

Vehicle restraint systems —

Part 2: Fundamentals of highway restraint systems

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

BSI Subcommittee 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 Subcommittee 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), 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.

In 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:

- a) Working Group 1 — Part 1 dealing with the fundamentals of safety fences, barriers, parapets and transitions in the UK;
- b) Working Group 2 — Part 2 dealing with the specification and layout of safety fences and barriers;
- c) Working Group 3 — Part 3 dealing with the installation, inspection and repair of safety fences;
- d) Working Group 4 — Part 4 dealing with the installation, inspection and repair of safety barriers;
- e) 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 the 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 to iv, pages 1 to 47 and a back cover.

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1 Scope

This part of PD 6634 describes the fundamentals of highway restraint systems in terms of their economic justification, impact test techniques, measurement of test data, measurement of vehicle characteristics, impact severity indices, computer modelling and the impact test reporting format with reference to British and European Standards.

2 The economic justification for safety barriers

2.1 General

Early constructions of safety barriers were elementary in design and materials (Freeman, 1934 [1]; Coburn, 1949 [2]), although bridge parapets were more robustly constructed in masonry and steel. Their vehicular impact characteristics were unsuitable for high speed vehicles. On impact the vehicle was likely to be brought to a severe stop with the possibility of overturn (Hewes, 1942 [3]).

Before the 1960s, the use of safety barriers in the UK as an established method of restraining vehicles leaving the carriageway was almost negligible. Exceptions were where there were particularly hazardous areas, such as on bridges and their approaches, or where the roadway ran alongside steep embankments. The rapid growth in traffic after World War II prompted the need to examine the effectiveness of safety barriers both from the consideration of their cost efficiency and from their vehicle impact performance.

2.2 The case for no median safety barriers on motorways

The separation of opposing traffic lanes reduces the risk of severe head-on collisions if the central median is sufficiently wide for the encroaching vehicle to be brought under control. In a study on cross median accidents on 22 roads (Hurd, 1956 [4]), 10 % of the accidents occurred where there was a 5 ft wide median, 5 % where there was an 18 ft median, 2 % where there was a 30 ft median and 1 % where medians were wider than 50 ft. On two roads with a 40 ft wide unpaved median sloped 3 ft to the centre (Hutchinson, 1962 [5]), observations revealed that vehicles travelled considerably long distances on the median. About 50 % travelled more than 300 ft and 10 % travelled more than 500 ft. There was some indication that a depressed median hinders a driver in regaining control of the vehicle.

A broad summary suggests that to reduce cross median accidents to an acceptable minimum, a median needs to be 50 ft to 100 ft wide, free of obstacles, fairly level and with a running surface that permits a driver to retain control of the vehicle. The saving in accidents needs to offset the cost of the land to achieve a positive cost advantage.

2.3 The case for median safety barriers on motorways

In the UK it is unusual for roads to have wide central reserves or medians. On most motorways, median width is about 4 m, although there is a growing need to encroach on the median area for road widening purposes, so reducing the width even further.

In an early analysis of non-median, median crossing and median-noncrossing accidents (Newby, 1962 [6] and Moore, 1964 [7]), it was shown that in median crossing accidents, about twice as many people were injured as in the other types of accident and about one third of the crossing accidents resulted in fatal or serious injuries.

The installation of a safety barrier is a cheaper option than a wide median; unfortunately there is a penalty to pay. The installation of barriers close to the carriageway increases the total number of accidents. The purpose of the safety barrier is primarily to restrain an errant vehicle from leaving its carriageway or traffic lane and entering an area more dangerous to the occupants. It follows that impact into the safety barrier needs to offer the possibility of a less severe injury to the occupants than that which might occur had the barrier not been installed.

Where traffic flow is light the risk of head-on collisions in median crossing accidents is less. To have an effect on the cross median accident rate it was considered that the average daily traffic flow should be in excess of 60 000 per day (Moskowitz and Schaeffer, 1960 [8]).

Consequently the potential benefits from the installation of safety barriers needs to derive from the consideration that the injuries arising from the inevitable increase in the number of accidents are of a low level compared to the severe or fatal accidents saved by the presence of the barrier.

One of the earliest studies in the UK to determine whether safety barriers are beneficial was carried out on the M1 motorway (Moore and Jehu, 1968 [9]). Two trial lengths of double sided blocked out w-section beam barrier [untensioned corrugated barrier (UCB)] of length 29 km were erected on the three lane, double carriageway. The rails were blocked out 20 cm on both sides of strong wooden posts, the top edge of the rail was 67.5 cm above road level.

Accident data were recorded during 1962-1963 before the barrier was installed. After installation, records were kept for the period 1965-1967. In the interval, traffic flow increased 12 %, to allow for this, accident data were recorded for an adjacent 61 km length of M1 motorway where no barrier was installed. Accident classes were divided into "on-median", "cross median no collision", "cross median with collision" and "median not entered".

The effect of the barrier practically eliminated all cross median accidents, but substantially increased other non injury accidents. Allowing for accident rate adjustments based on the 61 km control, and assigning monetary values (1966 prices) to the accident savings, the net effect of the cost/benefit calculation showed a saving of \$460 per kilometre per year. However, there was a very large statistical standard error arising from the fact that there were few fatal accidents and their high tariff had a considerable influence on the analysis (Dawson, 1965 [10]). The barrier and maintenance costs were in excess of the savings and consequently, at that time, there was a reluctance to generally install safety barriers.

Based on the double sided tensioned corrugated beam (DSTCB) barrier, a later re-assessment of the economic benefits of safety barriers on motorway central reserves (Moore and Newby, 1969 [11]) produced a refined analysis by introducing selective costing according to the larger number of casualties per vehicle in cross median accidents, and to the greater frequency of fatalities. The revised calculations indicated that the annual cost of safety barrier per kilometre was about \$457 (1969) and the annual net saving in accidents was \$1 165 per kilometre. Statistically, there was a 70 % chance of the true value lying between minus \$393 and plus \$2 723; with a 2 to 1 chance that the overall benefit was positive. It was concluded it was probably beneficial to install safety barriers on motorways where the traffic flow was in excess of 35 000 vehicles per day. There is also an underlying feeling that a driver who is killed by a vehicle that crosses a central median is the "innocent" party. Accordingly, if there is an engineering possibility that such accidents can be prevented then, although it might not be a sound basis for making policy decisions, it is incumbent upon highway authorities to make such provisions to implement that safety engineering.

2.4 The case for verge safety barriers on motorways

A safety fence working party (Benson, 1975 [12]) examined the cost/benefit of installing safety barriers on the verges of safety fences. Any conclusions drawn were very sensitive to the assumptions made on the severity of the accidents. It was possible to estimate the cost of accidents per mile where vehicles had left the motorway on the nearside. However, there were no comparable data available showing the cost of accidents involving verge safety fences, making a meaningful comparison impossible. Assumptions needed to be made that the cost of accidents involving verge barriers would be less severe and consequently less costly than accidents where the vehicles left the road to the nearside where no verge barrier was installed. There was little evidence to suggest a reduction in severity was to be expected.

To be cost effective verge safety fences would have to bring a marked reduction in total accident costs. For example, at an installation cost of \$15 000 per mile (1973), and a repair and maintenance cost of \$500 per mile per year, accident savings of \$1 800 per mile per year would be required to offset the costs. It was assumed 41 % of injury accidents involved only single vehicles, and that half of these would leave the road to the left.

Without knowing the efficacy of verge safety fences, there seemed to be no case for their use over the whole motorway network. Where there were high flows, reduction of accident costs of only 20 % could be sufficient to justify the installation of verge safety fences.

Taking into account the above restrictions, there is a case for the provision of verge safety fences only where there are special risks such as near bridge piers, lighting columns and sign poles.

2.5 The case for median safety barriers on all purpose roads

All purpose roads are those 60 mile/h to 70 mile/h dual carriageway roads not classed as motorways. The study (Sowerby, 1987 [13]) examined data from 350 km out of an existing total of almost 3 000 km of dual carriageway road. The sample included 142 km of roadway that had a safety barrier already installed on the central reserve.

The objective was to investigate accident data, road features and other parameters and, from the subsequent analysis, make prescribed recommendations for the installation of safety barriers at sites where they would be most cost effective. Accident data were categorized into fatal and serious, and then correlated by multiple regression with roadway variables which ranged over traffic flow, the presence of safety fence, median width, kerbs, cats-eyes, road lighting, metre strips and minimum radii of curvature.

For the unfenced sample of roadway, the accident frequency was 0.44 injury accidents per kilometre per year. Almost half of the total involved cross median accidents where vehicles entered the opposing carriageway.

The number of median accidents (accident frequency) varied strongly with traffic flow. The unfenced sample of 5.32 accidents per 100 million vehicle kilometres fell by 29 % to 3.76 accidents per 100 million vehicle kilometres. The reduction in median casualty rates was even more marked; the fenced sample at 6.72 injuries per 100 million vehicle kilometres was 35 % lower than the unfenced sample at 10.3 injuries per 100 million vehicle kilometres.

The regression analysis was found to be more successful in explaining the correlation of the chosen variables with accident frequency rather than casualty rate. Accident frequency positively correlated with average annual daily total (AADT).

The safety barrier term was statistically significant in both the “median” and “all” accident models. Geometric variables had little discrimination between accident frequency on the fenced and unfenced sites. A somewhat unexpected result showed that roads with kerbs had higher accident probabilities. Roads with offside metre strips were found to be safer.

On average a safety fence installation on a new road needs to recover a cost of £31 000/km (1985) including maintenance. On roads where kerbs are in place this threshold is reached at traffic flow above 10 000 vehicles per day.

Dual carriageways without kerbs formed about 70 % of the unfenced sample; on these roads the accident frequencies were lower.

On new roads, safety barriers were cost effective where traffic flows were above a base level of 10 000 vehicles per day, given an average barrier cost.

On existing roads, where traffic delay costs are included, safety barriers are justified at all rates of traffic flow in the range from about 10 000 to 35 000 vehicles per day.

For the majority of dual carriageway roads without kerbs, safety barriers are always cost effective for traffic flow of 10 500 to 33 500 vehicles per day. The cost model was based on the “all” accident model, from which casualties by severity are desegregated. The benefit of installing safety fences is highly dependent on reductions in fatalities per accident in the fenced sample; care was taken by further regression analyses to verify the assumptions. They demonstrated that the model was robust.

A further analysis in the form of a “before and after” study, revealed that the overall accident rate fell by 35 % after the installation of a safety barrier; the casualty rate of combined fatal and serious accidents fell by 52 %.

2.6 The case for higher containment barriers on motorways

2.6.1 Higher containment barriers on the central median

Higher containment safety barriers (HCSBs) are those that, on impact, are able to safely redirect vehicles of mass greater than private cars. Starting in the early 1980s HCSBs made of steel and of concrete were developed and tested by TRL.

The availability of these systems was stated publicly in the Motorway Safety Package announced in April 1988, (Thorndike, 1988 [14]). Whereas the car safety barrier was designed to safely contain a 70 mile/h, 1.5 t vehicle impacting at 20°, HCSBs were effective against heavy commercial vehicles (HCVs) up to 38 t, travelling at 50 mile/h and impacting at 20°.

Crossover accidents are considered to be random events; otherwise, if accidents frequently occur at one particular location then it is conceivable that the cause is due to a local defect in the road design. Over the years 1984 to 1987, on average there were 77 central median crossover accidents per year reported on motorways in England. Of this total, 42 accidents involved penetration of the barrier, of which about one half involved vehicles of over 1.5 t. The average number of casualties per year was 17 fatalities, 42 serious injuries and 79 slight injuries.

The HCSB was not expected to be successful against every heavy vehicle impact as there is a possibility of impact at speeds higher than 50 mile/h by vehicles of higher mass; also secondary collisions with the barrier, in which rebound occurs after primary impact with another vehicle, can induce barrier impacts at high angles. However, it was estimated that of the 77 recorded accidents it was expected that in 70 of these, the vehicle could be contained.

A discounted cost/benefit analysis at 1988 prices showed that, over a 20 year period the increased costs of installing HCSBs were three times greater than the increased benefits. This analysis did not take account of the potential increase in casualties to car occupants arising from the added stiffness of the HCSBs.

On these figures the installation of HCSBs on motorway medians in England was not economically justifiable.

Subsequent to the analysis carried out in 1988, a need arose for widening the M25 motorway. To achieve room for a fourth traffic lane some encroachment was necessary on the existing 4 m wide central median. The resulting narrower median, as well as the inclusion of central street lighting columns, restricted the full performance of the previously installed car based safety barrier. In this particular case, it was considered advisable to install an intermediate high containment concrete barrier. It had been proved, by controlled tests, that such a barrier can give successful impact response for cars and middle range commercial vehicles of 16 t.

2.6.2 Higher containment barriers on motorway verges

The case for installation of HCSBs on motorway verges is even less than that for the installation of HCSBs on central medians. However, there may well be sensitive sites where their use in small lengths is a justifiable precaution. One such case occurred adjacent to the Corley service station on the M6 motorway where it is possible that an HCV, which left the carriageway on the nearside, could crash through into a public restaurant. An HCSB has been installed in this area. Regional Authorities are advised to deal with similar roadside situations and install HCSBs according to the prevailing merits.

3 Controlled vehicle impact testing for safety barrier development

3.1 General

Vehicle accidents frequently bring with them the trauma of human distress. In the understanding that comes from accident reconstruction, there is the underlying possibility of avoiding, or at least reducing, the severity of impact. The mechanisms of vehicle impact into fixed objects is complex. The variables that need to be taken into account include vehicle speed, mass, structural stiffness of the vehicle and the object struck, angle of contact, road surface condition and the influence that these variables have on the severity of injury to the vehicle occupants.

Reconstruction of vehicle accidents by mathematical models, computer simulation, and in a few cases, the use of practical scale model cars, can play a part in the development of safety barriers. Nevertheless, there needs to be confirmation of proposed barrier designs by full scale vehicle impact testing.

The cost of executing and analysing such tests is high and so the essential information on barrier performance has to be gleaned from a restricted number of tests. The difficulty of the task is compounded by the range of possible barrier accidents and the concomitant number of impact variables that need to be considered. For example, the characteristics of the population of vehicles in the UK, in terms of their mass, maximum speed and dimensions, cover a very wide spectrum. The mass of a small private car can be as little 0.65 t, whereas a six axle heavy commercial vehicle has a maximum gross mass of 38 t and may increase to 44 t. The maximum speed permitted on UK designated roads is 70 mile/h although many vehicles, including the smaller private cars, can easily exceed this limit. The angle at which a vehicle, at speed, strikes and is constrained by a barrier is closely linked to the kinetic energy that the barrier and vehicle need to absorb in the impact; high impact angles generate high impact energy. It follows that the higher the value of energy dissipated, the greater the elastic and inelastic deformation of vehicle and barrier. It is evident that barriers that can absorb high levels of impact energy, and then successfully return vehicles on to a safe path, are likely to attract both high first costs and high repair costs.

However, cost/benefit analysis of accidents (see clause 2) has shown that the greatest saving derives from those barrier designs which were likely to be effective against private cars. Accordingly, the early consideration in the development of UK safety barriers was to set up impact test criteria that would meet the requirements for evaluation of car based safety barriers.

Subsequently, as the needs warranted, criteria for the testing of heavy commercial vehicles (HCVs) had to be taken into account.

3.2 Test criteria for safety barriers

3.2.1 Impact angle and critical speed

In a primary impact into a safety barrier, that is, where the vehicle has not rebounded from another object, the maximum angle at which the vehicle can turn to approach the line of the fence is limited by the adhesion, or coefficient of friction, μ_{tr} , acting between the tyres and the road surface (Jehu and Pearson, 1977 [15]). The critical speed, v_c , is the forward speed of the vehicle at the point at which adhesion is about to be lost and the vehicle will start to slide out of driver steering control. If the barrier is involved in a secondary impact, perhaps following contact with another vehicle, then this situation does not apply and the impact angle cannot easily be predicted.

The minimum radius of turn at the critical speed occurs at equilibrium of the inertial force due to the radius of turn of the vehicle, and the resistive side forces acting on the tyres, (see Figures 1 and 2) that is:

$$\frac{mv_c^2}{r} = mg\mu_{tr} \quad (1)$$

where

- m is the mass of the vehicle;
- r is the radius of turn;
- g is the gravitational constant.

From Figure 1 it can be shown that:

$$\cos \theta = 1 - \frac{r - w}{r} = 1 - \frac{w}{r} \quad (2)$$

where

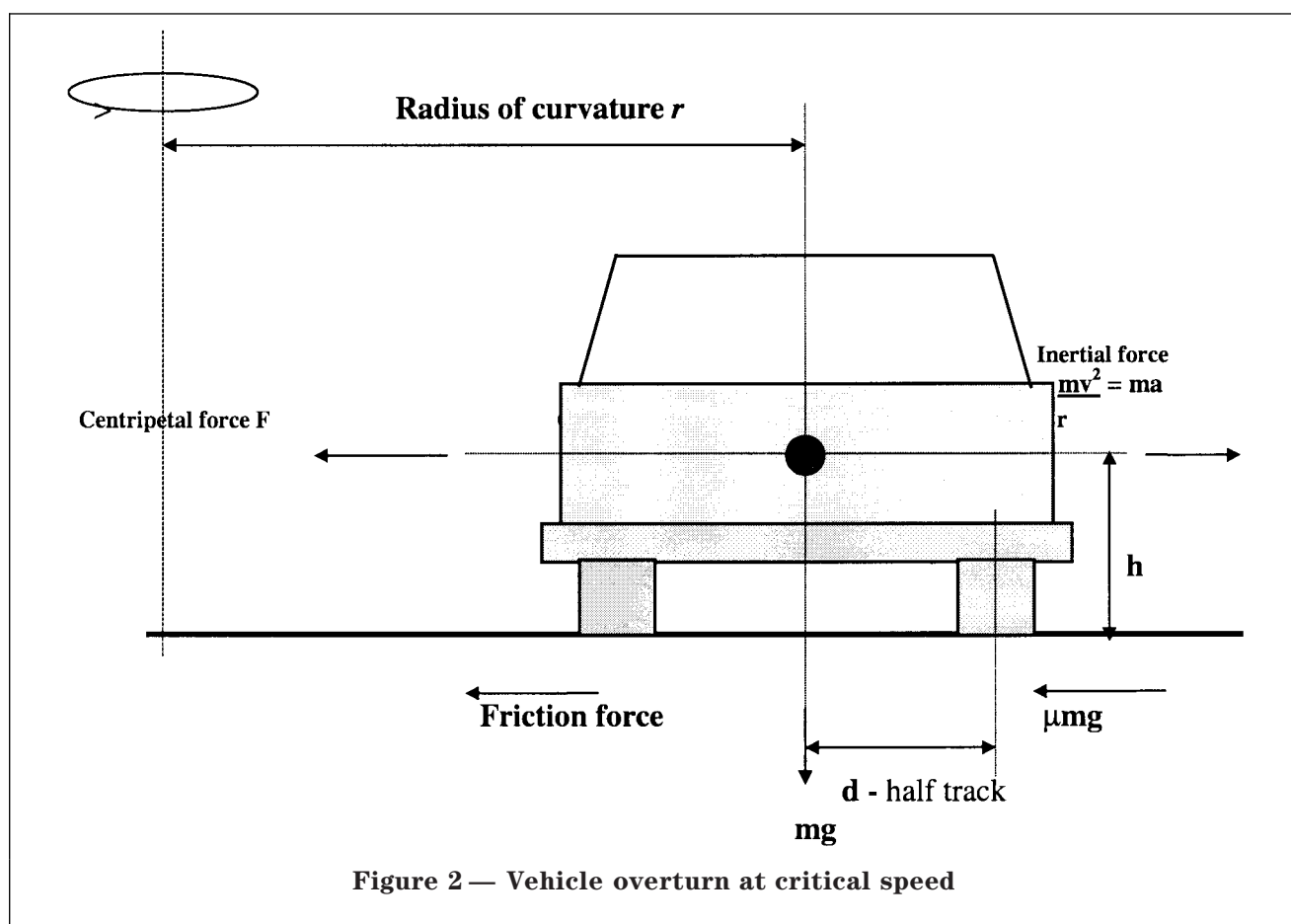
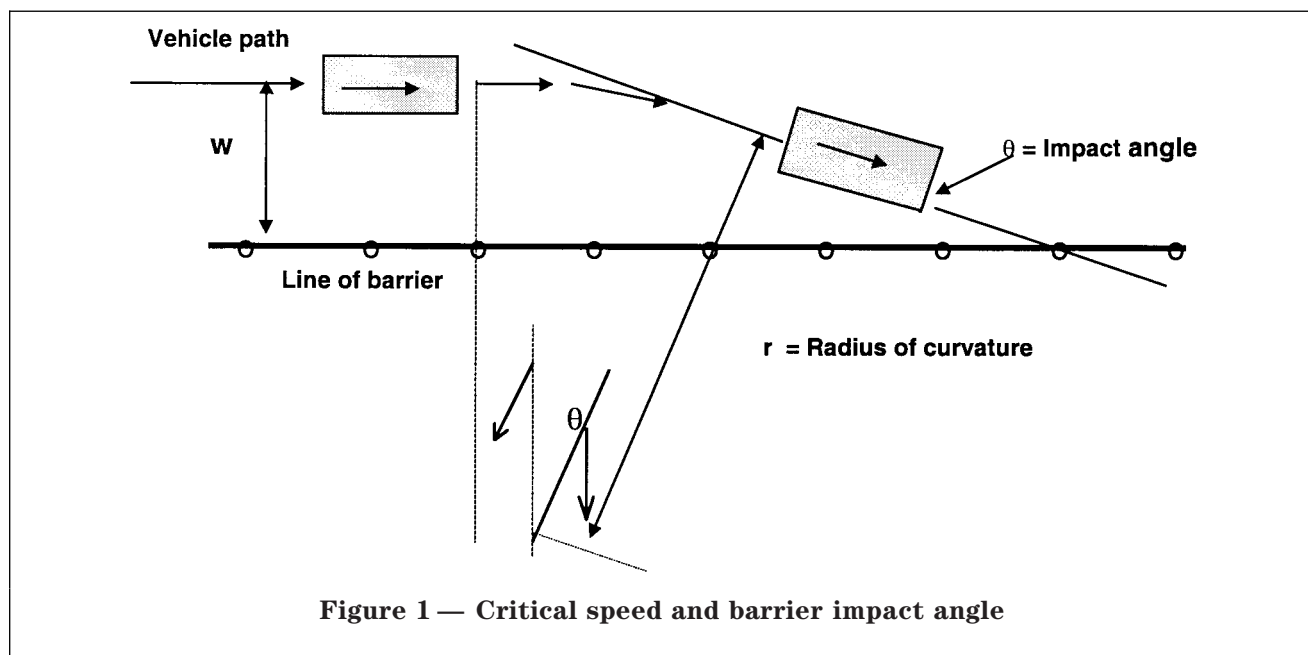
- w is the lateral distance of the car from the barrier at the moment it starts turn.

Combining equations (1) and (2) gives:

$$\cos \theta = 1 - \frac{gw\mu_{tr}}{v_c^2} \quad (3)$$

It can be seen that equation (3) is independent of the vehicle's mass and so it applies equally to private and heavy commercial vehicles.

The theoretical curves for a 2-lane and 3-lane carriageway, derived from equation (3), are shown on Figure 3; the value of the coefficient of friction between tyre and road is taken to be 0.7. Also included in Figure 3 are data gathered from a road side investigation of accidents on motorways within a 130 km radius of the Transport Research Laboratory (TRL) at Crowthorne, Berkshire (Macdonald, 1986 [16]). The 3-lane curve shows that for approach speeds of 113 km/h (70 mile/h) and 80 km/h (50 mile/h), the limiting angles are 20° and 30° respectively. Out of a total of 25 accidents investigated, only three exceeded the predicted maximum impact angle; burst tyres or secondary impacts could account for these.



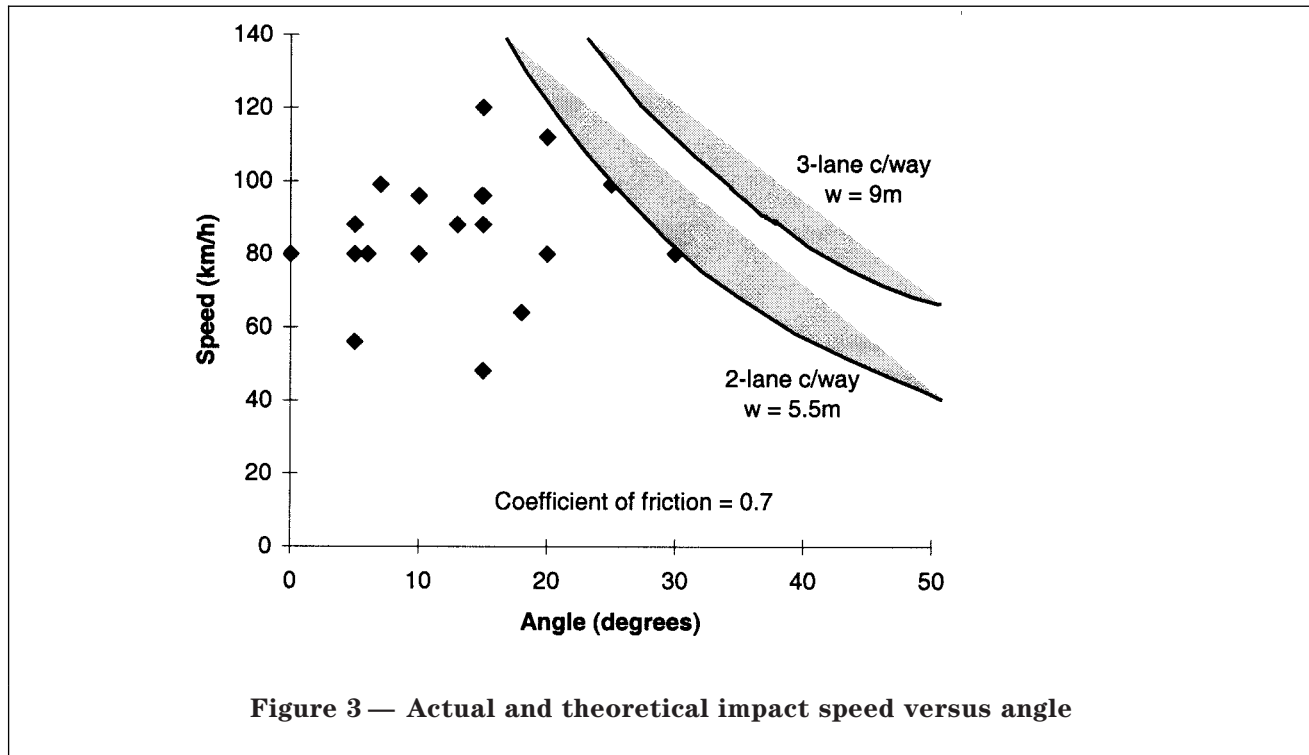


Figure 3 — Actual and theoretical impact speed versus angle

3.2.2 Vehicle stability — Sliding and overturning

A vehicle travelling at critical speed on a curve is at the point of losing adhesion between tyre and road. If adhesion is lost, simple theory of circular motion predicts that the vehicle will slide in a straight line on a tangent to the circular path; it will not slide radially outwards. The angle that the straight line makes with a longitudinally installed safety barrier is the angle of impact (see Figure 1).

It has been shown in 3.2.1 that a vehicle turning across a 3-lane road, 9 m wide, at the critical speed of 70 mile/h can hit the barrier at a limiting angle of 20° and when adhesion between tyres and road surface is lost, it initially tends to slide in a straight line. However, if the coefficient of friction is high, and the vehicle has a high centre of gravity (CG) compared with the width of the wheel track, there is a limiting condition wherein the vehicle will not slide, but can overturn.

It is of interest to examine whether a 70 mile/h vehicle at critical turning speed and at the limiting impact angle is in the pseudo stable condition of sliding, or is on the point of overturning.

Restating equation (1):

$$\frac{mv_c^2}{r} = ma_{\text{rad}} = mg\mu_{\text{tr}} \quad (4)$$

where

$$a_{\text{rad}} = v^2/r = \text{radial acceleration.}$$

From Figure 2, the vehicle is on the threshold of overturning when:

$$ma_{\text{rad}}h = mgd \quad (5)$$

where

- h is the height of CG;
- a_{rad} is the radial acceleration;
- d is the half width of wheel track.

Also from Figure 2:

$$a_{\text{rad}} = \mu_{\text{tr}}g \quad (6)$$

Combining equations (5) and (6) gives the threshold condition for overturn as:

$$\mu_{\text{tr}} \geq \frac{d}{h} \quad (7)$$

That is, when the coefficient of friction between tyre and road surface is greater than the ratio of half the width of the wheel track to the height of the CG, then the vehicle will start to overturn.

A typical value for half the wheel track width of a 1 500 kg car is 0.75 m. If the vehicle is negotiating a curve at the critical speed of 70 mile/h on a bend which has a tyre to road surface coefficient of friction of 0.7 then, from equation (7), the vehicle is on the point of overturning if the height of the CG exceeds 1.07 m. The CG height of such a vehicle when unladen is typically 0.53 m, consequently it is unlikely to overturn unless the contents of the vehicle doubles the height of the CG.

The speed at which it would overturn can be derived from equations (1), (4) and (5). For the conditions stated, equation (1) gives a radius of curvature of 143 m. equations (4) and (5) indicate the vehicle is on the point of overturning at a speed of just under 100 mile/h.

Elementary analysis has shown that a typical 1 500 kg vehicle, that has a half wheel track width of 0.75 m and a CG height of 0.53 m, when turning across a 9 m wide motorway at the critical turning speed of 70 mile/h, will enter a pseudo stable sliding condition and is not likely to overturn; the critical overturning speed of 100 mile/h is very much higher than the sliding speed of 70 mile/h; clearly, for this vehicle, the overturning speed cannot be achieved.

3.3 Standard controlled barrier impact test conditions

3.3.1 Private cars

The maximum speed for private cars on UK motorways is 70 mile/h. Examination of the national fleet revealed that the overwhelming majority weighed less than 1 500 kg. The exceptions were a small percentage of large luxury cars.

For a known coefficient of friction between tyre and road surface, a simple analysis of the maximum angle that a vehicle, at steady speed, can turn across a carriageway and impact a longitudinal safety barrier has been presented in 3.2. On a 9 m wide motorway carriageway a 70 mile/h vehicle is likely to impact the barrier at a maximum angle of about 20°, if the coefficient of friction is 0.7.

For private cars, this standard impact test criterion has been adopted in BS 6579 and BS 6779. That is, private car based barriers have to be successfully tested by collision with a 70 mile/h, 1 500 kg car impact, at an angle of 20°.

Although not included in BS 6579 and BS 6779, an impact test at the same speed and angle by a lightweight car (700 kg) was considered as an advisable additional test. Its purpose was to investigate the post-impact stability of small cars; they were considered likely to be more vulnerable to instability than the heavier car.

Cost/benefit analysis had shown that car based safety barriers were likely to be the most beneficial and so, from the mid 1960s, development of roadside barriers was concentrated in this area using the standard test impact conditions, supplemented by an impact with a small car.

Several successful designs were produced by DTp (TRL) and industry using these test criteria. The installation of safety barriers on UK roads began to take place in quantity in the early 1970s.

3.3.2 Heavy commercial vehicles

The economic case for heavy commercial vehicle (HCV) safety barriers could not be so well made as that for private cars. However, there had always been the need to protect sensitive areas from incursion by vehicles of all kinds; the most prominent case being the need for parapets on bridges. Early bridge parapet designs provided a starting point for the development of higher containment safety fences. Clearly, the potentially higher impact energy of HCVs compared with that of private cars, made the containment problem

significantly more difficult. However, impact tests on concrete bridge parapets, which later became known as normal containment parapets, had shown they easily contained the standard private car impact. In addition, the theoretical critical speed and impact angle into a safety barrier applies equally to the heaviest commercial vehicle as it does to lightweight cars (Figure 3).

In setting out an impact test matrix for a range of bridge parapet designs, for those parapets designated as having low containment characteristics, the impact angle was retained at 20° and the vehicle mass remained at 1.5 t, but the impact speed was lowered to 50 mile/h (BS 6779). For normal containment, the impact test speed, angle and vehicle mass were retained to be the same as for safety barriers, (the standard impact). But for high containment bridge parapets, although the 20° angle was retained, the vehicle mass was increased to a value of 30 t and the impact speed reduced to 40 mile/h. The balance of vehicle mass and speed was an engineering compromise to accommodate one of the most impact aggressive HCVs on UK roads, the rigid 4-axle 30 t tanker, and yet retain a realistic impact test speed and energy level that would not result in damage to the bridge deck on which the parapets were mounted.

The stock of UK bridges covers a range of designs; it was important to develop parapets of such strength, that impact into them would not cause more damage to the bridge than to the parapet. The repair of the parapet was likely to be much less difficult and costly than repairing the bridge deck.

Consequently, the impact test criteria for bridge parapets had to be a balance between the parapet stiffness and the bridge deck strength. With initial guidance from bridge parapet design, it was clear at the early stages of development of roadside higher containment safety barriers, that a compromise had to be reached between the energy level of impact against which the barriers would be effective and the complexity of the barrier design and cost. The compromise was reached by taking a unity value for the energy level of the standard impact of 1.5 t, 20° at 70 mile/h (1.5: 20: 70), due to the velocity normal to the barrier, and comparing this to a similarly derived energy level of the HCV test for high containment parapets, (30: 20: 40). The HCV parapet test has an energy level of about 6.5 times the standard impact.

For comparative purposes, an HCV on a motorway at its maximum permitted speed of 60 mile/h with gross mass of 38 t, has an energy level of about 18.5 times the standard impact; although, on impact, the articulated tractor of a 38 t HCV is more easily redirected, with the result that the impact tends to be less severe than impact by a 4-axle rigid, yet lighter, 30 t vehicle.

Taking account of environmental considerations, cost based engineering solutions and the possibility of high energy impacts, it seemed reasonable to place the impact conditions for higher containment roadside safety barriers at about midway between the energy levels of the standard impact and the energy level adopted for the 30 t HCV impact into high containment parapets. Accordingly, the impact energy for higher containment safety barriers was set at about three times that of the standard level.

The use of energy level, as a means of defining impact conditions, is useful in the sense that it provides a single value description of the collision, but it should be borne in mind that energy is a scalar rather than a vector quantity. A practical interpretation of this is to consider two impact conditions at the same energy level, derived from velocities normal to the barrier; one at an impact angle of for example 10° and the other at 90° . In the first case, because of the shallow angle of impact, the energy dissipated will be spread over a much longer length of barrier compared to the 90° impact. Consequently the disparate concentration of energy over the different lengths of barrier in the two examples means, for successful vehicle containment, the two barriers would need to be of very different design.

Based on this heuristic approach, the test conditions for the development of higher containment safety barriers were set at 16 t, 15° , at a vehicle impact speed of 50 mile/h. The selection of the 16 t flat bed HCV represented the most common heavy commercial vehicle in the UK fleet (although it can take many designs of chassis and body dimensions). After an exploratory period of development, it became evident that the impact angle could be increased to 20° to conform to the impact angle in other safety barrier and bridge parapet test regimes.

The test matrix of vehicle speeds, masses and angles for safety barriers and bridge parapets does not claim to represent every possibility of impact that can occur on the road; such a test matrix would make a test program prohibitively expensive. However, the matrix is intended to be sufficiently stringent to separate the performance of good barrier designs from those which could create unnecessary hazards.

3.3.3 Impact performance acceptance criteria

The requirements in the UK, for acceptable vehicle and barrier performance under controlled impact test conditions, are given in the British Standards BS 6579 (for safety barriers) and BS 6779 (for bridge parapets).

The standards deal in detail with the integrity of vehicle and parapet, the pre-impact and post-impact trajectories of the vehicle, and the impact severity in terms of theoretical head impact velocity (THIV) and post-impact head velocity (PHD). In brief, the

standards require that during the impact period the test vehicle shall be safely contained and redirected on a path close to the line of the barrier. There are exceptions to this general statement and the appropriate standard for either safety barriers (BS 6579) or bridge parapets (BS 6779) should be referenced for specific vehicle inertial masses, barrier types and their impact test requirements.

3.4 The European Standard for road side restraint systems

In 1990, under a Directive from the European Union (EU), the European Committee for Standardization (CEN) was instructed to begin work on the harmonization of the impact performance of roadside restraint systems, including vehicle safety barriers, that were prevalent in Member Countries. Under the Directive, CEN Technical Committee TC 226/WG1, Road restraint systems, formulated, as part of its mandate, a matrix of vehicle characteristics and impact conditions for the performance testing of vehicle safety barriers (EN 1317 series: EN 1317-1, EN 1317-2, prEN 1317-3).

Tables 1 and 2 are extracts from the European Standards EN 1317-1 and EN 1317-2. The tables give the range of vehicle characteristics, speed values and impact angles that are currently used in the performance testing of road restraint systems; both safety barriers and bridge parapet impact requirements are included in the tables.

4 Test vehicle propulsion and steering control

4.1 General

It was clear at the beginning of work on the development of road restraint systems that the use of manned test vehicles was prohibitive except for the most predictable of barrier tests. Impacts into rigid utility poles had shown that at low speed, about 20 mile/h, vehicle decelerations were sufficiently high to generate forces likely to cause occupant injury, (Moore and Christie, 1960 [17]). Even so, a few manned vehicle tests were made on shaped kerbs and barriers, but this technique was soon abandoned in favour of remote control testing.

4.2 Vehicle propulsion

Development of safety barriers in the UK began in about 1962, that is before the standard impact test condition had been formulated. The choice of vehicle propulsion system, at that time, was not therefore restricted to methods that could reach a speed of 70 mile/h. The intention was to achieve a "high speed impact", where the term "high speed" inferred speed values considerably in excess of the current experience, such as 30 mile/h in vehicle crash-block testing, or 20 mile/h to 25 mile/h achieved at that time, in lighting column testing.

Table 1 — Test vehicle characteristics

Inertial mass								
kg								
Vehicle mass ^a	825 ± 40	1 300 ± 65	1 500 ± 75	10 000 ± 300	13 000 ± 400	16 000 ± 500	30 000 ± 900	38 000 ± 1 100
Including maximum ballast ^b	100	160	180	—	—	—	—	—
Dummy	75	—	—	—	—	—	—	—
Total vehicle static mass	900 ± 40	1 300 ± 65	1 500 ± 75	10 000 ± 300	13 000 ± 400	16 000 ± 500	30 000 ± 900	38 000 ± 1 100
Dimensions								
m								
(tolerance ±15 %)								
Wheel track (front and rear)	1.35	1.40	1.50	2.00	2.00	2.00	2.00	2.00
Wheel radius (unloaded)	—	—	—	0.46	0.52	0.52	0.55	0.55
Wheel base (between extreme axles)	—	—	—	4.60	6.50	5.90	6.70	11.25
Number of axles ^c	1S + 1	1S + 1	1S + 1	1S + 1	1S + 1	1S + 1/2	2S + 2	1S + 3/4
Ground clearance of front bumper measured at corner	—	—	—	0.58	—	0.58	0.58	0.58
Centre of gravity^d								
m								
Distance from axle ±10 %	1.00	1.10	1.24	2.70	3.80	3.10	4.14	6.00
Lateral distance from centre line.	±0.07	±0.07	±0.08	±0.10	±0.10	±0.10	±0.10	±0.10
Height above ground. (inertial test mass ±10 %)	0.50	0.53	0.53	—	—	—	—	—
Load (+15 % to -5 %)	—	—	—	1.50	1.40	1.60	1.90	1.90
Type of vehicle	Car	Car	Car	Rigid	Rigid	Bus	Rigid	Articulated HGV
^a Includes load for heavy goods vehicle (HGV).								
^b Includes test equipment.								
^c S: steering (or steered) axle.								
^d Inertial test mass								

Table 2 — Vehicle impact test criteria

Test level	Impact speed km/h	Impact angle degrees	Total vehicle mass kg	Type of vehicle
TB 11	100	20	900	Car
TB 21	80	8	1 300	Car
TB 22	80	15	1 300	Car
TB 31	80	20	1 500	Car
TB 32	110	20	1 500	Car
TB 41	70	8	10 000	Rigid
TB 42	70	15	10 000	Rigid
TB 51	70	20	13 000	Bus
TB 61	80	20	16 000	Rigid
TB 71	65	20	30 000	Rigid
TB 81	65	20	38 000	Articulated

Energy for vehicle propulsion is a choice between the motive power of the engine, or the use of external power derived from motorized winch or towing systems. Running vehicles down short gradients is of limited use. A ramp height of 10 m would produce a terminal speed of less than 30 mile/h. The use of new vehicles for the purposes of crash testing is expensive. The used car market is usually the source for barrier test vehicles. Vehicles should be in road worthy condition, although vehicles of that period, whether new or second hand, could not be relied upon to reach an impact speed of 70 mile/h under their own power within the restricted distances available on crash test sites.

For the earliest higher speed barrier tests (1962), it was considered that acceptable and informative results could be obtained on barrier performance if the impact speed was in excess of 45 mile/h, for a moderate sized four door saloon of about 1.36 t. In preliminary tests of a concrete beam barrier, the test vehicles were manned and driven into the barrier at angles up to 20° at speeds of about 30 mile/h (V.J. Jehu, 1967 [18]). Using remote steering methods, higher impact speeds were possible by pulling the test car, attached to a long steel cable, with a high powered tow vehicle; the engine of the test car was not engaged. The cable passed through a pulley mounted on the back of the tow car, to a ground anchor. This mechanism provided a 2 to 1 speed ratio; the tow car had only to reach about 23 mile/h for the test car to reach impact speed at about 45 mile/h. Speeds in excess of about 50 mile/h were found to be difficult to achieve because of limitations in the remote steering system. Steering control was dependent on a balanced yoke connection between the tow cable and the car's track rod. It was important to keep a steady tension in the tow cable, otherwise the car could run off course; the method was found to be not suitable for speeds in excess of 45 mile/h to 50 mile/h.

It had been shown in earlier trials that the method of accelerating an unpowered test vehicle was feasible using two tow vehicles with pulleys that give a 4 to 1 speed advantage, (Laker and Blamey, 1961 [19]). Using this technique, a lightweight, unpowered, 1936, Morris 8 car had been accelerated to 40 mile/h in a distance of 50 m; the acceleration is equivalent to more than 3 m/s²; this is considerably in excess of the maximum acceleration of most present day high performance private cars. The vehicle was steered by a guidance shoe linked between the car's steering track rod and a ground rail; target impact precision was of the order of ±50 mm.

Subsequently, on a 190 m long test site at TRL, using the two towing vehicles method and remote radio control of the car's steering mechanism, impact test speeds of 62 mile/h were achieved (Jehu and Laker, 1967 [20]). This tow method of vehicle propulsion and radio control of an unpowered vehicle was found to be successful, and used, over the period of time during which current designs of

safety barrier, presently in use on UK highways, were initially developed. The benefit of not requiring engine power from the test car simplified the purchase of second hand test vehicles.

Later, improved crash site facilities became available at TRL. Barrier approach distances of over half a mile were possible. After being push-started by a high performance, 350 horse power car, impact speeds of more than 70 mile/h could be reached by using the engine power of the more modern test vehicle. The vehicles were steered by a radio link; the controller operated a remote steering wheel and braking system from a following car (LF78, 1967 [21]).

As the need grew for the use of heavy commercial vehicles in the development of higher containment barriers, it was clear that the installed engine power was not sufficient for regulatory testing of prototype barriers; in addition, impacts within small speed tolerances were needed. Furthermore, the precision of radio controlled steering could not provide the tolerances necessary in targeting critical impact points. To overcome the problem, TRL and the Motor Industry Research Association (MIRA) combined to build a high energy impact test facility on the MIRA proving ground. The motive power was provided by a winch system driven by two 500 horse power induction motors. The design specification was to propel a 38 t truck up to a speed of 50 mile/h in a distance of 366 m; this is equivalent to an acceleration of about 0.7 m/s². Experience with the winch system demonstrated that accuracies of better than 0 to +2 mile/h could be achieved for speeds up to 100 mile/h, (Bacon, 1986 [22]).

Table 3 gives some examples of the MIRA/TRL power winch characteristics.

Table 3 — Examples of winch performance

Vehicle type	Mass t	Distance m	Speed mile/h
Car	1.5	110	70
HCV	16	200	50
HCV	38	305	50
Sled	2.5	180	100

4.3 Remote steering control

Remote steering by radio control and vehicle guidance by a ground rail linked to the test car have been referred to in 4.1.

Vehicle control by radio has the benefit of flexibility; that is, the desired impact angle can be easily changed from test to test, and the technique lends itself to use between test sites. The disadvantages include the need for installation of fairly complex steering control equipment in the test car where it might suffer damage during the impact. In addition, steering by a controller operating a remote steering wheel from a following car may not provide sufficiently accurate contact with the target point on the barrier. The impact accuracy problem can be

overcome by the replacement of manual remote steering control, with an induction loop buried in the test track approach to the barrier; but the risk of damage to complex equipment remains and the flexibility of moving from site to site is lost.

Test vehicle guidance by a shoe connection between a ground rail and the car has the benefit of high accuracy in pin pointing the desired impact point on the barrier. The cross-section of the guidance rail needs to be substantial if the shoe connects directly to the chassis of the test vehicle, rather than through the steering linkage; particularly if the rail is intended to guide heavy commercial vehicles. It has been estimated that a lateral force of at least 100 kN can be exerted on the ground rail during remote guidance of a 40 t HCV.

An alternative compromise between radio control and a heavy ground rail is the use of a guide wire strung between two moveable ground anchors, and connected to the steered stub axle of the test vehicle, (Bacon and Roy, 1988 [23]). This method has the benefit of flexibility wherein it can be easily moved to approach the barrier at chosen impact angles, or transferred to another test site as required. The link between the guide wire and the car is disconnected just before impact; the vehicle steering is then free from any external constraints and the guidance mechanism, having been separated from the vehicle, is not subject to damage during the impact. Computer simulation of the system demonstrated typical lateral force on the cable peaking at about ± 2.5 kN, transitional loads ranged between 0.25 kN; the average lateral load was of course zero.

Using guide wire steering and propulsion from a 1 000 horse power induction motor winch, practical trials demonstrate the propulsion and guidance of a 16 t vehicle to a speed of 50 mile/h in a distance of 135 m.

4.4 Test car speed control

In early barrier testing, precise speed control of the test vehicle was not the main factor under consideration; barrier design and elimination of hazardous features was the prime concern.

Limitations in test-site space, or engine performance, or towing power, usually meant that the maximum speed achievable was the only one of interest. Eventually, drafting of technical standards that included parametric tolerances, highlighted the need for improved control of vehicle impact speeds.

Speed control of a powered winch is simpler than controlling the speed of used car engines. Propulsion of the test vehicle by a towing winch also avoids the need to purchase used test vehicles with engines that are in good working order. Clearly there could be a cost saving. Calibration trial runs provided settings for the winch that permitted impact speeds to be met within selected tolerances.

The main factor, with regard to stopping the test vehicle after impact with the barrier is the space available on the test site. The extent of vehicle damage sustained can be of interest in assessing the overall performance of the barrier. Damage caused by secondary impact into protective structures obscures such useful information. If site space permits, braking of the vehicle by aggregate arrester beds, or catch netting, is likely to be most effective.

Where space is limited, remote control of the car's braking system is an alternative. Unfortunately, damage to test vehicles during contact with a barrier can include the car's brakes. Remote braking is usually not progressive, and hard application of the brakes by perhaps stored pneumatic pressure, to damaged or unbalanced brakes, can result in vehicle instability and overturn. There is always the need to ensure that all personnel are protected should test vehicles go out of control.

5 Measurement of vehicle and restraint system test data

5.1 General

A central purpose for carrying out full scale impact testing of vehicle prototype road restraint systems is, at the simplest level, to separate devices of good performance from those that are unacceptable; the impact test can be said to act as a discriminating filter which separates good systems from bad. Some restraint systems, such as a flexible roadside safety barrier, might have impact characteristics that are easily observable; for example, a test vehicle might be seen to be contained and redirected in a safe and satisfactory manner. However, the task of discriminating between good and bad performance becomes more complex when a restraint system has necessarily to be more resistive, and so generates higher deceleration forces in the vehicle. This can arise where roadside conditions require a more rigid system for vehicle containment within a limited space, or where high containment systems, suitable for commercial vehicles, might produce undesirable effects on small car response.

Recording vehicle impact characteristics allows objective assessment of a restraint system's impact performance to be made, compared with an observer's momentary subjective appreciation of an event that may take place in only a fraction of a second. In addition, a permanent record of the results of the impact test is needed to assist approval procedures for the acceptance of candidate systems.

The specific vehicle criteria for impact test acceptance have mainly centred on speed, acceleration and angular position. Instrumentation for recording at this level allows confirmation to be made on whether the regulatory pre-impact speed has been met, it gives a measure of the forces generated during the impact and it permits the