WATER-PLASTIC CRASH ATTENUATION SYSTEM: TEST PERFORMANCE AND MODEL PREDICTION

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This paper presents the results of a model performance study on the Hi-Dro Cushion Cell Barrier (water-plastic impact cushion). A digital computer model was constructed to represent the dynamic response of the cushion system. The model was verified by comparing with actual full-scale crash tests. The verified model was then exercised to provide prediction of response to extremes of vehicle mass and speed. The simulated performance of the barrier is presented and compared with the square-wave or "constant-force" cushion. Predictions show that the water-plastic unit provides good performance across the spectrum of impacting vehicle momenta, and that it provides a response that takes advantage of almost all of the available stopping distance for impacts between 30 and 70 mph, employing vehicles weighing from 2,000 to 6,000 lb.

•THE DESIGNER of highway systems in today's era of high-speed family transportation is faced with the enigma of the roadside hazard: "Shall I move it or protect it, and if I protect it, how?" Often the use of hardware such as guardrail aggravates rather than moderates the hazard. This study treats one technique for dealing with immovable objects and guardrail terminals. Considerations essential to a cost-effective design are discussed, and the behavior of the water-plastic cushion is compared to performance standards and to the hypothetical alternative of the "constant-force" cushion. Application of the principles discussed should help to solve the problem of obstacle protection effectively and economically.

CRITERIA FOR CUSHION PERFORMANCE

The rational design of an impact cushion device must take into account a large number of factors, of which the following are important:

1. Occupant loads during impact must be tolerable. Average occupant deceleration levels should not exceed 12 g; deceleration peaks should have a duration above 12 g of less than 40 milliseconds (msec), with magnitudes as low as possible. Onset rates should be limited at 500 g/sec. Overall success may be measured by the Gadd index of severity, assuming typical seat-belt restraint.
2. Occupants of vehicles weighing from 1,600 to 4,500 lb should be adequately protected in head-on or glancing impacts up to 60 mph, with vehicles in glancing blows at angles less than 25 deg being usually fendered rather than arrested.
3. The device should be reusable, insofar as possible; one impact should not destroy its capability. Some protection should remain for subsequent impacts, even without maintenance. Ease and rapidity of maintenance are essential; cost judgments should include maintenance and road-system downtime costs, as well as cost of initial hardware and right-of-way space.

In every engineering design, it is not always possible to meet all design criteria within the limitations imposed by cost and space considerations. A design study on the

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water-plastic cushion used the preceding criteria in the development of cushion hardware (1). The following sections present the resulting design and its predicted performance.

DESCRIPTION OF CUSHION SYSTEM AND APPLICATIONS

The hydraulic-plastic protective barrier developed under this project utilized vertical cylindrical plastic cells as a primary building block (Fig. 1). These cells were closed at the bottom, equipped with orifices at the top as shown in Figure 2, and filled with water (2).

The functional characteristics of a single cell are controlled by selecting cell-wall material characteristics, size and number of orifices, water content, and cell geometry. Control of the characteristics of a cushion unit as a whole is accomplished by varying the number and distribution of various types of cells and cell spacing, and by including additional inertial or structural elements or both within the unit.

The prototype crash cushion consisted of clusters of water-filled plastic cells sandwiched between plywood-fiberglass plates. These were strung at 24-in. intervals along two heavy cables running parallel to traffic (Fig. 3). The main plates provided hinge points for overlapping deflector plates or "fish scales". The fish scales and main support cables provided a stiff but elastic redirection surface with low friction coefficient for glancing impacts, helping to avert pocketing. The cables also provide stability for absorbing head-on impacts.

The entire system was designed to provide capability for easy and rapid replacement of modules, ease of maintenance, and quick return to service after use. (Systems have been impacted repeatedly in engineering tests at conditions near design limits with only minor repairs between hits.) Usually only a simple reconfiguration and water-refilling procedure is required between crashes. Time required by a trained three-man crew to return test units to service after a 60-mph head-on impact has been less than 30 min.

For areas subject to freezing temperatures, the addition of calcium chloride to the water appears to solve the immediate freezing problem. The temperature-dependence of the plastic is, of course, another matter. The vinyl material used in the cells was compounded to maintain sufficient flexibility at -20 F, while maintaining sufficient rigidity at +110 F.

Most existing highway hazards associated with stationary structures could potentially be made safer by a properly designed water-plastic barrier. Figure 4 shows one hypothetical application. Other examples are given elsewhere (1).

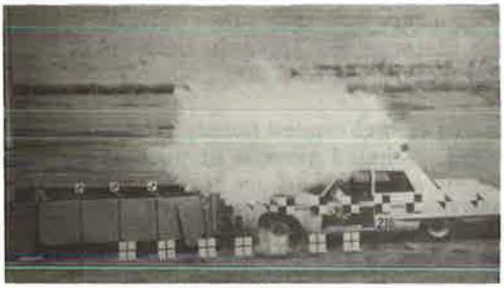


Figure 1. Crash test in progress.

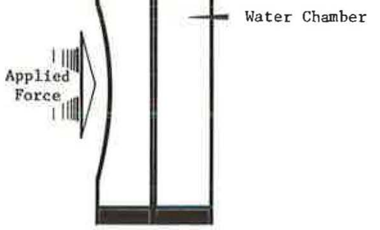
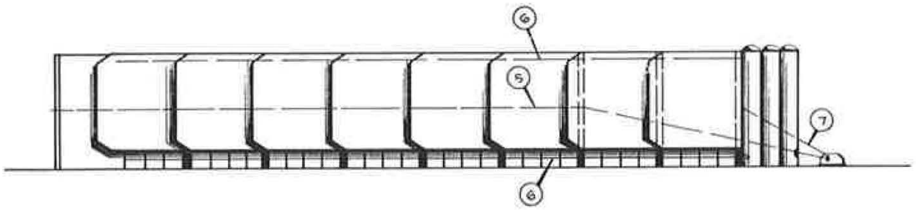


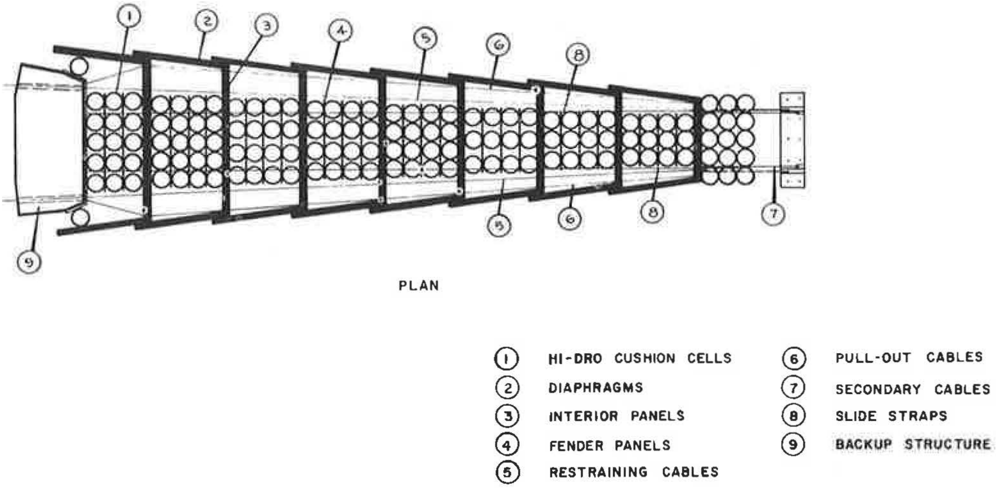
Figure 2. Cross section of typical polyvinyl chloride plastic cells. Typical dimensions of cells are 42 in. long by 6 in. outside diameter, with wall thickness varying.

COMPUTER MODEL AND VALIDATION

The mathematical model used for simulation of cushion behavior was a discrete-element representation, accounting for the



ELEVATION



PLAN

Figure 3. Cell sandwich unit of water-plastic cushion barrier.

essential characteristics of each component. The model took into account the strain-rate dependency of the plastic material, the nonlinear orifice resistance, the time-dependent mass, and the pressure-deflection dependency of the effective contact area between cells. The model parameters and functions were determined by dynamic tests in the laboratory, where actual loads and loading rates were simulated in a rapid-pressurization fixture. Occupant loads were predicted from a simple linear seat-belt model. The cushion model was constructed in such a way that either single-cell rows or effective-cell rows representing clusters of cells could be specified. It allowed inclusion of rigid beams of specified mass at the boundaries between cell cushions. The crushing behavior of the vehicle frontal structure was also simulated (3).

The accuracy of overall system behavior predicted by the computer model depended on the precision of the correspondence between model and experiment at the component level. Experimental verification of the various model subsystems was accomplished before the entire model was assembled. Full-scale crash tests conducted by various agencies have produced data showing good agreement with model predictions. Figure 5 shows the predicted vehicle deceleration pattern for a 4,720-lb_m, 60-mph impact compared with floor pan deceleration history recorded in a 4,690-lb_m, 61.8-mph impact by the California Division of Highways (unfiltered experimental data were hand-smoothed by the author). Figures 6, 7, and 8 show comparative predictions and test data for three different vehicle weights and speeds (test data were recorded by the Texas Transportation Institute, 4). The slight phase mismatch witnessed in some of the vehicle deceleration pulseforms may be attributed to the oversimplified representation

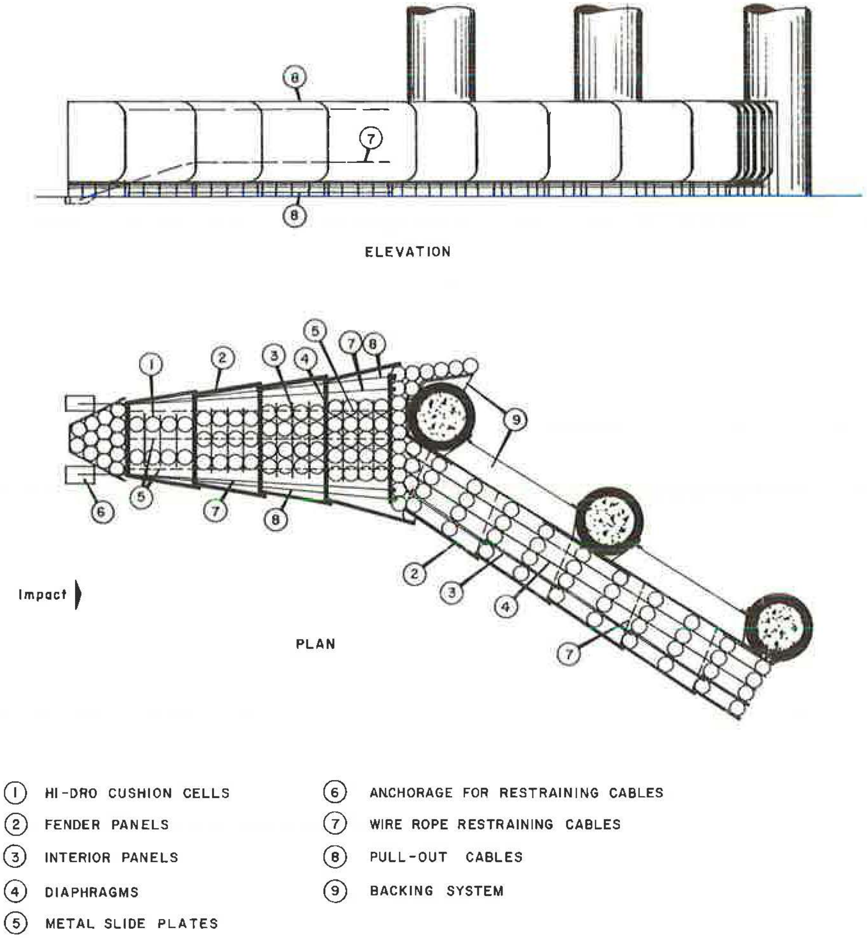


Figure 4. Specialized application of cell sandwich unit.

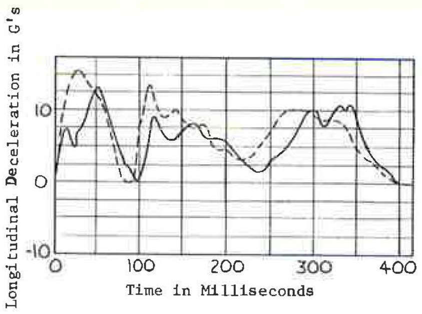


Figure 5. Full-scale crash test vs. simulation (California Division of Highways Test 216; head-on crash with Dodge). Solid line shows crash test with 4,690-lb vehicle at 61.8 mph; broken line shows simulated test with 4,720-lb vehicle at 60 mph.

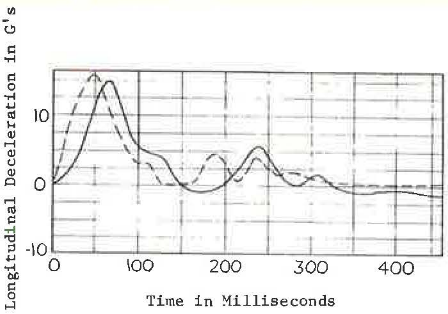


Figure 6. Full-scale crash test vs. simulation (Texas Transportation Institute Test 505R-A; head-on crash with Volkswagen). Solid line shows crash test with 1,820-lb vehicle at 40 mph; broken line shows simulated test with 1,500-lb vehicle at 40 mph.

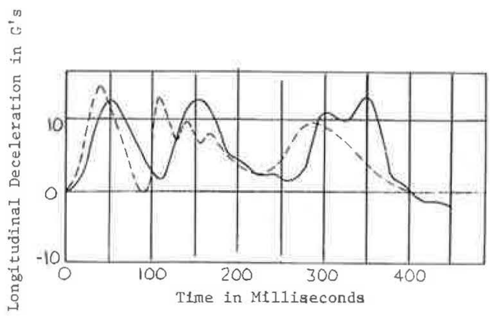


Figure 7. Full-scale crash test vs. simulation (Texas Transportation Institute Test 505R-B; head-on crash with Pontiac). Solid line shows crash test with 4,650-lb vehicle at 63 mph; broken line shows simulated test with 4,720-lb vehicle at 60 mph.

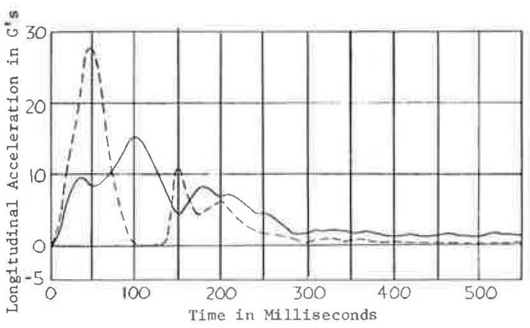


Figure 8. Full-scale crash test vs. simulation (Texas Transportation Institute Test 505R-D; head-on crash with Renault). Solid line shows crash test with 1,630-lb vehicle at 60 mph; broken line shows simulated test with 1,500-lb vehicle at 60 mph.

of the vehicle crush as a linear spring. Also, the very soft crush characteristic of the Renault vehicle was not simulated in the model for Figure 8, which may account for the mismatch in the early portion of the impact.

Table 1 gives a summary of data for the four tests shown in Figures 5, 6, 7, and 8. Gadd indexes for the tests were calculated from occupant model behavior (7). These comparisons with full-scale tests demonstrate acceptable validity for head-on impacts.

PERFORMANCE OF THE RESULTING DESIGN

The broad span of performance criteria discussed earlier pose a problem: Satisfactory system behavior under one or more of the conditions is changed. It is difficult to determine what the most cost-effective design point should be without a more complete definition of the average accidental collision. Conversely, evaluation test requirements plainly suggest that system performance be satisfactory at the most demanding conditions. Hence, the design point for the cushion system was chosen to be equivalent to the most critical energy-absorption case from the constraints given previously. It is the case of a 4,720-lb, 60-mph head-on impact. The total energy to be absorbed in this case is about 50,000 ft-lb$_f$.

It should be pointed out that, while this set of conditions probably is more severe than the average highway collision from the occupant's point of view, it does constitute

TABLE 1

COMPARISON OF PREDICTED AND ACTUAL BEHAVIOR

Predicted Results				Actual Results		
Nominal Vehicle Weight (lb_f)	Nominal Impact Speed (mph)	Peak Deceleration (g)	Gadd Index ($g^{5/2}$-sec)[a]	Agency and Number (weight, speed)	Peak Deceleration (g)	Gadd Index ($g^{5/2}$-sec)[a]
1,500	40	18	92	TTI505R-A (1,820, 40)	17	59.2
4,720	60	15	78	TTI505R-B (4,650, 63)	15	118
1,500	60	27	188	TTI505R-D[b] (1,630, 60)	18	92.3
4,720	60	15	78	CDH216 (4,690, 62)	14	75.4

[a] Occupant behavior simulated by one-dimensional dynamic model (Fig. 9) using either simulated or measured vehicle pulse forms.

[b] Soft frontal structure on vehicle.

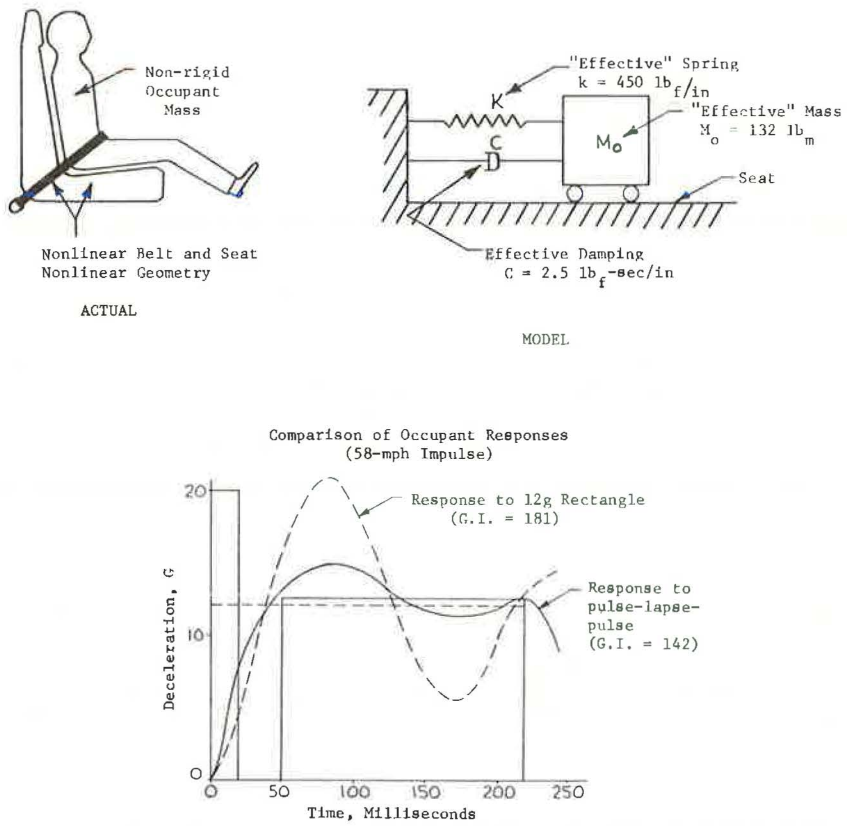


Figure 9. Idealized occupant restraint system.

a severe test of cushion system integrity. However, it is highly desirable that acceptance performance tests include an occupant-oriented test—one with a small car at high speed.

From a theoretical basis, the most efficient use of stopping distance is made by an energy absorber that gives a rectangular force-time response. Although this constant-force response optimizes energy absorption per unit length of cushion for one given mass and velocity, its response for other masses and velocities falls short of the optimum. Furthermore, the response of the seat-belted occupant to a square-wave vehicle response may be less than optimum (5, 6). Where the goal in the present work is to minimize occupant loads, some success may be realized by providing cushion characteristics that relieve vehicle loads after an initial impulse, taking advantage of the additional protection provided by the seat-belt restraints. Figure 9 shows a comparison of results of rectangular and two-pulse 60-mph vehicle deceleration waveforms on the simulated occupant responses. Occupant response is measurably improved by the two-pulse case, at the cost of a slight increase in stopping distance.

The design-point calculated performance of the water-plastic cushion is shown in Figure 10 in terms of the vehicle and occupant accelerations versus time. It may be seen that the occupant loads are within tolerable limits: 17 g peak, less than 8 g average. The Gadd severity index for this impact was 102. The stopping distance was approximately 15 ft. Figure 10 also shows data on pressures within the cushion and loads on the support structure.

Perhaps the most difficult demand on a highway energy absorber is the requirement that occupant response be tolerable regardless of vehicle mass. Hence, it is desirable

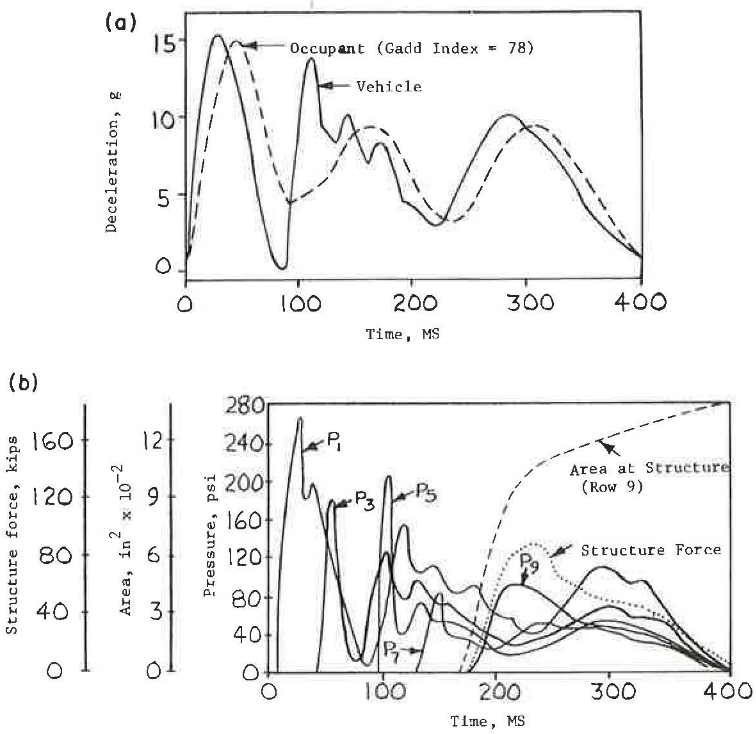


Figure 10. Predicted response for design point: (a) vehicle and occupant deceleration; and (b) pressures, area, and force.

to have a cushion that can somehow regulate its response to match the mass of the stopping vehicle. One way to do this is to provide low-energy and high-energy absorbers in tandem stages. This method may increase costs, however, by the inefficient use of stopping distance.

The simulated performance of the water-plastic cushion for the indicated spectrum of impact momentum is shown in Figures 11, 12, and 13 and given in Table 2. Occupant loads for 60-mph impacts are shown in Figure 11. Predicted peak occupant decelerations did not exceed 32 g for any case, and durations of peaks above 12 g were characteristically about 70 msec in the severe (light vehicle) cases. It may be noted that this violates the desired occupant protection criterion in some cases; however, occupant onset rates were less than 500 g/sec in all cases. The Gadd severity index ranged between 102 and 432 for the 60-mph simulated impacts compared to 113.5 for a 12-g rectangular pulse.

The ideal cushion is the one that gives a stopping force that is independent of mass. One comparison based on peak stopping forces is shown in Figure 12, where the peak force is shown as a function of the mass and velocity of the vehicle. Comparisons are drawn with simple linear-energy systems and the hypothetical constant-force system. The acceleration responses of the constant-force and linear cushions to vehicle mass (M) are approximately proportional to $1/M$ and $1/\sqrt{M}$ respectively. Thus for the constant-force cushion, a Volkswagen or Renault sedan would experience roughly double the deceleration of a Ford or Pontiac sedan. For the linear-spring cushion, it would experience about 1.4 times the heavier vehicle deceleration. As may be seen from the plotted points, the performance of the water-plastic cushion tends to follow that of an ideal linear spring; distributed mass and dissipative elements within the cushion provide a potential for mass-matching.

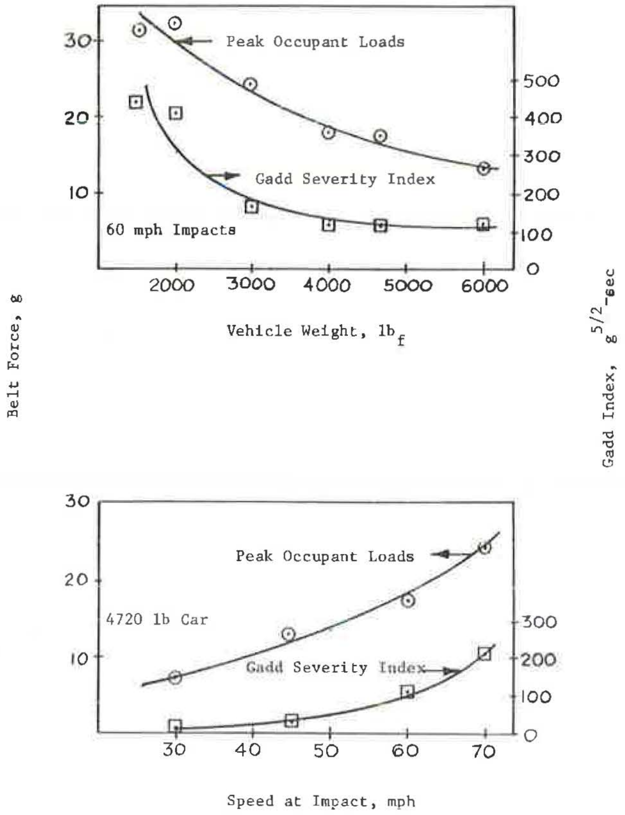


Figure 11. Occupant load and injury index predictions.

The lower part of Figure 12 shows the velocity sensitivity of the water-plastic cushion by comparison. The roughly linear velocity sensitivity causes the cushion to give a fairly uniform stopping distance.

The utilization of stopping distance is shown in Figure 13. Of course, the ideal case is that of uniform utilization, giving equally good response at all speeds and weights

TABLE 2

COMPARISON OF SIMULATED BEHAVIOR

Vehicle Mass (lb_m)	Initial Speed (mph)	Total Stopping Distance (in.)	Vehicle Crush (in.)	Vehicle Load				Occupant Load		Structure Load (kip)
				g		kip		Peak g	Gadd Index	
				Peak	Average	Peak	Average			
4,720	60	181	14	15.2	8.0	71.6	37.7	15	78.3	90
4,720	70	182	17	18.7	10.8	88	51	19	156	130
4,720	45	170	10	10.5	4.8	49.5	22.4	10	33	45
4,720	30	137	6.3	6.9	66	32.5	31	5	6	18
2,000	30	110	9.4	10	8.2	20	16.4	10	20	0
2,000	45	141	15.4	17	5.8	34	11.5	18	89	12
2,000	60	166	22	24.1	8.7	48.2	17.4	28	192	22
3,000	60	175	18	19.7	8.5	59	25.4	20	103	46
6,000	60	184	12	13	7.9	78	48	11	101	120
4,000	60	179	15	17	8.1	68	32.4	16	87	80
1,500	40	121	15	17	5.3	25.5	8.0	18	92	0
1,500	60	155	20	27.5	9.3	41.2	13.9	31	100	15

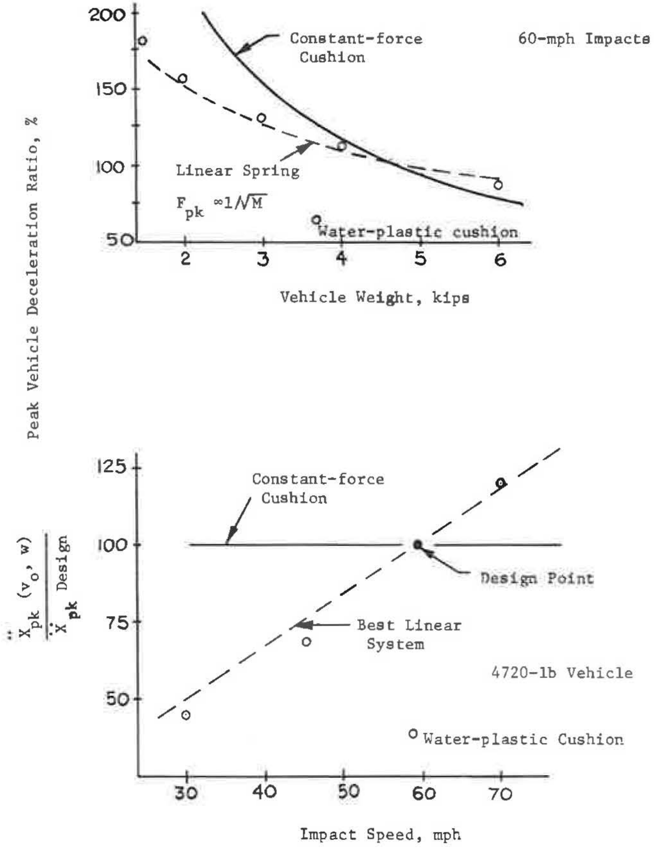


Figure 12. Peak deceleration ratio vs. vehicle weight and speed.

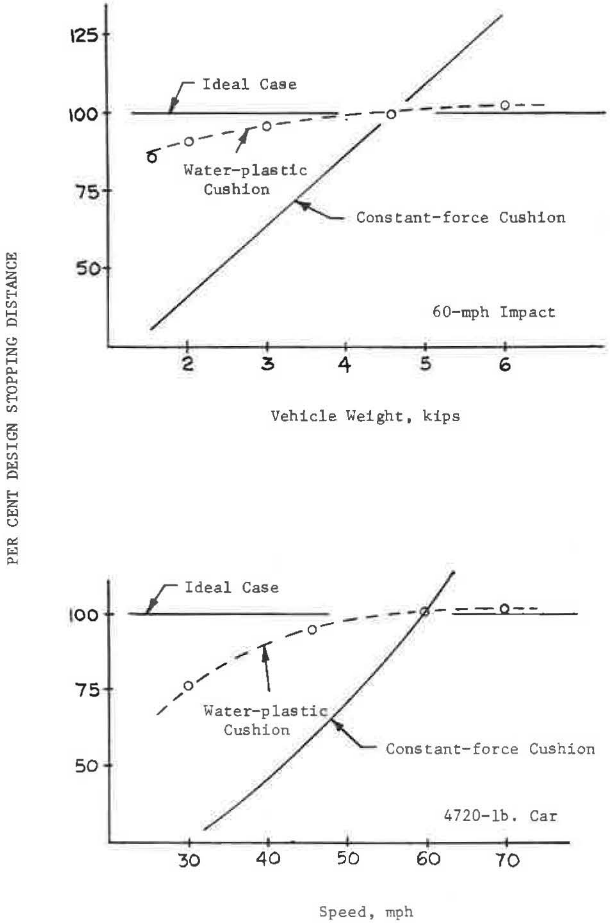


Figure 13. Stopping distance vs. weight and speed.

within the expected range. The water-plastic cushion gives an excellent performance, within ±8 percent of uniform space utilization over the entire mass range at 60 mph and only 25 percent reduction in effectiveness at half the design speed. The water-plastic cushion may be expected to provide good utilization of available stopping distance, producing resisting forces that compensate for vehicle mass and velocity. This attribute is particularly important for low-speed crashes, as the loads borne by the vehicle and occupants are considerably reduced from the constant-force case.

CONCLUSIONS

The mathematical model used for this study has been satisfactorily verified for head-on impacts by comparison with detailed full-scale crash results performed by several agencies. Behavior of the water-plastic cushion at the design condition provides an occupant response that is well within survivable limits.

An investigation of behavior for vehicle weights and velocities other than the design case shows that the water-plastic cushion provides survivable occupant responses over much of the range. This device is capable of a high degree of automatic self-adjustment, allowing it to satisfactorily match the resisting forces to the weight and speed of the impacting vehicle. Predicted stopping distances varied less than 10 percent for vehicle weights ranging from 2,000 to 6,000 lb and less than 25 percent for speeds ranging from 30 to 70 mph.

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