If a barrier has W section or universal beam-type guide rails, the rails are assumed to act in a combination of lateral bending and axial tension. As the rail deflects laterally, the bending resistance increases until plastic yielding occurs, then decreases as axial tension increases. When the rail yields in tension, the lateral bending resistance is assumed to be zero.

The three barrier models and the vehicle response model have been completely described previously (1, 2).

FULL-SCALE TESTS

Crash tests were performed to verify the mathematical description of vehicle reaction during collision with the barrier. In addition, the tests yielded some information for refining the assumptions made in the mathematical models. The department's personnel also conducted dynamic tests near Albany to determine post strength in soil for use in the barrier models.

The crash test site was a wide concrete ramp on a privately owned portion of the Niagara Falls Municipal Airport. Since most vehicles on the highway are American-made medium-priced sedans, the vehicles obtained for crash tests were standard 1957 Ford and 1959 Plymouth sedans. During the first year of testing, the vehicles were remotely controlled with radio-activated equipment generously loaned by the California Department of Public Works. For the second and third years of testing, Cornell Aeronautical Laboratory developed an electrical servo-control mechanism that was found to be more satisfactory.

Particular attention was given to photographic coverage of the crash, since reduction of the movie film would provide vehicle position and acceleration while in contact with the barrier. Four data cameras, with shutter speeds of about 1,000 fps, and two or more documentary cameras were used to record the impact. To provide duplication in case of camera failure, the data cameras were placed at each end of the barrier, in a tower, and facing the barrier. Common time references were provided by pips on the film edges and two flash bulbs fired as the vehicle passed over switch tapes located 5 and 15 feet from the impact point. The time between flashes also provided a means of computing vehicle velocity at impact.

Before performing full-scale tests, it was necessary to select realistic impact conditions. It was realized that when a car, traveling parallel to a barrier, is suddenly turned sharply toward the barrier, there is a minimum radius of curvature which the vehicle is capable of negotiating. The vehicle is unable to make a sharper turn simply because the tires will not develop enough centripetal force to provide the necessary radial acceleration. Therefore, by assuming a reasonable maximum coefficient of friction (0.7), the maximum probable impact angles could be computed for various speeds and widths of highway. Such an analysis indicated that the maximum impact conditions for the field tests should be 60 mph and 25°. The majority of tests were performed under these conditions.

VERIFICATION OF MATHEMATICAL MODELS

The high-speed data films 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. The reduction of vehicle motions from the film records may introduce a general error of about 10 percent and some peak decelerations may be as much as 20 percent in error.

Agreement between full-scale test results and computed results, using the actual speed and angle of impact, is best illustrated by comparing the vehicle position and, more importantly, vehicle deceleration during barrier impact. When comparing decelerations, durations were considered. A very high momentary vehicle deceleration would have little adverse effect on the occupants. The average deceleration over the highest 100-millisecond interval is considered more significant and was used in summarizing measured and computed values. For discussion, the barriers are classified by the way the rails resist vehicle impact.

Rails With Bending Resistance

Barriers which resist vehicle penetration primarily through the action of a strong rail were developed during the study as a result of a better understanding of the principles of barrier reaction to impact. In this type of barrier, posts are designed to allow lateral deflection of the rail and thus reduce vehicle deceleration. To keep deflection within acceptable limits, the rail must be stiff enough to distribute the impact load over a number of posts. The posts in turn must be able to absorb the lateral kinetic energy of the vehicle as it is redirected. This system is best applied to median barriers and bridge rails. During the program both types of barrier were developed and tested.

The median barrier is shown in Figure 2. Since the system consisted basically of a strong rectangular hollow rail, it was labeled a box-beam median barrier. The rail rests in saddles fastened to small posts which restrict lateral movement of the rail but allow the rail to remain at the original elevation when posts are struck down or deflected laterally.

Two tests were performed on this class of barrier. The first barrier had end anchors and the second did not. However, the results were not significantly different and only those of the second test are presented for verification of the mathematical model. The agreement obtained between measured and computed vehicle trajectories is illustrated in Figure 3 where the locations of vehicle center of gravity are shown

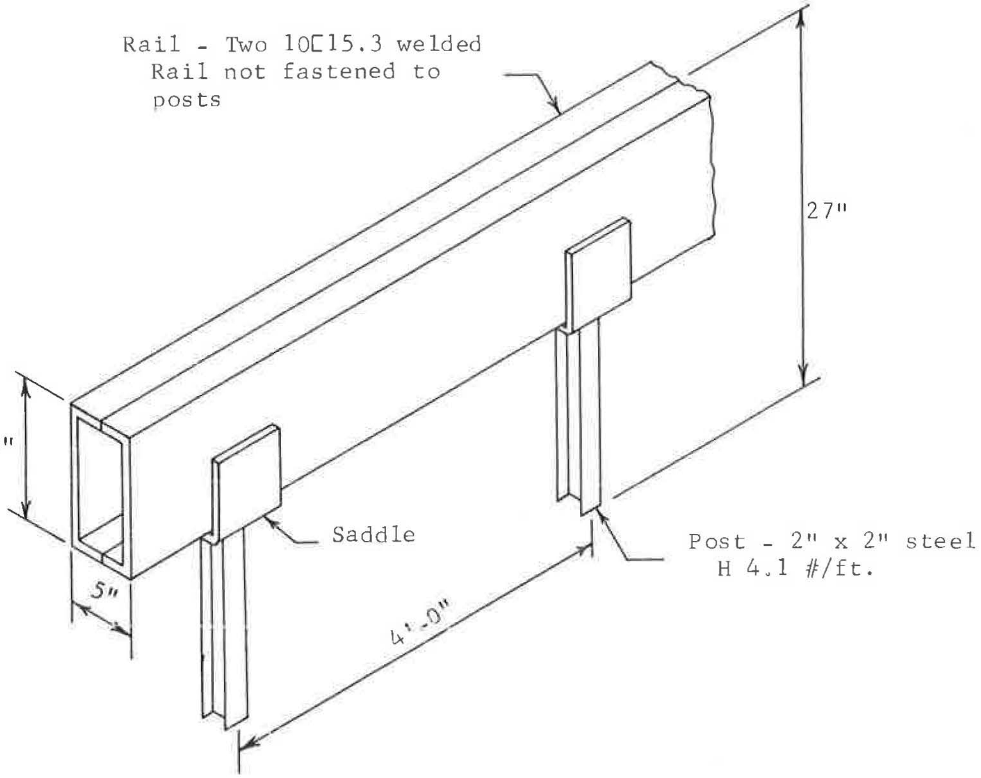


Figure 2. Box-beam median barrier.

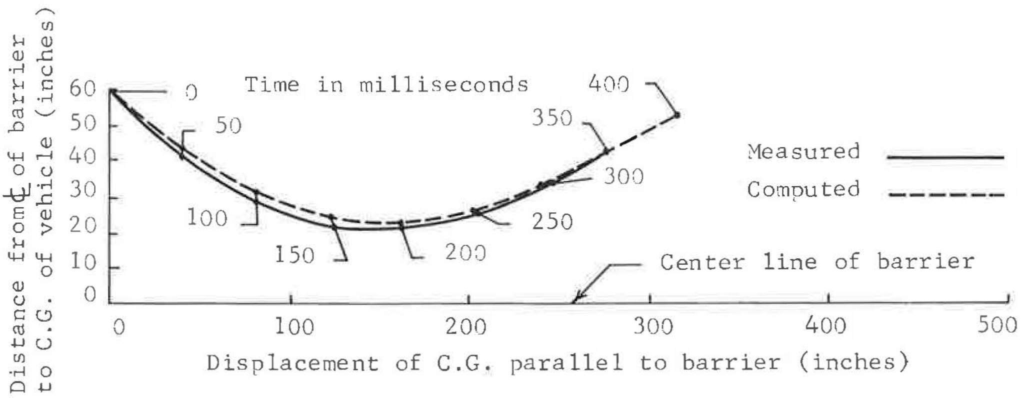


Figure 3. Vehicle trajectory, box-beam median barrier.

for each 50-millisecond interval. A very slight difference between the two curves is evident. The vehicle decelerations are plotted in Figure 4 and these also agree very well except for a high measured peak at about 125 milliseconds. The average measured total deceleration (7 g) over the highest 100-millisecond interval is not appreciably different from the computed value (6 g).

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.

Following the success of the box-beam median barrier tests, a bridge rail was designed using the same strong beam-weak post principle. In this system, two rails

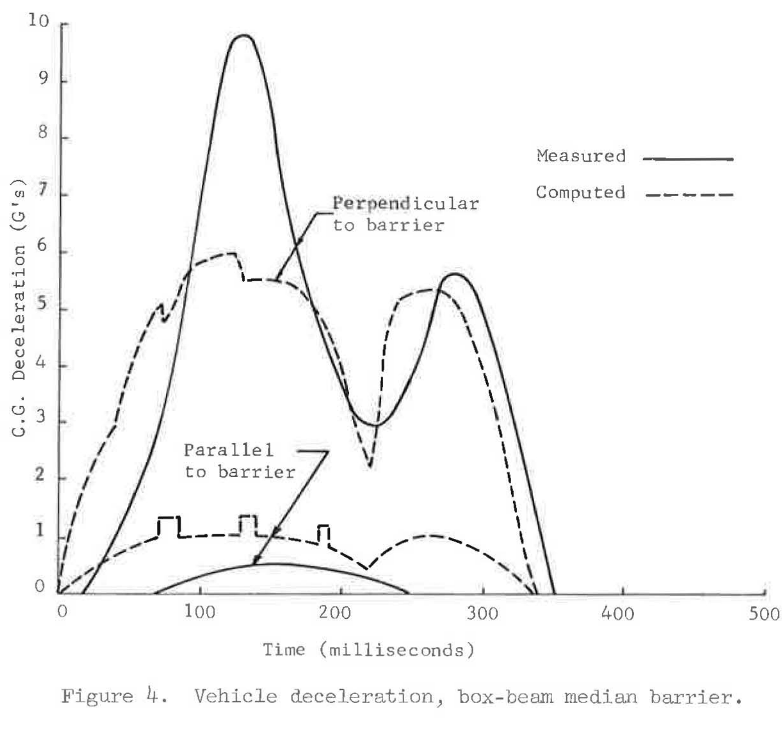


Figure 4. Vehicle deceleration, box-beam median barrier.

were fastened to the face of relatively weak posts. Although the posts were the same size as the median barrier posts, bolting them directly to the rails made the posts develop more resistance to lateral deflection and more resistance when struck by a vehicle. In addition, the location of the rails on the face of the posts meant that the vehicle contacted and knocked down fewer posts. This bridge rail, shown in Figure 5, was first impacted with a car and then tested with a school bus. In the calculation of the barrier force-deflection curve and vehicle responses, the rails were assumed to act as a single rail; this was verified by the test data films. In calculating the school bus response, the effects of crushing during first contact with the barrier had to be neglected.

Vehicle decelerations for these two tests are shown in Figures 6 and 7. The agreement between computed and measured responses is not quite so good as the agreement achieved with the median barrier. The computed vehicle responses depend on the assumption that the barrier absorbs nearly all of the lateral kinetic energy of the vehicle during impact. Since the barrier was relatively stiff, the car crushed and absorbed more energy than had been assumed. Therefore, the computed responses appear to be slightly in error. The computed deceleration curve for the car indicates that a secondary rear-end collision should occur (indicated by the second peak at about 250 milliseconds). However, the duration of this peak is so short that it is not significant. Both computed trajectory and deceleration curves indicate that the barrier is stiffer than the median barrier and the actual test results confirm this very clearly. The agreement between measured and computed responses for the school bus demonstrates the versatility of the model used for calculating vehicle responses.

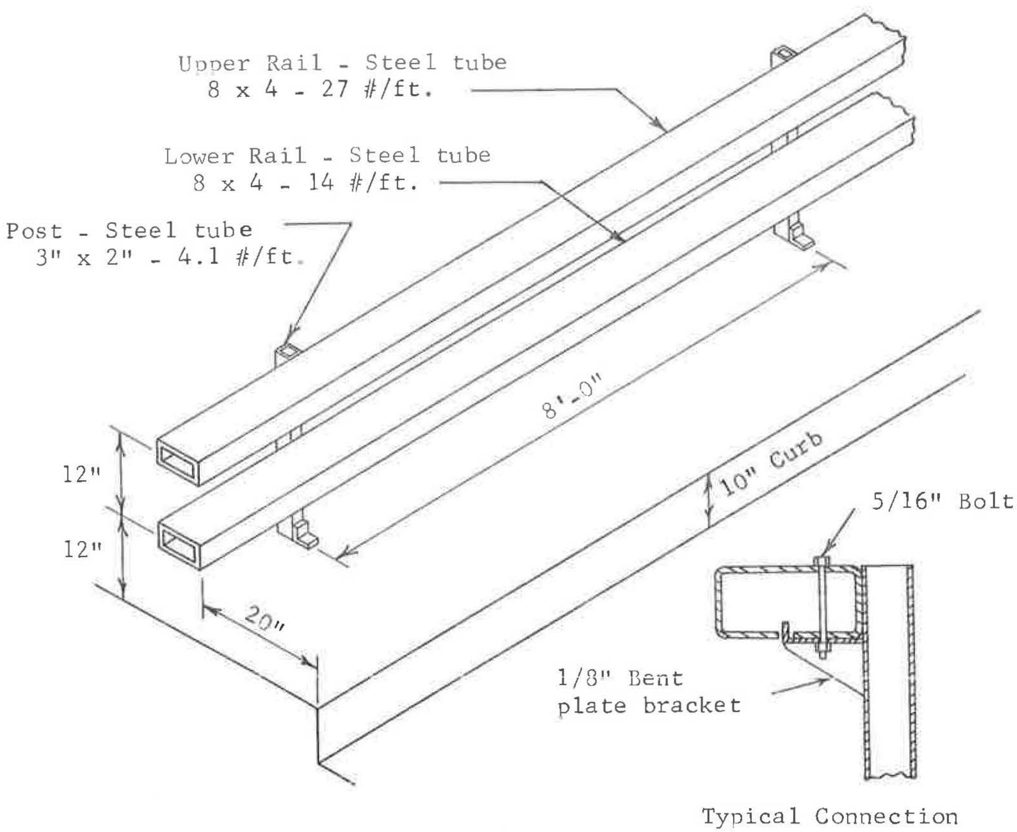


Figure 5. Box-beam bridge rail.

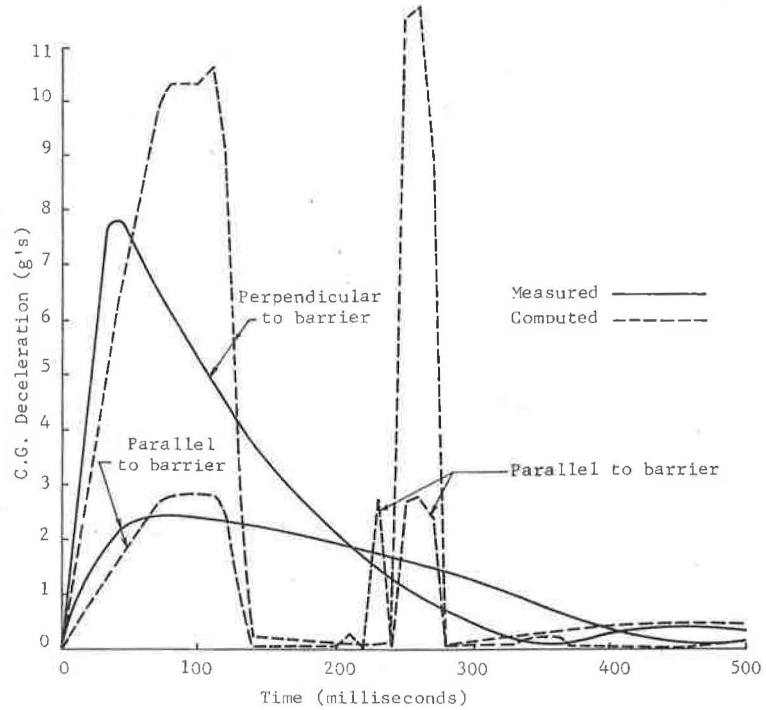


Figure 6. Car deceleration, box-beam bridge rail.

Rails With Axial Tension

The initial test was performed on a typical guide rail arrangement (Fig. 8) without first computing expected vehicle responses. The entire length of the vehicle penetrated the barrier with very little redirection; then the vehicle was severely pitched and rotated as the cable tightened around the strong posts. The computed vehicle responses could not show the effects of pitch and turning, but the occurrence of severe pocketing was indicated by the computed vehicle trajectory and heading angles. The center of gravity of the car passed the original face of the barrier at about 150 milliseconds after first contact. The computed heading angle at 150 milliseconds was nearly the same as at first contact, indicating that the vehicle was not being redirected and would remain in the barrier. Knowing the high strength of the steel posts, it could

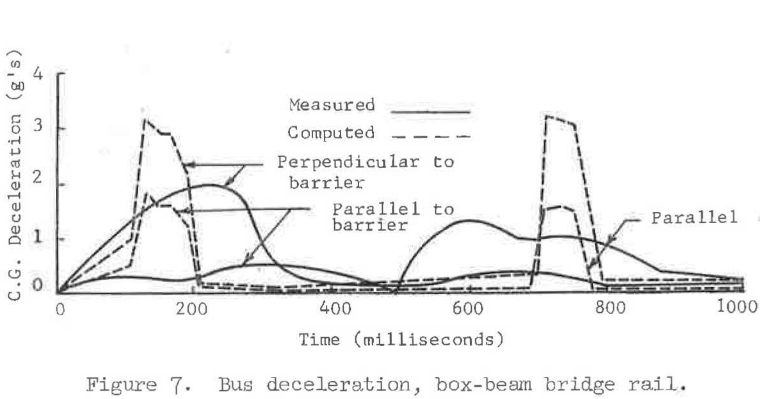


Figure 7. Bus deceleration, box-beam bridge rail.

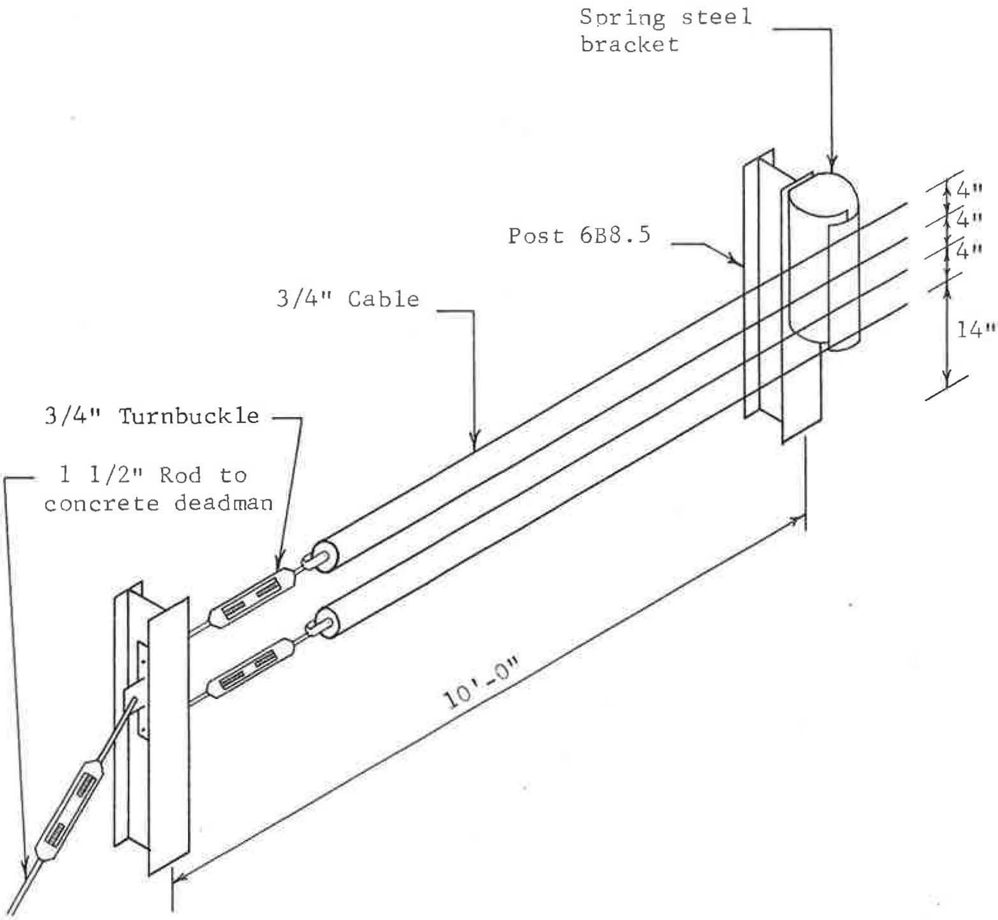


Figure 8. Typical cable guide rail.

only be concluded that the vehicle would be severely pocketed. The computed trajectory and heading angles were not available before the test; had they been, the barrier need not have been tested or at least not tested so severely.

A second cable guide rail arrangement (Fig. 9) was designed with the benefit of a better understanding of tension barriers and the influence of post strength on vehicle response. In this system the cables are supported by relatively weak posts which deflect easily when struck by a vehicle. The cables are fastened to the posts with J bolts which open when a post is struck directly or after the post has yielded and deflected too far to be effective. In addition, it was believed that when a vehicle struck the barrier at a shallow angle, the cables would be free to deflect without being pulled down by the posts. For testing, this barrier was placed in front of a ditch representing a highway fill on a 2 to 1 slope. This was done to study the effect the large anticipated deflections might have on vehicle roll. During the test of this barrier, the car actually passed behind several posts, became airborne, tipped slightly toward the road, settled onto the backslope and finally returned to the shoulder.

The computed and measured vehicle decelerations are shown in Figure 10. Agreement is extremely good perpendicular to the barrier up to about 400 milliseconds, when the computations assume a secondary (rear) collision which would increase the lateral deceleration. The cable was really in contact with the entire side of the car throughout most of the impact and no separate rear collision ever occurred. Deceleration parallel

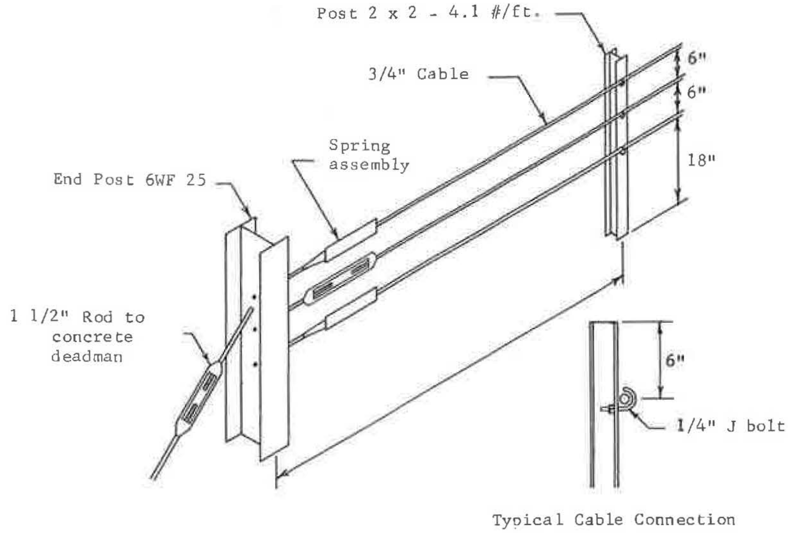


Figure 9. Modified cable guide rail.

to the barrier is influenced by the assumed coefficient of friction between vehicle and rail. A lower coefficient than used previously was assumed; however, the three cables pulled together and cut into the vehicle sheet metal. This action may have increased deceleration parallel to the barrier since the cables appeared to be wrapping and unwrapping as the vehicle passed. The fact that the vehicle was airborne for about 200 milliseconds and then came down on the backslope would also influence agreement. Considering all of these complications, agreement between measured and computed vehicle response is very good with this modified cable guide rail.

Rails With Combined Bending Resistance and Axial Tension

W section or universal beam-type guide rails usually act in a combination of bending resistance and axial tension. Two tests were performed on guide rail systems constructed with these rails, but in both cases pocketing occurred and was indicated by the calculated responses. A third test on the median barrier, illustrated in Figure 11, provided data better illustrating agreement between computed and measured vehicle response.

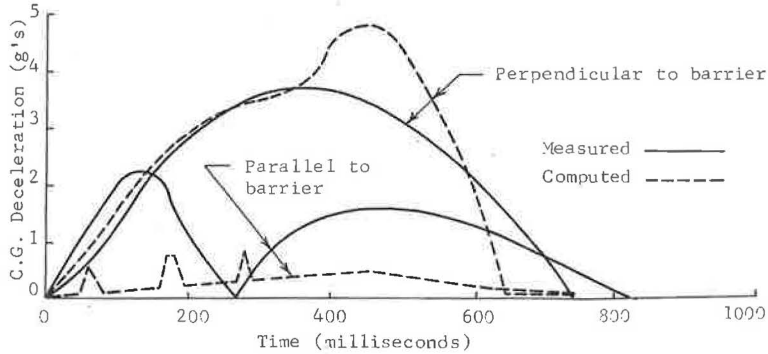


Figure 10. Vehicle deceleration, modified cable guide rail.

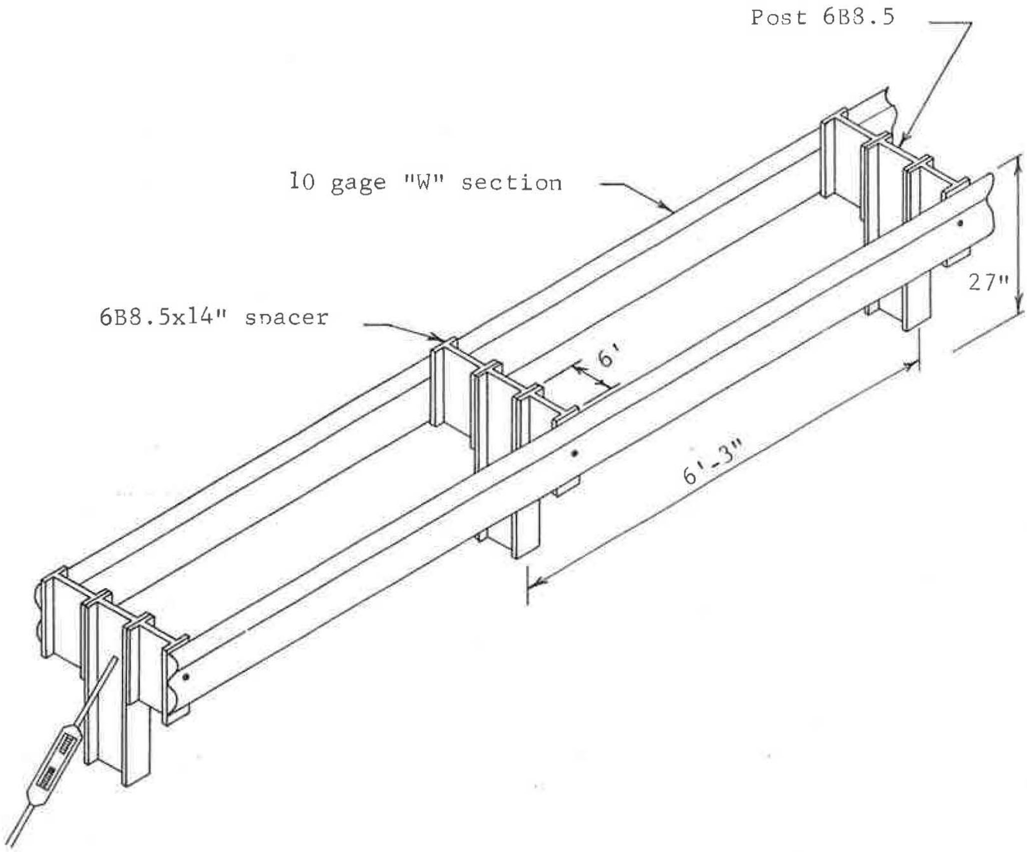


Figure 11. W section median barrier.

Considering that this barrier is "lumpy" (rigid at the posts and flexible midway between posts) and that secondary collisions are not computed precisely, the computed responses are remarkably close to the measured responses for the first 200 milliseconds of barrier contact (Fig. 12). The computed peak deceleration due to a rear

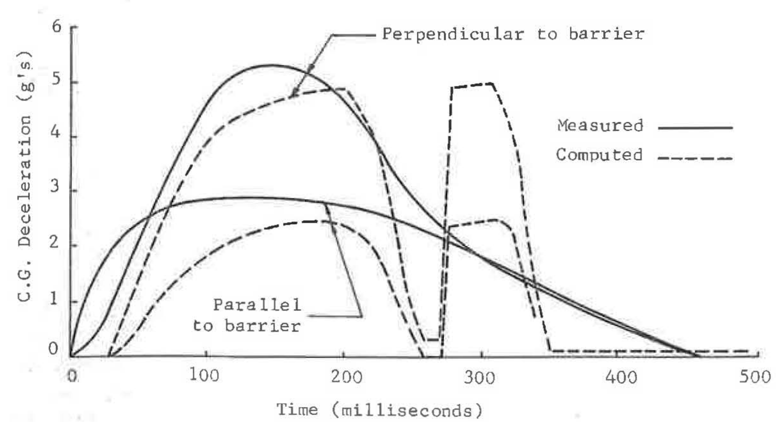


Figure 12. Vehicle deceleration, W section median barrier.

TABLE 1
MEASURED VS COMPUTED VEHICLE RESPONSE

Barrier Type	Impact Condition		Exit Speed (mph)		Exit Angle (deg.)		Max. Decel.[a] (g)		Max. Deflec. (in.)	
	Mph	Deg.	Meas.	Comp.	Meas.	Comp.	Meas.	Comp.	Meas.	Comp.
Box-beam median	52	24	47	44	7	6	7	6	10	13
Box-beam bridge rail:										
Car impact	55	25	37	44	5	3	7	9	5	5
Bus impact	30	20	25	23	6	2	2	3	4	5
Cable guide rail system:										
Modified	57	30	37	46	10	16	4	4	150	123
Typical			Vehicle pocketed as indicated							
W section median barrier	64	16	48	49	9	7	6	5	18	12

[a]Average over highest 100-millisecond interval.

collision at 300 milliseconds did not occur. However, the duration of this peak was very short and this discrepancy is not considered to be serious. The computed vehicle responses for this barrier are in good agreement with the measured responses; therefore, the models for this barrier and for the vehicle responses can be used with confidence to evaluate this type of barrier.

The verification of the mathematical analysis can be summarized as in Table 1. It is possible here to compare the measured and computed vehicle response for the three classes of barriers considered and to obtain a general idea of the ability of the barriers to fulfill the criteria of redirection, minimum injury potential, and containment.

SUMMARY

Full-scale dynamic tests of highway barriers provide factual information for barrier design. However, these tests are inefficient by themselves since at least one test is required for every factor to be evaluated. However, describing the vehicle reaction with mathematical equations is inadequate without verification by full-scale tests because of the great number of simplifying assumptions required. This investigation combined the theoretical approach with full-scale testing to produce mathematical models which will successfully describe the reaction of a vehicle during collison with a barrier.

In all, 19 full-scale dynamic barrier tests were run—4 guide rails, 5 median barrier and 10 bridge rail tests. The theoretical analysis resulted in the development of four mathematical models programmed for solution by electronic computer. These models were verified by the full-scale tests and found to be capable of predicting the performance of various barriers over a wide range of impact conditions. Characteristics of the vehicle and barrier, used as input for the mathematical models, were determined from structural analysis, direct measurement, published data, and dynamic post tests.

The complexity of the problem necessitated separate mathematical models for determining the force vs deflection characteristics of different types of barriers. The force vs deflection data obtained from the appropriate barrier model is used as input into another series of equations which yield printed tables of vehicle trajectory, vehicle deceleration and barrier deflection for each 10 milliseconds during the collision.

The use of the mathematical models has enabled New York State to revise its standard double beam median barrier and further refine the box-beam system developed during this investigation. In addition, the computer programs have permitted the evaluation of a new bridge rail design using principles developed during this project.

The mathematical models can be used either to extrapolate results from a limited number of full-scale tests or to provide a completely analytical evaluation of an untested barrier. New York State is continuing to obtain vehicle trajectories with the computer, thereby evaluating specific barrier designs over a wide range of impact conditions. In this way, information will be available on the level of protection offered by current barrier designs, and improvements that can be achieved by modification of these barriers. Moreover, new designs can be formulated which will provide optimum performance in a specific situation.

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