An Energy-Absorbing Barrier for Highways

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In recent years the unprecedented increase in traffic volume and speed compounded the problem of death on the highways. One of the most severe contributors is the head-on collision caused by an out-of-control automobile crossing the centerline of a highway.

An energy-absorbing barrier system to eliminate this hazard has been developed. The barrier consists of a series of corrugated concrete slabs extending above a road surface about 2 ft and arranged in a row in the center of the median strip of a highway.

An automobile or truck, out-of-control and commencing to cross into the lane of the oncoming traffic, will break off a number of these concrete barriers and stop, instead of causing a head-on collision.

Evaluation of this concept of automotive protection was made by both laboratory techniques (static) and field experiments (dynamic). The laboratory tests provided the basis for the appropriate selection of configuration and materials which provided the highest barrier performance. The field tests permitted evaluation of the dynamic performance of a row of these barriers.

In these experiments, a car was driven through a series of the barriers at 17 and 31 mph. Deceleration rates were determined by micromotion analyses of high-speed motion pictures used for instrumentation. A 16-mm film has been produced covering these experiments.

The feasibility of the concept of providing a collapsible barrier to govern the deceleration of out-of-control vehicles to prevent injury to the vehicle occupants has been demonstrated by these experiments.

● THE EVER EXPANDING volume and the continuing trend toward increase in speed of automobiles and trucks on the highways threaten an increasing death rate from highway collisions. These collisions are killing more people on highways in peace times than were killed by enemies in times of war. Deaths by automobile accidents have reached a point where they are considered to be a national epidemic.

Billions of dollars in research are being spent to develop more positive means for securing protection from enemies and still other billions to develop better methods for protecting soldiers in times of war, and yet an astounding apathy pervails toward the biggest killer—the highway accident, generally a collision of one kind or another. Of the more frequently occurring accident types, the two most deadly kinds of collisions are (a) the head-on collision of two vehicles traveling in opposite directions, and (b) the collision of a vehicle with a fixed object.

For sometime it has been evident to highway engineers that the placing of the high speed lanes adjacent to each other, separated only by a painted

line, is extremely hazardous. Two vehicles approaching each other at a speed of 55 mph have a closing speed of 110 mph (161 ft per sec).

Considering that two vehicles moving in adjacent highway lanes separated only by a 1-ft double line (total width) will pass with a clearance of from 3 to 6 ft in normal driving, momentary inattentiveness or loss of control of either vehicle can easily result in a head-on collision. Even at ordinary speeds, a sideswipe frequently leads to complete loss of control of one or both vehicles; the ensuing secondary impacts often result in fatalities or serious injuries. Driving under these conditions requires a motorist to function with the penalty of sudden death for one moment of inattentiveness. Man's inability to handle this task is documented by our annual death and injury toll in motor vehicle accidents.

Divided highways and freeways have contributed considerably towards the elimination of this hazard. However, this improvement is to some extent offset by the freeways tending to give drivers a feeling of safety at speeds of 70 or 80 mph. Out-of-control vehicles are crossing over the median strips of divided highways, resulting in head-on collisions at these higher speeds. Therefore, the divided highway has not completely solved the problem. In some places heavy steel barriers have been placed in the median strip to prevent an out-of-control vehicle from crossing into the lanes of opposing traffic. Although this guardrail is adequate for preventing a car from crossing the median strip, a vehicle striking one of these barriers may be deflected back onto the roadway and possibly across the lanes of high speed traffic. A very serious collision can occur as a result of this unexpected rebound of the out-of-control vehicle.

This problem then resolves itself into one of preventing a vehicle from crossing over the center line of the highway or being deflected back across lanes of traffic on its own side.

One possible solution to this problem would be to place an energy-absorbing barrier where the vehicle would pass after leaving the regular course of travel and before it could engage in a destructive collision. This barrier would absorb the kinetic energy of the vehicle, bring it to a safe stop, and thus eliminate serious danger to the occupants of the vehicle and to those in other vehicles in the immediate vicinity.

A great deal of work has been done by highway engineers and by others in developing safety barriers for highways. Most of these barriers have been designed with the thought of keeping the vehicle on the roadway with an insurmountable or impenetrable barrier. Very few have been developed with the thought of safely absorbing the kinetic energy of the vehicle while bringing it to a stop. It is the purpose of this paper to describe an energy-absorbing solution and only those references relating to such a procedure will be discussed.

One of the earliest approaches to the principle of absorbing the kinetic energy of an automobile by a highway barrier was the "Danish Safety Wall" (1). This barrier has been built on a mountain road in Denmark and has performed very successfully. Its principal application is limited to mountain or curved roadways with the attending disadvantage that the concrete rail must be cast to fit the curvature of the roadway. The high cost of custom manufacture has restricted its application.

The California Division of Highways has conducted considerable research on the design of curbs and bridge railings. A recent report (2) deals with

the full scale testing of highway curbs by automobile impact. The basic object of this study was to develop a curb that was insurmountable. Among the curbs tested were several undercut curbs designed to have an action similar to that of the Danish Safety Wall. Another report (3) by the California Division of Highways on full scale tests of highway guardrails covers the use of the above undercut curb in conjunction with bridge guardrails.

The Department of Civil Engineering of the Johns Hopkins University has conducted extensive tests using scale models to determine the effect of impact of a vehicle against both a cable and a beam type guardrail (4). This report deals directly with the measurement of the energy loss of a vehicle as the result of a collision with a guardrail composed of steel cable, brackets and posts. Calculations were made to determine the amount of energy absorbed by:

1. Friction between the cable and the vehicle.
2. Yielding of the barrier posts in the ground.
3. Yielding of the barrier cable.
4. Deflecting the mass of the vehicle from the approach angle to the exit angle.
5. Sliding friction between the tires and the roadway surface as a result of the deflection described.

Their findings suggest that the bulk of the energy was lost through friction between the cable and the vehicle. Also, the amount of loss was found to be dependent upon the contact pressure and the contact time. The relative position of contact with respect to the position of the guardrail posts was therefore an important factor. Actually, in order to prevent collision between the vehicle and a guardrail post, the points of contact had to be selected between the posts. The article suggests that in order to prevent post collisions a new type of post bracket will have to be developed. The above study comes the closest to approaching the problem of designing a safety barrier on an energy-absorbing basis. However, this aspect of the design comes as a by-product of a rail designed to keep a vehicle from running off a roadway.

To the authors' knowledge the only example of an energy-absorbing barrier being placed in a median strip is contained in a report by White (5), describing tests of driving an automobile into a shrub planting (Rosa Multiflora Japonica) at 30 mph without damage to either the automobile or driver. Here is a barrier that serves the purpose of absorbing the kinetic energy of a moving vehicle, bringing it to a stop without injuring the occupants or damaging the vehicle. This would seem to be an ideal solution to the problem under consideration. However, as a barrier for highways and freeways carrying large volumes of traffic, it has the following disadvantages:

1. Approximately 3 years are required for an adequate growth.
2. This plant life would be continually subjected to exhaust gas damage.
3. Fire damage (cigarettes) would require 3 years to replace growth.
4. Watering is required (at least in some areas).
5. Considerable space is necessary.
6. Frequent pruning is required if space is restricted.

The two basic requirements of a highway safety barrier are that it will: (a) permit an out-of-control vehicle to remove itself from the

roadway proper, and (b) absorb the kinetic energy of the vehicle and thereby bring it to a complete stop without injury to the occupants.

Rosa Multiflora Japonica plantings—in areas where they can be grown economically and in sufficient density—meet both of the above basic requirements. In large areas in the United States such a solution is beyond attainment. Moreover, there are additional desirable requirements some of which dictate the use of some other material. Among these requirements are that the material:

1. Be permanently reliable regardless of the weather conditions.
2. Be adaptable to the specific degree of energy absorption required for a given road situation.
3. Ensures a reasonably uniform deceleration.
4. Absorbs a considerable amount of energy for a small unit price.
5. Holds to a minimum the tendency to deflect the vehicle.
6. Be free from added hazards, such as sharp protrusions or cutting surfaces.
7. Allows high speed impact without throwing fragments into the oncoming traffic.
8. Be inexpensive to build.
9. Be easily replaced if damaged.
10. Presents an attractive appearance.
11. Does not collect paper or rubbish.

Requirement (a) "Permit an out-of-control vehicle to remove itself from the roadway proper," can be met by the proper placement of the barrier. Requirement (b) "Absorb the kinetic energy of the vehicle and thereby bring it to a complete stop without injury to the occupants," is to be satisfied by the characteristics of the barrier. A large amount of kinetic energy is associated with a motor vehicle traveling at high speed; thus, a somewhat unique solution is required to absorb such a large amount of energy in the manner prescribed.

As used in the normal operation of stopping an automobile, brakes convert kinetic energy into heat at the braking surfaces. However, in an out-of-control type of emergency the assumption is that brakes cannot be used or that they are ineffective and that the vehicle must be stopped by a supplementary decelerator. This decelerator should absorb the energy of the vehicle at a reasonably uniform rate over a sufficiently long period of time to minimize the possibility of injury to the occupants and function without causing excessive damage to the vehicle. It is to be understood that, in the context of this paper, a "sufficiently long period of time" is at most only a few seconds.

In searching for a material that can absorb large amounts of energy, it occurred to the senior author that in the action of forming sheets of metal by the stretch operation, large amounts of energy are required. Also, it is recalled that when a heavy object is dropped on a piece of timber, breaking it under the impact of the fall, much of the kinetic energy of the dropped object is utilized in breaking the timber.

An approach to the problem may be the utilization of the energy-absorbing potentialities of the stretching of metals and breaking of materials. The breaking of wood presents the possibility of sharp slivers and spikes which may lead to serious secondary damage. Stretching and breaking steel presents the danger of sharp knife-like cutting edges that might be as dangerous as broken wood. Breaking concrete presents the danger of throwing

broken pieces into the path of oncoming vehicles, thus causing secondary accidents. However, if concrete can be reinforced with steel in such a way as to prevent the pieces flying away from the impact, then it may be the logical material to use. If the reinforcement could be distributed throughout the concrete to tie it together after breaking, it might eliminate the fragmentation problem. This suggests the use of expanded metal lath as a possible solution.

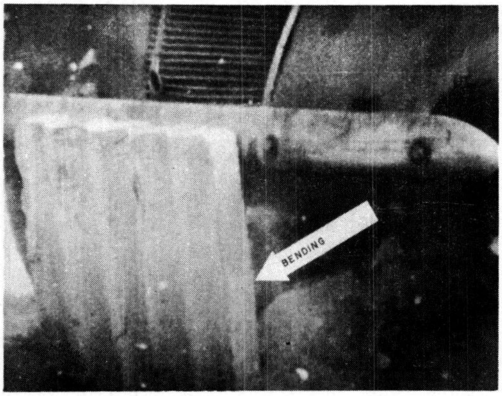

Figure 1.

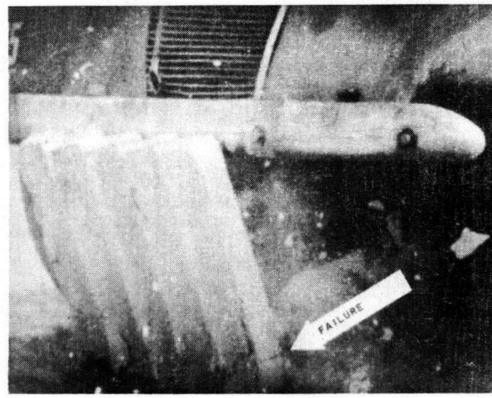

Figure 2.

It is therefore proposed that thin slabs of concrete reinforced with expanded metal lath be used as the element of the barrier. One end of the slab would be anchored in the ground; the other end would extend about two ft above the ground to form the barrier. A row or rows of these barriers some distance apart would then be placed down the center of the median strip of a highway. A vehicle going over the roadway curb and into this median strip, running into this row of barrier slabs and breaking them off consecutively, would be brought to a stop in the middle of the median strip. With a continuous row of barrier elements, the weight and speed of the vehicle becomes less important. It could break as many barriers as are required to absorb the energy it possesses. The total energy absorbed by a barrier element will be the sum of the energy absorbed by elastic bending, breaking, and accelerating of concrete particles.

Figure 3.

If barriers are designed to provide a deceleration rate of -0.6G for a small vehicle, it is also desirable for them to decelerate a truck at approximately the same rate. In most instances this cannot be done with a single row of barriers but a double row could be set up to stop trucks. Consequently, any degree of energy absorption can be designed into the safety barrier.

From the observation of many tests of reinforced concrete beams, it is recognized that failure in concrete tends to occur abruptly and that the

energy absorbed is therefore small. However, the breaking characteristics vary with the shape of the element. The selection of shape should, therefore, be one that prolongs the breaking period and breaks as much material as possible. Shaping the concrete beam into a corrugated configuration would tend to reduce its elastic deflection but would prolong the breaking process (Fig. 4). If the slab contains sufficient steel, the initial failure will be in the concrete. The crest of the corrugations will fail first, being the farthest from the neutral axis. The concrete will fail by crushing or shear, pieces breaking off on the outer surface at the area of maximum moment. Then the remaining concrete, being exposed by this breaking away, will be subjected to excessive stress and will also break away. This will continue until the slab has completely broken.

As the concrete breaks away and the neutral axis shifts, the steel also becomes stressed to the yield point at the crest of the opposite surface of the slab and yields, stretches, and then breaks. The steel, next in order, stretches and breaks. The shape of expanded metal lath is such that, after the concrete breaks away from it in the area of failure, the lath will straighten out, by plastic bending and stretching of the elements, thereby absorbing additional energy. Thus, breaking of both the concrete and the steel is progressive and is extended over a prolonged period of time.

In a curve in which the breaking force is plotted as the ordinate and the deflection of the slab as the abscissa, the energy absorbed will be equal to the area under the curve (Figure 4). To absorb a maximum amount of energy it is desirable to present a high resisting force, and then to sustain that force through as long a deflection distance as possible. This corrugated configuration of the slab with its feature of progressive failure prolongs this resistance and absorbs a maximum amount of kinetic energy.

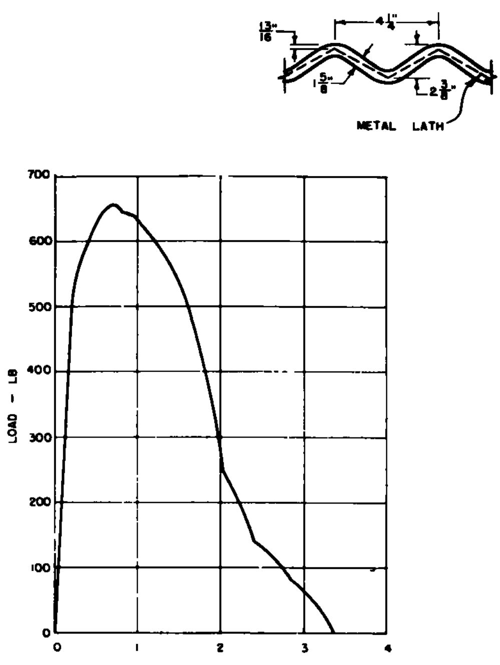

Figure 4.

For economy, it is desirable to have the barrier as light as possible. This can be accomplished by keeping the dimensions of the barrier small. By keeping the thickness of the barrier to a minimum and developing the necessary section modulus by the depth of the corrugations, the proper balance of economy and energy absorbing capacity should be obtainable.

After conducting suitable static tests (Fig. 5 and 6) there followed the impact tests consisting of two runs of an 1937 Ford sedan into a row of barriers. Figure 7 shows the car and barriers at the end of Run No. 2. The barriers, 55 in number, were set on end at 2 ft intervals in a trench 22 in. wide and 10 in. deep. Each barrier was held in place by an 8-in. slab of concrete against the back side and a 3-in. slab against the front

side. A plan view of the field setup is shown in Figure 8.

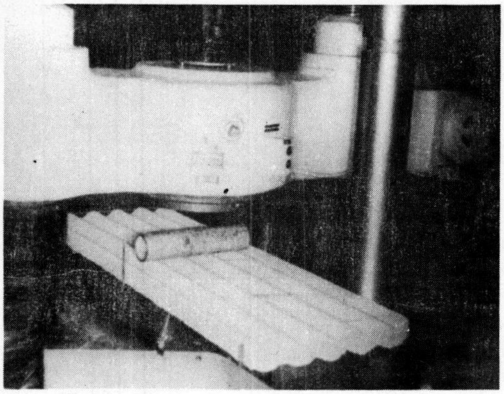

Figure 5.

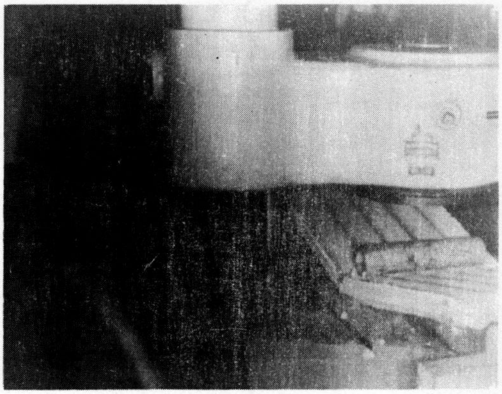

Figure 6.

As protection for the driver, the test car was equipped with a seat belt, shoulder harness and an expanded metal screen over the windshield as

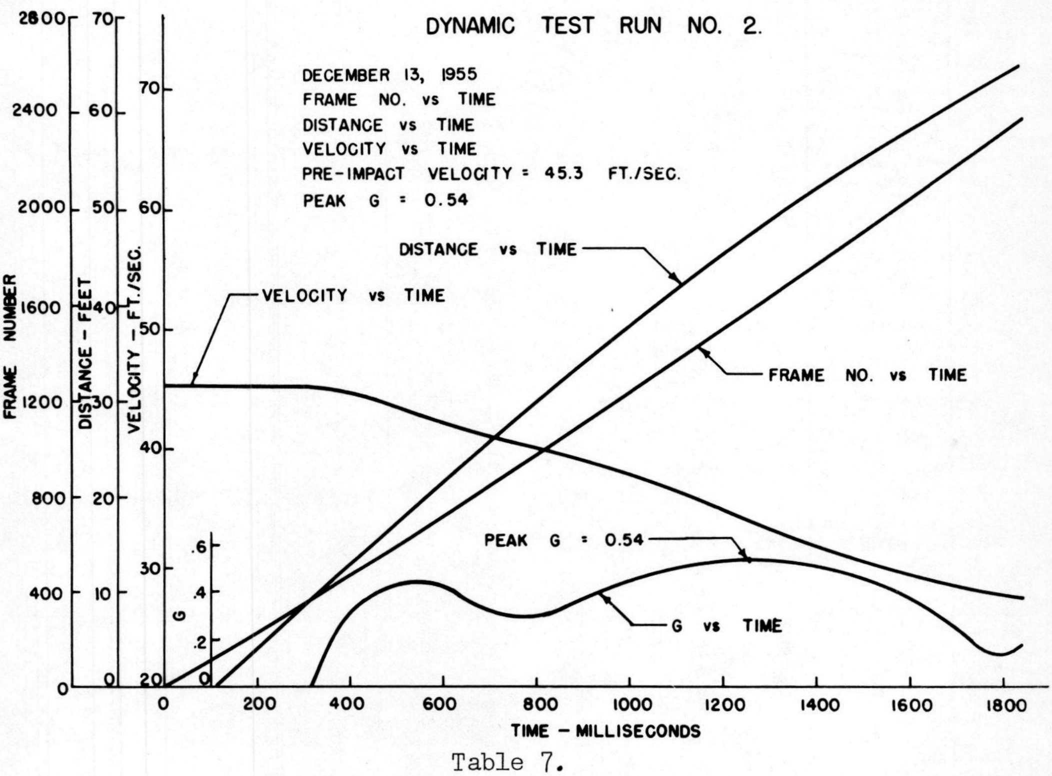

Table 7.

shown in Figure 9. The automobile was weighed after all alterations had been made. The total weight including the driver was 3,085 lb.

In the initial run the automobile struck the first barrier at 17 mph. It broke 23 barriers before coming to rest one foot from the 24th barrier. Figures 10 and 11 show car and barriers at the end of the run. The distance traveled in stopping was 52 ft.

PLAN OF TEST SITE

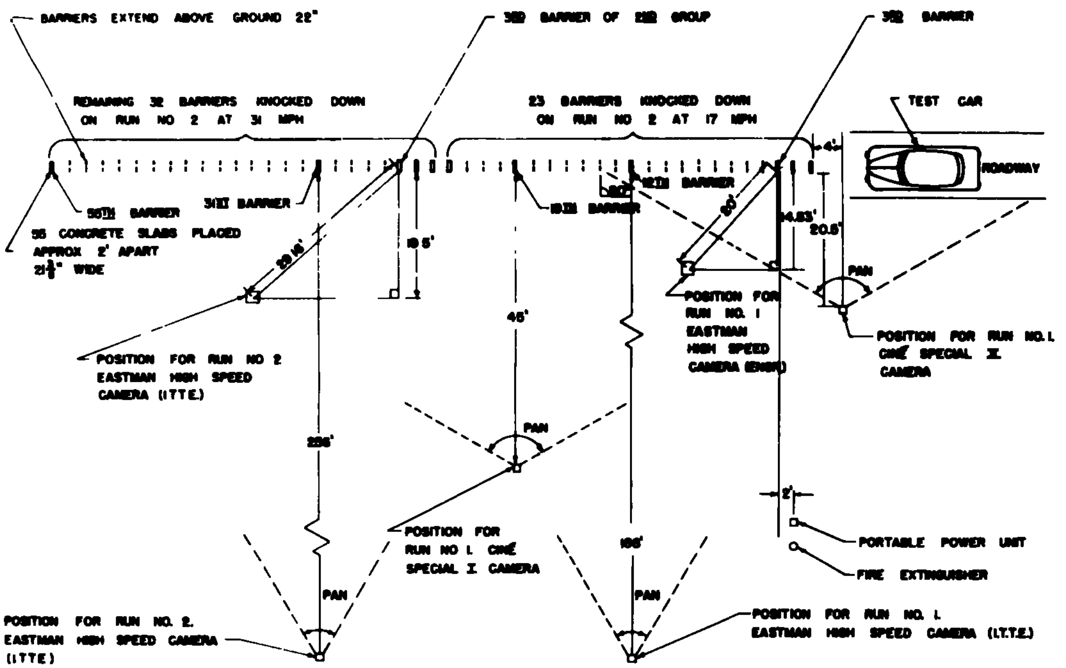

Figure 8.

The broken barriers were removed to clear the approach to the remaining barriers. In the second run the automobile struck the first barrier at 31 mph and mowed down the remaining 32 barriers. It was traveling at

Figure 9.

Figure 10.

approximately 8 mph at the end of the run. The brakes were then applied to stop the automobile. The distance traveled through the barrier was 72.5 ft.

By micromotion analysis of the high-speed motion pictures it was determined, after making allowance for ground friction and wind resistance, that the energy absorbed per barrier in run No. 1 was 1,000 ft lb, and in

run No. 2 was 2,500 ft lb. The average energy absorbed per barrier in the static tests was 1,258 in. lb or 105 ft lb. Comparing this value with the values obtained in the impact tests, it becomes evident that additional tests are required before any reliable relationship can be established between the capacity of a barrier for static and dynamic energy absorption. The absence of satisfactory correlation between static and dynamic experimental test results is commonly encountered in impact studies.

These experiments have shown that it is possible to develop a barrier of sufficiently low resistance to stop a light vehicle at as low a rate of deceleration as is practical. The opposite limit of performance now remains to be determined. This limit would be the maximum rate of deceleration possible without injury to vehicle occupants. By selecting the amount of steel and concrete in the barrier as well as the depth of the corrugation, a barrier can be designed with performance at some optimum value between these two limits.

After examining the extent of scatter of pieces of concrete during the high speed run (Fig. 3), it is apparent that better control of these pieces is necessary. It is suggested, therefore, that the barrier elements be reinforced with two layers of metal lath—one at each face rather than the single centrally located lath. Placing the reinforcing mesh at the extreme surface will give a maximum effective depth for the element and therefore maximum strength for a given amount of material. There should be no difficulty in casting the elements in this manner, since the paste and fines will readily flow into and around the mesh when vibrated. In previous castings uniformity of construction could not be maintained because it was difficult to place and hold the metal lath in the exact center of the element. If the metal lath is placed against the surfaces of the forms and the concrete poured between them, they can be accurately held in this position in all barrier elements, and uniformity will result. It is also suggested that the depth of corrugation be increased to provide a wide range of energy absorption.

Figure 11.

The problem of replacing broken barrier slabs will require additional study and experimentation. A suggested method would be to coat the lower end of the slab with some form of mastic. Thus, when the base concrete was poured it would be prevented from bonding to the lower end of the barrier slab, and the latter could be removed easily after the upper end had been broken off. A new barrier slab could then be set into the cavity formed in the original base pour. Thus, the base pour would have to be made only once and the slab elements could be easily and quickly replaced.

Testing the energy-absorbing capacity of barriers could be accomplished 1/ by a method used in reference (4). A large-negative still camera

1/ High-speed cameras and micromotion analysis are preferable.

would be set on a firm support and focused on the barrier to be tested. The automobile to be used to break the barrier would be marked with a target made of a reflective tape. The test should be run in poor light or at night, the only light source being a strobe light set to flash at a known high rate and at short duration. The camera lens should be open from a minimum of 4 flashes before the automobile strikes the barrier until 4 flashes after breaking the barrier. Micromotion analysis could be made as follows: the time interval between the strobe flashes and the distance between the target images before impact and after impact, measured in thousandths of inches on the negative when used with appropriate conversion factors, constants and formulas provide the basis for computing the energy absorbed, the velocity change and the average deceleration.

Barriers could be more economically tested in this manner since only one to three barriers are required. Thus, an optimum barrier could be developed relative to the specifications of concrete, reinforcement, and configuration with the expenditure of a minimum number of barriers.

Tests should also be made driving an automobile into the barrier at an approach angle, since the barrier will usually be encountered in this manner. Characteristics of rebound could be determined in this manner and any necessary modifications made in the design to improve its effectiveness.

CONCLUSION

These experiments have demonstrated the feasibility of decelerating an out-of-control motor vehicle at a rate sufficiently low to be non-injury producing by means of collapsing a series of reinforced concrete slabs. Further study is suggested to improve the performance of the unit barrier in order to:

1. Provide better control over the dispersal of concrete fragments during collapse. Barrier elements with two layers of metal lath, one at each face would improve this condition.
2. Increase the depth of corrugation to provide a wider range of energy absorption.
3. Increase the mass of the barrier. A more massive barrier will tend to offset the decrease in barrier performance for vehicles striking at higher velocities.
4. Devise an inexpensive and expeditious method for replacing barrier units following an accident. A suggested method consists of coating the portion of the barrier unit to be embedded in concrete with an anti-bonding agent so that the broken base can be extracted and replaced by a new element.

The maximum rate of deceleration developed in these test-runs was approximately one-half G. Since this is the normal stopping rate of automobiles using brakes, the experiments have established that this type of barrier can be designed to provide very low resistance to collapse. It remains now to develop and evaluate a barrier having optimum performance by giving appropriate consideration to the findings and recommendations provided by this study.

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