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Vehicle restraint systems —

Part 5: Development of barrier transitions and terminals

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Committees responsible for this Published Document

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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 — Data base*;
- — *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 6: Crashworthy roadside features — Impact attenuators.*

BSI Committee B/509/1, whose constitution is shown in this Published Document takes collective responsibility for its preparation under the authority of the Standards Committee. The committee wishes to acknowledge the personal contribution of Mr I B Laker.

Over the last 30 years the Department of the Environment, Transport and the Regions (DETR), the Transport Research Laboratory (TRL), 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 the 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 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 18, an inside back cover and a back cover.

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1 Scope

This part of PD 6634 describes the development of barrier transitions and terminals for vehicle highway safety barriers in the United Kingdom. Theoretical designs and practical tests involving vehicle impact into transitions and soft terminals are described.

2 Barrier transition and terminal concepts

The draft European Standard, EN 1317-4, defines a transition as the connection between two safety barriers of different designs and/or impact performance.

A terminal is the end-treatment of a safety barrier. In practice a terminal provides a transition from full impact performance at some point along the barrier where the LoN, begins, down to zero performance at the extreme end of the barrier. Inevitably, the terminal has a lower impact performance than the barrier structure to which it is connected.

The exposed end-post of a high containment barrier or bridge parapet, through its inherent strength, could cause considerable damage to an impacting vehicle, whether private car or heavy commercial vehicle (HCV). Similarly, the physical connection between a low and a high containment barrier could be equally hazardous unless the change in lateral stiffness is smoothed by a graded transition in lateral resistance. In addition, barriers which have identical vehicle containment capabilities, yet have different flexibility or working widths (see EN 1317-2), need to be linked together by a transition length.

By definition, the transition length from a low to a high containment barrier can only successfully function against an impact less violent than that which can be successfully contained by the high containment design. Should the higher level of protection be required on the approaches to a bridge, then the bridge parapet must be extended beyond the minimum bounds of the bridge structure.

The fundamental difficulty in any proposed design of transition is deciding on the length between the end of the lower containment barrier and the beginning of the higher containment structure. In descriptive terms its length needs to be approximately the distance between the end-point of the LoN of the lower and the start-point of the higher containment barrier. On the subject of transition length, draft EN 1317-4 states:

> “The distance from the end of a terminal or from the end of a transition, where any particular barrier reaches its full performance (LoN point) depends on the terminal/transition and on the barrier. This distance shall be demonstrated by a test according to EN 1317-2, or by rational thinking”.

The standard goes on to say that rational thinking for concluding the length is to say that the transition cannot be less than one-third of the installed test length. Since there are no restrictions in the standard on the test length that can be installed, other than its length should demonstrate the full performance of the barrier, this prescription does not lead to a unique conclusion. Alternatively, the stipulation that the point of the LoN can be determined by full scale tests is unique but its implementation can be prohibited by the high cost of the number of tests that are likely to be needed in order to determine this definitively.

As a possible solution to the problem of defining the length of a transition or a terminal, the following clauses attempt to apply the results of both practical full scale trials and simple dynamic theory to the design of prototype transitions and terminals; in other words, they attempt to assist the rational thinking process desired by EN 1317-4.

3 Practical trials and simple theoretical design concepts for safety barrier transitions

3.1 Practical vehicle impact trials

Table 1 lists results from full scale vehicle impact testing carried out by TRL, of transitions between barriers of similar containment levels but differing designs and barriers of different containment levels.

Of particular interest are test numbers D155 and D159. A transition was needed to connect a high containment P6 steel bridge parapet (see PD 6634-4, Table 1), intended for the containment of a 30 t HGV impact, to an open box beam (OBB) safety barrier system designed for the containment of a 1 500 kg car impact (Laker 1989 [1]).

The starting point of the transition design began with the knowledge that a double height double sided open box beam (DHDSOBB) safety fence, under test, had contained an 80 km/h, 15°, 16 t HCV impact (test number A106, PD 6634-3, Table 8). By definition, the containment level of the transition would necessarily have to be less than that of the 30 t capability of the P6 bridge parapet to which it was to be connected.

During the 16 t test, about 30 m of the fence was damaged. The maximum lateral deflection of the impact occurred at about 17 m from the point marking the beginning of the barrier damage; that is about halfway along the total damaged length. From this evidence, the presumption was made that a transition from safety barrier to parapet over a similar 17 m length would most probably produce a worst case condition for generating the possibility of an end-on impact with the bridge parapet anchorage.

Table 1 — TRL impact tests results on barrier transitions

Test no.	Date	Mass of vehicle kg	Mass of dummy kg	Speed km/h	Impact angle	Barrier type	Drawings	Contact length m	Maximum deflection m	PHD g	THIV m/s	Comment
Transitions between barriers of similar containment levels												
H215	7.11.90	1 465	75	116.8	20	WRSF/OBB	TRL-1040.00/S45.040 TRL-1040.00/000.S45	14.0	1.4	—	6.1	Satisfactory
H216	15.11.90	1 465	75	114.6	19	WRSF/OBB	TRL-1040.00/S45.040 TRL-1040.00/000.S46	23.5	1.4	—	3.8	Climbed OBB ramp
H0001	19.3.91	1 477	75	114.9	20	WRSF/OBB	TRL-1040.00/S45.040 TRL-1040.00/000.S47	14.0	1.3	—	5.0	Satisfactory
N0020	23.3.95	1 499	75	114.7	20	SHOBB/VCB	TRL-OBB 00/2	7.0	0.3	30.3	10.6	Failed BS 6579 and EN 1317
P0002	24.2.96	1 501	—	114.6	20	SHOBB/VCB	TRL-OBB 00/2	4.0	0.15	10.6	8.8	Complied with BS 6579 and EN 1317
Transitions between barriers of different containment levels												
D155	2.7.87	16 100	—	80.6	15	OBB/P6 steel	TRL-1040.00/000.486 TRL-1040.00/000.463	10.0	0.1	—	3.4	Satisfactory Linear transition
D159	15.9.87	16 300	—	80.3	15	OBB/P6 steel	TRL-1040.00/000.486 TRL-1040.00/000.491	10.0	0.15	—	3.4	Satisfactory Stepped transition
F202	5.1.89	16 000	—	81.6	15	OBB/P6 concrete	TRL-1040.00/000.583 TRL-1040.00/000.584	12.0	0.2	—	3.6	Contained but rolled on exit
L0022	11.3.93	13 283	—	73.2	20	OBB/P6 steel	Babtie Shaw & Morton Drawing S10842/S2	4.5	0.16	2.4	3.6	Satisfactory Exceeds CEN TB42
L0024	25.3.93	13 335	—	71.0	20	OBB/P6 concrete	Babtie Shaw & Morton Drawing S10842/S2	15.0	0.2	2.6	4.5	Severe damage OBB Normal
M0048	21.9.94	12 970	—	70.5	20.5	OBB/P6 concrete	Babtie Shaw & Morton Drawing S10842/13	>20.0	0.2	2.0	3.3	Satisfactory

Table 1 — TRL impact tests results on barrier transitions *(continued)*

Test no.	Date	Mass of vehicle kg	Mass of dummy kg	Speed km/h	Impact angle	Barrier type	Drawings	Contact length m	Maximum deflection m	PHD *g*	THIV m/s	Comment
L0021	11.3.93	12 599	—	72.4	20	P1/P6 steel	Babtie Shaw & Morton Drawing S10842/S2	9.0	0.16	3.5	4.0	Satisfactory Exceeds CEN TB42
L0023	22.4.93	12 936	—	64.7	20	P1/P6 concrete	Babtie Shaw & Morton Drawing S10842/S3	7.6	0.07	7.25	4.1	BS 6579 and CEN standards not met
N0019	30.3.95	1 504	75	111.0	20	SH/DH-OBB	TRL-OBB 00/2	8.0	0.7	5.9	6.1	Complied with EN 1317
P0003	15.8.96	10 080	—	81.1	15	SH/DH-OBB	TRL-OBB 00/3	12.7	1.1	2.9	3.5	Complied with EN 1317
01FB	10.1.96	1 505	—	113.8	20	SHOBB/P1 Steel	Mouchel 42030/PCON/05 - 06	Stopped in barrier	0.89	20.6	7.9	Failed BS 6579 and EN 1317
03FB	30.1.96	1 497	—	113.2	20	SHOBB/P1 Auminium	Mouchel 42030/PCON/09	13.0	1.55	9.3	7.2	Failed BS 6579 and EN 1317
05FB	19.12.96	1 501	—	110.9	20	SHOBB/P1 Steel	Mouchel 42030/TRAN/05	3.5 approx.	0.09	6.9	8.2	Satisfactory but exceeded ASI
01GB	20.1.97	1 503	—	112.5	20	SHOBB/P1 Aluminium	Mouchel 42030/TRAN/06	3.5 approx.	0.1	12.9	9.4	Satisfactory but high THIV value

NOTE 1 THIV = theoretical head impact velocity; PHD = post impact head deceleration. See PD 6634-2:1999, **7.6**, for definitions.

NOTE 2 WRSF = wire rope safety fence.
VCB = vertical concrete barrier.
SH = single height.
DH = double height.

Using this concept, the planned impact point on the transition, with a 16 t HCV was arranged to be 17 m from the end-post in order to simulate this worst condition. From these considerations the simple impact criterion, that the length of the transition should be approximately one-half of the vehicle contact length observed during a basic barrier test on the LoN, was adopted.

Given this criterion, selection of transition posts was based on a linear increase in cross-sectional bending strength, over the transitional distance of 17 m from the safety fence end-post to the first anchorage post of the parapet. Post sizes were chosen to fit the linear increase in strength.

Two types of transitions were built. In the first, the increase in post strengths closely followed a linear scale (see Figure 1); test results are given in Table 1 under test number D155.

In the second design, a courser gradation was chosen in the form of stepped increases in the strength of the posts' cross-sections (shown in Figure 1); test number D159, Table 1 gives test results.

Test D155 had eight posts graded in increasing strength from the DHDSOBB, Z-section barrier posts, to the I-section posts at the beginning of the bridge parapet end-anchorage. Test D159 had just three graded levels of posts between the barrier and the parapet.

In both tests, the 16 t vehicle was successfully contained and redirected. Maximum roll angles were recorded to be about 34°. The departure paths were close to the line of the parapet, at 1° and both exit speeds were 70 km/h. The maximum deflection at the top of the transition was 150 mm. In neither test were the in-service repairs regarded as being urgent.

Both designs of transition (D155 and D159) had achieved the objective of protecting the vehicle from impacting the very stiff end-anchorage of the bridge parapet. The transition using just three sizes of post section (D159) is probably the most attractive from the point of view of primary construction and repair costs.

The overall design requirement, that the transition should accommodate a 1 500 kg car impact, was met by reducing the lead into the DHDSOBB fence by a SHDSOBB fence. This design arrangement was confirmed by test N0019 (Table 1) in which a 111 km/h test vehicle was contained and redirected.

Table 1 shows a number of other tests for transitions between various configurations of safety barrier, as listed under barrier type. Reference is made in the table to drawings that highlight a range of designs; these drawings should be examined if detailed information is required.

However, as a general comment, those designs that are listed in Table 1 that did not successfully meet the requirements of vehicle impact testing mostly failed due to either a step change in the stiffness of the transition, such as a flexible metal barrier connected directly to a rigid concrete barrier, or because the gradient of the lateral stiffness was too great over a transition length that was too short.

3.2 A simple analytic design criterion for safety barriers of different lateral stiffness connected by a transition

The concept described in **3.1**, wherein the length of the transition should be about one-half of the vehicle's contact length as determined by a basic barrier test, is carried over into the following analytical analysis. Furthermore, it is presumed that the halfway point of the contact length is also the position of the barrier's maximum deflection.

In the development of a new design of safety barrier with an associated transition where a prototype has not been constructed and tested, there is no prior knowledge of the vehicle's contact length to the point of maximum lateral deflection. To overcome this difficulty, the following analysis begins by choosing an acceptable magnitude for the prototype lateral impact deflection. Simple equations of motion are then used to determine the average lateral force experienced by the prototype barrier and so a simple design for the lateral stiffness of the barrier is developed.

The contact length of the colliding car is calculated based on the assumption that it follows a circular horizontal arc, as shown in Figure 2. The length of the transition is then prescribed geometrically as half the length of this circular arc.

To provide an overall design for connecting two or more prototype safety barriers of differing containment levels, the desired lateral deflection of each is selected and the lateral stiffness of each is calculated. The stiffness gradient between the barriers can now be estimated which, along with a knowledge of the calculated half contact length, provides sufficient information for a complete design of the length and stiffness gradient of the transition.

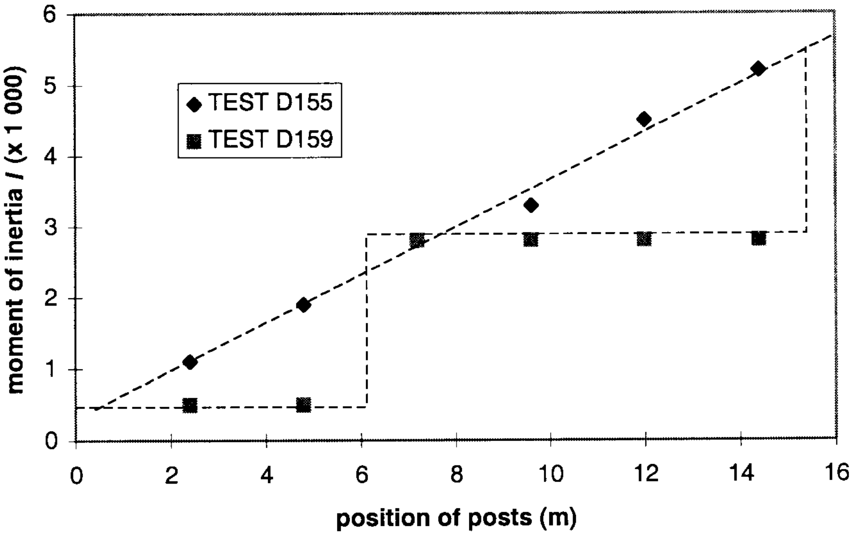

Figure 1 — Section moment of inertia of transition posts

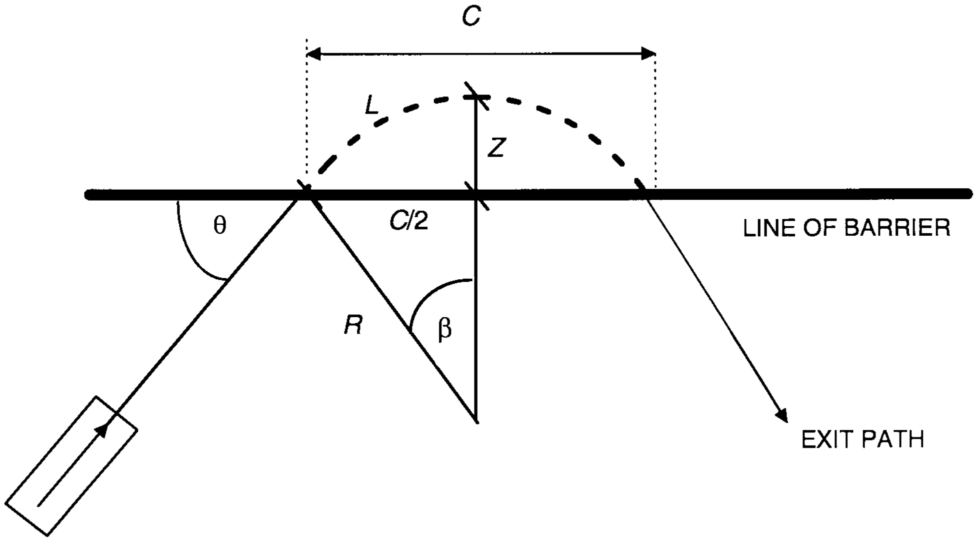

Figure 2 — Diagrammatic sketch of a barrier deflection on a circular arc of radius R

3.3 Analytic equations for prototype barrier design, vehicle contact length and transition length

Figure 2 is a diagrammatic sketch of a vehicle of speed V and mass M impacting a barrier at angle θ; after first contact, its centre of gravity (CG) moves a distance Z on a circular path of radius R, before leaving on its exit path.

Given chosen values for the deflection D of the barrier and the lateral crushing K, of the vehicle, the set of equations for calculating the barrier and transition characteristics are as follows.

The total lateral movement, Z, of the CG of the car is given by

$$Z = D + \mathrm{K} \qquad (1)$$

where

D is the chosen deflection of the barrier;
K is the lateral crush of the vehicle.

The equation for calculating the mean lateral acceleration, a, is

$$a = \frac{(V \sin \theta)^2}{2[c \sin \theta + b(\cos \theta - 1) + Z]} \qquad (2)$$

From Figure 2 the radius of curvature, R, is given by

$$R = \frac{C^2}{8Z} + \frac{Z}{2} \qquad (3)$$

where

C is the chord or undeflected length of the barrier in the contact area.
R is the radius of curvature of the vehicle's path through the barrier.

The radial acceleration a of a vehicle at speed V on a circular path is given by,

$$a = \frac{V^2}{R} \qquad (4)$$

Combining equations (3) and (4) to eliminate R gives

$$C = \left[\left(\frac{V^2}{a} - \frac{Z}{2}\right) 8Z\right]^{½} \qquad (5)$$

By inspection of Figure 2

$$\beta = \frac{\pi}{180} \sin^{-1}\left(\frac{C}{2R}\right) \qquad (6)$$

$$L = \beta \cdot R \qquad (7)$$

where

β is the angle subtended by the radial arc L, in radians;
L is half the barrier contact length (or length of the transition).

The point force P exerted on the barrier by the vehicle is given by

$$P = M \cdot a \qquad (8)$$

where

M is mass of vehicle;
a is radial (or lateral) deceleration acting at the vehicle's CG.

The distributed radial load, acting laterally on the barrier, generated by the point load acting at the CG of the impact vehicle, is a function of the post stiffness, the post spacings, the beam stiffness and the effective length of the impacting car. Full scale impact test results suggest that the point load P is typically spread over three to four posts for post and rail barriers or, for barriers mounted on a continuous footing, over the length of the vehicle.

For chosen values of barrier deflection D and vehicle damage K the contact length L, made by the vehicle against the barrier, can be found from equations (1) to (7). The theoretical point load acting laterally on the barrier can be found from equation (8).

The validity of equations (1) to (8) in predicting the design of prototype vehicle safety barriers and transitions has been checked against full scale impact tests. The results are shown in Table 2. The barrier maximum deflections D, recorded in the tests, were processed by the equations with the crush value K set at a fixed estimated value of 0.3 m.

The test values for the lateral point loads quoted in Table 2 were derived from a pair of orthogonal accelerometers mounted at the CG on board the test vehicle. The longitudinal and lateral acceleration time series were subsequently resolved in a direction transverse to the line of the barrier. The point loads acting in that direction were compiled by multiplying the resolved accelerations by the mass of the vehicle, to give the point load acting at the vehicle's CG. The reactive balancing force is generated by the stiffness characteristics of the barrier.

Table 2 shows that the test and the calculated values give reasonable comparison between vehicle to barrier contact lengths; lateral accelerations; and lateral loads. The maximum deflections are of course identical because that was a predetermined condition for the calculations.

Table 2 — Comparison of impact test results and calculated results

Barrier Type	Vehicle/barrier contact length m	Lateral acceleration m/s^2	Lateral point load kN	Maximum barrier deflection m
DHDSOBB				
Test E181				
(70 mph, 1.5 t, 20°)				
Test values	11.9	28.4	51	0.97
Calculated values	9.3	30.7	46	0.97
DHDSOBB				
Test A106				
(50 mph, 16 t, 15°)				
Test values	30.0	7.6	126	1.22
Calculated values	28.5	7.7	125	1.22
P6 steel				
Test E173				
(40 mph, 30 t, 20°)				
Test values	13.0	9.9	375	0.44
Calculated values	10.0	9.4	302	0.44

NOTE 1 For calculated accelerations, vehicle crush is estimated at a fixed value of 0.3 m.

NOTE 2 An example of the calculations is given in **3.4**.

3.4 Example of calculations for prototype barrier design, vehicle contact length and transition length

Calculations of the characteristics of a prototype barrier design are made from which, for a given impact energy, the length of vehicle contact can be determined. A transition design of suitable length and lateral stiffness gradient is derived, whose purpose is to link the prototype barrier to one of higher containment level, such as the P6 high containment parapet. The length of the transition is prescribed as half the contact length, as discussed in **3.1**.

The example calculation begins by choosing a desired value for the maximum lateral barrier deflection D. In practice, the choice for the maximum lateral deflection would be associated with the on-site road width available. To permit comparison of the calculated results with full scale test results the value chosen in this example is that quoted in Table 2 for test A106 at 1.22 m deflection. This test refers to a 16 t HGV impact into a double height double side open box barrier (DHDSOBB), with Z-posts (125 mm × 90 mm × 6 mm) at spacings of 2.4 m (see PD 6634-3:1999, Table 8). The value for lateral vehicle crush K was set at 0.3 m; it is based on an amalgam of vehicle damage observed in impact testing. Similar calculations were made for tests E181 and E173 but are not reproduced here; the results are given in Table 2.

Theoretical calculations for barrier and transition design (based on test A106)

Reference should be made to equations (1) to (7).

Total lateral movement Z of the CG of the car according to equation (1) is

$$Z = D + K = 1.52 \text{ m}$$

where

D = 1.22 m;
K = 0.3 m.

Mean lateral acceleration a, derived from equation (2), is

$$a = \frac{(V \sin \theta)^2}{2[c \sin \theta + b(\cos \theta - 1) + Z]} = 7.661 \text{ m/s}^2$$

where

θ = 5°;
b = 1.22 m;
c = 3.0 m;
Z = 1.52 m;
V = 22.71 m/s.

Radius of curvature R, of the circular path, derived from equation (4), is

$$R = \frac{V^2}{a} = 67.3 \text{ m}$$

Chord length C, of the contact area, derived from equation (5), is,

$$C = \left[\left(\frac{V^2}{a} - \frac{Z}{2}\right) 8Z\right]^{½} = 28.5 \text{ m.}$$

Angle β subtended by the radial arc L, derived from equation (6), is,

$$\beta = \frac{\pi}{180} \sin^{-1}\left(\frac{C}{2R}\right) = 0.213 \text{ radians.}$$

Transition length L, derived from equation (7), is

$$L = \beta \cdot R = 14.3 \text{ m.}$$

Point lateral force P exerted on the barrier by the vehicle, derived from equation (8), is

$$P = M \cdot a = 124.8 \text{ kN.}$$

where

$$M = 16\,300 \text{ kg.}$$

Full scale impact test results suggest that for fully installed barriers, the point load is typically spread over three to four posts for post and rail barriers, or approximately over the length of the vehicle for barriers mounted on a continuous ground base.

For a 16 t HCV of length 9.3 m in collision with a barrier of 2.4 m posts spacing:

— the number of posts per vehicle length is about 9.3/2.4 = 3.875 posts;

— the distributed load per post is then 124.8/3.875 = 32.2 kN.

NOTE PD 6634-3:1999, Table 1, shows the yield force for a 125 mm × 90 mm × 6 mm Z-post is 39.6 kN at a loading height of 0.61 m.

3.5 Summary

In summary the calculated results of barrier and transition design based on test A106 show reasonable comparison with the full scale impact test results as follows. However, the calculations should be regarded as only a rough guide; they should be checked by full scale vehicle impact testing.

Barrier design

— For a prescribed maximum lateral deflection D of 1.22 m, the calculated vehicle contact length $2L$, was 28.5 m. Test A106 gave 30.0 m. (See Table 2.)

— The calculated point loading on the fence by the 16 t HCV was 124.8 kN. This compared well with the measured A106 test result of 125.8 kN. (See Table 2.)

— The calculated safety barrier post stiffness was 32.2 kN. The theoretical Z-posts yield force, for those used in test A106, was 39.6 kN at a height of 0.61 m (see PD 6634-3:1999, Table 1).

Transition Design

— Calculations showed the transition length L should not be less than 14.3 m. In practice the transition length was set at 15 m (see Figure 1); this produced successful HCV impact results in tests D155 and D159 (see Table 1).

— Transition post selection based on a linear increase in post stiffness proved successful in full scale testing for two types of transitions. In the first, the increase in post strengths closely followed a linear scale (see Figure 1 and Table 1, test D155). In the second design, a courser gradation was chosen in the form of stepped increases in the strength of the posts' cross-sections (see Figure 1 and Table 1, test D159).

4 Practical trials and simple theoretical design concepts for safety barrier terminals

4.1 General

A terminal is defined as the end-treatment of a safety barrier. For those types of barrier that rely on development of a tensional force in the horizontal beams, the terminal also functions as an anchorage. Other barriers, such as those manufactured from concrete, may not require end-treatment different in constructional form from the length of need (LoN), nevertheless it is advisable to protect the end of the barrier by some type of a terminal, such as a concrete ramp or, in improved designs, a transition to another type of barrier.

4.2 Practical vehicle impact trials

Table 3 shows test results from impact tests, carried out by TRL on a standard single sided tensioned corrugated beam (SSTCB) barrier terminal and on a series of prototype terminals both with and without latch release mechanisms.

Figure 3 is a diagrammatic sketch of a standard TCB barrier terminal. The horizontal beam is connected to a ramped down section that is securely bolted above ground level to an anchor post. The terminal is protected from vehicle end-on impact by a shaped concrete haunch bolted to ground fixings. In test C131 (see Table 3) this type of terminal was impacted end-on by a 1 020 kg car travelling at 115 km/h. On impact, the underside of the vehicle was severely damaged by contact with the concrete haunch as it rode up and along the ramped section.

The car was then airborne for about 20 m, whilst rotating 90° clockwise about its longitudinal axis, before landing on its side on top of the fence. The car continued about a further 20 m and eventually came to rest on its roof.

Table 3 — Vehicle impact tests on TCB latched terminals

Test no.	Date	Mass of vehicle kg	Speed km/h	Impact conditions	Barrier type	Vehicle performance	Comments
C131	22.5.86	1 020	115.1	1° to terminal end Offset to nearside −0.2 m	SSTCB No latch	Airborne 20 m. Vehicle rolled and landed on its roof	Standard TCB terminal with a concrete haunch.
C132	9.6.86	1 006	110.7	Centre line of car in line with terminal end	SSTCB Latch released	Travelled 20m on top of fence. Vehicle landed on its wheels.	TCB with concrete haunch replaced by below ground terminal release latch.
C133	10.6.86	1 010	114.2	1° to terminal end Offset to nearside − 0.15 m	SSTCB Latch released	Travelled on top of collapsed fence. Vehicle landed on its wheels.	TCB with concrete haunch replaced by larger below ground terminal release latch area and slotted end post.
C144	11.6.86	1 442	113.0	20° to side at 22 m from down stream latched terminal	SSTCB Latch held	Vehicle contained and redirected then yawed anti clockwise	Standard angled test to demonstrate no pre-release of latch to side impact.

To overcome the tendency for the vehicle to become airborne the ramp bolted fixing was replaced by the latch release mechanism shown in Figure 4.

The latch release terminal in test C132 was impacted end-on by a 1 006 kg car at a speed of 110.7 km/h. The downward force of the vehicle caused the latch to release and the vehicle, gradually lifted by the now free ramped section beam, became airborne for a short distance whilst travelling some 20 m on top of the partly collapsed fence before it came to rest on all four wheels beside the line of the barrier.

The trench containing the latch release mechanism was widened to provide more clearance for the ramped section to collapse after it became detached in the impact, and a further impact, test C133, at 114.2 km/h was made with 1 010 kg car. The latch successfully detached and the length of fence was pushed to the ground. The vehicle, whilst travelling along the partly collapsed fence, almost became airborne, then landed heavily on the fence and slid off sideways on to its four wheels. It continued travelling alongside the fence before meeting a test site safety obstruction.

During these trials the end of the test length of TCB barrier remote from the vehicle impact was also fitted with a latch joint. The normal performance of the fence, when struck at some point along its LoN, should not be influenced by premature detachment of the terminal release mechanism. This possibility was investigated in test C144. The latch mechanism held, and so no unwanted pre-release of the barrier anchorage occurred.

4.3 Simple analysis and design assessment of vehicle end-on impacts into a safety barrier soft terminal

A soft terminal is one intended to redirect or bring an errant vehicle safely to rest. The draft European Standard EN 1317-4 gives requirements for performance levels for vehicle impact into safety barrier terminals and transitions; it lists four levels of performance, P1 to P4, to which terminals may be designed and tested. For a terminal with performance level P1 the vehicle is permitted to overturn after impact; this category is not dealt with here. Performance levels P2 to P4 are graded according to vehicle impact responses at various speeds, masses and angles of approach. The full matrix of tests at each performance including side impacts, the impact test criteria, deformation limits and vehicle approach paths are detailed in EN 1317-4.

The analysis discussed in **4.4** and **4.5** (see Laker 1997 [2]) investigates vehicle response to central end-on impact, one-quarter offset end-on impact, and side impact. The first condition is shown in Figure 5, in which the vehicle makes central contact with the end of the barrier, or terminal; in Figure 6 the vehicle impacts the terminal at an end-on offset of one-quarter the width of the vehicle.

The purpose of the analysis is to provide a simple assessment of the physical design requirements of a terminal which are necessary to contain and control an impacting vehicle within a prescribed terminal length and furthermore to define and quantify those factors that could lead to vehicle spin-out in a one-quarter offset impact on the end of the barrier.

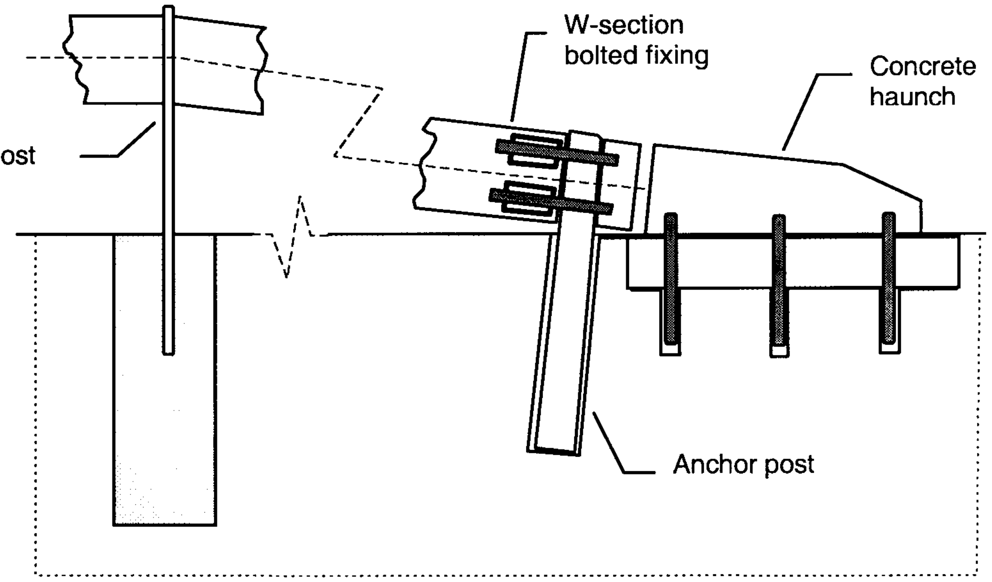

Figure 3— Standard TCB barrier terminal

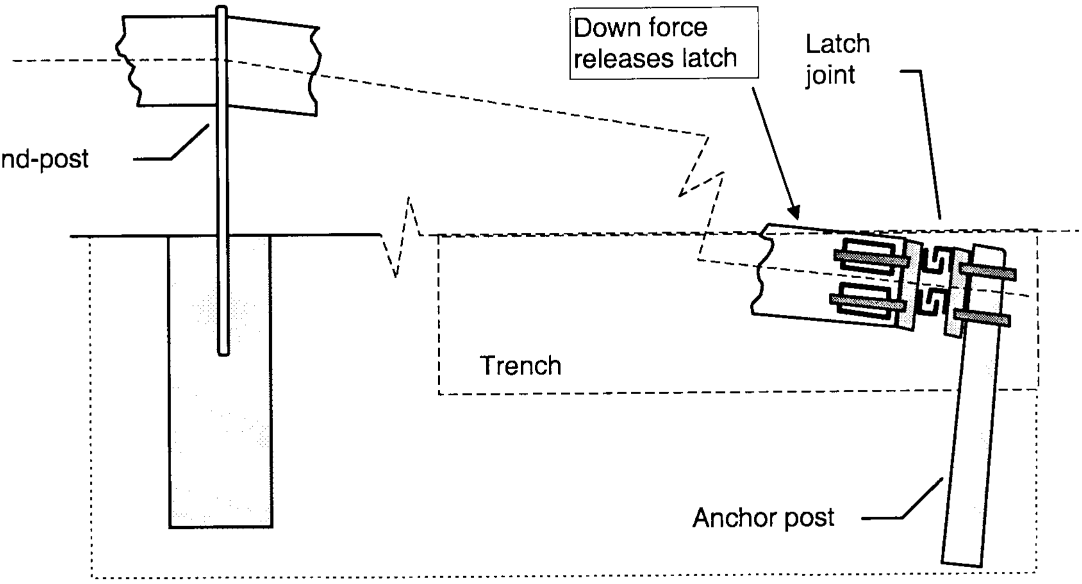

Figure 4 — TCB barrier latch joint release terminal

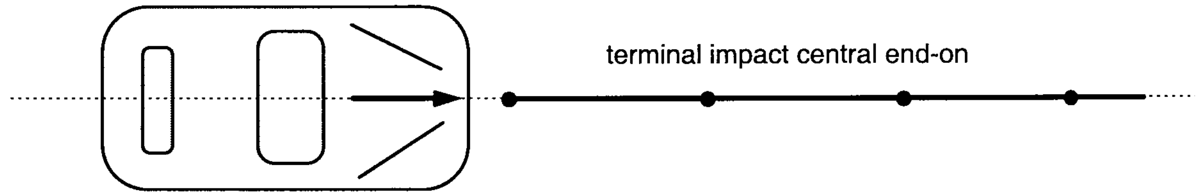

Figure 5 — Central end-on impact with terminal

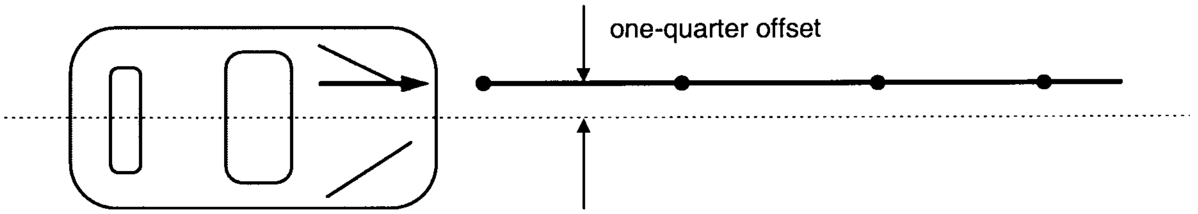

Figure 6 — End-on impact with terminal at one-quarter offset

4.4 Vehicle deceleration and resistive force in a central end-on terminal impact

Vehicle average deceleration may be computed from the equation of motion

$$V^2 = U^2 - 2aS \qquad (9)$$

where

V is the final speed;

U is the initial speed;

a is the deceleration;

S is the stopping distance.

Figure 7 is derived from equation (9) for $V = 0$; it shows the value of vehicle deceleration rate generated in bringing a vehicle to rest, in a given stopping distance, from initial speeds of 50 km/h, 80 km/h and 110 km/h.

For example, a vehicle brought to rest in a distance of 25 m from an initial speed of 110 km/h decelerates at a rate of about 1.9 *g*. In an extreme case and from the same speed, a vehicle would need to decelerate at 20 *g* if it was brought to rest in about 2.3 m; other examples can be taken from Figure 7.

The respective deceleration time period, *t*, can be obtained from:

$$V = U - at \qquad (10)$$

The value of *t* is 1.64 s for the 25 m length, and 0.16 s for the 2.3 m length.

A vehicle undergoing such decelerations from end-on impact with a terminal should not experience a resistive force to the front of the vehicle of such magnitude that could cause the terminal components to penetrate the vehicle passenger compartment or cause invasion of the compartment by movement of the bulkhead or the engine and its mounting.

Experimental frontal impacts with vehicles into massive concrete blocks show that the engines of typical passenger vehicles begin to move on their mountings at vehicle decelerations of about 15 *g* to 20 *g*.

The resistive force *P* required to decelerate a vehicle of given mass *M* is

$$P = Ma \qquad (11)$$

Figure 8 shows that the resistive force required to decelerate a 1 500 kg vehicle at a rate of 1.9 *g* is about 27 kN. Therefore, a terminal having a 27 kN constant resistive force along its length, would bring the 1 500 kg vehicle to rest, from a speed of 110 km/h, in a distance of 25 m.

In a central end-on impact there should be little risk of vehicle spin-out. However, the resistive force of 27 kN would need to be distributed over sufficient frontal area of the car to ensure that the terminal end did not penetrate, or cause excessive compression of, the passenger compartment.

In addition, for a terminal that includes a ramped down end, the ramp should not cause the vehicle to become airborne. Care should be taken in the design of a ramped end terminal such that it can easily become detached from its anchorage as the impacting vehicle rides it down.

A ramped terminal constructed from horizontal beams of substantial mass, such as W-section beams, is likely to have sufficient inertial properties to induce an impacting vehicle to climb the ramp and become partially airborne, even if a latch mechanism is devised to disconnect the W-beam from its anchorage; in effect, the mass of metal cannot move out of the way sufficiently quickly for the vehicle's wheels to remain in contact with the ground.

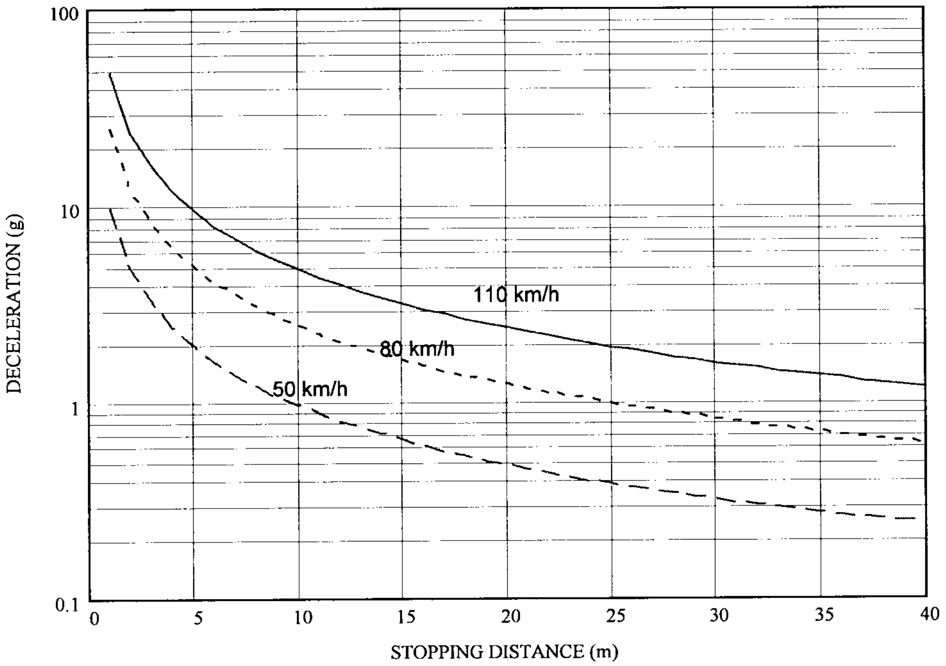

Figure 7 — Stopping distance versus deceleration

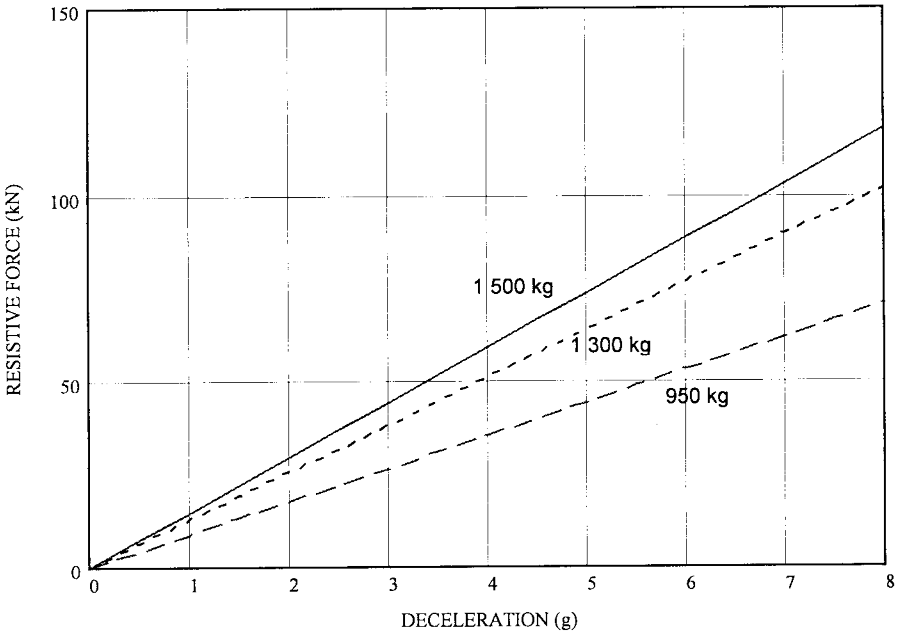

Figure 8 — Resistive force versus deceleration

4.5 Resistive force of the terminal and vehicle spin-out

Figure 9 is a labelled diagram representing a vehicle end-on impact, offset by a distance, y, into a barrier terminal.

Simplifying assumptions are made as follows:

— on impact, the vehicle tends to rotate about a vertical axis through the centre of gravity (CG);

— the CG is equidistant from front and rear axles;

— the wheels remain in contact with the running surface;

— the vehicle remains in effective contact with the terminal during the impact period.

Taking moments about the CG gives the following equilibrium equation.

$$\begin{pmatrix}\text{Applied moment}\\ \text{at offset } y \text{ due}\\ \text{to deceleration}\\ \text{force } P\end{pmatrix} = \begin{pmatrix}\text{Angular resistive}\\ \text{inertial torque } T\end{pmatrix} + \begin{pmatrix}\text{Tyre side force}\\ \text{moment about}\\ \text{CG}\end{pmatrix}$$

That is,

$$Py = I\dot{\varpi} + 2Rx \qquad (12)$$

where

$$\dot{\varpi} = \frac{d^2\,\theta}{dt^2}$$

θ is the angle of vehicle rotation;

t is the time;

P is the deceleration force;

M is the mass of vehicle;

I is the vehicle moment of inertia;

R is the $M\mu g/2$ for a single axle;

g is the gravitational constant (9.806 65 $\mathrm{m/s^2}$);

μ is the tyre/road coefficient of friction;

y is the offset of impact;

x is the distance of axles from CG.

Substituting and rewriting equation (12) gives the angular acceleration $\dot{\varpi}$ as,

$$\dot{\varpi} = \frac{Py - M\mu gx}{I} \qquad (13)$$

For ease of notation let

$$\frac{Py - M\mu gx}{I} = A$$

now

$$\dot{\varpi} = \frac{d^2\theta}{dt^2} \text{ by definition}$$

and

$$\frac{d^2\theta}{dt^2} = A \qquad (14)$$

Integrating equation (14) gives

$$\frac{d\theta}{dt} = At + \varpi_{\mathrm{int}} \qquad (15)$$

Now $\frac{d\theta}{dt}$ is the angular velocity, ϖ, when $t = 0$; so ϖ_{int} is the initial angular velocity.

Integrating equation (15) gives

$$\theta = \frac{At^2}{2} + \varpi_{\mathrm{int}}\,t + K$$

When $\theta = 0$, then $t = 0$, and so $K = 0$, and the above equation becomes

$$\theta = \frac{At^2}{2} + \varpi_{\mathrm{int}}t \qquad (16)$$

Rewriting equations (15) and (16) gives the following:

the angular velocity ϖ is

$$\varpi = \left(\frac{Py - M\mu gx}{I}\right)t + \varpi_{\mathrm{int}} \qquad (17)$$

and the angular displacement θ is

$$\theta = \left(\frac{Py - M\mu gx}{I}\right)\frac{t^2}{2} + \varpi_{\mathrm{int}}t \qquad (18)$$

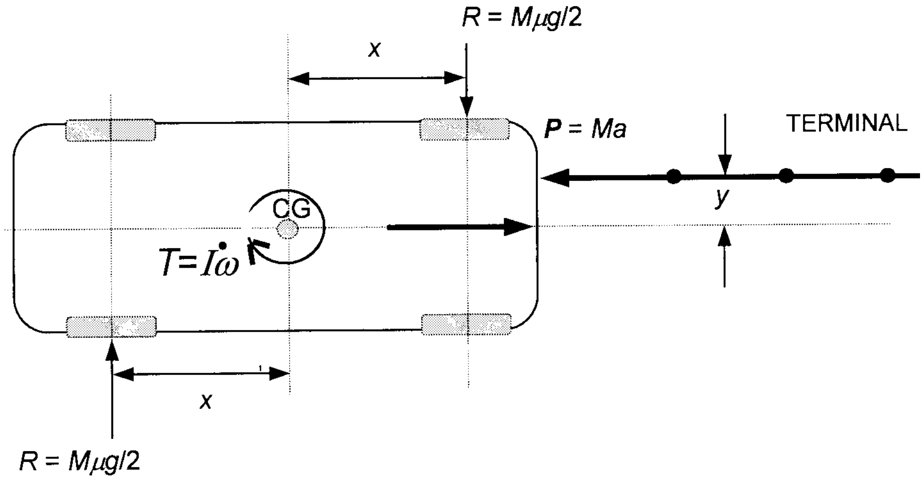

Figure 9 — Labelled diagram of offset end-on terminal impact

4.6 Limitation of spinout by tyre side force

Tyre side force depends on the wheel loading and the coefficient of friction between the tyre and its contact with the running surface. Equation (12) may be rewritten as,

$$I\dot{\varpi} = Py - M\mu gx$$

Since $I\dot{\varpi}$ is the inertial torque there will be a positive rotation of the impacting car about its vertical axis through the CG when,

$$Py \geq M\mu gx \qquad (19)$$

When the above conditions are not fulfilled, an algebraic negative value of inertial torque is generated. Under those conditions this indicates the resistive moment developed by the side thrust on the tyres is greater than the inertial torque and so the vehicle will not rotate.

The limiting spinout value for the tyre/road coefficient can be deduced from equations (11) and (19), and is given by,

$$\mu = \frac{ay}{gx} \qquad (20)$$

Figure 10 gives the value of spinout angle for an end-on, one-quarter offset impact by a 900 kg car at a speed of 100 km/h with a terminal of performance level P4. The angle of spinout θ is the angle between the line of the barrier and the centre line of the vehicle at time t, or when it comes to rest at the end of the collision with the terminal [see equation (18)].

The parametric notation and the value of the variables for the impact conditions are given in Figures 9 and 10. Figure 10 represents a 900 kg small car terminal impact to performance level P4 in EN 1317-4 and shows that the critical coefficient of friction μ at which spinout is likely to occur is about 0.9. A friction value of this magnitude is not likely to be observed on normal road surfaces.

The implication is that a soft crash cushion, that was initially designed to decelerate a 1 500 kg vehicle from a speed of 110 km/h in a distance of 25 m, will require an even softer nose on the terminal to accommodate the smaller 900 kg car impact. It should be recalled from **4.4** that the resistive crush force required in the terminal construction needed to be 27 kN to decelerate the 1 500 kg vehicle and, without a softer front end, the smaller car will be exposed to this strength of terminal structure.

Figure 11 represents a one-quarter offset impact by a 1 500 kg car at 110 km/h; this test is not required in EN 1317-4, but it is included for comparison with Figure 10 for informative purposes. Figure 11 shows that, for the 1 500 kg car, the critical spinout tyre/road coefficient μ has reduced from 0.9, for the 900 kg car, to about 0.51. This value of μ is quite common on UK roads. However, if through wet conditions μ reduces to 0.4, then Figure 11 shows that an impacting vehicle will spinout about 55° by the time it comes to rest.

Analysis shows that a 110 km/h, 1 500 kg car on a 0.51 tyre/road coefficient is unlikely to spinout in an offset end-on impact with a terminal (see Figure 11); however, a 100 km/h, 900 kg car impacting the same terminal, will spinout through an angle of about 90° (see Figure 10).

A simple analysis and some examples for the design of terminals for end-on impact have been given in **4.4** and **4.5**; other designs can be developed using the same techniques.

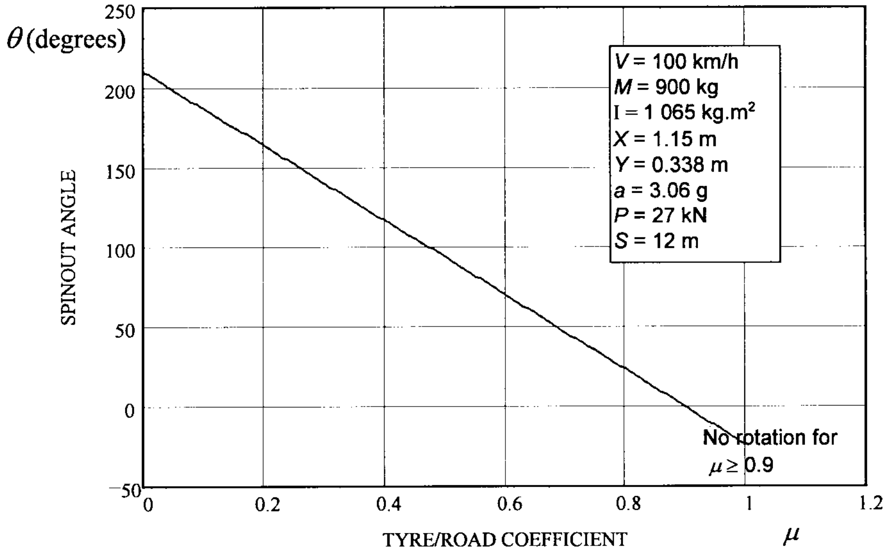

Figure 10 — Limitation of tyre road coefficient μ on vehicle spinout (one-quarter offset, 900 kg car at 100 km/h, P4 level transition)

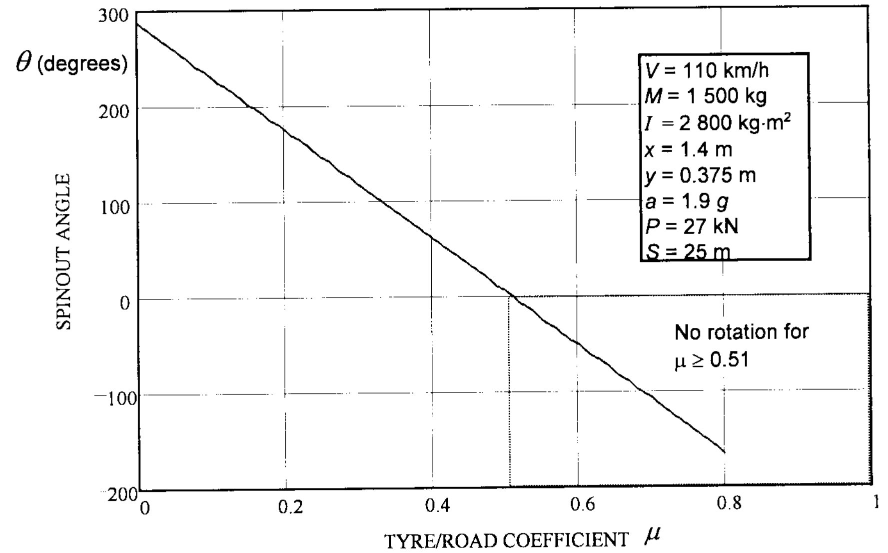

Figure 11 — Limitation of tyre road coefficient μ on vehicle spinout (1/4 offset, 1 500 kg car at 110 km/h)

4.7 A design for side impact on a soft terminal

The permanent lateral deflection limits for a terminal are given in EN 1317-4. Classes of deflection are given in a range from D1 to D6. Class D2, in which the deflection limit is 1.5 m, is selected as an example in the following terminal design for containment of a side impact. In addition, for this example, terminal performance level P4 is selected; that is, containment of an impact at 15° by a 110 km/h, 1 500 kg car.

The mean transverse deceleration, $\bar{a}$, of the CG of a vehicle impacting a barrier at an angle θ is given by

$$\bar{a} = \frac{(V \sin \theta)^2}{2(c \sin \theta + b(\cos \theta - 1) + Z} \qquad (21)$$

where

V is the impact speed;

c is the distance of the CG from front of the vehicle;

b is the distance of the CG from the side of the vehicle;

Z is the lateral deformation of the terminal and the vehicle (it takes the value for D2 as 1.5 m if the deformation of the car is ignored).

Assuming the vehicle takes a circular path during side impact with the terminal, the trajectory is given by

$$\bar{a} = \frac{V^2}{r} \qquad (22)$$

where r is the radius of the circular path whose chord depth D and length L is defined by

$$r = \frac{D}{2} + \frac{L^2}{8D} \qquad (23)$$

Combining equations (22) and (23) eliminates the circular radius r, to give the vehicle contact length L, with the side of the terminal as

$$L = 2\left[D\left(\frac{2V^2}{\bar{a}} - D\right)\right]^{½} \qquad (24)$$

where D takes the value of D2 (1.5 m), the lateral deformation of the terminal, as before.

Finally, recalling equation (11), $P = M{\cdot}a$, the resistive characteristics of side impact into a soft terminal can be assessed as follows.

EXAMPLE

In equation (21), let $\theta = 15°$; $b = 0.86$ m; $c = 2.2$ m; Z = D2 = 1.5 m; and $V = 30$ m/s.

From equation (21), the mean transverse deceleration $\bar{a}$, then takes the value of nearly 15 m/s^2.

From equation (11), the side resistive force required from the terminal to contain a 1 500 kg car side impact becomes 22.5 kN and, from equation (24), the length L over which this resistive force must be maintained, by the crushing or lateral deflection of the terminal, is about 26.5 m.

4.8 Design example of a graded soft terminal

EN 1317-4 specifies that a terminal of P4 performance level needs to be tested by the following impacts:

— a head-on one-quarter offset impact with a 100 km/h, 900 kg car;

— a head-on central impact with a 110 km/h, 1 500 kg car;

—a 165° impact with a 100 km/h, 900 kg car;

—a 15° impact with a 110 km/h, 1 500 kg car.

It has been shown that a soft terminal, 25 m in length, which successfully decelerates a 110 km/h car to rest with a resistive force of 27 kN in a central end-on impact, will cause a one-quarter offset impact by a 100 km/h car to spin out unless the tyre/road coefficient is greater than 0.9 (see **4.6**).

Clearly it is unrealistic to expect a central median, verge or even road surfaces to have such high coefficient values. Consequently, the following design example considers a graded soft terminal that provides two adjacent, successive sections, or lengths, of terminal. The first section has a resistive level to decelerate to rest, without spinout, an end-on impact at one-quarter offset, by a 100 km/h, 900 kg car. The 110 km/h, 1 500 kg car impact will not be stopped by this first length of terminal unless it is constructed in a considerably longer length. To avoid this, the second section is designed to have a higher resistive level, to accommodate the higher energy impact of the 1 500 kg car and so bring it safely to rest.

The design of the terminal begins with the assumption that a surface with a road/tyre coefficient μ, of 0.5, is available.

Invoking equation (20) gives the deceleration rate a of the car as,

$$a = \frac{\mu g x}{\mathrm{y}} = \frac{0.5 \times 9.807\mathrm{m/s^2} \times 1.15}{0.338} = 16.7\mathrm{m/s^2}.$$

From equation (11) the terminal resistance P is,

$$P = Ma = 900 \times 16.7 = 15 \text{ kN}.$$

Thus the longitudinal resistive force, of the first section, to decelerate the 900 kg car is 15 kN.

The length of the first section, according to equation (9), is,

$$S = \frac{V^2}{2a} = \frac{(27.78 \text{ m/s})^2}{2 \times 16.7 \text{ m/s}^2} = 23 \text{ m}.$$

The 1 500 kg car impact is central and end-on, so spinout is not a problem. Impact with the first section of terminal of resistance 15 kN gives a deceleration rate a of,

$$a = \frac{P}{M} = \frac{15\ 000}{1\ 500} = 10 \text{ m/s}^2.$$

Under these conditions the 1 500 kg car would be travelling at about 21 m/s (47 mile/h) at the time it reaches the end of the first section. If this level of deceleration of 10 m/s^2 was accepted, to bring the vehicle to rest, then the terminal would need to be 45 m in total length. However, since the 900 kg car has stopped in the first 23 m, the second section of terminal can be made more resistive without fear of spinout or in any way influencing the trajectory of the 900 kg car.

It is a design choice to select the value for the higher resistive level for the second section, but for this example assume the 16.7 m/s^2 deceleration of the 900 kg car is acceptable for the 1 500 kg car, and so the terminal resistive value P becomes,

$$P = Ma = 1\,500 \times 16.7 = 25 \text{ kN}.$$

The length S of the second section is given by,

$$S = \frac{V^2}{2a} = \frac{21^2}{2 \times 16.7} = 13.2 \text{ m}.$$

Hence the total length of the terminal is 23 m + 13.2 m = 36.2 m, rather than 45 m if it was constructed at the lower resistive level over its whole length.

The side impact characteristics for the design of the terminal may be obtained from **4.7**.

The final design of a graded soft terminal then takes the form shown in Figure 12.

The analysis presented provides the opportunity to make explorative examination of many other practical designs.

4.9 Summary

The European Standard for roadside safety systems, EN 1317-4, gives the performance requirements of safety barrier end-treatments, or terminals, in terms of a matrix of impact speeds, approach paths and vehicle weights.

This analysis provides analytic mathematical equations to explore the deceleration rate and spinout properties of vehicle end-on collisions, including offset impacts, into safety barrier soft terminals.

Equations are given for the longitudinal resistive force required of a soft terminal to decelerate a vehicle in a prescribed length.

Equations are also developed for the design of the resistive side force of a soft terminal to withstand angled impacts.

Simple examples are given of practical soft terminal designs. The analysis presented permits other exploratory calculations to be made of many other designs.

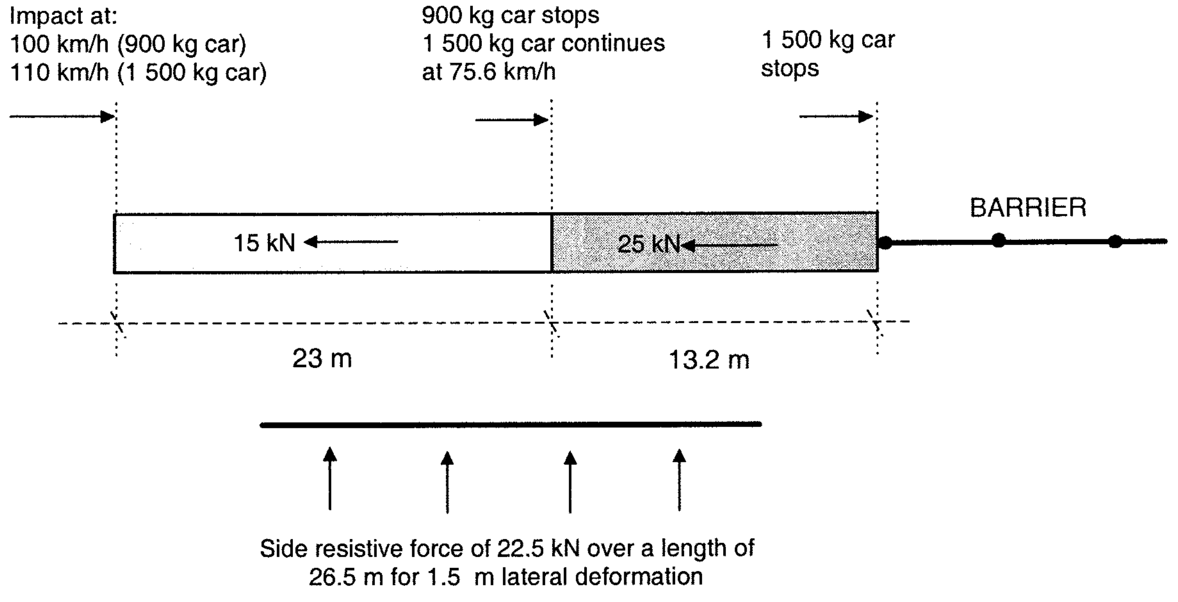

Figure 12 — Design of graded soft terminal from calculations

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