# Dynamics of Highway Guardrails: Laboratory Experiments (II)

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This is the third report in a series dealing with small-scale model experiments on the effect of vehicle impact against guardrails. The variables include vehicle impact speed and direction, impact location, initial static tension in the cable, post spacing, and coefficient of sliding friction between wheels and ground. Additional variables introduced into this phase of the investigation include yielding of the post foundations, yielding of the end anchorage, use of a "tension spring" in series with the cable, and use of elastic supports between the cable and the posts. Among the recorded quantities are maximum dynamic cable tension, speed and direction of the vehicle after impact, and post displacement. A correlation has been made between the kinetic energy lost by the vehicle as a result of the impact, and the work done by the frictional forces, by the displacement of the posts, and by the displacement of the end anchorage. A limited investigation of beam-type guardrails has been included. All of the results are presented in terms of full-scale values. General conclusions have been drawn.

● THIS is the third report in a series on the scale model investigation of the dynamics of vehicle impact against highway guardrails. The first report (*1*) discusses the basic ideas underlying the investigation and includes the model analysis, the model to prototype scaling relationships, a general description of the experimental methods, and the bibliography. The second report (*2*) describes the revised form of the laboratory apparatus and discusses the results of the first group of tests on cable-type guardrail supported by "rigid" posts, including the effects of varying the coefficient of transverse sliding friction between the wheels and the ground.

This report includes the following:

(a) principal symbols and constants;
(b) general conclusions for the entire series of investigations;
(c) a list of recommendations based on the results and on general observation of the model tests;
(d) some suggestions for full-scale experimentation and collection of information from actual field conditions;
(e) a tabulated index of the test conditions and results;
(f) graphs of the detailed results of the second group of tests showing the effects of yielding of the end anchorage and of the posts, the use of cable tension springs and of elastic cable offset brackets, and a limited comparison of beam-type and cable-type guardrails;
(g) details of the experimental apparatus;
(h) suggestions for further application of small-scale model tests.

A complete final report (*3*) covering the first two reports, this report [excepting parts (c), (d), and (h) listed above], and many details of the experimental methods not otherwise published, has been prepared for limited distribution.

## PRINCIPAL SYMBOLS AND CONSTANTS

The basic characteristics of the prototype are as follows:

### *Vehicle*

"Design" vehicle shown by E. R. Ricker (*4*), overall length 216 inches, overall width

76 inches, wheel base 127 inches, assumed weight, 4000 pounds.

*Cable-Type Guardrail*

Three ¾ inch-parallel steel cables, 135 feet long.

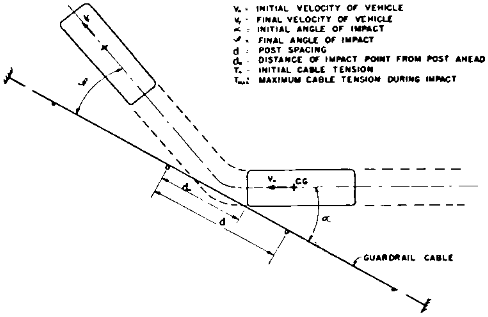

**Figure 1. Schematic plan view of vehicle path and guardrail. $V_0$ = Initial velocity of vehicle; $V_f$ = Final velocity of vehicle; $\alpha$ = Initial angle of impact; $\beta$ = Final angle of impact; $d$ = Post spacing; $d_0$ = Distance of impact point from post ahead; $T_0$ = Initial cable tension; $T_{\max}$ = Maximum cable tension during impact.**

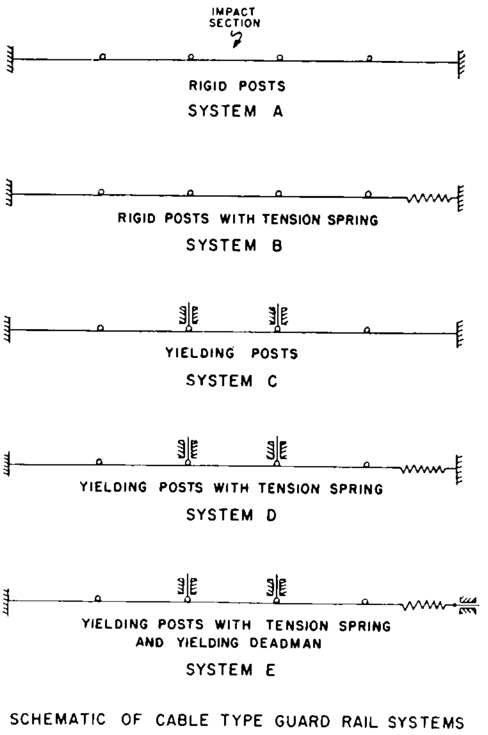

**Figure 2. Schematic of cable-type guardrail systems.**

*Beam-Type Guardrail*

Continuous steel beam having properties similar to an "average" of the guardrail beams of several manufacturers. Further details have been given in Table 1.

Diagrams showing the geometry of the vehicle impact path, the meanings of the symbols, and the main variations in the cable-type guardrail model will be found in Figures 1 and 2.

## GENERAL CONCLUSIONS FOR THE ENTIRE SERIES OF INVESTIGATIONS

In evaluating the results it should be kept in mind that the purpose of the investigation has been to determine the general pattern of response of the vehicle and guardrail for a wide range of variables. This has been done by carrying out six series of tests, each series comparing, in a systematic manner, the effects of variation in a particular parameter or group of parameters.

Many compromises have been made in the construction of the model, including the use of a mechanical device, rather than soil, to allow movement of the posts and end anchor; the representation of the ground surface as a smooth, non-deforming material in a horizontal plane; the representation of the vehicle as a free-running rigid body mounted without springs on fixed-direction wheels; and the complete omission of the effect of human driver reaction.

In full-scale testing it is necessary to make compromises also, mainly in the great reduction of the allowable number of tests. Furthermore, in full-scale testing the number of parameters is often so large that it becomes very difficult to control the tests and to relate cause to effect.

In the ideal combination of full-scale field—and model-scale laboratory—experimentation the relatively inexpensive and easily controlled model tests are used to determine the general pattern of response, while the field tests are employed to check selected portions of the model tests, thus tying the latter to reality, and to investigate the variation of the parameters that cannot well be included in the model testing.

The model test conditions and results have been indexed in Table 1. The first five series relate to cable-type guardrail, the first four

TABLE 1
INDEX OF TEST CONDITIONS AND RESULTS

| "Rail" | Offset Brackets | Tension Spring | End Anchor | Post Setting | Ground Friction Coefficient, $\mu$ | Total Initial Cable Tension $T_0$ lbs. | Post Spacing, $d$ Feet | Impact Location, $d_0/d$ | Impact Angle | Plotted Results | Fig. No. | Test Series |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | *degrees* | | | |
| 3¾-Inch steel cables, each 135 feet long | None | None | Rigid | Rigid | 0.33 | Slack* to 12,000 | 16, 24 | ½, ¾ | 15, 22.5, 30 | $(T_{\max} - T_0)$ vs. $V_0$<br>$V_f$ vs. $V_0$ | See ref. (*2*) | 1 |
| | | | | | | 8000 | 24 | ¾ | 10 to 40 | $\beta$ vs. $\alpha$ | | |
| | | | | | 0.18, 0.33, 0.70 | Slack* to 12,000 | 24 | ¾ | 15, 22.5, 30 | $(T_{\max} - T_0)$ vs. $V_0$<br>$V_f$ vs. $V_0$<br>$\beta$ vs. $V_0$ | See ref. (*2*) | 2 |
| | | | | | 0.18 | 0 to 12,000 | | | 15 | $\beta$ vs. $V_0$ | | |
| | | With and without | Rigid and yielding | Rigid and yielding | 0.33 | 8000 | 24 | ¾ | 15, 22.5, 30 | $(T_{\max} - T_0)$ vs. $V_0$<br>$V_f$ vs. $V_0$<br>$\beta$ vs. $V_0$<br>Energy loss vs. $V_0$ | 3<br>4<br>5<br>9 | 3† |
| | | None | Rigid | Rigid to "very yielding" | 0.33 | 8000 | 24 | ¾ | 15, 22.5, 30 | $(T_{\max} - T_0)$ vs. $V_0$<br>$V_f$ vs. $V_0$<br>$\beta$ vs. $V_0$ | 6<br>7<br>8 | 4 |
| | With and without | None | Rigid | Rigid | 0.33 | 8000 | 24 | ¾ | 15, 22.5, 30 | $(T_{\max} - T_0)$ vs. $V_0$<br>$V_f$ vs. $V_0$<br>$\beta$ vs. $V_0$ | See ref. (*3*) | 5 |
| Steel beam | None | — | — | Rigid | 0.33 | — | 12.5 | ½ | 15, 22.5, 30 | $V_f$ vs. $V_0$<br>$\beta$ vs. $V_0$ | 10<br>11 | 6 |

* Slack, 0, 4000, 8000 and 12,000-pound total initial cable tension. Initial tension in *each* cable = $T_0/3$.

† Five different systems tested. See Figure 2.

being without offset brackets, and the first two without tension springs and with rigid anchors and posts. The parameters varied in each series were as follows, other than impact angle and impact speed $V_0$ which were varied in all series:

1. Initial cable tension, post spacing, impact location.
2. Coefficient of transverse sliding friction between wheels and ground surface; initial cable tension.
3. Various combinations of guardrail components, including tension spring, yielding anchor, and yielding posts.
4. Yield point of post foundation ("soil").
5. Use of elastic offset brackets.
6. Comparison of beam-type and cable-type guardrails.

The graphs of results generally show the maximum dynamic increment of total cable tension ($T_{\max} - T_0$), the final speed $V_f$, and the reflection angle $\beta$ of the vehicle path, plotted against the impact speed $V_0$.

### *Cable-Type Guardrail—Conclusions*

Maximum cable tension and final speed of the vehicle are considerably more predictable in magnitude than the reflection angle of the vehicle path.

*Impact Speed.* Maximum dynamic increment of cable tension and final speed of the vehicle both tend to increase approximately linearly with increase in the impact speed of the vehicle. The reflection angle generally increases when the impact speed is increased, although under some conditions it may decrease with further increase of the impact speed.

*Impact Angle.* Maximum dynamic increment of cable tension increases non-linearly as the impact angle is increased, a change in $\alpha$ from 15 to 22.5 degrees resulting sometimes in an increase of as much as 100 percent in maximum cable tension, while a change from 22.5 to 30 degrees usually resulted in a relatively small increase in cable tension. The final velocity decreases as the impact angle is increased, the change in velocity being very roughly linear over the range tested. The reflection angle generally increases as the impact angle is increased, but in a rather erratic manner; at high impact speeds the reverse may be true.

*Initial Cable Tension.* It was found early in the investigation that the maximum dynamic increment of cable tension and the final speed of the vehicle are both nearly independent of the initial static cable tension. However, the reflection angle may be affected considerably by the initial tension, the reflection angle tending to decrease as the initial tension is increased. The maximum cable tension may be estimated by adding the initial cable tension to the maximum dynamic increment.

*Post Spacing.* The maximum dynamic increment of cable tension and the final velocity are relatively independent of the post spacing. However, the reflection angle was found to be considerably affected by post spacing, but in a rather unpredictable manner. These conclusions are based on only two spacings: 16 and 24 feet. Smaller spacings were not investigated because it is felt that they are undesirable. From the viewpoint of statistics alone, it can be said that the smaller the spacing the more liable the vehicle is to strike a post.

*Impact Location.* The maximum dynamic increment of cable tension decreases and the final velocity shows a tendency to increase as the distance from the point of impact to the first post ahead of the vehicle is increased, that is, as the impact location ratio $d_0/d$ is increased. The reflection angle is also influenced by the impact location but not in a definite manner. The above conclusions are based on only two values of $d_0/d$: $\frac{1}{2}$ and $\frac{3}{4}$.

The most important conclusion, relative to impact location, is that the smaller the value of $d_0/d$ the more liable the vehicle is to collide with the post ahead in a secondary impact. The maximum impact velocities obtained in the tests were limited by the occurrence of secondary impacts with the posts, or by cable breakage, and not by any limitation imposed by the vehicle accelerating device. In the prototype there is of course no possibility of control over the impact location. The difficulty found in the model tests in avoiding secondary impacts indicates the importance of providing suitable offset brackets on the posts of prototype cable guardrails.

*Coefficient of Transverse Sliding Friction between Wheels and Ground.* The final velocity decreases slightly and the reflection angle generally may decrease greatly as the result of an increase in the coefficient of friction. At high impact speeds and large impact angles, however, there is a tendency for the reflection angle to increase rather than to decrease. The variation in maximum dynamic increment of cable tension follows a rather unpredictable pattern, the lowest tension maxima being associated with the intermediate value of the friction coefficient. However, this is not entirely unreasonable when one considers the highly non-linear nature of the system.

*Yield Point of Post Foundation ("Soil").* The general trend is for the final velocity and the reflection angle to decrease when the post foundations are made more yielding, that is, when their ability to dissipate energy is increased. Under some conditions, however, the opposite was true of the reflection angle. The variation of the cable tension was less definite; however, the trend was generally to increase when the posts were allowed to yield. By far the largest variations occurred in the reflection angle.

*Comparison of Various Combinations of Guardrail Components.* Comparative tests were run on the five different types of systems shown in Figure 2. The lowest maximum dynamic increments of cable tension were found in the systems containing a tension spring, and the highest occurred in the system having yielding posts and no tension spring. The use of a yielding end anchor shows a definite tendency, as expected, to place an upper limit on the maximum cable tension and thus to act as a sort of "safety valve."

The highest energy losses, and hence the lowest final velocities, occurred, as expected, with the systems having energy absorption elements in the form of yielding posts and yielding end anchor. Furthermore, the presence of the tension spring in conjunction with the former elements allows greater displacement of the posts, hence greater absorption of energy, and consequently a further lowering of the final velocity.

No definite trends were found in the variation of the reflection angle.

*Use of Elastic Offset Brackets.* The use of cable offset brackets on the posts does not reveal, in the laboratory, an explainable advantage over the system without brackets. However, it is felt that properly designed brackets are desirable on the prototype in helping to prevent the vehicle from coming into direct contact with the post.

*Sources of Energy Loss.* By far the greatest energy losses were found to occur in sliding friction between the vehicle and the cable. This appears to be the most important available means of energy dissipation for reducing the velocity of the vehicle.

Since it was not thought feasible, we did not attempt to determine, by small-scale experimentation, the energy dissipation that takes place in the deformation of the surface and structure of the vehicle.

### *Beam-Type Guardrail—Conclusions*

Relatively few experiments were made on the beam-type model, partly because of lack of time and partly because it is felt that many of the results of experiments made with the cable-type model—for example, the tests on yielding of the post foundations and on changes in the ground friction coefficient—are also applicable to the beam-type system.

In the small scale laboratory tests the final velocity of the vehicle is lower with the cable-type guard than with the beam-type, probably due to lower frictional losses in sliding contact between the vehicle and beam than between the vehicle and cable. (A comparison of the friction coefficients in sliding contact between vehicle surface materials and various types of guardrail materials could readily be made with full-scale elements in a laboratory.)

The small-scale laboratory tests show considerably smaller reflection angles occurring with the cable-type guard than with the beam-type, except in the case of the lowest impact angle ($\alpha = 15°$) for which the reflection angles for the two types of construction are approximately equal. It should be recalled that the reflection angle has generally been found throughout the investigation to be the variable that is the most difficult to predict.

## RECOMMENDATIONS BASED ON THE MODEL TESTS

The following recommendations are based on the general observation of the tests as well as on the quantitative results:

1. Every effort should be made to reduce the probability of the vehicle striking a post. It therefore seems desirable to make the post spacing as great as is compatible with the other requirements of the structure. However, too great a spacing may result in a weak structure, in excessive flexibility and "pocketing" between posts, and in spreading of the cables.

A post spacing of about 16 feet for cable-type guardrails seems reasonable. The 24-foot spacing, which was found to be more satisfactory in the model tests, is probably too great for practical use in the field.

2. The use of smooth elastic offset brackets, deep enough to prevent the vehicle from coming into direct contact with the posts, seems highly desirable. It is suggested that offset brackets may also be desirable on beam-type guardrails.

3. As far as possible all projections, or other conditions tending to "snag" the vehicle, should be eliminated.

4. The initial value of the cable tension does not appear to be critical. However, it should be great enough to hold the cables in proper position without sag and to prevent excessive deflection of the system under impact. Tension springs are desirable.

5. Excessively rigid post settings are dangerous. A significant amount of energy may be absorbed by the yielding of the posts in the soil.

6. The end anchorage should be capable of developing a load no greater than the safe design tension of the cable. It is suggested that the anchorage be designed so that it can move in the soil when the impact tension in the cable reaches the design limit, or that an adjustable yielding element be inserted in the cable at the anchor.

7. In the design of a yielding structure care must be taken that it is not made so yielding as to result in the "pocketing" of the vehicle.

8. The sliding friction between the vehicle and the guardrail is an important source of energy dissipation. Anything that can be done to increase the friction coefficient will be advantageous.

9. In order to provide the driver of the vehicle with maximum opportunity to correct the path of the vehicle after impact with the guardrail, the clearance between the guardrail and the pavement should be the maximum possible and the surface should be maintained in a manner to minimize skidding.

The above recommendations are probably not greatly different from conclusions that may be reached in the field. The authors will be very much interested in any statistics that can be made available to them on accidents involving guardrails and on full-scale tests of vehicle-guardrail impact.

## SUGGESTIONS FOR FULL-SCALE EXPERIMENTATION

The authors would like to make the following suggestions:

1. That all available information on full-scale tests and on recorded accidents involving guardrails be collected and analyzed, and that additional tests be made to fill the gaps in the information. It is hoped that the results of the model tests will assist in interpreting the full-scale tests and in planning new tests.
2. That a reporting system be instituted for gathering information on the performance of guardrails involved in future accidents.
3. That for certain types of full-scale tests, a special rugged test vehicle, either catapulted or self-propelled, could be used.
4. That comparative full-scale transverse loading tests be made on posts embedded in soil under realistic conditions, using static loads as well as direct impact loads.
5. That comparative full-scale loading (static as well as dynamic) tests be made on anchors, with particular attention being paid to developing the anchor as a "safety valve" for the cable and as a means for dissipating energy through movement of the anchor in the soil. The planning of these tests, as well as those suggested for the posts, could well be guided by preliminary, small-scale, laboratory tests.

## INDEX OF MODEL-TEST CONDITIONS AND RESULTS

Table 1 provides an index to the test conditions and results included in this report as well as in the preceding one (*2*) of the series.

## GRAPHS OF RESULTS OF THE SECOND GROUP OF MODEL-TESTS

### *Use of Tension Spring, Yielding Posts and Yielding End Anchorage*

The five different types of systems have been shown schematically in Figure 2.

*Variation in Maximum Dynamic Increment of Cable Tension;* Figure 3. ($T_{\max} - T_0$) is shown plotted against $V_0$ for five systems of guardrail fixity. No very definite relationship among the different systems is apparent, except that those containing the tension spring (systems B, D, and E) generally show lower dynamic increments. The use of a yielding deadman (system E) shows a definite tendency

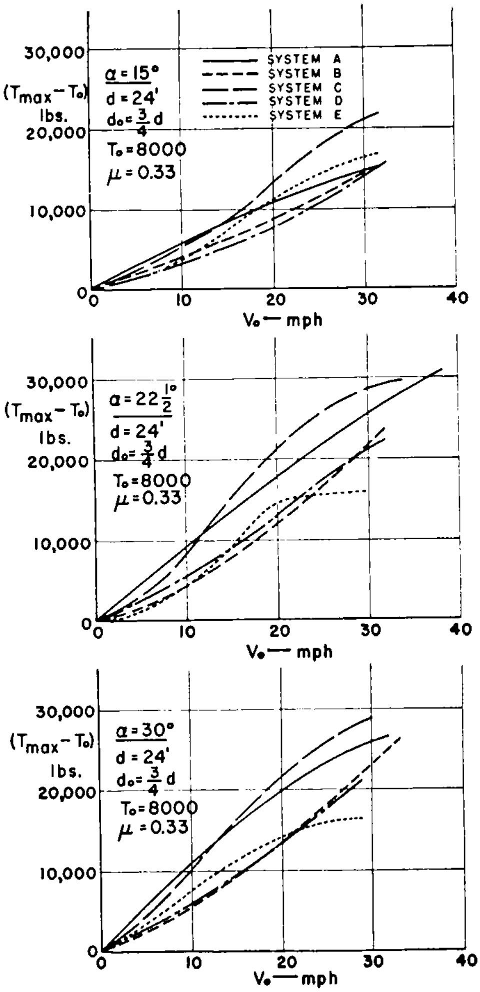

**Figure 3. Maximum dynamic increment of total cable tension versus impact velocity of vehicle. Five variations of cable-type guardrail.**

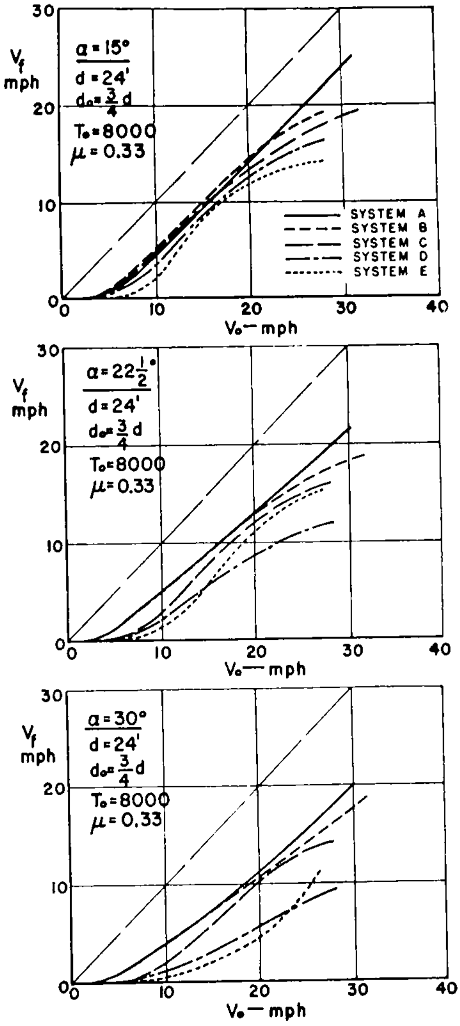

**Figure 4. Final velocity of vehicle versus impact velocity. Five variations of cable-type guardrail.**

to limit the dynamic increment. This is to be expected because once the anchorage starts to slide the cable tension theoretically cannot be increased. System C, having yielding posts but no tension spring and no yielding of the anchorage, shows the highest dynamic increment.

*Variation in Final Velocity* $V_f$; Figure 4. Systems C, D, and E, all of which include energy dissipation elements (yielding posts and yielding deadman), result in lower values of final velocity than systems A and B. This is particularly true for large values of the impact angle $\alpha$.

*Variation in* $\beta$; Figure 5. When the angle of impact $\alpha$ is low, the family of curves is more uniform than at the high angles of impact. However, as we have found before, $\beta$ is generally much less predictable than either $(T_{max} - T_0)$ or $V_f$, and there do not appear to be definite conclusions relative to the effect on $\beta$ of changes in the cable-type guardrail structure.

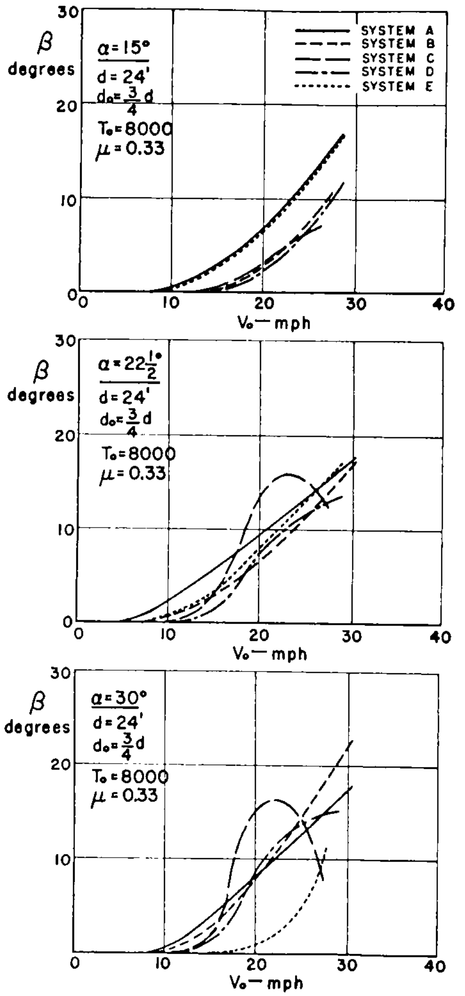

Figure 5. Reflection angle of vehicle path versus impact velocity. Five variations of cable-type guardrail.

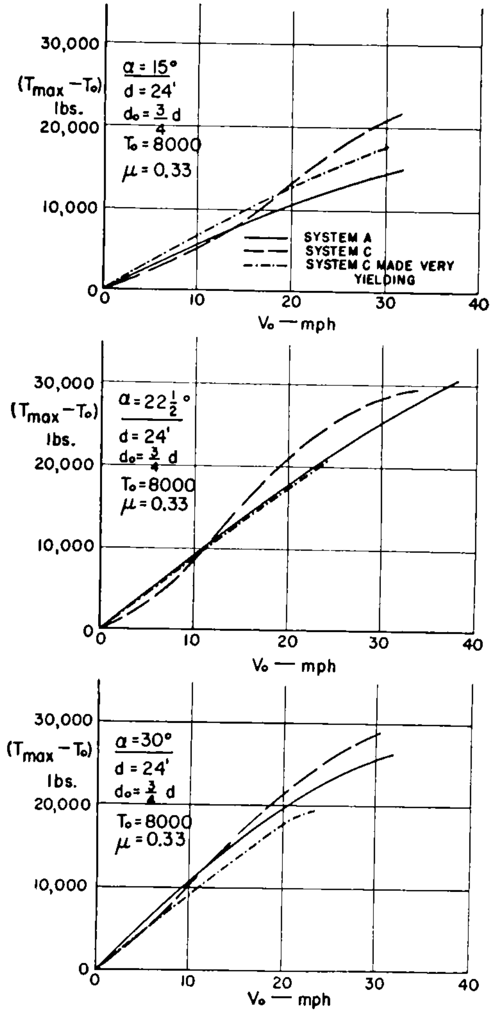

Figure 6. Maximum dynamic increment of total cable tension versus impact velocity. Variation in yielding of post foundation. (See Figure 2 for diagrams of System A and System C.)

### *Variation in "Yield Point" of Posts*

*Variation in* ($T_{max} - T_0$). Figure 6 shows the effect on the dynamic increment of varying the foundation condition of the posts from "rigid" to "very yielding." The impact criteria used in defining the conditions of yielding will be given later. It is interesting to note that both the "rigid" and the "very yielding" foundation conditions result in generally lower dynamic increments of cable tension than the "intermediate yielding" condition. This is not unreasonable if one considers the highly nonlinear nature of the system.

*Variation in* $V_f$*;* Figure 7. As would be expected, the effect on $V_f$, due to varying the foundation condition, is much more readily explainable than the effect on cable tension. As the post foundation is made more yielding, the ability of the system to absorb energy is increased. Consequently, we find a decrease in final velocity when the yield point is lowered.

*Variation in* β*;* Figure 8. The general tendency is for β to decrease when the yield point is lowered. However, there are notable exceptions in the "intermediate yielding" case.

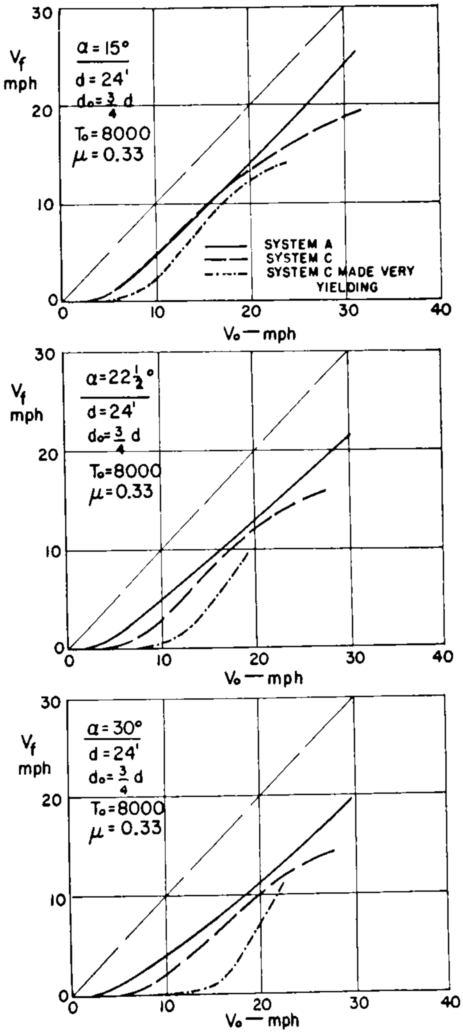

**Figure 7. Final velocity of vehicle versus impact velocity. Variation in yielding of post foundation.**

*Variation in Maximum Attainable $V_0$.* As has been pointed out before, the upper end points of the curves represent the maximum impact velocities attainable without the vehicle striking the "far" post. It is evident that when the yield point is lowered, the "maximum attainable" velocity is also lowered.

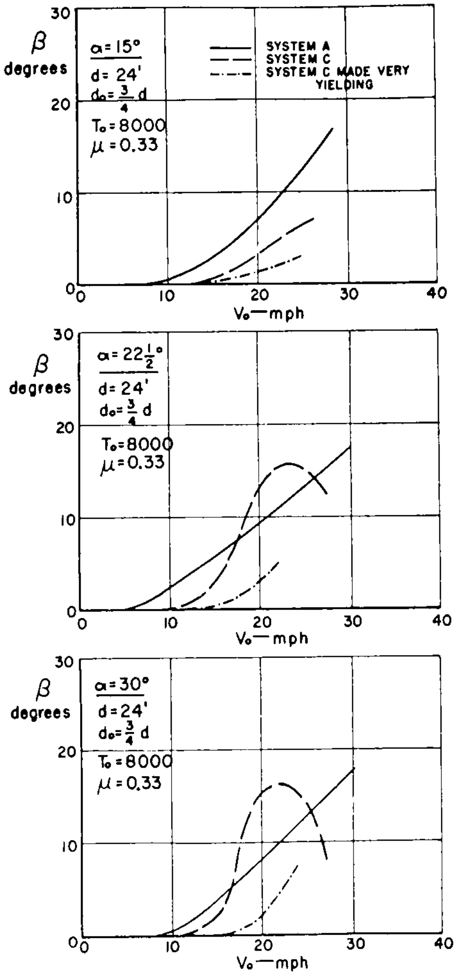

**Figure 8. Reflection angle of vehicle path versus impact velocity. Variation in yielding of post foundation.**

*Use of Elastic "Offset Brackets"*

A complete set of comparative tests was made on a cable-type guardrail model having elastic offset brackets and on one without brackets. The methods and results have been described in reference (*3*). No very significant differences were found in dynamic increment of cable tension, final velocity, and reflection angle. However, it is felt that in the full-scale guardrail, offset brackets are of considerable importance in helping to keep the vehicle from coming into direct contact with the post.

*Energy Losses*

The total energy loss of the vehicle is equal to $W(V_0^2 - V_f^2)/2g$. There are various ways that the energy loss can be accounted for, namely, by sliding friction between the vehicle and the cable, by transverse sliding friction between the vehicle tires and the ground, by the yielding of the posts in the soil, and by the yielding of the end anchorage. Since the model vehicle is a rigid body, the distortions of the front end and side have not been taken into account. Furthermore, as already pointed out, it is assumed that the driving force and braking force are zero. The loss due to rolling friction in the wheels has been neglected since it is a very small quantity relative to the other losses.

Figure 9 shows a graph of total energy loss in foot-pounds (full scale) versus the initial velocity $V_0$. The general trend is for the energy loss to increase as the angle of impact is increased and also for the differences in energy loss among the various systems to increase. The energy loss increases greatly as $V_0$ is increased. When the guardrail structure is made more yielding, the total energy loss increases. The least energy loss is found with the rigid post system, which is to be expected. Systems D and E, containing yielding posts and tension spring, and yielding posts, tension spring and yielding anchorage, respectively, generally result in the greatest energy losses. The foregoing conclusions are reasonable and could have been determined, indirectly, from Figure 4.

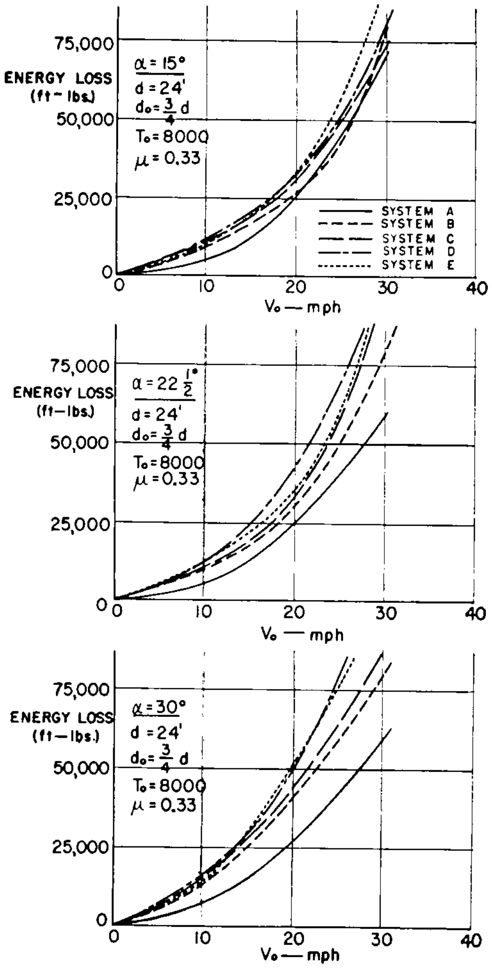

**Figure 9. Total energy loss versus impact velocity. Five variations of cable-type guardrail.**

Table 2 lists five energy balance calculations that have been made in an attempt to account for the various parts of the total energy loss. All quantities are listed in foot-pounds of energy (full scale). The details of the calculations have been shown in reference (*3*). In spite of apparent inaccuracies the results show with little doubt that by far the greatest energy loss occurs in sliding friction between the vehicle and cable.

### *Beam-Type Guardrail*

We will make the following assumptions: (1) The weight of the beam is negligible in comparison with the weight of the vehicle; (2) the posts (beam supports) are rigid; (3) the beam is continuous across the supports; (4) the effect of direct tension is negligible. The beam model is a compromise that is similar in load-deflection properties to several steel guardrail beams that are on the market.

No attempt was made to measure the stress in the model, although it could be done readily enough by the use of wire-resistance strain gauges. Curves of $\beta$ versus $V_0$, and $V_f$ versus $V_0$ have been plotted and compared with the results of tests of the cable-type guardrail. The friction coefficient for sliding between the wheels and the ground surface was constant at a value of 0.33.

*Variation in $V_f$;* Figure 10. The final velocity of the vehicle after impact with the beam-type guardrail is higher than with the cable-type. It is believed that the difference is due primarily to greater frictional losses between the vehicle and cable than between the vehicle and beam. At the low angles of impact $\alpha$, the final velocity is not greatly different from the initial velocity. As the angle

TABLE 2
SAMPLE CALCULATIONS FOR ENERGY BALANCE
$T_0$ = 8,000 lb., $d$ = 24 ft., $\mu$ = 0.33

| (1) System | (2) Test No. | (3) $\alpha$ Degrees | (4) $V_0$ (mph) | (5) Total Energy Loss | (6) Friction With Ground | (7) Friction with Cable | (8) "Near Post" Yielding | (9) "Far Post" Yielding | (10) Anchor Yielding | (11) Total of Columns (6–10) | (12) Balance | (13) % Balance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1-76 | 15 | 20 | 33,160 | 2,500 | 30,400 | — | — | — | 33,000 | −160 | −0.485 |
| B | 0-226<br>0-230 | 30 | 30 | 84,000 | 6,300 | 99,250 | — | — | — | 105,550 | +21,500 | +20.4 |
| C | 0-247<br>0-251 | 30 | 20 | 47,500 | 5,640 | 53,700 | 6,250 | 450 | — | 66,040 | +18,540 | +28.1 |
| D | 2-260<br>2-265 | 22½ | 20 | 57,700 | 4,000 | 54,900 | 0 | 0 | — | 58,900 | +1,200 | +2.04 |
| E | 0-313<br>0-317 | 30 | 20 | 58,400 | 3,850 | 54,800 | 2,680 | 0 | 8,670 | 70,000 | +11,600 | +16.6 |

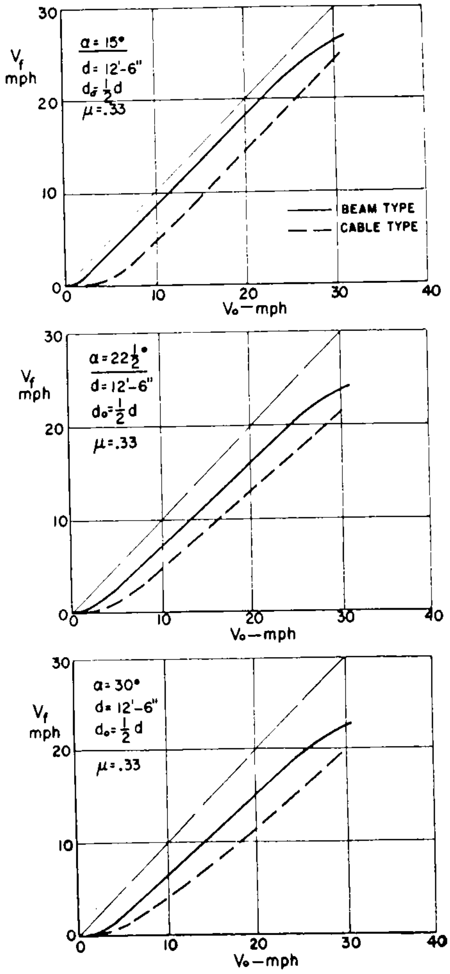

**Figure 10. Final velocity of vehicle versus impact velocity. Comparison of beam-type and cable-type guardrail.**

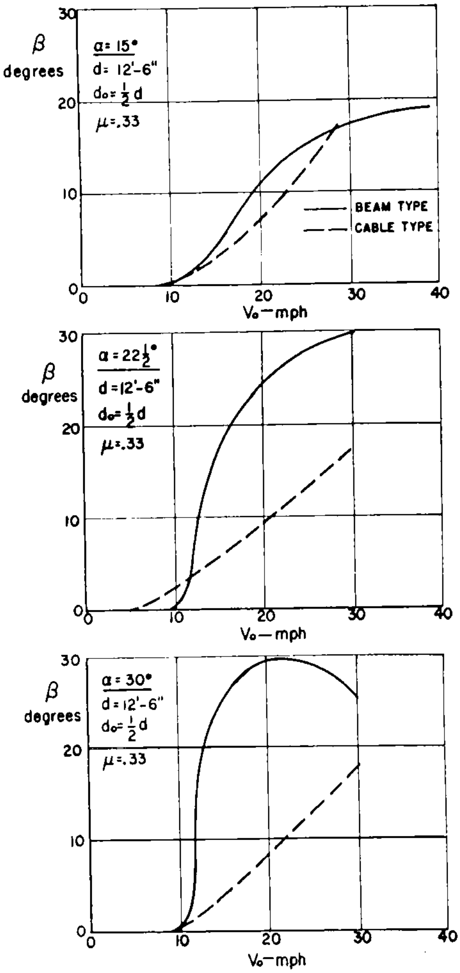

**Figure 11. Reflection angle of vehicle path versus impact velocity. Comparison of beam-type and cable-type guardrail.**

of impact is increased, the final velocity decreases.

*Variation in $\beta$;* Figure 11. There is a definite tendency for the angle of reflection $\beta$ to be rather large, considerably larger than the reflection angle for the cable-type guardrail. As the impact angle is increased, $\beta$ increases in a highly non-linear manner. There is a great variation in $\beta$ at low impact velocities and high impact angles. As the initial velocity is increased, $\beta$ reaches a maximum, and with large angles of impact starts to decrease as $V_0$ is subject to further increase.

It should be recalled that the reflection angle has already been found, in the earlier phases of the investigation, to be the variable that is the most difficult to predict.

## DETAILS OF THE EXPERIMENTAL APPARATUS

Figure 12 shows the general arrangement of the laboratory apparatus, and Figures 13 to 16 show the details of the yielding post, the yielding anchor, and the beam-type guardrail.

Yielding of the posts was provided for by mounting the posts on hinges and by connecting one end of each to a dry-friction device which would slip, i. e., yield, under a specified impact condition. For the "intermediate post setting" the "near post" was adjusted so as to yield when $\alpha \geq 22.5$ degrees and $V_0 \geq 20$ mph. The conditions for the "very yielding" setting were $\alpha \geq 15$ degrees and $V_0 \geq 15$ mph. In both cases, the impact location was

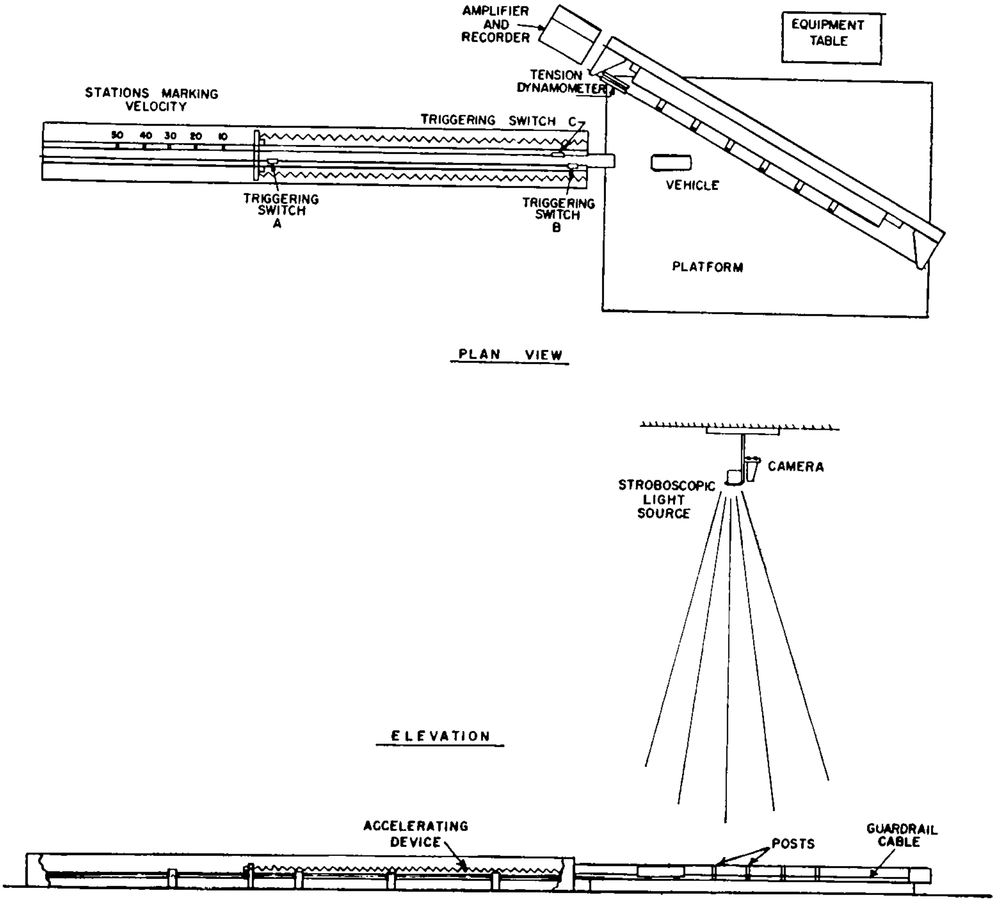

**Figure 12. Schematic diagram of laboratory apparatus.**

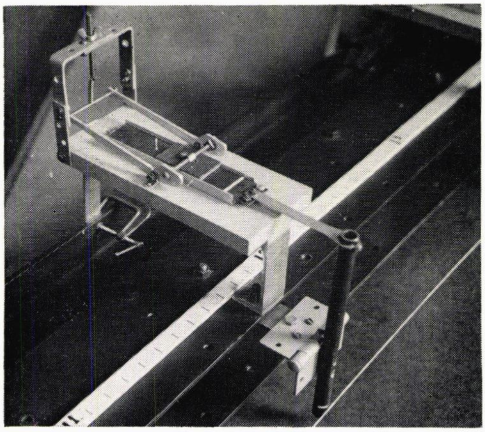

**Figure 13. "Yielding post," consisting of hinged post and dry sliding friction device to represent yielding of soil.**

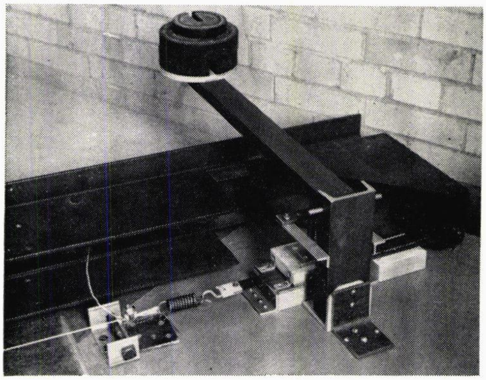

**Figure 14. "Yielding anchor," consisting of dry sliding friction device to represent yielding of soil around anchor. Cable tension spring included.**

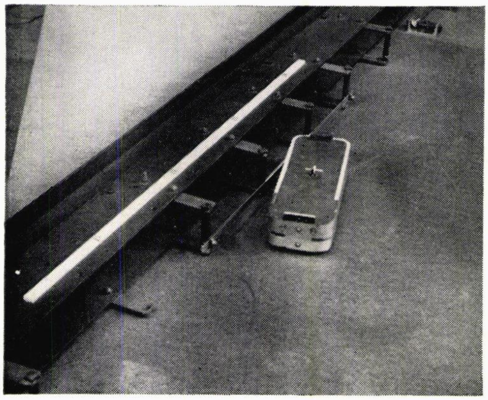

**Figure 15. Vehicle striking beam-type guardrail model.**

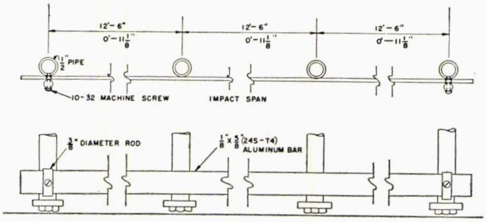

**Figure 16. Schematic diagram of beam-type guardrail with rigid posts.**

given by $d_0/d = \frac{3}{4}$. The yielding end ancho is also a dry-friction device. More complete details may be found in reference (*3*).

The modeling of the cable-type guardrail has already been described (*1*, *2*). The modeling of the beam requires the following additional comments:

The ratio of the flexural stiffness *EI* of the model beam to the *EI* of the prototype is equal to the force scale multiplied by the square of the length scale, thus,

$$\frac{E_m I_m}{E_p I_p} = \frac{f_m}{f_p}\left(\frac{l_m}{l_p}\right)^2$$

Making use of the already established scales for force ($\frac{1}{430}$) and for length ($\frac{1}{13.5}$), letting the modulus of elasticity of the prototype beam (steel) be $E_p = 30 \times 10^6$ lb./in.$^2$ and of the model beam (structural aluminum alloy), $E_m = 10.3 \times 10^6$ lb./in.$^2$, the relation between the moments of inertia of the cross-sections of the model and prototype beams is given by

$$I_m/I_p = \frac{1}{26{,}900}$$

Assuming that the prototype moment of inertia $I_p = 2.52$ inches$^4$, the desired moment of inertia of the model beam is given by $I_m = 0.0000936$ inches$^4$.

The model beam was a standard, rectangular cross-section, aluminum alloy bar, $\frac{1}{8}$ inch by $\frac{5}{8}$ inch (actual dimensions 0.126 inch by 0.627 inch), having a moment of inertia of 0.0001045 inches$^4$ in the most flexible direction.

## SUGGESTIONS FOR FURTHER APPLICATION OF SMALL-SCALE MODEL TESTS

It is suggested that small-scale tests, using apparatus of the general type employed in this investigation, could also be used in the preliminary study and development of vehicle barriers designed for maximum energy absorption by the barrier with minimum damage to the vehicle, and of various types of rigid deflecting surfaces designed for deflecting the path of the vehicle after a grazing impact.

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