

SAFETY BARRIERS FOR MOTORWAYS

Shoulder and bridge safety barriers and impact attenuators surveyed  
and assessed

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## SUMMARY

This report is a survey of the various types of safety barriers for shoulders and civil engineering structures (viaducts, bridges and tunnels) on and alongside motorways. These devices can be subdivided into deformable steel barriers (guide rails) and non-deformable concrete barriers. We also consider devices designed to guard isolated obstacles (impact attenuators).

The report lists the practical qualities of deformable and non-deformable barriers. Each type is assessed on the basis of its performance in the event of a collision. With this in mind, the functional requirements which a safety barrier must satisfy have been formulated. The main criteria are that the vehicle must not be allowed to penetrate or traverse the barrier, it must not rebound into the stream of traffic, it must not be allowed to overturn and the occupants must not suffer serious injury. Impact attenuators must bring the vehicle to a halt before it reaches the obstacle, in the event of a head-on collision.

Given these functional requirements, the following constructional aspects are important to the proper functioning of barriers. In the case of steel barriers: the beam must be rigid and, if hit, remain at an adequate height and continue to protect the supports (usually posts); the supports and/or spacers must deflect and/or deform progressively, absorbing the collision energy (i.e. the energy transmitted must not be reimpacted to the vehicle). A concrete barrier must be sufficiently strong and sufficiently high; it must prevent the wheels of a vehicle mounting too high on the barrier; the vehicle should be guided primarily by its wheels, so that the contact forces between vehicle bodywork and barrier are prevented from becoming too great. The various types of impact attenuators differ so much in essentials of design that it is not possible to draw up a systematic series of constructional requirements.

Taking into account the relatively poor quality of available safety criteria, the main conclusions which can be drawn from the tests as regards barriers are:

- various types of deformable barriers (steel guide rails) perform well when hit by cars, even under severe conditions (impact speeds up to approx. 100 kmph, approach angles up to approx. 20°);

- various types of deformable barriers perform satisfactorily when hit by rather heavy vehicles, provided the impact conditions are not too severe (impact speeds up to approx. 80 kmph, impact angles up to  $15^{\circ}$ ); under more severe conditions the vehicle often penetrates the barrier;
  - non-deformable (concrete) barriers give reasonable protection to cars only when the impact conditions are not too severe (speeds up to 80 kmph, angles up to approx.  $15^{\circ}$ );
  - rigid barriers perform better than easy deformable ones when hit by heavy vehicles, although there may be a danger of overturning in the case of vehicles with a high centre of gravity;
  - the way non-deformable barriers perform seems to be more dependent on weather conditions than is the case with deformable barriers.
- Regarding impact attenuators it may be concluded that only those types which are designed for European vehicles are suitable for use on European motorways.

As regards steel barriers, further research should be done into the relationship between vehicle deceleration and transverse beam displacement, in conjunction with research into the effect of barriers operating progressively. As regards concrete barriers, research needs to be done into better designs which give lower vehicle decelerations and prevent mounting by the wheels.

Finally, this report emphasises the need for more suitable safety criteria, since these are rather fundamental in the evaluation of the performance of barriers.

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FOREWORD

This report surveys and assesses the many types of safety barriers which have been developed for motorways in recent years in various countries. Two separate types are considered: continuous safety barriers for shoulders and bridges (which can also be used for viaducts and tunnels) and safety barriers for isolated obstacles.

The report is based on the assumption that it is necessary to fence off a danger zone with a safety barrier. The underlying criteria are set out in summary form. The various types of barrier are assessed essentially as to the way they function when hit. Some general practical features are described in brief.

The data on the various types of barrier are taken from the literature. SWOV's judgement of these is based on consideration of the fundamental collision process between vehicle and safety barrier and the results of tests (where adequate tests have taken place). A few of the results with certain types of safety barrier reported here derive from mathematical simulations. These were carried out using the VEDYAC vehicle model developed, at the request of SWOV, by Program Development & Technical Appliance Ltd (SPAT) in Milan.

The report has been written at the request of the Società Iniziative Nazionali Autostradali "SINA S.p.A." and the Associated Companies "Autostrada dei Fiori S.p.A."; "Autostrada Ligure-Toscana S.p.A."; "Autostrade Valdostane S.p.A."; "Società Autostrada Torino-Milano S.p.A."; Società Autostrada Torino-Alessandria-Piacenza S.p.A.". The authors are C.C. Schoon, T. Heijer, W.H.M. van de Pol and D.J.R. Jordaan.



## 1. INTRODUCTION

This report deals with the various devices designed to guard danger zones alongside motorways. Examples of danger zones are the other carriageway with oncoming traffic, a parallel road or a cycle track. To penetrate one it is necessary to cross a central reserve or separating strip. The shoulders may also constitute a danger zone owing to the presence of obstacles, steep inclines etc. The following locations are eligible for barriers: shoulders, bridges, viaducts and tunnels. Special locations such as bridge approaches, tunnel entrances and terminal points are also on the list. Danger zones can be guarded with the aid of barriers designed for this purpose. In this report we deal with those types which have been demonstrated to work well when hit or which may be expected to do so. Barriers which are employed a good deal but work less effectively when hit are also discussed.

The primary aim of the study is to survey the state of affairs regarding steel and concrete safety barriers alongside motorways. The following points are considered:

- the technical requirements which safety barriers must satisfy;
- the results of full-scale tests and mathematical simulations.

Secondly, we assess the effectiveness of the various types of safety barrier. In appropriate cases we indicate where knowledge is lacking and how this can be remedied. Where further research is required we make recommendations.

The survey is preceded by a theoretical consideration of the essential operation of the various types of safety barrier, focusing on the dynamic behaviour of a vehicle hitting a safety barrier.

## 2. BRIEF THEORETICAL DISCUSSION

The safety barriers dealt with in this report are all designed to prevent motor vehicles partially or entirely leaving the carriageway. They must therefore be capable of nullifying all the lateral movement components of a vehicle in one way or another while there is contact between vehicle and barrier, by exerting contact forces. These must ensure that:

- the vehicle does not leave the road (i.e. block it);
- the path of the vehicle, if it is still moving after the collision, remains parallel to the barrier as far as possible to prevent it rebounding and colliding with other road uses (i.e. guide it).

The principle is always that a collision between vehicle and barrier ('substitute accident') produces considerably less danger to vehicle and occupants than the vehicle leaving the road (where there is a danger zone).

The forces required for blocking and guiding are generated by the deformation of vehicle and barrier. The position and magnitude of the deformations depend above all on the design specifications of the barrier. The smaller the deformation, the higher the vehicle deceleration. In this respect barriers can be divided into two main categories:

- a. barriers which are themselves capable of deforming and thus largely determine the magnitude and direction of the contact forces; and
- b. barriers which do not themselves deform, so that the magnitude of the forces is determined mainly by the deformation of the vehicle; the barrier determines mainly the direction and points of contact.

In general, barriers ensure that the energy of the lateral movement components of the vehicle is converted into heat through deformation and friction work, or into other forms of energy (rotation). After this the brakes, tyres, suspension (shock absorbers) or bodywork bring about the final conversion of energy through friction or deformation.

The lateral movement of the vehicle in relation to the road may arise as a result of either translation (veering) or rotation (skidding, overturning). In general, existing barriers are designed to guide translated vehicles at an angle to the longitudinal axis of the barrier which is not too great (approx.  $30^{\circ}$ ), whereas rotating vehicles are blocked.

## 2.1. Course of collision

A collision between a vehicle and a barrier designed to guide vehicles contains two phases:

- a. Primary contact, in which part of the front of the vehicle usually touches the barrier first; here the contact is usually so far in front of the vehicle's centre of gravity that not only is lateral translation impeded, the vehicle is also forced to rotate away from the barrier. This rotation can be combated partly by the moments of frictional force between vehicle and barrier and between vehicle and road surface. The rotation is mainly yawing (rotation around a vertical axis).
- b. Secondary contact (the 'rear-end effect'), which occurs if the rear of the rotating vehicle hits the barrier. Since the point of contact is then behind the vehicle's centre of gravity, the original rotation is entirely or partially stopped. The rear-end effect does not always occur; it depends on the course of the primary contact and the friction conditions.

The lateral translation of the vehicle immediately after the collision depends on the degree of elasticity of the primary and secondary collision. The rotation of the vehicle immediately after the collision is usually stopped by friction on the road and in the suspension. As a result the vehicle's final angle of travel depends not only on the elasticity of the collision but also on the road surface conditions in the immediate vicinity of the safety barrier.

## 2.2. Operation of the different types of barrier

Essentially there are two types of barrier, deformable and non-deformable.

### 2.2.1. Deformable barriers

These barriers are designed to absorb energy and generally consist of three main components:

- a continuous longitudinal beam;
- supports which keep the beam a certain height above the carriageway;
- connectors which connect beams to supports.

There are often also auxiliary components to improve the stability or rigidity of the construction, e.g. diagonals in barriers with a rail on either side. All the main components can in theory participate in the deformation; the extent to which each does so is highly dependent on the design features. Sometimes one of the components is absent (where the beam is attached directly to the post or to a wall or rock surface).

The functions of the main components in a collision can be described as follows. The beam provides contact with the vehicle and deflects horizontally as a result of the contact forces. Its rigidity must be such that the deflection takes place over a sufficient length of barrier for several supports and connectors to be involved in the deformation so that the energy absorption is distributed. This also provides a favourable contour for guiding the vehicle. The beam must also be able to absorb the longitudinal tensile forces caused by friction between vehicle and beam and deflection of the latter; there must not be any great plastic deformation or collapse as a result. The amount of energy absorbed by the beam as a result of deflection (plastic deformation) must not be large, otherwise there is a danger of local collapse (distension, fracturing).

The connectors may perform various functions or combinations of functions, depending on the design: they may

- fasten the beam to the support;
- maintain the distance between beam and support to prevent the support being hit, increase the resistance of the beam to flexion or, in conjunction with the support, maintain the height of the beam when it deflects;
- absorb the energy in the event of deformation (flexion, denting, friction etc).

The supports similarly perform various functions or combinations of functions: they may

- maintain the height of the beam;
- absorb collision energy by flexion, ploughing through the ground or fracturing components specially fitted for this purpose; or
- absorb the tensile load on the beam (without great displacement).

The length and depth of deflection during a collision determine the angle between the barrier and the longitudinal axis of the road, and thus the path of the vehicle while it is in contact with the barrier. The barriers are designed in such a way that collisions take place with the minimum elasticity possible, so that rebounding is avoided and the contact between vehicle and barrier is maintained as long as possible. As a result the angle of deflection, in conjunction with the resulting rotation of the vehicle once it leaves the barrier, determines the exit conditions. Rigid barriers which do not deflect a great deal (a small angle) but produce relatively large transverse forces thus cause more severe vehicle rotation than flexible barriers. The more rigid barriers, then, depend for their effectiveness more on the frictional conditions between vehicle and road surface immediately after the collision than the more flexible barriers.

#### 2.2.2. Non-deformable barriers

These barriers consist of prismatic beams of a special cross-section whose base is level with the carriageway. They are designed not to absorb energy and often constructed of concrete or similar heavy materials. Their operation in the event of a collision is based on wheel-guiding, i.e. their shape is designed to generate the transverse forces in the primary and secondary collision phases through the vehicle suspension and transmit them to the vehicle. The transverse forces are created mainly by having the wheels revolve on a plane with a certain transverse inclination, and to a much lesser extent by colliding with parts of the bodywork. The incline also produces vertical force components which cause the vehicle not only to move around the vertical axis but also to rotate around the longitudinal and lateral axes. Since the barrier itself does not absorb any collision energy and the suspension also absorbs little energy immediately, collisions are highly elastic: virtually all the lateral energy just before the collision that is not converted into rotational energy is still present immediately after the collision. It is therefore mainly the shock absorbers, tyre friction and any plastic deformation of the suspension that are left to dissipate the energy. If the vehicle hits the barrier at a larger angle there is also contact between bodywork and barrier; the more bodywork deformation takes place,

the more lateral energy is absorbed. Because of the vehicle rotation that occurs with these concrete barriers, they depend more on the state of the road and the vehicle for their ability to provide effective guidance than rigid guide rails. Because much less energy is usually dissipated by a non-deformable barrier than a deformable one, the kinetic energy of the vehicle immediately after the collision is proportionately much higher.

### 2.3. Load on foundations

In both types of barrier the entire forces are passed on to the foundations. Although the lateral forces which cause the vehicle to rotate are in both cases of at least the same order of magnitude, their distribution among the various points differs: the highly rigid wheel-guiding barrier distributes them better than the flexible barrier, which may thus pass on higher point loads to the foundations or supports.

Since the longitudinal frictional forces between guide rail and bodywork are greater than those between concrete barrier and wheels, the longitudinal forces passed on to the foundations are also greater in the case of the deformable types. The vertical forces also differ between the two types: if a guide rail flexes, its supports produce upward tensile forces in the foundations (the magnitude depends very largely on the construction), whereas a non-deformable barrier produces vertical compressive forces.

When blocking a deformable barrier generally exerts lower local forces on the foundations than a non-deformable one.



### 3. LOCATIONS REQUIRING PROTECTION

A safety barrier enables a 'substitute' accident to take place instead of the accident that might take place if a vehicle leaves the carriageway. The aim of the exercise is to introduce a 'predictable accident' with 'known' results, rather than one which is likely to have serious results. Collisions with safety barriers are not without risk to the vehicle occupants, however. A safety barrier should therefore be installed only after the potential risks have been properly considered.

It is difficult to quantify the risk factors. To date no precise indicators of the seriousness of a collision have been found. Some data are however available from empirical research and accident statistics. It is known, for example, that precipices, waterways and rigid obstacles constitute serious dangers to vehicles. The shoulder can also be dangerous, since large irregularities or soft ground make it very difficult to control the vehicle, which may for instance overturn or land back on the road with virtually no steering control. There may also be a secondary road or cycle track adjacent to the shoulder, in which case crossing the shoulder entails the danger of collision with other road users. In most cases the shoulder, whatever its nature, is too narrow for controlled vehicle manoeuvres: it can be deduced from American research (Huelke & Gikas; not published) that the width required is about 12 m, and the area must be free of obstacles and the ground sufficiently flat and firm. If the shoulder does not meet these requirements, it is eligible for protection.

#### 3.1. Shoulders

If shoulders are not sufficiently free of obstacles this may sometimes be remedied by moving or removing obstacles or levelling the ground.

Obstacles such as lamp standards, traffic and route signs cannot however be placed outside the 12 m zone. In these cases it is sometimes possible to make the obstacles themselves 'collision-friendly', by making them collapsible or guarding them with impact attenuators, for instance. It is not necessary then to protect the entire shoulder with a safety barrier.

When deciding whether to install guide rails, consideration should be given to the effect not only on the seriousness of accidents but also on their frequency and ease of access for the emergency services. The visual guidance afforded by a barrier may help to prevent accidents on the shoulder, for instance; on the other hand the barrier may be a serious impediment to the emergency services should an accident occur.

### 3.2. Bridges and viaducts

Bridges and viaducts are hardly ever able to meet the requirements for a sufficiently obstacle-free zone and must always therefore be protected by a safety barrier. The risk involved in leaving the road is so great, furthermore, that there must be absolutely no question of vehicles penetrating or traversing the barrier. This situation raises considerable design problems in practice, since rigid barriers are needed, which produce a high ground load, whereas the permissible load is restricted by the construction of the bridge deck. There is no obvious standard solution to this problem, and in practice a wide variety of constructions are used, the effectiveness of which is by no means always apparent. In view of the restriction on loads, attempts are often made to provide 'multi-stage' protection where there is sufficient space available.

### 3.3. Special locations

#### 3.3.1. Junctions with bridges etc.

Where a road joins with a bridge, viaduct or tunnel, the junction must be properly protected. If both the structure and the shoulder are protected by safety barriers, these should meet properly. Firstly, the transition should be gradual; secondly, if there is a difference in flexibility between the two barriers, the link should be constructed in such a way that the change is gradual. If the shoulder is not protected by a barrier, a transitional barrier of gradually increasing rigidity must similarly be installed between the shoulder and the barrier protecting the structure. This transitional barrier should prevent a car which leaves the road ending up behind the barrier protecting the structure.

### 3.3.2. Slip roads

In general, shoulders on approach and exit roads do not differ markedly in construction from shoulders on normal roads. The curve radii are an exception: these are usually much smaller on slip roads than on a normal road. The safety barriers on shoulders of slip roads thus require special consideration, since the impact angles can be much larger. Moreover, the upbuilding of the forces takes place differently because of the curvature of the barrier, and with small radii the camber of the road is fairly large, so that the level of the barrier in relation to the road level is important.

### 3.3.3. Gore areas

Gore areas occur on motorways at the start of an exit road. A dangerous situation can arise at such locations in two ways: (a) if there is a rigid obstacle there, e.g. a pillar for a route sign, and (b) if two guide rails needed to protect danger zones meet there. If the ends of the rails are buried flush with the start of the exit road, a car leaving the road could end up on the guide rails or pass between them and land in the zone behind. If the two ends of the rails are joined with a curved rail, the barrier itself has become a more or less rigid obstacle. In either case an impact attenuator can be effective.

#### 4. FUNCTIONAL REQUIREMENTS OF SAFETY BARRIERS

Broadly, the various types of safety barrier can be categorised either as continuous barriers to guard danger zones extending over a great length or as short barriers to guard isolated danger points (impact attenuators). Two types of barrier have proved effective for guarding extended danger zones: steel and concrete barriers. Impact attenuators have been developed to guard danger points: when hit from the side they guide the vehicle and when hit head-on they bring it to a halt in an acceptable manner.

Steel and concrete barriers must meet the following requirements when hit:

- the vehicle must not break through the barrier, ride or tip over it or pass under it;
- the vehicle must not overturn during or after the collision or be deflected back into the stream of traffic;
- the occupants must not suffer serious injury;
- the barrier must remain effective after being hit;
- it must be possible to repair the barrier quickly.

Depending on the situation (e.g. on bridges) impenetrability may be regarded as the most important requirement; the other requirements then take on rather a secondary nature.

An impact attenuator should meet the following functional requirements when hit:

- when hit head-on it should function in such a way that the vehicle is brought to a halt within the length of the impact attenuator; this must also be the case if it is hit head-on diagonally or eccentrically;
- when hit at the side it should have the same effect as a guide rail: it should change the direction of the vehicle so that it is guided alongside the protector and the obstacle;
- the halting or guiding of the vehicle must not result in any serious injury to the occupants;
- in the case of a head-on collision the vehicle must not come to a halt on the carriageway; this means that during a collision the vehicle must not rotate too much and the rebound must be slight;

- if the impact attenuator is hit at the side the exit angle should be small;
- a protector which has been hit must not end up on the carriageway, nor must any parts break away.

## 5. DESCRIPTION OF STEEL BARRIERS

Over the years numerous types of steel barrier have been developed and tried. In this chapter we shall confine ourselves to the principal categories and a few important sub-categories. The discussion will concentrate on their essential operation. We shall consider separately barriers for shoulders and barriers for bridges, viaducts and tunnels.

### 5.1. Some general features

Before we describe the various principal and sub-categories, let us consider some general features of steel barriers. To begin with, it should be noted that steel guide rails are open in section. For riders of two-wheeled vehicles an open construction of this kind is more dangerous in a collision than a closed one, e.g. a concrete barrier. One advantage of a steel barrier over a concrete one, however, is that it is possible to incorporate special facilities to provide access to the other carriageway via the central reserve in emergencies (Jordaan & Van de Pol, 1977). This can be of great value to the emergency services after an accident, especially if the distances between approach roads and exit roads are large.

Both ends of a steel barrier must be anchored in the ground because of the great longitudinal forces which can occur if it is hit. Where the ground is soft, allowance must be made for the fact that the lateral and vertical soil resistance may not be sufficient; consequently broader sections have to be employed. Where the ground is hard there may be excavation problems, and anchor plates are required on structures. There may also be expansion problems on the latter as a result of the different expansion coefficients of steel and concrete: in this case expansion joints must be fitted. One disadvantage of these is that they weaken the barrier and can thus permit greater deflection if it is hit (Van de Pol, 1975; SWOV, 1975).

Steel barriers require more maintenance than concrete ones and they must be regularly inspected for collision damage (even slight). They must also be checked at set times to ensure that the guide rails have not come too

close to road level as a result of either subsidence or a higher road level due to resurfacing.

Before we discuss the particular types, it is worth mentioning, lastly, that anti-dazzle screens can easily be fitted to steel barriers.

## 5.2. Guide rails for shoulders

The various types of guide rails for shoulders can be divided into three principal categories and a number of sub-categories:

### 1. Single beams

- (a) beam fastened directly to supports (posts);
- (b) beam fastened to posts with spacer.

### 2. Composite beams

- (a) beam fastened directly to posts;
- (b) beam fastened to posts with spacer.

### 3. Self-restoring barriers

- (a) single beam hinged to spacer;
- (b) composite beam supported on specially shaped posts.

We shall now discuss the particular operation of each type.

#### 5.2.1. Single-beam barriers (fig. 1)

The operation of a single-beam barrier fastened directly to the posts (fig. 1a) relies mainly on the absorption of energy by the movement of the post through the ground. This depends on two factors: the shape of the post and the soil structure. A wide post provides high ground resistance; it may be so high that the post is not able to move if hit. In this case there is a good chance that the rigidity of the single rail will not be sufficient to enable it to withstand such a load, and plastic deformation (distention) is inevitable. In a situation of this kind a weak post will bend or snap at ground level, and the rigidity of the single rail is large enough to distribute the energy among several bending or snapping posts; however, the vehicle then comes into contact with the bent posts (AASHTO, 1977; Bronstad et al., 1985; Bryden & Phillips, 1985; Gösswein, 1977; Michie & Bronstad, 1971; Troutbeck, 1975).

If the beam is fastened to the posts with spacers (fig. 1b), these ensure that collision with the posts can take place at a much later stage. The area of rail in contact with the vehicle moreover remains at the right height for longer, even if the post bends at ground level. It is also possible to employ spacers which will deform to a certain extent. During a collision both longitudinal and transverse forces are applied to the barrier. The longitudinal forces in the beam act through the spacers to create torsion in the posts. If the posts collapse or turn in the ground under this force, the distance between beam and post decreases and the barrier performs increasingly like one without spacers (AASHTO, 1977; Bronstad et al., 1985; Innenministerium Baden-Württemberg, 1969; Ivey et al., 1982; Michie & Bronstad, 1971; Troutbeck, 1975).

#### 5.2.2. Composite-beam barriers (fig. 2)

A second rail increases the rigidity of a beam fastened directly to the posts (fig. 2a). It is important that the two rails be connected together properly. The greater rigidity of the beam provides a better distribution of forces among the posts. The barrier is better able to cope with a collision, although at a somewhat later stage all the effects of a single beam without spacers occur as described (AASHTO, 1977; Bronstad et al., 1985; Bryden & Phillips, 1985; Gösswein, 1977; Michie & Bronstad, 1971; Troutbeck, 1975).

In the case of a composite beam fastened to the posts with spacers (fig. 2b) the rigidity of the beam is increased by fastening the two rails some distance apart. It is important that the rails be interconnected at regular intervals. The rigidity of the beam can be additionally increased - considerably - by employing diagonals, for instance, or lattice work. This construction also decreases the torsion in the posts due to longitudinal forces. A symmetrically constructed barrier is capable of resisting impact on both sides (central reserve barrier). In a flexible construction where the posts can cut through the ground relatively easily, after a serious collision the rear rail is pushed against the ground, creating additional resistance to any further deflection. The front rail also remains more at the correct height and the posts are still more or less protected. After the collision the barrier retains some operational



capacity (AASHTO, 1977; Bronstad et al., 1985; Gösswein, 1977; Innenministerium Baden-Württemberg, 1969; Michie & Bronstad, 1971; Troutbeck, 1975).

If the posts are sufficiently able to cut through the ground, the pivot of a moving post is somewhat below ground level. The projection of the front rail keeps it in front of the point where the post comes out of the ground; the posts are scarcely likely to be hit. If the ground resistance is so high that the post bends, this will occur at ground level, and the front rail will not provide adequate protection for the posts; in this case the posts can be hit. The seriousness of a collision of this kind (damage to vehicle front suspension) can be reduced by including a collapsible element in the post construction. This does however reduce the operational capacity after a collision.

Whether the front rail remains at the correct height depends partly on the rigidity of the connection between post and spacer. If the rail is connected to the spacer at an oblique angle such that the initial impact between vehicle and rail occurs with the upper part of the rail, an upward torque is created at the connection. Once the post has deflected somewhat the lower part of the rail also comes into contact with the vehicle. The upward movement of the front rail keeps the area of contact between vehicle and barrier sufficiently high and there is little risk of the front rail being pushed down by the impact. If the lower part of the spacer is deformable, the lower corrugation of the rail can give way somewhat under the load, thus keeping the area of contact sufficiently large and preventing serious damage (to vehicle or rail). This lessens the likelihood of the rail collapsing.

Recently experiments have been conducted on a three-wave rail (with three corrugations), which has greater inertia than a two-wave rail and is higher. This enables the height of the barrier to be increased so that goods vehicles etc. are restrained more at their centre of gravity and small vehicles still cannot be caught under the barrier.

### 5.2.3. Self-restoring barriers (fig. 3)

The principle on which the self-restoring barrier operates is that only

the beam is displaced in a collision; the posts should not in theory be allowed to deform or cut through the ground. In a collision the beam is forced obliquely upwards, over a large length because of its high rigidity. A large part of the collision energy is absorbed by inertial forces. After some time the beam will return to its original position, depending on whether there is any plastic deformation. One result of this is that part of the energy is reimpacted to the vehicle, which may be disadvantageous to the further course of the collision.

We shall consider two types of barrier in rather more detail. These can be used both on shoulders as well as on bridges and viaducts and in tunnels.

The first type consists of a single beam hinged to spacers (fig. 3a). The beam comprises two three-wave rails side by side. It is attached to the posts with hinged connectors. Additional spacers are attached between beam and posts. In theory these can be designed so that they deform in a collision as a result of pressure from the beam (Bronstad et al., 1983; Bronstad & McDevitt, 1984).

The second type consists of a composite beam supported on specially shaped posts (fig. 3b). The beam comprises two rails interconnected with spacers. The spacers rest on top of the posts, which are concave in section. If the barrier is hit the rails and spacers are forced to follow this outline. Because of its symmetrical shape this type of barrier can be used on a central reserve (Bronstad & McDevitt, 1984).

### 5.3. Guide rails for bridges, viaducts and tunnels

Guide rails on bridges and viaducts and in tunnels typically differ from those on shoulders in that there is no possibility of the posts cutting through the ground. The supports must therefore be attached to foundations. In this respect the situations on bridges and viaducts and in tunnels are similar. Barriers designed for these situations are henceforth referred to as bridge rails. As regards the danger of penetration, a distinction should be made between bridges and viaducts on the one hand and tunnels on the other; this will be considered when discussing the different types of construction.

The bridge rails developed over the years can be divided into four principal categories and a number of sub-categories:

1. Bridge rails without energy-absorbing devices:

- mounted on the bridge deck;
- mounted against the side of the bridge;
- mounted on a ledge.

2. Bridge rails with energy-absorbing devices:

- with energy-absorbing posts;
- with energy-absorbing spacers.

3. Self-restoring bridge rails. Essentially these are of the same construction as those used on shoulders; only the type of mounting differs. Since their operation has already been described (see para 5.2), these are not considered again here.

4. Special bridge rails to prevent penetration.

The particular operation of each type is discussed below.

5.3.1. Barriers without energy-absorbing devices (fig. 4)

Barriers without energy-absorbing devices comprise single or double-rail beams fastened to the posts either directly or with short spacers. The principle on which this type operates relies mainly on blocking, although in severe collisions some energy may be absorbed by the posts flexing, snapping or shearing. If the beam has sufficient rigidity, the load will be absorbed by several posts and the vehicle will also be guided. Only if the posts collapse is there a danger of it hitting them. If the resistance of the beam is not sufficient, the beam may be subject to distension (serious plastic deformation), as a result of which the vehicle may collide 'head-on' with the next post, with a considerable likelihood of severe damage to vehicle and barrier.

Since in these barriers great forces are exerted on the posts, the latter must be adequately anchored at the base. They may be mounted on the bridge deck (fig. 4a) or against the side (fig. 4b); in many cases they are mounted on a ledge (fig. 4c). The latter gives undesirable side-effects: the vehicle first makes contact with the high concrete curb with its wheels, which may create a tipping force. Depending on the height of the curb, the size of the wheels, the speed and angle of the vehicle and

the distance from the front of the curb to the guide rails, the vehicle may in addition take on an upward motion such that its behaviour becomes unpredictable, as does the extent to which it is guided by the barrier (AASHTO, 1977; Bronstad & Michie, 1981; Bronstad et al., 1983; Bronstad et al., 1985; Michie & Bronstad, 1971).

### 5.3.2. Barriers with energy-absorbing devices (figs. 5 and 6)

The energy absorption of energy-absorbing bridge rails is achieved mainly by building weak points into the connectors or supports.

Barriers with energy-absorbing posts (fig. 5) have a deliberate weak point in the connection between posts and foundations. These may be welds or cross-sectional designs based on tests. In minor collisions energy is absorbed merely by flexion; in more serious collisions fractures occur. The more rigid the beam, the more posts participate in energy absorption. Additional resistance is needed for severe collisions. This two-stage effect can be achieved by having the rear rail rest, in the event of a collision, on the road surface (suitable for central reserves - fig. 5a), against a handrail at the edge of the bridge (fig. 5b) or against a concrete ledge (fig. 5c).

The posts can also be weakened by making them of a special shape (fig. 5d) or allowing them to rotate around a pivot at the base, with most of the kinetic energy absorbed by a hydraulic shock absorber (see fig. 5e; AASHTO, 1977; Innenministerium Baden-Württemberg, 1969; Michie & Bronstad, 1971; Ross & Nixon, 1976; SWOV, 1975).

In barriers with energy-absorbing spacers (fig. 6) the deliberate weak points are in the spacers, which in theory may be of numerous deformable cross-sections. The most common is the tubular section: low large ring (fig. 6a) or high small ring (fig. 6b). If the damage caused by a collision is to be restricted to the spacers, the posts must be sufficiently heavy. It is also possible in theory to attach the beam directly to a concrete wall (e.g. in tunnels) with energy-absorbing spacers (AASHTO, 1977; Kimball et al., 1976; Michie & Bronstad, 1971; Wiles et al., 1977).

### 5.3.3. Self-restoring barriers (fig. 7)

Like self-restoring barriers for shoulders, those for bridges can be divided into the following categories (Bronstad & McDevitt, 1984; Bronstad et al., 1977):

- barriers with a single beam hinged to spacers (fig.7a);
- barriers with a composite beam supported on specially shaped post (fig. 7b).

For their essential operation see para. 5.2.3. It should be noted that the concrete curb in fig. 7a which ends up outside the barrier after a collision can exert certain influences on the wheel of the vehicle and thus on its behaviour.

### 5.3.4. Special barrier to prevent penetration (fig. 8)

This barrier is designed to meet - theoretically - the requirement of impenetrability. The design is based on very severe collision conditions: a vehicle mass up to 50 tonnes, impact speeds up to 80 kmph and angles up to 25-30°. This construction differs from the previous one in its heavy weight, the shape of the posts (leaning towards the carriageway) and the high guide rail (1.8 m). This prevents vehicles with a very high centre of gravity tipping. Since this type of barrier is not suitable for guiding cars, 'normal' guide rails are placed in front of it (Van de Pol & Edelman, 1977).

## 6. DESCRIPTION OF CONCRETE BARRIERS

Concrete barriers can be used both on shoulders as well as on bridges and viaducts and in tunnels. The distinguishing feature of the various types is their cross-section. Two-sided sections are used on central reserves, single-sided on shoulders. The height is about 80 cm. The barriers can be installed on shoulders as separate prefabricated elements or cast in situ using sliding formwork.

### 6.1. Some general features

Concrete barriers are closed in section and thus present less of a danger to two-wheeled vehicles hitting them than open steel barriers.

Proper attention must be paid to the foundations of concrete barriers designed for shoulders. Allowance has to be made for the weight of those structures. In tunnels the barrier can be integrated in the tunnel wall. Drainage holes should be included where necessary to allow water to escape. Less attention needs to be paid to anchoring the ends than in the case of steel barriers, since the longitudinal forces occurring as a result of a collision are slight. Temperature changes cause expansion and contraction of the material; where these are great it may be necessary to fit shrinkage joints. Concrete barriers require little maintenance in general; only after serious collisions may repairs be necessary.

Anti-dazzle screens and noise insulation screens can be fitted on concrete barriers. In some countries they carry other street furniture, e.g. lamp standards. It is not advisable, however, to fit rigid, uncollapsible posts on barriers since it is fairly common for a vehicle colliding with a barrier to mount so high that it lands on top of it. Recesses can be made in the barrier to take cables; it may be divided lengthwise to accommodate these.

Mobile units can be used to protect temporary danger zones, e.g. road-works.

## 6.2. Description of the various designs

Various designs have been developed in the United States: the main types are General Motors, New Jersey and Configuration F. A type known as Tric Bloc has been developed in Sweden. The designs are illustrated in fig. 9.

The American types are 81 cm high. Starting at the base they have a low upright curb followed by a bevelled plane at an angle of  $55^{\circ}$  going into an almost vertical plane (at an  $80-84^{\circ}$  angle with the base). The first difference between the designs is in the height of the curb (or base height): this is approx. 5 cm on the General Motors type and approx. 7.5 cm on the two others. The second difference is in the height of the line dividing the oblique and almost vertical planes. This is highest on the General Motors design, 38 cm; it is 33 cm and 25 cm high on the New Jersey and Configuration F designs respectively (AASHTO, 1977; ACPA, 1979; Michie & Bronstad, 1971).

As well as the New Jersey design, a New Jersey Modified design is used in the United States; this is discussed in the description of the accident studies. The only difference between the modified and ordinary design is that the base is 2.5-5 cm higher on the former. As far as we know, no full-scale tests have been carried out with this type.

The Swedish design differs in various respects from the American types. The cross-section is curved; the overall height is 97 cm; the base height is 20 cm. If the base is embedded rather than placed on a level with the carriageway, the base height is 13 cm (Lidström & Turbell, 1978; Schoon, 1979; Turbell, 1981).

## 7. DESCRIPTION OF IMPACT ATTENUATORS

Impact attenuators are units which can be used to protect danger zones where continuous barriers are not feasible. The following danger zones are suitable.:

- obstacles and danger zones behind gore areas;
- isolated obstacles on shoulders where guide rails are not feasible or not the best solution;
- temporary isolated obstacles, e.g. roadworks.

Over the years many different types of impact attenuator have been developed, particularly in the United States, to halt and/or guide vehicles. Many of these types, however, are little used because of their ineffectiveness or complex construction; we shall not consider these here. We shall discuss the types which are commonly used in the United States and one type developed in the Netherlands.

The designs can be divided into three main categories: collapsible constructions with fenders, energy-absorbing drums and collapsible barrier terminals.

### 7.1. Collapsible barriers with fenders

A collapsible barrier with fenders comprises a U or V-shaped set of fenders (panels or guide rails) which telescope together, with cross-struts on wheels or slides in between. Between the struts is energy-absorbing material. Usually there is a nose section which can also absorb energy (to a small extent). The construction is attached to foundations at the rear. Devices are fitted to restrict lateral movement.

If the impact attenuator is hit head-on, the fenders telescope together; the kinetic energy of the vehicle is absorbed mainly by the energy-absorbing material. If the vehicle hits the barrier on the side it is guided by the fenders. The displacement is slight because of the lateral rigidity of the construction.



The various types differ most markedly in the type of energy-absorbing material used. The main types are:

- GREAT (Guardrail Energy Absorbing Terminal); USA; material: crushable vermicular (see fig. 10; EAS, 1975);
- Hi-Dro Cell Sandwich; USA; material: plastic cylinders filled with water (see fig. 11; AASHTO, 1977);
- Hi-Dri Cell Sandwich; USA; material: crushable vermicular (see fig. 12; AASHTO, 1977);
- Steel drums; USA; (see fig. 13; AASHTO, 1977; Sicking et al., 1982);
- RIMOB; Netherlands; material: aluminium crumpling tubes (see fig. 14; Quack & Schoon, 1982; Schoon, 1982).

### 7.2. Energy-absorbing drums

The typical difference between impact attenuators comprising energy-absorbing drums and the barriers discussed above is that the former lack fenders. The most common type in recent years has been the Energite (Energite Module Inertial Barrier; see fig. 15).

This works as follows (SWOV, 1980; Troutbeck, 1976). When they are hit the drums burst one by one, with the result that a mass of 'floating' sand provides continuous energy absorption. The first drums, which are hit at the highest speed, contain the least sand; following drums contain increasing quantities. The last drums, which finally have to bring the vehicle to a standstill, contain the largest amount of sand. This arrangement makes the deceleration fairly even. The sand is distributed in and among the drums in such a way that the centre of gravity of the sand in the impact attenuator is at the same height as the average centre of gravity of cars. The drums are free-standing and can be placed in any arrangement; no foundations are needed.

### 7.3. Collapsible barrier terminals

Barrier terminals are particularly dangerous to vehicles leaving the road. In special cases (e.g. gore areas) they can be protected with an impact attenuator, which is then joined to the end of the guide rails, for instance. In the Netherlands the ends of guide rails are buried, with an incline of 1:25 (see fig. 16; Slop, 1970).

In the United States a special device has been developed for the ends of guide rails (see fig. 17; Troutbeck, 1976). It consists of a rail bent into the shape of a 6; the foremost posts are collapsible, being made of wood or attached to the foundations with a special device (e.g. a sliding device or welds which break easily). It transpires from full-scale tests that this type of integrated safety device is not effective under certain impact conditions.

Accident research has revealed that in many cases injuries (some of them serious) occur in collisions with it. Because of this we shall not give this device any further consideration in this report.

Recently a new type of collapsible barrier terminal has been developed in the United States. This consists of overlapping rails which telescope together if hit. Although the authors of this report are not aware of any full-scale tests, they would expect this type of device to work more effectively in a collision than the other type discussed.

## 8. TEST RESULTS WITH STEEL BARRIERS

This chapter presents the results of full-scale tests on the safety barriers described in Chapters 5-7 and, where available, mathematical simulations. Use has been made of test results from the following countries: the United States, Federal Republic of Germany, Great Britain and the Netherlands. Appendix 1 describes the conditions under which the American and Dutch tests took place.

Despite the fact that not all the results are well documented and methods of recording vary considerably, we have tried to interpret the results as best we could. Appendix 2 sets out the criteria for the seriousness of a collision. The most common criterion is the Acceleration Severity Index (ASI). A maximum ASI value of 1 is regarded as acceptable for vehicle occupants not using seat belts; the usual value for seat belt users is 1.6. Appendix 3 discusses the way in which measurements were carried out in the full-scale tests.

### 8.1. Guide rails for shoulders

#### 8.1.1. Single-beam barriers (fig. 1)

The tests on barriers with a single beam attached directly to the posts (fig. 1a) were carried out mainly with heavy types of car weighing up to approx. 2,200 kg; a few light cars were also tested. The barrier worked well with impact angles that were not too large and speeds up to approx. 100 kmph. Up to about 15° the damage was slight, to both barrier and vehicle. The exit angles ranged up to 20°. At larger impact angles (speed up to approx. 110 kmph) damage to the vehicle increased. A few vehicles even overturned. The exit angles ranged from 20° to 35°. There was also wide variation in the damage to the barrier, from little damage to distension or snapping of the beam. Usually the posts were hit. In a few tests it was also found that the vehicle left the ground. One test was carried out with a goods vehicle, at an impact angle of 15° and a speed of 70 kmph. The result was bad: the barrier was completely destroyed (AASHTO, 1977; Bronstad et al., 1985; Bryden & Phillips, 1985; Gösswein, 1977; Michie & Bronstad, 1971; Troutbeck, 1975).

The tests on barriers with a single beam attached to the posts with spacers (fig. 1b) mainly used cars in the 1,800-2,200 kg class and a few light cars in the 1,000-1,400 kg class. The barrier worked well at impact angles that were not too large (up to  $15^{\circ}$ - $20^{\circ}$ ) and speeds up to about 110 kmph. The exit angles ranged up to  $10^{\circ}$ . At larger impact angles the damage to vehicle and barrier increased. At angles of  $25^{\circ}$  and upwards vehicles overturned and crossed the barrier; the exit angles also increased, reaching up to  $25^{\circ}$ . Overturning and barrier penetration only occurred in the case of barriers lower than 76 cm. The beam was distended where the intervals between posts were large (3.8 m). In general there was large lateral deflection of the beam over a relatively short length. At impact angles up to  $20^{\circ}$  the ASI value was not much above 1; at angles over  $20^{\circ}$  it was able to exceed 2 (AASHTO, 1977; Bronstad et al., 1985; Innenministerium Baden-Württemberg, 1969; Ivey et al., 1982; Michie & Bronstad, 1971; Troutbeck, 1975).

Tests with goods vehicles and buses of 15,000 kg and 10,000 kg respectively gave reasonable results at an impact angle of  $15^{\circ}$  and a speed of 60 kmph. If the speed was increased to approx. 95 kmph the vehicle tipped even with a barrier height of 84 cm. With a 90 cm-high barrier no tipping was observed (Innenministerium Baden-Württemberg, 1969; Ivey et al., 1982; Troutbeck, 1975).

Because of the spacers the posts were hit only on the more severe collisions; there was serious damage to the vehicle.

#### 8.1.2. Composite-beam barriers (fig. 2)

The tests on barriers with a composite beam attached directly to the posts (fig. 2a) used cars with a mass of 1,000-1,800 kg. The impact angles were  $20^{\circ}$  and  $25^{\circ}$  and the speeds approx. 60-110 kmph. The barriers were damaged, but vehicles were guided well. Damage to the vehicles was serious. The exit angles ranged from  $5^{\circ}$  to  $13^{\circ}$ . The ASI values were over 1.6 (AASHTO, 1977; Bronstad et al., 1985; Bryden & Phillips, 1985; Gösswein, 1977; Michie & Bronstad, 1971; Troutbeck, 1975).

Two tests were carried out with a goods vehicle (mass 10,000 kg) at an impact angle of  $15^{\circ}$  and a speed of 70 kmph. In one test it tipped; in the other the exit angle was  $7^{\circ}$ . The damage was serious in both cases, to both barrier and vehicle (Gösswein, 1977).

The tests on barriers with a composite beam attached to the posts with spacers (fig. 2b) used cars, goods vehicles and buses. The tests described here relate to types 2b/3. The barriers worked well with cars at impact angles that were not too large ( $15-20^{\circ}$ ) and speeds up to about 110 kmph. The largest exit angle observed was  $9^{\circ}$ ; the rolling angles remained small. When the impact angles were increased the exit angles were generally also larger (up to  $60^{\circ}$ ) and the damage to vehicle and barrier increased; the structure of the latter remained intact, however. Overturning was not observed. It was found that adding a collapsible device between post and spacer had advantages only in the case of severe collisions and where the vehicle would otherwise get stuck in the barrier. The ASI values observed ranged from 1 to 2 (AASHTO, 1977; Bronstad et al., 1985; Gösswein, 1977; Innenministerium Baden-Württemberg, 1969; Michie & Bronstad, 1971, Troutbeck, 1975).

The barriers worked reasonably well with goods vehicles and buses provided the impact conditions were not too severe (angles up to  $20^{\circ}$  and speeds up to 80 kmph). Above these values the deflection of the barrier rose to such an extent ( $>1.8$  m) that the posts were hit. The exit angles ranged from over  $10^{\circ}$  to  $45^{\circ}$ . Other tests with goods vehicles (mass 10,000 kg) had a less satisfactory outcome. The main reason was that the front rail did not rise when deflecting because the bumper or cab restricted its freedom of movement. This placed such a great load on the front rail that it snapped in a number of cases and the vehicle penetrated the barrier. The impact angle in these tests was  $20^{\circ}$  and the speeds ranged from 65 kmph to 76 kmph (Gösswein, 1977; Innenministerium Baden-Württemberg, 1969).

With this type of barrier not only full-scale tests but also mathematical simulations were carried out. In this way SWOV examined the differences between collisions with a relatively rigid and a relatively flexible barrier. The flexible type is often preferred by highways authorities; if space is inadequate, rigid guide rails are installed.

Rigidity can be increased by:

- using more posts;
- increasing the ground resistance around the post;
- stiffening the beam.

It was assumed that in a 'standard collision' the deflection of a rigid

guide rail is 0.5 m and that of a flexible barrier 1.5 m. The 'standard collision' was taken to be one with between a medium-weight car (mass approx. 850 kg) and a guide rail at a speed of 100 kmph and an impact angle of  $20^{\circ}$  (Schoon, 1985).

The results of the simulations were as follows. The seriousness of a collision with a rigid barrier was greater than that of a collision with a flexible barrier. In terms of combined decelerations (ASI) the difference was about 35% on average. The amount of rebound can be indicated in terms of the exit angle and the yawing angle. The more flexible the barrier, the smaller the exit angle. Under the various impact conditions a rigid barrier gives exit angles about  $5^{\circ}$  larger on average than a flexible barrier. The combination of large impact angle and low speed (which is more likely to occur on single-lane roads than on two-lane roads) gives larger exit angles than the combination of small impact angle and high speed. This is more the case with the rigid barrier than with the flexible one. An additional  $5^{\circ}$  or so in impact angle in general gives an increase of about  $2^{\circ}$  in the exit angle. The yawing angle does not really depend on the type of barrier but mainly on the inertia of the vehicle around its vertical axis and the friction coefficient of the road surface.

### 8.1.3. Self-restoring barriers (fig. 3)

One test was carried out with a barrier comprising a single beam hinged to spacers (fig. 3a). It used a car (mass 2,018 kg); the impact angle was  $25^{\circ}$ , the speed 96 kmph. The collision was so severe that a few posts ploughed through the ground and were displaced about 20 cm. The spacers prevented the posts being hit. The damage to the barrier was slight, but the vehicle was badly damaged (Bronstad et al., 1983; Bronstad & McDevitt, 1984).

The barrier with a composite beam supported on specially shaped posts (fig. 3b) was tested with two cars (mass 2,062 kg and 907 kg) and a bus (mass 18,000 kg). The barrier worked well with the cars (impact speed approx. 95 kmph, angles  $26^{\circ}$  and  $17^{\circ}$ ). In the collision with the heavy car the posts were slightly displaced. The damage to the barrier was zero. In the collision with the bus (impact angle 91 kmph, angle  $14^{\circ}$ ) there was

some damage to the beam; a few rails and the guiding mechanism were bent. The rolling angle reached  $17^{\circ}$ . The bus suffered damage only to the bodywork (Bronstad & McDevitt, 1984).

## 8.2. Guide rails for bridges, viaducts and tunnels

### 8.2.1. Barriers without energy-absorbing devices (fig. 4)

In these barriers the beam was attached directly to the posts, which were mounted on or against the side of a simulated bridge deck. Tests were carried out with various cars (mass 1,020 - 2,040 kg). In those with a high impact speed and a large angle (100 kmph,  $20^{\circ}$ ) a large dynamic deflection occurred, exceeding 1 m. In practice there is a considerable likelihood of the vehicle leaving the bridge in such a case. The damage to vehicles and barriers was considerable.

A test was also carried out with a bus (mass 9,070 kg). The impact angle was small ( $7.5^{\circ}$ ); the speed was 77 kmph. The maximum rolling angle of the vehicle was  $15^{\circ}$ . The bus was still driveable after the collision. The damage to the barrier was moderate.

Tests were also carried out with barriers mounted on a 25 cm high concrete curb. Cars with a mass of approx. 1,575 kg were used. The impact angles ranged from  $7^{\circ}$  to  $35^{\circ}$  and the speeds from 64 kmph to 98 kmph. The 25 cm concrete curb caused considerable damage to the front suspension. The vehicles were not observed to 'jump', however. Tests with a lower (15 cm) concrete curb produced less damage to the front suspension (AASHTO, 1977; Bronstad et al., 1983; Bronstad & Michie, 1981; Bronstad et al., 1985; Graham et al., 1967; Michie & Bronstad, 1971).

### 8.2.2. Barriers with energy-absorbing devices (figs 5 and 6)

The barrier with energy-absorbing posts (fig. 5) was tested with cars, buses and goods vehicles with a mass of approx. 1,000 kg, 10,000 kg and 3,500-10,000 kg respectively. Except in the tests with the heaviest goods vehicle the barrier worked well. The exit angles were between  $4^{\circ}$  and  $12^{\circ}$ . The damage to vehicles and barrier was moderate. In the tests with a handrail behind the barrier it was clear that the handrail had a significant share in the favourable outcome of the collision, owing to the

two-stage effect. In the test with the 10,000 kg goods vehicle the hand-rail was not strong enough (Innenministerium Baden-Württemberg, 1969; Michie & Bronstad, 1971; Ross & Nixon, 1976; SWOV, 1975).

Tests were also carried out with a barrier with energy-absorbing spacers (fig. 6) with a length of approx. 60 cm; the barrier was approx. 1.5 m high. The tests with cars had a satisfactory outcome. The large exit angles (approx.  $12^{\circ}$ ) were no doubt caused by the low rigidity of the beam. The damage to barriers and vehicles was slight. The ASI values were over 1 in all the tests.

In the test with a light bus (8,600 kg) there was moderate damage to the barrier; in that with a heavy bus (18,000 kg) the barrier was seriously damaged (post-bridge connection). The maximum rolling angle was  $20^{\circ}$ . The test with a light tractor and semi-trailer (18,000 kg) caused the same damage to the barrier as the bus tests.

When the connection between post and bridge was weakened and the beam made more rigid there was less structural damage in the collisions with the heavier vehicles. The tests with these latter clearly showed the value of a high barrier (approx. 1.5 m): none of the vehicles tipped (Kimball et al., 1976).

Lastly, six tests were carried out with low barriers (70 - 80 cm) and shorter energy-absorbing spacers (15 cm). Only cars were used (mass ranging from 966 kg to 2,040 kg). The outcome was good: slight damage to barriers and vehicles. The vehicles were still driveable after the collisions (AASHTO, 1977; Wiles et al., 1977).

### 8.2.3. Self-restoring barriers (fig. 7)

In the test on the barrier with a single beam hinged to spacers (fig. 7a) the barrier was mounted on a concrete curb. When the beam was pushed back, this brought the curb outside the operating area of the beam. The rail worked as intended: in collisions with lighter cars (about 1,000 kg) the rail moved obliquely upwards. No damage to the barrier was observed. The vehicle did come into contact with the curb, but was still driveable afterwards. In collisions with heavier cars (mass about 2,000 kg) the outcome was similar but the damage to the vehicles was greater: the suspension was dislocated, probably because of hitting the curb. Tests with buses (mass 9,000-18,000 kg) also had a good outcome. The largest



rolling angle observed was  $15^{\circ}$ . The damage to barriers and buses was slight (Bronstad et al., 1983; Bronstad & McDevitt, 1983).

The barrier with a composite beam supported on specially shaped posts (fig. 7b) was not tested, but its effect is likely to correspond to that of the similar barrier for shoulders (see para. 8.1.3).

#### 8.2.4. Special barrier to prevent penetration (fig. 8)

No full-scale tests were carried out with this type of bridge barrier; various mathematical simulations with heavy types of vehicle (mass 30,000-40,000 kg) were however done. The maximum deflection of the barrier which occurred in the simulations was about 1.2 m. This was such that the wheels of the vehicle remained on the carriageway. The rolling angles showed that the beam height accorded well with the centre of gravity of the vehicles selected. Because of the heaviness of the barrier high vehicle decelerations occurred in collisions with lighter goods vehicles and buses (Van de Pol & Edelman, 1977).

## 9. TEST RESULTS WITH CONCRETE BARRIERS

The General Motors and New Jersey designs are the most common. When discussing these we are able to make use of the results not only of full-scale tests and mathematical simulations but also of accident studies. The Configuration F design developed in the United States and the Swedish Tric Bloc design will be discussed on the basis of the results of full-scale tests. See fig. 9.

### 9.1. General Motors and New Jersey types

#### 9.1.1. Results of accident studies

In the early seventies an accident study was carried out into collisions with three types of concrete barrier: General Motors, New Jersey and New Jersey Modified (Bronstad et al., 1977). A total of 540 accidents were collected and classified according to the seriousness of the outcome (see Table 1); other factors considered were whether the vehicle overturned and whether it mounted the barrier.

There were relatively more accidents involving injury with a serious outcome with the General Motors type than with the other two types. The only reported accident with a fatal outcome involved a New Jersey Modified barrier. The lowest number of roll-over accidents occurred with the ordinary New Jersey type: 4% of the total number of accidents with this type. The figures for the General Motors and New Jersey types were 6% and 12% respectively. In only a few cases was it reported that the vehicle mounted the barrier. This occurred four times with the General Motors type and once with the New Jersey type. Such accidents can cause serious injuries if posts (e.g. lamp standards) are mounted on the barrier.

Another study dealt only with accidents with the General Motors type. In one year 170 accidents were reported and subsequently analysed (Schlosser, 1973). The outcome was as follows:

- 67% of the vehicles came to a halt near the barrier;
- 18% of the vehicles rebounded onto the carriageway; in a quarter of the cases this resulted in a secondary collision;
- 7% of the vehicles mounted the barrier;

- 8% of the vehicles went over the top (13 accidents in all); five landed on the other carriageway.

It should be realised that these accident studies looked only at recorded accidents, which are generally accidents with a fairly serious outcome. The following survey (Bronstad et al., 1977) gives some idea of how these accidents relate to the total number of collisions with a concrete barrier. It was established at two locations how many contacts took place with a barrier (on the basis of traces) over a certain period and how many accidents were recorded. Altogether 100 contacts were found, 32 of which were recorded as accidents.

### 9.1.2. Full-scale tests

#### Tests with cars

In American tests (AASHTO, 1977; Bronstad et al., 1977) using cars with a mass of approx. 2,000 kg at impact speeds of approx. 100 kmph the General Motors type produced a somewhat larger rolling angle (vehicle rotation around the longitudinal axis) at small impact angles (approx.  $7^{\circ}$ ) than the New Jersey type. The exit angles did not exceed  $7^{\circ}$ . At an impact angle of approx.  $15^{\circ}$  there was little difference between the two types. The exit angle was larger with the New Jersey type than with the General Motors type ( $12^{\circ}$  and  $5^{\circ}$  respectively). Only the New Jersey type was tested at an impact angle of  $25^{\circ}$ : the vehicle deceleration in terms of ASI was very high; in two of the 12 cases the vehicle overturned. The exit angles were no more than  $8^{\circ}$ . In these tests with heavy cars under similar impact conditions the ASI values found differed a good deal (by a factor of 2-3).

Tests have also been carried out using cars with a mass of approx. 1,000 kg; the impact angles differed, and the speed was approx. 90 kmph. At an impact angle of  $7^{\circ}$  little difference was found in rolling angle between the General Motors and New Jersey types. The ASI values were higher with the General Motors type than with the New Jersey type. The exit angles did not exceed  $4^{\circ}$ . At an impact angle of  $15^{\circ}$  the General Motors type was tested with one vehicle, which overturned. With the New Jersey type the rolling angles of the two vehicles in the test were small, as were the

exit angles. Only the New Jersey type was tested at an impact angle of  $20^{\circ}$ . The rolling angle was small; the ASI value, on the other hand, was about twice that for an impact angle of  $15^{\circ}$ .

Various tests have been carried out with five different versions of the General Motors and New Jersey barriers in Great Britain (Jehu & Pearson, 1977). The differences were mainly in the height of the vertical base. A barrier with a horizontal plane halfway up was also tested. Two tests were carried out involving a medium-weight car with a mass of approx. 1,500 kg and eleven with small cars with a mass of 760 kg (including ballast). All the tests were made at an impact angle of  $20^{\circ}$  with speeds ranging from 85 kmph to 116 kmph. The outcome of the tests with the eleven small cars was generally bad. In most cases the front wheel mounted to a height of over 75 cm. In seven cases the vehicle overturned. In several cases this was due to vehicle rotation on the carriageway, with the vehicle ending up on the non-metalled part of the test strip. The exit angle did not exceed  $10^{\circ}$ . The longitudinal deceleration ranged from 1 g to 9 g. In general there was not much difference between the various types tested. The three tests with a New Jersey barrier without base gave relatively the best outcomes; the front wheel mounted no higher than 70 cm and in one case the car overturned. In the two tests with medium-weight cars little difference was found between the General Motors and New Jersey types (both with a higher base than normal). The front wheel mounted to a height of 80 cm, the exit angle was no more than  $8^{\circ}$  and the vehicles did not overturn.

The New Jersey barrier was tested in France with a medium-weight car; the impact speed was 84 kmph and the angle  $30^{\circ}$ . The car did not overturn and the exit angle was small (Guimarho, 1978).

As regards damage to cars, in general it may be noted that there was little damage to bodywork in collisions at small impact angles; the vehicles retained steering control afterwards. In collisions at large impact angles, on the other hand, serious damage to the chassis was possible. The vehicles did not then usually retain steering control. There was little difference between the damage to cars hitting the General Motors barrier and those hitting the New Jersey barrier.

### Goods vehicles and buses

Full-scale tests have been carried out with heavy vehicles in the United States with the principal aim of testing the strength of concrete barriers. These involved tractors and semi-trailers, Intercity buses and school buses. The mass of the vehicles ranged from 9,000 to 23,000 kg. The height of their centre of gravity ranged from 77 to 160 cm; that of the semi-trailers was approx. 180 cm. In most of the vehicles it was thus above the height of the concrete barriers, which is 81 cm. The barriers were tested at impact speeds of approx. 55-100 kmph; the angles ranged from  $6^{\circ}$  to  $20^{\circ}$  (AASHTO, 1977; Davis et al., 1981; Wiles et al., 1977). A striking result of the tests was that on collision the heavy vehicles rotated towards the barrier; cars rotated in the opposite direction. This is due to the heavy vehicles' higher centre of gravity. The higher the vehicle speed, the greater the rolling angle. At 100 kmph the vehicle tended to overturn (rolling angle  $45^{\circ}$ ). In two cases the front wheel on the collision side mounted over 50 cm. The exit angles were  $10^{\circ}$  or less, except in the case of the school buses, which were tested at the highest speed, almost 100 kmph; here the exit angle was approx.  $15^{\circ}$ .

The decelerations were significantly lower in the case of the Intercity buses than in the case of the goods vehicles and school buses. It seems reasonable to assume that this is related to the difference in bodywork construction. The front wheels of the Intercity buses are protected by continuously low bodywork, and they are further back. If an Intercity bus hits a concrete barrier the greatest force is exerted on the deformable bodywork. In the case of the school buses and goods vehicles the largest transverse force is brought to bear more or less directly on the rigid suspension, which causes much greater decelerations.

After the collisions the Intercity buses still retained steering control in most cases. The school buses had their front wheels knocked away from under them in both collisions, which subsequently resulted in the bus overturning. It should be noted here that the impact speeds of the school buses were over 10 kmph higher than those of the Intercity buses.

The tractors of the goods vehicles with torpedo steering still retained steering control after the collision, but the impact speeds were not particularly high (54-72 kmph). The one test involving a tractor with front steering (impact speed 85 kmph) had a bad outcome due to the overturning cab becoming separated.

In the initial tests with goods vehicles and buses the barriers were seriously damaged. In subsequent tests they were in most cases strengthened with steel beams and sandbags at the rear.

A collision test involving a bus was carried out in Great Britain on a New Jersey barrier with a height of 150 cm instead of the usual 81 cm. The impact speed was 72 kmph and the angle  $20^{\circ}$ . The rolling angle was  $13^{\circ}$  towards the barrier. This rotation by the bus was limited by contact between the raised top of the barrier and the side of the bus; the front, side and rear windows were broken. The bus continued its way parallel to the barrier, which was not damaged structurally (Jehu & Pearson, 1977).

A New Jersey barrier was tested in France using a goods vehicle with a mass of 10,000 kg (impact speed 72 kmph, angle  $20^{\circ}$ ) and a bus (impact speed 70 kmph, angle  $20^{\circ}$ ). In neither test did the vehicle go over the top; the exit angles were small. The concrete barriers were not damaged (Guimarho, 1978).

#### 9.1.3. Mathematical simulations

In the case of the General Motors and New Jersey barriers SWOV (Schoon et al., 1985) has investigated mathematically what effect changes in speed, impact angle and vehicle mass have on vehicle deceleration (expressed in ASI) and mounting by the front wheel on the collision side. The latter gives a better idea of the vertical position of the vehicle in relation to the barrier than the rolling angle; if both front wheels (or even the entire vehicle) rise to the same extent, the rolling angle stays low. The results of the mathematical simulations were verified first of all against the results of full-scale tests. This showed that the results of collisions at small impact angles are fairly reliable; at larger angles they must be regarded as an indication.

More simulations were carried out under various impact conditions with medium-weight cars (mass approx. 850 kg) than with light and heavy ones; consequently rather more general tendencies can be indicated in this class. The speeds selected ranged from 60 kmph to 100 kmph and the impact angles from  $5^{\circ}$  to  $30^{\circ}$ .

Fig. 18 shows that vehicle deceleration increases as impact angle and speed increase, both with the General Motors and the New Jersey type. In this respect there is not much difference between the two types.

Fig. 19 shows the effect on mounting by the front wheel, which increases as impact angle and speed increase in the case of the New Jersey type. At 100 kmph mounting is already unacceptable at an impact angle as low as  $10^{\circ}$ . With the General Motors type mounting is less predictable; unacceptable mounting heights can occur at lower speeds and smaller impact angles.

The simulations with light and heavy cars (mass 600 kg and 1,250 kg respectively) were carried out under four sets of impact conditions: 100 kmph/ $10^{\circ}$ , 100 kmph/ $15^{\circ}$ , 80 kmph/ $20^{\circ}$  and 60 kmph/ $30^{\circ}$ . The ASI values and mounting by the front wheel are plotted against a combination of impact speed and angle in figs. 20 and 21. The component used for impact speed was that at right angles to the barriers, expressed as  $v \cdot \sin \alpha$  (where  $v$  = speed and  $\alpha$  = impact angle. This component helps to determine the kinetic energy of the vehicle.

Fig. 20 shows the ASI values from simulations with the New Jersey type for the three types of vehicle (light, medium-heavy and heavy). Except in the case of the impact conditions 60 kmph -  $30^{\circ}$  with a medium-heavy vehicle, the curves are smooth: the light vehicle yields the highest ASI values, the heavy vehicle the lowest and the medium-heavy vehicle intermediate values.

The New Jersey type gives a reasonably smooth pattern as regards mounting by the front wheel for the light and heavy cars as well: as  $v \cdot \sin \alpha$  increases the mounting height also increases (fig. 21). With the General Motors type there is more of a falling tendency. If we look at the impact conditions only at speeds of 80 kmph and 100 kmph (angles  $10^{\circ}$ ,  $15^{\circ}$  and  $20^{\circ}$ ), we find that the light car mounts least on the New Jersey type, whereas the heavy car mounts least on the General Motors type (maximum mounting height in both cases 45 cm). The light car climbs very high on the General Motors type, the heavy car on the New Jersey type (mounting height approx. 100 cm).

In addition, SWOV carried out a limited number of mathematical simulations with a car (850 kg) and the New Jersey barrier. The results indi-

cate that mounting of the car is reduced as the friction coefficient of the barrier decreases. Overturning could then be prevented, even under serious impact conditions. On the one hand this implies that the effectiveness of the construction is dependent on weather conditions that influence the friction coefficient of concrete, but on the other hand it may indicate possibilities for improving effectiveness. The friction coefficient of the pavement next to the barrier has also an influence on the operation of the barrier; in this case reduced friction degrades its effectiveness.

## 9.2. Configuration F and Tric Bloc types

The difference between the Configuration F and New Jersey types is only in the height of the dividing line between the two inclined planes: this is lower in the former (see fig. 9). Full-scale tests at relatively small impact angles ( $7^{\circ}$  and  $15^{\circ}$ ) show that a lower dividing line has a better effect on mounting by the front wheel; this applies to both the 1,000 kg and 2,000 kg class of vehicle. At an impact angle of  $25^{\circ}$  there is little difference between the Configuration F and New Jersey types. The vehicle decelerations and exit angles are of the same order with the Configuration F type as with the two other American types (Lidström & Turbell, 1978).

The Tric Bloc type features a cross-section which follows a certain curve radius. It has been modified several times. We are aware of three documented tests with the latest design. In all three (impact angles  $15^{\circ}$  and  $25^{\circ}$ ) the vehicles mounted particularly high up the barrier (over 80 cm). The vehicle decelerations were not recorded (Lidström & Turbell, 1978; Turbell, 1981).



## 10. TEST RESULTS WITH IMPACT ATTENUATORS

The types of impact attenuator described in Chapter 7 have been tested in head-on and sideways-on collisions. In the former the majority of the kinetic energy ( $= \frac{1}{2} mv^2$ ) of the vehicle should be absorbed by the barrier. The greater the mass and speed of the vehicle, the more stringent the requirements on the impact attenuators should be.

The impact attenuators developed in the United States are designed for heavy American vehicles. With these the deceleration is distributed as evenly as possible over the duration of the collision. If a lighter (European or Japanese) vehicle collides with a barrier of this kind the deceleration is much higher. In recent years the proportion of lighter cars in the United States has increased considerably, and the test conditions applied there now take account of this. The American impact attenuators described in this report are all (as far as we know) still constructed for the heavier types of car with a mass of about 2,000 kg.

The RIMOB has been developed in the Netherlands and is designed for Dutch (European) cars. It is accordingly lighter in construction than the American types. The vehicle used in tests with the RIMOB had a mass of 850 kg (including dummy and instruments).

In this chapter we give a brief account of the results of tests with the collapsible barriers with fenders and the energy-absorbing drums. Results of accident research are also given.

### 10.1. Collapsible barrier with fenders

In general, it may be concluded from the full-scale tests carried out in the United States that the impact attenuators developed there work well. In head-on collisions the cars were brought to a halt within the length of the impact attenuator; in sideways-on collisions the barrier guided the car well. In offset head-on collisions (i.e. where the axes of vehicle and impact attenuator were offset : 40-50 cm) there was vehicle rotation. This can result in the vehicle coming to a standstill on the carriageway. In the tests with heavy (American) cars the vehicle decelera-

tion (expressed in ASI) was unacceptable if the occupants are not using seat belts but acceptable if they are. Lighter (European) cars gave deceleration levels unacceptable even for occupants with seat belts (AASHTO, 1977; Segal, 1976; SWOV, 1980; Troutbeck, 1976).

The RIMOB, developed in the Netherlands, worked in the same way as the American devices described above in head-on and sideways-on collision tests. In the offset tests there was again vehicle rotation. The decelerations (expressed in ASI) measured on cars with a mass of about 850 kg were at a level which is unacceptable for occupants without seat belts but acceptable for occupants with seat belts (Quack & Schoon, 1982; Schoon, 1982).

During the 1980-82 period a study was carried out into accidents involving impact attenuators in the American state of Kentucky. The following types were included: Hi-Dro Cell, GREAT, steel drums and sand barrels. Altogether 116 accidents were analysed. The study showed that in 85% of cases the impact attenuator worked satisfactorily. In the remaining cases the devices did not work well, causing vehicles to overturn or rebound excessively, among other things. The percentage of accidents with injuries was fairly high (38); the proportion of accidents with deaths or fatal injuries was 16%. In nine cases a lighter category of car was involved; here the proportion of accidents with injuries was 67%, significantly higher than in the overall figures. No large differences between the various types of impact attenuator are ascertainable from the study (Pigman et al., 1984).

Since 1983 about 50 RIMOB impact attenuators have been installed in the Netherlands. So far seven accidents have taken place with this type; none of them involved injuries.

## 10.2. Energy-absorbing drums

The Energite impact attenuator described in Chapter 7 has been tested in various ways with American and European (Japanese) cars. In a number of head-on collisions involving an American test vehicle the car shot through the entire barrier. This did not happen with lighter types of

car. In head-on collisions at an angle the vehicle rotated severely. In the head-on collisions the vehicle deceleration was acceptable for occupants with seat belts. Tests with sideways-on collisions gave poor results: either the vehicle rotated severely or it shot through several drums and hit the protected obstacle (AASHTO, 1977; SWOV, 1980; Troutbeck, 1976; Young, 1975).

## 11, EVALUATION OF TEST RESULTS

In this chapter we give an assessment of the way steel guide rails, concrete barriers and impact attenuators work on the basis of the test results. The steel and concrete barriers are judged on the basis of a checklist of constructional aspects arising from the functional requirements formulated in Chapter 4.

### 11.1, Steel barriers

#### 11.1.1. Constructional aspects

The functional requirements for safety barriers can be translated into the following constructional aspects in the case of steel barriers:

- the beam must be rigid;
- the beam must be strong enough to prevent penetration;
- the beam must operate at and over an adequate height, even at full deflection;
- the beam must protect the supports sufficiently, even at full deflection;
- the supports and/or spacers must progressively deflect and/or deform when hit, absorbing the collision energy;
- energy which is absorbed must not be reimpacted to the vehicle; it may be absorbed by plastic deformation and friction; elastic or potential energy absorbed must not be released until the vehicle has left the barrier.

#### 11.1.2. Assessment of the various types

The types are assessed in the same order as that in which they are described in Chapter 5.

##### Single-beam barriers for shoulders (fig. 1)

The barriers in which the beam is attached directly to the posts (fig. 1a) are not suitable, because:

- the posts are hit in a collision;
- the beam does not remain at the correct height when it deflects;
- the beam cannot easily be stiffened.

The barriers with spacers (fig. 1b) are also not suitable. The type shown in fig. 1b-1 is not suitable because the area of contact between vehicle and beam drops as the beam deflects (danger of overturning). The types shown in figs 1b-2 and 1b-3 are not suitable because the rigidity of the beam cannot easily be increased and progressive deflection cannot be programmed.

#### Composite-beam barriers for shoulders (fig. 2)

The types where the beam is attached directly to the posts (fig. 2a) are not suitable because the beam does not remain at the correct height when it deflects and the posts are hit. The type with spacers shown in fig. 2b-1 is also not suitable because the area of contact between vehicle and beam drops as the beam deflects (danger of overturning). The types with spacers shown in figs 2b-2 and 2b-3 are suitable; the latter is to be preferred because:

- the beam remains more at the correct height when hit;
- the posts are not so likely to be hit;
- there is a two-stage effect in the case of collisions involving heavy vehicles.

#### Self-restoring barriers for shoulders (fig. 3)

Both types of self-restoring barrier are suitable. The transverse deflection is less than with the type shown in fig. 2b-3. It is not known what effect this has on the risk of injury to the occupants. It is easier to obtain a progressive effect with the type in fig. 3a than with that in fig. 3b.

#### Bridge rails with energy-absorbing devices (fig. 4)

This type is not suitable: if it has rigid posts which do not deform easily the vehicle decelerations are too high; if it has weak posts, the same objections apply as to similar barriers for shoulders.

#### Bridge rails with energy-absorbing devices (figs 5 and 6)

The types with energy-absorbing posts shown in figs 5a, 5b and 5c are suitable. It should however be noted that the connection between post and foundation consists of a 'programmed' weld. If the weld breaks completely the beam may deflect too far and rotate. The types in figs 5d and 5e are

also suitable in theory, but there is too little empirical experience of their operation.

The types with energy-absorbing spacers (fig. 6) are both suitable, although it should be noted that the amount of transverse displacement differs from one type to another; what effect this has on vehicle deceleration - and thus on the risk of injury - is not clear.

#### Self-restoring bridge rails (fig. 7)

Both types of self-restoring barrier are suitable; see also the comments on the self-restoring barriers for shoulders.

#### Special bridge barrier to prevent penetration (fig. 8)

This type is suitable, but can only be employed in combination with a safety barrier in front of it.

### 11.2. Concrete barriers

#### 11.2.1. Constructional aspects

The main constructional aspects of concrete barriers are:

- the barrier must be sufficiently strong;
- the barrier must be sufficiently high;
- the barrier must prevent the wheels from mounting too high;
- the vehicle must be guided primarily through its wheels; this obviates excessive contact forces between bodywork and barrier.

#### 11.2.2. Assessment of the various types

Before judging the various types we should like to make some general comments. Because of the low area of contact in a collision there is a tendency for heavier vehicles with a high centre of gravity to tip. With the normal barriers, with a height of approx. 80 cm, this can result in overturning. This problem does not present itself in tunnels if the barrier is integrated in the tunnel wall. In collisions involving cars there is the problem of the wheels on the collision side mounting the barrier; this is not permissible because of the risk of overturning. Here again overturning is less likely to occur if the barrier is integrated in

the tunnel wall. When hit at small impact angles the concrete barriers essentially work well on the basis of wheel guidance. At greater impact angles the wheels are not usually guided in the first instance but there is direct contact between bodywork and barrier. This causes high vehicle deceleration, which increase the risk of serious injury.

#### General Motors and New Jersey types (fig. 9)

With the New Jersey type the front wheel mounts higher the greater the impact angle; with the General Motors type mounting by the front wheel is unpredictable. Impact speeds over 80 kmph and angles over about  $25^{\circ}$  give unacceptable mounting heights with both types (with the risk of overturning).

#### Configuration F type (fig. 9)

The Configuration F type produces slightly higher vehicle decelerations in collisions than the General Motors and New Jersey types. The front wheel mounting height with the Configuration F type is significantly smaller at small impact angles ( $5-15^{\circ}$ ) than with the other two types; at larger angles ( $20-30^{\circ}$ ) the mounting height is as unacceptable as with the other two types.

#### Tric-Bloc type (fig. 9)

Nothing can be said about vehicle deceleration because of the absence of measurements. The front wheel mounting height with this type is unacceptable.

### 11.3. Impact attenuators

The following general comments must suffice as an assessment of impact attenuators. The types which can be regarded as good barriers are those which collapse when hit head-on and are fitted with fenders. They must have a progressive effect geared to the common types of vehicle. For use in a country with mainly lighter cars the RIMOB impact attenuator is suitable, as are the American types geared to European and Japanese types of car. The impact attenuator with energy-absorbing drums is not suitable because of the absence of fenders.

## 12. CONCLUSIONS

Taking into account the relatively poor quality of available safety criteria, the following conclusions can be drawn from the tests.

Good steel barriers can be identified as having a rigid beam which does not as a rule suffer plastic deformation, and supports and connectors which absorb the collision energy. It is important in a collision that the area of contact between vehicle and construction be high and remain so even if the beam deflects. Self-restoring barriers are also essentially good, provided the collision energy absorbed by the barrier is not reimpacted to the vehicle.

Various types of steel barriers perform well when hit by cars (impact speeds up to 100 kmph, approach angles up to  $20^{\circ}$ ); when hit by rather heavy vehicles various types perform satisfactorily, provided the impact conditions are not too severe (speeds up to 80 kmph, angles up to  $15^{\circ}$ ). Before a choice can be made among the many types further research is needed into matters including the relationship between vehicle deceleration and transverse beam displacement, in conjunction with research into the effect of progressive barrier operation.

In their present form the non-deformable concrete barriers can be regarded as unsafe when hit by cars under severe impact conditions (speeds  $> 80$  kmph, angles  $> 15^{\circ}$ ) because of the mounting effect and the possibly excessive vehicle decelerations. When hit by heavy vehicles the concrete barriers perform satisfactorily. In the case of vehicles with a high centre of gravity, however, there is a danger of overturning. The latter does not occur if the barrier is integrated in a tunnel wall. Research is needed to indicate how far the design can be improved, specially with respect to the friction coefficient of the barrier and the surrounding pavement.

A good impact attenuator can be identified as bringing the vehicle to a halt in an acceptable way when hit head-on and guiding it when hit at the side. In the European situation only those types geared to European cars are acceptable.



### 13. RECOMMENDATIONS FOR RESEARCH

It was stated in Chapter 11 whether each particular type of safety device is suitable. Restrictions were indicated for some types which were otherwise regarded as suitable; these were necessary because in many cases there is not sufficient knowledge on which to base a well-grounded judgement. This chapter indicates what research is needed to establish the relationships between the collision process (in particular impact conditions and outcome of accident) and the constructional features of various of the barriers examined. These relationships must be known:

- for the most effective safety barrier to be selected;
- for existing barriers to be modified;
- for the basic features of a new type of safety barrier to be decided.

#### 13.1. Research into injury criteria

The most common indicator of the seriousness of a collision with a safety barrier is vehicle deceleration. Using very rough criteria the risk of serious injury can be estimated. It is better to use indicators which give an immediate idea of the violent forces acting on the occupants. A good deal of research is still needed, however, before good estimates of the risk of injury can be made. In any event a good knowledge of the overall acceleration field in the vehicle is needed for present or future criteria to be applied; Appendix 4 sets out how the accelerations at any given point in a vehicle can be calculated.

This seems not exactly an item which fits into the framework of research into safety barriers. It will however have to be determined, in a more applied form, what influence the large difference in vehicle decelerations between deformable and non-deformable barriers has on the risk of serious injury; the difference is in fact about a factor of 3 (expressed in ASI) against the non-deformable concrete barriers.

#### 13.2. Research into constructional aspects

More research is needed into various constructional aspects; these are outlined below in main categories.

### 13.2.1. Steel barriers

A. The relationship between transverse deflection and risk of injury.

Comment

With various types of barriers for shoulders a deflection of 1-1.5 m is reached in a collision involving a car. With barriers for bridges the deflection is often only 20-30 cm.

B. The relationship between a progressive build-up of forces in beam deflection and the risk of injury.

Comment

It is probably desirable to have a 'soft' impact at the beginning of the collision (relatively easy deflection) followed by an increase in reactional forces the more the barrier deflects. A progressive build-up of this kind also helps to cope with the large differences in mass between the various types of vehicle involved.

C. The relationship between the rigidity (deflection) of the barrier and the magnitude of exit angle and vehicle rotation. The friction between vehicle and road surface (surface of shoulder) probably has a considerable influence here.

Comment

The rebound may be greater with rigid barriers than with flexible ones. The exit conditions are likely to be better the greater the friction coefficient between the vehicle and the ground. There is a large difference in friction coefficient between a layer of asphalt and a sand or grass shoulder.

D. The relationship between the height of the guide rails (in conjunction with the transverse deflection) and the overturning of vehicles with a high centre of gravity.

Comment

The height of the present guide rails seems to be sufficient for most types of vehicle. In some cases it may be necessary to eliminate the danger of overturning as far as possible for higher types of vehicle.

13.2.2. Concrete barriers

A. The relationship between cross-sectional design and/or friction coefficient and the extent to which the wheels on the collision side mount the barrier.

Comment

The front wheel mounting heights of cars are unacceptable with the present barriers. It should be investigated to what extent they can be improved.

B. The relationship between the height of the barrier and the danger of tipping in the case of goods vehicles.

Comment

Unlike cars, goods vehicles tend to tip towards the barrier in a collision.

C. The course of the collision in relation to the friction between vehicle and road surface.

Comment

We have the impression that the collision takes a better course the greater this friction. If this is the case, it should be taken into account when installing concrete barriers on shoulders, for instance.



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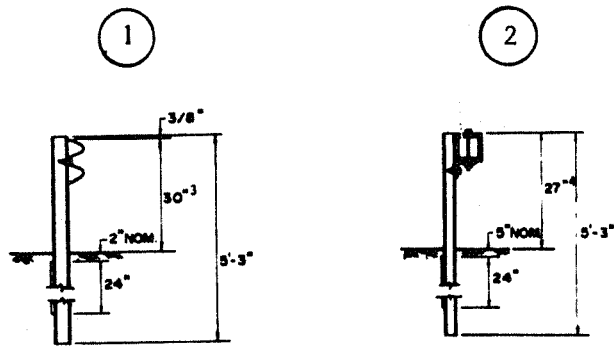
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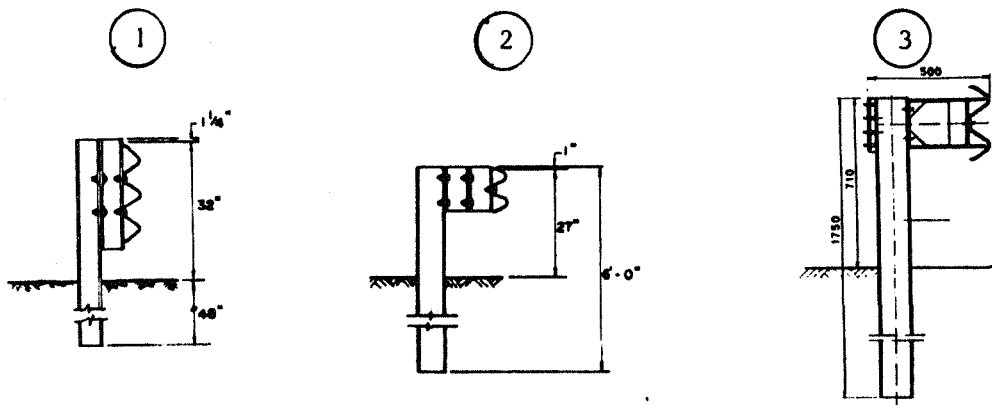
Barrier type	Number of accidents					
	PDO	Hosp. injuries	Fatalities	Total	Vehicle rollovers	Mounting
General Motors	225 (75%)	74 (25%)		299 (100%)	19 (6,4%)	4 (1,3%)
New Jersey	133 (79%)	35 (21%)		168 (100%)	6 (3,6%)	1 (0,6%)
New Jersey Modified*	58 (79%)	15 (20%)	1 (1%)	73 (100%)	9 (12,3%)	
Total	416 (77%)	124 (23%)	1 (0,2%)	540 (100%)	34 (6,3%)	5 (0,9%)

\* Initial step 4-5 in. instead of New Jersey Standard 3 in.

Table 1. Number of accident cases for three barrier types in the United States (Source: Bronstad et al., 1976)

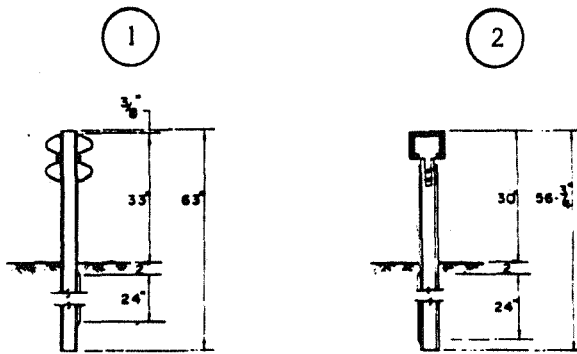


a. Beam fastened directly to the post.

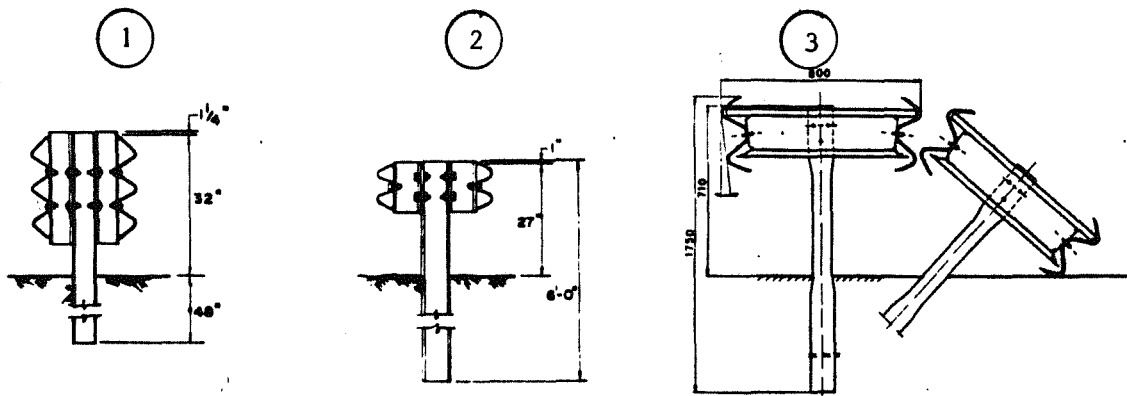


b. Beam fastened to the post with spacers.

Figure 1. Roadside barriers with a single beam.

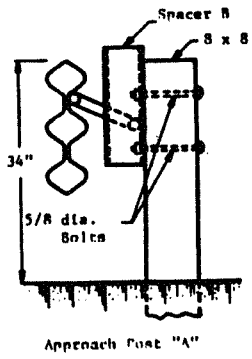


a. Both beams fastened directly to the post.

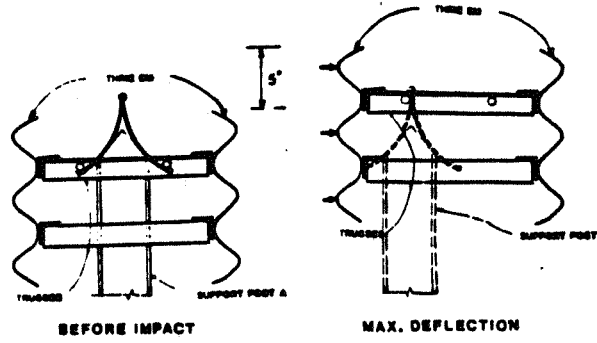


b. Both beams fastened to the post with spacers.

Figure 2. Median barriers with a composite beam.

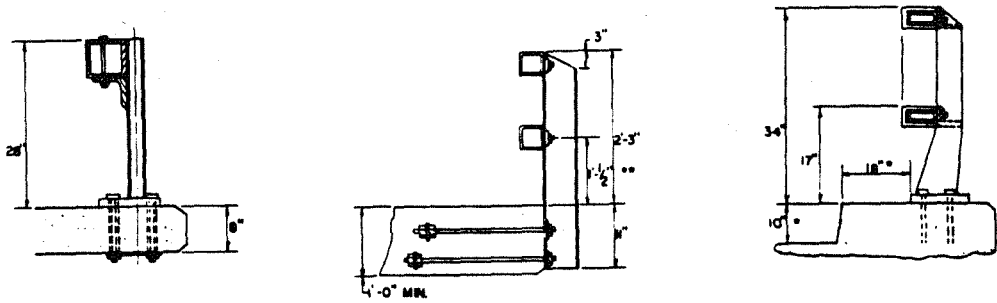


a. Roadside



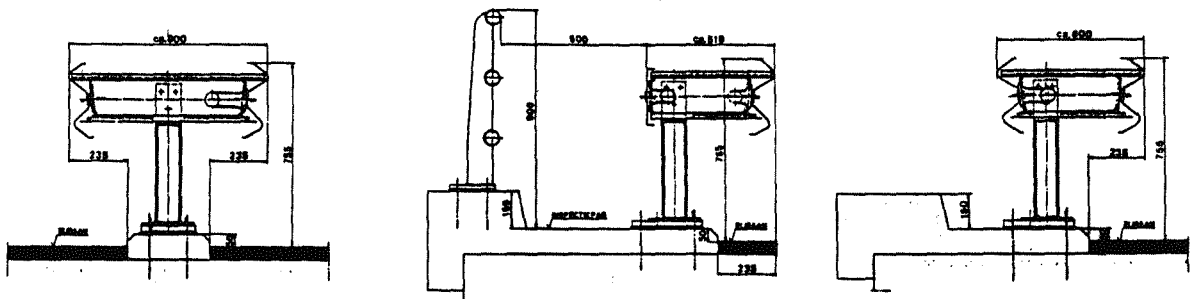
b. Median

Figure 3. Self-restoring safety devices.



Fitting: a. on the bridge b. against the bridge c. on concrete ledge

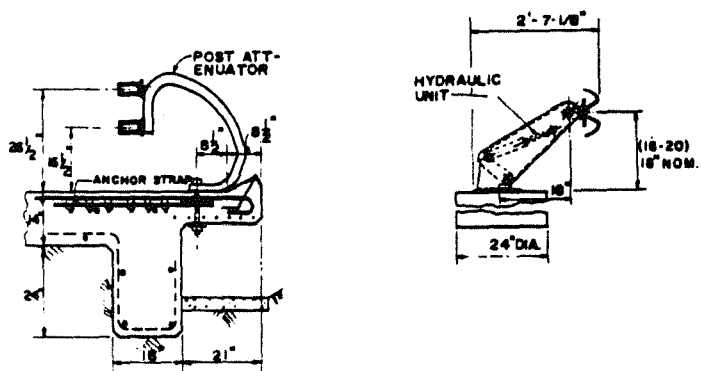
Figure 4. Bridge rails without energy-absorbing systems.



a. median

b. with handrail

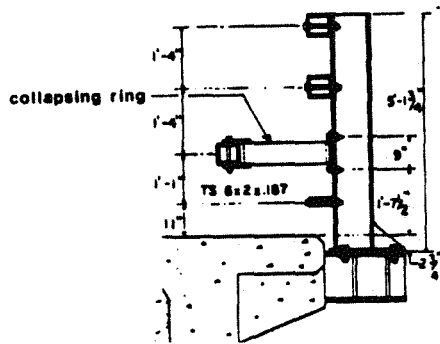
c. with concrete ledge



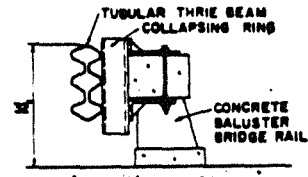
d. post attenuator

e. hydraulic unit

Figure 5. Bridge rails with energy-absorbing systems.

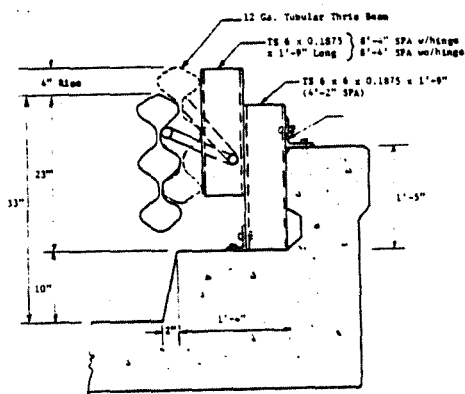


a. ring

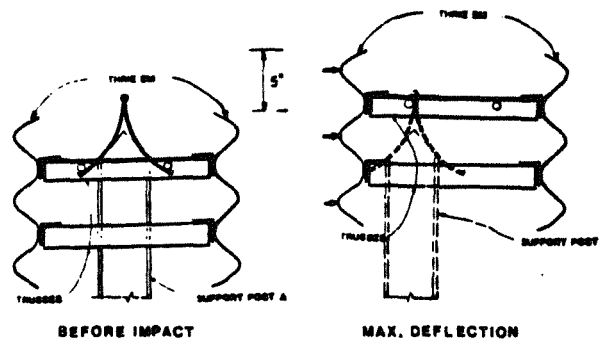


b. ring (tube)

Figure 6. Bridge rails with energy-absorbing spacers.



a. roadside



b. median

Figure 7. Self-restoring bridge rails.

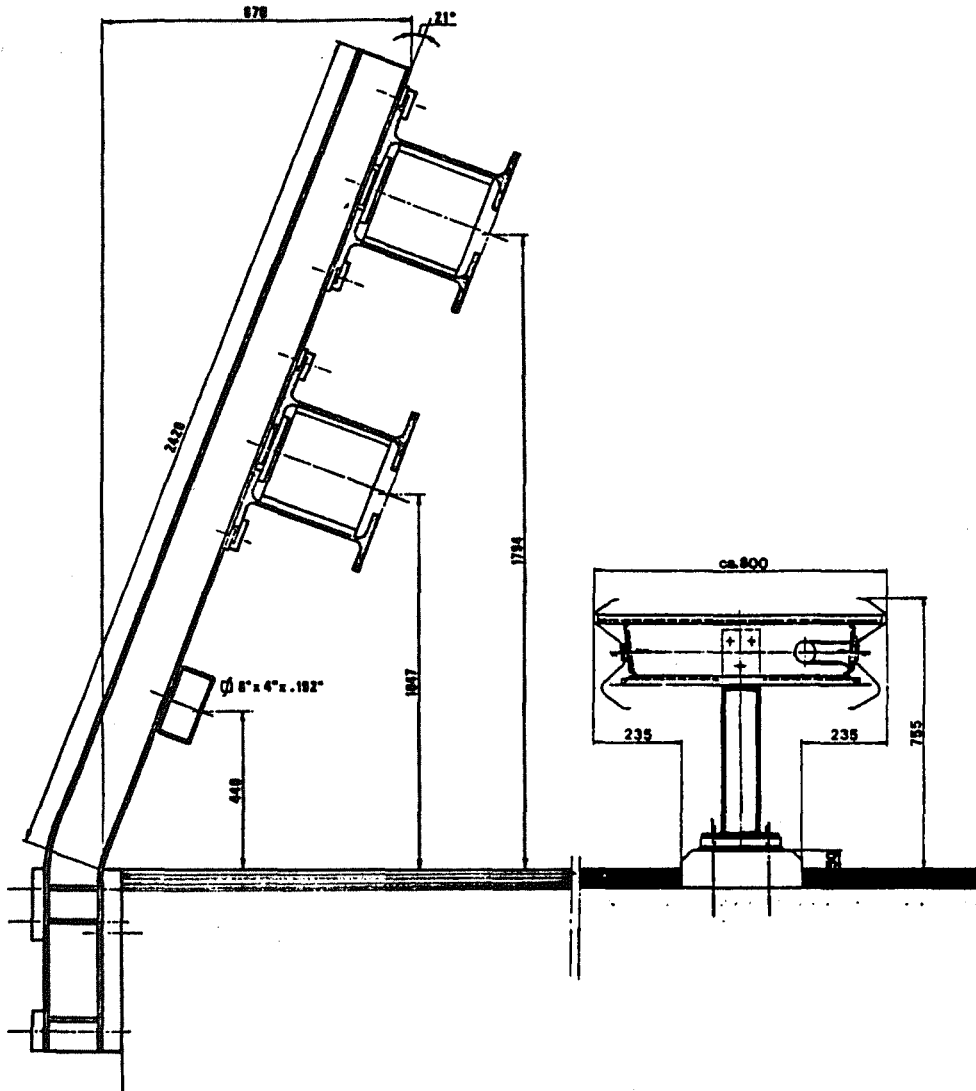


Figure 8. A specific bridge safety device to prevent penetrating.

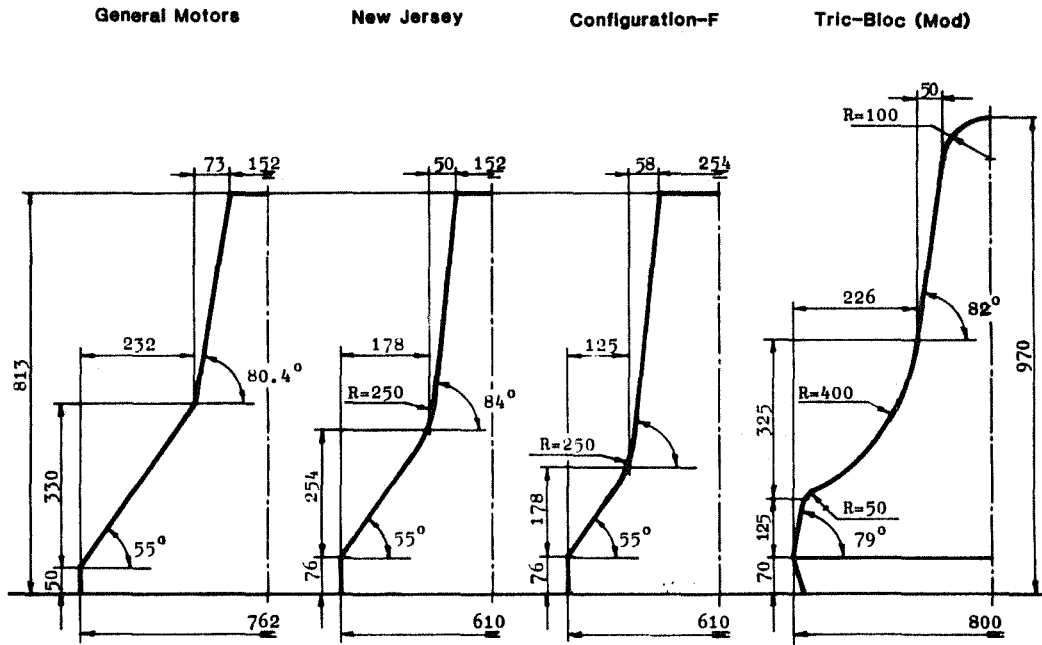


Figure 9. Some profiles of concrete barriers.



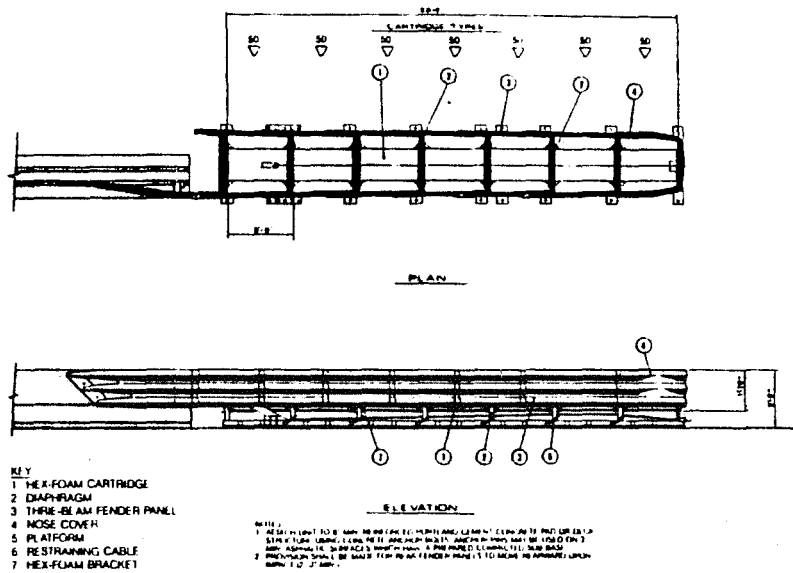


Figure 10. "Great" crash cushion with hexagonal foam cartridges.

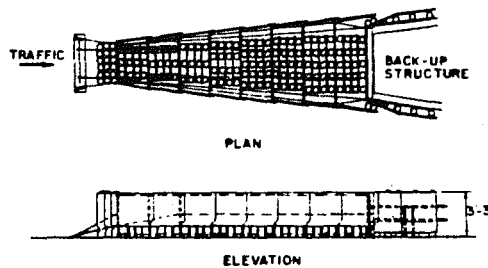


Figure 11. "Hi-Dro" crash cushion with polyvinyl chloride plastic cells, filled with water.

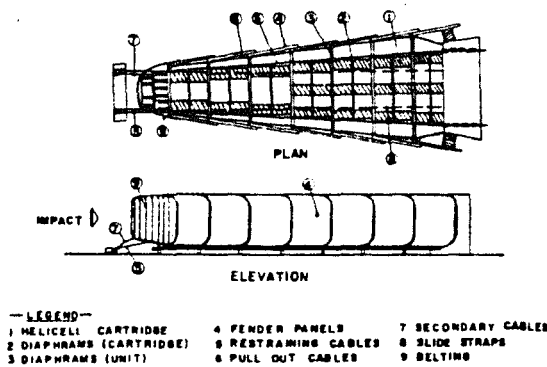


Figure 12. "Hi-Dri" crash cushion with vermiculite heli-cell cartridges.

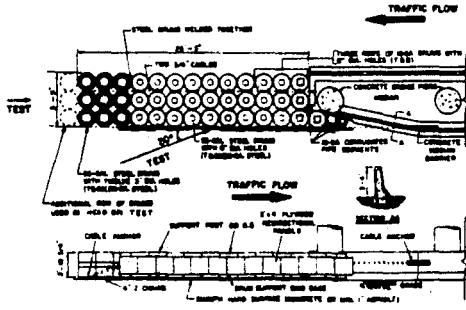


Figure 13. Crash Cushion, with steel drums.

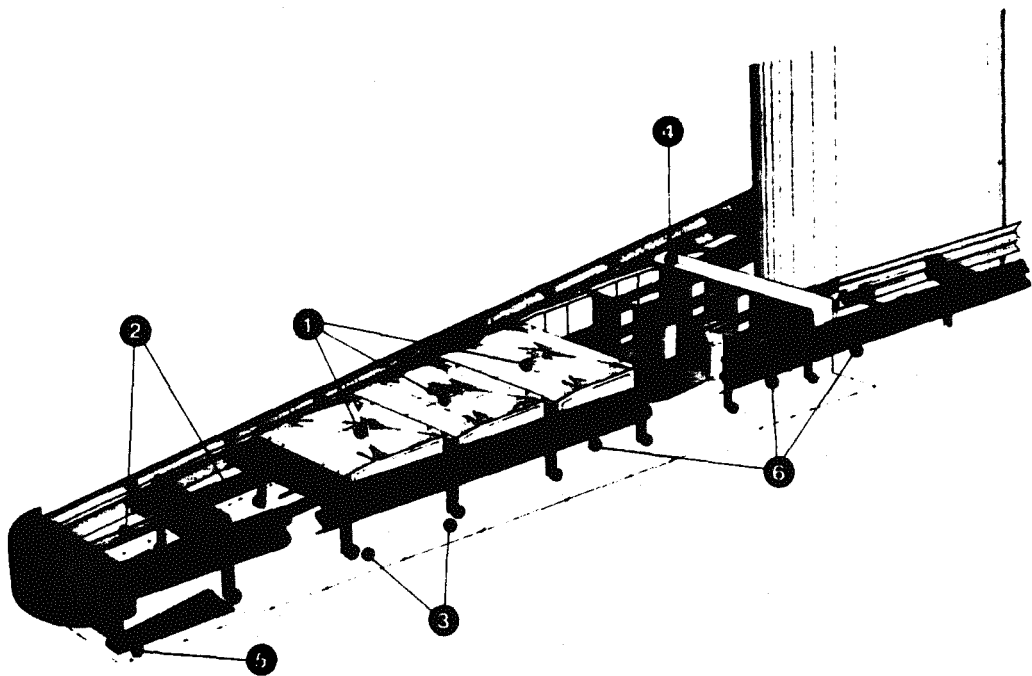


Figure 14. The RIMOB crash cushion with aluminium crumpling tubes.

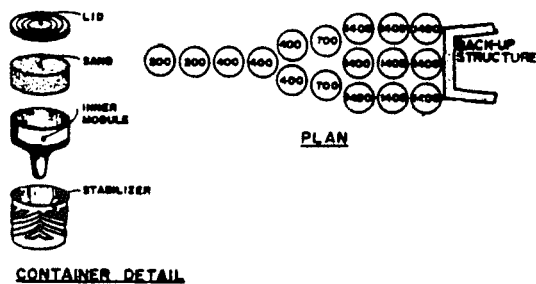


Figure 15. Crash cushion, composed of separate plastic containers filled with sand.

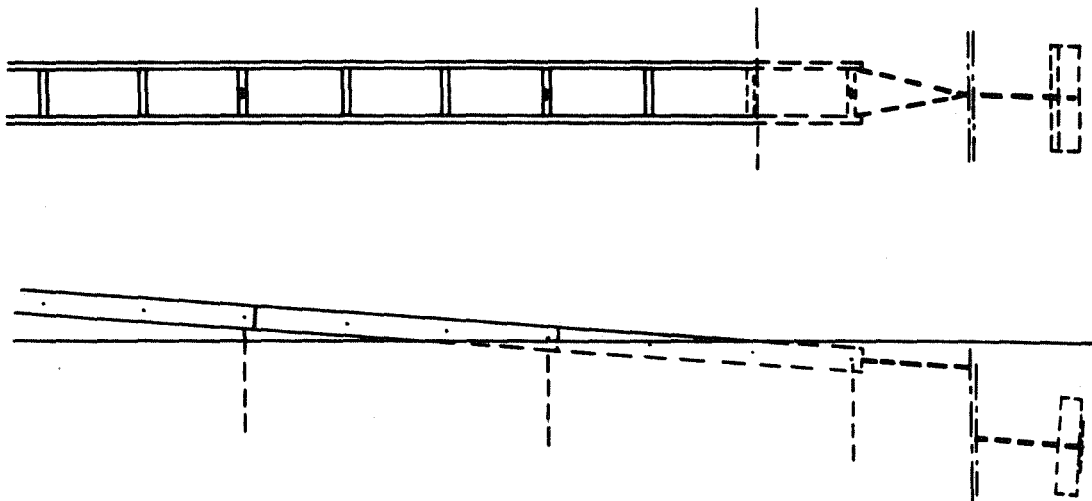
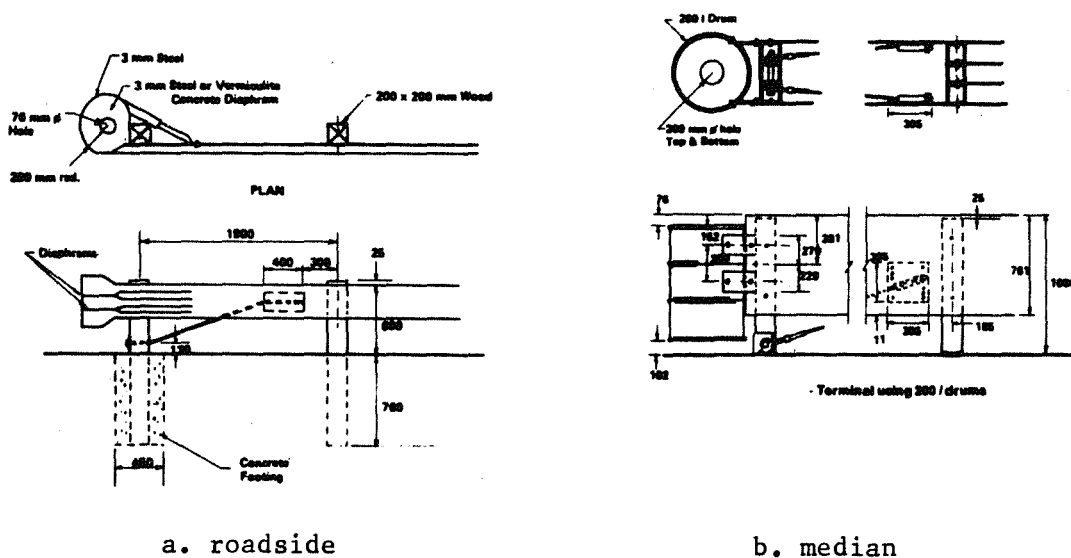


Figure 16. Anchorage of an embedded end beam (Netherlands).



a. roadside

b. median

Figure 17. Breakaway-cable-terminal end treatment (USA).

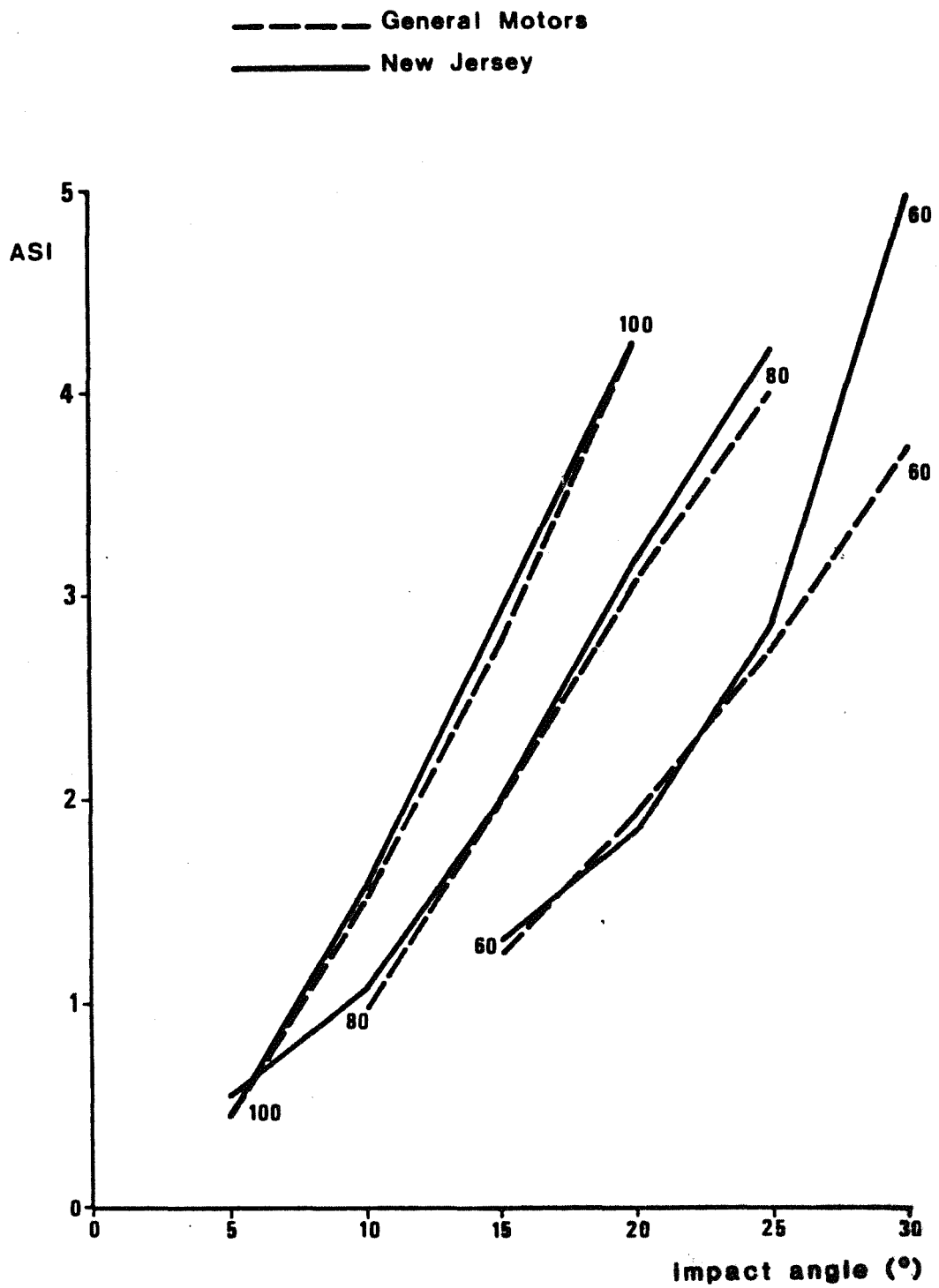


Figure 18. Relation between impact angle and vehicle deceleration (expressed in ASI) for a medium-heavy car in simulated collisions against the General Motors and the New Jersey barriers, with vehicle speed as a parameter.

----- General Motors  
 \_\_\_\_\_ New Jersey

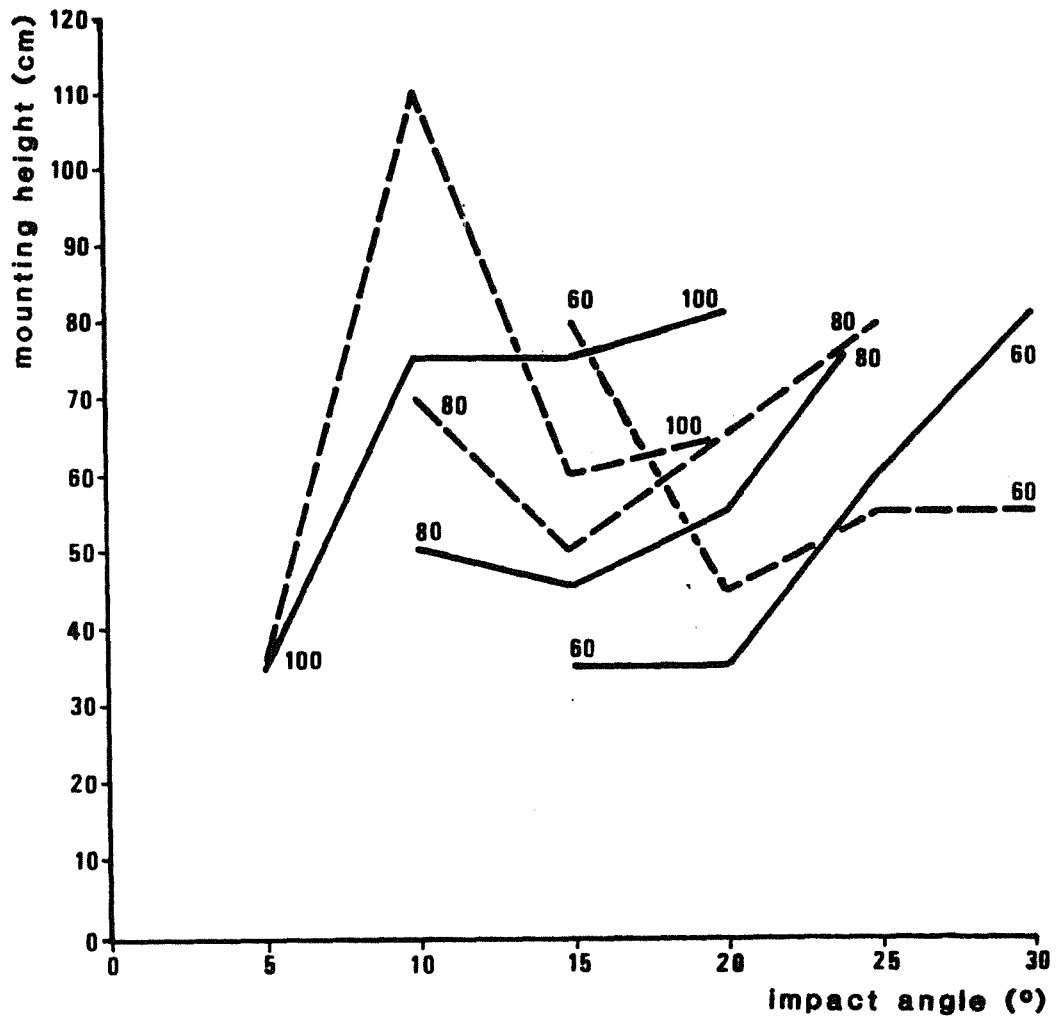


Figure 19. Relation between impact angle and front wheel mounting height for a medium-heavy car in simulated collisions against the General Motors and the New Jersey barriers, with vehicle speed as a parameter.

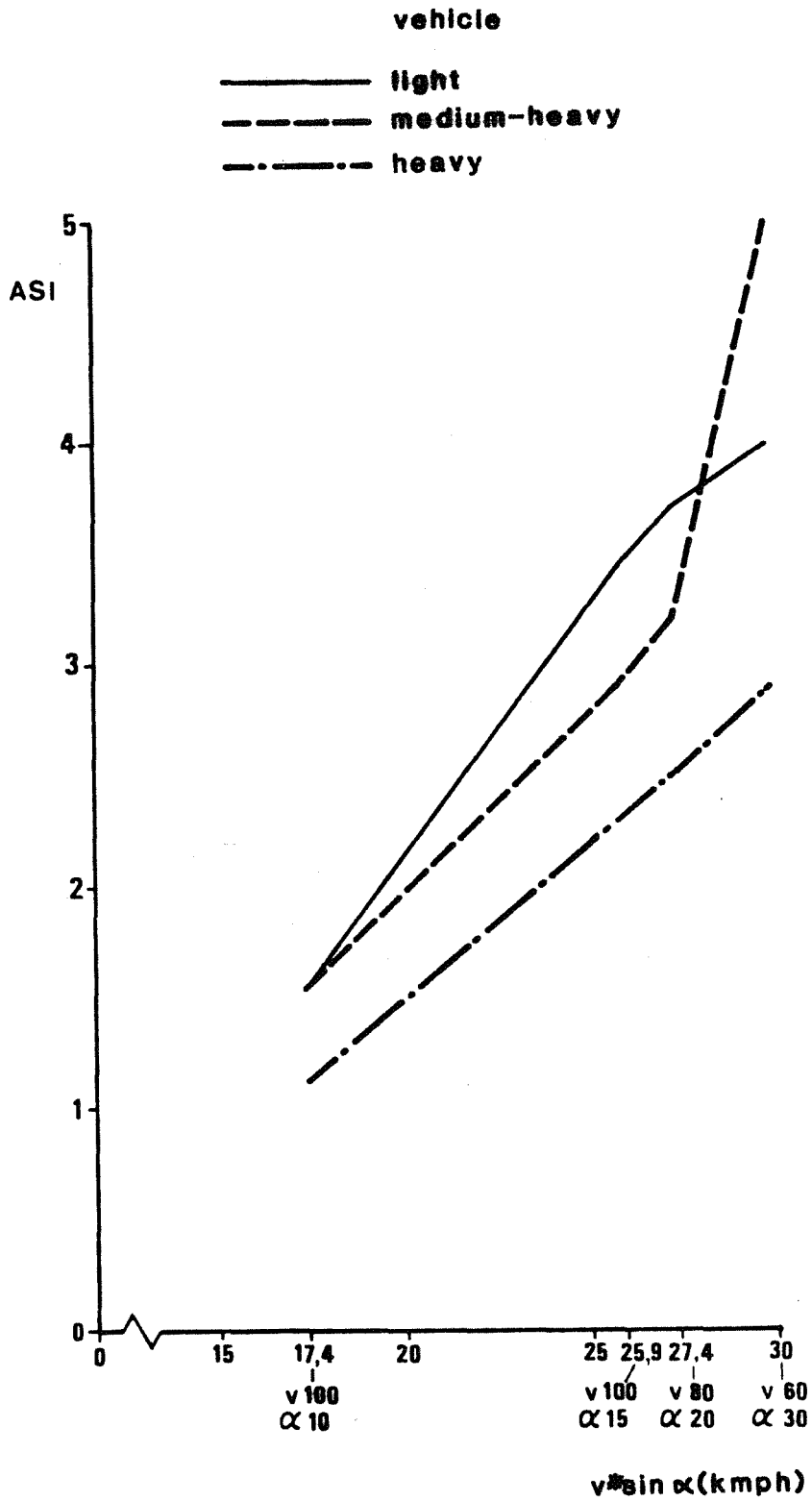


Figure 20. Relation between  $v \cdot \sin \alpha$  (speed times the sine of the impact angle) and vehicle deceleration (expressed in ASI) for light, medium-heavy and heavy cars in simulated collisions against the New Jersey barrier.

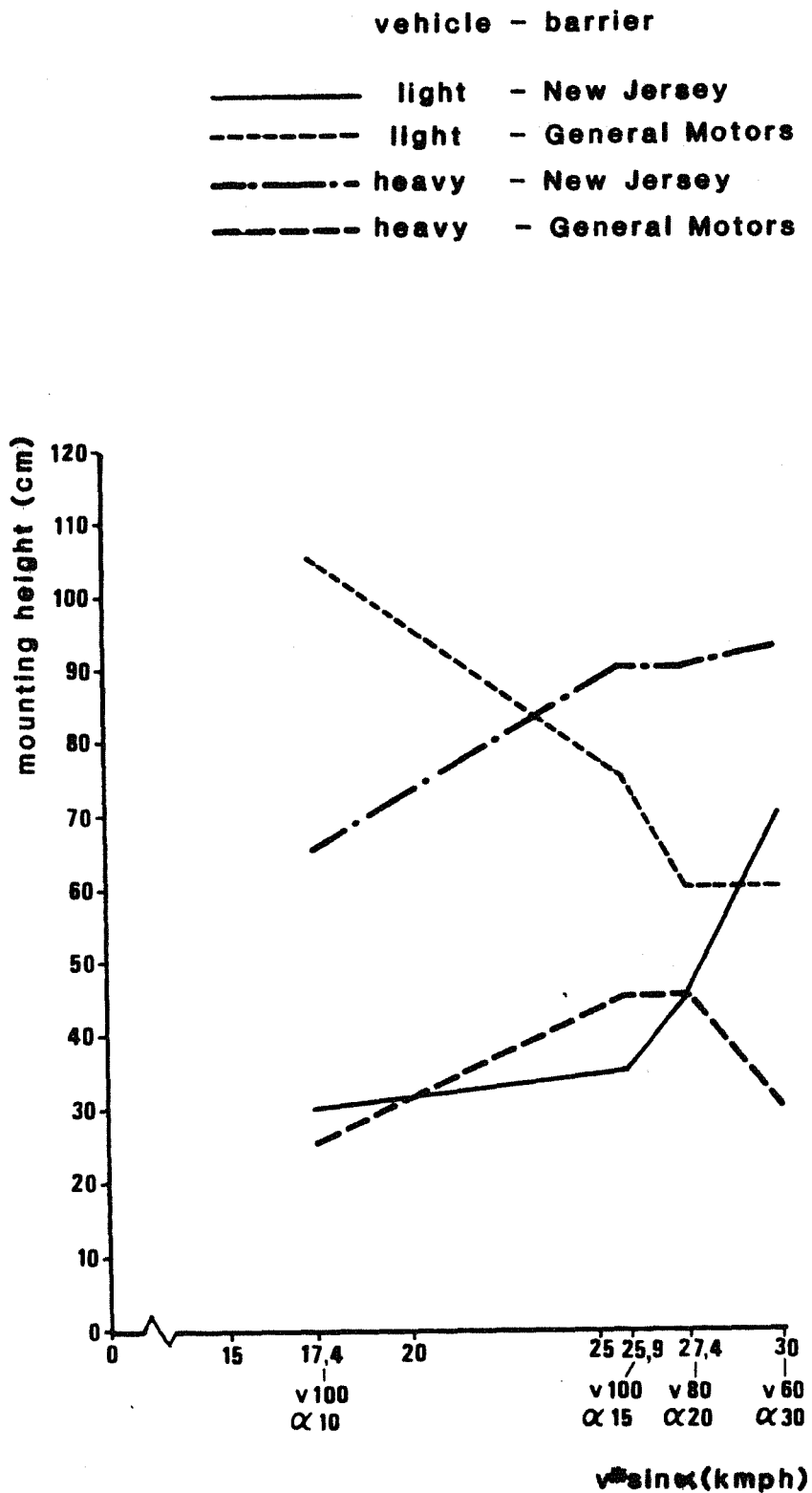


Figure 21. Relation between  $v \cdot \sin \alpha$  (speed times the sine of the impact angle) and front wheel mounting height for light and heavy cars in simulated collisions against the General Motors and the New Jersey barriers.





APPENDIX 1: TEST CONDITIONS



## 1. INTRODUCTION

The test conditions constitute the types of vehicles used and the impact conditions chosen (speed and angle). This appendix deals only with the test conditions in the United States and the Netherlands, since to date more extensive and systematic full-scale tests have been carried out there than in other countries.

## 2. VEHICLE TYPES

### 2.1. United States

The following vehicle types are recommended for tests carried out in the United States according to a recommended procedure for testing street furniture (Michie, 1981). The vehicle mass (including dummies and ballast) is given in brackets.

#### Cars

Mini compact sedan	(885 $\pm$ 22.5 kg)
Sub-compact sedan	(1,135 $\pm$ 45 kg)
Large sedan	(2,045 $\pm$ 135 kg)

#### Buses

Utility bus	(9,100 $\pm$ 225 kg)
Small Intercity bus	(14,500 $\pm$ 340 kg)
Large Intercity bus	(18,200 $\pm$ 455 kg)

#### Tractors and semi-trailers

Freight carriers	(36,000 $\pm$ 1,000 kg)
Tankers	(36,000 $\pm$ 1,000 kg)

The reasons for choosing the vehicle types listed above are not stated in Michie's report.

## 2.2. Netherlands

### 2.2.1. Vehicle types chosen in the Netherlands

#### Cars

light (approx. 600 kg) - type: Fiat 126  
medium-heavy (approx. 850 kg) - type: Opel Kadett B  
heavy (approx. 1,250 kg) - type: Volvo 244  
The masses given exclude dummies and ballast.

#### Bus

Coach (approx. 16,000 kg) - type: DAF MB200  
The mass given is the maximum permissible weight (GVW - Gross Vehicle Weight). To date no mathematical simulations have been carried out with this type of bus.

#### Goods vehicle

Closed model (approx. 16,500 kg) - type: DAF FA2105  
The mass given is again the maximum permissible weight.

### 2.2.2. Reasons behind the choice of vehicles in the Netherlands

#### Cars

To date modules of three types of car have been used for mathematical simulations: Fiat 126, Opel Kadett B and Volvo 244. The choice of these types is based on mass and two other factors assumed to influence vehicle stability: length of wheel base and track. The vehicles were selected on the basis of the cumulative distribution of these factors among all cars according to sales figures in the Netherlands (CBS, 1973-75; CBS, 1976-78; Boesmans, 1976). On the basis of cumulative distribution the Opel Kadett B can be regarded as representative of the medium category and the Fiat 126 and Volvo 244 of the light and heavy categories respectively.

#### Bus

Statistics on the Dutch bus and coach fleet (1970-75) indicate that the 16,000-16,500 kg class is strongly represented (proportion: 44%). Other classes represent proportions of no more than 20%. Within the 16,000-

16,500 kg class the DAF MB200 and Mercedes 0 303 are the most common types (Boesmans, 1976).

#### Goods vehicle

The choice of goods vehicle was based on the CBS market figures for types of goods vehicle from 1967 to 1978 (CBS, 1973-75; CBS, 1976-78). These indicate that 77% of registered goods vehicles have closed cargo areas. The same sources were used to choose the mass of the goods vehicle for simulation. The data selected were divided into mass classes. The period was divided into three 4-year periods, revealing a trend in the relative proportions of the various classes. In the last period the number of vehicles in the 16-18 t and 20-24 t classes increased most, mainly at the expense of the lighter classes. The 16-18 t class was most strongly represented (27%) and was therefore chosen. Within this class a closed vehicle with a maximum permissible weight of 16.5 t was selected.

### 3. IMPACT CONDITIONS

The impact conditions - speed and angle - can be based on various premises: accident situations, physically attainable conditions (depending on such things as driving speed and carriageway width), or a combinations of the two. In every case there is a clear link between impact speed and angle. The conditions in the United States are stated by Michie (1981). No reasons are given. In the Netherlands the choice was based on accident studies carried out in the United States. To establish what relationship exists between the impact conditions used in the two countries and the physically attainable conditions, we shall first of all set out the latter.

On physical grounds a vehicle can describe a certain curve with a minimum radius on a carriageway. The radius depends on the speed of the vehicle and the friction between the tyres and the road surface. At this minimum radius the vehicle is on the verge of skidding and/or rolling (depending on the friction coefficient). The impact angle can be calculated from the radius. It increases the greater the distance from the vehicle's original position to the safety barrier. This distance depends on the number of lanes, the vehicle's position in the lane, whether there is an emergency stopping lane and the width of the shoulder between it and the barrier.

Graph A shows the relationship between vehicle speed and the physically attainable impact angle for two friction coefficients (AGV, 1983):

$\mu = 0.4$  (wet road surface)

$\mu = 1.0$  (very rough road surface)

The graph indicates the relationships for two and three 3.5 m-wide lanes. The emergency stopping lane and shoulder are taken to be 3 m and 0.5 m wide respectively. The graph gives the following relationship between speed and physically attainable impact angle; minimum and maximum values are given for the impact angle depending on the state of the road surface (wet and very rough):

2 lanes, velocity 100 kmph: impact angle approx. 15-25°

3 lanes, velocity 100 kmph: impact angle approx. 20-30°

Corresponding impact angles can be calculated for other speeds in the same way.

### 3.1. United States

The following impact conditions are recommended for full-scale tests with cars in the United States (Michie, 1981):

100 kmph - 25° (continuous barriers)

100 kmph - 15° (continuous barriers)

100 kmph - 20° (impact attenuators)

100 kmph - 0° (impact attenuators)

The following combination is also frequently used in trials with concrete barriers (not recommended by Michie):

100 kmph - 7°.

The American conditions are on the verge of the physically attainable impact angle with two lanes. The maximum with three lanes (30°) is not reached.

Michie report recommends the following impact conditions for goods vehicles and buses:

100 kmph - 15°

80 kmph - 15°

70 kmph - 7°

### 3.2. Netherlands

#### 3.2.1. Impact conditions used in the Netherlands

The following impact conditions are used with cars in the Netherlands:

100 kmph - 15°

80 kmph - 20°

60 kmph - 30°

As regards the physically attainable conditions these values are on the 'wet two-lane road' curve, which is the one which gives the least serious impact conditions.

#### 3.2.2. Reasons behind the impact conditions used in the Netherlands

In the Netherlands SWOV was guided in its choice of impact conditions by the accident studies carried out in the United States, which relate not to collisions with safety barriers but with vehicles leaving the road.

##### Impact angle

The relationship between impact angles and the percentage of cars exceeding them, as shown in Graph B, is taken from various studies (Balz, 1964; Bitzl, undated; Deleys & McHenry, 1967; Dunlap & Grote, 1972; Garrett & Tharp, 1969; Hutchinson, 1962; Ross & Nixon, 1976). The authors are listed beside the curves. So as not to have to take account of exceptional cases, an impact angle value was determined which is not exceeded in 85% of the cases in which vehicles leave the carriageway. The following method was used to establish the value using the curves from the literature. The outermost curves shown were regarded as the limits of the "bandwidth" of the relationship between impact angle and percentage of vehicles. An impact angle was established roughly in the middle of the "bandwidth" at the arbitrary percentage of 15. From this follows an impact angle of 25°. This means that, on the basis of the above data, no more than about 15% of vehicles are likely to leave the carriageway at a greater impact angle than 25°.

##### Impact speed

In general it is difficult to obtain reliable data on the speed at which

vehicles leave the carriageway. Better data than those in Graph C are not available, as far as we are aware; these will therefore have to be used for the time being. Graph C plots impact speeds against percentages of vehicles exceeding them (Balz, 1964; Deleys & McHenry, 1967; Garrett & Tharp, 1969). The relationship between impact speed and percentage of vehicles involved can be established using "bandwidth" in the same way as with the impact angle. If the 15% value is again used here, the maximum impact speed is approx. 100 kmph.

#### Relationship between impact speed and angle

The literature reveals a connection between impact speeds and angles, which is shown in Graph D (Balz, 1964; Deleys & McHenry, 1967; Garrett & Tharp, 1969; Olson et al., 1970). The same reservations regarding the reliability of the data apply as to "impact speed" above. In general it can be deduced from Graph D that the higher the impact speed is, the smaller the angle is. Here again a "bandwidth" can be established and an "average" within it. These 50% and 85% lines are also shown. On the basis of the 85% line the relationship between impact velocity and angle is: 100 kmph - 10°; 80 kmph - 15°; 60 kmph - 25°.

It has been deduced from a comparison, carried out by SWOV, of accident research and results of full-scale tests that the impact angles stated above are probably too small; it would not seem unrealistic to add 5° to them. In a recent SWOV study the following impact conditions were used:

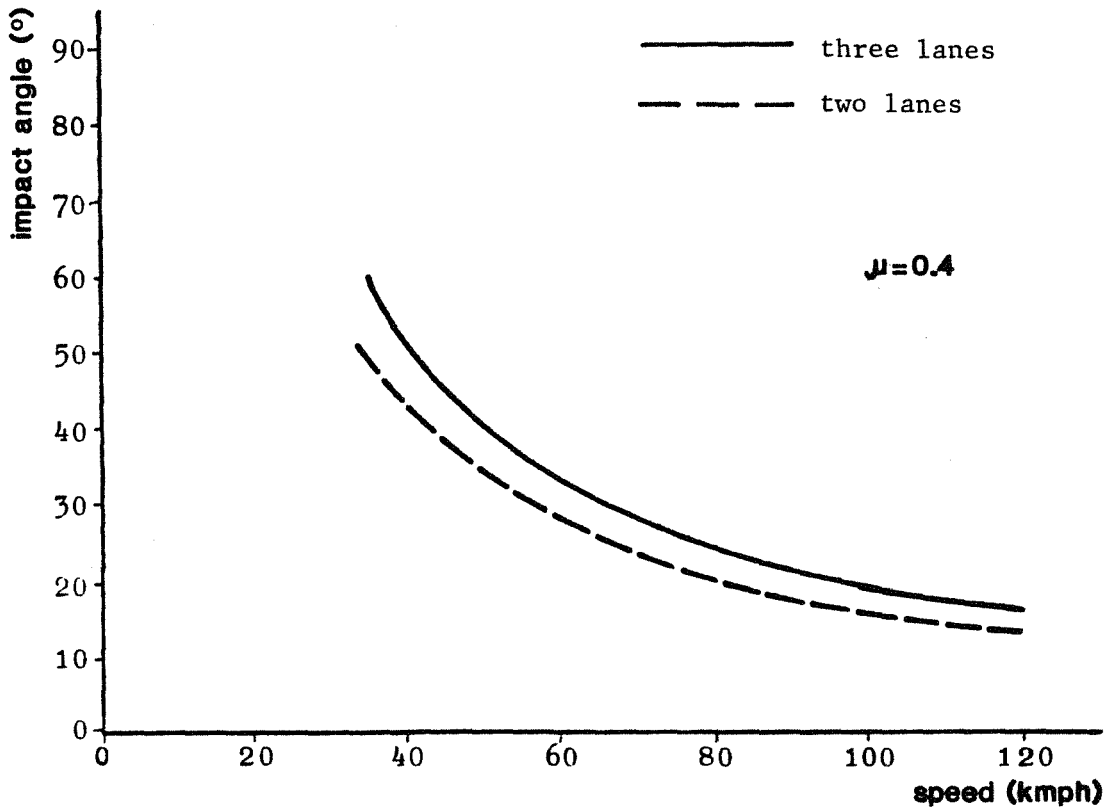
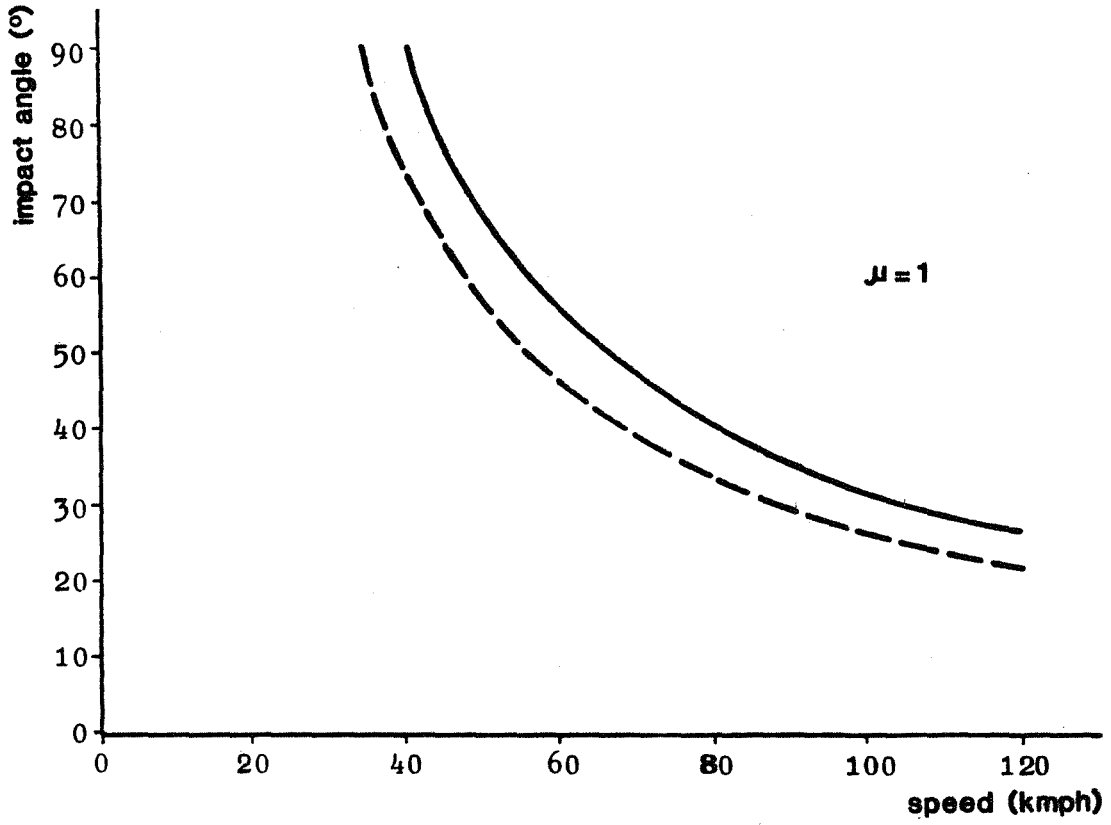
100 kmph - 15°  
80 kmph - 20°  
60 kmph - 30°

#### REFERENCES

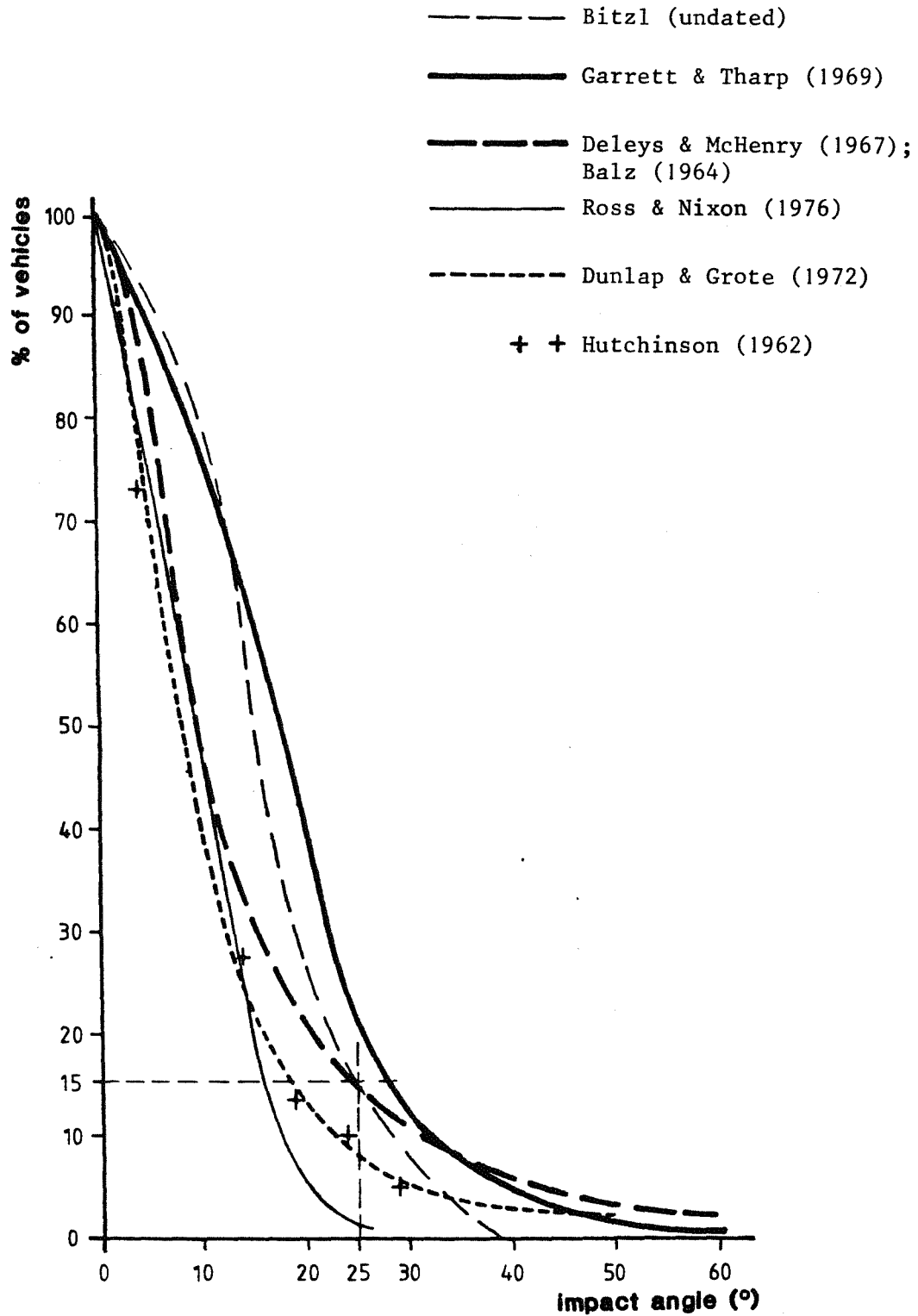
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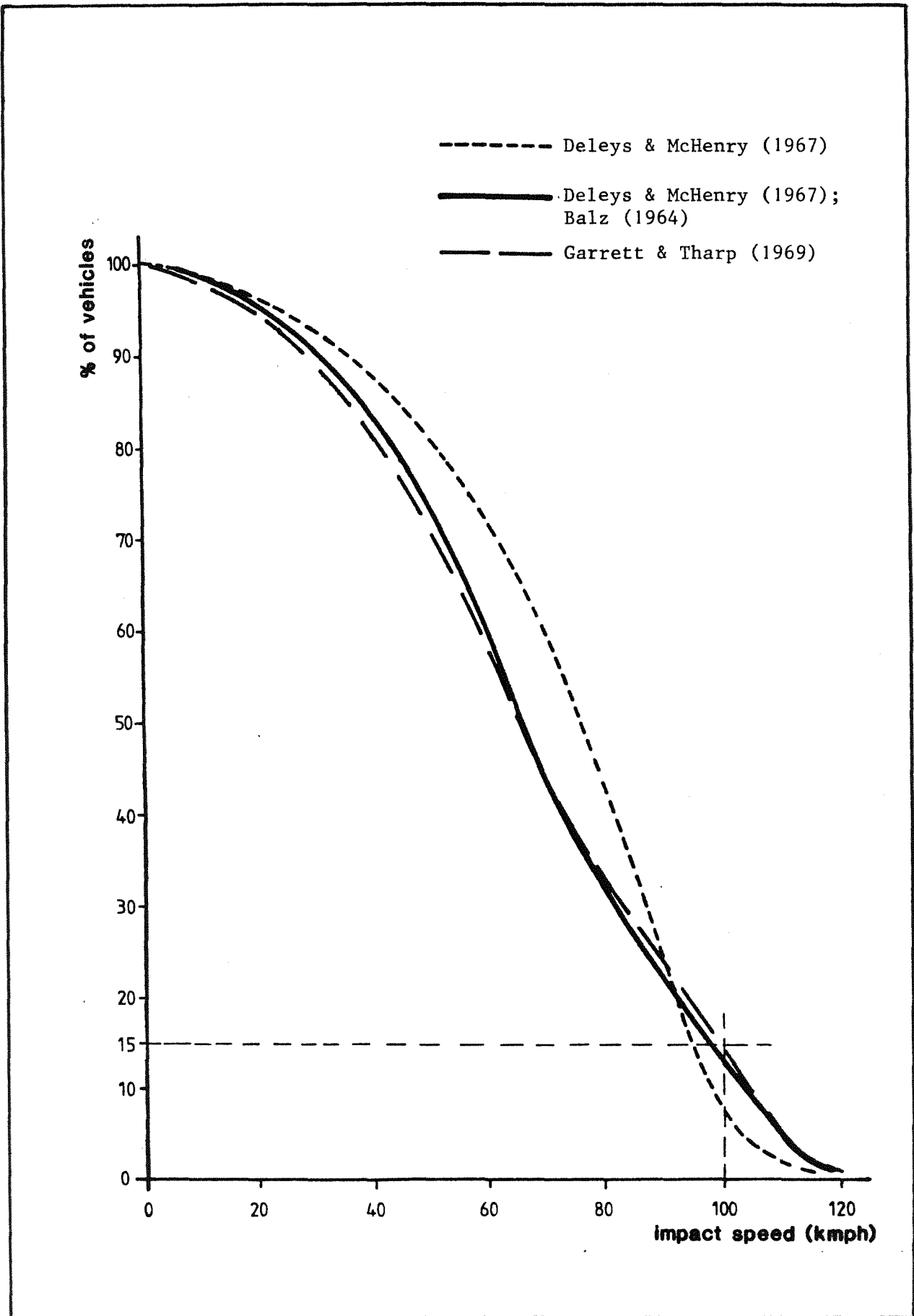
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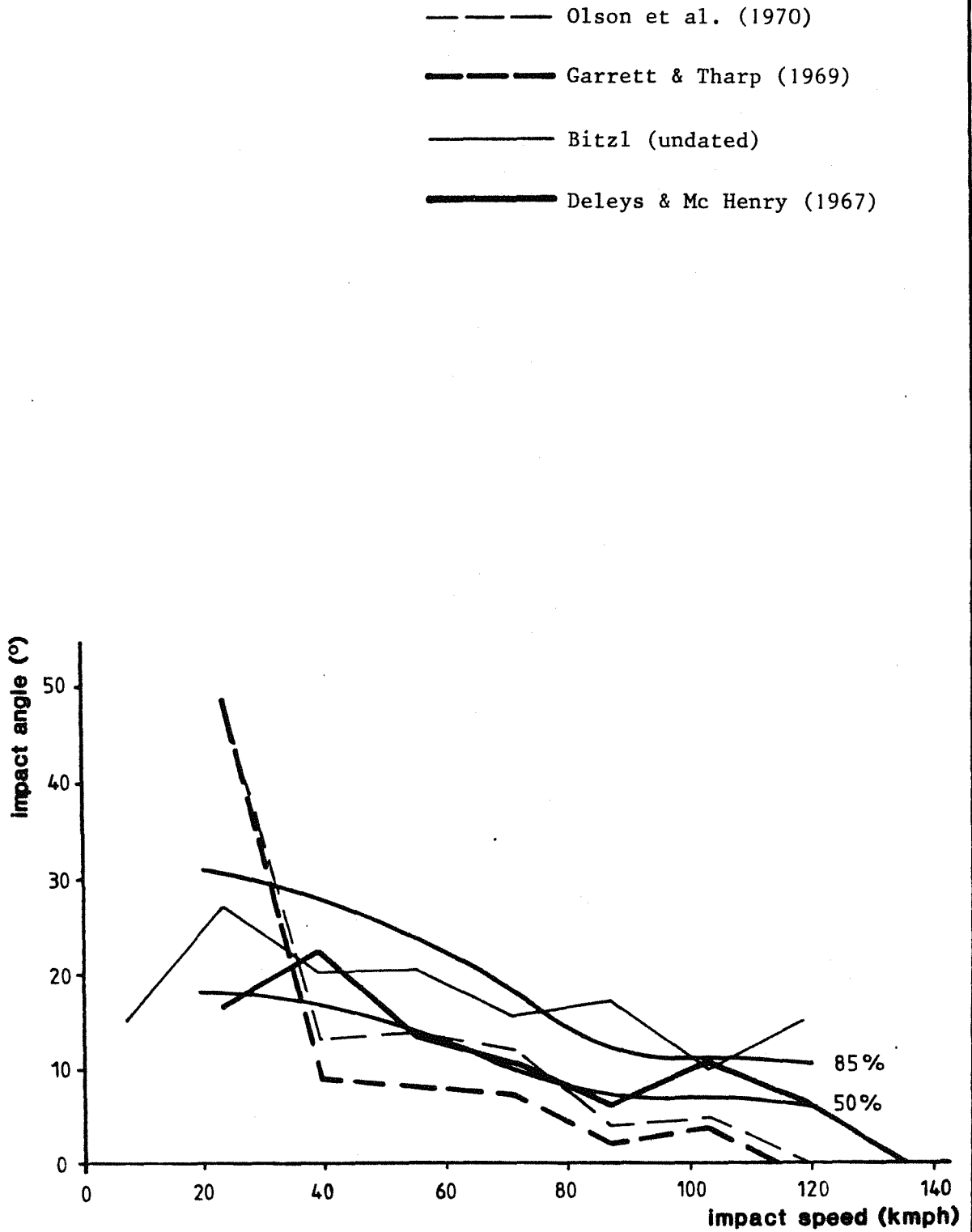
Graph A. Relationship between vehicle speed and the physically attainable impact angle for two friction coefficients.



Graph B. Percentage of vehicles exceeding a given impact angle as found in various accident studies.



Graph C. Percentage of vehicles exceeding a given impact speed as found in various accident studies.



Graph D. Relationship between impact speed and angle as found in various accident studies.



APPENDIX 2: INDICATORS AND CRITERIA





## 1. INTRODUCTION

The safety of vehicle occupants in a collision is determined by the seriousness of the injuries they could suffer. These are the result of a number of factors:

1. contact forces between parts of the body and parts of the vehicle;
2. accelerations and associated inertia forces and moments;
3. individual susceptibility to injury.

Factors 1 en 2 are related in a complex way to vehicle accelerations, deformation characteristics of the vehicle interior and exterior and whether safety devices (seat belts, airbags, etc.) are used. Factor 3 depends on largely unknown individual characteristics, which may in fact be assumed to have a relatively large range.

It is clear from these considerations that it is difficult to obtain a clear idea of the 'safety' of a collision simply by looking at the kinematic characteristics of the vehicle. Nevertheless, these data are often the only measurable quantity in full-scale tests. A number of empirical criteria have been devised to give the best possible idea of safety; these are based on the linear accelerations and velocities at certain points in the vehicle: the Acceleration Severity Index (ASI), and the Occupant Impact Velocity (OIV) and Occupant Ridedown Accelerations (ORA), the last two used in American barrier trials.

Criteria based on the direct influence of violent forces on the body have also been devised (injury criteria).

## 2. CRITERIA BASED ON VEHICLE DATA

### 2.1. ASI

In theory the ASI can be calculated for any point in the acceleration field; if the angular accelerations are small, the ASI for the centre of gravity will suffice. If they are large, the ASI must be calculated separately for each passenger seat (AASHTO, 1977). This criterion weights the accelerations in three principal directions and averages the absolute value of the weighted accelerations over successive time intervals of

50 ms. The highest value found during the entire period of measurement then determines the safety. A value of 1 is usually taken as the limit of safety for occupants without seat belts and a value of 1.6 for those with seat belts. The general equation is:

$$ASI = \sqrt{\left(\frac{g_{long}}{g_{long_a}}\right)^2 + \left(\frac{g_{lat}}{g_{lat_a}}\right)^2 + \left(\frac{g_{vert}}{g_{vert_a}}\right)^2}$$

long = longitudinal  
lat = lateral  
vert = vertical  
index a = acceptable

## 2.2. OIV

The OIV is based on trials in which dummy heads were hurled at wind-screens with a certain initial velocity (Michie, 1981). It was found on the basis of the applied Head Injury Criterion (HIC; see 3 below) that if the initial velocity does not exceed certain values, the HIC remains below the desirable limit of 1000. The OIV is calculated as follows: the longitudinal and transverse velocity components at passenger seats in the vehicle are calculated by integration from the acceleration curve of the vehicle's centre of gravity. These velocities are compared to maximum values of 12 m/s (longitudinal) and 9 m/s (transverse). It should be noted that these are absolute maximum values, and any feasible lower limit may be used. Depending on the type of safety barrier, the safety factors given in the literature are maximum values of 1.33 to 2.67.

## 2.3. ORA

The ORA averages longitudinal and transverse vehicle acceleration components at the centre of gravity over successive time intervals of 10ms. The maximum values of these averages are compared - as with the OIV - with the absolute maximum values of 20 g in both directions. Here again safety factors can be given: the literature mentions a factor of 1.33, for instance (Michie, 1981).

## 3. INJURY CRITERIA

The criteria based on vehicle data are only a superficial yardstick, since they take no account of all the contact forces between body and

vehicle; this is to ignore a major source of injuries. Moreover, with both the OIV and ORA the vehicle rotation and angular acceleration must be small, since these criteria are based on measurements solely of linear acceleration at the vehicle's centre of gravity. This requirement is by no means always practicable, which reduces the usefulness of these criteria.

A better idea of the seriousness of a collision can be obtained by using physical or mathematical human models. In the first case full-scale tests have been carried out with vehicles containing dummies on which contact forces and accelerations were measured at a number of vital places (e.g. head, thorax and pelvis) in a collision. In the second case all or part of the collision of the vehicle with occupant(s) is simulated, providing similar data and in more detail. The mathematical model can simulate the entire collision of vehicle and bodies, but it can also be 'fed' with the vehicle movements measured in the tests.

Both methods give a better idea of the seriousness of collisions than vehicle-related criteria, but they are still limited because of the lack of good injury criteria. The only existing criterion is the Head Injury Criterion (HIC), which performs badly in practice. This is calculated from averaged linear accelerations at the centre of gravity of the head:

$$HIC = \left( \frac{\int_{t_1}^{t_2} (a_r dt)}{t_2 - t_1} \right)^{2.5} (t_2 - t_1)$$

$a_r$  = resultant acceleration

$t_1, t_2$  = successive minimum values in acceleration curve

Until such time as there are internationally accepted injury criteria, the following empirical values are being used:

- maximum HIC value of 1000, or resultant acceleration at centre of gravity of head: max. 80 g;
- resultant acceleration in thorax: max. 60 g;
- maximum force on femur: 10,000 N;
- maximum lateral velocity difference in collision: 9.1 m/s.

The following may also be used:

- maximum force on shouldergirdle: 8000 N;
- maximum relative compression of thorax (frontal): 40%.

It is not known whether an unambiguous connection can be found between the injury criteria given here and the criteria based on vehicle data. It is clear that dummies are expensive; consequently mathematical simulation must be regarded as an important aid with which to add to the empirical criteria.

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**APPENDIX 3: MEASUREMENTS IN FULL-SCALE TESTS**



## 1. INTRODUCTION

In general measurements must provide sufficient data to enable the following factors to be ascertained subsequently:

- what damage the vehicle has suffered;
- whether the path of the vehicle was properly corrected;
- whether the safety of the occupants satisfied the available criteria.

In practice a combination of optical and electro-mechanical monitoring instruments are usually employed; the optical instruments are used mainly to ascertain the path of the test vehicle, measure speeds and assess any damage to vehicle and barrier. The electro-mechanical instruments measure mainly accelerations, which also give some idea of safety. Optical aids such as high-speed films are also used to ascertain vehicle acceleration, or acceleration measurements are integrated in order to reconstruct the path of the vehicle; in both cases allowance has to be made for relatively large inaccuracies.

## 2. MONITORING METHODS IN FULL-SCALE TESTS

In many American tests both optical observations and measurements of acceleration were carried out. The optical observations consist mainly of high-speed films, and the measurements of acceleration are often confined to biaxial measurements at the vehicle's centre of gravity (longitudinal and transverse direction of vehicle). The effectiveness of the barrier is measured in terms of the path of the vehicle, the vehicle rotation and occupant safety criteria. Data on the absolute or relative accuracy of the monitoring instruments used can be found, for example, in the FMVSS regulations, which apply to American tests.

As also pointed out in Appendix 2: Indicators and criteria, angular accelerations of the vehicle can have a considerable effect on local values of safety criteria. Since severe vehicle rotation can occur with both deformable and non-deformable barriers, some caution is called for when using criteria based solely on centre-of-gravity accelerations. Even when using these criteria as relative values for comparing various types of barrier, it is essential that the angular accelerations be extremely small or that they reach a comparably high level in every test.

### 3. PREFERRED MONITORING SYSTEM

If we wish to make a proper reconstruction of the entire acceleration field in the vehicle for ASI calculations or mathematical simulations, a much more complex configuration of sensors is required than that used in most American tests. Appendix 4 demonstrates that in this case four tri-axial accelerometers are needed, and they must be fitted to the vehicle as follows:

- the axes of all four must be parallel;
- not three must be on the same line;
- the four must not be in the same plane.

There are also some practical requirements relating to accuracy:

- their positions must be known, in relation to the distances between them, to a sufficient degree of accuracy;
- they must be sufficiently rigidly anchored to the vehicle to keep vibrations outside the measuring range;
- their absolute error must be small in the measuring range (0-25 g approx.); a small relative error in a very large measuring range in fact produces a large error in the range under consideration!

As regards the specifications of monitoring and recording instruments: the important vehicle movements are in the frequency range 0-12 Hz approx.; where the sensor signals are recorded using analogue techniques, in order to avoid phase errors the filter frequency for pre-filtering should be much higher than 12 Hz, and preferably >100 Hz.

Since the recorded measurements eventually have to be processed by a computer, analogue data must be sampled at a sampling frequency no lower than 25 Hz and preferably much higher, e.g. 500 Hz. The final filtering of the most interesting frequency range can then be carried out, without loss of accuracy, on the computer. It is also possible to sample the measurements directly, without the intervention of analogue recording; this method is probably cheaper and certainly faster. Digital recordings can moreover be copied without losses.



APPENDIX 4: A METHOD OF CALCULATING ACCELERATIONS AT ANY POINT  
IN A VEHICLE



## 1. INTRODUCTION

In collision tests with cars remote sensing is used to record many signals describing the collision process for subsequent analysis. Here we are concerned with signals from accelerometers, a number of which are attached to the vehicle bodywork at suitable points. We want to calculate the instantaneous acceleration of any given point in the car from these signals. The algorithm used is described here.

## 2. DEFINITION OF THE PROBLEM

The physical problem concerns a three-dimensional rigid body (automobile) which is capable of performing an arbitrarily accelerated linear or rotary movement. A (clockwise) rectangular system of coordinates is imagined as being attached to the body ( $\bar{x}, \bar{y}, \bar{z}$ ) and originates at the center of gravity of the rigid body. The instantaneous acceleration state of such a rigid body can be described by the following three vectors:

1.  $\bar{u}$  , the acceleration vector of the center of gravity
2.  $\bar{\phi}$  , the angular acceleration vector around an axis through the center of gravity
3.  $\bar{\omega}$  , the angular velocity vector around an axis through the center of gravity,

where  $\bar{u}$  is a vector  $\bar{u} = (u_x, u_y, u_z)$  etc.

The contribution of  $\bar{\omega}$  is the centripetal acceleration due to the instantaneous rotation around the axis  $\bar{\omega}$ . It will be recalled that this contribution is independent of the direction of rotation: left or right rotation gives the same centripetal acceleration.

3. ANALYSIS OF THE PROBLEM

A given point in the car, described in the system of coordinates  $(\bar{x}, \bar{y}, \bar{z})$  is indicated by  $\bar{r} = (x, y, z)$ . The local acceleration of the point projected in the same system of coordinates is indicated by  $\bar{a}(\bar{r})$ . Expressed in  $\bar{u}, \bar{\phi}, \bar{\omega}$  this becomes  $\bar{a}(\bar{r}) = \bar{u} + \bar{\phi} \times \bar{r} + \bar{\omega} \times (\bar{\omega} \times \bar{r}) \dots \dots \dots (1)$

where  $\times$  denotes the vector product.

It is worthwhile to rewrite this expression, which is linear in  $\bar{r}$ , using tensor notation :

$$\bar{a}(\bar{r}) = \bar{u} + \bar{\phi} \times \bar{r} + \bar{\omega} (\bar{\omega} \cdot \bar{r}) - \omega^2 \bar{r} \dots \dots \dots (2)$$

$$\bar{a}(\bar{r}) = \bar{u} + \bar{r} \cdot \bar{\xi} \cdot \bar{\phi} + \bar{r} \cdot \bar{\omega} \bar{\omega} - \omega^2 \bar{r} \dots \dots \dots (3)$$

in which  $\bar{\xi}$  denotes the completely antisymmetrical 3x3x3 tensor in which

$$\xi_{ijk} = 0 \text{ if two or three indices are equal}$$

$$\xi_{ijk} = 1 \text{ if } i, j, k \text{ are an even permutation of } x, y, z$$

$$\xi_{ijk} = -1 \text{ if } i, j, k \text{ are an odd permutation of } x, y, z$$

and where  $\bar{\omega} \bar{\omega}$  denotes the symmetrical tensor with components  $(\bar{\omega} \bar{\omega})_{ij} = \omega_i \omega_j$  and the dot  $\cdot$  represents the scalar product of two vectors or tensors.

If we define  $\bar{A} = \bar{\xi} \cdot \bar{\phi} + \bar{\omega} \bar{\omega} - \omega^2 \bar{I} \dots \dots \dots (4)$

in which  $\bar{I}$  is the tensor of unity

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

then we can rewrite (3) into:

$$\bar{a}(\bar{r}) = \bar{u} + \bar{r} \cdot \bar{A} \dots \dots \dots (5)$$

The components of  $\bar{A}$  are the following:

$$\bar{A} = \begin{bmatrix} -\omega_y^2 - \omega_z^2, & -\phi_z + \omega_x \omega_y, & \phi_y + \omega_x \omega_z \\ \phi_z + \omega_x \omega_y, & -\omega_z^2 - \omega_x^2, & -\phi_x + \omega_y \omega_z \\ -\phi_y + \omega_x \omega_z, & \phi_x + \omega_y \omega_z, & -\omega_x^2 - \omega_y^2 \end{bmatrix}$$

It is important that the relationship between  $\bar{a}(\bar{r})$  and  $\bar{r}$ , as expressed by (1) or (5), is a linear one. Now we have to derive  $\bar{u}$  and  $\bar{A}$  from the signals of the accelerometers.

Together,  $\bar{u}$  and  $\bar{A}$  make  $3+3 \times 3=12$  unknown variables; therefore 4 accelerometers, having 3 signals each for the x,y and z components resp., must be sufficient. We will denote the place of these 4 accelerometers by  $\bar{r}_0, \bar{r}_1, \bar{r}_2$  and  $\bar{r}_3$  and the corresponding accelerations by  $\bar{a}(\bar{r}_0), \bar{a}(\bar{r}_1)$  etc.. Equation (5) will be the basis of our following calculations by substituting  $\bar{r}$  by  $\bar{r}_0, \bar{r}_1$  etc. thus obtaining a set of 12 linear equations in 12 unknown variables. We will solve this set in the following manner:

We define the differential vectors  $\bar{K}_i$ ,  $\bar{K}_i = \bar{r}_i - \bar{r}_0 \dots (i=1,2,3) \dots \dots \dots (7)$

and

the differential acceleration vectors  $\bar{a}_i$ ,  $\bar{a}_i = \bar{a}(\bar{r}_i) - \bar{a}(\bar{r}_0) \dots (i=1,2,3) \dots (8)$

Using (7) and (8) we can rewrite (5) :

$$\bar{a}_i = \bar{K}_i \cdot \bar{A} \quad (i=1,2,3) \dots \dots \dots (9)$$

or, writing (9) in a matrix notation:

$$\bar{a} = \bar{K} \cdot \bar{A} \quad \dots \dots \dots (10)$$

in which

$$\bar{a} = (\bar{a}_1, \bar{a}_2, \bar{a}_3) = \begin{bmatrix} a_{1x}, a_{2x}, a_{3x} \\ a_{1y}, a_{2y}, a_{3y} \\ a_{1z}, a_{2z}, a_{3z} \end{bmatrix} \dots \dots \dots (11)$$

$$\text{and } \bar{K} = (\bar{K}_1, \bar{K}_2, \bar{K}_3) \dots \dots \dots (12)$$

We can calculate the inverse of  $\bar{K}$ :

$$\bar{K}^{-1} = \begin{bmatrix} \bar{K}_1^{-1} \\ \bar{K}_2^{-1} \\ \bar{K}_3^{-1} \end{bmatrix} \dots \dots \dots (13)$$

$$\text{with } \bar{K}_1^{-1} = \frac{\bar{K}_2 \times \bar{K}_3}{\bar{K}_1 \cdot (\bar{K}_2 \times \bar{K}_3)} \dots \dots \dots (14)$$

$\bar{K}_2^{-1}$  and  $\bar{K}_3^{-1}$  may be derived in a similar way by cyclic rotation of indices..  
(The denominators are all equal to the determinant of  $\bar{K}$ )

This inversion is only possible if  $\text{Det}(\overline{\mathbf{K}}) = \overline{\mathbf{K}}_1 \cdot (\overline{\mathbf{K}}_2 \times \overline{\mathbf{K}}_3) \neq 0$  which means that  $\overline{\mathbf{K}}_1, \overline{\mathbf{K}}_2$  and  $\overline{\mathbf{K}}_3$  do not lie in a single plane and which also implies that the points  $\overline{\mathbf{F}}_0$  to  $\overline{\mathbf{F}}_3$  do not lie in one plane. From equation (10) , by multiplying both sides by  $\overline{\mathbf{K}}^{-1}$ , we derive  $\overline{\mathbf{A}}$  :

$$\overline{\mathbf{K}}^{-1} \cdot \overline{\mathbf{a}} = \overline{\mathbf{A}} \dots\dots\dots(15)$$

Using (11) and (13) and applying the same convention as used to obtain the tensor  $(\omega\omega)$  from vector  $\omega$  we can rewrite (15) as :

$$\overline{\mathbf{A}} = \left( \overline{\mathbf{K}}_1^{-1} a_1 \right) + \left( \overline{\mathbf{K}}_2^{-1} a_2 \right) + \left( \overline{\mathbf{K}}_3^{-1} a_3 \right) \quad \text{with} \quad \left( \overline{\mathbf{K}}_1^{-1} a_1 \right)_{ij} = K_{1i}^{-1} a_{1j}$$

Thus, having calculated  $\overline{\mathbf{A}}$  , its is simple to find  $\overline{\mathbf{u}}$  from (5) as  $\overline{\mathbf{u}} = \overline{\mathbf{a}}(\overline{\mathbf{0}})$ , since the center of gravity is also the origin of our system of coordinates: we can substitute either one of the vectors  $\overline{\mathbf{F}}_i$ , ( $i=0,1,2,3$ ) into equation (5).

Having found both  $\overline{\mathbf{A}}$  and  $\overline{\mathbf{u}}$  we can use (5) again to calculate the accelerations in any point  $\overline{\mathbf{F}}$ .

Furthermore, we can derive  $\overline{\boldsymbol{\phi}}$  and  $\overline{\boldsymbol{\omega}}$  from  $\overline{\mathbf{A}}$ ;  $\overline{\boldsymbol{\phi}}$  from the anti-symmetrical part of  $\overline{\mathbf{A}}$  and  $\overline{\boldsymbol{\omega}}$  from the symmetrical part.

APPENDIX 5: THE ITALIAN SAFETY BARRIERS FOR MOTORWAYS

A summary of a supplement report at request of SINA





## INTRODUCTION

A supplement report has been written at the request of the Società Iniziative Nazionali Autostradali (SINA), Milan.

This report surveys and assesses the types of safety barriers which have been used in Italy in recent years.

The following types are considered: steel and concrete safety barriers for shoulders and bridges (which can also be used for viaducts and tunnels) and safety barriers for isolated obstacles (impact attenuators). A summary of the relevant parts is given.

### 1. STEEL BARRIERS

#### A. Guide rails for shoulders

The various types of guide rails barriers for shoulders can be divided into three principal categories and a number of sub-categories:

##### 1. Single-beam barriers

(a) beam fastened directly to supports (posts)

(b) beam fastened to posts with spacers

##### 2. Composite-beam barriers

(a) beam fastened directly to posts

(b) beam fastened to posts with spacers

##### 3. Self-restoring barriers

(a) single beam hinged to spacer

(b) composite beam supported on specially shaped posts.

#### Single-beam barriers with spacers

The SINA barriers type 7 and 8 (Figure 1.7 and 1.8) as well as the SATAP barrier (Figure 1.10) belong to category A1(b) barriers.

The rigidity of the beam of the SINA barriers type 7 and 8 is greater than of the beams of similar barriers discussed in the report on Safety barriers for motorways (par. 11.1.2). But under more severe impact conditions the same objections occur: the rigidity of the beam cannot easily be increased and progressive deflection cannot be programmed.

Barriers with spacers like the SATAP barrier are not suitable, because of the fact that the area of contact between vehicle and beam drops as the beam deflects (danger of overturning).

The SINA barrier type 2 (Figure 1.2) is more or less a mixture of the single beam and the composite beam. The barrier is a single block out barrier. The composite beam is build up with one rail and two IPE-180 balks connected to each other with energy-absorbing devices. No tests were available. This type 2 barrier has the most rigid beam, but it also misses the second stage effect. One may expect that this barrier will give about the same test results as the SINA barrier type 1.

#### Composite beam barriers with spacers

The SINA barrier type 5 (Figure 1.5) belongs to category A2(b) barriers. The rigidity of the beam is additionally increased by adding an U-profile at the back side of both rails. The beam is less wide than the beam of comparable barriers as described in par. 5.2.2. of the report on Safety barriers on motorways. For this reason the front rail does not always maintain the correct height and the posts are less protected. No tests are available.

This barrier may be even better than those without stiffer beams.

#### B. Guide rails barriers for bridges, viaducts and tunnels

The bridge rails barriers developed over the years can be divided into four principal categories and a number of sub-categories:

1. Bridge rails barriers without energy-absorbing devices:

- (a) mounted on the bridge deck;
- (b) mounted against the side of the bridge;
- (c) mounted on a ledge.

2. Bridge rails barriers with energy-absorbing devices:

- (a) with energy-absorbing posts;
- (b) with energy-absorbing spacers.

3. Self-restoring bridge rails barriers. Essentially these are of the same construction as those used on shoulders; only the type of mounting differs.

4. Special bridge rails to prevent penetration.

#### Barriers with energy-absorbing posts

The SINA barriers type 4, type 6 and type 9 (Figure 1.4, 1.6 and 1.9) belong to category B2(a) barriers. The rigidity of the beam is addition-

ally increased by adding an U-profile at the back side of both rails (type 4) or of only one rail (type 6 and 9). During a collision the posts will bend at bridge deck level. No tests are available.

It should be noted that, under severe impact conditions, post-snagging will take place.

#### Barriers with energy-absorbing spacers

The SINA barriers type 1 and type 3 (Figure 1.1 and 1.3) - single block out barriers - belong to category B2(b) barriers. The composite beam is build up with one rail and two IPE-180 balks connected to each other with energy-absorbing devices.

Three tests were carried out: one with a car and two with buses, with a mass of approx. 800 kg, 10,800 kg and 12,700 kg respectively. The impact conditions for the car were 19° and 80 kmph, for the buses 15°, 68 kmph and 10°, 75 kmph.

The results of the tests were good. The vehicles were steerable after the first impact. The decelerations were acceptable. Some posts were bend as result of the tests with the buses. In the test with the 10.800 kg bus the exit angle was 3° and the lateral deflection 40 cm.

## 2. CONCRETE BARRIERS

In Italy four types of concrete barriers are used: type II and III are semi-rigid, type IV and V are rigid (Figure 2).

The semi-rigid barrier type II is build of reinforced concrete posts and a reinforced concrete tube as a beam, directly fitted to the posts. The post distance is ca. 2.5 m; the beam height is ca. 0.5 m. Behind this barrier there is a wall. The maximum allowable deflection is ca. 13 cm. Energy-absorbing devices are fitted between beam and wall each 1.25.

Type III is build of reinforced concrete ports and two reinforced concrete girders as a beam, directly fitted to the ports. The port distance is 2 m; the beam height is ca. 6 m, behind this barrier there is a wall. The maximum allowable deflection is ca. 13 cm. Energy-absorbing devices are fitted between the lower balk of the beam and the wall. Also an one-balk version is present. Both barriers are tested with a car of approx. 930 kg. Each barrier is tested with two impact angles of approx. 10° and 12.5°. Under these light impact conditions the decelerations were rather

high. The exit angles ranged up to  $9^\circ$  and the maximum distance observed between car and barrier was 5.6 m before a second impact occurred. One car crossed the road after the second collision with the barrier. The cars were still steerable after the collision.

So these barriers type II and III are not suitable, because under severe impact conditions overturn will take place and severe damage of the vehicle will occur. The height of the beams is too low. Also the decelerations will be too high.

The rigid barrier type IV is a vertical wall with a horizontal beam at the height of ca. 3 m. The results of test on type IV are not so good. The decelerations under these light impact conditions were high and severe front wheel damage occurred.

The barrier type V is the so called New Jersey barrier. The test results are similar to the test results described in para. 9.1 of the report on Safety barriers for motorways. The exit angles were  $7^\circ$ . The decelerations were high. No rolling angles or mounting heights of the front wheels were mentioned.

### 3. IMPACT ATTENUATORS

To protect toll-houses on highways SINA uses two types of barrier (see Figure 3). One with the nose consisting of a bend guardrail (type B) or another with two bend guardrails (type A). Behind the nose section of the barriers two bend rail sections are build with (much) stronger posts. The nose sections are connected with SINA barriers type 7 or type 8. Approx. 2 m behind the nose of barrier type A there is a heavy concrete block. There are no results of full-scale tests available.

### 4. CONCLUSIONS

Good steel barriers can be identified as having a rigid beam which does not as a rule suffer plastic deformation, and supports and connectors which absorb the collision energy. It is important in a collision that the area of contact between vehicle and construction is high and remains so even if the beam deflects.

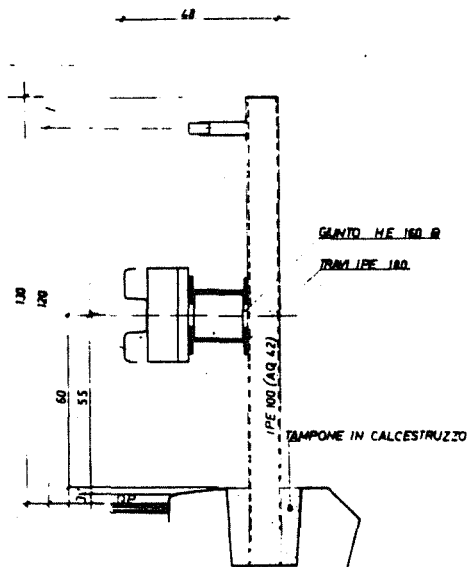
The SINA steel barriers will perform well when hit by cars (impact speeds

up to 100 kmph, approach angles up to 20°). Under more severe impact conditions (heavy vehicles) the results are satisfactorily. To find the boundaries of these barriers more tests are necessary with (very) heavy vehicles under severe impact conditions.

The SINA deformable concrete barriers are not safe. The beam is not high enough. Under severe impact conditions, especially with heavy good vehicles, overturn will take place and severe damage of the vehicle will occur. Also the decelerations will be too high.

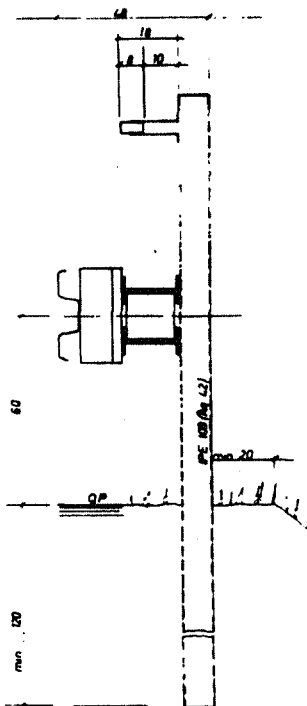
The SINA impact attenuators are unsafe. The stopping distance is too short.

1) PER PONTI VIADOTTI E MURI DI SOSTEGNO

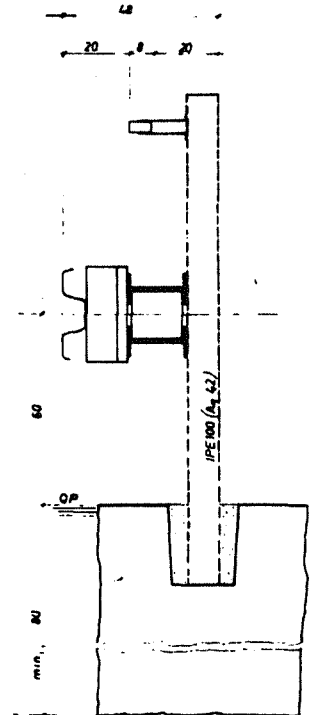


N.B. L'INSTALLAZIONE DELLA BARRIERA (A) CON MONTANTI DIRETTAMENTE INFISSI NEL TERRENO PUO' ESSERE EFFETTUATA RIDUCENDO IL PASSO A m 150

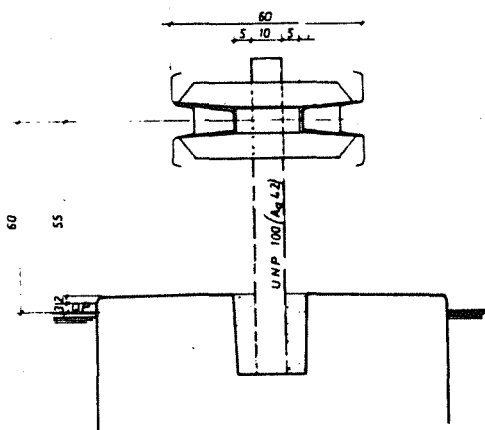
2) PER ALTI RILEVATI CON MONTANTI INFISSI



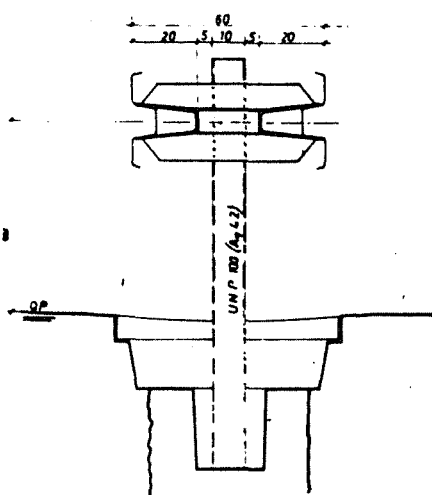
3) PER ALTI RILEVATI O TRATTI A VIE SFALDATE CON MONTANTI SU FONDAZIONE



4) IN RETTIFILLO



5) IN CURVA



6) PER SPARTITRAFFICO SU MONTANTE DOPPIO, CEMENTATA

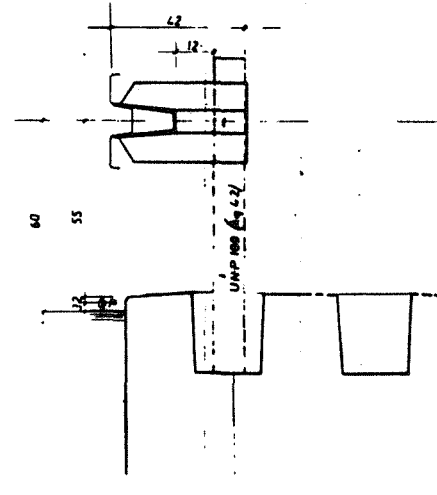
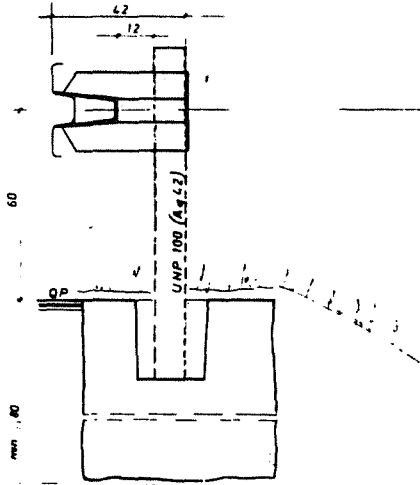
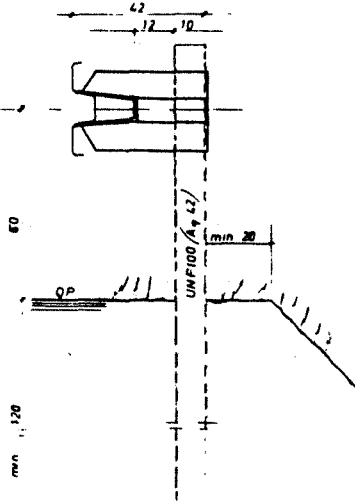


Figure 1. Steel barriers used by SINA.

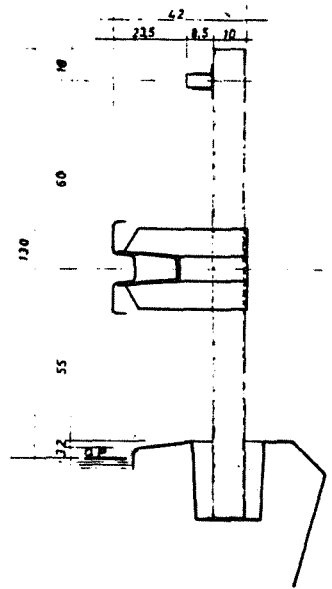
7) PER CIGLIO LATERALE CEMENTATA



8) PER CIGLIO LATERALE INFISSA



9) PER INSTALLAZIONI SU CORDOLO COMPLETA DI CORRIMANO



10) SATEP

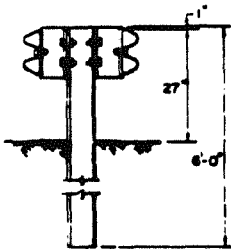
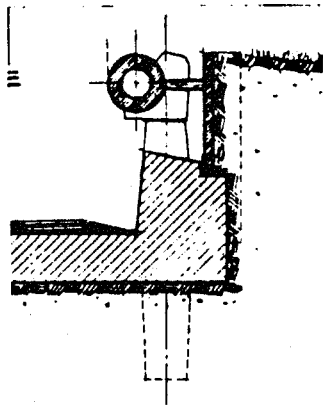
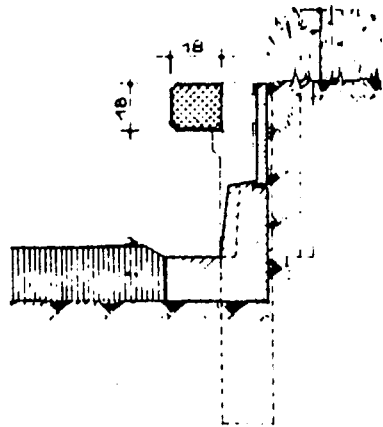


Figure 1. Steel barriers used by SINA.

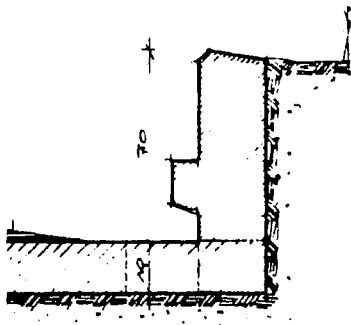
type II



type III



type IV



type V

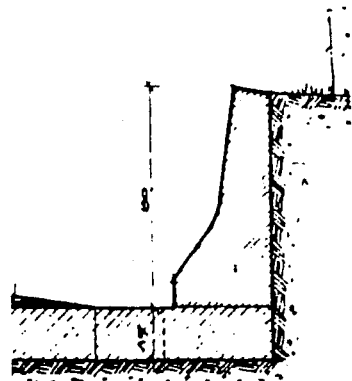
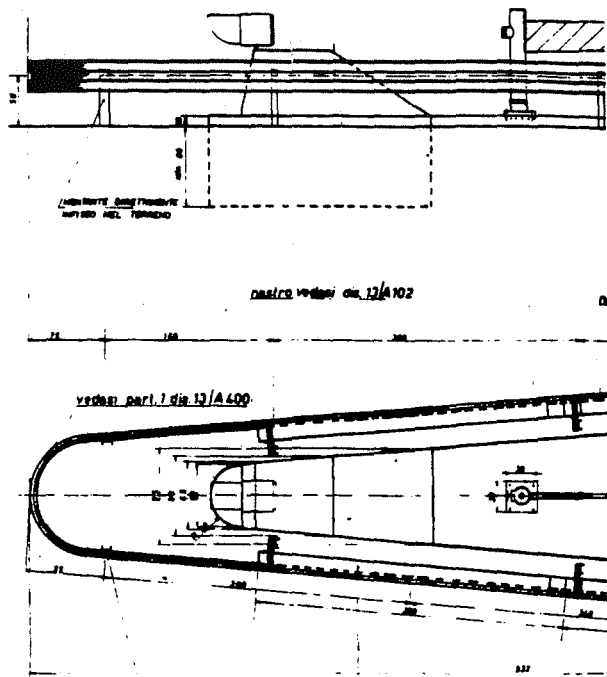


Figure 2. Concrete barriers used by SINA



Type B



Type A

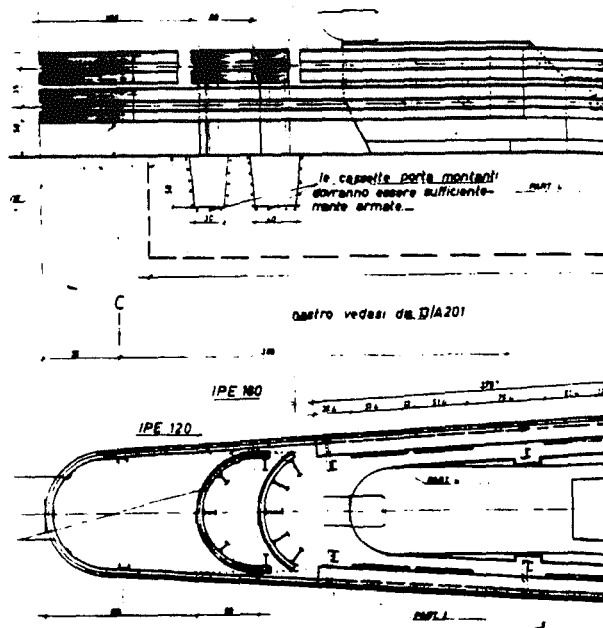


Figure 3. Rail crash cushion used by SINA.

