CRASH BARRIERS - STATE OF THE ART

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THE PROBLEM

Present estimates of the motor vehicle accident deaths and injuries for the year 1969 indicate the following: deaths, approximately 61,000; injuries, approximately 4.5 million; total dollar cost, approximately 13 billion dollars. Approximately 36% of these deaths and injuries are the result of single vehicle accidents which involve vehicles running off the road, overturning, or striking some fixed object such as bridge piers, retaining walls and abutments, sign posts, lightpoles, trees, guardrails, bridge rails, etc.

On high-speed freeways, expressways, and interstate highway facilities, an analysis of the accident statistics indicates that 60% of the deaths and injuries due to motor vehicle accidents are the result of single vehicle accidents leaving the roadway, overturning, or colliding with fixed objects adjacent to or near the travelway. Approximately 7% of these fatalities and injuries resulted from collisions with highway sign supports placed along our roadways; approximately 5% of these fatalities and injuries resulted from collisions with lightpoles; approximately 20% resulted from collisions with guardrails; and the remaining 28% overturned or struck other fixed objects such as bridge piers, concrete walls and abutments, trees, utility poles, etc. It is not known how many of the guardrail collision fatalities and injuries involved
guardrails which were used to protect such rigid obstacles as bridge piers, sign posts, lightpoles, etc.

In the early 1960's, researchers and highway engineers realized that protecting many of the rigid obstacles along our roadway with guardrails did not necessarily reduce the hazards of the roadway facility, but merely substituted in many cases another more serious hazard than the one guarded.

**VEHICLE IMPACT ATTENUATION BY BREAKAWAY STRUCTURES**

Early in the 1960's, the Texas Transportation Institute and the Texas Highway Department, in cooperation with the Federal Highway Administration, developed the first successful breakaway highway signs to replace the rigidly-mounted roadside signs which were widely used by the highway departments of this nation.

This "breakaway" principle has now been applied to highway illumination supports (lightpoles). Such breakaway lightpoles are now being installed along our nation's highways with gratifying results.

**VEHICLE IMPACT ATTENUATION BY CRASH CUSHIONS**

Since many rigid obstacles along our roadways cannot be removed or made breakaway, work has been under way by many groups to develop crash cushions or vehicle impact attenuation devices which can be used to reduce the severity of vehicle collisions with immovable obstacles. In March 1968 the Texas Transportation Institute developed and tested such a device fabricated from 38 fifty-five gallon oil drums. A 1964 four-door sedan weighing 3,200 lb and traveling 60 mph was stopped in 13.3 ft
The average deceleration of the vehicle was 9 g's and very minor damage resulted. In fact, only one of the four headlights was broken. This test proved unquestionably that such crash cushions are feasible, practical, and economical.

At the present time, five types of vehicle impact attenuation barriers are installed on our nation's highways. These are:

1. Texas barrel or steel drum crash cushion,
2. Fitch Inertial Barrier - frangible plastic drums filled with sand (Fitch Inertial Barrier Systems, 44 School St., Boston, Mass. 02108),
3. Hi-dro Cushion Crash Moderation Systems (Energy Absorption Systems, Inc., 221 N. Lasalle St., Chicago, Ill. 60601),
4. Light Weight Cellular Concrete Crash Cushion - limited installations in Wisconsin and Florida,
5. Chain Link Fence Vehicle Arresting System - utilizes metal bender energy absorbers (Syro Steel Co., 1170 North State St., Girard, Ohio 44420) - limited installations in Texas.

In addition to the above, the barrels or steel drums have been made into a crash cushion trailer to be towed behind slowly moving or parked highway maintenance vehicles. This crash cushion trailer can protect the motorist as well as the maintenance equipment and personnel. These trailers are being used in Texas.

Research is now underway to develop crash barriers using corrugated steel pipe and waste automobile tires. Two concepts are being developed
for use of waste automobile tires. The first is the Goodyear Concept which uses several hundred tires tied together as a compression barrier. The other concept is a tire-sand inertia barrier which uses stacks of waste tires as sand containers which are placed in front of a rigid object as a crash barrier.

The following discussion will attempt to present some of the basic design criteria and concepts now used.

**Human Tolerance to "Eye Balls Out" Acceleration**

Figure 1 summarizes to a large extent the "state-of-the-art" of bio-dynamic data concerning human tolerance to accelerations which would be experienced by restrained automobile occupants in a head-on collision. From such data, the Federal Highway Administration (Ref. 2) has tentatively established the following criteria for the design of vehicle crash cushions:

- **Permissible Average Vehicle Deceleration** - 12 g's maximum
  - while preventing actual impact or penetration of the protected roadside hazard.
- **Permissible Deceleration Onset Rate** - 500 g's per second.

**Minimum Stopping Distance**

Using the maximum permissible average vehicle deceleration of 12 g's one can readily determine the minimum distance required to stop a speeding vehicle. Using simple physics the distance required is

\[
D = \frac{v^2}{2gG}
\]
Figure 1. Maximum human tolerance to transverse acceleration (eye balls out). After Eiband, 1959 (Ref. No. 1).
where $D =$ vehicle stopping distance in ft

$V =$ vehicle speed ft per sec

$G =$ average vehicle deceleration g's

$g =$ acceleration due to gravity 32.2 ft per sec$^2$

In order not to exceed 12 g's, Table 1 shows the minimum stopping distance required.

**TABLE 1. MINIMUM STOPPING DISTANCE FOR VARIOUS VEHICLE IMPACT SPEEDS IN ORDER NOT TO EXCEED 12 g's AVERAGE DECELERATION.**

<table>
<thead>
<tr>
<th>Vehicle Impact Speed mph</th>
<th>Minimum Stopping Distance ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>2.51</td>
</tr>
<tr>
<td>40</td>
<td>4.45</td>
</tr>
<tr>
<td>50</td>
<td>6.96</td>
</tr>
<tr>
<td>60*</td>
<td>10.02*</td>
</tr>
<tr>
<td>70</td>
<td>13.64</td>
</tr>
<tr>
<td>80</td>
<td>17.81</td>
</tr>
</tbody>
</table>

The Federal Highway Administration has also tentatively established that vehicle crash cushions shall be designed to stop 2000 lb and 4500 lb vehicles traveling at a minimum speed of 60 mph. Consequently, vehicle crash cushions should be capable of providing the minimum stopping distance of 10 ft for a 60 mph impact speed.

**Vehicle Impact Attenuation Concepts**

Presently available vehicle crash cushions basically used one of the
following two concepts to stop a speeding vehicle before it strikes a rigid obstacle or hazard.

The **first concept** involves absorption of the kinetic energy of the speeding vehicle by use of "crushable" or "plastically" deformable materials or structures or by use of hydraulic "dashpots" or energy absorbers placed in front of the hazard. Devices of this type need a rigid backup or support to resist the vehicle impact force and deform the energy absorbing material or structure. Figures 2 and 3 illustrate this principle applied to a compression type barrier and a net (or snagging) device, respectively.

In Figure 2, the stopping force \(F\) need not be constant, but the area under the force \(F\) vs deformation \(D\) graph of the crash cushion should equal the kinetic energy of the impacting vehicle. The crash cushion should be designed so that it will stop a small 2,000 lb vehicle traveling at 60 mph with \(D\) equal to or greater than the minimum required stopping distance of 10 ft. Additional material and distance should also be provided so that the device will also be capable of stopping a 4,500 lb vehicle traveling 60 mph.

In Figure 3 the metal tape tension or "drag force" \(T\) will usually be constant. The designer must select the proper combination of "drag force" \(T\) and tape run-out distance \(R\) so the device will stop a small 2,000 lb vehicle traveling 60 mph with a stopping distance \(D\) equal to or greater than the minimum required stopping distance of 10 ft. Additional tape run-out capacity \(R\) should be provided so the device will be capable of stopping a 4,500 lb vehicle traveling at 60 mph. It should be noted that from simple
**Figure 2. Principle of Absorbing Vehicle Kinetic Energy — Compression Device**

**Before Impact**
- Rigid support
- Deformable material
- Stopping force
- Length of deformation

**After Impact**
- Stopping force
- Speed
- Kinetic energy of vehicle:
  \[ W \frac{V^2}{2g} \]
- Energy absorbed by crash cushion:
  \[ FD \]
- Formula:
  \[ FD = \frac{WV^2}{2g} \]
ROLL OF METAL TAPE WHICH EXERTS "DRAG FORCE" AS TAPE IS PULLED OUT OF "REEL".

\[ V = \text{SPEED} \]

\[ W = \text{WT.} \]

\[ \text{VEHICLE} \]

\[ \frac{WV^2}{2g} \]

\[ \text{KINETIC ENERGY OF VEHICLE} \]

\[ L = \text{LENGTH OF NET} \]

"WIRE NET"

BEFORE IMPACT

\[ R = \text{TAPE RUN OUT DISTANCE (LENGTH)} \]

\[ T = \text{TAPE TENSION OR DRAG FORCE} \]

\[ 2TR = \text{ENERGY ABSORBED BY METAL TAPES} \]

\[ 2TR = \frac{WV^2}{2g} \]

AFTER IMPACT

\[ D = \text{STOPPING DIST.} \]

\[ L/2 \]

\[ R \]

\[ T \]

\[ V = 0 \]

\[ V \]

FIGURE 3. PRINCIPLE OF ABSORBING VEHICLE KINETIC ENERGY—NETS OR SNAGGING DEVICES.
geometry of Figure 3, the relationship between stopping distance \( D \) and tape run-out \( R \) is

\[
D = \sqrt{R^2 + RL} \quad \text{or} \quad R = \frac{-L + \sqrt{L^2 + 4D^2}}{2} \quad \text{(approx.)}
\]

The second concept involves transfer of the momentum of the speeding vehicle to some expendable masses of material located in the path of the vehicle. The expendable masses (or weights) are usually containers filled with sand although water and other materials can be used. Devices of this type need no rigid backup or support to resist the vehicle impact force since the kinetic energy of the vehicle is not absorbed, but merely transferred to the other masses. This type of crash cushion is sometimes referred to as an "Inertia Barrier".

Figure 4 illustrates this principle applied to a speeding vehicle impacting a series of five masses or containers filled with sand.

By the Law of Conservation of Momentum, the vehicle speed after first mass impact (assuming rigid body plastic impact) is

\[
V_1 = V_0 \left[ \frac{W}{W + W_1} \right]
\]

The vehicle speed after second mass impact is

\[
V_2 = V_1 \left[ \frac{W}{W + W_2} \right]
\]

The final speed after fifth mass impact will be

\[
V_5 = V_4 \left[ \frac{W}{W + W_5} \right]
\]

To obtain a constant change in velocity as the vehicle strikes each container \( W_1 \) through \( W_5 \) it can be seen that containers must increase in weight (or mass) as they get closer to the hazard.
HAZARD

TOTAL LENGTH OF BARRIER

$V_0 = \text{INITIAL SPEED}$

MOMENTUM OF VEHICLE =

$\frac{W}{g} V_0$

BEFORE IMPACT

$W_1$ ASSUMES VEH. SPEED $V_1$

MOMENTUM OF VEHICLE AND 1st MASS IMPACTED =

$\frac{(W + W_1)}{g} V_1$

AFTER IMPACT

MOMENTA BEFORE IMPACT = MOMENTA AFTER IMPACT

$W V_0 = (W + W_1) V_1$

$V_1 = \frac{W}{W + W_1} V_0$

FIGURE 4. PRINCIPLE OF TRANSFERRING VEHICLE MOMENTUM TO EXPENDABLE MASSES — ASSUMING PLASTIC RIGID BODY IMPACT
Thus

$$\Delta V_1 = V_o - V_1 = V_o \left[1 - \frac{W}{W + W_1}\right]$$

and

$$\Delta V_2 = V_1 - V_2 = V_1 \left[1 - \frac{W}{W + W_2}\right]$$

and so forth. 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 after the final container is impacted.

If the Inertia Barrier illustrated by Figure 4 were designed to slow a 2,000 lb vehicle traveling at 60 mph down to 10 mph with five containers (each slowing the vehicle 10 mph), the containers should each weigh:

$$W_1 = 2000 \left[\frac{60}{50} - 1\right] = 400 \text{ lb}$$
$$W_2 = 2000 \left[\frac{50}{40} - 1\right] = 500 \text{ lb}$$
$$W_3 = 2000 \left[\frac{40}{30} - 1\right] = 667 \text{ lb}$$
$$W_4 = 2000 \left[\frac{30}{20} - 1\right] = 1000 \text{ lb}$$
$$W_5 = 2000 \left[\frac{20}{10} - 1\right] = 2000 \text{ lb}$$

As in the design of any vehicle crash cushion, the weight and number of containers and length of the barrier should be proportioned to stop a small 2,000 lb vehicle traveling at 60 mph with a stopping distance (D) equal to or greater than the minimum required distance of 10 ft. Additional containers and distance should be supplied so the device can also stop a
Vehicle Impact Attenuation - Geometric and Design Details

In the preceding sections, the basic design criteria and concepts used in the development of most presently available vehicle impact attenuation devices were presented. To make a crash cushion work as intended by the design, however, careful attention must be given to several other geometric and design details.

Figure 5 illustrates how a vehicle may ramp and jump over the vehicle impact attenuation device if the resultant stopping force provided by the crash cushion is considerably lower than the vehicle center of gravity (C.G.). The energy absorbing material may deform more at the top than at the bottom and thus form a ramp for the vehicle.

Figure 6 illustrates how a vehicle may also flip end over end due to the couple formed by the eccentricity of the resultant stopping force and vehicle inertia force.

On the other hand, Figure 7 illustrates how a vehicle may submarine under the vehicle impact attenuation device if the resultant stopping force is considerably higher than the vehicle center of gravity. To guard against such behavior as shown in Figures 5 and 6, the resultant stopping force provided by the energy absorbing material or inertia masses should be located approximately 22 to 24 in. above the roadway or ground. (This is the approximate location of passenger vehicle's center of gravity.) In addition, the energy absorbing crash cushion
THE VEHICLE MAY RAMP AND JUMP OVER THE CRASH CUSHION.

FIGURE 5. RESULTANT STOPPING FORCE LOWER THAN THE VEHICLE CENTER OF GRAavity (C.G.). HEAD-ON IMPACT.
FIGURE 6. RESULTANT STOPPING FORCE LOWER THAN THE VEHICLE CENTER OF GRAVITY (C.G.) HEAD-ON IMPACT.
THE VEHICLE MAY SUBMARINE UNDER THE CRASH CUSHION

FIGURE 7. RESULTANT STOPPING FORCE HIGHER THAN THE VEHICLE CENTER OF GRAVITY (C.G.)
materials are usually stabilized by a cable or other anchoring system to prevent the material from moving up, down, or sideways during the collision.

Figure 8 illustrates how a vehicle may "pocket", "spin out", and even "roll over" in a head-on off-center impact. This type behavior can occur if the vehicle crash cushion is extremely massive and/or stiff thus generating a large eccentric stopping force and rotation couple on the vehicle.

Thus far we have discussed Vehicle Impact Attenuators (VIA) when hit head-on. Of importance also is the behavior of these devices when the vehicle impacts them at an angle with respect to the VIA's longitudinal axis. Figure 9 illustrates how a typical Vehicle Impact Attenuator will behave under an angle impact near the nose. In this case sufficient distance and energy absorbing material are usually available between the point of impact and the rigid hazard to stop the colliding vehicle safely. In such cases it is satisfactory to allow the vehicle to "pocket" and come to a complete stop short of the rigid hazard.

Should the vehicle impact the VIA at an angle at a point near the rear of the VIA a severe collision may occur when the vehicle strikes the rigid hazard. Figure 10 illustrates this potential problem. In such a collision, distance and energy absorbing material are usually insufficient to stop the vehicle safely before it strikes the rigid hazard. In an attempt to remedy this potential hazard, many VIA designers are cladding the sides of the vehicle impact attenuators.
FIGURE 8. VEHICLE IMPACT ATTENUATOR IS TOO MASSIVE AND STIFF (STOPPING FORCE TOO LARGE). AN OFF CENTER HIT MAY CAUSE THE VEHICLE TO "POCKET", "SPIN-OUT", AND "ROLL-OVER."
FIGURE 9. VEHICLE ANGLE IMPACT NEAR THE NOSE OF THE IMPACT ATTENUATOR
FIGURE 10. VEHICLE ANGLE IMPACT NEAR THE REAR OF THE VEHICLE IMPACT ATTENUATOR
with hard, stiff, and smooth panels which will prevent the vehicle from "pocketing" and thus redirect it as shown in Figure 11. The provisions for redirection must be such that the VIA has lateral stability and still maintain the relatively "soft" crush characteristics under head-on impacts.

Summary of Desirable Impact Attenuation Barrier Characteristics

For impact attenuation barriers to be effective and acceptable for use on our nation's highways, test results and experience gained through field installations indicate that it would be desirable for such barriers to have the following characteristics.

1. Vehicle Impact Attenuation Barriers (Crash Cushions without Redirection Capability)

A. A crash cushion should smoothly stop a selected vehicle impacting it head-on. The vehicle should not vault over the barrier and should not become unstable and roll over. (It would be desirable for simple crash cushions to have the capability of stopping a vehicle impacting anywhere along its length and at any angle up to the maximum design conditions of impact speed, vehicle weight, and impact angle.)

B. A crash cushion should minimize vehicle decelerations in such a manner that occupants restrained by seat belts can survive, preferably uninjured.

C. A crash cushion should remain essentially intact during and following a vehicle collision. A vehicle impact should not dislodge any hazardous elements into the travelway.
FIGURE 11. VEHICLE ANGLE IMPACT INTO VEHICLE IMPACT ATTENUATOR DESIGNED TO REDIRECT VEHICLE RATHER THAN STOP IT.
D. A crash cushion should be compatible with the roadway and fixed object it is guarding. It should not protrude into the travelway or shoulders provided for emergency or evasive maneuvers by a vehicle.

E. A crash cushion should be susceptible of quick repair. All elements of a barrier should be so designed that when repairs are necessary they can be done quickly and with a minimum of special equipment.

F. A crash cushion should be mechanically reliable and dependable. It should be durable and stand up under extreme environmental exposure -- heat and cold, wet and dry, and corrosive elements expected under service conditions.

G. The foregoing requirements should be met by giving emphasis first to safety, second to economics, and third to aesthetics.

II. Vehicle Impact Attenuation Barriers (Crash Cushions with Redirection Capabilities)

A. A crash cushion with redirection capabilities should satisfy all the service requirements of a simple crash cushion of item I when a selected vehicle impacts it head-on.

B. A crash cushion with redirection capabilities should restrain and smoothly redirect a selected vehicle which impacts it along its length or side. The impacting vehicle should not penetrate or vault over the barrier. The vehicle should not snag or pocket under side angle impacts.

C. A crash cushion with redirection capabilities should be compatible with adjoining or abutting longitudinal barriers
guardrails, bridge rails, or median barriers) in order to prevent collisions with the ends of the adjoining or abutting barriers. A smooth redirection should be obtained at the transition point between the two barriers.

Summary of Vehicle Impact Attenuation Devices

The objective of this paper was to present some of the basic design criteria and design concepts for vehicle impact attenuation devices for use on roadways. This is a new field of endeavor and much research is under way to develop new criteria, concepts, and devices. Consequently, the material presented here is an attempt to summarize briefly the current thinking and "state-of-the-art" concerning vehicle impact attenuation devices.

The presently available vehicle impact attenuation devices are for the most part designed to reduce the severity of vehicle collisions with fixed hazards which cannot be removed, relocated, or made "breakaway" (to yield to the colliding vehicle). In general, these devices are designed for vehicles weighing from 2,000 lb to 4,500 lb and traveling at about 60 mph, and they are not generally designed to safely stop heavy trucks or buses. The kinetic energy of such vehicles is usually extremely large, and a very large quantity of energy absorbing material or inertial masses would have to be used to safely stop them. The geometry and location of the center of gravity of such vehicles are quite different from the typical passenger automobile.
The development of these vehicle impact attenuation devices has provided the highway engineers with an effective tool for use in the design and construction of a forgiving roadside.
ACKNOWLEDGMENTS

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The opinions, findings, and conclusions expressed in this paper are those of the author and are not necessarily those of any agency identified herein.
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