PD 6634-6:1999

Vehicle restraint systems —

Part 6: Crashworthy roadside features — Impact attenuators

ICS 93.080.30

Committees responsible for this Published Document

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Association of Safety Fencing Contractors
British Cement Association
British In-situ Concrete Paving Association
British Precast Concrete Federation Ltd.
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Department of Transport (Highways Agency)
Institution of Civil Engineers
Motor Industry Research Association
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Contents

Foreword

This part of PD 6634 has been prepared by Subcommittee B/509/1. The other parts in the series are:

- — *Part 1: Fundamentals — Database;*
- — *Part 2: Fundamentals of highway restraint systems;*
- — *Part 3: Development of vehicle highway barriers in the United Kingdom;*
- — *Part 4: Development of bridge parapets in the United Kingdom;*
- — *Part 5: Development of barrier transitions and terminals.*

Over the last 30 years the Department of the Environment, Transport and the Regions (DETR), the Transport Research Laboratory (TRL), the British Standards Institution (BSI) and other organizations have been involved in research, testing, design and the preparation of specifications and standards for vehicle restraint systems such as safety fences, barriers and bridge parapets. Much of this work has been published in the form of Transport Research Laboratory reports, drawings, specifications and standards.

Over recent years, particularly since the introduction of quality assurance schemes for both the manufacture of components and the erection of safety fences and parapets, the need for additional advice, guidance and background information has been highlighted. In 1988 the then Department of Transport (DTp) and BSI agreed to the preparation of a comprehensive British Standard or reference manual on vehicle restraint systems.

A steering group of representatives from BSI, DTp and TRL was formed to supervise the project and the following terms of reference were formulated.

> “To prepare the draft of a comprehensive document on safety fences, barriers and bridge parapets covering research and development, design, specification, manufacture, installation, repair and maintenance.”

It was decided to split the reference manual into several parts and the following groups were formed:

- — Working Group 1 — Part 1 dealing with the fundamentals of safety fences, barriers, parapets and transitions;
- — Working Group 2 — Part 2 dealing with the specification and layout of safety fences and barriers;
- — Working Group 3 — Part 3 dealing with the installation, inspection and repair of safety fences;
- — Working Group 4 — Part 4 dealing with the installation, inspection and repair of safety barriers;
- — Working Group 5 — Part 5 dealing with all aspects of bridge parapets.

Of these proposed parts PD 6634 forms part 1 and BS 7669-3 forms part 3. Work on the other parts has been suspended.

This publication does not purport to include all necessary provisions of a contract. Users are responsible for its correct application.

This Published Document is not to be regarded as a British Standard.

Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 21 and a back cover.

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Introduction

The purpose of a roadside impact attenuator is to reduce the severity of vehicle impact with a fixed object into a less severe collision. Typical examples are where crash cushions are placed to protect vehicles from direct contact with rigid roadside features such as bridge piers, ends of roadside safety barriers and toll booths. In many cases the installation of a crash cushion to protect against collision with every roadside hazard is both cumbersome and prohibitively expensive. Accordingly, where direct contact can be made with roadside features such as lighting columns, telegraph poles or road-sign poles, the severity of impact can be reduced by the inclusion of a yielding slip joint in the shaft of the pole or column.

The installation of a crash cushion or other impact attenuator may not reduce the total number of accidents but, if it is well designed, it should reduce the risk of injury to vehicle occupants; it is a passive safety device.

Impact attenuators decelerate a vehicle both by absorbing energy and by transferring energy to another medium. For example, a crash cushion may be designed to predominantly absorb energy, transfer energy or use a combination of both qualities. An example of the first type would be a design whereby the energy of a colliding vehicle is absorbed by plastic deformation (non-elastic) of the metal structure of the cushion. In an example of the second case, the vehicle's energy may be transferred to sand or water in drum containers; the energy is absorbed by projection of the contents of the containers. A vehicle run-off trap or arrester bed located on a steep hill for the emergency stopping of vehicles with brake failure, is a typical example of an energy transfer attenuator (Laker, 1971 [1]). A metal crash cushion of substantial mass may decelerate a vehicle by transferring energy from the car into acceleration of this mass, as well as by absorbing energy through plastic deformation of the metal (AASHTO, 1989 [2] Macdonald, 1989 [3]).

To protect civil engineering teams on highways, energy absorbing crash cushions may be fitted to the rear of shadow vehicles to give protection to staff in those situations where traffic may erroneously enter the work zone. The lorry or truck mounted crash cushion (LMCC) is located in a position where staff can work in the protective shadow of the vehicle (TD 49/97, 1997 [4]).

Slip joints inserted into utility poles reduce the severity of impact that can occur during impact into an unmodified pole; in this case, little energy absorption takes place. A good design should permit the vehicle to run on while also ensuring that driver control of the vehicle is not lost; the vehicle is brought to rest by braking. However, because little energy is absorbed both the vehicle and the detached pole can be a hazard if other vehicles or pedestrians are close by; the roadside siting of such devices should take this into account.

There are locations where earth mounds on roadsides, primarily used as noise barriers, have some potential to restrain errant vehicles. The attachment of a horizontal barrier rail to these mounds, although not primarily energy absorbers, can reduce the severity of impact that has been shown to occur when a vehicle is brought abruptly to rest by digging in or penetrating the unprotected earth mound.

1 Scope

This part of PD 6634 describes impact attenuators, including ground-based crash cushions, lorry mounted crash cushions, vehicle arrester aggregate beds, rose bush arrester beds, bull nose small radius safety fences and earth acoustic mounds. It also examines the effects of impacts into utility poles such as street lighting columns, road signs and telegraph poles.

2 Roadside and lorry mounted crash cushions

2.1 Basic concepts of roadside crash cushions

In the situation where a driver of an errant vehicle is unable to avoid collision by application of the brakes or by steering control, then on contact with a crash cushion the vehicle needs to be brought to rest with the minimum risk of injury to the occupants.

There is no simple relationship between the deceleration of a vehicle and an unrestrained occupant. Even in the case where seat belts are worn, the deceleration of the wearer may take a different pattern from that of the vehicle; however, once the occupant has come into contact with the interior he may experience decelerations similar to the vehicle. Initially, injury may be caused by the occupant making primary contact with the interior of the passenger compartment; following this, deceleration forces acting on the body organs can cause injury as the occupant follows the deceleration pattern of the vehicle. If, during an accident, the person is ejected from the car, contact with the road and surrounds are likely to be a prime cause of injury. It is reasonable to presume that vehicles undergoing low levels of deceleration are less likely to cause injury to occupants.

The wearing of seatbelts can reduce injuries caused by occupant contact with the interior of the vehicle, and so crash cushions could be designed for relatively high levels of deceleration given that seat belts are used. However, high vehicle decelerations in the longitudinal direction may cause considerable deformation of the passenger compartment, with penetration of the engine into the compartment a real hazardous possibility.

The rate at which vehicles can be brought to rest or decelerated are subject to the equations of motion as follows:

$$V^2 = U^2 - 2aD \qquad (1)$$

where

V = final speed in metres per second (m/s) ($V = 0$ in this simple analysis);

U = initial speed in metres per second (m/s);

a = deceleration in metres per second squared (m/s^2);

D = stopping distance in metres (m).

NOTE Values of "a" in units of "g" = a/9.806 7 m/s^2.

The information in Table 1 is taken from the European Standard prEN 1317-3 and shows the required impact tests to meet a range of crash cushion performance classes.

Table 1 — Crash cushion impact tests
(prEN 1317-3)

Approach path	**Vehicle mass** kg	**Speed** km/h
Head-on centre	900	50
	900	80
	900	100
	1 300	80
	1 300	100
	1 500	110
Head-on ¼ vehicle offset	900	80
	900	100
On the nose at 15°	1 300	80
	1 300	100
	1 500	110
Side impact at 15°	1 300	50
	1 300	80
	1 300	100
	1 500	110
Side impact at 165°	1 300	80
	1 300	100
	1 500	110

Figure 1 shows the mean deceleration levels derived from equation (1), in values of "g" for given stopping distances D, from speeds of 110 km/h, 80 km/h and 50 km/h.

For example, it is possible to achieve a deceleration level of 1.0 g in a suitably designed aggregate arrester bed. Figure 1 shows that at this deceleration level a 50 km/h vehicle can be brought to rest in a distance of about 10 m. However, a 110 km/h vehicle would need to be decelerated at a level of about 5.0 g; to achieve this magnitude of deceleration a degree of resistive force considerably higher than that possible in an aggregate arrester bed is required. Plastic deformation of a metal structure or energy transfer in a sand-bin type crash cushion can produce this level of force.

Consequently, for end-on impact conditions the first constraint on the design of a cushion is that a prescribed minimum length of cushion is necessary to uniformly decelerate a vehicle of given speed to rest (see Figure 1).

In practical cases, some crash cushions do not generate uniform deceleration. They are designed to accommodate small car impacts by having a softer nose than the subsequent stiffer length.

In simple designs, the calculated average deceleration will approximate to the mean uniform deceleration, as defined by equation (1), although short peak decelerations may arise through complex interaction of the vehicle and the cushion. Simple analysis does not permit their derivation; full scale instrumented tests are necessary to determine peak values.

In the preceding considerations, the crush distance of the vehicle has not been taken into account. This distance will usually be fairly small in comparison with the length of a typical cushion; its exclusion provides a conservative estimate for the performance of the cushion. Nevertheless, for cushions of short length the crush distance of the car can considerably reduce the deceleration levels.

So far in this discussion the mass of the vehicle has not been a factor in the design of a crash cushion. The above discourse has demonstrated that a crash cushion designer needs firstly to consider impact speed and the mean level of vehicle deceleration, which itself is a function of the stopping distance or effective length of the cushion.

After due consideration of the likely maximum impact speed and the space available for its installation, the effective resistive force necessary to decelerate the vehicle in this available space needs to be determined. This force is a function of the mass of the vehicle; it is defined by the following equation:

$$P = Ma \qquad (2)$$

where

P = resistive force in newtons (N);

M = mass of vehicle in kilograms (kg);

a = deceleration in metres per second squared (m/s^2).

Figure 2 shows the resistive force required to decelerate vehicles of mass 1 500 kg, 1 300 kg and 900 kg for given levels of deceleration in units of "g". For example a 1 500 kg car requires a resistive force of about 300 kN to decelerate it at 20 g; about half this value is required for a 900 kg car.

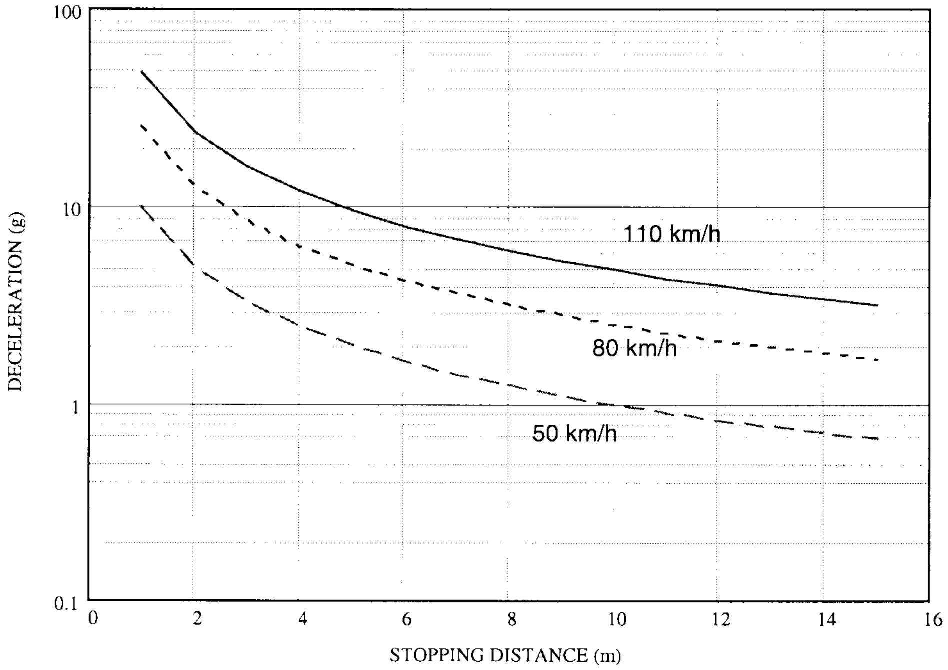

Figure 1 — Deceleration for given stopping distances

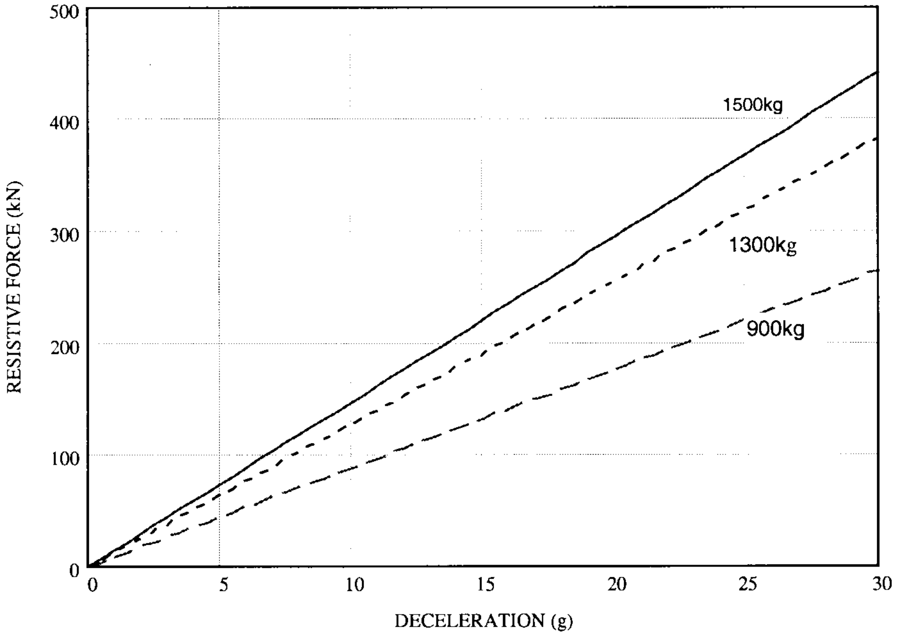

Figure 2 — Resistive force to decelerate vehicles of given mass

For an end-on impact into a crash cushion at zero degrees, the cushion generates a resistive force on the front of the car just above bumper height (see Figure 3). To minimize the risk of injury to the occupants it is necessary that the passenger compartment is not substantially deformed or intruded by displacement of the engine. TRL impact tests with cars into a concrete block have shown that an engine is likely to be displaced at vehicle deceleration levels of 20 g to 30 g; intrusion into the passenger compartment is not likely below a deceleration level of about 25 g (Neilson et al, 1968 [5]).

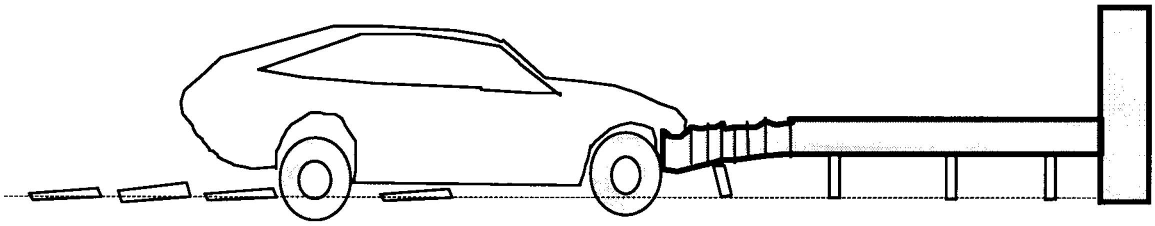

Figure 3 — Crash cushion impact just above bumper height

Hence the second constraint on a crash cushion design is that the resistive force generated during vehicle contact should not excessively deform or cause intrusion into the passenger compartment.

From these elementary considerations of vehicle integrity and a knowledge of the roadside space available in which to install a crash cushion, it is possible to make practical approximations for their length and crush strength.

For example, given that the prime feature is that the passenger compartment should not be intruded by the engine, a conservative mean deceleration of 12 g requires a crash cushion to have the following characteristics as derived from equations (1) and (2) and shown in Table 1.

Practical crash cushions can exhibit non-linear crush characteristics, consequently deceleration/time patterns and peak levels need to be recorded during full scale tests.

Table 2 shows that to bring vehicles of different mass to rest from speed requires different resistive characteristics of a crash cushion. While the stopping distances in Table 2 are theoretically sound, controlled crash tests and real life experience show that installed crash cushions should be somewhat longer because a practical cushion can be crushed only to a finite length.

Table 2 — Resistive force and stopping distance at 12 g deceleration

Vehicle mass kg	Speed km/h	Resistive force kN	Stopping distance m
900	50	106	0.76
	80	106	2.12
	110	106	4.16
1 300	50	152	0.76
	80	152	2.12
	110	152	4.16
1 500	50	177	0.76
	80	177	2.12
	110	177	4.16

Clearly, it is not acceptable to arrange for roadside cushions to protect cars of only one single mass. The resistive force of the cushion needs to be sufficient to decelerate the heaviest and fastest vehicle for which it is designed. This should be consistent with good impact performance for the smaller vehicles. Consequently, either a compromise should be reached in the crush strength of the cushion, or it should be designed to have a graded resistive crush strength; perhaps by providing a soft nose to accommodate the impact of the lighter vehicle.

To confirm that good impact performance is maintained for the lighter vehicles, it is necessary to include vehicles of different masses to form an impact test matrix. It is not sufficient to carry out tests with the heaviest vehicle and then scale down to determine the impact response characteristics of vehicles of lighter mass.

For development test purposes it seems reasonable to select vehicle masses that represent the heaviest and lightest ends of the vehicle population distribution to ensure that the crash cushion performs well under fairly extreme conditions. Three masses of vehicle have been included in the European Standard prEN 1317-3 to form the test matrix; these are 900 kg, 1 300 kg and 1 500 kg.

The maximum speed limit on UK roads is 70 mile/h (113 km/h). Many European countries have maxima close to this although in some cases there are no upper limits. From practical considerations of roadside space and cost of units, it is unreasonable to expect that crash cushion designs can perform as well for the heaviest and fastest impacts as for the more likely and consequently more frequent impacts of the more popular cars. Nevertheless, it is conceivable that even the heaviest and highest speed impact will be ameliorated by the cushion.

It is likely that uses for crash cushions will mostly be found in areas where the higher speed limit zones exist. Taking this into account it is proposed that cushions for these roads should be tested at 70 mile/h (110 km/h) and 50 mile/h (80 km/h). For dense urban areas, a single test at 30 mile/h (50 km/h) is included mainly to confirm good performance at low speed, after the more severe tests have proved successful.

The European Standard prEN 1317-3 includes two test impacts that are axially end-on to the length of the cushion; the first at zero offset and the second with the car offset to one quarter of its width. The first test examines mainly the crush performance of the cushion and the impact severity of the collision; the second establishes the likelihood or degree of vehicle spin-out.

Crash cushions of any substantial length are also likely to suffer side impacts. Simple analysis has shown that for safety fences on motorways, high speed impacts are likely to be infrequent at angles above 20° to the line of the fence (see PD 6634-2:1999, clause **3**). For crash cushions which necessarily are likely to have a lower performance than the length of need (LoN), an impact angle of 15° has been adopted for side impact testing.

An approximation of the spin-out characteristics of an offset set impact on a crash cushion may be obtained from consideration of the analysis given in PD 6634-5:1999, **4.4**. For ease of reference the salient parts are reproduced in Figure 4.

The angular velocity ω is:

$$\varpi = \left(\frac{Py - M\mu gx}{I}\right)t + \varpi_{\mathrm{int}}$$

and the angular rotation θ is:

$$\theta = \left(\frac{Py - M\mu gx}{I}\right)\frac{t^2}{2} + \varpi_{\mathrm{int}}t$$

θ = Angle of vehicle rotation
I = Vehicle moment of inertia
μ = Tyre/road coefficient of friction
ϖ_{int} = Initial approach angle
P = Deceleration force
R = $M\mu g/2$ for a single axle
y = Offset of impact
M = Mass of vehicle
g = Gravitational constant
x = Distance of axles from CG

The equations for angular velocity and angular rotation rely on the broad assumptions that the crash cushion crush characteristics are uniform and that the vehicle remains in contact with the ground and with the cushion during the whole time period of the impact. It is for these reasons that calculated estimates of angular rotation, θ, should be treated only as first approximations.

2.2 Full scale impact tests on prototype UK roadside crash cushions

To assist in the development of British Standards for roadside crash cushions a programme of prototype development and full scale testing was set up by the then DTp and Road Research Laboratory (RRL) (now TRL). The impact performance criteria to be met were as follows:

— maximum test vehicle speed: 70 mile/h;
— maximum test vehicle mass: 1 500 kg;
— impact approach angles: on the nose and in line; on the nose, at an angle; on the side, downstream; on the side, upstream;
— small car test: 850 kg;
— average deceleration end-on intact: less than 8 g: passenger compartment;
— length of cushion: to suit maximum deceleration and site distances;
— applications: end treatment for safety fences and protection of roadside hazardous obstacles;
— suitable for installation on rough ground;
— should not disintegrate or shed loose members, sand or aggregate;
— should remain operative after brushing contact by vehicles;
— low cost and easy to repair.

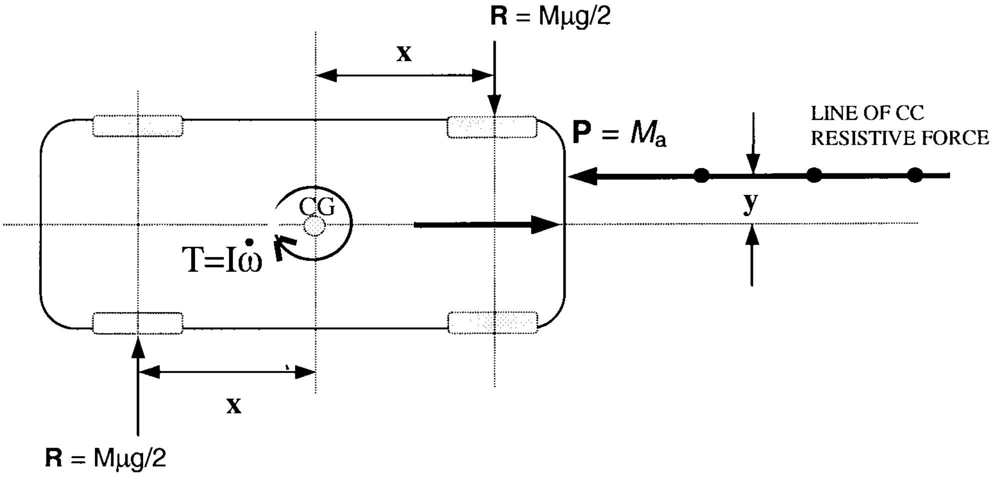

Figure 4 — Labelled diagram of offset end-on crash cushion impact

The basic design adopted for the prototype crash cushion consisted of an array of diamond-shaped shaped elements supported on frangible posts, with two restraining wire ropes running the full length of the cushion. Figure 5 gives a pictorial view of the prototype design.

The matrix of development tests is given in Table 3. Initially tests were made with the crash cushion backed-up by a concrete block. After successful proving of this configuration, the cushion design was transferred as an end-treatment to a tensioned corrugated beam (TCB) safety fence and further tests were made.

The TRL design principle was initially assessed by impact with a 1 010 kg car at 57.6 km/h into a 3.8 m long crash cushion. The diamond-shaped elements, 310 mm deep, were constructed in 10 gauge mild steel mounted on a single row of posts connected by shear bolts to the cushion (D153, Table 3); the whole assembly was backed-up by a concrete block anchorage.

The full performance criteria were met in Test F200 by collision with a 1 500 kg car at 113.8 km/h into a 9.7 m long crash cushion consisting of diamonds 600 mm deep in 10 gauge mild steel, two rows of posts with frangible bases and two wire ropes extended over the length of the cushion.

The most significant stages of the development of the crash cushion are represented by the following tests:

- — E158: end-on impact by a 1 500 kg, 115.9 km/h, 0° vehicle, into an 8.9 m long, singlepost, crash cushion connected to a concrete block;
- — E184: side impact by a 1 500 kg; 115.8 km/h, 20° vehicle, into a 9.8 m long, double-post crash cushion connected to a concrete block. Two rows of posts and wire ropes were used to resist the lateral loads of the side impact;
- — F200: end-on impact by a 1 500 kg, 113.8 km/h, 0° vehicle, 9.7 m long, double post crash cushion connected to a TCB safety fence;
- — F204: side impact, angled on the nose, by a 1 500 kg; 112.6 km/h, 20° side impact crash cushion connected to a TCB safety fence.

E158 demonstrated that the car could be brought to rest within about 90 % of the 8.9 m length of the cushion and with an acceptable average longitudinal deceleration of 7 g and a peak value of 12.2 g.

E184 showed successful containment with good redirection and an acceptable THIV value.

In test F200, with the cushion backed-up by a TCB safety fence, a similar performance to E158 was achieved; the average longitudinal deceleration was 5.2 g with a peak of 15.2 g.

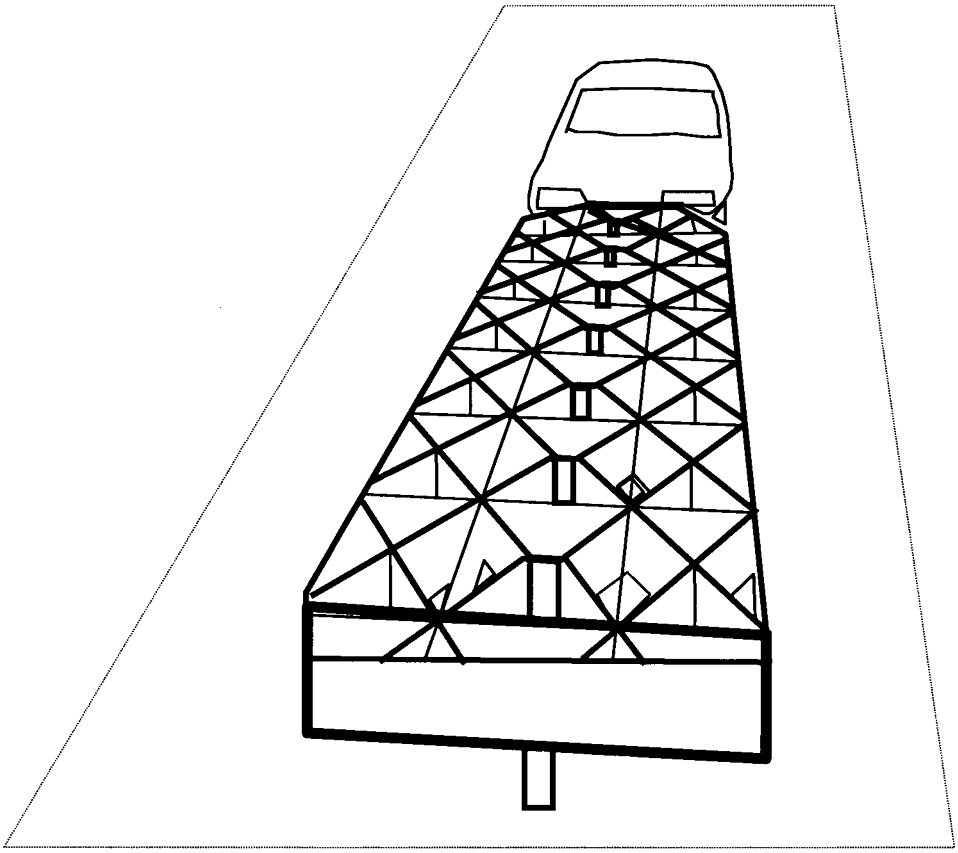

Figure 5 — Crash cushion design based on crushable diamond-shaped elements

Table 3 — Vehicle impact tests on crash cushions based on diamond-shaped elements

Test no.	Date	Mass of vehicle	Mass of dummy	Speed	Impact conditions		Cushion details				Result		Comments
					Angle	Offset	Width (gauge) [standard wire gauge (swg)]	Length	Depth	Height	Crush	Decel.	
		kg	kg	km/h	°	m	m	m	m	m	m	g	
D153	20.5.87	1 010	75	57.6	0.0	0.2	1.50 (10 swg)	2.93	0.31	0.77	2.9	4.4	Fully crushed against block
D154	20.5.87	1 435	75	57.2	0.0	0.3	1.61 (8 swg)	3.77	0.31	0.77	2.0	4.0	CC lifted up onto car
D156	16.7.87	1 440	75	115.2	0.0	0.0	1.61 (8 swg)	7.21	0.31	0.77	2.0	6.6	CC lifted vertically
E158	10.9.87	1 445	75	115.9	0.0	0.0	1.61 (8 swg)	8.89	0.41	0.77	6.0	7.0	CC 90 % crushed; all K energy absorbed
E170	27.11.87	1 055	75	80.0	20.0	Angled on the nose	1.60 (8 swg)	8.89	0.41	0.77	2.5+	9.4	Car contained; abruptly stopped
E171	9.12.87	1 450	75	114.0	19.5	Angled on the nose	1.60 (8 swg)	8.89	0.41	0.77	5.2+	10.0	Car redirected Rotated 160°
E172	11.2.88	1 440	75	114.8	21.0	Angled on the nose	1.60 (9 swg)	8.89	0.41	0.77	7.5	6.5	Car redirected; CC debris pushed to side
E184	16.6.88	1 445	75	115.8	19.0	Angled on the nose	1.70 (10 swg)	9.82	0.60	0.77	½ width THIV 8	2.6	Satisfactory side impact
E189	26.9.88	1 450	75	115.4	20.0	Angled on the nose	1.76 (10 swg)	9.69	0.60	0.77	80 % THIV 10	4.5	TCB backup Car launched
F200	17.1.88	1 445	75	113.8	1.0	On the nose	1.77 (10 swg)	9.69	0.60	0.77	70 % THIV 13	5.2	TCB backup Test successful
F204	16.2.89	1 430	75	112.6	20.0	Angled on the nose	1.77 (10 swg)	9.69	0.47	0.77	½ width THIV 10	7.0	TCB backup Test successful
J0008	9.10.91	1 436	75	115.4	20.0	Angled on side	1.77 (10 swg)	8.85	0.47	0.77	½ width THIV 9	7.0	TCB backup Test successful
J0009	23.10.91	1 440	75	115.6	20.0 Down-stream	Angled on side	1.77	8.85	0.47	0.77	½ width THIV 11	4.0	TCB backup Test successful
J0013	25.11.91	1 439	75	115.8	0.0	50 % offset	1.77 (10 swg)	9.35	0.47	0.77	80 % THIV 9	2.2	TCB backup Yaw: 440°
M0059	30.11.94	828	75	101.0	0.0	0.0	1.77 (10 swg)	9.35	0.47	0.77	3.9+ THIV 11	3.9	TCB backup Test successful
M0062	8.12.94	839	75	101	0.0	25 % offset	1.77 (10 swg)	9.35	0.47	0.77	3.5+ THIV 12	4.4	TCB backup Test successful

Test F204, a side impact on the nose, showed a significant lateral force component as reflected in the vehicle deceleration. Average values were longitudinal 7.0 g and lateral 1.9 g.

During the period of this work the drafting of British Standards was overtaken by their replacement with European Standards. The results obtained from the UK test programme were instrumental in the drafting of the European Standard prEN 1317-3. This standard included the requirement for an additional test on crash cushions by a 900 kg vehicle impact end-on and a second test offset one quarter vehicle width. Both of these tests were completed successfully on the TRL crash cushion in tests M0059 and M0062.

2.3 Basic concepts of lorry mounted crash cushions (LMCC)

Road workers on the highway can be protected from injury by an errant vehicle entering their work area if their activities are in the shadow of a following heavy vehicle. The driver of the shadow vehicle is exposed to injury if the energy of the errant vehicle, colliding with the rear of the lorry, is not sufficiently attenuated by the fitting of a crash cushion to the rear of the shadow vehicle for the purpose of absorbing some of the impact energy.

A simple dynamic analysis is given in the following paragraphs of impact by an errant vehicle into a crash cushion fitted to the rear of a shadow vehicle.

In Figure 6 the errant vehicle, M_1, impacts the shadow vehicle at speed, U_1, and decelerates under force, P, exerted by crushing, a distance, S, the crash cushion mounted on the rear of the shadow vehicle, M_2; if there is significant crushing of the front of the car this length should be included in distance, S. If all the kinetic energy of M_1 has not been dissipated in crushing the crash cushion, the shadow vehicle will be pushed forward a distance D.

To avoid the possibility of the shadow vehicle, M_2, becoming a hazard to road workers by being knocked too far forward, it is necessary to determine the relationship between the kinetic energy of impact of M_1 and the distance of the shadow vehicle, M_2, moves for given characteristics of the crash cushion and the vehicles involved.

The work-energy balance equation is:

Kinetic energy of M_1 = Work done in moving shadow vehicle M_2 + Work done in crushing crash cushion

$$\frac{M_1U^2}{2} = PS + \mu M_2Dg \qquad (3)$$

where

$P = M_1a_{\text{crit}};$ (4)

μ = the tyre/road coefficient of friction of the shadow vehicle.

The value of a_{crit} determines the resistive force, P, of the crash cushion for an errant vehicle of given mass, M_1. If the value of P is too low, the crash cushion will crush easily without absorbing the maximum energy of the errant vehicle, M_1, before the shadow vehicle, M_2, is pushed forward; in this case, the crash cushion has not been fully effective. Alternatively, if the resistive force of P is too high, the cushion will not crush and the shadow vehicle is immediately pushed forward on impact; the crash cushion in this situation has been ineffective.

The maximum value that the resistive force, P, can take to fully utilize the energy absorption capabilities of the crash cushion is that which is needed to just move the shadow vehicle, M_2, forwards.

That is:

$$P_{\text{crit}} = \mu M_2g \qquad (5)$$

Combining equations (4) and (5) gives:

$$a_{\text{crit}} = \frac{\mu M_2g}{M_1} \qquad (6)$$

Combining equations (3), (4) and (6) gives:

$$D = \left(\frac{M_1U_1^2}{2\mu M_2g} - S\right) \qquad (7)$$

When, in equation (7), the following equality applies:

$$\frac{M_1U^2}{2\mu M_2g} = S \qquad (8)$$

the shadow vehicle will not move during crushing of the crash cushion a distance S.

NOTE The crushing of the car contributes to the overall value of S.

If the condition is not met equation (7) predicts the movement, D, of the shadow vehicle; clearly, D cannot take a negative value.

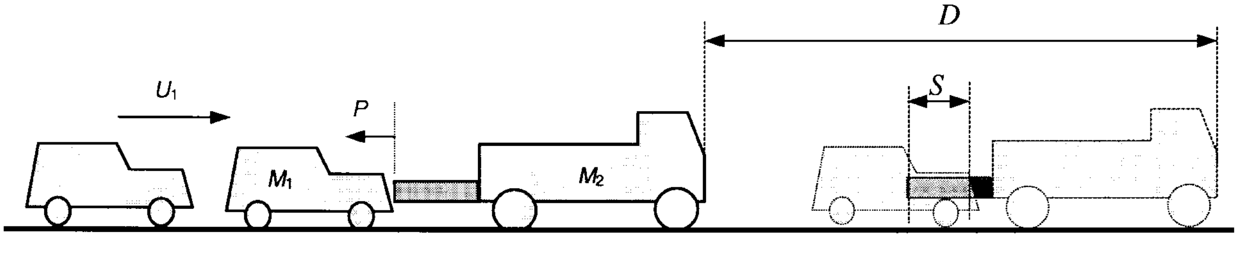

Figure 6 — Impact of an errant vehicle into a shadow vehicle

If the shadow vehicle still retains kinetic energy after full crushing has taken place, both vehicles, assuming they remain in physical contact, move off immediately at a combined speed. This situation can occur through the cushion having insufficient length for a given design value for the critical deceleration, a_{crit}.

The speed, V_1, of the errant vehicle at the end of the crush period is:

$$V_1 = (U_1^2 - 2a_{\text{crit}}S)^{½} \quad (9)$$

Assuming both the errant and the shadow vehicle remain in contact they move off together at the combined speed V_{comb} given by:

$$V_{\text{comb}} = \left(\frac{V_1 M_1}{M_1 + M_2}\right) \quad (10)$$

The deceleration to rest, a_2, of both vehicles after the impact that occurs at the end of the crushing period, is given by:

$$a_2 = \frac{V^2_{\text{comb}}}{2D} \quad (11)$$

If the driver of the shadow vehicle is sitting in the driving seat with his head a flail distance, *FD*, from the back panel of the cab, and it is assumed his head remains stationary relative to a terrestrial axis, the panel will move forward and collide with the back of his head at speed, V_{THIV}, given by:

$$V_{\text{THIV}} = (V^2_{\text{comb}} - 2a_2 FD)^{½} \quad (12)$$

The *Design manual for roads and bridges* (Volume 8, Section 4, Paragraph 4.6) [4] gives details of the requirements for lorry mounted crash cushions when used as a shadow vehicle during highway lane closures. A suitable range of vehicle weight is suggested as not less than 7.3 t and up to 17 t. Head restraints should be fitted to the shadow vehicle. The distance between the shadow vehicle and work vehicles should be maintained, but should not be less than 50 m.

2.3.1 *Graphical analysis of impact into a LMCC*

Equations (3) to (12) are invoked to give the following graphical analysis.

Figure 7 shows the effect of a change in the road/tyre coefficient of friction, μ, on the movement, *D*, of a 12 000 kg shadow vehicle when struck by a 110 km/h, 1 500 kg car. With the coefficient of friction at 0.75 the movement of the shadow vehicle is shown to be about 5 m for a crush distance of 3 m. If the cushion deformation is increased to 6 m the movement of the shadow vehicle reduces to about 2 m.

On a poor road surface where the coefficient has reduced to about 0.17, perhaps due to rain or icy conditions, the movement of the shadow vehicle for the same level of impact energy increases to nearly 30 m. Clearly, care should be taken to observe the prevailing weather conditions when LMCCs are employed for the protection of road staff.

Figure 8 shows the effect on the movement of the shadow vehicle of increasing the impact speed of the errant vehicle. For the respective masses of 12 000 kg and 1 500 kg the shadow vehicle does not move for an impact speed of about 60 km/h into a 3 m cushion; the equivalent cushion length for no shadow vehicle movement after an 85 km/h impact is about 6 m.

Figure 9 shows that the shadow vehicle moves the same distance of 10 m for an impact by a 2 000 kg car into a 3 m cushion as it does for a 2 400 kg vehicle impact into a 6 m LMCC.

In Figure 10 the shadow vehicle moves the same distance of 5 m for a 110 km/h impact into a 11 200 kg shadow vehicle with a 3 m cushion as it does for the same energy impact into a 15 000 kg LMCC with a 6 m cushion.

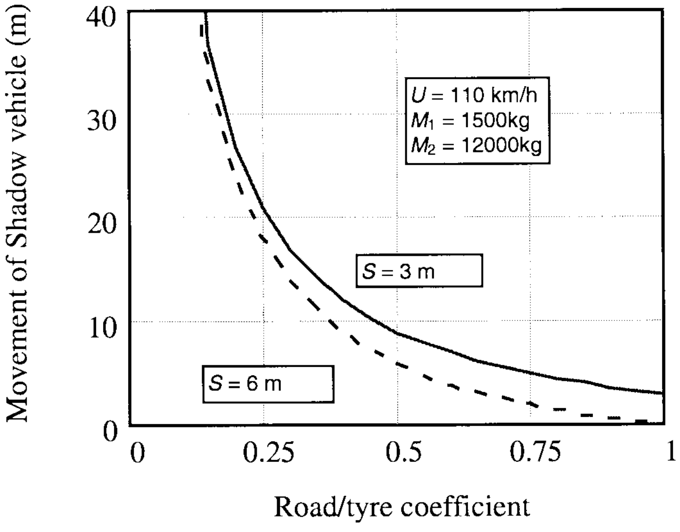

Figure 7 — Effect of road tyre coefficient, μ, on shadow vehicle movement, *D*

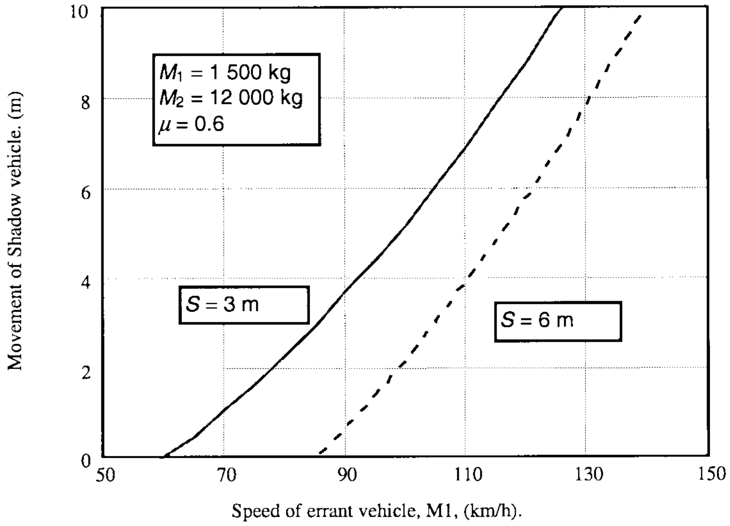

Figure 8 — Effect of impact speed on shadow vehicle movement

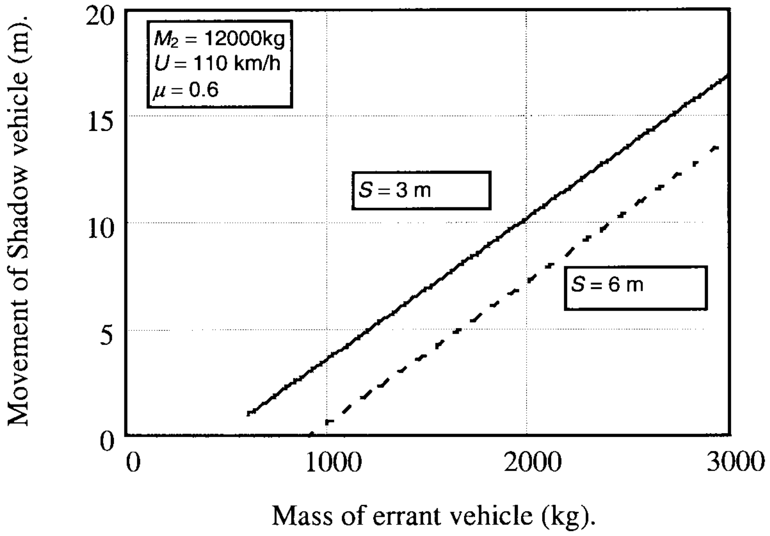

Figure 9 — Effect of errant vehicle mass on movement of shadow vehicle

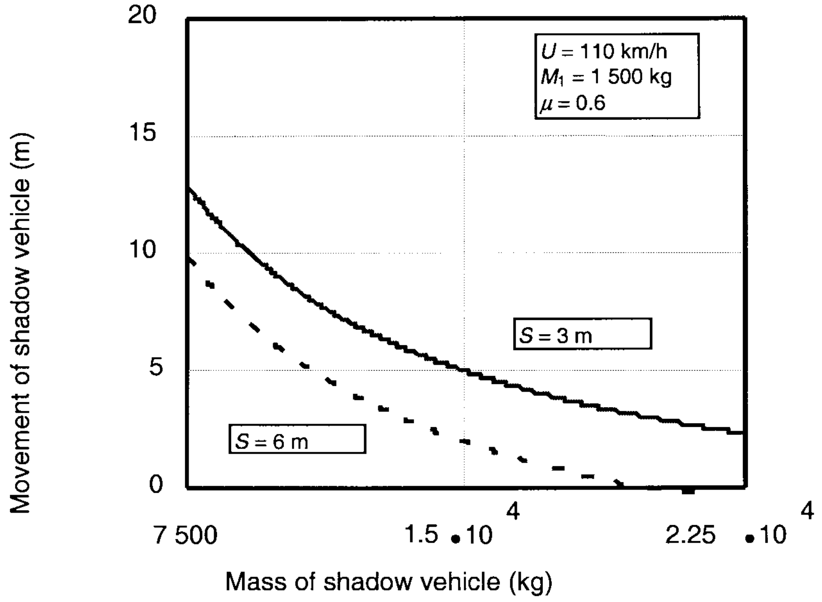

Figure 10 — Effect of shadow vehicle mass on movement of shadow vehicle

The examples have demonstrated that the formulae given in equations (3) to (12) provide the opportunity to estimate the safe working space for road staff who are operating in front of shadow vehicle. The area should be sufficiently large to give adequate distance for movement under impact conditions, but not too large so that traffic, after passing the shadow vehicle, attempts to turn back into the work area causing severe danger to the road staff.

2.4 Full scale impact tests on a lorry mounted crash cushion

A proprietary crash cushion, manufactured by Energy Absorption Inc, USA, was subjected to a series of impact tests; the results are given in Table 4. Impact vehicles of nominal masses 900 kg and 1 500 kg were impacted into shadow vehicle of nominal masses 7 500 kg and 10 000 kg.

Vehicle speeds ranged between 80 km/h and 100 km/h. Table 4 gives the lengths of the crash cushions and their crushed lengths after impact, including the crushed distance of the impact cars.

The shadow vehicle under these impact conditions was shown to move distances which ranged between 1.9 m and 4.7 m. As shown in the graphical analysis of **2.3.1**, the distance a shadow vehicle moves is highly sensitive to the tyre/road surface coefficient on which it is parked. The coefficient of the test area surface was measured by a pendulum tester at seven points within 30 m of the front of the shadow vehicle. The average coefficient was found to be 0.8. With regard to highways this value, in terms of skid resistance, represents the top dressing of a good, dry, road surface.

The measured movements of the shadow vehicle, under impact test conditions, were compared with calculated results derived from equation (7). The effective length of the crash cushion was taken to be its overall manufactured length, although it is only possible to compress it into a finite space; nevertheless some compensation for this was made in the calculations by neglecting the crush distance of the front of the test car.

Table 4 — Impact tests on lorry mounted crash cushions (LMCC)

Test number	**Date**	**Speed** km/h	**Mass** kg	**Average deceleration** g	**Shadow vehicle mass** kg	**LMCC model**	**Length of CC** m	**LMCC crushed length** m	**Test car crushed length** m	**PHD**[a] g	**THIV**[b] m/s	**Road surface coefficient**	**Movement of shadow vehicle** m
M0051	23.8.94	101.4	1 498	14.4	7 490	Alpha 60MD	3.75	1.75	0.4	—	—	0.8	4.7
N0025	25.5.95	80.1	1 500	11.3	7 548	Alpha 2001MD	3.00	1.47	0.6	17.3	10.5	0.8	2.9
N0026	1.6.95	81.8	1 505	14.4	10 020	Alpha 2001MD	3.00	1.85	0.8	20.0	10.8	0.8	2.0
N0027	12.6.95	82.1	906	12.9 g	7 515	Alpha 2001MD	3.00	1.85	0.2	15.3	12.6	0.8	1.9

[a] PHD = Post-impact head deceleration.

[b] THIV = Theoretical head impact velocity.

The calculated results in Table 5 are shown to give sufficiently good comparison warranting the use of the analytical analysis technique in the development of LMCCs. Of equal importance, the analytical equations allow estimates to be made of the siting of the shadow vehicle relative to the location of staff working on the roads. This facility may be useful where LMCCs are considered for use under poor road and weather conditions.

Table 5 — Comparison of calculated and test results for the movement of the shadow vehicle

LMCC test number	Movement of shadow vehicle m	
	Calculated	Measured
M0051	6.3	4.7
N0025	3.3	2.9
N0026	2.0	2.0
N0027	1.0	1.9

The calculated results and test results show similarities that do not differ by more than 1.6 m; this difference in length is of little consequence in terms of the margin of 50 m recommended between the work force and the placing of the shadow vehicle (TD 49/97 [4]).

It should be recalled that the analytical equations depend on a calculated critical value for the deceleration of the errant vehicle whilst it is in contact with the crash cushion and, in turn, the critical value is dependent on the frictional properties of the road surface.

To achieve the average skid resistance value of 0.8 the shadow vehicle would need to be on a very good, dry, road surface with all wheels locked, if minimal or no movement of the shadow vehicle was to take place under the designed impact conditions. Accordingly, where the safety of staff is concerned, a large safety factor should be applied to analytically predict movements of the shadow vehicle; particularly if an LMCC is used for staff protection within confined road lengths under adverse conditions such as those that occur on rural roads when rain or black ice has affected the road surface.

3 Vehicle arrester beds

3.1 General

The purpose of an arrester bed is to provide an opportunity for a runaway vehicle experiencing brake fade or failure on a down gradient to come safely to rest with minimum risk of injury to the occupants or severe damage to the vehicle. The length of the arrester bed depends on the speed, mass and construction of the vehicle and, most importantly, on the efficiency of the arrester bed to absorb the kinetic energy of the vehicle.

Under normal operation of vehicle brakes a deceleration of 0.5 g would be felt by an occupant as very firm braking; he or she would be propelled forward relative to the interior of the vehicle by a force equal to about 50 % of the person’s mass. Similarly, cargo transported by goods vehicles would experience braking forces which, under everyday travel conditions, would not cause difficulties if the material carried was adequately secured to meet this level of braking load. With these factors in mind an emergency stop by entering an arrester bed should generate similar levels of deceleration, if the vehicle occupants are not to be injured or the payload of goods vehicles is not to be jettisoned.

Nevertheless, road side site space can be at a premium at those locations where vehicles are likely to run out of control; they might run through the bed if it is too short, or the level of braking is too low. In those circumstances it is beneficial, if there remains some level of braking facility within the vehicle’s braking mechanism, for the arrester bed to provide higher deceleration levels if the run away vehicle is partially braked whilst in the bed.

Several materials and techniques have been tested to achieve these braking requirements including, hedges, natural stone aggregates and manufactured aggregates.

3.2 Rose bush hedges

In the early 1960s, at the time when discussions were taking place on the need for safety barriers on the central reserve of motorways, aesthetic and practical considerations were given to the use of shrubs, in particular rose hedges, to act as a median barrier.

A hedge of *Rosa multiflora japonica* (blackberry rose) was planted in 1957 and allowed to grow for six years. The rose shrubs were planted at 1.5 m intervals, staggered in a diagonal pattern; each row was spaced at 1.2 m intervals. The hedge had reached a height of 3.6 m and a width of 4.5 m to 6 m by the time tests were conducted. A 1 125 kg car was run into the hedge at approach angles of 90°, 20° and 10°, at speeds of 30 km/h, 51 km/h and 46 km/h respectively (Laker, 1966 [6]).

In the 90° and 20° tests the car passed completely through the hedge but in the 10° test it stopped in the hedge. Vehicle decelerations ranged between 0.4 g to 0.5 g and peaked at about 0.8 g.

As motorway central reserves are about 4 m wide, it was evident that a hedge of shrubs was not a sufficiently positive barrier for vehicles travelling at motorway speeds, although such a hedge would considerably reduce headlight glare from on-coming vehicles. Furthermore, it was evident that the use of shrubbery at run off points was not practical from vehicle recovery and shrub re-growth timescale considerations.

3.3 Aggregate arrester beds

Initial tests carried out by TRL in which cars were driven into beds of gravel at speeds from 16 km/h to 96 km/h revealed that small stones graded 10 mm to 6 mm decelerated a car somewhat better than larger stones graded 38 mm to 20 mm; and rounded gravel was more efficient in slowing a car than angular gravel. The smaller sized angular stones, laid to a bed depth of 300 mm, decelerated an un-braked 48 km/h vehicle at 0.45 g and a braked vehicle at 0.98 g from a speed of 64 km/h; the stopping distance in the later case being about 17 m (Laker, 1966 [7]).

In further tests, (Jehu and Laker, 1969 [8]) the vehicle range was extended to include rigid and articulated commercial vehicles of masses up to 21 000 kg running into beds of angular gravel graded 20 mm to 13 mm and tapered to a depth of 760 mm. Test runs were also made into a short length bed of man-made aggregate manufactured from sintered fuel ash. This material produced decelerations for an unbraked, 1 120 kg, 50 km/h car of 0.58 g and for a 7 500 kg, 30 km/h vehicle of 0.46 g.

The encouraging results obtained from the tests on the short bed of manufactured aggregate led to the construction of a bed sufficiently long enough to accommodate entry speeds of up to 86 km/h, for a 1 220 kg car.

In addition, a single track bed in which only the nearside wheels of a car could enter was constructed to examine the possibility of using such a design of arrester bed to stop vehicles which suffered brake failure on a hill leading down into the city centre of High Wycombe in Buckinghamshire. The single track width arose from the constraints of the carriageway width available on the hill.

A cross-section of the final design is shown in Figure 11. The bed was about 1.5 m wide and 400 mm deep, filled with man-made aggregate manufactured from sintered fuel ash. On the roadside where the bed was to be installed, pedestrians had access to one side and traffic to the other. For pedestrian safety an hydraulic safety barrier was installed on the pavement side of the bed.

A full width sintered fuel ash bed was also constructed for test purposes, suitable for end-on and side entry by commercial vehicles. The arrester bed shown in Figure 12 was backed up by a low concrete barrier against which the leading wheels of a commercial vehicle could engage should there be a risk of the vehicle running through the bed.

Vehicle trials confirmed that soft arrester beds are a practical means of stopping vehicles which lose their braking ability on long down gradients but that they do not constitute a positive central reserve barrier for out of control vehicles on motorways.

The following list provides a summary of the main findings on arrester beds.

— The safest and most effective arrester bed for dealing with brake failure is one sited so that runaway vehicles can be steered into it end-on. Given that its depth should be 0.380 mm to 0.450 mm and its width 4 m, the required length of the bed can be deduced from the formula:

$$L = \frac{V^2}{127}$$

where L is the length in metres (m) and V is the entry velocity in kilometres per hour (km/h).

— If site restrictions allow only end-on entry at an angle to the length of the bed, a kerb and safety barrier will be required to redirect runaway vehicles along the bed. An hydraulic safety barrier produced a satisfactory solution but other barrier installations are feasible.

— Vehicles which are deliberately driven off the road into the side of an arrester bed will usually enter it an angle of 5° to 10°. In the case of a dual-track bed, 4 m wide, a barrier along the far side should contain vehicles within the bed (see Figure 12). In the case of a single-track bed, 1.5 m wide, a safety barrier should be mounted on the kerb (see Figure 11).

— A single-track arrester bed with a safety barrier decelerates un-braked vehicles at about 0.3 g on level ground. Used on a hill with a 1 in 10 down gradient the deceleration is reduced by 0.1 g. In this circumstance the bed is not highly efficient but this is partly compensated by the fact that long lengths may be installed and in this way runaway vehicles may be driven into it before reaching high speeds. Furthermore, in many cases the arrester bed will be supplementing poor or fading brakes rather than dealing with complete failure of both foot and hand brakes.

— Aggregate which has been thrown on to the road surface during an arrester incident may constitute some nuisance or hazard to pedestrians and traffic. Its prompt removal is desirable and would be especially important for the single-track bed sited down a long length of hill. Economic and site considerations will clearly determine the choice of aggregate in particular applications.

DTp Advice Note TA 57/85 [9] gives details on the installation of arrester beds. Information on arrester beds to contain vehicles of gross masses of up to 79 t and speeds of up to 97 km/h is given in work done by the Materials Engineering Branch, Main Roads, Western Australia, Perth [10].

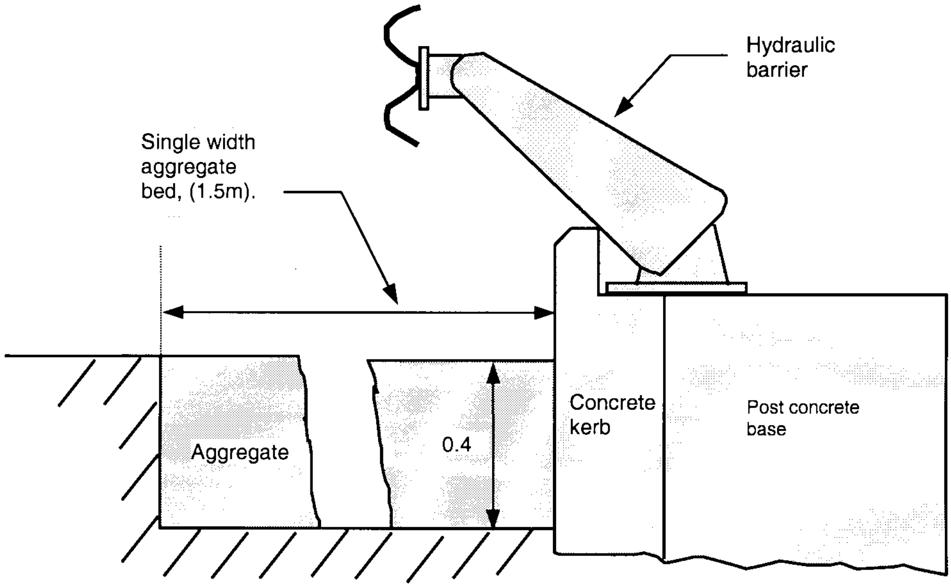

Figure 11 — Single-track sintered fuel ash bed suitable for installation on a city centre hill

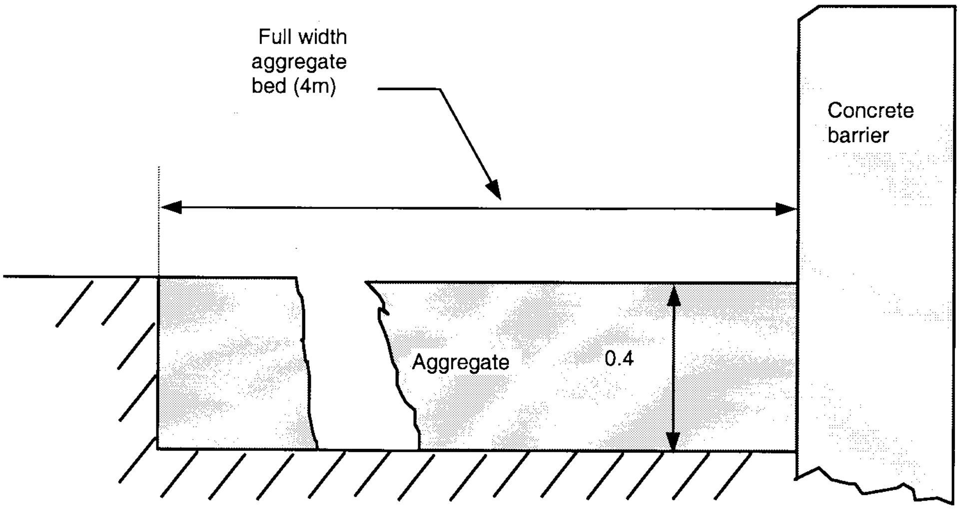

Figure 12 — Full width sintered fuel ash bed with a low concrete barrier

3.4 Bull nose safety barriers

Arrester beds have been installed on large roundabouts to restrain vehicles that overshoot the junction. Safety barriers, such as TCB and open box beam fences (OBB) of small radius of curvature may be installed on the circumference of roundabouts to perform the same functions; because of their tight curvature they are sometimes referred to as bull nose barriers. Although bull nose barriers do not act on errant vehicles in the same manner as arrester beds, they are used in comparable circumstances, and so are briefly mentioned here.

Figure 13 shows an OBB bull nose barrier on a 6 m radius fitted to TCB transient lead-in approach lengths. The barrier, designed by TRL, was tested by an 84.5 km/h impact with a 1 497 kg car. The car stopped in the bull nose after deflecting it 2.45 m. The THIV value was 12.9 m/s and the PHD was 6.1 g.

The test was repeated on the bull nose barrier; the impact direction was parallel to one arm of the transient lead-in as shown in Figure 14. The vehicle was deflected and stopped close to the line of the fence in a distance of about 6 m.

The THIV and PHD values were 9 m/s and 15 g respectively.

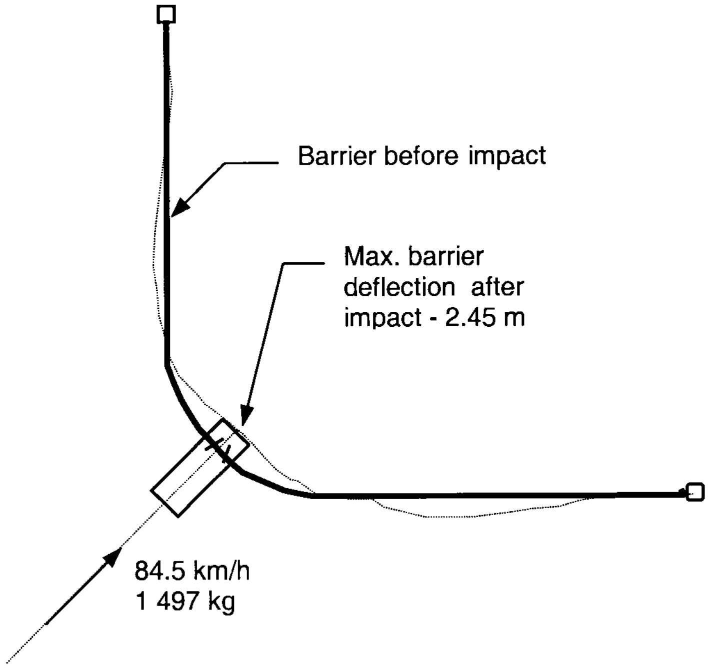

Figure 13 — Bull nose 6 m radius OBB barrier with TCB lead-in: radial impact

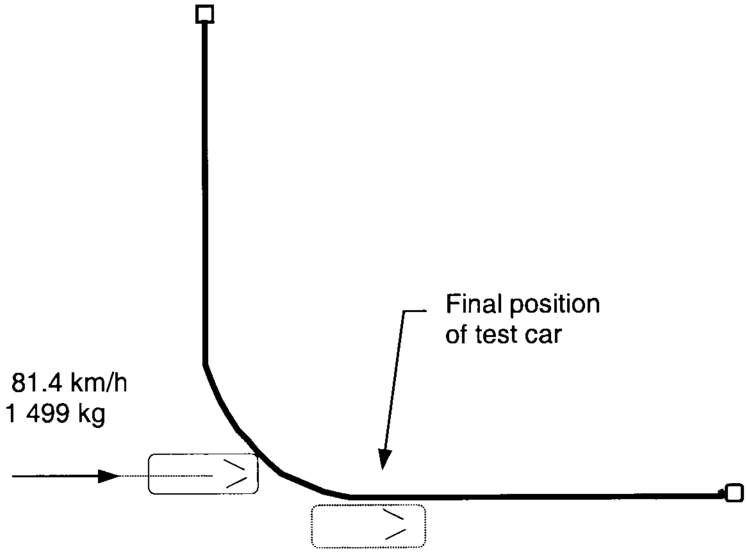

Figure 14 — Bull nose 6 m radius OBB barrier with TCB lead-in: parallel impact

4 Earth acoustic mounds as safety barriers

Consideration was given to whether noise absorption acoustic barriers, built on the verge area of motorways, could also act as vehicle safety barriers. To test the proposition an earth bank was constructed, 10 m long, of horizontal layers of mesh filled with compacted hogging; each layer was about 300 mm deep stacked to about 2.0 m in height (TRL, 1980 [11]). The face was inclined at 70° to the horizontal as shown in Figure 15.

The bank was impacted at an angle of 20° by a 1 524 kg vehicle at a speed of 104 km/h.

The test vehicle impacted at a point approximately 4 m from the approach end of the mound; the damage to the bank extended for a length of 5 m up to a height of 1.2 m. The car remained at its initial angle for the first part of the impact and then dug into the bank, very severely crushing the front impact side. The car yawed anticlockwise, spun out and rolled over. It completed one and a half rolls before coming to rest on its roof approximately 10 m from the end of the bank. The average decelerations of the vehicle were 8 g lateral and 7 g longitudinal. The engine was forced back into the passenger compartment, the front of the floorpan was distorted and the front occupant space was considerably reduced.

The earth bank was reconstructed as shown in cross-section in Figure 16. The impact side of the bank was made vertical and an OBB section rail was added at a height of 600 m above ground level, at a distance of 600 m from the face.

The assembly was impacted by a 1 515 kg car at 20° and 101.4 km/h.

The test vehicle contacted the OBB rail at a point about the centre of the barrier length; it remained in contact for about 8.5 m. The car was redirected at a small angle, it would have re-contacted an extended earth bank about 30 m from the end of the existing construction. The vehicle came to rest 50 m from the end of the barrier and 12 m behind it. Damage was confined to the impact side, with the front wheel forced backwards.

It is not recommended that acoustic earth banks are used on their own as verge safety barriers; although attachment of an OBB rail section to the face of the mound considerably improves the impact performance.

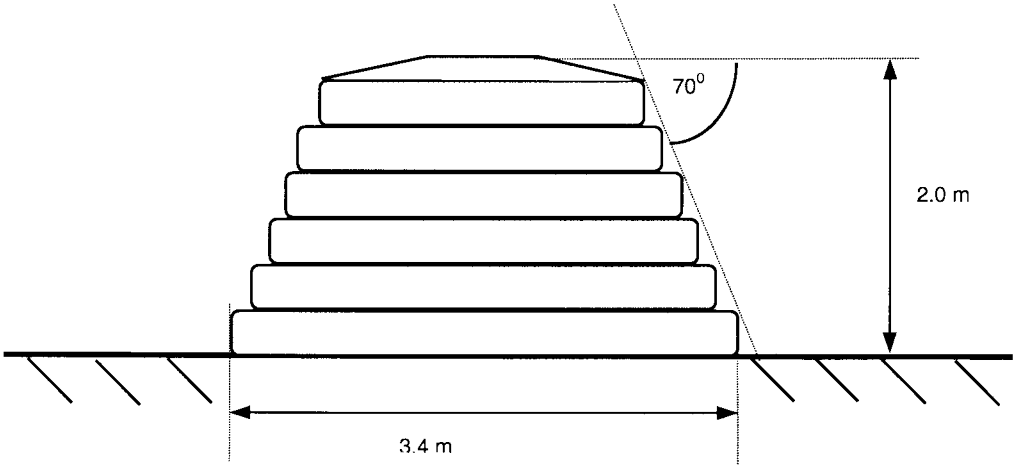

Figure 15 — Earthbank: compacted hogging in mesh

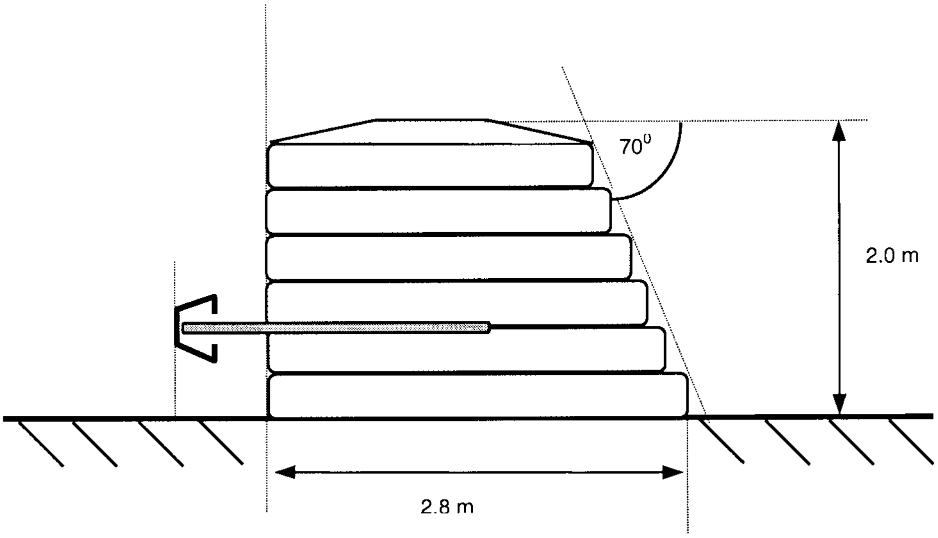

Figure 16 — Earthbank with OBB mounted at 0.6 m height

5 Impact into utility poles

Impact between vehicles and utility poles, such as lighting columns, telegraph poles and road signs, can generate extremely high deceleration forces. The damage to the vehicle can be extreme, particularly if collision is with the side of the car.

Impact tests carried out by TRL during the late 1950s, with pre-war cars, demonstrated that impacts at low speeds, about 20 mile/h, generated peak deceleration forces of 35 g on impact with a concrete column and about 20 g with a steel column (Moore and Christie, 1960 [12]).

The impact periods lasted 0.1 s and 0.2 s respectively for each test; the vehicles' engines were pushed back 20 mm in the steel column impact and 65 mm in the concrete column.

Figure 17 shows the moment of impact into a steel column, at an initial speed of 22.5 mile/h.

Impact into a telegraph pole by a similar vehicle at 28.4 mile/h generated a peak deceleration of 40 g (C. Blamey 1970 [13]). The THIV was recorded at 9.8 m/s, for an occupant flail distance of 0.46 m. A linear adjustment suggests the THIV value at 0.6 m for the telegraph pole impact increases to 12.8 m/s.

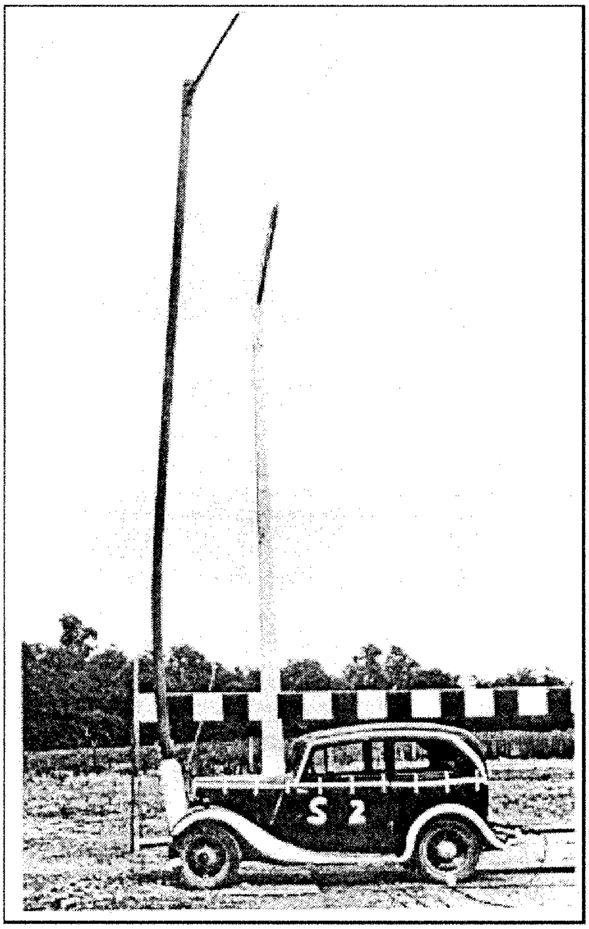

Figure 17 — Impact into a steel column at 22.5 m/h by a 1936 Morris 8 saloon car

Many solutions were tried to reduce the severity of impact into utility poles. These included using columns constructed of thin sheet steel, fibre glass, aluminium and columns stayed by straining wires. Knock off frangible base columns were designed with attachments which included shear bolts and a high tensile wire through the centre of the column which was sheared on impact by a guillotine.

Cambridge University Engineering Department, under contract to TRL, was asked to consider a means of introducing a frangible joint into a column without reducing the maximum bending resistance. A slip base was developed which, on impact, permitted the four retaining bolts to slip out of their open V-slot housings as the column moved on initial impact (see Figure 18). The THIV value reduced to 0.9 m/s at a flail distance of 0.46 m.

Following a series of tests it was concluded that thin sheet steel columns incorporating the breakaway joint, shown in Figure 18, gave the most consistent performance and lowest decelerations in collisions at speeds up to 100 km/h.

Figure 19 compares the deceleration traces of a standard 7.6 m high steel column with a 12 m column fitted with a slip joint.

In low speed collisions, below approximately 30 km/h, as the shaft of a breakaway column tends to fall on top of the colliding car it was important that the mass of the column should be as low as possible consistent with the wind load requirements.

This led to the development of formulae for designing tapered metal lighting columns and the subsequent production of working drawings suitable for the manufacture of thin sheet steel and aluminium breakaway columns. The drawings included details of a pull-out electrical connection device which in experimental collisions had ensured that the electricity supply to the shaft of the column was automatically disconnected when a collision took place.

At this stage in the development of the breakaway columns confidence in their safe performance was such that manually driven tests took place on several occasions and a small pilot scale public installation of tubular steel columns fitted with breakaway joints was erected on a roundabout in Gloucestershire. Four subsequent installations of lightweight breakaway columns were erected between 1969 and 1972 at sites near Doncaster on the A1, near Reading, at Calne on the A4 and on the Runcorn Expressway.

The use of breakaway columns in or behind the verges of fast roads with few pedestrians considerably reduced the severity of accidents in which lighting columns were involved. Most of the recorded accidents were in the damage only category. In less than half of these accidents the damage was so slight the vehicles were driven away without being identified.

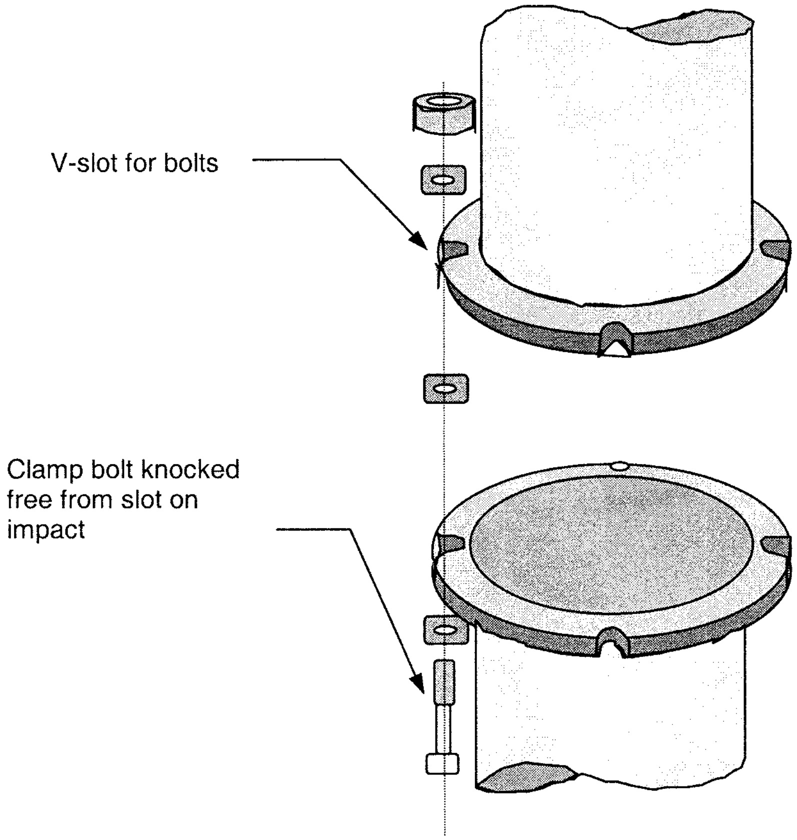

Figure 18 — Frangible slip base column joint

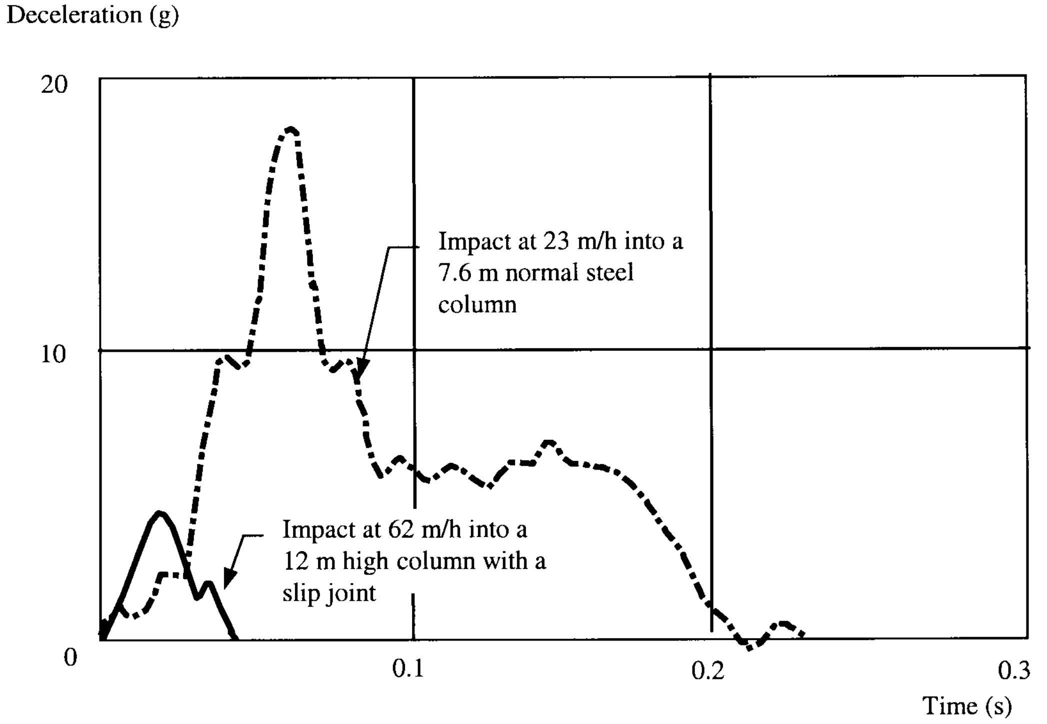

Figure 19 — Deceleration curves from impacts into a slip joint column and a normal column

Bibliography

Standards publications

prEN 1317-3:1996, *Road restraint systems — Part 3: Crash cushions — Performance classes, impact test acceptance criteria and test methods.*

PD 6634-2:1999, *Vehicle restraint systems — Part 2: Fundamentals of highway restraint systems.*

PD 6634-5:1999, *Vehicle restraint systems — Part 5: Development of barrier transitions and terminals.*

Other publications

[1] LAKER, I.B. *Tests to determine the design of roadside soft arrester beds*. Crowthorne, Berkshire: TRL, 1971 LR376.

[2] AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS (AASHTO). *Roadside Design Guide*. Washington DC: 1989.

[3] MACDONALD, M.D. *A progress report on the development of the TRRL crash cushion*. Crowthorne, Berkshire: TRL, 1989 VS/89/8.

[4] TD 49/97, The mobile lane closure technique. *Design manual for roads and bridges*, 1997. Volume 8, Section 4, Part 4.

[5] NEILSON, I.D., *et al. Controlled impact investigations: head-on impacts of four similar cars from different speeds against a rigid barrier*. Crowthorne, Berkshire: TRL, 1968 LR 132.

[6] LAKER, I.B. *Vehicle impact tests on a hedge of Rosa multiflora japonica*. Crowthorne, Berkshire: TRL, 1966 RRL No. 3.

[7] LAKER, I.B. *Vehicle deceleration in beds of loose gravel*. Crowthorne, Berkshire: TRL, 1966 RRL No. 19.

[8] JEHU, V.J. and I.B. LAKER. Vehicle decelerations in beds of natural and artificial gravels. Crowthorne, Berkshire: TRL, 1969 LR 264.

[9] DEPARTMENT OF TRANSPORT. *Roadside features: arrester beds*. London: DEPARTMENT OF TRANSPORT, 1989 TA 57/87 Advice Note.

[10] MATERIALS ENGINEERING BRANCH, MAIN ROADS. *Truck arrester bed*. Engineering Excellence Award 1995. Institute of Engineering Australia. Western Australia, Perth.

[11] TRL (Internal). *Earth noise barriers — Impact tests*. Crowthorne, Berkshire: TRL, 1980 File No. 304/365/21.

[12] MOORE, R.L. and A.W. CHRISTIE. *A preliminary analysis of the results from impact tests on three types of street lighting column*. Crowthorne, Berkshire: TRL, 1960 Research Note RN/3835/RLM, AWC (unpublished).

[13] BLAMEY, C. Results from impact tests on telegraph poles. *Highways Br.* 1964, **32**(1576), 7–8, 13.

Further reading

CHRISTIE, A.W. *A review of the work on the design of street lighting columns*. Crowthorne, Berkshire: TRL, 1962 Laboratory Note LN/1 19/AWC (unpublished).

CHRISTIE, A.W. and H.J. HIGNETT. *Formulae for designing tapered metal lighting columns*. Crowthorne, Berkshire: TRL, 1967 Ministry of Transport, TRL Report No. LR 144.

HIGNETT, A.J. and WALKER, A.E. *Collision tests with breakaway street lighting columns fitted with suspension cables*. Crowthorne, Berkshire: TRL, 1971 Ministry of Transport, TRL Report No. LR 387.

HIGNETT, H.J. *A sideways impact test into a 12.2 m (40 ft) lighting column fitted with a breakaway joint.* Crowthorne, Berkshire: Road Research Laboratory, 1969 Ministry of Transport RRL Report No. LR 241.

HIGNETT, H.J. *High speed impact tests on a 40 ft lighting column fitted with a breakaway joint*. Crowthorne, Berkshire: TRL, Ministry of Transport RRL Report No. LR 67.

LAKER, I.B. *Street lighting columns with frangible joints based on steel retaining wires*. Crowthorne, Berkshire: TRL, 1963 Laboratory Note LN/340/IBL (unpublished).

LAKER, I.B. *Test to determine the design of roadside soft arrester beds*. Crowthorne, Berkshire: TRL, 1971 LR 376.

LAKER, I.B. and I.B. WALKER. *Tests on 25 ft mounting height Group A street lighting columns frangible joints based on single shear bolts*. Crowthorne, Berkshire: TRL, 1964 Laboratory Note LN/628/IBL, AEW (unpublished).

MOORE, R.L. and A.W. CHRISTIE. The design of lamp columns for roads with few pedestrians. *Light and Lighting*, 1960, **53**(11) 330–334.

STANSFIELD, K. *Tests on a Group A street lighting column supported by short stay wires designed to have low impact resistance*. Crowthorne, Berkshire: TRL, 1963 Laboratory Note LN/313/KS (unpublished).

STANSFIELD, K. *Tests on a fibreglass column for Group A street lighting*. Crowthorne, Berkshire: TRL, 1963 Laboratory Note LN/417/KS (unpublished).

WALKER, A.E. *Collision tests on a motorway hazard post fitted with breakaway joints*. Crowthorne, Berkshire: TRL, 1970 Ministry of Transport, TRL Report No. LR 312.

WALKER, A.E. *Further results from impact tests on three types of Group A street lighting columns*. Crowthorne, Berkshire: TRL, 1961 Research Note RN/4042/AEW (unpublished).

WALKER, A.E. *Impact tests on three types of Group A Aluminium Alloy, street lighting columns*. Crowthorne, Berkshire: TRL, 1962 Laboratory Note LN/33/AEW (unpublished).

WALKER, A.E. *The results of impact and static loading tests on two prototype tubular wooden Group A street lighting columns*. Crowthorne, Berkshire: TRL, 1964 Laboratory Note LN/557/AEW (unpublished).

WALKER, A.E. *The results of impact tests on a prototype Group A street lighting column designed to have low impact resistance*. Crowthorne, Berkshire: TRL, 1962 Laboratory Note LN/113/AEW (unpublished).

WALKER, A.E. *The results of impact tests on three modified thin sheet steel Group A street lighting columns*. Crowthorne, Berkshire: TRL, 1962 Laboratory Note LN/63/AEW (unpublished).

WALKER, A.E. *The results of impact tests over a range of speeds on two types of Group A concrete street lighting columns*. Crowthorne, Berkshire: TRL, 1963 Laboratory Note LN/3121/AEW (unpublished).

WALKER, A.E. and H.J. HIGNETT. Breakaway lighting columns. *Highway Publication Works*. 1967, **35**(1689) 28–29, 31, 33, 35.

WALKER, A.E. and I.B. LAKER. *Impact tests on street lighting columns*. Crowthorne, Berkshire: TRL, 1961 Research Note RN/3930/AEW, IBL (unpublished).

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