SCALE-MODEL TEST OF AN ENERGY-ABSORBING BARRIER

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A scale-model test of the "Texas barrel barrier" was conducted to demonstrate the great utility of scale modeling in the study of energy-absorbing highway barriers. This barrier consists of an array of empty 55-gal drums attached together and fastened in place so that energy from an impacting automobile is absorbed in the plastic deformation of the drums. The results of this test were found to agree very well with results from a full-scale test that was modeled. The modeling techniques are presented, and the similitude requirements for the scale modeling of the car and the barrier are developed.

•A SCALE-MODEL TEST of the "Texas barrel barrier" was conducted at the Denver Research Institute (DRI). The test was restricted to a head-on collision of a model car impacting an array of scale-model 55-gal drums. The results were compared to the results of the actual tests conducted by the Texas Transportation Institute (1, 2). Specifically, the test modeled by DRI was test 1146-5 (2), which used a Dodge sedan weighing 3,360 lb, impacting head-on at 52.5 mph into a modular crash cushion. This cushion or barrier consisted of a rectangular array of 16-gage, 55-gal drums, 9 drums long by 3 drums wide, with a tenth row, 2 drums wide, placed at the impact point.

The scaling laws were determined using standard techniques discussed in the following section. For the specific test conducted, emphasis was placed on accurately scaling the dimensions, weight, and velocity of the car and the dimensions, weight, and static force-deflection curve for the drums. Briefly, it was found that, if the linear dimensions were scaled in the ratio of

$$\frac{\text{Model dimensions}}{\text{Prototype dimensions}} = n_1$$

the velocity would scale as

$$\frac{\text{Model velocity}}{\text{Prototype velocity}} = (n_1)^{1/2}$$

and the forces would scale as

$$\frac{\text{Forces on model}}{\text{Forces on prototype}} = (n_1)^3$$

The results of the test are shown in a later section. It is apparent from these results that even a simplified model, such as that used in this test, can give valid results provided strict attention is paid to the governing parameters.

DIMENSIONAL ANALYSIS

The variables assumed to be sufficient to describe the impact problem under discussion are given in Table 1. Using standard techniques, the variables may be com-

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TABLE 1

IMPACT VARIABLES

Variable	Name	Basic Dimensions
Dependent		
a	Deceleration	LT^{-2}
Independent		
V	Velocity (initial)	LT^{-1}
w	Rotational velocity (initial)	T^{-1}
I	Polar moment of inertia of automobile	ML^2
θ	Obliquity angle at impact	—
u_1	Coefficient of friction between tires and road surface	—
γ_i	Characteristic dimensions of automobile	L
F_i	Force to operate barrier over the ith increment of stroke	MLT^{-2}
L	Stroke of barrier	L
u_2	Coefficient of friction between the barrier and the roadway	—
λ_i	Characteristic dimension of barrier	L
M	Mass of automobile	M
ρ	Density of the barrier material	ML^{-3}
g	Acceleration due to gravity	LT^{-2}
ϕ	Yaw angle at impact	—
k	Percent springback of barrier	—

bined into 13 dimensionless groups. For the present purpose, these have been taken as follows:

$$\pi_1 = aM/F_i \qquad \pi_8 = u_2$$
$$\pi_2 = \omega L/V \qquad \pi_9 = \rho V^2\gamma_i^2/F_i$$
$$\pi_3 = I/M\lambda_i^2 \qquad \pi_{10} = \phi$$
$$\pi_4 = \theta \qquad \pi_{11} = gM/F_i$$
$$\pi_5 = u_1 \qquad \pi_{12} = \lambda_i F_i/V^2M$$
$$\pi_6 = \gamma_i/L \qquad \pi_{13} = k$$
$$\pi_7 = L/\lambda_i$$

The design conditions for a true model are that the π terms for the model equal the corresponding π terms for the prototype; i.e., $(\pi_n)_m = (\pi_n)_p$, where the m and p subscripts refer to the model and prototype respectively.

There are three basic dimensions (mass, length, and time) for the variables considered and, therefore, three scale factors may be chosen arbitrarily that scale these basic dimensions. The scale factors chosen for the present case are $n_1 = (\lambda_i)_m/(\lambda_i)_p$ (scales length), $n_2 = g_m/g_p$ (scales time), and $n_3 = (F_i)_m/(F_i)_p$ (scales mass).

For our laboratory, a desirable linear scale for the model is $(\lambda_i)_m/(\lambda_i)_p = n_1 = 1/25$, while the most practical value for the ratio of the gravitational constants is $g_m/g_p = n_2 = 1$. The force ratio is conveniently chosen as $(F_i)_m/(F_i)_p = n_3 = n_1^3$, thus preserving the natural relationship between the length, volume, and weight or mass of the model. Using these scale factors and equating the terms gives the following complete similitude requirements:

$$a_m = a_p \qquad L_m = n_1 L_p$$
$$V_m = n_1^{1/2} V_p \qquad u_{2m} = u_{2p}$$
$$\omega_m = n_1^{-1/2}\omega_p \qquad \lambda_{im} = n_1\lambda_{ip}$$
$$I_m = n_1^5 I_p \qquad M_m = n_1^3 M_p$$
$$\theta_m = \theta_p \qquad \rho_m = \rho_p$$
$$u_{1m} = u_{1p} \qquad g_m = g_p$$
$$\gamma_{im} = n_1\gamma_{ip} \qquad \phi_m = \phi_p$$
$$F_{im} = n_1^3 F_{ip} \qquad k_m = k_p$$

These values (with $n_1 = 1/25$) were used in the model test described in the following sections.

FACILITIES

Model Car

The car used in these tests (Fig. 1) was modeled to a scale of 1:25 and was specifically weighted to simulate the 3,360-lb Dodge used in test 1146-5 (2). The scale factors for the car mass, length, width, and velocity were

$$M_m = n_1^3 M_p = M_p/15{,}600$$

$$L_m = n_1 L_p = L_p/25$$

$$W_m = n_1 W_p = W_p/25$$

$$V_m = n_1^{1/2} V_p = V_p/5$$

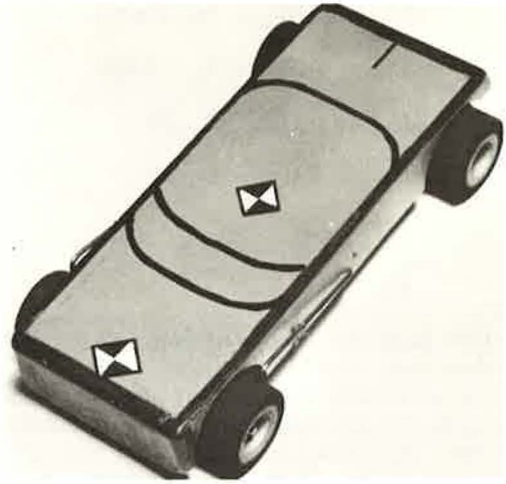


Figure 1. Scale-model car measures 6³/₈ by 2½ in. The targets on the car (black and white triangles) were added after the test described in this paper to facilitate more accurate measurements from the high-speed film.

As a first trial at the problem of modeling the impact on a modular crash barrier, the linear dimensions, the weight, and the velocity of the car were given primary consideration. Other factors such as tire friction, tire spring constant, ground pressure, and center of gravity were not considered significant because the test was confined to a straight, head-on impact where it could be assumed that these factors would play a negligible role. It was believed that this model was the simplest one that could be relied on to produce valid data and would therefore require the least expenditure of time and money to construct and operate.

One factor that was deemed to be of significance was the resistance of the car to motion with the motor turned off and the gear shift lever in the drive position (automatic transmission) or in high gear (standard transmission). In the actual test (2), the motor is turned off (brakes not applied) just prior to impact causing the rear wheels to run against the compression of the motor down to about 20 mph for an automatic and all the way down to a dead stop for a standard drive. How far the car rebounds depends on these factors because a car with automatic transmission in drive, for example, will roll backward rather easily, whereas a car with standard transmission engaged in third gear, say, offers a very great resistance to any force trying to accelerate it backwards. Thus, it was felt that for purposes of initial testing some method of braking the model in the direction of rebound should be incorporated. This was done by fastening a wire to each side of the car (Fig. 1) in such a way that the front wheels could not rotate backward. This also took into account some of the differences in the road surface used in the two tests, which in the case of the model was simply a wooden table top covered with grid paper.

The car was constructed of a solid block of redwood with axle holes drilled completely through the block front and rear. To model the weight correctly it was necessary to hollow out a large portion of the underside. The axles were one piece and threaded on both ends. The wheels were a common type used for "slot cars" and were attached directly to the axles.

Drums

Using the similitude requirements discussed earlier, models of the 16-gage, 55-gal drums were constructed (Fig. 2). The mass, static peak load, diameter, height, density, and springback of the model drum were respectively given as follows:

$$M_m = n_1^3 M_p = M_p/15,600$$

$$P_m = n_1^3 P_p = P_p/15,600$$

$$D_m = n_1 D_p = D_p/25$$

$$H_m = n_1 H_p = H_p/25$$

$$\rho_m = \rho_p$$

$$K_m = K_p$$

The material selected was dead soft aluminum foil (since the springback characteristic of the real drums was not known but was assumed to be small) 0.003 in. thick. It was formed into cylinders (1-in. diameter by 1.4-in. long) by wrapping the material around a 1-in. diameter tube and gluing the seam with contact cement. The top was modeled by gluing an aluminum strip 0.005-in. thick by 0.1-in. wide over each end of the model barrel. The model was then compressed in a static testing machine to obtain the load deflection curve. The results of this test are shown in Figure 3, which also shows a plot of the load-deflection curve of an actual drum scaled down to model dimensions. The data in Figure 3 show that the load-deflection curve for the model has the same prominent features as the prototype, these being the sharp initial slope and the peaking effect with the subsequent rapid decrease in the load with continued increase in displacement. (Note that these curves were both obtained from only one test. To properly characterize the barrels, a statistical sample would be required.) It was found that considerable change in the peak load for the model could be achieved by varying the width of the end strip, making it possible to simulate a large number of designs. Furthermore, as indicated by the results of the present work, the load-deflection curve for the model drum need not be an exact duplicate of the prototype

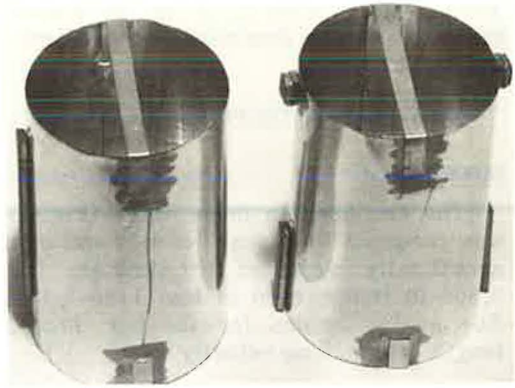


Figure 2. Scale models of the 55-gal drums used in the "Texas barrel barrier." A "center" drum is shown on the right and an "outside" drum on the left. Note small lead weights used as spacers on the center drum (photograph taken before painting the barrels).

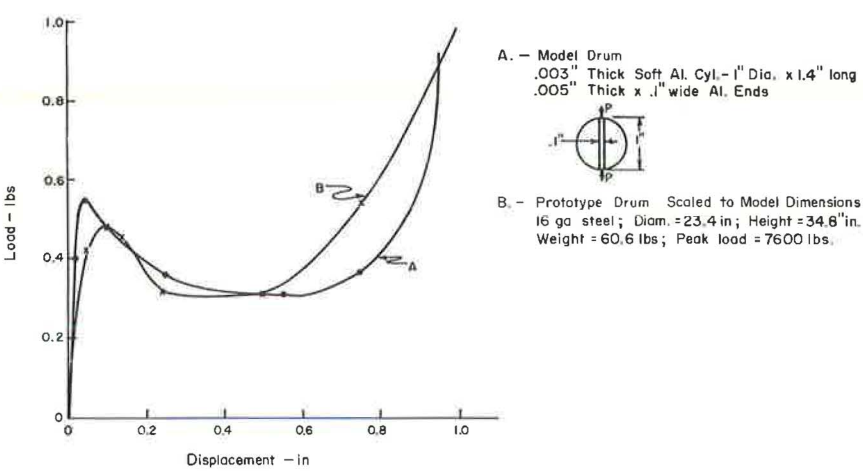


Figure 3. Relationship of the load versus deformation curves for the model and prototype drum.

curve, but must retain the essential character of the curve. It is, therefore, reasonable to assume that the top of the model drum need not duplicate physically the top of the prototype.

The drums used in the model test incorporated spacers that simulated rolling hoops. These were formed by gluing lead weights to each side of the center barrel in each row. This provided the necessary space between the center and outside drums for the wire used to simulate the steel cable used in the actual test. Also, the lead weights were necessary to bring the weight of the models up to the necessary values because the aluminum alone was too light. The weights used on the outside drums also served to raise them off the table in a manner similar to that of the "Re-Bar" chairs used in the actual test. Thus, the model 55-gal drums, individually as well as collectively, showed a close similarity to the actual drums.

Model Car Launching Facilities

The model car discussed previously impacted the barrier at 10.6 mph (equivalent to 53 mph for the prototype). This velocity was attained by a compressed air launcher operating at 150-psi air pressure (Fig. 4). The car was maintained on course for the first 12 in. by two guide rails. On leaving the guides, the car passed through the timing station where it interrupted two light beams, starting and stopping a Beckley (100,000-cps) chronograph. The time required for the car to traverse the distance between the light beams was used to determine the velocity of the car.

The motion of the car and the barrier was recorded by a 16-mm high-speed camera. This camera, a Fairchild Model HS101A capable of film speeds up to 10,000 frames per second, is shown in Figure 4 mounted to take a plan view of the collision. From the film obtained in this fashion, an accurate analysis was made of the motion of the car and the barrier (Fig. 5). A mirror was used to give a side view of the event, making it possible to observe vertical motion of the car and drums. This side view is visible in Figures 5 and 6.

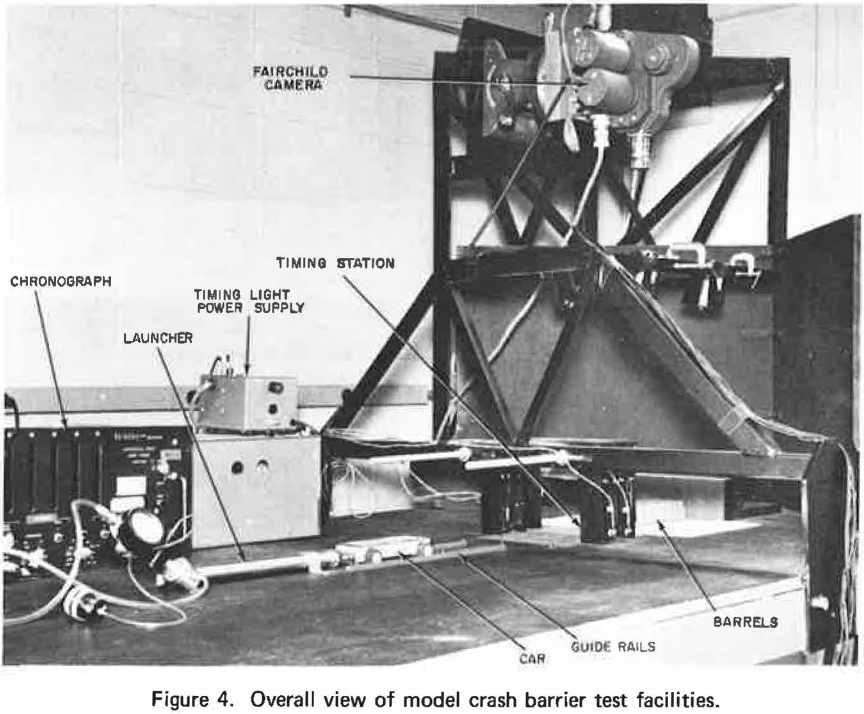
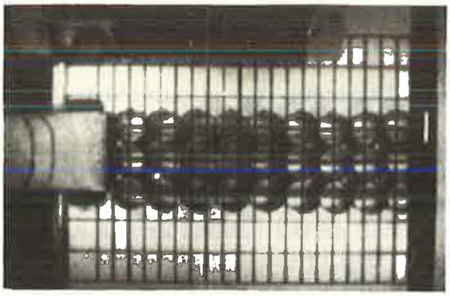


Figure 4. Overall view of model crash barrier test facilities.



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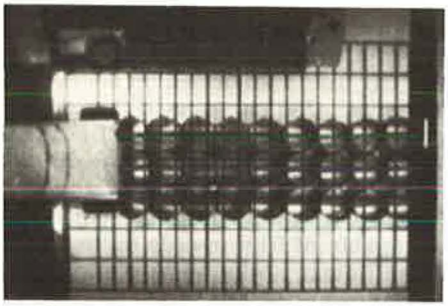

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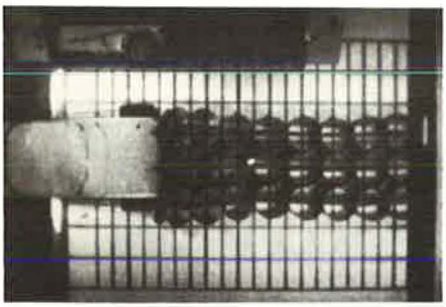

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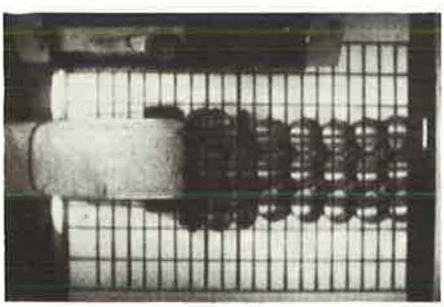

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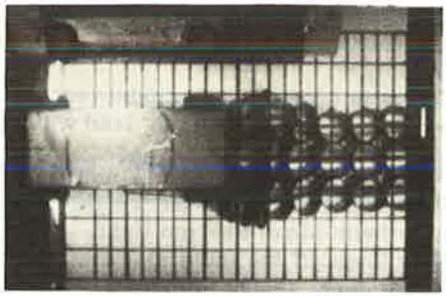

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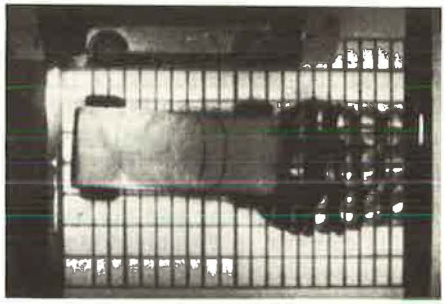

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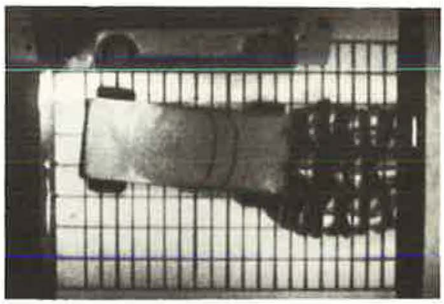

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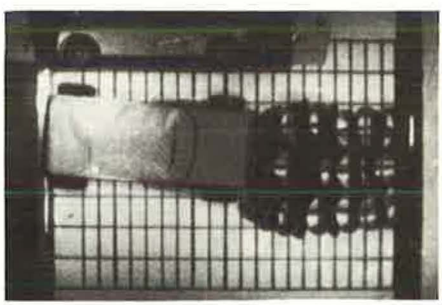

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Figure 5. Sequence taken from 16-mm high-speed movie film (3,000 frames per second) during the scale-model test of the "Texas barrel barrier."

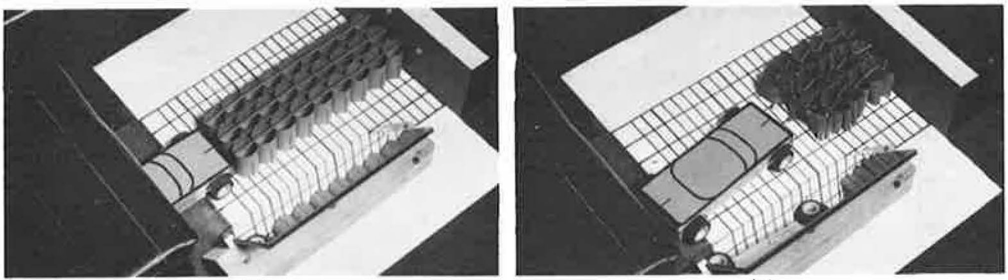

Figure 6. Simulated car and barrier (a) at impact and (b) after impact.

RESULTS

The results obtained in the test are shown in Figure 7. The distance, velocity, and G curves are plotted as a function of time after impact for the model car. Also, the distance-time plot for the prototype (1964 Dodge, 3,360 lb) is shown to the scale of the model. Because of the good correlation of the model data with the prototype data, only the data for the model were actually differentiated to produce the velocity and G curves. The average deceleration in G for the model was computed (2) from the equation

$$G_{ave} = \frac{V_0^2}{2gS}$$

where

V_0 = initial velocity at time of impact,
S = movement of the vehicle center of gravity in feet from its position at first contact to its position when its longitudinal velocity is zero, and
g = 32.2 feet per second.

Thus, for the model, $(G_{ave})_m$ = 7.35 while for the prototype the value was given (2) as $(G_{ave})_p$ = 7.6. A further indication of the validity of the test can be obtained from a visual comparison of the barrier after the test to the after photograph of the prototype barrier (both cases are for the rectangular array of 3 by 9). In these photographs (Fig. 6 in this report, photograph on p. 10 of reference 1, and Figs. 6 and 11 of reference 2), the first two rows appear to crush somewhat uniformly, while thereafter there is a distinctive pattern wherein alternate rows do not crush uniformly. This behavior is very evident in the high-speed movie (3,000 frames per second) taken during the model test. An explanation for this nonuniform behavior lies in the manner in which the force is applied to successive elements of the barrier. The first two rows undergo catastrophic deformation due to the relatively high impact velocity. By the time the car travels approximately the distance equivalent to these two drum diameters, the second row has wrapped back around the third row, causing the load to be spread out over a much greater area. This row, having a more distributed load, is not as easily crushed. (Note that the kinetic energy of the car at this time has decreased by about 30 percent.) The fact that the third row is not crushing as rapidly implies that the fourth row is now being affected by a more concentrated load and therefore deforms more readily. This chain of events continues until, in the end, it appears that every other row is affected in this manner. Similar behavior, but to a lesser extent, was reported in test 1146-3 (2, Fig. 9). However, this last set of barrels was originally a slightly different array, which may account for the more uniform deformation.

The fact that the drums behave in this nonuniform manner clearly indicates an important role that modeling can play in barrier design. That is, a modular crash cushion can be studied experimentally to determine changes in design required to obtain uniform deformation, thereby applying the most uniform decelerating force to the

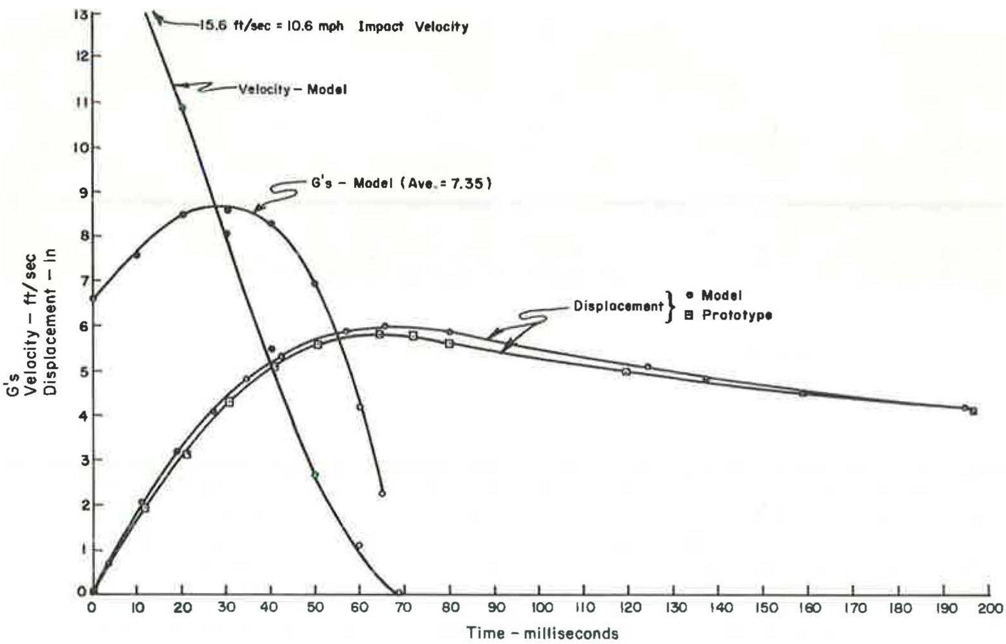

Figure 7. Results of the scale-model impact test compared to the results of the actual test (1146-5). The actual test data have been scaled down to the model dimensions of distance and time.

vehicle over the shortest distance. Simultaneously, the data from all tests may be compiled for use in developing and correlating analytical models. The same techniques may be applied to barriers of any design with the ultimate goal of designing a barrier that is optimized with regard to overall efficiency, including the cost of materials and labor to build and install the barrier. These points and others such as angle impacts and side impacts resulting in automobile redirection can be studied experimentally, using models, at a fraction of the cost of using full-size cars and barriers. For example, the cost of running a test such as that described in this paper is estimated to be less than $400, including direct labor, complete film coverage, materials, and data reduction. Some barrier tests would be expected to be considerably less expensive because, with the modular barrier, the largest expense is involved in construction of the individual elements. Simpler designs would cost less for labor and hence would be less expensive to test and evaluate.

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