SIMPLIFIED CRITERIA FOR EVALUATING FLEXIBLE BRIDGE RAIL PERFORMANCE

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Simplified criteria are derived for evaluating the capability of a flexible bridge railing system to safely contain impacting vehicles ranging in size from subcompacts to heavy trucks. The evaluation is based on comparison of the static force versus deflection characteristic of the railing system with an associated integral characteristic that is easily obtained. The criteria have been applied to typical high-performance bridge railing designs such as the collapsing ring barrier and another hybrid barrier system. The barrier performance predicted by the simplified criteria agrees well with the dynamic results obtained from full-scale tests and computer simulations. The simplified criteria should prove valuable to the highway engineer in evaluating current and proposed designs of flexible bridge railings and in providing a guide to design improvements if required.

•THE present standards of the American Association of State Highway and Transportation Officials for bridge rails are intended to ensure the containment of 4,000-lb (1814-kg) passenger vehicles. However, the satisfaction of these standards does not necessarily imply that the bridge rail will safely redirect an errant passenger vehicle; the most common failing is that the vehicle occupant (especially at the higher velocities and impact angles) will experience intolerably high deceleration levels. In the case of heavy vehicles [weights ≥ 40,000 lb (18 144 kg)], it is unlikely that the same bridge rails will even contain the vehicle. Consequently, there is a need to generate new standards for bridge rails that will overcome the above-mentioned deficiencies. In essence, bridge performance criteria are required that will ensure the safe containment and redirection of all classes of vehicles, from the subcompact level [2,250 lb (1021 kg)] to the heavy, articulated tractor-trailer vehicle [≥40,000 lb (18 144 kg)].

The standards developed by ENSCO cover the required performance of both flexible (or semirigid) bridge rails and rigid concrete bridge parapets. Because of the different modes of operation of these two types of barriers, a single set of standards does not suffice for both types. However, both involve some type of containment criteria. The containment criteria to be discussed in this paper relate to some of the major performance requirements of flexible bridge rails. Criteria covering all of the major performance requirements, for both flexible and rigid barriers, are discussed elsewhere (1).

The overriding requirement for a high-performance, flexible bridge rail is that it safely redirect all vehicles (within a certain weight range) that impact the barrier with impact conditions up to some worst case [probably 60 mph (97 km/h) and 15 deg]. This implies that the lateral motion of the impacting vehicle must be halted without excessive lateral deceleration and that the barrier deflection must not exceed some maximum associated with the barrier and its location.

It would be extremely useful if simple criteria were available to evaluate the ability of a given barrier to satisfy this containment requirement, for any given set of performance requirements, such as the range of impacting vehicles to be contained, maximum allowable lateral deceleration, and maximum allowable barrier deflection for impact conditions in the worst case. The criteria developed in this paper are intended to meet this objective.

HYPOTHESES BASED ON EMPIRICAL OBSERVATIONS

Extensive simulation studies of vehicle impacts with typical flexible railings, performed by ENSCO (1), have yielded two empirical results that are important to this work:

1. The maximum lateral force experienced by the impacting vehicle of mass m occurs at about the maximum dynamic deflection δ_m experienced by the barrier (for that impact), and this force is approximately equal to the associated value given by the point static barrier characteristic $F(\delta)$. This implies that inertia and damping forces for typical barriers are small compared with the static force generated by the barrier; furthermore, the contact area at peak barrier deflection appears limited so that the vehicle-barrier force levels are about the same as those predicted by the point static characteristic for the same maximum deflection.
2. The strain energy under the point static characteristic $F(\delta)$ up to $\delta = \delta_m$ is typically some constant fraction α of the vehicle's initial lateral kinetic energy $\frac{1}{2} mv_L^2$ (the remainder being dissipated in occurrences such as vehicle crush, vehicle-roadway interaction, barrier friction, and barrier deformations at more than one location). A value of $\alpha = \frac{1}{2}$ seems to more or less fit a wide range of vehicles and impact conditions; however, to allow for more general application, the criteria development uses the constant α.

Based on these hypotheses, simplified criteria have been developed for evaluating the point static characteristic $F(\delta)$ of a given barrier, which can be used to predict barrier performance and to determine whether the barrier can safely contain impacting vehicles ranging in mass from m_o to M. [The static force versus deflection characteristic $F(\delta)$ can be determined either experimentally, theoretically, or from a computer model such as BARRIER VII (5).] The validity of the resulting criteria (and of the underlying hypotheses) has been spot-checked by comparing the performance predicted by the criteria with that obtained from full-scale tests and computer simulations, for a few typical high-performance bridge railing designs. This is discussed subsequently.

DERIVATION OF SIMPLIFIED CRITERIA

The foregoing hypotheses imply that for any vehicle of mass m the corresponding peak barrier deflection δ_m satisfies the relationship

$$\int_0^{\delta_m} F(\delta)d\delta = \alpha \tfrac{1}{2} mv_L^2 \tag{1}$$

The maximum lateral force experienced by this vehicle is $F(\delta_m)$. Then by Newton's Law, the maximum lateral acceleration experienced by the vehicle is

$$a_{max} = \frac{F(\delta_m)}{m} \tag{2}$$

We require that this maximum acceleration be less than or equal to some predetermined tolerable acceleration limit, a_{tol}, or

$$\frac{F(\delta_m)}{m} \le a_{tol} \tag{3}$$

From equation 1, we obtain

$$m = \frac{2}{\alpha v_L^2} \int_0^{\delta_m} F(\delta)d\delta \tag{4}$$

Substituting this expression for m in inequality in equation 3 yields

$$F(\delta_m) \leq \frac{2a_{tol}}{\alpha v_L^2} \int_0^{\delta_m} F(\delta)d\delta \tag{5}$$

We require that this inequality be satisfied for all values of δ_m in the interval (δ_{m_o}, δ_M), where δ_{m_o} is the maximum barrier deflection corresponding to the smallest vehicle m_o and δ_M is the maximum deflection corresponding to the largest vehicle M. This will ensure that all vehicles in the range from m_o to M will experience peak lateral decelerations less than a_{tol}.

Let us define an integrated barrier characteristic $P(\delta_m)$ by

$$P(\delta_m) \triangleq \frac{2a_{tol}}{\alpha v_L^2} \int_0^{\delta_m} F(\delta)d\delta \tag{6}$$

Then inequality in equation 5 can be expressed as

$$P(\delta_m) \geq F(\delta_m) \quad \text{for } \delta_{m_o} \leq \delta_m \leq \delta_M \tag{7}$$

From equations 6 and 4, we obtain

$$P(\delta_m) = m\, a_{tol} \tag{8}$$

Hence,

$$P(\delta_{m_o}) = m_o a_{tol} \tag{9}$$

and

$$P(\delta_M) = M\, a_{tol} \tag{10}$$

Then for any barrier, inequality in equation 7 can be easily checked by plotting $F(\delta_m)$ and $P(\delta_m)$ on the same graph and determining the interval of interest (δ_{m_o}, δ_M) from equations 9 and 10. [The intersection of a horizontal line of value $m_o a_{tol}$ with $P(\delta_m)$ occurs at δ_{m_o}; similarly, a horizontal line of value $M a_{tol}$ intersects $P(\delta_m)$ at δ_M.]

One more criterion must be satisfied to ensure satisfactory barrier lateral performance, namely, that the peak barrier deflection δ_M, corresponding to the maximum vehicle M, does not exceed some predetermined maximum deflection δ_{tol} that is allowable from barrier strength or space considerations. This is readily determined from the same graph since δ_M is directly available from equation 10 as indicated previously.

The physical significance of the criterion in equation 7 can be summarized as follows. For a given barrier, the associated integral characteristic $P(\delta_m)$ yields the maximum allowable force ($m\ a_{tol}$) associated with the peak deflection δ_m caused by a vehicle of mass m. The actual peak force experienced by this vehicle is simply $F(\delta_m)$. If this is less than $P(\delta_m)$, then the actual peak acceleration of m will be less than the allowable value a_{tol}. If this condition holds true for all peak displacements between δ_{m_o} and δ_M (as obtained from equations 9 and 10), then all vehicles in the range from m_o to M will experience peak accelerations less than a_{tol}. Thus $P(\delta_m)$ forms a kind of tolerable limit curve associated with the static characteristic $F(\delta_m)$. The final criterion for satisfactory barrier performance is simply that the peak displacement δ_M associated with the maximum vehicle M be less than a predetermined limit δ_{tol}.

Note that the maximum deflection δ_m caused by a vehicle of mass m is independent of the allowable acceleration a_{tol}. Referring to equations 6 and 4, we see that

$$\frac{P(\delta_m)}{a_{tol}} = \frac{2}{\alpha v_L^2} \int_0^{\delta_m} F(\delta) d\delta = m \tag{11}$$

Thus we could plot m versus δ_m directly to determine the maximum barrier deflection associated with any mass. However, this same information is available from the curve of $P(\delta_m)$ versus δ_m since the ordinate in this case equals $m\ a_{tol}$ where a_{tol} is some constant. Furthermore, the same curve $P(\delta_m)$, when compared to $F(\delta_m)$ in the interval of interest (δ_{m_o}, δ_M), determines whether or not the peak decelerations are acceptable for the range of vehicles under consideration. Thus the single curve $P(\delta_m)$ yields the maximum deflection δ_m for any m and, when compared to $F(\delta_m)$, also determines whether the peak decelerations are less than a_{tol} for vehicles in the range of interest.

Besides facilitating the foregoing simplified criteria, the $P(\delta_m)$ and $F(\delta_m)$ curves also yield much additional information. Regardless of whether or not the limit criterion of equation 7 is satisfied, these curves can be used to predict the peak deflection and acceleration for any vehicle. Equation 8 states that the peak deflection δ_m of any vehicle can be obtained from the intersection of the $P(\delta_m)$ curve with a horizontal line whose value is equal to $m\ a_{tol}$. When this value of δ_m is used, the peak force $F(\delta_m)$ can be directly obtained from the $F(\delta_m)$ curve. Then, the peak acceleration of the given vehicle is simply $F(\delta_m)/m$.

The foregoing implies that the first intersection of the $P(\delta_m)$ and $F(\delta_m)$ curves can define the smallest vehicle m_o that will experience tolerable deceleration levels. The reason for this is that $P(\delta_m)$, formed by integrating $F(\delta)$, must always start below the $F(\delta_m)$ curve. As δ_m is increased, $P(\delta_m)$ will increase at a faster rate than $F(\delta_m)$ and finally cross $F(\delta_m)$. By defining the intersection coordinates as (δ_{m_o}, $m_o a_{tol}$), we have ensured tolerable deceleration levels for the corresponding value of m_o. As we take larger values of δ_m, the $P(\delta_m)$ curve will generally lie above the $F(\delta_m)$ curve; this indicates acceptable levels of peak acceleration for these larger vehicles as well. However, it is possible to define a barrier characteristic such that the $F(\delta_m)$ curve rises above the $P(\delta_m)$ curve for some large vehicle of mass M. In any event, the range of vehicles from m_o to M that will experience tolerable peak accelerations can be obtained directly from the intersections of the $P(\delta_m)$ and $F(\delta_m)$ curves.

GUIDE TO USE OF CRITERIA

The use of the above-derived criteria can be illustrated by the following example. Figure 1 shows an arbitrary barrier static characteristic $F(\delta_m)$ that is linear up to 100,000 lbf (445 kN) at 30 in. (0.76 m) and is constant thereafter. The assumed impact conditions for the worst case are 60 mph (97 km/h) and 15 deg from which the lateral velocity v_L is calculated to be 273.4 in./sec (6.94 m/s). The assumed value of α is 0.5, and the tolerable acceleration limit is chosen as 10 g. The integral characteristic $P(\delta_m)$ defined by equation 6 is then

$$P(\delta_m) = 0.207 \text{ in.}^{-1} \int_0^{\delta_m} F(\delta)d\delta$$

In the general case, the integration of $F(\delta)$ would be done either numerically (by a computer program) or graphically (by a planimeter). In this simple example, however, the integration can be done analytically since $F(\delta)$ is known in analytic form. Therefore, we have

$$F(\delta) = \begin{cases} 3{,}333 \text{ lbf/in.} \times \delta & \text{for } 0 \leq \delta \leq 30 \text{ in.} \\ 100{,}000 \text{ lbf} & \text{for } \delta > 30 \text{ in.} \end{cases}$$

Hence for $\delta_m \leq 30$ in. (0.76 m),

$$P(\delta_m) = 0.207 \text{ in.}^{-1} \times 3{,}333 \text{ lbf/in.} \ (\delta_m^2/2)$$

or

$$P(\delta_m) = 345 \text{ lbf/in.}^2 \times \delta_m^2$$

For $\delta_m > 30$ in. (0.76 m),

$$P(\delta_m) = 345 \text{ lbf} \times (30)^2 + 0.207 \text{ in.}^{-1} \times 100{,}000 \text{ lbf } (\delta_m - 30 \text{ in.})$$

or

$$P(\delta_m) = 310{,}500 \text{ lbf} + 20{,}700 \text{ lbf/in. } (\delta_m - 30 \text{ in.})$$

(Note: In the above equations 1 lbf = 4.45 N, 1 lbf/in. = 175.1 N/m, and 1 in. = 2.54 cm.)

The integral characteristic $P(\delta_m)$, as in the equations above, is also shown in Figure 1. An examination of the two curves shows that the intersection occurs at an estimated force level of 32,200 lbf (143 kN). Setting that equal to 10 $m_o g$, we see that vehicles greater than 3,220 lb (1461 kg) would experience peak lateral accelerations less than 10 g.

If we are interested in containing vehicles up to 40,000 lb (18 144 kg), we can check the barrier deflection corresponding to that maximum vehicle. A horizontal line of value, 40,000 lb/g (18 144 kg/g) × 10 g, or 400,000 lbf (1779 kN), intersects $P(\delta_m)$ at a value of δ_m equal to about 34.3 in. (0.87 m). If this is less than the maximum allowable barrier deflection δ_{tol}, then the barrier would be judged acceptable for containing vehicles up to 40,000 lb (18 144 kg). Conversely, if δ_{tol} is less than 34.3 in. (0.87 m), say for example 30 in. (0.76 m), then the intersection of a vertical line at δ_{tol} = 30 in. (0.76 m) with $P(\delta_m)$ will inherently define the maximum vehicle capability of the barrier. As in Figure 1, such a line would intersect $P(\delta_m)$ at a force level of about M a_{tol} = 310,000 lbf (1379 kN) so that the maximum vehicle M that the barrier could contain would be about 31,000 lb (14 061 kg).

We can explore this example further to show the potential of the $P(\delta_m)$ criteria for providing guidelines to barrier design modifications. Suppose we would like a modification that would make the barrier performance satisfactory for vehicles as small as 2,250 lb (1021 kg). The modified $F(\delta_m)$ curve of Figure 2 [for 60 mph (97 km/h) and 15 deg, α = 0.5, and a_{tol} = 10 g] is one solution. Here, we have introduced a stiff initial characteristic up to 22,500 lbf (100 kN), which then remains constant at this value until it joins the original $F(\delta_m)$ curve (of Figure 1). The associated $P(\delta_m)$ curve for the new characteristic is also shown in Figure 2. The intersection of the two curves now occurs at a force level of 22,500 lbf (100 kN), which corresponds to an m_o of 2,250 lb (1021 kg). The modification provides a more rapid buildup of $P(\delta_m)$ and, at the same time, limits $F(\delta_m)$ to a value of $m_o a_{tol}$ until the two curves can cross.

Interestingly enough, this modification not only results in a tolerable peak acceleration for all vehicles greater than 2,250 lb (1021 kg) but also results in a slightly smaller peak barrier deflection δ_M for the maximum vehicle M under consideration. For M = 40,000 lb/g (18 144 kg/g) the corresponding value of δ_M is about 33.6 in. (0.85 m), or about 0.7 in. (0.02 m) less than the original value.

Another option open to the designer would be the further reduction of peak deflection δ_M without producing unsafe levels of deceleration for any vehicle under consideration. Since $P(\delta_m)$ is considerably higher than $F(\delta_m)$ for large δ_m, as shown in Figure 2, we could increase the stiffness of the barrier characteristic beginning at some δ_m without affecting the deceleration behavior for smaller vehicles. This type of modification is shown in Figure 3 [for 60 mph (97 km/h) and 15 deg, α = 0.5, and a_{tol} = 10 g]. The associated integral characteristic $P(\delta_m)$ is still above $F(\delta_m)$. This ensures safe containment of all vehicles under consideration. However, the peak barrier deflection δ_M, for M = 40,000 lb/g (18 144 kg/g), has now been reduced to 30 in. (0.76 m).

The static characteristic of a given barrier may differ from one point to another. For example, the static characteristic of a barrier taken at a point midway between two posts may be softer than the characteristic taken at a post. For the barrier performance to be judged satisfactory, it must satisfy the criteria when applied to both the softest and stiffest characteristics of the barrier. In general, these two characteristics will have to be reasonably close to one another if the barrier performance is to satisfy the criteria. This will inherently provide some protection against pocketing as well; however, separate criteria to ensure against pocketing are described elsewhere (1).

APPLICATION TO TYPICAL HIGH-PERFORMANCE BARRIERS

The $P(\delta_m)$ criteria have been applied to some typical high-performance bridge barriers. These include the collapsing ring barrier and the ENSCO-designed, two-stage, New York-T1 barrier.

The collapsing ring barrier was designed by the Federal Highway Administration and has been extensively tested by Southwest Research Institute (2). The barrier consists of a box section bump rail attached by 18-in.-diameter (0.46-m) steel rings to a strong backup rail. The rings partially collapse during minor impacts; more severe impacts totally collapse the rings, and the vehicle is restrained by the stiff backup rail. The barrier demonstrates a graduated force-deflection characteristic providing restraint

Figure 1. Application of criteria to theoretical barrier 1.

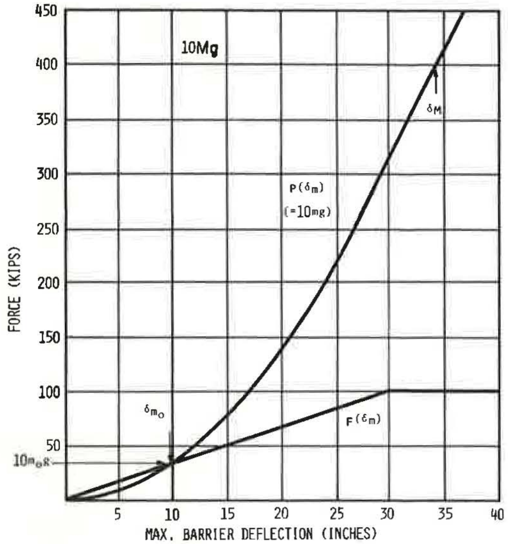


Figure 2. Application of criteria to theoretical barrier 2.

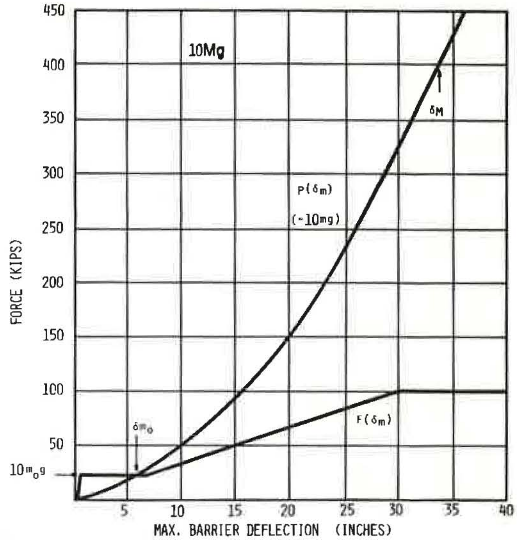


Figure 3. Application of criteria to theoretical barrier 3.

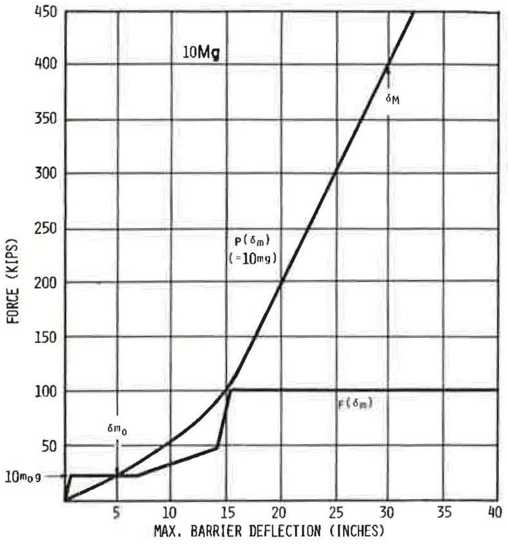
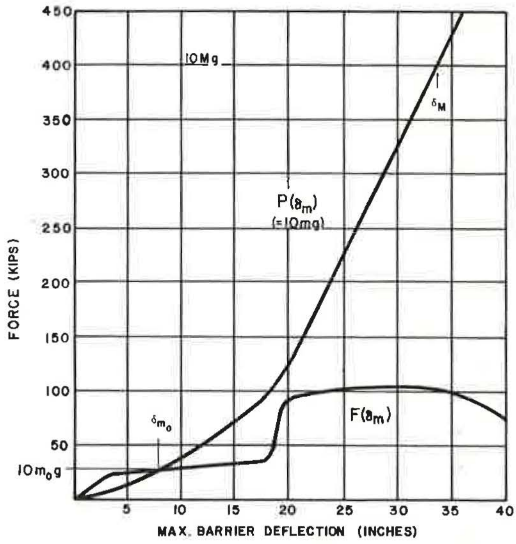


Figure 4. Application of criteria to collapsing ring barrier.



for heavy vehicles [40,000 lb (18 144 kg)] combined with low deceleration for both light and heavy vehicles.

The two-stage, New York-T1 barrier is a hybrid design using the New York box beam barrier (3) as a traffic rail and a modified version of the Texas T-1 (4) (or thrie beam) barrier as a backup rail. The New York box beam barrier consists of a strong box section rail mounted on weak 3S5.7 posts and provides low-force levels for light vehicles. When this barrier is mounted 14 in. (0.36 m) in front of the modified T-1D barrier [two overlapping W-beam rails mounted on 38-in.-high (0.97-m) 10W21 posts], the combination provides a behavior similar to that of the collapsing ring barrier.

To determine the static force-deflection curve $F(\delta)$ for the barriers, the BARRIER VII computer simulation was used (5). This program provides a two-dimensional simulation of vehicle-barrier impacts and contains a highly sophisticated barrier model. When a lateral point load is applied to the barrier and barrier mass and damping are removed, the overall static force-deflection characteristic can be obtained from the program. The $F(\delta_s)$ curves together with the corresponding $P(\delta_s)$ curves [for 60 mph (97 km/h) and 15 deg, $\alpha = 0.5$, and $a_{tol} = 10\ g$] are shown in Figure 4 (collapsing ring barrier) and Figure 5 (New York-T1 barrier).

As shown in Figure 4, the two curves intersect at a force level of about 25,000 lbf (111 kN), which shows that vehicles as small as 2,500 lb (1134 kg) would experience peak accelerations less than or equal to 10 *g*. A 40,000-lb (18 144-kg) vehicle would produce a peak deflection δ_M of about 33.5 in. (0.85 m), which is acceptable for this barrier. The collapsing ring barrier incorporates some of the desirable characteristics discussed in the preceding section, namely a stiff initial characteristic up to a value corresponding to 10 g for a light vehicle [2,500 lb (1134 kg)] a flattening out near this value until the $P(\delta_m)$ curve can reach and cross this value, and a stiff characteristic beginning at some larger value of δ_m to minimize peak barrier deflection δ_M.

The $F(\delta_s)$ characteristic for the combination New York box beam and Texas T-1 barrier (New York-T1 barrier) and the associated $P(\delta_s)$ characteristic are shown in Figure 5. The intersection of the two curves occurs at a force level of about 12,500 lb (56 kN), which implies tolerable peak accelerations for vehicles as small as 1,250 lb (567 kg). However, the deflection δ_M required to contain a 40,000-lb (18 144-kg) vehicle is about 37 in. (0.94 m), which may be more than can be tolerated. The performance of the two-stage New York-T1 barrier can be classified as similar to that of the collapsing ring barrier.

CHECK OF CRITERIA VALIDITY

As discussed earlier, the simplified $P(\delta_s)$ criteria are based on certain hypotheses that have been gleaned from empirical results. The validity of these hypotheses and the criteria can be checked by comparing the peak acceleration and barrier deflection for many different vehicle-barrier impacts with the corresponding results of actual full-scale tests or computer dynamic simulations. This has been done to a certain extent in the case of the collapsing ring barrier and the two-stage, New York-T1 barrier. Although more corroborative evidence is necessary to establish criteria validity (or the realm in which the criteria are valid), the results of these comparisons to date have been encouraging.

Data from three of the full-scale tests of the collapsing ring barrier [those with $^3/_8$-in.-thick (0.01-m) BR5-6-8 rings] performed at Southwest Research Institute have been compared with results predicted by the simplified criteria. Maximum deflection and maximum deceleration from the test data and from the criteria are given in Table 1. Only permanent maximum deflections were available from the full-scale test data; therefore, when these data are compared with the maximum dynamic deflections predicted by the criteria, allowance should be made for elastic springback. The results compare well for all three tests that involved vehicles ranging from 2,090 to 19,000 lb (948 to 8618 kg).

Table 2 compares maximum barrier deflection and maximum deceleration as predicted by the criteria with those of computer-simulated impacts with the collapsing ring barrier. The BARRIER VII simulation was used to simulate impacts of vehicles from 2,250 lb (1021 kg) to 40,000 lb (18 144 kg). Table 3 gives a similar comparison based on the New York-T1 barrier. Again in both cases, good correlation was obtained.

Note that the test conditions given in Tables 1, 2, and 3 are not all for 60 mph (97 km/h) and 15 deg. Thus, the $P(\delta_s)$ curves of Figures 4 and 5 were appropriately scaled to reflect the actual lateral velocity in each case (equation 6) so that predicted results could be obtained from the criteria. The value of $\alpha = 0.5$ was left unchanged; the fact that this still produced good agreement with full-scale and computer-simulated tests indicates that α may be considered constant over a fairly wide range of test conditions.

Figure 5. Application of criteria to combination New York-T1 barrier.

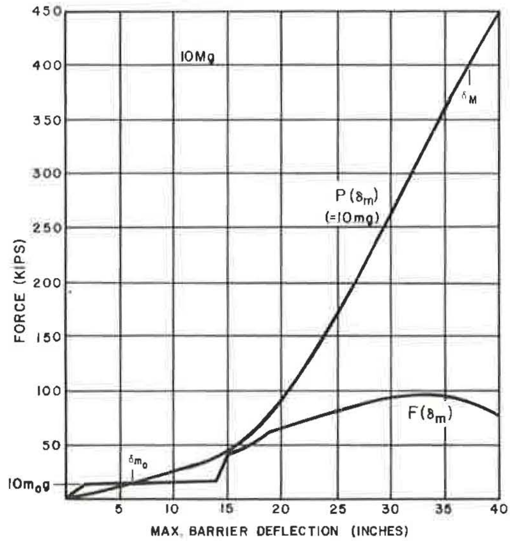


Table 1. Full-scale test results versus results predicted by criteria for collapsing ring barrier.

Test Number[a]	Vehicle Type	Vehicle Mass (lb)	Impact Speed (mph)	Impact Angle (deg)	Maximum Lateral Deflection (in.) Actual[b]	Maximum Lateral Deflection (in.) Predicted by Criteria[c]	Maximum Lateral Deceleration (g) Actual	Maximum Lateral Deceleration (g) Predicted by Criteria
BR6	Car	2,090	55.7	23.5	4.38	9.80	13.06	13.25
BR5	Car	3,910	56.1	23.9	14.25	16.95	8.60	8.90
BR8	Bus	19,000	60.9	13.9	20.44	22.50	4.02	5.20

Note: 1 lb = 0.45 kg. 1 mph = 1.6 km/h. 1 in. = 0.0254 m.

[a]Southwest Research Institute. [b]Permanent relaxed. [c]Dynamic.

Table 2. Simulated test results versus results predicted by criteria for collapsing ring barrier.

Vehicle Type	Vehicle Mass (lb)	Impact Speed (mph)	Impact Angle (deg)	Maximum Lateral Deflection (in.) Simulated[a]	Maximum Lateral Deflection (in.) Predicted by Criteria	Maximum Lateral Deceleration (g) Simulated[a]	Maximum Lateral Deceleration (g) Predicted by Criteria
Car	2,250	60	15	5.20	6.70	10.53	10.09
Car	2,250	60	25	14.42	13.50	17.11	13.55
Car	4,000	60	15	8.16	10.00	6.58	6.87
Bus	19,000	59	15	25.30	22.50	4.40	5.20
Bus	40,000	55	15	32.40	30.50	3.23	2.55

Note: 1 lb = 0.45 kg. 1 mph = 1.6 km/h. 1 in. = 0.0254 m.

[a]BARRIER VII.

Table 3. Simulated test results versus results predicted by criteria for New York-T1 barrier.

Vehicle Type	Vehicle Mass (lb)	Impact Speed (mph)	Impact Angle (deg)	Maximum Lateral Deflection (in.) Simulated[a]	Maximum Lateral Deflection (in.) Predicted by Criteria	Maximum Lateral Deceleration (g) Simulated[a]	Maximum Lateral Deceleration (g) Predicted by Criteria
Car	2,250	60	15	7.74	9.20	8.83	6.13
Car	4,000	60	15	11.84	14.50	5.51	7.25
Car	4,000	60	25	18.32	20.60	12.30	17.03
Truck	40,000	60	15	38.27	36.90	3.68	2.36

Note: 1 lb = 0.45 kg. 1 mph = 1.6 km/h. 1 in. = 0.0254 m.

[a]BARRIER VII.

The term good agreement, used to describe how predicted results compare with actual or computer-simulated test results, may disturb some readers, who see a few cases of wide differences, in Tables 1, 2, and 3. However, considering the variability of full-scale and computer-simulated test results, even for relatively small changes in vehicle-barrier initial conditions, the results given in Tables 1, 2, and 3 are indeed considered to be in good agreement. In the majority of cases, the predicted peak deflections and accelerations are within 25 percent of those obtained from full-scale and computer-simulated tests. In no case did this difference exceed 40 percent. (The apparently larger difference in the case of comparison with the deflection of full-scale test BR6 in Table 1 is attributable to the fact that peak dynamic deflection was not measured. Considering the likely magnitudes of elastic springback, the results given in Table 1 are in good agreement.)

CONCLUSIONS

The simplified criteria given in this paper for evaluating the containment performance of bridge railing systems appear to be quite effective. The peak deflections and accelerations predicted by these criteria agree well with those obtained from full-scale and computer-simulated tests of a few typical high-performance barrier systems. Although this limited sample of results is not sufficient for a complete validation of the criteria, there is sufficient evidence to suggest that the criteria can be a useful tool for evaluating and improving current and proposed designs of high-performance barrier systems.

Further investigation of the potential of these simplified criteria is certainly warranted. Some possible areas for future study are the following:

1. Comparison of results predicted by the criteria with those of full-scale tests and computer-simulated impact tests, for many different barriers.
2. Determination of whether two or three different values of α might be desirable to obtain closer correspondence with full-scale and simulated test results, for the extremely wide range of vehicle types and impact conditions.

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