TEST AND EVALUATION OF A TIRE-SAND INERTIA BARRIER

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Many rigid obstacles located on highways cannot be removed or made to break away and consequently are hazardous to motorists. Vehicle impact attenuators have been developed to protect the public from these obstacles. Most of these attenuators are expensive, and some obstacles remain unprotected since available funds are directed to protecting more cost-effective locations. An inexpensive vehicle impact attenuator composed of scrap tires and sand has been developed and tested at the Texas Transportation Institute. This inertia barrier uses a base that is crushable, plywood disks, scrap tires, sand, and a weatherproof covering. The principle of the conservation of momentum is used in the design. In addition, curves have been developed to assist the designer.

•THERE are many rigid obstacles on our nation's highways that cannot be removed or made to break away and that consequently are hazardous to the motoring public. Vehicle impact attenuators have been developed to protect the motoring public from impacting these obstacles directly. In general, most of these attenuators are expensive, and some obstacles remain unprotected since available funds are directed to protecting more cost-effective locations. This study was undertaken to develop an inexpensive and effective barrier that could be used to protect motorists from many hazards located near our primary and secondary roads.

Two previous studies had been made (1, 2) to show that a vehicle impact attenuator composed of scrap tires filled with sand was effective and feasible. The conclusions expressed in both reports were that the tire-sand inertia barrier was both effective and economical for selective locations and that the bases should be constructed so that they will not build up under the impacting vehicle and cause ramping. Three distinct possibilities of base designs meeting the criteria are possible:

1. The base could collapse on impact and slide under the impacting vehicle without causing ramping,
2. The base and sand container could be flexible laterally so that it would fragment on impact, and
3. The base could be stiff and light and an integral part of the module and thus could be knocked out of the way during impact.

Bases made of scrap tires with the annular space filled with empty metal beverage cans, those made of welded wire mesh, and those made of portions of used, 55-gal (208-liter) paint drums were investigated.

DEVELOPMENT OF DESIGN

The design of an inertia barrier is based on the conservation of momentum and has been documented by Hirsch (1) and Hirsch, Marquis, and Buth (2). D. L. Hawkins, when he was with the Texas Highway Department, first conceived of the idea of using scrap or salvage tires filled with sand as a vehicle impact attenuator in December 1965. At that time, he proposed using modules around high-level lighting standards and proposed this in a sketch.

The concept of the conservation of momentum is shown in Figure 1. The momenta before impact are equal to the momenta after impact. For rigid body plastic impact (i.e., the coefficient of restitution = 0),

$$V_o M = V_1(M + M_1) \tag{1}$$

where

V_o = the velocity of the vehicle before impact;
V_1 = the velocity of the vehicle and first mass after impact;
M = the mass of the impacting vehicle, W/g;
W = the weight of the vehicle;
M_1 = the mass of the impacted module, W_1/g;
W_1 = the weight of the impacted module; and
g = the acceleration due to gravity.

Multiplying both sides of the equation by g and solving for V_1 give

$$V_1 = V_o\left(\frac{W}{W + W_1}\right) \tag{2}$$

assuming that the first mass impacted, W_1, remains independent of the vehicle.

The vehicle speed after second mass impact is

$$V_2 = V_1\left(\frac{W}{W + W_2}\right) \tag{3}$$

The vehicle speed after the i th mass impact is

$$V_i = V_{i-1}\left(\frac{W}{W + W_i}\right) \tag{4}$$

If s is defined as the distance between the expendable mass centers, the average deceleration among the masses is

$$G = \frac{v_{i-1}^2 - v_i^2}{2gs} \tag{5}$$

For design purposes, the above equation may be solved for v_i as the minimum velocity to maintain an average specified deceleration G for spacing s and gives

$$v_i = \sqrt{v_{i-1}^2 - 2Ggs} \tag{6}$$

The weight of the module can be obtained by solving for W_i by

Figure 1. Principle of transferring vehicle momentum to expendable masses, assuming rigid body plastic impact.

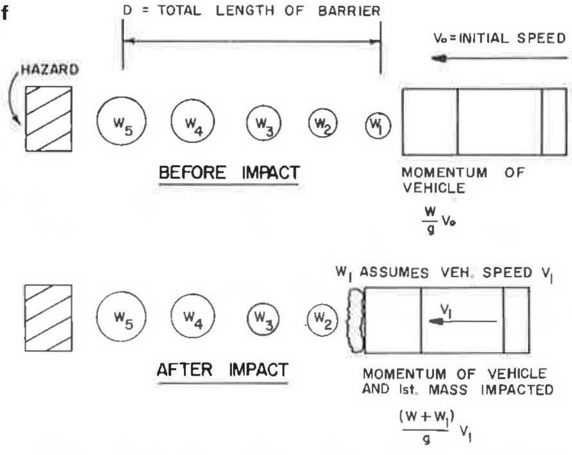


Figure 2. Design modules for tire-sand inertia barrier.

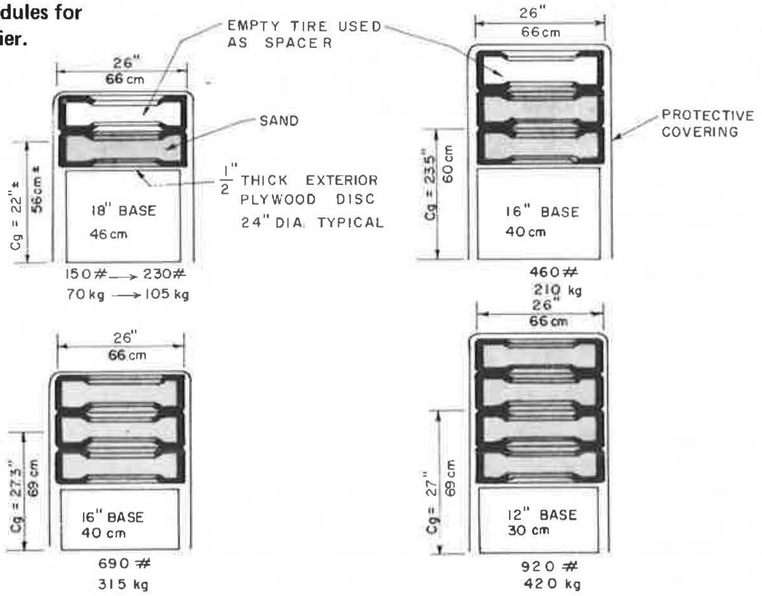
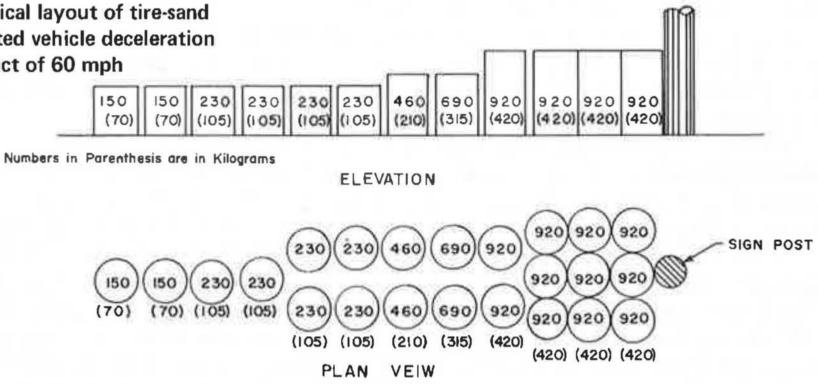


Figure 3. Design of a typical layout of tire-sand inertia barrier and estimated vehicle deceleration data based on initial impact of 60 mph (97 km/h).



2000 # (900 kg) Vehicle	G_{avg}	6.5	5.6	7.0	5.7	7.9	5.3	5.4	3.2	0.6			Avg = 5.6 g
	V_L mph	55.8	51.9	46.6	41.8	34.0	27.6	18.9	11.1	5.8			
	km/h	89.8	83.5	75.0	67.3	54.7	44.4	30.4	17.9	9.3			
4500 # (2040 kg) Vehicle	G_{avg}	3.2	2.7	4.0	3.8	6.1	5.1	7.3	6.6	4.7	2.9	1.1	Avg = 4.0 g
	V_L mph	58.0	56.2	53.5	50.8	46.1	41.8	34.7	26.6	18.9	11.7	7.3	
	km/h	93.3	90.4	86.1	81.7	74.2	67.3	55.8	42.8	30.4	18.8	11.7	

$$W_i = \frac{W(V_{i-1} - V_i)}{V_i} \qquad (7)$$

It is apparent that theoretically the vehicle cannot be stopped completely by this principle. Practically, however, it is usually adequate to design the inertia barrier to reduce the vehicle speed to about 10 mph (16 km/h).

The remaining energy is dissipated by the ploughing action (1, 2) from sand and additional modules placed in the vehicle path.

Statistical Data

Since scrap automobile tires vary in size and weight, statistical data were needed for design purposes. Hirsch (1) collected one hundred twenty-four 14 and 15-in. (36 and 38-cm) used automobile tires from a local disposal area to determine their average weight, diameter, and weight and height filled with sand. The method of filling each tire was by hand so that the entire space was used. The average weight of the tires was 18.5 lb (8.4 kg), and the standard deviation was 3.8 lb (1.7 kg). The outside diameters of the tire ranged from 25.5 to 27.5 in. (65 to 70 cm) and averaged 26.25 in. (67 cm), which was adequate for design purposes. After these data were determined, the tires were filled with sand and were weighed. The procedure was to fill a tire, weigh it, and measure the thickness. A second tire was placed on the first, filled with sand, and the combination weighed and measured. The process was repeated until the stack was four tires high. The process was continued until 108 tires were processed. The average total weight of the tires filled with sand was 228 lb (103 kg); 230 lb (104 kg) were used for design, and the standard deviation was 23.54 lb (10.7 kg). The average height for tires filled with sand was 7.5 in. (19 cm). The average height for empty tires was 5.5 in. (14 cm).

Standard Modules

These statistical data led to the development of standard modules as shown in Figure 2. The lightest module [150 to 230 lb (68 to 104 kg)] is used on the nose of the barrier. This is the only module in which the average weight will vary. The variation may be accomplished easily by using a container of known volume and weight to measure the sand. The other three modules are progressively heavier up to a limit of four tires filled with sand, which have an average weight of 920 lb (417 kg). These modules may be used singly in each row or in multiples of two or three per row.

A typical barrier design and estimated vehicle deceleration data based on initial impact of 60 mph (97 km/h) are shown in Figure 3. The design presented conforms to the latest FHWA criteria for vehicle impact attenuators (5). The final row of modules is used to stop the vehicle by ploughing action.

Two successful supports were tested. The first was a wire cage that collapsed when impacted. The wire cage was constructed of 14 gauge galvanized welded wire fabric with 1 by 2-in. (2.5 by 5-cm) openings. Details (plan view) of construction are shown in Figure 4. The details of the second successful support are shown in Figure 5. This support is made of used, 55-gal (208-liter) steel drums that have the stiffening tops and bottoms removed and that then are cut vertically at 16 equidistant points. These cuts made the support weak laterally but still retained sufficient strength vertically to support the heaviest module. One 18-in.-high (46-cm) support was tested in a universal static testing machine. A compressive load of 2,300 lb (1043 kg) was slowly applied, held for several minutes, and then released. The support was undamaged, and at no time did it exhibit any tendency toward instability. From this test, it was concluded that there was no strength problem. This was proved in erecting the test installation.

In addition to equations 4, 5, 6, and 7, graphs have been developed to aid in the

Figure 4. Wire cage support details.

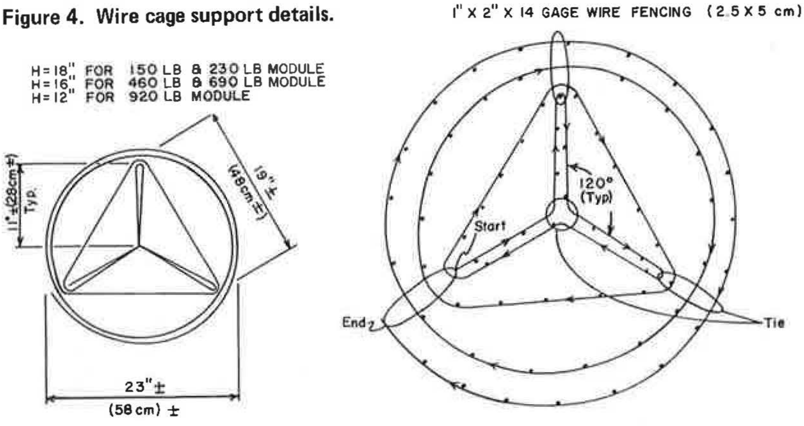


Figure 5. Steel drum support details.

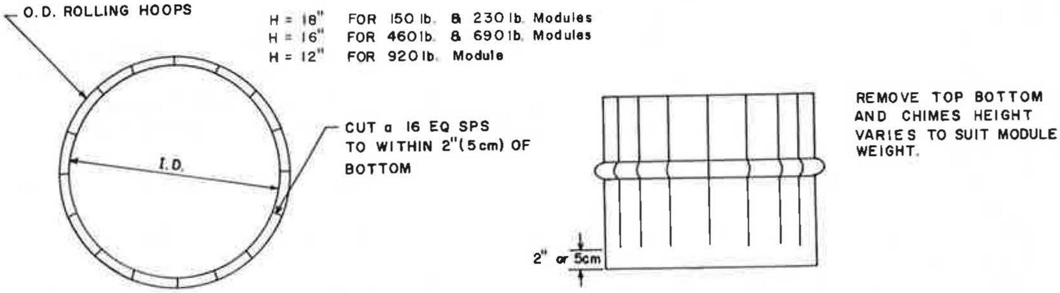
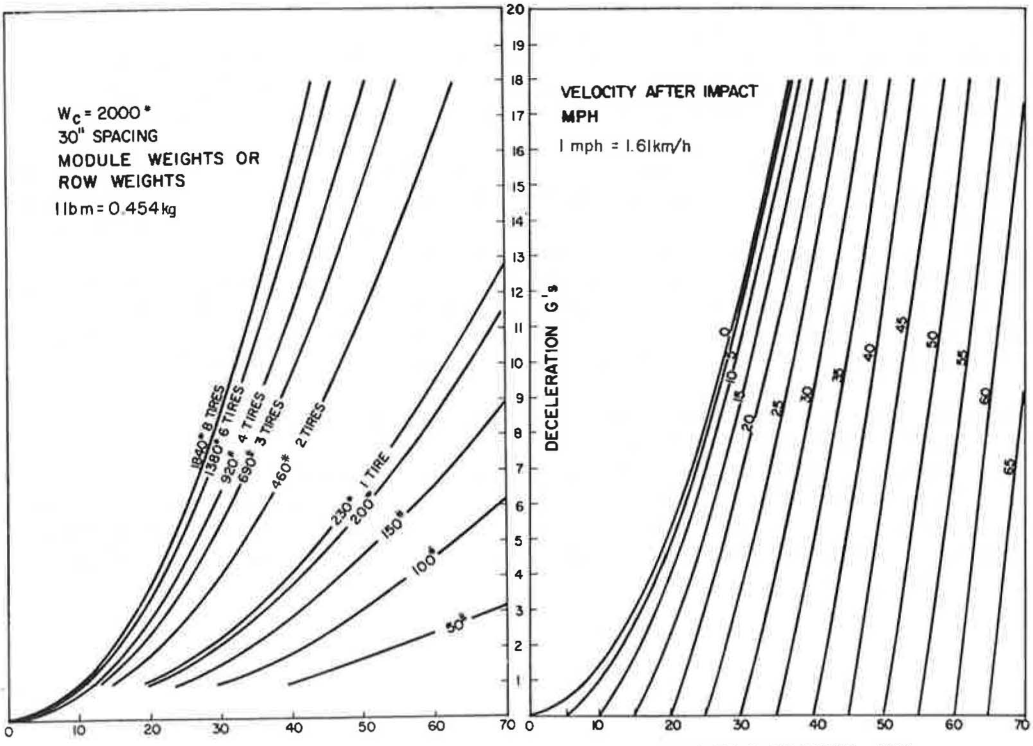


Figure 6. Sand-tire inertia barrier design curves for 2,000-lb (907-kg) vehicle.



design of inertia barriers. These graphs based on the number of tires for a 30-in. (76-cm) spacing of modules are shown in Figures 6 and 7.

VEHICLE CRASH TESTS

Four additional vehicle crash tests were conducted for the Texas State Department of Highways and Public Transportation. Earlier tests on the tire-sand inertia barrier were conducted for the National Cooperative Highway Research Program (2).

In test 2146-I-3, the first one in the department program, the annular space of tires was filled with used beverage cans, and the tires were banded together to form a base. The tires containing sand were then lashed to the bases. The vehicle ramped during the test, and the idea of the tire base was abandoned.

In the next test, 2146-I-4, the bases used were the wire fabric cages, which were designed to collapse on impact and not produce an uplift force on the vehicle as they rolled under the vehicle (Figure 4). This test was conducted without the benefit of a backup structure.

The vehicle used for this test was a 1967 Dodge Monaco with a gross weight of 4,290 lb (1946 kg). Figure 8 shows the vehicle and barrier before the test.

The vehicle impacted the center of the barrier. The speed was 64 mph (103 km/h). The vehicle behaved as anticipated during impact. However, the majority of the mass was propelled to a place well ahead of the vehicle, and the vehicle stopped approximately 18 ft (5.5 m) after it passed the original end of the barrier. Figure 9 shows the vehicle and barrier after the test.

Two tires were hurled more than 100 ft (30 m) during impact. This occurred in previous tests (1, 2) with the tire-sand barrier.

The protective coverings were polyethelene sleeves of 4-mil (0.1-mm) thickness, such as those used by service stations.

In the third test, 2146-I-5, the barrier was constructed according to the design in Figure 3. The bases were fabricated from used paint drums modified in accordance with Figure 5, except that the top and bottom of the drum remained as an integral part of each base. The covering for the modules was made of 0.025-in. (0.6-mm) aluminum (the lightest readily available). The vehicle impacted the nose of the barrier at an angle of 15 deg with the barrier's longitudinal axis.

The vehicle used for the test was a 1961 Chevrolet weighing 4,090 lb (1855 kg) including the weight of the anthropometric dummy. The hood conformed to the current trend in American-made vehicles in that it extended to the windshield without an intermediate cowling.

The vehicle impacted the barrier in the center at 61.9 mph (99.6 km/h) and performed as mathematically predicted until the vehicle penetrated the barrier. The chimes and bottoms of the drums made the bases very stiff; they tended to build up under the vehicle, and the vehicle ramped. The hood came open but remained on the vehicle.

For the final test of the series, 2146-I-6, the typical barrier (Figure 3) was tested. The supports were made from steel drums designed according to Figure 5; that is, the tops or bottoms and chimes were removed. The protective covering was made from Armstrong Decolon vinyl rugs (linoleum) at a cost of approximately \$0.11/ft^2 (\$1.18/m^2).

The vehicle was a 1968 Chevrolet weighing 4,000 lb (1814 kg) including the dummy. Figure 10 shows the vehicle before and after the test.

The barrier was located in front of a simulated luminaire standard as shown in the top half of Figure 11. The vehicle impacted the center of the barrier at 43.1 mph (69.3 km/h). The vehicle performed as predicted except that there was a slight tendency to ramp that was evident toward the end of impact. Again, the hood came ajar but remained on the vehicle.

Figure 7. Sand-tire inertia barrier design curves for 4,500-lb (2041-kg) vehicle.

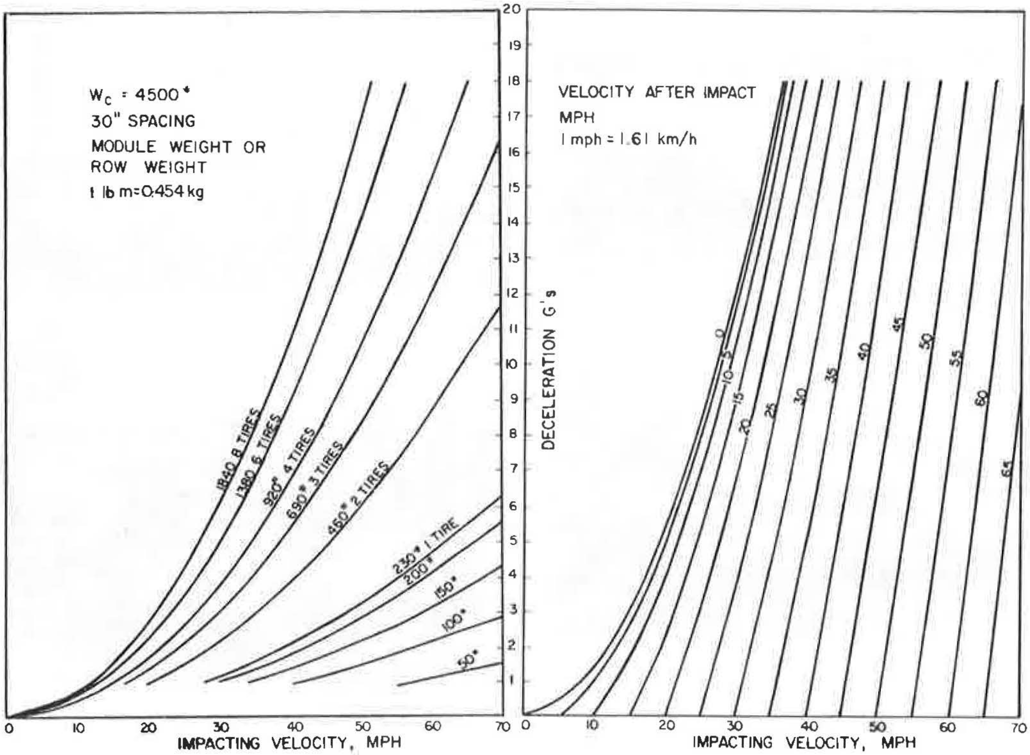


Figure 8. Test I-4 vehicle and barrier before impact.

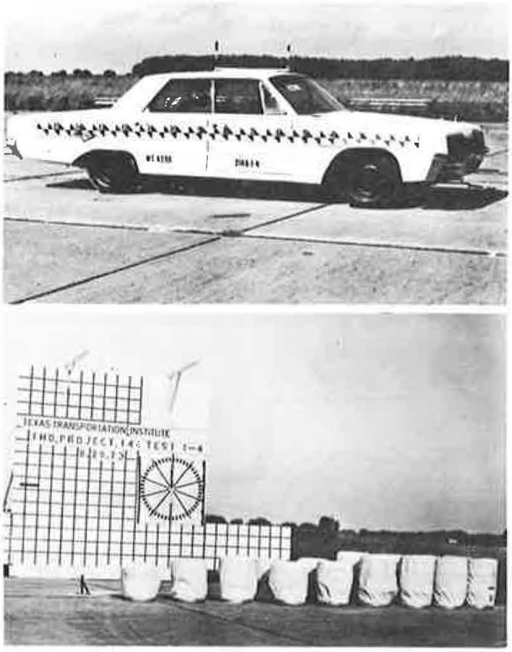


Figure 9. Test I-4 vehicle and barrier after impact.

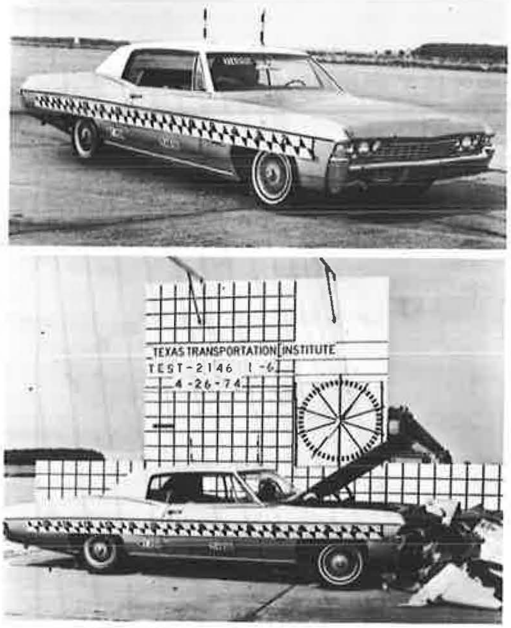


Figure 10. Test I-6 vehicle before and after impact.

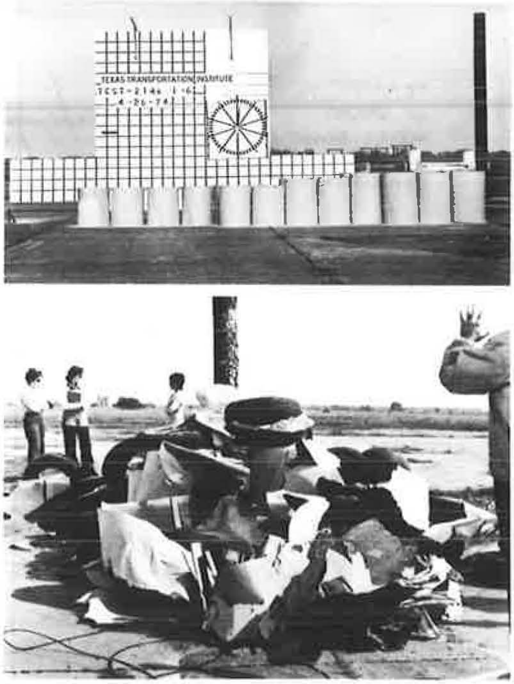


Figure 11. Test I-6 barrier before and after impact.

Table 1. Test data.

Item	Test I-3	Test I-4	Test I-5	Test I-6
Vehicle				
Make	Ford	Dodge	Chevrolet	Chevrolet
Year	1964	1967	1961	1968
Weight, lb	4,500	4,290	4,090	4,000
Impact angle, deg	0	0	15	0
Film data				
Initial speed, mph	62.2	64.0	61.9	43.1
Final speed, mph	0	0	28.7	0
Maximum forward motion, ft	Vehicle ramped	43.9		
Time, sec		2.25		
Accelerometer data				
Peak				
Longitudinal (*g*)	11.6		6.3	4.9
Transverse (*g*)	2.2		3.9	1.0
Average deceleration				
Longitudinal (*g*)	5.0		3.4	2.6
Over-time, sec	0.2		0.4	0.5
Maximum seatbelt force, lbf	1,395		460	290

Note: 1 lb = 0.45 kg. 1 mph = 1.6 km/h. 1 ft = 0.3 m. 1 lbf = 4.4 N.

DISCUSSION OF TESTS

The four full-scale tests were conducted on tire-sand inertia barriers with bases of four designs. Pertinent data from high-speed photography and accelerometers are given in Table 1. The stopping characteristics of the barriers were as predicted by the equations until the vehicle vaulted as in test I-3 or penetrated the barrier as in tests I-4 and I-5.

The base for the modules used in test I-3 was tires banded together as described earlier. The vehicle in test I-3 had traveled approximately 5 ft (1.5 m) when the first tires were dragged underneath the vehicle. The base of each module was crushed, and friction resistance with the ground caused the tires to move at a slower speed than the vehicle. This pulled the tires underneath the vehicle. The tires holding the sand were tied to the bases and were pulled under the vehicle. The result was that at about 0.172 sec or after the vehicle had traveled 10 to 12 ft (3 to 3.7 m) it began to climp up the modules. This chain of events caused the vehicle to end up with the front of the vehicle undercarriage resting on top of the concrete backup wall. The rear end of the vehicle was dragging the ground when it came to rest. None of the modules or individual tires had been sent flying as was the case in all previous tests (1, 2). It appears that tying the base tires to the container tires was instrumental in lessening the vaulting effects and in keeping the rear of the vehicle on the ground. The concept did not go far enough to prevent vaulting. Modules banded together so that sand that could not escape would probably move in front of the impacting vehicle. If so, the vaulting would be eliminated, but the total mass would move instantaneously and increase the severity of the impact. This is what would occur according to procedures recommended by Gadd (7). This solution would not necessarily be the best trade-off.

The wire cage used to support the sand mass in test 2146-I-4 collapsed on impact and rolled underneath the vehicle as intended. There was no tendency for the vehicle to ramp during this test. The vehicle behaved essentially according to the mathematical predictions until after the last module had been impacted. Since there was no backup wall to stop the tires or the sand mass, they were moved ahead for a considerable distance. The vehicle ploughing action into the debris (which is necessary to completely stop the vehicle) eventually brought the vehicle to a complete stop 43.9 ft (13.4 m) from the initial impact point. The majority of the tire and sand debris was located in the space 15 to 20 ft (4.5 to 6.0 m) in front of the vehicle. This required a total distance of 60 to 65 ft (18 to 20 m) to contain a vehicle with no hazard immediately behind the barrier. This distance can be greatly reduced by adding a few much heavier modules at the rear of the barrier. The required distance for the ploughing action and the space to collect debris would thereby be reduced since the heavier modules would help stop the bulk of the sand and tires from going beyond the back of the barrier. Regardless of the design, some additional space must be supplied behind the barrier for penetration and collection of debris when no rigid obstacle or backup wall is present.

The hood was forced open in test I-3. The hinges of the hood on the vehicle used in test I-4 were broken, which caused the hood to fall off (0.350 and 0.749 sec). Similar incidents have occurred in three previous tests on other projects, as well as in tests reported by California on a similar type of barrier (9).

Recent model American-made vehicles have been designed without the intermediate cowl between the hood and windshield. Researchers were concerned about the possibility of these hoods breaking loose from their hinges and penetrating the windshield. The two final tests were conducted using vehicles without the intermediate cowling. In both tests, the hoods flew open on impact but the hinges held, and the hoods remained with the vehicles. The hinges comply with the latest federal motor vehicle safety standards and are adequate to withstand the impact intensities without allowing the hinges to fracture.

The base used in test I-5 was fabricated from used, 55-gal (208-liter) steel paint drums and was similar to the base shown in Figure 5. The major difference from Figure 5 was that the end chimes and top or bottom of the drum were used as support for possible soft soil. These bases proved to be too stiff and caused the vehicle to ramp as it crossed through the barrier on a 15-deg impact angle.

The cover used in this test was 0.025-in. (0.6-mm) aluminum, the thinnest available. It also was too stiff to be of practical benefit.

The base used in test I-6 was fabricated as shown in Figure 5 from used, 55-gal (208-liter) paint drums. The chimes and tops and bottoms were removed, and the base was not so stiff laterally as were the bases used in test I-5; these performed satisfactorily.

The protective cover used in this test is inexpensive and satisfactory. The linoleum should last several months in the weather and appears to contain the tires so that the missile problem is reduced. Special care should be exercised to attach the top of the covering so that rain or atmospheric moisture will not penetrate the sand and change the impact characteristics of the modules.

The top speed of the vehicle was only 43.1 mph (69 km/h), and the deceleration values were low. Because the design was for a relatively flat deceleration curve, the longitudinal deceleration and the seatbelt pull were both much smoother for test I-6 and test I-5 than for previous tests in which a much harder nose was used.

CONCLUSIONS

Scrap tires filled with sand will make an effective inertia type of vehicle impact attenuator for selected locations. The sand-filled tires used in each module need to be supported on easily crushable bases such as treated cardboard cartons (2), wire cages developed on this project (Figure 5), or bases fabricated from used, 55-gal (208-liter) paint drums (Figure 6).

The center of gravity (c.g.) of vehicles on the road generally varies from a low of 18 in. (46 cm) to a high of 23 in. (58 cm) (8). The average height of the c.g. is about 20 in. (50 cm). The crushable bases should be sized to raise the c.g. of the module to approximately 20 in. (50 cm) or more except for the first module impacted.

The following conclusions can be made:

1. The theory of conservation of momentum will provide a satisfactory design method for the tire-sand inertia barrier;
2. The state of the art of inertia barriers is sufficiently advanced so that the tire-sand inertia barrier can be considered for selected use; and
3. Tire-sand inertia barriers should be installed only in locations where the effects of flying or rolling tires or flying or loose sand and other debris associated with the barrier would not become a secondary hazard to other traffic as is the case on elevated sections.

In all high-speed impacts to date, a considerable amount of sand has accumulated on the engine, which could make it temporarily inoperative; however, this same sand could minimize the probability of fire. Additional research is recommended to determine the effectiveness of the tire-sand barrier in protecting guardrail ends.

The research in this paper indicates that the tire-sand inertia barrier would be an economical and effective crash cushion for use in front of rigid obstacles along the roadside where the scattered sand and tires are not likely to fall on the paved roadway. The estimated total installed cost of the tire-sand inertia barrier is approximately $800 when the barrier is installed by state employees.

ACKNOWLEDGMENT

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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