Automobile-Barrier Impact Studies Using Scale Model Vehicles

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•THIS is a report on the continuing development of scale models as tools in the study of vehicle dynamics. In this case, models were used to study the automobile-center barrier impact phenomenon.

The particular intent of the initial study was to develop design criteria for non-yielding concrete center barriers, such as those installed on the New Jersey State Highway System. The method for evaluating proposed criteria was to build scale models of the barriers and to test the effect of the incorporated design features by catapulting scale model vehicles into them at various speeds and angles. The resulting trajectory and attitudes of the model vehicle, as observed by high-speed movies, would then give an indication of the effectiveness of various design features.

The design data were not realized in this effort, due to circumstances mentioned later, but we feel that indications of the usefulness of models as tools in testing vehicle restraining devices were established.

BACKGROUND

The use of scale models in the evaluation of design features has an extensive history. Their use in aerodynamic studies in wind tunnels is common knowledge. Hydrodynamic studies on hull shapes and rudders are only slightly less well known.

Considerably less well known is the use of models in off-road mobility research. The Davidson Laboratory (4, 5) pioneered this application after World War II; the field has since grown to the point where some off-road equipment manufacturers and several laboratories have soil bins in which model tests can be run. Model testing is now a standard, accepted alternative to theoretical and full-scale work in the evaluation of vehicles and components to be used in media ranging from water through marsh and mud to solid packed earth.

Not completely proven, but actually less complicated, is the modeling of roadway vehicle dynamics. Here the road-tire/wheel interface does not need to include soil sinkage and cohesion; however, the tire-pavement interface is still complicated enough. I will mention four particular efforts.

An early effort in road vehicle simulation by modeling is the work of Kamm (8) in Germany. During the early 1930's he tested the effects on stability and direction holding of uneven brake application in multi-axle truck-full trailer configurations. For these purposes he constructed $\frac{1}{10}$-scale self-powered models with remotely actuated electric brakes on each wheel. These models had complete suspension systems with friction dampers, operating differentials, and selective all wheel drive. Initially these were run across a gym floor, but later this work was transferred to a rolling road.

In the late 1950's, Kamm returned to model work (9). Again he studied stability and direction holding, this time under the impact of wind forces. He built a highly sophisticated model, operated on a rolling road, which incorporated remote steering and brake application. During the running of the model, it was possible to change the center of gravity fore-aft and laterally, as well as the attack point of the wind forces.

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More recently, in 1960 the Davidson Laboratory (6, 7) studied the stability properties of a train of four jeeps and the controls necessary to operate it at roadway speeds. By modeling only the steering linkages, backbones, and rear axle differentials (on the rolling road), we found the changes needed to allow the train of vehicles to track truly and also to be stable at 50 mph, whereas the original configuration became unstable at 20 mph.

Closer to our effort is the study performed by Ayre and his associates (1, 2, 3) at Johns Hopkins University in the early 1950's. Under study there were energy-absorbing cable and post-type guardrails. The layout consisted of a track along which the model was propelled until it achieved its desired speed; the model then rolled freely on a platform where the cable, anchored at one end, was stretched at an angle in the path of the oncoming model vehicle. The other end of the cable was attached to a tensioning device which could be adjusted to yield initial tension and included a strain-gaged section to record maximum tension during impact. Posts were set into the platform behind the cables to simulate the upright supports of a cable guardrail. There was no solid connection between the cable and the posts.

The model consisted, essentially, of a box mounted on four wheels. The wheels were ball bearings, the outer race of which acted as the tire. The surface of the platform was varied to yield different coefficients of friction. Most of the results were given for a coefficient of 0.33. The vehicle was scaled essentially by what is called Froude's law for time, mass and distance, and a law for force which was determined by the ratio of the elastic properties of the full-scale cable to the model cable. As no vertical motion was contemplated by the investigators, they judged this to be sufficient for modeling the phenomenon they were studying.

Their results yielded data about the relationship of the angle of departure and maximum cable tension under various initial angles of vehicle impact and velocity.

Our attempt reversed the foregoing procedure, in that our model was dynamic and our barrier rigid. We allowed for vertical motion of the model vehicle, and so extended the list of vehicle parameters required to be modeled correctly. The restriction to non-yielding barriers made the modeling of the trajectory and attitude of the vehicle depend entirely on the vehicle itself, the barrier playing the passive role of just being there. When a model is built which faithfully simulates the impact of a full-scale vehicle against such a barrier, it can be assumed to be a good model and may be used with confidence in studies with other rigid barrier shapes and active restraining devices. This is the approach we have attempted.

EQUIPMENT DESIGN

Scaling Laws

In our case, which involved a free-moving body impacting a rigid, non-yielding barrier, the choice of scaling laws to follow was relatively straightforward. The vehicle would move forward on the test platform, climb the barrier under its own momentum, be propelled vertically and laterally from the face of the barrier, and descend onto the platform (or the barrier) and continue its motion, either rolling on its wheels or sliding on its body. Inertial and gravitational effects tend to predominate over frictional and other dissipative forces. We are clearly then in the realm of Froude scaling. The modeling formulas used are as follows.

Froude's law

$$\frac{V}{\sqrt{LG}} = \frac{v}{\sqrt{lg}} \tag{1}$$

$$\frac{MV^2/L}{MG} = \frac{mv^2/l}{mg} \tag{2}$$

$$G = g$$
$$V = L/T$$
$$v = l/t \tag{3}$$

For scale factor

$$L = \lambda l \tag{4}$$

$$V = \sqrt{\lambda v} \tag{5}$$

$$T = \sqrt{\lambda t} \tag{6}$$

Ground pressure

$$P = F/L^2$$
$$p = f/l^2$$
$$\frac{F}{f} = \frac{L^2}{l^2} = \lambda^2 \tag{7}$$

For equal ground pressure

$$F = \lambda^2 f \tag{8}$$

$$W = \lambda^2 w \tag{9}$$

Newton's law

$$F = ML/T^2$$
$$f = ml/t^2 \tag{10}$$

$$\lambda^2 = \frac{F}{f} = \frac{M}{m}\,\frac{L}{l}\,\frac{t^2}{T^2} = \frac{M}{m} \tag{11}$$

$$M = \rho_p L^3$$
$$m = \rho_m l^3$$
$$\lambda^2 = \frac{\rho_p L^3}{\rho_m l^3} = \frac{\rho_p}{\rho_m}\,\lambda^3$$
$$\rho_p = \frac{1}{\lambda}\,\rho_m \tag{12}$$

Equal density

$$\rho_p = \rho_m$$

$$\frac{F}{f} \quad \frac{M}{m} = \frac{\rho_p L^3}{\rho_m l^3} = \lambda^3 \tag{13}$$

For this presentation, full-scale parameters are indicated by capital letters and model parameters by lower case letters. Froude's law postulates the equality of the dimensionless quantity: velocity over the square root of distance times the acceleration of gravity, for both the full-scale vehicle and the model (Eq. 1). If this ratio is squared and the numerator and denominator are multiplied by mass, this law states that the relative effects of inertia (in the numerator) and gravity (in the denominator) should be the same on the vehicle and the model (Eq. 2).

Clearly, G = g. From this, the fact that V = L/T, v = l/t (Eq. 3), and that the lengths are related by the scale factor λ (Eq. 4), we see that velocity and time scale with the factor $\sqrt{\lambda}$ (Eqs. 5, 6).

In the determination of how to scale forces, we are faced with some difficulty.

An instinctively satisfying assumption, and one which is used in off-road mobility work and some on-road vehicle modeling, is to require that ground pressure (Eq. 7) under the tire contact patch be equal for the prototype and the model. This yields a force relation with λ^2 as the scale factor (Eq. 8). In particular, weight scales as λ^2 (Eq. 9). The density scaling factor may be derived by the application of Newton's law (Eq. 10). The ratio of masses is λ^2 (Eq. 11), and it is also the ratio of densities times λ^3. This yields a density relationship which is as $1/\lambda$ (Eq. 12).

Two problems appear, one practical, the other theoretical. Practically, scaling a 1000-lb car by $\frac{1}{8}$ scale gives 62 lb as the weight of the model; even at $\frac{1}{12}$ scale the model weighs 28 lb. If the foregoing theory were beyond question, we would be limited to using only heavy models. But to say that the forces involved in the tire-road interactions at various speeds and road surfaces are directly and predominantly related to ground pressure is quite presumptuous. The tire-road interactions are a combination of elastic deformation, mechanical reaction, and friction phenomena which are still not entirely understood. This makes a force scaling based on equal ground pressure rather tenuous.

An alternative is to assume equal densities between prototype and model and to use Newton's law to derive a relation between forces. This yields a cube law for scaling (Eq. 13). It also forces the model tires to be so constructed that the measurable effects of the tire-road interaction hold according to this cube scaling law. These include cornering force, static radial and side deflection (spring ratio), and coefficient of friction. These quantities do not yield the entire description of a tire, but the state of the art is not sufficiently advanced to do much more. Dynamic deformations, rolling moments of inertia, etc., can be measured, but one is almost forced to scale down the measuring device to validate the model tires built according to these parameters.

The model described here was constructed according to the cube law for force scaling.

Prototype Data and Scaled Quantities

A description of a full-scale vehicle sufficiently complete to build a model has so far been impossible to locate. As the effort undertaken by Davidson Laboratory did not include the testing of full-scale vehicles, we were forced to rely on published and industry sources for full-scale data. General Motors, Monroe Auto Equipment Co., and the research labs of Uniroyal Corp. were cooperative in supplying such data as they had, but for proprietary reasons, and because of their lack of need for such data, we could not get information on many parameters needed for complete and accurate scaling. Nevertheless, we used what we could get.

The following table gives the physical parameters of the full-scale vehicle we tried to model: a typical 1964 low-priced, full-size 4-door sedan loaded with four passengers.

Parameters	Full-Scale Vehicle	Scale Factor	Model	
			Ideal	Actual
Wheelbase	118 in.	$\lambda = 1/8$	14.75	14.0
Track				
Front	60.3 in.	λ	7.54	7.4
Rear	59.6 in.	λ	7.46	7.4
Center of gravity				
Lateral	0.26 in. (left of center)	λ	0.03	0.0
Longitudinal	59.2 in. (front axle)	λ	7.39	7.4
Vertical	21.1 in. (ground)	λ	2.64	2.6
Tire OD	25.5 in.	λ	3.19	3.2
Weight	4353 lb	λ^3	8.50	8.5
Front	2216 lb	λ^3	4.33	4.3
Rear	2137 lb	λ^3	4.17	4.2
Moment of inertia				
Pitch	2935 slug ft^2	λ^5	415.0	415.0
Static ride rate				
Front	191 lb/in.	λ^2	2.985	3.0
Rear	203 lb/in.	λ^2	3.165	3.2
Tire vertical	925 lb/in. at 25 psi	λ^2	14.45	31.2
Spring rate	1100 lb/in. at 30 psi	λ^2	17.18	31.2

The second column shows the scale factors of each particular parameter. For this study we chose a 1/8-scale model. The column labeled "ideal" shows what the parameters of the model would be under exact application of the scaling law, and the last column shows the parameters of the model as actually constructed. Briefly, this table calls for a model with a 14 3/4-in. wheelbase, 7 1/2-in. track, and weighing about 8 1/2 lb. One discrepancy is that the model tires are about twice as stiff as called for by the ideal value, because we did not get the tire data in time to acquire the appropriate materials before this model was tested.

Important by their absence are the parameters for which we got no full-scale data. Roll and yaw moments of inertia, unsprung weight, and the restoring moments of the front wheels are important values for automobile-barrier impact studies. We made educated guesses at these quantities.

Overall Configuration

In the model we constructed (Fig. 1), a backbone partly of 3/4-in. aluminum box section is rigidly connected to two beams to which the rear end is connected. The solid rear axle is connected by a fake drive shaft to the backbone with a ball joint which allows all but fore-aft motion. The Panhard rod, partly hidden in the photo, provides lateral rigidity.

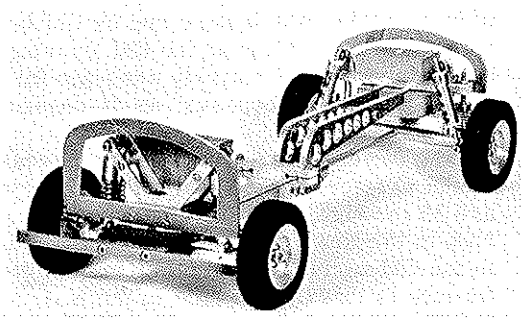

Figure 1. Fully assembled model.

Suspension, Wheels and Tires

The rear suspension consists of two coil springs and shock absorbers mounted forward of the axle. Rear weights and a roll bar are shown.

The front end uses an unequal length parallel A-arm suspension supported by concentric shock absorbers and coil springs. (This may be seen more clearly in Figs. 7, 8 and 9.)

Figure 2 shows the shocks when extended, compressed and disassembled. The rod is about $3\frac{1}{4}$ in. long, the body about $1\frac{1}{2}$ in. long.

The wheels are made of two machined disks of aluminum screwed together. They are supported on $\frac{3}{8}$-in. tempered steel stub axles by small roller bearings.

The tires are machined from polyurethane foam of 10 pci density, and coated. The density of the foam is the major way to vary tire characteristics, with the coating and the dimension of the tire retainer affecting side wall strength and cornering force characteristics to some degree.

The body of the shock absorber assembly (Fig. 3) is $\frac{1}{2}$-in. OD brass tubing with Teflon end seals which act as bearings for the rod. The piston is mounted rigidly on this rod. Different compression and rebound damping rate is achieved by drilling holes in the piston and mounting a flapper valve against one side. When the rod wants to move up (compression), fluid forced through the holes opens the valve and flows around the edge of the piston and through the holes. When the rod wants to move down (rebound), the fluid closes the flapper valve and seals the holes, thereby allowing fluid to pass only around the piston. Damping rates can be varied by changing the size of the piston, the number and size of the holes, and the density of the fluid.

Barriers

The purpose of the model, of course, was to test barriers, in this case the New Jersey concrete barrier curb (Fig. 4b). The GM barrier (10) is very similar to the N.J. barrier (Fig. 4a). It is included in this study because it was the only concrete barrier against which recorded crash tests had been run. It turned out that the movies

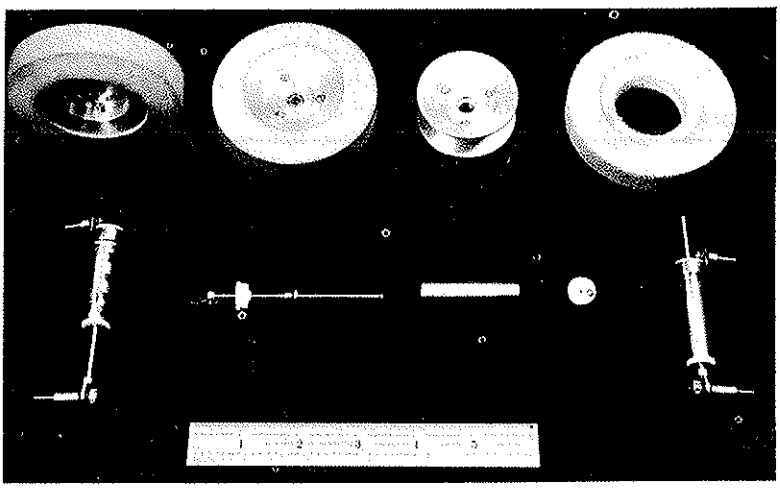

Figure 2. Shock absorber and wheels.

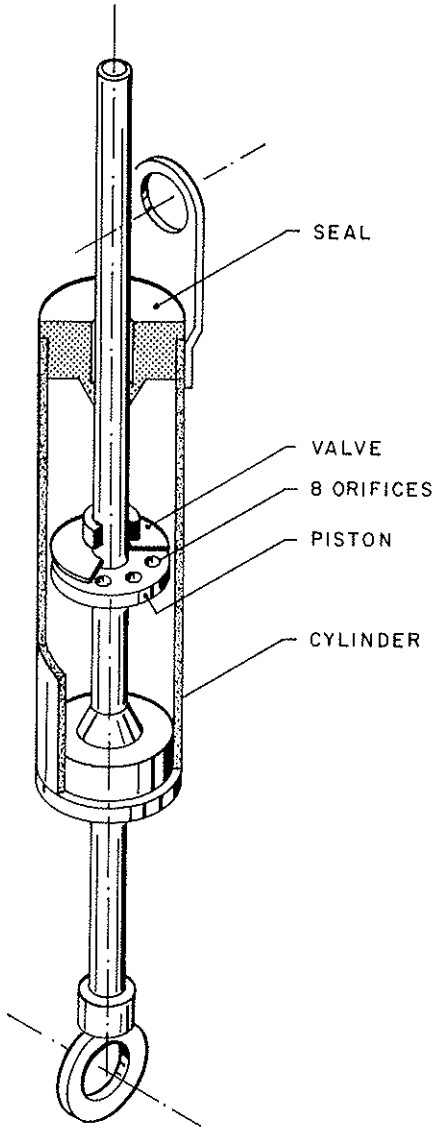

Figure 3. Shock absorber assembly.

of these tests, which were run by GM before their installation at the GM Proving Grounds, were not entirely adequate for model validation purposes, as discussed later.

The dimensions shown are the 1/8-scale model barriers. Full scale, these barriers are 32 in. high, with the center cut 10 in. high in the New Jersey barrier and 13 in. in the GM barrier. The other major difference is that the top face in the N.J. barrier makes a 6-deg angle with the vertical, whereas the top face of the GM barrier makes about a 10-deg angle with the vertical.

The New Jersey State Highway Department has been using these barriers as center barriers on state highways. The actual heights, as installed, range from 18 to 40 in. GM has installed its version of this barrier as bridge parapets on two bridges in the proving ground.

The model barriers we constructed were originally made of wood, but we found that the metal rims of the wheels took large chunks out as the model impacted. (The model barriers in Figs. 7, 8 and 9 were made out of concrete.)

Test Layout

Figure 5 shows the overall plan of the test facility. A compressed-air catapult is used to propel the model, guided by a track, under the timing gate and into the face of the barrier. The speed of the model is picked off by two cat whiskers through which the front and rear roll bars of the model complete a timing circuit with a 100,000 cps counter. The front bar starts the counter, the rear bar stops it. The barrier is placed on a platform under an overhead camera running at 128 pictures per second (pps). A higher speed camera, running at 700 pps, is mounted in front of the model and points in a direction parallel to the face of the barrier. Lights are arranged in two rows, one behind the barrier, the other facing the barrier on the other side of the indicated lane markers. A sequence timer synchronizes the camera, lights, and catapult when a test is being run.

To achieve various angles of impact, the barrier is moved in relation to the catapult and the entire platform is moved to present the same view to the cameras. Speed of the model is controlled by the pressure in the catapult accumulator.

Test Procedure

The test procedure is very simple. The model is positioned, the catapult accumulator is filled to the desired pressure for the desired speed (we were able to hit a planned speed within 2 to 3 ft/sec), the cameras are loaded, and a sequence timer is started.

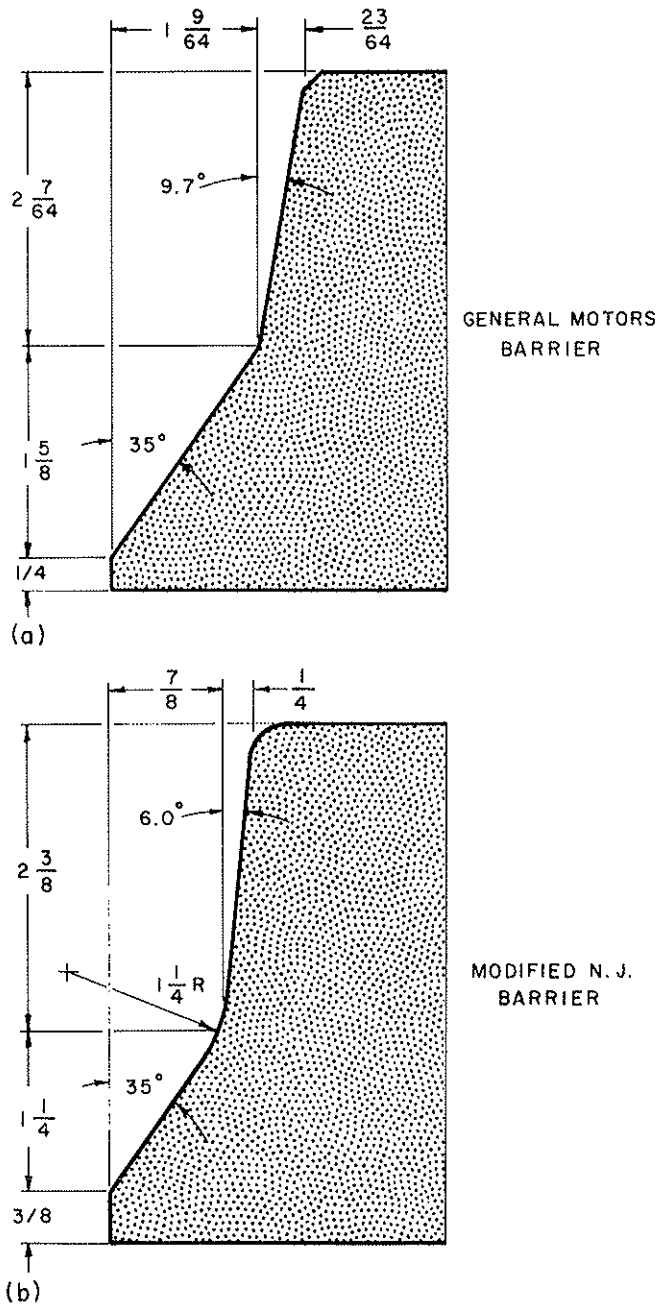

Figure 4. Model barriers (model dimensions in inches).

At the proper times the camera starts, gets up to speed, the lights go on, and the catapult fires.

Even with film changes and planned model configuration changes, 20 or 30 impact tests can be conducted in half a day.

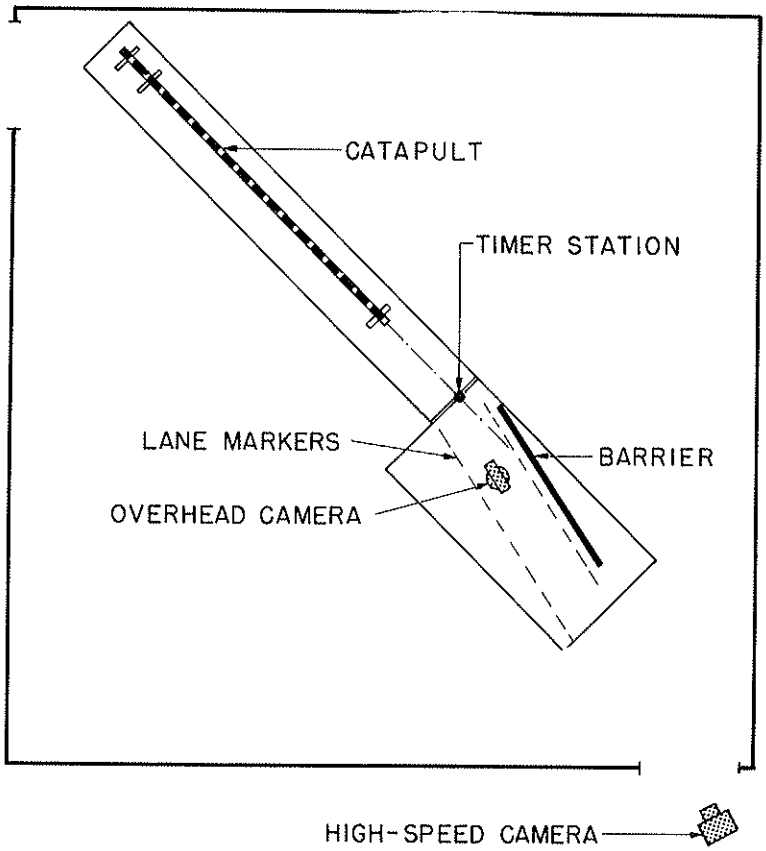

Figure 5. Test layout showing catapult, barrier and cameras.

RESULTS AND FUTURE PLANS

Results

In a model investigation the burden is on the model builder to prove that his model properly simulates the full-scale event. At the start of this effort, we had hoped that there existed sufficient data describing automobiles and several film-documented full-scale impacts to allow us to validate the model or evaluate modeling distortions. This hope was never completely or satisfactorily realized.

Some of the vehicle parameters needed for modeling about which we were unable to find adequate information have been mentioned. Furthermore, we found only one recorded impact with a concrete barrier: that by GM when they were studying barriers to find a suitable one to use as a bridge parapet. The GM tests, which preceded ours by several years, were not run to obtain information precise enough for modeling; consequently, the test practice included many features which compromised its value for our purposes. The overhead/side view camera was panning, the undercarriage of the car remained in shadows for most of the test, the exact speed was not measured, the friction characteristics of the road surface were not measured, and the high-speed film stopped before the action was complete.

The upshot of this is that we were not able to validate the model with confidence. At present, we have built a model with the information we had available and have tried to compare its overall aspects to the GM film.

The significant action of the GM test is shown in Figure 6. Figure 7 shows the model run which closest approximates the GM run, but the speed was significantly

Figure 6. Full-scale vehicle, General Motors barrier, 50 mph, 12-deg angle of impact.

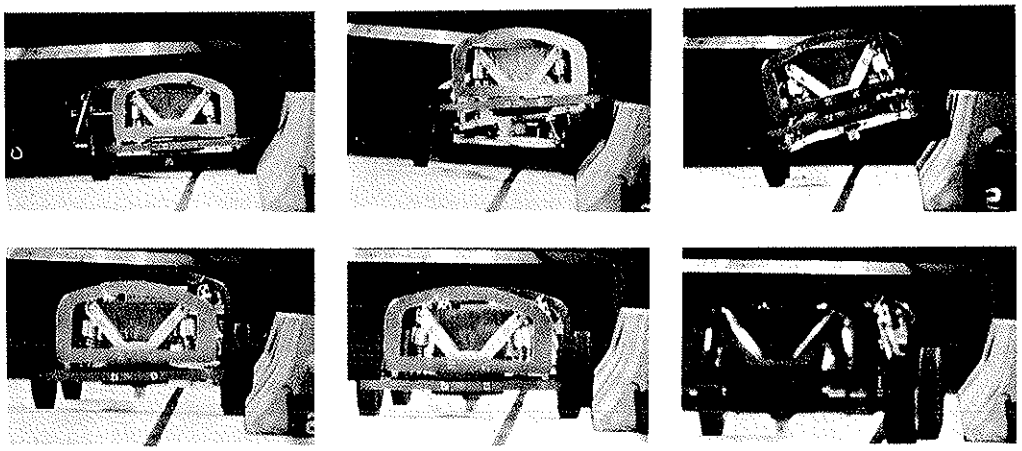

Figure 7. Davidson laboratory model, General Motors barrier, 23.8 mph, 12-deg angle of impact.

lower. Model runs at speeds comparable to the GM test are shown in Figures 8 and 9, Figure 8 showing a model run against the GM barrier and Figure 9 showing a run against the New Jersey barrier.

The major discrepancy between these two high-speed model runs is that against the GM barrier the model rolls away from the barrier and lands on its right wheels, whereas against the New Jersey barrier the model rolls toward the barrier and lands on the left wheels. This action was consistent at all speeds and angles tested.

That the model shown does not accurately simulate the GM test may be seen by the fact that at speeds comparable according to modeling laws, the model climbs much higher on the barrier and rolls to a greater degree. Also, the rear axle bottoms in the model runs, but it does not appear to do so in the GM test. To correct these deficiencies, we would have to know the roll moment of inertia, the restoring rates of the steering system, and the unsprung weights of the rear and front suspension assemblies.

In all, there are overall similarities and some significant deviations between the full-scale run and the model impact.

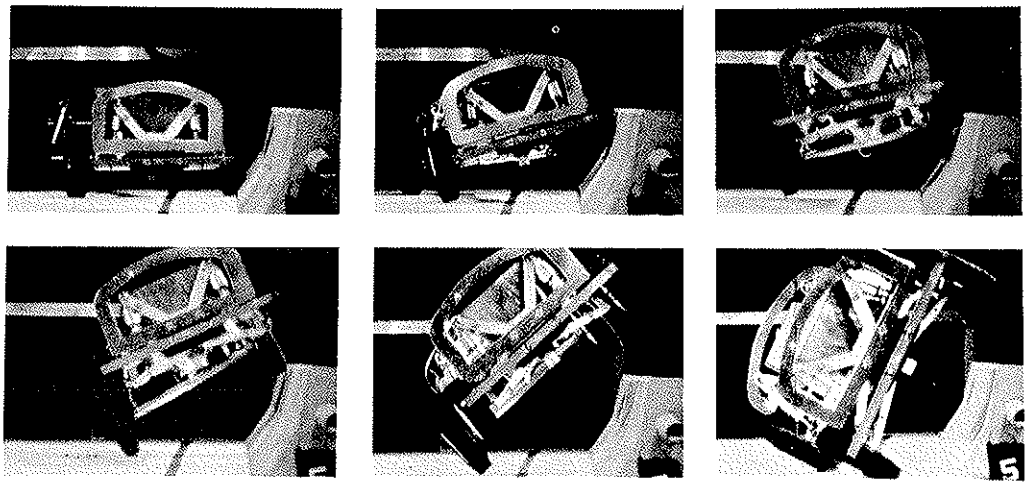

Figure 8. Davidson laboratory model, General Motors barrier, 43.0 mph, 12-deg angle of impact.

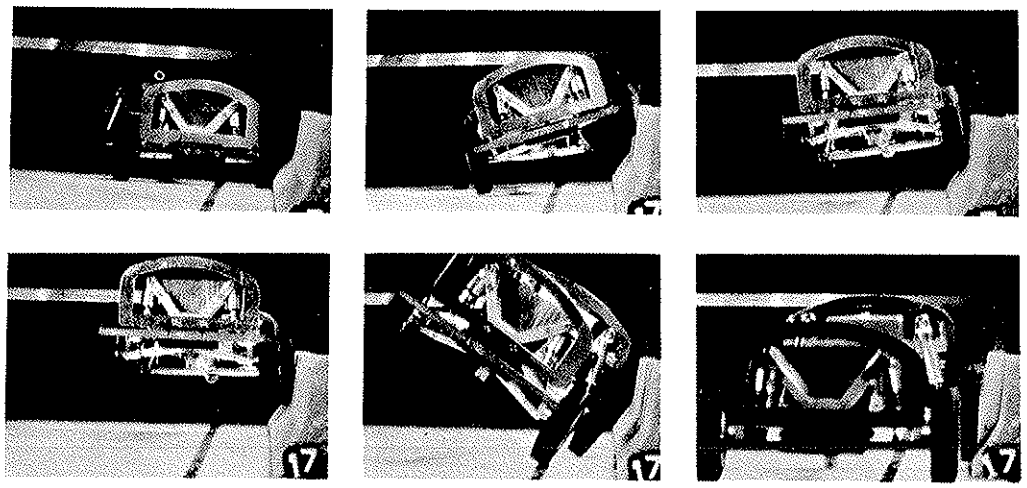

Figure 9. Davidson laboratory model; New Jersey barrier, 40.5 mph, 12-deg angle of impact.

There were several things which could have made the model a more valid representation: softer tires, steerable front wheels, and greater roll inertia. A flexible steering would have allowed the front wheels to assume a position more parallel to the barrier face and would have "steered" the car along and down the barrier much like the full-scale vehicle. We feel that proper tire and chassis distortion modeling are also important areas of improvement.

However, a trade-off shows itself. Even if we could duplicate what is on the GM film, it would not constitute a validation. No information is known about how representative the GM run is, how the undercarriage components act during impact, and just what the tire-road/barrier interactions are. Until such information is available, it seems inappropriate to spend more money building a better model.

Plans

Should vehicle description data become available, it should be a relatively simple step to complete the model to represent it faithfully. Then a serious model testing

program to investigate the action of many barrier configurations can be undertaken.

With a model, and its ability to generate large amounts of data quickly, a statistically valid experiment is straightforward to run. Controlled and systematic variation of parameters can be introduced to many variables in the barrier design, and precise information about height of the vehicle climb, degree of roll, force of impact against the barrier and road can all be generated in several weeks of running. In addition, studies could introduce energy-absorption materials into the experiment. Both yielding barriers and vehicle-mounted absorption devices could be studied. However, it must be realized that the introduction of yielding structures introduces significant dissipative forces, whose scaling is a harder problem than that described here. Conceptually, few problems appear in the scaling of strength of materials; practically, there are sure to be some.

In summary, it would seem that this effort shows vehicle model testing of impact phenomenon is a feasible method of data gathering and points to a flexible and inexpensive way of testing new restraining devices for our highway systems.

ACKNOWLEDGMENTS

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