



Traffic calming and vehicle emissions: A literature review

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Executive Summary

With the introduction of the UK National Air Quality Strategy, local authorities will be required to undertake periodic reviews of air quality in their area. Authorities will have to compare current and future air quality with standards and objectives to be set out in regulation. If air quality is not likely to meet the objectives for 2005, then the authority will be required to draw up an air quality management plan aimed at achieving compliance. Traffic management is one tool that may help authorities meet the objectives, although information on the relative impact of alternative schemes on air quality is limited and imprecise at present. To improve the level of understanding of the subject of environmental impacts, the Driver Information and Traffic Management (DITM) Division of the Department of the Environment, Transport and the Regions (DETR) has commissioned a programme of research on the subject. This Literature Review represents the first output from one of the DITM Projects within the programme (UG127: 'Traffic Management Schemes and Vehicle Emissions'), and focuses on the main stages involved in the assessment of the impact of traffic calming schemes on vehicle emissions.

The Review includes details of the measures employed to calm traffic, the changes in driver behaviour imposed by traffic calming schemes, factors affecting emissions from road vehicles in the context of traffic calming, case studies of the impact of traffic calming schemes on vehicle emissions, and damage to public service and emergency service vehicles reported to have been caused by traffic calming measures.

The six most common traffic calming measures (by number of schemes implemented) were found to be 75 mm high flat-top humps, 75 mm high round-top humps, speed cushions, single lane working chicanes, thermoplastic humps ('thumps') and 2-way working chicanes. Schemes comprising mainly of road humps are currently the most common type, although the proportion of schemes containing speed cushions is increasing.

The relationships between vehicle speeds and hump spacing, together with speeds at humps, are well documented for 75 mm humps (and 'thumps'). Similar relationships for cushions and chicanes are more complicated because the number of variables involved is greater. It appears that 1800-1900 mm wide cushions give comparable crossing speeds to road humps of a similar height, whereas narrower cushions have crossing speeds about 5 mph higher. Cushions are generally straddled centrally by buses, and by approximately half of cars, at sites where parking does not cause obstruction. The effectiveness of single-lane-working chicanes is dependent on the flow along the road. In non free-flow conditions speeds can be reduced by a further 10 mph.

A review of previous case studies led to the conclusion that there is only limited agreement on the effects of traffic calming on vehicle emissions. The area-wide studies reviewed showed a decrease in NO_x emissions as a result of calming. However, these studies were less conclusive in terms of the changes in emissions of CO and HC.

The studies of the effects of traffic calming based on single sections of road produced a wide range of results. This was particularly evident in the case of NO_x , for which some studies have shown decreases of up to 30%, whilst others have shown large increases. It was not immediately obvious why this is the case, nor why discrepancies have arisen between the 'single road' studies and the area-wide studies. The single road studies did show a consistent increase in fuel consumption and emissions of CO and HC due to traffic calming, although the HC data is limited and wide variations in the changes in CO emissions were recorded.

Increased vehicle maintenance costs have been reported by some bus companies, although some local authorities have reduced the severity of ramps to reduce the likelihood of damage.

1 Introduction

1.1 The National Air Quality Strategy

One function of the Environment Act 1995 was to impose on the Secretary of State a duty to prepare, and periodically review, a strategy for the management and improvement of air quality in the UK. This duty has manifested itself as the National Air Quality Strategy (Department of the Environment *et al.*, 1997). Section 82(1) of Part IV of the Act has also laid the foundations for a nationwide system of local air quality management. Local authorities have been presented with new responsibilities, including obligations to perform a periodic review and assessment of the quality of air in their area, and to assess present and likely future air quality against standards and objectives which are to be set out in regulation. These obligations fall to district and unitary authorities in England, and to all local authorities in Scotland and Wales.

DETR expects local authorities to have completed their reviews and assessments of local air quality by April 1999 at the latest. Following this assessment, some authorities may have to designate Air Quality Management Areas (AQMAs) where air quality objectives are not likely to be met by the year 2005. The authority is then required to draw up an air quality management plan which will lead to the air quality objectives being met on time. A further report on the assessment of air quality within the AQMA must be prepared within 12 months.

1.2 The proposed role of traffic management in the National Air Quality Strategy

Given that road vehicles are a major source of some priority pollutants, such as carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x), the achievement of the air quality objectives will require substantial reductions from the road transport sector. The Government has set out the key principles that it would follow to secure reductions in air pollution resulting from road transport (Department of the Environment *et al.*, 1997). These are:

- i Improvements in vehicle and fuel technology to reduce emissions.
- ii Tighter controls on the existing vehicle fleet, its management and operation.
- iii Development of environmental responsibilities by fleet operators, particularly public service fleet operators, and by the public at large, in transport and vehicle use.
- iv Changes in planning and transport policies which would reduce the need to travel and reliance on the car.

The Government has recognised that an effective strategic policy must incorporate all these four elements. It thinks that the largest reduction in emissions will result from improvements in vehicle technology, although such reductions alone may not be sufficient to meet all of the air quality objectives. In the words of the Department of the Environment *et al.* (1996a):

'Cleaner fuels and vehicles must be the backbone to any strategy to reduce emissions from vehicles. However, technological changes can take a long time to impact and will not tackle local problems...The Government therefore accepts that a further contribution should be sought from national and local measures on vehicle maintenance and traffic management.'

The Environment Act 1995 has ensured that traffic management schemes can be used for air quality purposes. Plans drawn up by local authorities under Section 84(2) of the Environment Act 1995 may include alterations to existing, or the development of new, traffic management schemes on air quality grounds. Schemes should generally aim for an overall reduction in vehicle emissions, primarily by reducing congestion on sensitive parts of the network. Where local authorities consider that traffic management can make an appropriate contribution to improving air quality, they should consider and carefully evaluate all the opportunities available to them, and set out a balanced and integrated approach tailor made to their specific local circumstances (Department of the Environment *et al.*, 1996b).

In order to facilitate this approach, Abbott *et al.* (1995) have suggested that:

'The congestion/safety/environmental aspects of the different types of traffic management will need to be integrated into a multi-criteria framework such that each aspect can be quantified and the relative effects of different policies examined and optimal solutions obtained.'

The development of such a framework requires that the environmental impacts of various traffic management schemes be subject to extensive investigation.

1.3 Assessing the environmental impact of traffic management schemes

'Traffic management' is a term that covers a very wide range of schemes or policies that may be employed to control traffic. It relates not only to physical barriers that restrict traffic movement, but also to more subtle schemes that attempt to coerce drivers into a different pattern of vehicle use. It can also be undertaken for a number of reasons: to make roads safer, to improve the local environment, to reduce congestion or to improve accessibility to particular areas of town. The concept of traffic management is therefore widely understood to be both multi-faceted and multi-objective.

Although many *individual* traffic management schemes are also multi-objective, they can be divided into two broad categories that reflect their main objectives. The categories are:

- i Congestion reduction schemes designed to restrict motor vehicle use in urban areas and/or to improve traffic flow. Such schemes include improvements in traffic signal operation, park and ride, road pricing, and parking restrictions.

- ii Accident reduction schemes, which generally resort to physical traffic calming measures like road humps, chicanes and road narrowings, but may also include features such as speed cameras and pedestrian islands. These schemes are designed primarily to reduce vehicle speeds and create an environment conducive to safe driving.

The relationship between traffic management and its environmental impacts is a relatively new and, as yet, inexact science (Abbott *et al.*, 1995). Therefore, the extent to which traffic management schemes bring about environmental improvements or otherwise is difficult to quantify at present. To improve the level of understanding of environmental impacts, the Driver Information and Traffic Management (DITM) Division of DETR has commissioned a programme of research on the subject. A number of projects within the programme are being conducted by TRL.

This Literature Review represents the first output from one of the DITM Projects within the programme (UG127: 'Traffic Management Schemes and Vehicle Emissions'). The Review is dedicated mainly to the assessment of the effects of traffic calming schemes on emissions. Some consideration has also been given to the problems that traffic calming can introduce for public service vehicle operators and the emergency services.

The format of the Review relies heavily upon the general procedure for assessing the environmental impact of all traffic management schemes proposed by Abbott *et al.* (1995). This procedure is characterised by five distinct stages, and can be summarised as follows:

- i The imposition of a traffic management scheme will introduce changes to the traffic which need to be defined accurately in order that environmental appraisal can proceed to the next stage. Drivers will respond to controls by modifying their behaviour. Such changes may include modifications to average and maximum speeds, rates and numbers of accelerations and decelerations, gear changing etc. Trip lengths, traffic flows, traffic composition and modal split may also be affected.
- ii Changes in driver behaviour will result in modified patterns of vehicle operations specified by various engine and vehicle parameters like engine speed and load, their rates of change, and engine and exhaust temperature profiles.
- iii These changes will influence rates of emissions (as well as noise and vibration levels).
- iv If vehicle emissions are affected then local levels of air pollution (as well as traffic noise and vibration) exposure will also be affected.
- v Finally, the impact of changes in exposure on people in different community settings must be adequately assessed. This would complete the connection between the design of traffic management schemes and the environmental impact that the resulting traffic changes have on people whether they are drivers, pedestrians or at home.

Since the aim of the current Literature Review is to gain an insight into the effects, or potential effects, of traffic calming on vehicle emissions, stages (iv) and (v) of this procedure will not be considered in detail, although changes in air pollution associated with traffic calming will be briefly mentioned in the review of case studies. Short descriptions of the engineering measures employed to calm traffic and, occasionally, the philosophy underlying their implementation, are provided in Chapter 2. The purpose of Chapter 3 is to discuss the next step in the assessment procedure: driver behaviour and the changes in behaviour imposed by traffic calming schemes. This will mainly include details on the effects of various measures on vehicle speeds and traffic flow. Chapter 4 comprises a review of factors affecting emissions from road vehicles in the context of traffic calming, concentrating mainly on operational parameters. Chapter 5 is presented as a summary of previous assessments of the impact of traffic calming schemes on vehicle emissions, and Chapter 6 includes a brief review of the problems that traffic calming introduces for public service and emergency service vehicle operators.

2 Traffic calming measures

2.1 Background

Detailed histories of traffic calming and numerous useful case studies have been presented by some authors, notably Hass-Klau *et al.* (1992), Pharoah and Russell (1989), Tolley (1989), County Surveyors' Society (1994) and Devon County Council (1991). There is no intention to repeat this work in this Section of the Review. The objectives of traffic calming and the devices commonly employed are described only in outline.

Changes in mean traffic speed have been shown to be related to changes in accident occurrence. By examining the results from studies on various types of road in several countries, Finch *et al.* (1994) found that a 1 mph speed reduction gave a 5% reduction in accidents. A similar relationship has been observed for 20 mph zones, where it has been demonstrated that the same reduction in traffic speed equates to a 6.2% reduction in accidents (Webster and Mackie, 1996). Such results have encouraged the use of traffic calming measures.

Devon County Council (1991) has noted that the term 'traffic calming' is largely open to interpretation, although it does convey the basic objective of the approach - to reduce the adverse effects of road traffic by adapting the volume, speed and behaviour of traffic to the primary functions of the streets through which it passes. Alternatively, Pharoah and Russell (1989) have defined traffic calming as

'the attempt to achieve calm, safe and environmentally improved conditions on streets'.

It was acknowledged by Pharoah and Russell that the principal objectives vary from scheme to scheme, but

generally include reduction of accidents, reclamation of space for non-traffic activities, promotion of greater feelings of security (particularly among residents, pedestrians, cyclists and others engaged in non-traffic activities), creation of environmental improvements, and promotion of local economic activity.

2.2 Traffic calming measures

The recent relaxation in the regulations governing the nature of traffic calming devices (see Appendix A) has led to a diverse range of measures on UK roads, although many of these measures have been used extensively on the continent for some years. The main calming measures include:

Vertical deflections	Horizontal deflections
Round-top humps	Half chicanes/Build-outs (one-way/two-way)
Flat-top humps	Full chicanes (one-way/two-way)
Speed cushions	Pinch points
Raised junctions	Narrowings
‘Thumps’	Central islands
Rumble devices	Refuges
Other devices	
Mini-roundabouts	Street furniture
Surface treatment	Visual effects
Entrance treatment	Planting
Gateways	Speed cameras
Road closures	Speed limits (fixed or variable)
Changed priority	Weight & width restrictions

Such measures may be implemented individually, but it is increasingly common for authorities to implement a combination of measures in area-wide schemes. Indeed, this approach has been encouraged for a number of years. For example, Devon County Council (1991) have regarded the list of specific measures as a ‘palette’ to be used in combination to meet specific objectives. The main features of the most important measures are discussed in Sections 2.2.1 to 2.2.5.

Of 152 schemes submitted to the County Surveyors’ Society for inclusion in their guide to traffic calming, just over half of the schemes (56%) were located in urban residential areas, with 29% occurring on main roads in rural locations and the remaining 15% in town centre areas (County Surveyors’ Society, 1994). From the assertion by Devon County Council that traffic calming works by adapting the characteristics of traffic to the functions of the streets through which it passes, it follows that different approaches will be required for these different sections of the road network. For example, vehicle speeds must be kept low throughout an urban residential 20 mph zone. The position in the road hierarchy that a 20 mph zone occupies ensures that vehicles entering the zone are not travelling at particularly high speeds, and consequently fairly severe traffic calming measures can be employed. In contrast, vehicles entering a rural village on a main road will be travelling at higher speeds, and the proportion of

HGVs in the traffic will be considerably greater. The design of any traffic calming measures employed to reduce speeds through such a village would obviously need to take these factors into account.

In order to inform prospective practitioners of traffic calming of the recommended procedures and legislative requirements concerning the implementation of schemes, the Government has published an extensive series of Traffic Advisory Leaflets (e.g. Department of Transport, 1996). Other publications that offer advice on implementation include those by Devon County Council (1991), Hass-Klau *et al.* (1992) and the County Surveyors’ Society (1994). Some details of the more important traffic calming measures are provided in the following Sections, but for a more in-depth view these publications should be consulted.

2.2.1 Vertical deflections

Road humps

Devon County Council (1991) described a road hump as a raised portion of carriageway laid at right angles to the direction of traffic. Humps generally have either a circular (round-top) or trapezoidal (flat-top) profile with ramps leading up to and down from a plateau. Road humps are the most commonly used traffic calming measure in Britain (Hass-Klau *et al.*, 1992), and this is no doubt due to their effectiveness as a speed-reducing device.

Round-top humps were first used in the UK in the 1980s (Baguley, 1981). They were 3.7 metres long in the direction of travel, and had a permitted height of 75 to 100 mm. Flat-top humps made their first appearance in the UK during the 1990s. Originally, these had to be at least 3.7 metres long in the direction of travel, with maximum and minimum permitted heights of 100 mm and 50 mm respectively. Ramp gradients of 1:6 were allowed initially, but these have subsequently been regarded as too severe unless very low speeds are required. The County Surveyors’ Society (1994) have noted that ramp gradients between 1:10 and 1:15 combine the greatest effectiveness with the least harshness. Flat-top humps may also be used in conjunction with Pelican and Zebra Crossings.

The most effective humps at reducing vehicle speeds are 100 mm high but, because of passenger discomfort or grounding, they are not usually suitable for bus routes or on routes which are frequented by the emergency services. The use of 75 mm humps can substantially lessen the likelihood of grounding with little or no erosion of the speed reduction obtained using 100 mm high humps (Webster and Layfield, 1996). Where the higher humps would have been unacceptable to the emergency services, bus operators and residents, humps with lower profiles and shallower gradients have been implemented.

Speed cushions

As Layfield (1994) indicated, one of the main problems with road humps is that the effect on larger vehicles such as buses, mini-buses and emergency vehicles is more severe than for cars, and thus the discomfort for passengers in larger vehicles can be more pronounced than in cars. Road humps can cause delays for emergency vehicles and

can also be uncomfortable for cyclists. On the continent, and more recently in Britain, the solution to these problems has taken the form of speed cushions.

Speed cushions are raised areas in the carriageway that occupy only part of the traffic lane in which they are installed. Cars and other vehicles with narrow track widths (between 1100 mm and 1400 mm) cannot avoid them, and have to cross with at least one wheel of each axle on the cushion, but larger vehicles with wider tracks can cross by straddling the raised area. Thus buses, fire appliances and some ambulances should be able to cross them relatively unimpeded, whilst cars have to slow down to avoid discomfort (Layfield, 1994). However, on many British roads operators run different makes of bus, which often have various axle widths and ground clearances. Thus the ideal speed cushion will be difficult to design.

Speed cushions are generally located in pairs, arranged transversely across the carriageway, but single cushions centrally positioned, 'three abreast' versions and double pair arrangements have also been used (Department of Transport, 1994c). Other alternative designs, comprising of sets of three and five cushions, have been evaluated in on-road trials by Layfield (1994).

Raised junctions

Webster (1993a) explained that raised junctions are a development of the flat-top hump. The whole junction is raised to road-hump level with ramps on all arms. Such features can make drivers more aware at problem junctions and form an attractive speed-reducing feature. It can also help pedestrians to cross the road if constructed to footway level. They are most useful in an area-wide scheme at junctions which are known to be hazardous, and where major reconstruction would not be justifiable or viable.

'Thumps'

'Thumps' are mini-humps that are made of thermoplastic and span the full width of the carriageway. According to the Government (Department of Transport, 1994d), it is a matter for individual authorities to determine whether thumps provide a suitable alternative to road humps in particular circumstances. For the design of the thumps, the DOT suggested that they be circular in profile, 37 mm high, around 900 mm wide, spaced at around 50 metre intervals, and used on roads with speed limit no greater than 30 mph.

Rumble devices

Rumble devices (rumble strips and jiggle bars) introduce a type of noise and vibration that contrasts with a tarmac surface and therefore gives a clear indication to drivers that they should reduce their speed. Designs and materials may vary, but the strips are generally formed by a vertical change in the road surface material applied across the carriageway. The Highways (Traffic Calming) Regulations (1993) stipulate a maximum height of 15 mm for rumble devices. When used in residential areas, there can be problems with this traffic calming measure because of increased noise and vibration levels. In some cases the strips have been removed after complaints from residents (Hass-Klau *et al.*, 1992).

2.2.2 Horizontal deflections

According to Hass-Klau and Nold (1994), the opposition to road humps from emergency services, bus operators and residents has encouraged local authorities to shift the emphasis from vertical to horizontal measures. Horizontal measures were defined by Hass-Klau and Nold as a lateral shift in the carriageway with the intention of reducing vehicle speeds and, in some cases, creating pedestrian crossing points. To achieve this effect, and to limit the driver's long distance view of the road, the paths of vehicles have to be deflected to some degree, often in conjunction with a narrowing of the carriageway.

Build-outs/Half-chicanes

A build-out consists of a feature extending into the road with the intention of narrowing the existing carriageway. These features can be constructed in very different ways: as pavement extensions, planted areas, or with the use of plant pots or tubs. Build-outs can either be connected with the pavement, or a channel may be left between the build-out and the pavement so as to leave the existing drainage unaffected. If wider gaps are left, a cycle path may be incorporated (Hass-Klau and Nold, 1994). The narrowed carriageway, even if reduced to a single lane, still allows most vehicles to be driven relatively quickly through the available gap, unless there is opposing traffic to prevent this (Department of Transport, 1994e).

Full Chicanes

A full chicane is formed when two build-outs are implemented on alternate sides of the carriageway. The number of chicane designs appears to be almost unlimited. The most effective chicanes need a narrow carriageway width, but these are only recommended when the traffic flow is very low (Hass-Klau *et al.*, 1992). Chicanes are generally not suitable for use on main roads with large volumes of traffic, although they may be applicable on certain roads if traffic flows are lower. However, where this occurs the stagger length may need to be so long that car drivers can adopt a relatively straight line through the chicane, and therefore the speeds of cars are not reduced (Department of Transport, 1994e).

While chicanes must have sufficient carriageway width to allow access to emergency or large vehicles, this may cause them to lose some of their effectiveness at reducing the speed of cars. This, to some extent, can be overcome by the use of overrun areas which tend to be avoided by cars but not by larger vehicles.

Pinch points

Pinch points are created when two build-outs are constructed on directly opposite sides of the carriageway to form a feature which reduces the width of the carriageway over a distance of around 5-10 metres. The form and shape of pinch points can vary substantially, and the distinction between pinch points and chicanes is often blurred. By implementing this measure the carriageway width can be restricted so that only one vehicle at a time can negotiate the point (when the width is around 2.75-3.2

metres), or that two cars can pass each other slowly (when the width is around 4.6-4.8 metres).

If rat-running traffic is the problem, rather than excessive traffic speed, reducing the carriageway to one lane by pinch points can be effective in deterring through traffic by causing delays (Hass-Klau *et al.*, 1992).

Carriageway narrowing

The varied objectives of carriageway constrictions include: to limit the ability of vehicles to pass one another (and thus to limit speeds and/or to interrupt traffic flow), to limit overtaking, to reduce pedestrian crossing distance, to restrict the size of vehicles entering a road, to provide priority for buses, to prevent on-street parking, and to define or shelter on-street parking spaces. In contrast to the construction of pinch points, carriageway narrowing is carried out over the total stretch of road that needs to be traffic calmed. Roads can be narrowed by hatched road markings or by physical measures in the form of pavement widening, central reservations, cycle and bus lanes, side strips and tree planting (Hass-Klau *et al.*, 1992).

Traffic islands/Pedestrian refuges

Islands can provide refuge for crossing pedestrians, improve lane discipline by restricting overtaking, lower vehicle speeds by reducing lane width, and separate cyclists from other traffic when used with cycle lanes. They are most commonly implemented to reduce the carriageway width or to form chicanes and pinch points (Hass-Klau *et al.*, 1992).

2.2.3 Other devices

Roundabouts

Roundabouts have been a traditional traffic management device in Britain for many decades. They are used to reduce speeds, smooth the traffic flow and reduce vehicle conflicts. Speed reduction results from the creation of a lateral shift in the carriageway, and priority to traffic from the off-side. A negative element of roundabouts is the increased danger faced by cyclists as a result of conflicting movements. They are also difficult to negotiate for pedestrians (Hass-Klau *et al.*, 1992). The design of conventional roundabouts tends to limit their use and therefore mini-roundabouts are often used in residential areas (Devon County Council, 1991). These are an effective way of treating specific junctions with poor accident records.

Road markings/Surface treatments

A change in the surface material, or the colour of the carriageway, can define a central reservation or cycle lane and will help to create the impression of a reduced carriageway width (Hass-Klau and Nold, 1994). According to Devon County Council (1991), the objectives of road markings are to guide drivers, to improve predictability of vehicle paths for the benefit of pedestrians and cyclists, and to indicate priority.

Entrance treatments

Entrance treatments are design features intended to make car drivers more aware when they are entering a traffic calmed area, or generally mark the beginning of an area where reduced speed is required (Hass-Klau and Nold, 1994). Hence, they can be an effective means of identifying the beginning of a 20 mph zone.

Entrance treatments have been developed for use at side roads so that drivers leaving a major road are in no doubt that they are entering a road of different character. Depending on the features they incorporate, they may be used alone or to indicate to a driver that he is about to encounter other traffic calming measures. Indeed, Hass-Klau *et al.* (1992) pointed out that the effect of gateways is largely psychological and is not very effective if it is used in isolation without any further traffic calming measures in the area itself. The design of an entrance treatment can itself incorporate a wide variety of features, including build-outs, pinch points, changes in surface texture or colour, vertical deflections, and planting (Department of Transport, 1994a).

Gateways

Gateways are most often implemented at the approach to villages on principal rural roads. They usually incorporate vertical features at the sides of the road, but can also include a village nameplate, speed limit regulatory signs and warnings of further traffic calming (examples are given in Wheeler *et al.*, 1997). According to the County Surveyors' Society (1994), gateways tend to be ineffective at reducing speeds unless they incorporate some form of physical narrowing. The effect of gateways can be short-lived, and repeater features are required to maintain speeds at a lower level.

Road closure

Road closure is a well-established traffic calming measure in Britain. Whatever traffic calming measures are implemented on a particular road, through traffic cannot be completely eliminated where arterial roads are blocked or congested. In such circumstances drivers will try to avoid the congestion by taking residential roads, whether they are traffic calmed or not (Hass-Klau *et al.*, 1992). Road closure is a measure that is taken specifically to remove the possibility of rat-running.

The effects of road closure on parallel streets, and the actual number of road closures in a residential area, are important. If one street is closed, and through traffic can move into parallel streets, this can cause problems for the residents living there. If there are too many road closures in one area then the additional trip distances created can become a significant problem. Another argument against road closure is that it lengthens trips for emergency vehicles. The need to close roads is often a sign that other car-restraining policies are needed.

2.2.4 Area-wide traffic calming

As stated earlier, car drivers who have been forced to give up one rat-run because it has been traffic calmed often switch to another. This can be avoided by area-wide

calming, with the best results being achieved by use of a combination of traffic calming measures. The ugliness of tarmac road humps becomes very obvious if used on an area-wide basis, but even if more attractive block-paved humps are used, it has to be made clear how emergency services would be affected if they had to get to a location in the middle of a network of streets equipped with road humps, not to mention problems over the comfort of patients being carried in ambulances (Hass-Klau *et al.*, 1992).

Webster (1993a) noted that the area-wide approach aims to ensure that only suitable traffic uses each type of road. This can be achieved by establishing a hierarchy for the roads enclosed by main thoroughfares and installing physical measures to encourage appropriate traffic onto appropriate roads. Varying the type and height of measures can help to define the hierarchy of the area. This can be achieved by placing the most severe measures on the roads which are unsuitable for through traffic, and less severe measures on other roads.

2.2.5 Speed limits

Speed cameras

Speed cameras have become an increasingly common sight along main and local distributor roads in urban areas in the UK, but their effects on speed tend to be very localised. Abbott *et al.* (1995) observed that the development of speed-enforcement technology that can detect excessive speeds along a route, rather than excessive speeds at particular locations, may give speed-enforcement technology a greater role in accident reduction and traffic calming.

20 mph zones

The Department of Transport advises that 20 mph zones are most appropriate in areas where an urban safety strategy has been developed. The zone itself will normally be residential in character, and in order that zones do not become too large, no road within it may be more than 1 kilometre from the boundary of the zone (Department of Transport, 1991).

Zones are subject to the consent of the Secretary of State for Transport. An eighteen month experimental period (temporary approval) is required to ensure that the required speed reduction has been achieved before permanent approval is granted. In Britain, physical measures are usually required to obtain this speed reduction, and the eighteen month period allows the authority time to construct them. Hodge (1992) noted an apparent lack of variation in the type of measure implemented in 20 mph zones. Flat-top humps appeared to be the device most frequently used.

2.3 Most frequently implemented types of scheme in the UK

The types of traffic calming measure most frequently implemented in the UK are listed in Table 1. The ranking is based on details of schemes authorised by the Road Safety Division of DETR, a number of TRL reports and the personal knowledge of the authors. Each measure has been evaluated according to the percentage of schemes

Table 1 Common traffic calming measures in the UK

Popularity ranking	Approx. % of schemes	Main type of measure in scheme	Description
1	40%	Flat-top hump	75 mm high
2	35%	Round-top hump	75 mm high
3	10%	Speed cushions*	1700-1800 mm wide
4	7%	Chicanes	Single lane working
5	5%	Thumps	37 or 42 mm high
6	3%	Chicanes	2-way working

* Note. Cushions can vary from 1600 to 1900 mm wide

implemented in which that particular measure was the most prevalent device. The percentage values presented are very approximate, since some of the features listed are often used in combination with each other or with mini-roundabouts. The relative positions of the measures in the list are changing constantly, and regional disparities in the ranking will also exist. The main point to note is that schemes comprised mainly of road humps are easily the most common type, although the proportion of schemes containing speed cushions is increasing.

3 Traffic calming and driver behaviour

The first main stage in the determination of the environmental impact of a traffic calming scheme is the assessment of the modifications to driver behaviour imposed by the scheme, and a common approach is to consider behaviour before and after implementation. This Chapter of the Review is mainly concerned with the factors influencing driver behaviour in urban areas in general, and also observed changes in behaviour in relation to various calming measures.

3.1 What is driver behaviour?

'Driver behaviour' is a term that refers to the way in which drivers are *observed* to operate their vehicles (e.g. their chosen speed). There is a distinction between driver behaviour and driver performance. The latter is associated with the *ability* of a driver to judge the speed of his or her vehicle, to control the vehicle at that speed, and to react to hazards (Evans, 1991).

Two basic types of information that describe driver behaviour were identified by the COST 319 Action, 'Estimation of Pollutant Emissions from Transport' (European Commission Directorate General for Transport, 1995). These are:

- i Vehicle control. This includes detailed data on parameters relating to vehicle control, such as speed and gear selection.
- ii Activity data. This includes information on trips such as journey purpose, duration, mode, time of day, time of year.

These two aspects are explored briefly in Sections 3.1.1 and 3.1.2. Section 3.2 relates to the effects of traffic calming on driver behaviour.

3.1.1 Vehicle control

In urban traffic a driver normally has a wide choice of possible accelerator positions and gears. He thereby determines the operating parameters of the engine and consequently the fuel consumption and exhaust emissions of his vehicle. The variety of possible control options means that measurements of parameters that are dependent on these options are likely to be quite variable. For example, Waters (1992) stated that different drivers can obtain substantially different fuel consumption figures in the same model of car. When nine drivers were asked to drive the same car around a TRL test route, Waters reported that there was a large difference (50%) between the least and most economical drivers.

Abbott *et al.* (1995) understood that the detailed assessment of the vehicle control element of driver behaviour was one of the key stages in the environmental appraisal of traffic management schemes. Drivers will respond to traffic controls by modifying the way in which they operate their vehicle. Such changes may include modifications to average and maximum speeds, rates and numbers of accelerations and decelerations, braking and gear selection. This will result in modified patterns of vehicle operations as specified by various engine and vehicle parameters (e.g. engine speed and load and their rates of change) and hence changes in emission rates.

It is important to understand the diverse aspects of vehicle control and to discover where and why particular modes of driving are encountered so that, hopefully, drivers can be coerced into driving safely and economically, and encouraged to treat a particular road in the manner for which it was designed.

Evans (1991) noted that, notwithstanding the lack of any effective overall model of how people drive, a great deal has been learned about various specific aspects of the driving task. The techniques for studying driver capabilities and performance have included observing actual drivers in traffic, experiments using instrumented vehicles, and studies using driving simulators of varying degrees of complexity and realism. Work relating to driver behaviour has usually been concerned with its relationship not to vehicle emissions, but rather to accidents. Consequently, existing studies invariably relate to speed selection and not necessarily to other parameters known to affect emission rates (e.g. acceleration rates, gear selection, pedal operation). This is reflected in much of the information that follows in this Chapter.

Personal choices concerning, for example, mean speed, speed variation and steering behaviour certainly depend on a large number of factors, some of which have not been subject to extensive study. These factors can be differentiated in a number of ways but, for the purposes of this Review, they have been separated into the five general categories listed below. There are probably numerous interactions between factors that are in different groups.

- i Personal characteristics: e.g. gender, attitudes, age and experience, reaction times and vehicle ownership.
- ii The vehicle environment: e.g. factors relating to interior layout, ergonomics (such as actuating forces of the steering wheel, foot pedals and gear lever) and comfort,

and factors relating to vehicle performance (such as available power).

- iii The road environment: e.g. gradient, width, lateral slope, curvature, surface quality, speed limit, adjacent land use, number of pedestrians.
- iv The traffic environment: e.g. volume of traffic, behaviour of other drivers.
- v Other factors relating to the trip: e.g. available time, time of day, weather and light level, commercial pressures.

These distinctions appear to fit in reasonably well with the way in which information on driver behaviour has been reported. For example, Jørgensen and Polak (1993) observed that the topic of drivers' speed selection is one that has attracted considerable research effort in recent decades, with most of the work having concentrated on the relationship between speed selection and the characteristics of the road (alignment, number of lanes, surface condition etc.) or the driver's vehicle (type, age, engine capacity etc.). Researchers have also sought to develop a better understanding of the factors affecting drivers' speed selection by extending the scope of analysis to include drivers' personal characteristics and attitudes (e.g. Quimby and Watts, 1981). Such work has established the importance of a number of factors, including drivers' perception of safety, their sensitivity to the perceived cost implications of alternative speeds, and the availability and comprehension of information regarding speed limits.

Rothengatter (1993) noted that the relative importance of the different factors underlying specific behaviours is still largely uncharted territory and needs study, since these determine to a large extent the efficacy of the various behaviour modification approaches.

Personal characteristics

The study of the physical and psychological constitution of an individual, and their relationship to driver behaviour, constitutes a substantial field of research in its own right. Personal characteristics will only be examined in outline in this Review, and the characteristics that have been selected are not necessarily the most important; the intention here is to provide a general background. The factors that have been included are age, experience, gender and driver attitudes. Much of the available information derives from work on accident causation. Researchers have frequently focused on travel at higher speeds on, for example, motorways, rural and other inter-urban roads, and inferences about behaviour in urban residential areas cannot always be made from such work.

Ageing imposes a variety of changes on driver performance and behaviour. For those approaching old age the main concerns are the increased restrictions on sensation and perception. Older drivers generally have reduced response speeds and reduced abilities in the various aspects of vision compared to younger ones. According to Brown (1993), drivers will continue to acquire new behaviours, or at least tend to modify existing behaviours, as impairments associated with ageing begin to take their toll. It has been pointed out that there are

enormous individual differences in the effects of ageing on behaviour and performance in general and, in particular, in the extent to which drivers perceive, accept, modify, or compensate for any adverse effects of ageing on performance. On a two-lane rural road with a posted speed limit of 45 mph, Wasielewski (1984) found that the speed of unimpeded vehicles decreased systematically with the age of the driver.

It has been shown in a variety of domains that both qualitative and quantitative changes in the processing of information occur as people develop expertise (Groeger and Clegg, 1994). There is evidence from a number of studies that increased driving experience increases drivers' vehicle handling and perceptual skills (Jørgensen and Polak, 1993), and 'expert' drivers show greater anticipation of hazards. Groups of people that are highly similar to each other, except with regard to the amount of actual driving experience they have had, differ substantially in the ways in which they judge typical driving scenes. As experience of the traffic system grows, these judgements become more coherent and organised. For novice drivers, it has been suggested that their differentiation of judgement becomes clearer with increasing miles driven since they passed their test, but not with increasing time spent as a licensed driver (Groeger and Clegg, 1994). However, Evans (1991) has argued that it is almost impossible to investigate experimentally the phenomenon described as 'road sense' or 'good traffic judgement' which develops over many years.

According to Jørgensen and Polak (1993), there is little evidence indicating that gender has a direct influence on a driver's performance, but observations of behaviour have generally indicated higher speeds for males (Wasielewski, 1984). Men (especially young men) have been observed driving faster, following the car in front more closely, failing more frequently to comply with road markings, driving closer to the centre line, having a higher rate of accelerator input, and being less consistent in their operation of the accelerator than women. However, it may be possible that the behaviour of young women drivers is becoming similar to that of young men (Harré *et al.*, 1996).

Among the attitudinal factors contributing to drivers' speed choice is a systematic underestimation of the probability that they will be killed (Lichtenstein *et al.*, 1978). Another factor is that speed is often desired for its own sake, for pleasure rather than for practical motives such as saving time (Evans, 1991). The results of a survey in the United States have indicated that educational experiences are not generally thought to increase driver concern for safe driving. What does encourage safe driving, in the minds of drivers, is the possibility of negative consequences: being in a crash, being fined, losing one's licence or paying more in insurance costs. Both the threat of these events and their actual occurrence are said by many drivers to motivate safe driving practices (Williams *et al.*, 1995).

Vehicle characteristics

The design of a vehicle affects the driver's behaviour in a variety of ways, including not only factors relating to the

available power and performance, but also ride comfort and ergonomic aspects of vehicle interior layout (such as actuating forces of the steering wheel, foot pedals and gear lever). It is likely that certain vehicle characteristics pertaining to performance and ride quality will be an important determinant of driver behaviour through a traffic calming scheme. In the case of road humps, for example, the extent to which the vehicle's suspension makes the negotiation of humps less uncomfortable could encourage drivers to negotiate the humps at higher speeds. It is also conceivable that vehicles with comparatively stiff suspension units which limit roll could negotiate some horizontal deflections more quickly than those vehicles equipped with more yielding units.

In the study referred to earlier, Wasielewski (1984) did not note any significant relationship between speed and vehicle weight for passenger cars. It was observed by Evans and Rothery (1976) that the way the driver of a following car judged the distance to the lead car was uninfluenced by whether the lead car was large or small. Spacing judgements were, however, influenced by the characteristics of the following car. Identical spacings were judged to be greater when viewed from a small car than from a large car, since the view from the small car exposed a greater distance of roadway between the two vehicles (on account of the bonnet being smaller and lower). It was considered that this finding offered an explanation of a number of field and experimental observations that small cars follow at closer headways than larger cars.

Wasielewski (1984) also found that vehicle age had a weak negative impact upon speed selection (i.e. older cars were found to be travelling at lower speeds). Vehicle make and body style were also considered. It was argued that differences in driver behaviour for different makes and models observed in this study reflected the characteristics of the drivers of these vehicles rather than more subtle influences associated with the 'image' of a particular make or body style.

In modern vehicles the high standards of comfort and low levels of noise and vibration contribute to the likelihood of drivers becoming isolated from the accompanying sensations that travelling fast in vehicles used to bring. These factors may mislead drivers into believing that they are travelling more slowly than is actually the case (PACTS, 1996).

Research has also supported the general insight that drivers change their behaviour when provided with improved braking. Evans and Rothery (1976) found that when cars stopped at two signalised intersections, drivers of newer cars used higher levels of deceleration than drivers of older cars. It was thought possible that the drivers of older vehicles were adjusting their behaviour to compensate for the reduced mechanical condition of their vehicles (Evans, 1996). German research has suggested that cars fitted with Anti-lock Braking Systems (ABS) were involved in just as many accidents as those without. This may be because some people drive faster with ABS fitted, while others may not understand how to obtain the most benefit from the systems (PACTS, 1996).

According to Grime (1987) several vehicle

characteristics influence steering behaviour, including the stiffness of the tyres in the sideways direction, the position of the centre of gravity, and the moment of inertia of the vehicle about a vertical axis through the centre of gravity. It was remarked by Evans (1991) that a skilled driver is relatively unaware of the gain in the steering system of a vehicle (the amount the steering wheel must be turned to alter the vehicle's direction by a given angle). When transferring to cars with higher (or lower) steering system gains, experienced drivers do not travel more (or less) sharply around corners, or have difficulty in maintaining lane position. Instead, they react to the visual information by making the steering input necessary to achieve the desired visual result without being much aware how much they moved the wheel, and in such a manner that there are no observable changes in the behaviour of the vehicle. Less experienced drivers are more aware of the changes in steering system gain, and their driving can be noticeably influenced by transferring to a different vehicle.

Gassmann and Breuer (1989) investigated the effects of four different final drive ratios on driver behaviour. The experiments were carried out on three drivers with different personal driving styles. 'Shorter gearing' did not lead to significantly higher numbers of gear changes per kilometre. Drivers compensated for 'longer' final drive ratios by choosing lower gears to satisfy their personal driving style.

Road environment

There are a number of competing demands for a driver's attention. The components of the visual scene - that area of the road and surroundings which is visible to the driver - are therefore of great importance. Drivers extract information from the visual scene to make decisions about their position on the road, their course of travel, and the distance they maintain from other vehicles. Road width, gradient, alignment and layout are important determinants of speed choice on a particular stretch of road. They affect not only what is physically possible for a given vehicle, but also what seems appropriate to a driver (ETSC, 1994).

A wide straight road is an invitation to accelerate, whereas a narrowing or a bend induces caution. Speeds can be kept below 20 mph by limiting the driver's perceived acceleration distance by introducing 'events' at regular intervals, from a major change such as a square, to simpler breaks marked by building angles or the narrowing of the roadway. Street junctions also affect the driver's perceptions of road space. Wide, raking curves at street corners create vistas which encourage motorists to 'glance and carry on'. A more sharply angled kerb-line, reflecting the angle of a corner of a building, defines a junction more clearly and forces a driver to stop before turning (Thorne, 1993).

Drivers' perception of the appropriate driving speed is influenced by the relationship between the width of the street and the height of vertical elements such as buildings or trees. Speeds are generally lower where the height of vertical features is greater than the width of the street (Devon County Council, 1991). Pharoah and Russell (1989) noted that, in addition to this so-called 'optical effect', the speed-reducing effects of narrow carriageways and driving

lanes might also be explained by the perceived higher risk of collision in narrow streets. Figure 1 shows how the percentage of vehicles travelling above a given speed decreases as the carriageway becomes narrower. However, the graph probably hides a number of effects unrelated to the perceived risk of collision. For example, from the information presented it is not clear whether drivers tended to choose lower speeds on narrower roads because the road was narrow or because, as may be the case, the narrower roads were subject to lower speed limits.

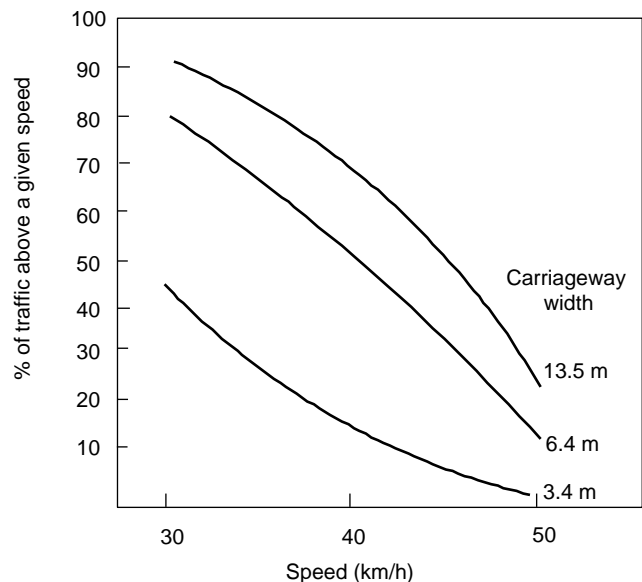


Figure 1 Relationship between carriageway width and traffic speed (based on Amundsen, 1984)

Fuller (1993) explained how highway engineers can take advantage of optical effects to modify driver speeds. Drivers learn to relate the rate of flow of peripheral vision stimulation to actual speed, with higher flow rates becoming associated with higher perceived speed. Thus drivers drive more slowly on roads and lane widths which are narrow, have more roadside 'furniture', and which have buildings, trees etc. close to the edge of the roadway. The rate of flow effect can be artificially increased to slow down drivers by the use of consecutive lateral lines painted on the road surface at decreasing intervals.

Ferguson (1996) remarked on the short term difficulty drivers have in adapting their speed to one more appropriate to the prevalent roadway conditions after a period of time driving at a markedly different speed. This phenomenon is known as the 'speed adaptation effect' and is of great concern when a driver moves from a high speed zone to a lower speed zone.

Traffic environment

The magnitude of the traffic flow rate along a particular road imposes considerable restrictions on a driver's speed selection. Choices of speed arise mainly, according to Evans (1991), in isolated, relatively unconstrained driving. Much driving is spent constrained by a vehicle in front, although there does not appear to be any quantitative estimate of the

fraction of driving spent following vehicles. Each vehicle (except the lead) in a platoon of vehicles reacts, after a time delay, to a stimulus arising from its relationship with the vehicle in front. The reaction is an acceleration or deceleration, although it appears that the following driver does not attempt to, or is unable to, maintain a desired spacing by accelerating or decelerating when the actual spacing becomes larger or smaller than desired.

However, existing information on the relationships between traffic flow and driver speed invariably relates to average conditions and not detailed effects. For example, the Design Manual for Roads and Bridges (DMRB) (Highways Agency *et al.*, 1996) presents nationally-derived relationships between traffic flow and average speed for different types of road. The relationships take the form of a family of curves, differentiated according to the geometric characteristics of each road. The curves for urban roads are given in Figure 2.

The urban speed relationships are based on average journey speeds observed in towns and conurbations in England. The average speed of traffic decreases uniformly with increasing flow, although there is a constraint deliberately imposed on the minimum speed. This minimum speed is determined by the slowest urban speeds in practice. The minimum speeds in DMRB are 15 km/h for central areas, and 25 km/h for non-central areas.

The relationships for urban roads apply to the main road network in towns and cities where there is a 30 mph speed limit. The legends 'Good', 'Typical' and 'Poor' relate to varying degrees of roadside development. For example, 'good' conditions are defined as those where 50% of the roadside contains either business or residential property. The corresponding levels of development giving 'typical' and 'poor' conditions are 80% and 90% respectively.

In built-up areas, generally subject to a local speed limit, the road network becomes more dense and intersections play a more significant role in determining speeds. It is, however, doubtful whether these relationships have any

real use in the assessment of traffic calming, except perhaps in hypothetical studies.

Trip characteristics

Brown (1993) suggested that, judging by observation, drivers exhibit more aggressive and competitive behaviour when commuting to work than when they are engaged on a leisure trip. In other words, drivers acquire a repertoire of behaviours specific to trip purpose and vehicle occupancy. It seems highly probable that drivers of commercial vehicles will acquire specific behaviours dictated by the conditions and objectives of their job.

For any journey, two criteria against which drivers might judge their speed are planned duration and perceived safety. It can be assumed that these two criteria are not independent and that drivers will, at various stages of a journey, compare actual time elapsed with planned time and may allow discrepancies to modify their decisions in relation to speed choice. If, for example, the planned trip duration was unrealistically short, then drivers might be motivated to drive at higher speeds than they would otherwise do (Fuller, 1993).

Brown (1993) found it difficult to believe that driver behaviour would not be influenced by the presence of family members in the vehicle, and in the study by Wasielewski (1984), the average speed of cars without passengers was found to be significantly higher than that of cars with accompanied drivers. However, Galin (1981) observed no speed effect due to passenger occupancy.

Driver speed will also be influenced considerably by the lighting conditions (day/night) and by the weather. Drivers usually respond to adverse weather conditions, such as rain, snow or fog, by reducing their speeds.

The problem of route choice on a trip can be defined as choosing the best route through the network in terms of some criterion or criteria, while facing temporal and geographical constraints. The best route is most often

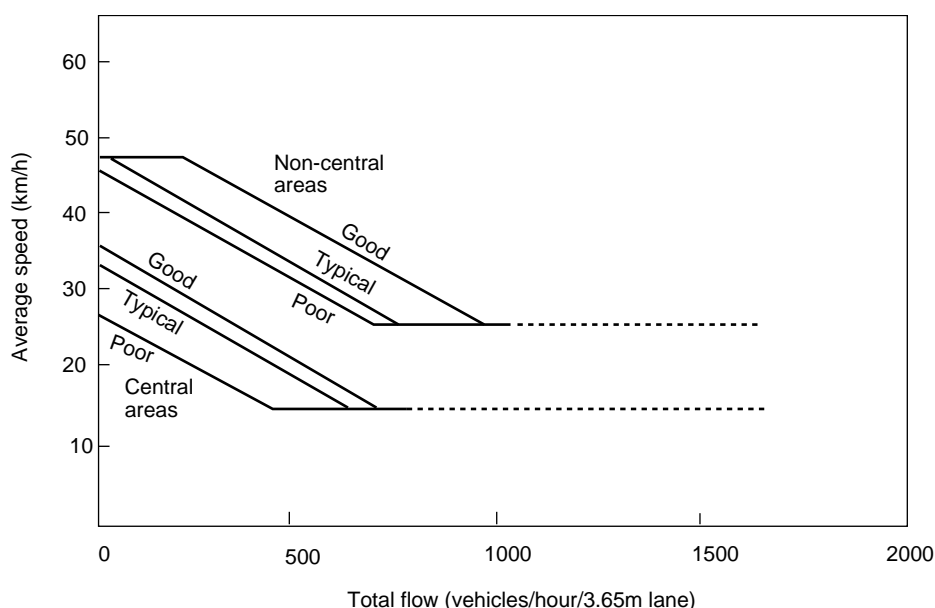


Figure 2 Typical urban speed/flow relationships (Highways agency *et al.*, 1996)

thought to be the one that minimizes travel disutility (e.g. travel time, distance, or general travel cost). In reality, the problem of route choice faced by a driver is complex because of the large number of possible alternative routes through the road network, and the complex patterns of overlap between the route choice alternatives (Abdel-Aty *et al.*, 1994).

3.1.2 Data on activity

In the context of the current Review, 'data on activity' relates to the type of data obtained from travel surveys and observation, such as the purpose and length of trips, the time elapsing between successive trips, the origin, the destination and the chosen route, all as a function of the time of day, month, season or year. For the specific purpose of determining the emissions associated with a particular scenario, it is also important to disaggregate this information in terms of the characteristics of vehicles that affect emissions, such as engine type and emission control technology.

There is obviously some overlap between this type of information and that described in the preceding section. However, where the previous Section was concerned with how the nature of a particular trip influenced the driver's choice of speed and driving style, and hence emission rate, data is also required to determine scaling factors that can then be used to determine the total emissions associated with a given scenario.

In the case of traffic calming, the type of data required to determine the impact of a given scheme on emissions include traffic composition and traffic flow rates, both along the calmed section and along potential diversionary routes before and after implementation of the scheme. It is likely that such data will be specific to a given scenario, and general observations of activity on regional and national scales are not particularly helpful.

3.2 Effects of traffic calming on driver behaviour

The engineering elements of a traffic calming scheme fall into two broad modes of function: those that physically restrain road users and prevent them from certain actions, and those that might be termed 'psychological', encouraging certain types of behaviour. It is possible for a single feature to combine both approaches. A road hump that looks severe, for example, may have an effect over and above that due to physical restraint. A single feature can also function differently for different road users; a flat-topped hump may act as a physical restraint on vehicle speeds along a carriageway whilst at the same time draw pedestrians to use it as an easy-to-negotiate crossing place (Transnet, 1992).

According to Devon County Council (1991), the immediate environment of urban roads needs to convey to the motorist that it would be wholly inappropriate and anti-social to drive at other than a low speed. For Pharoah and Russell (1989), measures or factors which create a direct and perceived risk or discomfort to the driver are those which are most effective in ensuring slow speeds. The same authors suggested, however, that there is a fear that very low speeds create driver frustration, and thus greater dangers, if they are required over long distances. Drivers

might be more likely to reduce their speed if schemes were more varied, and driver acceptance of, and compliance with, low speeds might depend not only on the physical measures themselves but also on the visual appearance of the street as a 'living area' rather than a 'traffic road'.

Some drivers may wish to avoid traffic calming schemes altogether. Drivers may completely change their route and consequently penetrate areas well away from the treated zone. In the view of Collins (1990), up to a certain individual 'acceptance threshold', a driver will tolerate and absorb the increased behavioural cost (an expression describing the disutility incurred by the driver) resulting from traffic calming. Above that threshold, other alternative options will be considered. Collins listed alternative options open to drivers wishing to avoid calmed areas. Drivers can, in theory, change their origin, destination or route. They can also change their mode of travel or combine their journey with another one. Finally, they can just not travel at all. Collins added that the ways in which these options are exercised are both individual and complex, and the greater the impedance that drivers encounter, the more radical are likely to be the reactions. Severe traffic calming may therefore reduce the volume of traffic using the calmed route. It was reported by Sumner and Baguley (1979) that the extent to which traffic flow is affected was related to the availability of alternative routes.

Although the interactions between the factors listed in Section 3.1 are complex, when combined they manifest themselves in the form of measurable values such as a speed profile, with associated gear selection and route choice, for a given vehicle along a particular section of road. Knowledge of this continuous driver behaviour, and changes in traffic flow and composition, is a fundamental requirement for accurately determining changes in vehicle emissions along the same stretch of road. However, although vehicle speeds at given points are one of the most frequently measured parameters in the assessment of traffic calming schemes, it is precisely this kind of continuous information that is not widely available. In the following Sections, analyses of the quantifiable aspects of traffic calming schemes have been reviewed. A problem with reporting on speed measurements associated with traffic calming is that authors do not always state where and how measurements have been made. Where each type of traffic calming measure has been reviewed, reference has been made mainly to studies in which this information has been recorded.

3.2.1 Vertical deflections

Road Humps: general

Road hump schemes have been the most successful way of reducing vehicle speeds in residential areas, and reductions in the frequency of accidents of up to 70% have been reported (Webster, 1993a). The effectiveness of road humps in achieving speed reductions is partly due to the fact that they can be designed to suit the type of road on which they are installed.

Fwa and Liaw (1992) have argued that, in order to achieve effective speed control, two aspects of hump

design must be addressed: geometric design and layout design. Hump geometric design refers to the shape and size of individual humps (height, gradient of on/off ramps); hump layout design refers to the determination of hump spacing and number of humps to be installed. However, besides hump geometry and spacing, the choice of speed is also affected by factors including vehicle operational characteristics, the personal characteristics of the driver and perceptions of discomfort.

In reference to road hump schemes, driver behaviour is normally assessed in terms of the speed of vehicles between the humps and the speed over the humps. According to Fwa and Liaw (1992), drivers will usually decelerate on the approach to a hump and accelerate after crossing the hump. Driver behaviour on calmed roads in Leicester was evaluated subjectively by Buxton and Newby (1995). Drivers were categorised in terms of their acceleration and braking at road humps. Driver reaction towards traffic calming varied on individual streets, but overall the results showed that 39% of drivers showed no real change in speed, 41% 'braked slightly', 18% 'braked fairly strongly' and 2% 'braked very strongly'. These observations indicate that the roads humps studied were associated with only slight acceleration and braking. In a Finnish study (Huttunen, 1995), the height of the road hump and the distance between road humps was found to influence deceleration and acceleration, although the mean rates were again comparatively low. Average decelerations were in the range 0.43 - 0.77 m/s² and acceleration values were 0.49 - 0.85 m/s².

Fwa and Liaw (1992) noted that the lowest speeds are found at hump locations and, in general, it may be said that lower hump-crossing speeds lead to lower speeds between the humps. The same conclusions were also reached by Barbosa (1995). For road humps in 20 mph zones, Webster and Mackie (1996) showed that the overall mean crossing speed was 13.2 mph (range 8 to 19 mph) and the mean speed between measures was 17.8 mph (range 14 to 23 mph). The average spacing of measures was approximately 85 metres.

De Wit and Slop (1984) observed that the effect of a traffic calming hump extends along a length of roughly 50 metres before to 60 metres after the hump at a maximum. So, when a more-or-less constant speed profile is wanted along a whole road section, the distance between humps must be somewhere between 40 and 60 metres.

In terms of achieving a 'calm' driving style, Pharoah and Russell (1989) suggested that the best results are obtained when the street can be driven at a fairly constant speed, without the driver experiencing any major discomfort, or having to make frequent use of gear shifts, brakes or steering. Hence, the maximum spacing of humps should be 50 metres, and a spacing of 30 metres or less was considered appropriate in order to prevent drivers speeding up in between. The authors argued that the use of severe-profile humps every 50 metres may produce slow average speeds, but the driving style and ambience of the street will rarely be described as 'calm'.

Round-top humps

For 100 mm high round-top humps installed at 30 locations, Webster (1993a) found that the mean crossing speeds for vehicles was 13.8 mph. In a study of 72 sites where 75 mm humps have been used, for those that were of a circular profile Webster and Layfield (1996) reported a mean crossing speed for vehicles of 14.7 mph. The authors also derived a relationship for estimating the mean speed between both 75 mm and 100 mm high humps based on hump spacing and the 'before' speed:

$$V = 6.6 + 0.058S + 0.31V_b$$

Where V = mean speed (mph) between 75 or 100 mm high humps

S = hump separation (m)

V_b = mean before speed (mph)

If, for example, a mean before speed (V_b) of 30 mph, and a hump spacing (S) of 85 metres are assumed, then the equation yields a mean speed between humps of 21 mph (equivalent to a reduction of 9 mph).

The crossing speeds for buses were found by Webster and Layfield (1996) to be approximately 5 mph lower than car crossing speeds for 75 mm high humps.

Flat-top humps

For flat-top humps, Webster (1993a) found that the mean crossing speed for vehicles was 13.0 mph for 80-100 mm high humps with on/off ramps of gradients 1:6 to 1:20. The corresponding mean speed for 70 - 80 mm high humps with ramp gradients of 1:10 to 1:15 has been shown to be 12.8 mph (Webster and Layfield 1996). As with round-top humps, Webster and Layfield also gave a combined (75 and 100 mm humps) relationship for flat-top humps:

$$V = 0.8 + 0.055S + 0.51V_b$$

Where V = mean speed (mph) between 75 mm (1:10 - 1:15) or 100 mm (1:8 - 1:10) high humps

S = hump separation (m)

V_b = mean before speed (mph)

Again, assuming a mean before speed of 30 mph and a spacing of 85 metres, the equation yields a mean speed between humps of 21 mph (a reduction of 9 mph).

The crossing speeds for buses were found by Webster and Layfield (1996) to be approximately 5 mph lower than car crossing speeds for 75 mm high humps.

For all the 100 mm high humps studied by Webster (1993a), the changes in traffic flow associated with the schemes varied between +13 and -59%, with the decreases being more prevalent.

Low humps (50 mm high)

Low humps, 50 mm high, do not reduce vehicle speeds to the same level as higher humps of 75 or 100 mm. Investigations at seven sites showed that the 85th percentile speeds were reduced from 41 mph to 31 mph. The speeds at the humps

were not measured, but subsequent observations indicated that there was very little acceleration or braking by the majority of vehicles, including buses (Webster, 1994).

Speed cushions

The investigation of the effects of speed cushions on driver behaviour is more complex than for conventional road humps. Firstly there is an increased number of layout options available, and secondly drivers may alter the path of their vehicle in order to negotiate the cushions in a way that they would probably not do to negotiate road humps.

In a study of speed cushions in Sheffield and York, Layfield (1994) assessed their effects on traffic speeds and flow. It was found that the mean 'before' speeds were reduced by 8 to 15 mph, resulting in 'after' speeds of 14 to 20 mph at the cushions. The overall cushion width was generally found to be a good determinant of mean speeds, with wider cushions resulting in lower speeds. Trials indicated that single-pair cushion layouts with cushions of height 75 mm, an on/off ramp gradient of 1:8, a side ramp gradient of 1:4, a platform width of around 1200-1300 mm, and an overall width of 1800-1900 mm will reduce overall mean speed at the cushions to around 14 mph. It was also shown that a similar layout, except using cushions with an overall width of around 1600 mm, will reduce mean speed at the cushions to around 19 mph. It was added that double-pair layouts generally reduce mean speeds to a level about 1 mph lower than the single-pair layouts. However, this small extra speed reduction is likely to be offset by increased parking problems, extra discomfort and increased cost. The mean speeds at three-abreast layouts were slightly higher (2 mph) than at the single-pair layouts in carriageway narrowings allowing two-way traffic on the same road.

An additional aspect of driver behaviour that concerns the study of speed cushions is that of straddling. Layfield (1994) also showed that half of the cars and most buses straddled the cushions centrally when unaffected by parking. The cushion crossing speeds for buses and cars were comparable for both narrow and wide cushions. Nottinghamshire County Council (1994) reported on the straddling of cushions by vehicles on Bagnall Road, Nottingham. The results are given in Table 2.

Table 2 Results of driver behaviour from Bagnall Road, Nottingham

For 1.6 metres wide cushions (3 abreast)	
Type of manoeuvre over cushion	% of drivers
Two wheels in left hand gutter	7%
Straddle left cushion	52%
Aim for gap between left and centre cushion	41%
For 1.88 metres wide cushions (2 abreast)	
Type of manoeuvre over cushion	% of drivers
Two wheels in left hand gutter	18%
Straddle left cushion	65%
Aim for gap between the 2 cushions	17%

Parry and Layfield (1997) studied 34 schemes involving the use of speed cushions. Cushions were found to be effective as a speed-reducing measure, although not quite as effective as road humps. The overall average mean and 85th percentile speeds at the cushions (17 and 22 mph respectively) were 2 to 7 mph higher than those measured at 75 mm high flat-top humps and round-top humps.

They investigated the relationship between speed at the cushions and cushion dimensions. Decreasing width, increasing length and shallower gradients resulted in higher speeds at the cushions. The relationship between mean vehicle speed at the cushions and cushion width is presented in Figure 3. It was argued that narrow (1600 mm) cushions may not provide sufficient speed reduction in 20 mph zones without additional measures. Mean speeds at 1600 mm wide cushions are likely to be about 19.5 mph, while 1900 mm cushions would give mean speeds of about 15 mph.

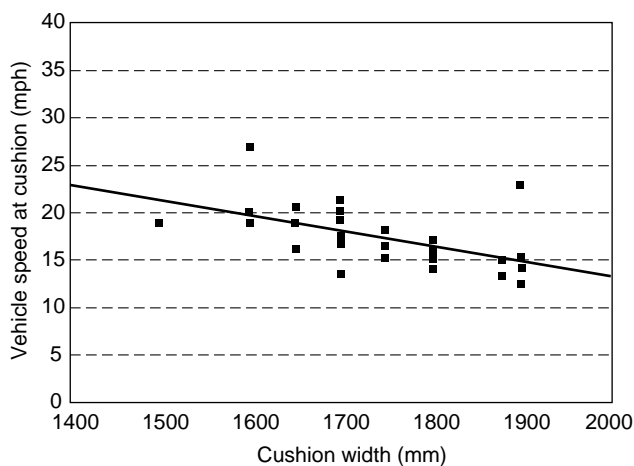


Figure 3 Mean vehicle speed at cushions (Parry and Layfield, 1997)

Spacing between the cushions varied between 50 and 125 metres with an average of about 75 metres. The overall average mean and 85th percentile speeds midway between the cushions (22 and 26 mph respectively) were 1 to 2 mph higher than those measured between 75 mm high humps spaced on average at about 85 metres.

The relationship between speed midway between the cushions and cushion spacing was also investigated. Figure 4 shows that, at a spacing of 60 metres, a mean speed of about 20 mph may be expected. Increasing the spacing from 60 to 100 metres, increases mean speed by about 5 mph.

Vehicle flows were found to have decreased on roads with speed cushions, with reductions in flow varying between 13 to 48 per cent. The overall average reduction in flow was 25 per cent, a reduction in flow similar to the overall average reduction found on roads with 75 mm high humps.

Video observations of driver behaviour at some of the sites indicated that when the approach and exit from a cushion layout was unaffected by parking, about 55 per cent of cars and 90 per cent of buses were found to straddle the cushions centrally, or approximately centrally. In the paired cushion layouts, nearly 20 per cent of the

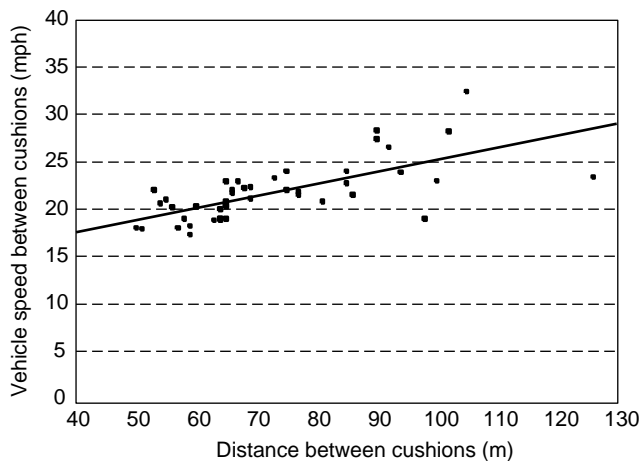


Figure 4 Mean vehicle speeds between cushions (Parry and Layfield, 1997)

drivers drove in the middle of the road between the cushions. In the three-abreast layouts, about 40 per cent of the drivers drove between the nearside and the middle cushions. At some cushion layouts with relatively wide central gaps between cushions, motorists have tended to drive through the gap rather than over the cushions, resulting in complaints and collisions. Gap sizes have subsequently been reduced. In general, this problem is likely to develop at sites with central gaps between cushions greater than 1200 mm.

Parked vehicles can prevent cars from straddling the cushions centrally, and will therefore increase the discomfort for drivers and passengers. When cushion layouts were combined with carriageway narrowings, the parked vehicles had less effect on vehicles approaching the cushions. Most cyclists and motor cyclists avoided the cushions and used the gaps between the cushions and the kerb. When these were obstructed by parked vehicles, cyclists and motor cyclists generally moved to the centre of the road and avoided riding over the cushions.

Thermoplastic humps ('thumps')

The effects of thermoplastic humps ('thumps') were reported by Webster (1994). The results showed that 85th percentile speeds between the thumps were reduced on average from 37 to 28 mph. On Ash Grove in South Elmsall, where the thumps were spaced at 75 metre intervals, the 85th percentile speeds at the measures were 27.6 mph (compared with 28.8 mph in between). This indicated that there was very little acceleration or braking by the vehicles. The reported changes in 85th percentile speed between thumps and traffic flow are given in Table 3.

Rumble devices

Webster and Layfield (1993) observed that after the introduction of rumble devices, average 85th percentile speeds were reduced by around 3 mph (corresponding to a 6% reduction). However, evidence was found to show that the initial speed reduction diminished with time, and it was also suggested that faster drivers may maintain or increase their speed at some sites to lessen the effect of the devices.

Table 3 Summary of 85th percentile speeds between measures and flows in 'thump' schemes (Adapted from Webster (1994))

Location	85th percentile Speed (mph)		Thump spacing (m)	Thump Height (mm)	Traffic flow change
	Before	After			
Wakefield	39	28	45	37	23% reduction
South Elmsall	34	28	75	37	23% reduction
Bradford	42	29	63	42	Not reported
Golcar	32	25	50	35	No change
Gateshead	35	25	40	57	6% increase
Solihull	40	35	60	36	Not reported

3.2.2 Horizontal deflections

Hill (1996) suggested that horizontal deflections reduce the temptation for high speed on long sections of residential road. According to Devon County Council (1991), speed reductions are achieved in two ways: by enforcing turns and introducing lateral shifts in the carriageway which limit the driver's forward view and help to concentrate the driver's attention on the road immediately ahead. Lateral shifts for this purpose do not need to be severe, although sufficiently severe to enforce the physical turn or to limit the forward view, otherwise the speed reduction may be minor.

In two-way streets, the provision of sufficient carriageway width at lateral shifts to enable vehicles to pass allows drivers to take a 'racing line' and thus negates the speed reducing effect. This problem applies particularly when traffic flows are below about 100 vehicles per hour, or when the traffic is predominantly in one direction (Devon County Council, 1991).

Horizontal deflections are generally less effective than vertical ones in achieving reductions in speed. However, their effectiveness has been seen to increase when used in combination with vertical deflections.

Chicanes: general

According to Pharoah and Russell (1989), the effectiveness of chicanes in reducing vehicle speeds depends on the particular design, and chicanes are much more susceptible to design failure than vertical deflections. Hass-Klau *et al.* (1992) found that chicanes created by semi-circular pavement extensions were less effective than those built in square forms. Additionally, if the road is not narrowed down severely, semi-circular chicanes may even have a speed-increasing effect, not only because they create a race-track appearance but also because they encourage race-track behaviour in some motorists.

Off-road trials of chicanes were conducted on the TRL test track by Sayer and Parry (1994). The trials simulated the likely speed reduction for unopposed traffic using a single lane approach to a chicane. The trials showed that different variables (e.g stagger length, free view width, lane width and visual restriction) can all be used to a varying extent to control vehicle speeds.

A second study by Sayer and Parry (1996) of 49 schemes on public roads showed that chicanes gave

accident reductions of 41%. The number of accidents was small and therefore this accident reduction value is only a guide. Speed measurements were also performed at 10 single-lane-working and 6 two-way-working chicane schemes. An overall average reduction of approximately 12 mph was recorded at the chicanes in both mean and 85th percentile speeds. Mean and 85th percentile speeds through the chicanes were reduced to an overall average of about 23 mph and 28 mph respectively.

This overall average mean speed through the chicanes (23 mph) was substantially higher than the average speeds that have been recorded over road humps. Webster and Layfield (1996) found the overall average mean speed over 75 mm high flat-top and round-top humps to be 13 mph and 15 mph respectively. However, it should be noted that the chicanes were installed on roads with vehicles being driven at higher speeds; the mean 'before' speeds on the roads where chicanes were installed were about 7 mph higher, on average, than on the roads where the 75 mm high humps were installed.

The overall average mean and 85th percentile 'after' speeds at the two way working chicanes were about 5 mph higher than those at the single lane working chicanes. Some of this difference may be due to differences in chicane dimensions, but some may also be due to the generally higher 'before' speeds (about 3 mph on average) at the two-way-working sites.

Chicanes: single lane working

In Finnish schemes containing chicanes with only one lane working, Huttunen (1995) reported that the average speed was 34.1 km/h when the speed limit was 30 km/h and the narrowing was on the driver's side. When the narrowing was on the other side of the carriageway the mean speed was reported to be 38.1 km/h. Narrowings were only found to have reduced speeds in situations where vehicles met one another.

Broadbent and Salmon (1993) devised a chicane system which consisted of a series of build-outs on alternate sides of the road. These build-outs resulted in average 'free-flow' traffic speeds of 28 mph and average 'non-free-flow' speeds of 18 mph, which can be compared with the mean 'before' speed of 33 mph. These results clearly showed that opposing flow is required to reduce speeds to any great extent using build-outs/chicanes (the flow was reduced from 3,000 to 2,700 vehicles/day). There appeared to be a slight increase in average 'free flow' speeds with time, but it had reached an equilibrium level by about 8 weeks.

Chicanes: two-way working

Huttunen (1995) revealed that for Finnish schemes containing chicanes with both lanes working, the average speed was 50.4 km/h with a speed limit of 40 km/h, and 42.5 km/h when the speed limit was 30 km/h.

At Cromer, mean vehicle speeds were found to be reduced by 8-11 mph from 38 mph (Mayhew, 1995). Studies of driver behaviour through the chicanes showed that half of the vehicles avoided the overrun areas, 32% used the inner overrun area and 4% used both overrun areas.

Pinch points

Hass-Klau *et al.* (1992) have asserted that pinch points leaving a total carriageway width of around 4.6 metres or more have hardly any speed-reducing effect, because two vehicles can pass each other. Giving priority to one direction of travel tends to have the effect that only the speed of vehicles in the other direction is reduced. Davies *et al.* (1997) observed that, at pinch points, drivers were more likely to wait behind cyclists, probably due to the threat of oncoming traffic.

Road narrowings

In 1989 Pharoah and Russell noted that the speed-reducing effects of narrow carriageways and driving lanes have not been precisely determined, and the situation has not changed substantially since then. Some inferences might be made from known relationships between vehicle speeds and street width. Hass-Klau *et al.* (1992) stated that reducing the carriageway width by marking hatched areas along the sides or in the middle of the carriageway has almost no influence on vehicle speeds. Physical width restrictions can be more effective in reducing speeds, but there seems to be a noticeable effect only when lanes are reduced below 3 metres. Amundsen (1984) described a road narrowing device at one site in Norway, where the average speed of traffic was reduced from 33 km/h to 30.8 km/h.

Central islands

Hass-Klau *et al.* (1992) argued that central islands have a limited effect on reducing speeds, and their effectiveness depends on their combination with other, more restrictive, measures.

3.2.3 Other devices

Roundabouts

In the Swedish city of Växjö a research project aiming at the development and testing of a traffic safety programme has been running since 1986 (Hydén *et al.*, 1995). One aspect of the programme was aimed at reducing speeds on arterial roads. Twenty-one intersections were provided with mini-roundabouts, eleven intersections were provided with give-way signs from all approaches, and the speed limit was reduced to 30 km/h. It was found that speeds at roundabouts and intersections were reduced from 48.7 km/h to 30.4 km/h (a reduction of 18.3 km/h), and from 46.8 km/h to 35.8 km/h (a reduction of 11.0 km/h) respectively. The greater the extent to which drivers were forced to change their paths at roundabouts, the lower the recorded speeds. Variation in speed was also reduced.

The average speed on links between intersections decreased on average from 53 to 45 km/h. Again, the speed variation was also reduced. It was also shown that the magnitude of the speed reduction between intersections was dependent upon the distance of separation, with the speed reducing effect diminishing with increasing separation. When the distance between roundabouts was around 150 metres or more, the speed reduction effect almost ceased. Speeds in the 30 km/h zone decreased from 35.8 km/h to 34.1 km/h (1.7 km/h reduction).

Changes in road surface

Changes in road surface, whether they are changes in material or colour, are not used alone for reducing speeds but are usually employed in combination with other measures. They can reduce the speeds of vehicles where drivers are unfamiliar with the area. Hass-Klau *et al.* (1992) found that the speed-reducing effects of hatched road markings were negligible.

Gateways

During 1992, gateway schemes were implemented on the approaches to ten villages or small towns in Devon, and eight villages in Gloucestershire. A study by the Transport Research Laboratory involved measurement of the changes in mean speeds associated with the gateways (Wheeler *et al.*, 1993). The study concluded that gateways can be a useful device for reducing speed by a limited amount in certain circumstances (speed reductions of up to 8 mph were recorded).

TRL has carried out further monitoring of the effects of traffic calming on major roads, and this work has yielded more information on the effects of gateways.

At the village of Craven Arms on the A49 trunk road in Shropshire, a variety of traffic calming measures were installed. On each main road approach to the village, countdown signs and 'dragon teeth' were introduced in advance of gateway features. The gateways comprised 30 mph speed limit signs mounted above large village nameplates on each side of the carriageway, together with an area of bright red surfacing and a painted '30' roundel. In the village itself, red surfacing, mini-roundabouts and speed cushions were also installed. Mean and 85th percentile speeds at the gateways fell by 8-9 mph, although the 85th percentile speeds were still up to 10 mph above the speed limit. Once through the gateways, lower speeds than before scheme installation were maintained on the approach to the centre of the village by the other traffic calming measures. It was not known which of the measures employed on the approach to, and at, the gateways contributed most to the speed-reducing effect (Wheeler *et al.*, 1996).

When Wheeler *et al.* (1997) measured vehicle speeds before and after the introduction of gateways on the A47 on the approaches to the village of Thorney, the mean and 85th percentile values were seen to have been reduced by 8-9 mph at the gateways. The gateways featured prominent signing, contrasting surface treatment and slight carriageway narrowing. Signs warning of traffic calming ahead were placed in advance of the gateways, and chicanes were introduced a short distance beyond each gateway. Again, it was not known which of the measures employed on the approach to, and at, the gateways contributed most to the speed-reducing effect.

3.2.4 Speed limit enforcement

Winnett (1994) provided evidence suggesting that the effects of speed cameras on vehicle speed are likely to be local to the camera. The author observed a decrease in mean speeds of around 3 mph.

4 Vehicle emissions

In order to determine the impact of traffic calming schemes on exhaust emissions, it is important to understand the complex relationships between traffic characteristics, vehicle operation and rates of emission. This Chapter deals briefly with the factors affecting emission rates from individual vehicles.

It has been generally observed that the exhaust emissions produced by a particular vehicle depend on a large number of factors. Abbott *et al.* (1995) divided these factors into two broad categories:

- technical factors relating to the design and engineering of the vehicle: its weight, engine type, exhaust after-treatment, aerodynamic properties etc.
- operational factors relating to the way in which the vehicle is used: its speed, rate of acceleration, maintainance, road gradient etc.

Of these two groups, the factors most likely to be influenced by traffic calming schemes are those relating to vehicle operation (e.g. speed, acceleration). To create changes in these parameters is, after all, the primary objective of traffic calming. Consequently, more attention is paid to this aspect in the current Review. Technical factors affecting vehicle emissions are only summarised, since traffic calming does not usually influence these (unless it leads to the exclusion of certain vehicle types).

4.1 Technical factors

The emissions that a vehicle produces are influenced, to an extent, by all aspects of its design and construction. The fundamental differences between vehicles are very significant in accounting for variations of their emission rates (Abbott *et al.*, 1995). Some of the technical factors that are known to affect vehicle emissions are listed in Table 4.

Table 4 Some technical factors affecting vehicle emissions

<i>Factor</i>	<i>Example options</i>
Engine design	Spark ignition/compression ignition
Fuel type/composition	Petrol/diesel/alternative fuels
Transmission	Automatic/manual
Engine management	Electronic ignition/mechanical timing
Exhaust after-treatment	Oxidation or three-way catalyst/particulate trap/no controls
Maintainance level	
Other characteristics	Aerodynamics/size/weight/age

It was noted by Abbott *et al.* (1995) that there may also be effects from items that are not listed above. Either these effects are relatively small, or there are insufficient data to quantify them. An example of this type would be the material from which an engine is constructed: steel and aluminium have different thermal properties which will influence the combustion of fuel and therefore the formation of pollutants.

4.2 Operational factors

According to Abbott *et al.* (1995), a single vehicle of a particular type will display wide variations in emissions depending on the way it is being used. Much of the information relating to the importance of operational factors on emission rates has been obtained from studies geared to finding improved ways for modelling emissions (e.g. Jost *et al.*, 1992). The effects of some operational factors are better known than others; most of the existing work has related to the speed-dependence of emissions and, more recently, the influence of acceleration. There is also some information relating to gear selection and the effects of road gradient and altitude (e.g. Potter and Savage, 1982).

4.2.1 Average speed

The most common way of representing vehicle emission rates has been as a function of average speed, and Joumard *et al.* (1995) pointed out that, for passenger cars at least, the characteristic variation of emissions with speed is well known. The average speed is determined from the time taken, including stops, to cover a drive cycle of a given length. Typical average speed/emission curves for CO, HC and NO_x are shown in Figure 5. The presentation of emissions data in this way became customary during the early 1980s (Abbott *et al.*, 1995).

The highest emissions of CO and HC are associated with low average speeds. Abbott *et al.* (1995) explained that low speed journeys are typified by frequent stops and starts, accelerations, and decelerations in response to traffic congestion or other disruptions to a vehicle's progress, and those operations are inefficient in fuel usage, fuel combustion and the operation of emission control systems. As the average speed increases, the operation of the vehicle becomes more efficient, so less fuel is used and less pollutant emissions are produced. At high speeds, there is a tendency for emissions to increase again because the operation of an engine to deliver the power needed to travel at high speeds is not the optimum in terms of fuel consumption and pollutant formation. Oxides of nitrogen display rather different behaviour. They are created by the combination of nitrogen and oxygen in the air and fuel mixture delivered to the engine, and their rate of formation is governed largely by the peak temperatures reached during combustion. Because temperatures are highest when an engine operates under high speed and load conditions, NO_x emission rates are highest at high average vehicle speeds.

Some studies (e.g. Jensen, 1995) have shown that the average vehicle speed over a given stretch of road is a dominant factor in determining emissions. However, considering the emission rates as a function of average speed, Joumard *et al.* (1995) noted that there can be significantly different emission results for cycles with approximately the same average speed. The way in which a particular average speed is achieved is also of importance in determining the emission performance of the vehicle.

Driver behaviour at traffic calming schemes has usually been represented by mean traffic speeds. However, it is obvious that there are substantial problems involved in

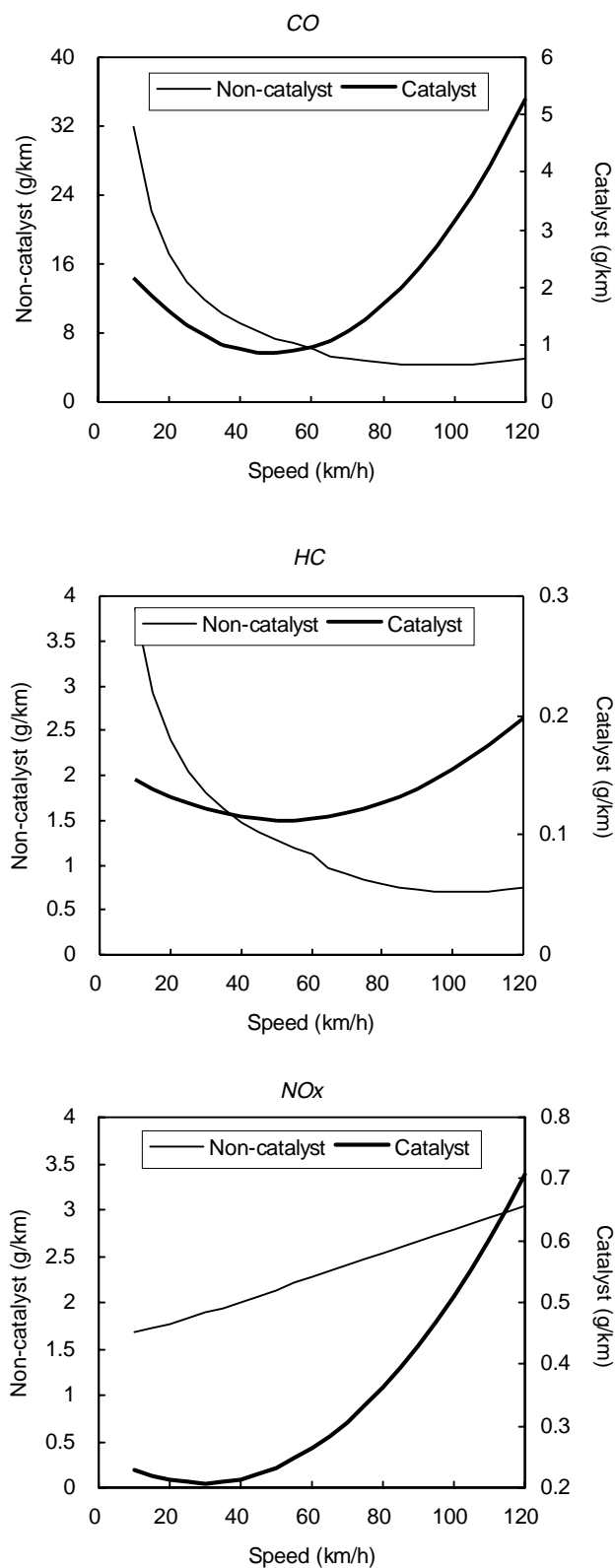


Figure 5 Average speed-dependent emissions of CO, HC and NO_x from non-catalyst and catalyst petrol cars (note different scales) (Eggleston *et al.*, 1993)

using average speed/emission relationships to establish the impact of traffic calming schemes on emissions. Before speeds and after speeds often conform to significantly different operational regimes. Although schemes are usually successful in reducing vehicle speeds, calming often appears to have had the additional effect of increasing speed variation.

For example, Hansen *et al.* (1995) noted that as the flow of traffic becomes limited by either traffic regulation or congestion, it is expected that the variability of the traffic speed will increase as the number of accelerations and decelerations increases. When both the average speed and the standard deviation of speed for a trip along a given road were normalised for the rated speed of the road, the authors observed a clear trend of increasing speed deviation as the average trip speed decreased.

There are, however, limitations in applying average speed emission factors to measurements of driver behaviour (Hickman *et al.*, 1997). For emission tests, the average speed is almost invariably the overall mean speed of the vehicle for the complete test. However, surveys of traffic speeds are often made at individual locations on the road network, and then the average speed represents not that of a vehicle during a journey, but the average of all vehicles at one point of their journeys. Depending on the location of the observation the two could be quite different.

4.2.2 Average speed and speed variation

Joumard *et al.* (1995) suggested that an improved representation of exhaust emissions would result if variations in operating conditions were also taken into account. Hickman *et al.* (1997) showed that the description of a trip in terms of its basic driving modes (e.g. acceleration, deceleration, cruising and idling) could be used to calculate overall emissions as the sum of those produced when driving in each mode.

In their study described above, Hansen *et al.* (1995) also considered the relationship between statistical descriptors of driving patterns and emissions. The authors measured emissions from a number of passenger cars using drive cycles selected to represent a wide range of average trip speed and speed variation. The parameter chosen to represent speed variation was the standard deviation of the instantaneous driving speed over the entire driving cycle. Average trip speeds ranged between 10 and 90 km/h, and speed deviations from 0-20 km/h.

The results for both catalyst and non-catalyst petrol cars showed similar trends. For CO and HC the average trip speed was seen to be the most significant factor, though at the lowest and highest speeds emissions increased with increasing speed deviation. Speed deviation had little effect at the intermediate speeds. For HC emissions the effect of speed deviation was generally smaller than for CO. For NO_x the lowest emissions were observed at the lowest speeds and lowest deviations, while the highest emissions were found for cycles with lowest speeds and highest variations. In general it was noted that for CO and HC, trip speed was the more dominant factor in determining emissions, with deviation playing a lesser role. In the case of NO_x, the relative effects of speed and deviation were more equal.

4.2.3 Instantaneous speed and acceleration

According to Joumard *et al.* (1995), the acceleration rate of a vehicle is a direct measure of the variation in speed, and is therefore an important parameter to consider. However,

the operation of a vehicle's engine necessary to achieve a certain rate of acceleration also depends on the vehicle's speed. For a given engine input, a slow moving vehicle will accelerate at a considerably higher rate than a fast moving vehicle. A better indication of the demand on the engine, which ultimately determines the rate of emission, is given by the product of the vehicle speed and acceleration, as instantaneous parameters. If the emissions and fuel consumption recorded at one second intervals can be successfully related to the corresponding driving and operating conditions (through detailed modal analysis), then it is possible to present emissions and fuel consumption as a function of the instantaneous speed and the acceleration in order to characterise driver behaviour (Jost *et al.*, 1992). Examples of instantaneous emissions are presented in Figure 6.

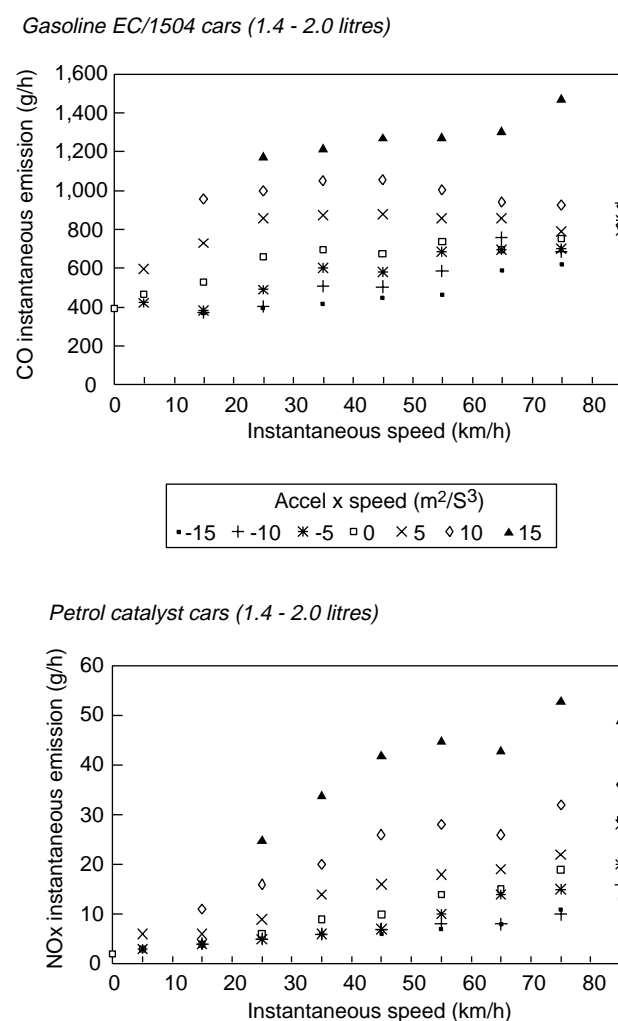


Figure 6 Examples of instantaneous emissions of CO from non-catalyst (EC/1504) and NO_x from catalyst petrol cars as a function of speed and speed x acceleration (Joumard *et al.*, 1995)

4.2.4 Other operational parameters

Gear selection

The speed of the engine in relation to the speed of the vehicle is determined by the gear selected. As the speed of the engine affects the rate of fuel consumption, gear selection is therefore an important factor determining emission rates.

Pearce and Davies (1990) performed constant-speed emission tests on passenger cars. The vehicle sample comprised just one catalyst and one non-catalyst petrol car, but the study did provide a little information on the effect of gear selection on emissions. Some of the tests were carried out with the car in fifth gear (at speeds of 60, 80 and 100 km/h) and some in third gear (at speeds of 30, 50 and 70 km/h). The results of the study suggest that for a given speed in the 50-70 km/h range, emission rates do not differ greatly if either third gear or fifth gear is selected. Potter and Savage (1982) found that on-road CO emission rates at steady-state speeds varied with speed and selected gear, but did not follow a consistent pattern.

Gradient

The power required to propel any vehicle at a given speed will increase or decrease according to the inclination of the road on which it is travelling. During on-road driving, it was observed by Potter and Savage (1982) that hill ascents produced consistently high NO_x emission rates, whilst descents resulted in low NO_x emissions. However, it was noted by Hassel (1996) that it cannot be assumed that the extra emission when travelling uphill is fully compensated by a corresponding reduction in emissions when travelling downhill. The author noted that methods have been developed for the calculation of emission factors for different gradient classes. Hassel described the calculation of gradient factors that reflected the change in emissions along roads with a range of gradients compared to the case of a flat road. The effects of gradient are greatest for heavy-duty vehicles, although Hickman *et al.* (1997) suggested that road gradient could be an important factor governing emissions from catalyst cars if the necessary performance of the engine is outside the range for which the engine management system is optimised.

Cold starting

The operational effects mentioned so far have all related to 'hot' engines working at around 80-90°C. Before an engine warms up, emissions of exhaust pollutants, particularly CO and HC, are elevated considerably. The extent of the increase depends on a number of factors including the engine temperature at the onset of a trip, the trip length and the ambient temperature, and also varies greatly from vehicle to vehicle (Boulter, 1997). Cold starts pose a particular problem in the assessment of emission changes associated with traffic calming since, in the residential areas where calming is employed, car engines will frequently be running cold. At present there is little information relating to the impact of detailed vehicle operation on cold start emissions, and it is therefore unclear how such emissions are affected by traffic calming.

5 Traffic calming schemes and vehicle emissions: case studies

5.1 Background

Where traffic calming schemes have been implemented in the UK, the main objectives have almost always been to reduce the speed of traffic in order to reduce the frequency of accidents. When judged by the criteria of speed reduction and accident reduction, many schemes have been successful. For example, from their survey of 35 traffic calming schemes in Britain, Hass-Klau *et al.* (1992) calculated that the schemes resulted in a typical speed reduction of around 10 mph.

The other aims of traffic calming, including the freeing of road space for non-traffic activities, removal of extraneous traffic, and encouragement of motorists to drive 'calmly', have often been viewed as secondary. The experience of Bicknell (1993) indicates that for schemes where the secondary objectives have received attention, local conditions have tended to determine which objectives have been afforded priority. Only recently have engineers used the environmental impact of traffic as a criterion in the design of traffic control methods, and the 'environmentally improved conditions' desired by Pharoah and Russell (1989) have often been compromised as a result of budgetary restrictions.

There is a lack of information on certain effects of traffic calming schemes. One example is the impact of schemes on vehicle emissions. This has not, however, prevented authors from airing their views on the subject.

Many have remained optimistic about the potential benefits of traffic calming in terms of general environmental improvement and in relation to vehicle emissions:

'Traffic calming techniques...can directly improve the safety and environmental quality of streets in built-up areas and, in combination with other policies, can help to limit the growth of traffic and promote the use of alternative means of travel with the associated environmental benefits.' (Devon County Council, 1991)

'Sufficient experience exists that demonstrates that (traffic calming) techniques are available to...improve the environment.' (Bicknell, 1993)

'Traffic calming measures may have significant effects in noise and air pollution reduction.' (Velasco, 1996)

'...environmental characteristics are enhanced by lowering the noise and vehicle emissions.' (Craus *et al.*, 1993)

'The benefits of reducing the speed and dominance of traffic include...reducing noise and air pollution...' (Durkin and Pheby, 1992)

'Redesigning streets...creates opportunities to make streets more attractive and 'liveable'. Noise and exhaust pollution can also be reduced if (traffic calming is) carried out on an area-wide basis.' (Stonham, 1992).

However, these claims probably rely to some extent on the removal of extraneous traffic. Suggestions that traffic calming can lead to environmental improvement can appear to be at odds with the findings of surveys of residents. For example, Bulpitt (1995) found that although schemes in Kent were reducing both speeds and accidents, opinion surveys showed that many residents considered that the reductions were achieved at some cost to their local environment in terms of increased air pollution.

There has been some debate about the impact of the reduced speeds associated with traffic calming on emissions from individual vehicles. On the one hand there has been a degree of awareness that the changes in driver behaviour following the implementation of a traffic calming scheme might well increase emissions:

'One of the problems with the use of physical traffic calming measures is that speeds are reduced to a low level at the traffic calming measure but rise on the stretch of road between measures. This uneven speed profile may result in increased fuel consumption and vehicle emissions but one would also need to take into account any absolute changes in speed, traffic volume and composition when calculating the net effect. The interactions between the changes can be complex and all of them need to be taken into account when calculating the net effect' (Abbott et al., 1995).

Alternatively, Döldissen (1990) has argued that reductions in emissions could be achieved if traffic calming resulted in smoother driving - driving with less variation of speed - at lower engine speeds, although she recognised that this principle would not hold under congested traffic conditions, where acceleration, deceleration and idling are more common. However, congestion is not generally a problem associated with traffic calming schemes, since schemes tend to be located in areas where traffic flow is comparatively low.

The idea of a smooth traffic flow espoused by Döldissen is a common theme included in strategies to reduce the environmental impact of traffic. Döldissen believed that this idea should be used to influence the placement of new traffic calming elements, in that elements should not be placed so far apart that the result is high speeds between measures followed by abrupt braking.

Since the effects of traffic calming on vehicle emissions have not been studied in great detail, any claims appear to be somewhat premature and speculative. There has not yet been a detailed study of the effects of traffic calming on vehicle emissions and/or air pollution. The variation in driver behaviour that tends to be associated with traffic calming is one factor contributing to the uncertainty surrounding the effects of schemes on emissions.

Pharoah and Russell (1989) commented that the results of general evaluation studies are valuable to those implementing traffic calming measures, but there is a need for careful interpretation. The effects of individual measures (such as a speed hump or a chicane) cannot easily be evaluated in isolation from the scheme in which

they are embedded. Traffic calming devices are not usually implemented in isolation, that is to say, it is not so common to see one particular device (e.g. a road hump) being repeated over a long section of road. Indeed, the use of a variety of measures is often seen as a positive step.

Pharoah and Russell noted that the particular combination of measures in a street has a powerful influence on the behaviour of drivers and others. Thus an individual measure may be ineffective or have a different effect when implemented in isolation, but be both popular and effective when used in conjunction with other measures. In addition, intervention in one street may affect conditions in neighbouring street, especially if traffic is diverted. Consequently, most general evaluations have been carried out for whole areas, including surrounding roads. This helps to spot any migration problems.

5.2 Case studies

The remainder of this Section is dedicated to the existing studies of the changes in vehicle emissions associated with traffic calming schemes incorporating physical engineering measures. Some of these studies relate to the changes in emissions associated with area-wide schemes, whilst others relate to single sections of road. The studies included here have been categorised according to the country of origin. A summary of the results is provided at the end of the Chapter.

5.2.1 Results by country of origin

Germany

In a series of Federal demonstration projects during the 1980s, area-wide traffic calming using 30 km/h zones, including physical traffic calming measures, was carried out on an experimental basis in the large cities of Berlin and Mainz and in the medium-size cities of Ingolstadt, Esslingen and Buxtehude. The effects of the schemes on vehicle emissions were evaluated, but only the results of the Buxtehude study were reported extensively.

Buxtehude is a medium-sized town (population 30,000) lying 35 km west of Hamburg. The northern half of the town was chosen for area-wide traffic calming. The scheme has been widely acclaimed as achieving all-round benefits at reasonable cost. The studies of the scheme have shown that the nature of the speed reduction measures, and the styles of driving which they generate, are important factors in determining the impact on emissions.

The area-wide scheme was implemented in two stages. In October 1983 the first stage was implemented at low cost. This included a change of speed limit from 50 km/h ('Tempo 50') to 30 km/h ('Tempo 30'), a change of priority rule at junctions and some narrowing of carriageways using temporary objects. Stage 2 involved more permanent measures to create a self-enforcing speed limit of 30 km/h. This included the provision of new surfaces and lighting at all entrances, footpath and cycle crossings at important junctions, carriageway narrowing, re-designed on-street parking, road width restrictions, road humps, gateways etc. This work was completed in November 1986. A planned third stage to exclude through

traffic by road closures and barriers turned out to be unnecessary. The 'after' study of the environmental effects of the second phase was performed in October 1987 (Holzmann, 1988).

As part of the investigation, vehicle emissions were assessed at the 'before' and 'interim' stages. Using a floating vehicle to reflect the local driving style, test journeys were made over 6 routes (each 1-2 km long) within the scheme. The speeds, gear selection and fuel consumption were recorded, and the routes were later reproduced on a dynamometer. Emissions were measured from seven test vehicles. The results indicated that the scheme had led to reductions in NO_x, CO and HC emissions of around 30%, 20% and 10% respectively, but an increase in fuel consumption of around 5% (Holzmann, 1988). According to Pharoah and Russell (1989), however, these improvements relate mainly to the residential streets which carried only 20-30% of total traffic and were therefore unlikely to have had a major effect on air pollution problems on the regional scale.

Holzmann also showed that if drivers were encouraged to adopt a 'calmer' driving style, further improvements could be achieved. The 'calm' driving style was also simulated on the dynamometer. This calm style implied earlier changing up of gear, always using the highest possible gear (i.e. driving at low rpm). Under these test conditions, reductions in emissions of NO_x, CO and HC were observed to be 50%, 25% and 25% respectively, and fuel consumption was seen to have been reduced by 10%. It was noted that these results contradicted the often-repeated assumption that slowing down traffic can be expected to result in a general worsening of emissions. The Buxtehude study is therefore regularly cited as an example of a situation in which a traffic calming scheme has been shown to be beneficial in terms of vehicle emissions. The results formed the basis of Döldissen's argument (Section 5.1).

The results from the other demonstration projects have not been as widely reported. In Esslingen, where only three small 30 km/h zones were established, the measurement of emissions was carried out over short distances only. The results indicated a significant decrease in NO_x and a significant increase in CO. In Mainz the 30 km/h zone incorporated single intensive, though infrequent, traffic calming measures. This led to local speed reductions and an uneven driving pattern, although reductions in NO_x emissions (-5 to -22%) were recorded. The effects on emissions of HC and CO (HC, +1 to -23%; CO, +28 to -16%) were less clear. In Berlin, where extensive traffic calming resulted in low vehicle speeds, emissions of NO_x and HC were found to have reduced significantly. Emissions of CO and fuel consumption were seen to increase (German Federal Ministries of Planning, Transport and Environment, 1992).

Overall, the emission results were variable, with consistent decreases in NO_x, but with increases and decreases in HC, CO and CO₂ emissions and fuel consumption. The variation reflected the local differences in type and extent of physical traffic calming measures that were used to control speed (German Federal Ministries of Planning, Transport and Environment, 1992).

United Kingdom

Webster (1993b) constructed speed profiles for hypothetical traffic calming schemes which had either round-top or flat-top road humps placed at 50, 75 and 100 metre intervals over a 300 metre stretch of road. The 'sawtooth' profiles were based on the relationships between speed and hump separation derived from extensive experimental data on speeds at, and between, humps obtained from a large number of schemes. It was assumed that vehicles accelerated for 67%, and decelerated for 33%, of the distance between the humps.

Webster used emission data relating to instantaneous speed and acceleration (from Jost *et al.*, 1992) to calculate the passenger car emissions associated with these speed profiles. Emissions of CO, HC, NO_x and CO₂ were obtained for petrol non-catalyst cars of two engine sizes. Values were also obtained for steady speed emissions of 20, 25 and 30 mph over the same stretch of road. The aim of this was to give an impression of the emissions before calming.

Schemes with a 75 metre hump spacing (and with associated average speeds of around 15-17 mph), were compared to the situation before calming (i.e. a constant speed of 30 mph). The calculated emissions for schemes with flat-top humps and circular profile humps were found to be similar for each engine size.

Petrol non-catalyst cars showed increases in CO and HC of around 70-80% and 70-100% respectively, and an increase in CO₂ of around 50-60%. NO_x emissions were predicted to be around 0-20% lower after calming. For a constant speed of 25 mph before calming, the increases in CO, HC and CO₂ were predicted to be lower, and NO_x emissions were calculated to be reduced by about a further 20%.

In order to examine the effect of 'smoother' driving after the installation of humps, Webster also calculated the change in emissions associated with moving from a constant speed of 30 mph to a constant speed of 20 mph. CO and HC were now predicted to increase by around 40-80%, and CO₂ increased by 30-40%. Predicted emissions of NO_x, however, were also seen to increase by around 20-30%.

Sweden 1

A Swedish research project aiming at the development and testing of a traffic safety programme has been running since 1986 (Hydén *et al.*, 1995). One aspect of the programme was aimed at reducing speeds on arterial roads in the city of Växjö. Twenty-one intersections were provided with mini-roundabouts, eleven intersections were provided with give-way signs from all approaches, and the speed limit was reduced to 30 km/h.

A floating vehicle was used to record a series of speed profiles through the scheme before and after construction. From the speed and acceleration data obtained, emissions and fuel consumption figures were calculated using a Swedish emissions model. The effects of the roundabouts on mean vehicle speeds were described in Section 3.2.3.

Emissions were reported to have increased for cars that passed over the roundabouts along the main roads, but to have decreased for cars passing over them from side roads. On average, the introduction of the roundabouts at non-signalised intersections increased CO emissions by 5.6%

and NO_x emissions by 4%, taking into account traffic flows. The reduction in emissions and fuel consumption on side roads was, on average, 1.4 times greater than the increase on the main roads. Thus, the change in emissions at any particular intersection was dependent upon the relative flows on the main and side roads. In theory, if the proportion of traffic entering from the side road became greater than 70% of the traffic flow on the main road then there would be a net improvement in total emissions and fuel consumption at a roundabout. However, this seemed to be a fairly unlikely scenario for intersections in Växjö, where the traffic volume on the main route is, on average, around three times higher than the volume on the side streets.

The introduction of a roundabout at a conventional signalised intersection led to a 29% reduction in CO emissions and a 21% reduction in NO_x emissions.

Over the whole system of mini-roundabouts, CO emissions were calculated to have increased by 2%, NO_x by about 1.2%, and fuel consumption by 0.4%. The increases were considered to be insignificant in relation to the emissions from the entire town.

Sweden 2

In the assessment of the impact of traffic calming on emissions, Höglund (1995) considered the calculation of effects to provide a sufficient first approximation. In order to model the changes in emission associated with a small number of alternative scenarios involving the placement of road humps, Höglund used the Nordic Calculation Model for Vehicle Exhaust Pollution.

The author firstly considered the effects of introducing road humps on vehicle speed profiles. Four idealised scenarios were assumed for a 1.5 kilometre section of road:

- i No humps/constant vehicle speed (unspecified). This was taken to represent the situation before calming.
- ii One hump resulting in a speed change of 50 to 30 km/h before the hump, and then back up to 50 km/h after the hump.
- iii Ten humps resulting in 10 of the speed changes described in scenario (ii).
- iv Ten humps, but only one decrease in speed (50-30 km/h) at the beginning and one increase (30-50 km/h) at the end of the road. A constant speed of 30 km/h was assumed for the mid-section.

The rates of both acceleration and deceleration were assumed to be constant (1.5 m/s^2). The percentage changes in fuel consumption and emissions of CO and NO_x associated with calming were calculated by comparing each of the 'after' scenarios (ii, iii and iv) with the 'before' scenario (i). The results generated by the emission model were presented for both non-catalyst and catalyst-equipped cars.

The introduction of a single hump was predicted to increase emissions along the section of road by up to 20%, and fuel consumption by around 5%. The predicted increases in emissions were magnified when 10 humps were introduced. The transient profile (scenario iii) yielded two or three-fold increases in emissions of CO and NO_x

from both types of vehicle, and increases in fuel consumption of 40-50%. It was, however, predicted that adopting a constant speed of 30 km/h over the humps would result in a smaller increase.

It was noted by Höglund that the acceleration and deceleration values used were limited by the lack of emission data for more rapid changes. In normal braking, a deceleration of 1.9 m/s^2 would be typical, but hard braking can result in a deceleration rate of $3.5\text{-}4.5 \text{ m/s}^2$. In first or second gear, accelerations are normally between 1.8 and 2.7 m/s^2 . It was therefore concluded that real changes in emissions could be greater than those predicted by the model.

It has also been reported that the Swedish city of Vasteras has been the site of 'negative humps', or hollows and depressions in the road surface. A before and after investigation of the effects of this device revealed that fuel consumption had increased by 20% (Moses, 1988).

Denmark

In Denmark, measurements and calculations of air pollution were performed in conjunction with traffic calming projects on the main through roads in the small pilot towns of Vinderup, Ugerløse and Skærbæk.

Before the conversion there was a speed limit of 60 km/h in all three towns. After the conversion the speed limit was 40 km/h in Vinderup and Ugerløse, and 50 km/h in Skærbæk. The exact nature of the traffic calming elements varied in each town, but features generally included rumble strips, gateways, surface markings, narrowing of traffic lanes, side and central islands, staggering (build-outs) and parking spaces (Herrstedt, 1992).

The quantities of lead, CO and nitroendioxide (NO_2) were studied before and after the conversions in the three towns. The lead content of the air was determined by means of biological monitoring. The quantities of CO and NO_2 were calculated using a Scandinavian air pollution model (Herrstedt, 1992).

In the outer zones of Vinderup, where speeds had been reduced by almost 10 km/h whilst flow remained smooth, lead concentrations were reduced, but the lower speed resulted in a very small increase in CO and NO_2 . The fuel consumption of the through traffic had decreased by 9% after the conversion. There was no reported change in the daily traffic flow (Herrstedt, 1988). In Skærbæk air pollution was unchanged on the central part of the stretch of road. Lead concentrations dropped on the edges of town, while the quantities of CO and NO_2 rose slightly. In Ugerløse lead pollution reduced slightly in the central part of town, while it increased at the newly-installed roundabouts.

The overall conclusion from traffic calming studies in Denmark is that a reduction of car speeds will have no great influence on air pollution. There may be small increases in air pollution, but the more even the driving pattern the more air pollution is reduced (Danish Road Directorate, 1993).

Holland

Two areas in the Dutch towns of Eindhoven and Rijswijk were selected as sites for an experiment to investigate the effects of restructuring urban areas. The areas contained

three types of traffic calming in residential areas. The most limited, 'option one', involved the introduction of one-way streets, construction of parking bays and the introduction of road humps. 'Option two' and 'option three' measures were progressively more extensive, so that option three measures included all those in option one, plus partial pedestrianisation, raised junctions, re-alignment of the road axis, narrowing of the carriageway and other features.

The effects of the measures on air pollution were ascertained by measuring exhaust gas emissions on a number of test trips. The measurements showed that emissions of CO per km travelled rose fractionally in option two streets, those of NO_x dropped somewhat and those of HC remained virtually the same. In option three streets emissions of CO and HC per km rose noticeably, whereas those of NO_x fell. The rise in CO emissions in option three streets is due to the numerous bends made in the road, which cause drivers to release and then depress the accelerator frequently. Because of the halving of the motorised traffic in option three streets, however, total emissions of exhaust gases there dropped to some extent (SWOV/ DVV, 1985).

Austria

An Austrian study of the impact of road humps on vehicle emissions produced results which showed the changes to be considerably greater than those measured or predicted in other studies (except the Swedish study by Höglund). In the experiment, a medium-sized petrol catalyst car, fitted with equipment to measure emissions, was driven over a 1.5 km stretch of road containing six road humps spaced at 200 metre intervals. The speed of the vehicle was limited to 30 km/h and the test was carried out in two phases. In the first phase the vehicle slowed down to 15 km/h before the humps and accelerated to 30 km/h after the humps. In the second phase the vehicle came to a halt before each hump (AIT/FIA, 1994).

When the emission values obtained with the humps in place were compared with a pseudo-before calming situation, in which a constant speed of 30 km/h was maintained, the following changes in emissions were observed. For phase one and phase two, NO_x emissions were ten and eight times higher respectively, while CO was seen to have increased by a factor of three. Both CO₂ emissions and fuel consumption were found to have risen by 25% with the humps in place. The equipment employed was not sensitive enough to measure hydrocarbon emissions. Unfortunately, no further information has been made available to suggest why the changes in emissions obtained were so great.

Australia

Van Every and Holmes (1992) assumed that fuel consumption could be used to provide a surrogate measure for assessing the likely impact of speed changes on air quality. Passenger car fuel consumption on a 500 metre calmed stretch of a local street system was calculated using a theoretical model. The model was used to calculate fuel consumption for three scenarios: five road humps spaced at 100 metre intervals, 5 flat-top road humps spaced at 100 metre intervals and 2 roundabouts spaced at 250 metres.

The average speed before calming was assumed to be 50 km/h. The assumed average speeds at, and between, the measures are given in Table 5.

Table 5 Assumed speeds associated with traffic calming measures (Van Every and Holmes, 1992)

<i>Measure</i>	<i>Speed at measure (km/h)</i>	<i>Speed between measures (km/h)</i>
Round-top road humps ('Watts humps')	15	20
Flat-top road humps ('plateaux')	20	25
Roundabouts	25	40

The model predicted that fuel consumption would increase after the implementation of the round-top humps, flat-top humps and roundabouts by 73%, 36% and 33% respectively. Given these increases, the authors suggested that air quality might deteriorate by a similar amount, although it was recognised that air quality also depends on other factors and localised changes will not necessarily affect the immediate vicinity.

5.2.2 Summary of case studies

The results from the case studies that have been reviewed here are summarised in Table 6. A distinction has been made between those studies relating to area-wide calming and those relating to single sections of road. The figures relate to emissions from individual vehicles and do not include any overall emission changes due to changes in traffic volume. The area-wide studies reviewed all showed a decrease in NO_x emissions as a result of calming. However, these studies were less conclusive in terms of the changes in emissions of CO and HC.

The studies focusing upon the effects of traffic calming along single sections of road have produced a wide range of results. This is particularly evident in the case of NO_x, for which some studies have shown decreases of up to 30%, whilst others have shown large increases. It is not immediately obvious why this is the case, nor why discrepancies have arisen between the 'single road' studies and the area-wide studies. The single road studies did show a consistent increase in fuel consumption and emissions of CO and HC due to traffic calming, although the HC data is limited and wide variations in the changes in CO emissions were recorded.

6 Public transport and emergency services: problems caused by traffic calming

6.1 Buses and taxis

Public transport and traffic calming are both considered as approaches geared to reducing car use in urban areas, and therefore any conflict between the two could be counter-productive. It is possible that bus services could become unpopular in areas with calmed roads as a result of increases in journey times and passenger discomfort. Services might

Table 6 Summary of results from case studies (N/A = not available; F.C. = fuel consumption)

<i>A Area-wide calming</i>						
Country	Measures	Vehicle type (all petrol)	Changes in vehicle emissions			
			NO _x	HC	CO	CO ₂ /F.C.
Germany	Area with extensive traffic calming	Non-catalyst	-38 to 60%	-10 to -25%	+71 to +7%	+19 to +7%
	30 km/h zone	Non-catalyst	-5 to -31%	+2 to -23%	+28 to -20%	+14 to -6%
Holland	Road humps	N/A	Decrease	No change	Slight increase	N/A
	Extensive calming	N/A	Decrease	Increase	Increase	N/A
<i>B Single road sections</i>						
Country	Measures	Vehicle type (all petrol)	Changes in vehicle emissions			
			NO _x	HC	CO	CO ₂ /F.C.
UK	Road humps, 75m spacing, 30mph 'before'	Catalyst & non-catalyst	0 to -20%	+100 to +70%	+80 to +70%	+60 to +50%
Sweden 1	30 km/h limit, mini-roundabouts	N/A	+1%	N/A	+2%	+<1%
Sweden 2	1 Road hump constant 'before' speed	Catalyst	+18%	N/A	+20%	+4%
		Non-catalyst	+22%	N/A	+11%	+5%
	10 Road humps constant 'before' speed	Catalyst	Three-fold increase	N/A	Three-fold increase	+37%
		Non-catalyst	Three-fold increase	N/A	Two-fold increase	+51%
Denmark	40 km/h limit, various calming	N/A	N/A	N/A	N/A	-9%
Austria	6 Road humps, 200m spacing, 30 km/h 'before'	Catalyst	Ten-fold increase	N/A	Three-fold increase	+25%
Australia	5 Road humps, 100m spacing 50km/h 'before'	N/A	N/A	N/A	N/A	+73 to +36%
	2 Roundabouts, 250m spacing 50km/h 'before'	N/A	N/A	N/A	N/A	+33%

NB: The UK, Swedish and Australian results are from emission/fuel consumption models

even be withdrawn, especially if substantial maintenance costs are incurred by operators whose buses have been damaged by humps. Unfortunately, as traffic calming becomes widespread, conflicts are increasingly experienced.

Damage to buses has been reported by Trench and Ball (1995). Midland Fox has estimated that damage resulting from traffic calming costs an estimated £40,000 a year, with double-decker buses being the worst affected. Minor incidents have occurred in the Highfields area of Leicester, resulting in broken springs, skirting and exhausts, and in Warwickshire, where Midland Red have complained of a collapsed suspension. Bulpitt (1995) reported that traffic

calming measures in Kent were imposing extra repair costs on operators due to grounding.

After objections to humps from bus operators, who claimed that the buses would require increased maintenance costs as a result of traffic calming, Broadbent and Salmon (1993) devised a chicane system which consisted of a series of build-outs on alternate sides of the road.

There is also some concern about injuries to bus drivers and passengers. Drivers with the Leicester company Citybus have reported injuries to the lower neck and the base of the spine. In South Australia, complaints from bus drivers and passengers about injuries claimed to have been

suffered when crossing raised paving have resulted in the State Government Department responsible for the Occupational Health and Safety Act ordering the State Transport Authority to re-route the buses.

Stephens (1986) reported of a study on a scheme comprising 100 mm high road humps, in which vertical accelerations ('g' values) for an empty (air suspension) bus were measured at the driver's seat and at the back passenger seat. The results showed that the driver was subjected to a higher 'g' (about 50%) at speeds up to 20 mph but for speeds of 25 mph and above the back passengers had higher 'g' values.

Bus companies now appear to be satisfied with schemes containing 75 mm high road humps (Webster and Layfield, 1996) and distributor road schemes (Webster, 1995), as few adverse comments have been reported to local highway authorities, even though they have sometimes shown concern before implementation.

It should be noted that some local authorities have reduced the slopes of humps to assist buses (Jones and Farmer, 1993) without adversely affecting the crossing speeds of vehicles (only a 1 mph increase). In Australia, humps with ramps of 1:20 - 1:25 were found to be suitable for bus routes (Jarvis and Giummara, 1992).

Taxi drivers often use standard saloon cars and therefore additional maintenance costs would be expected if higher than average mileages were covered. However, it would be difficult to discover if road humps cause any additional maintenance cost in practice.

6.2 Emergency vehicles

It is very important that the emergency services are consulted (Department of Transport, 1994b) before any traffic calming schemes are implemented, so that the needs and characteristics of their vehicles can be taken into account in any overall strategy. Reviews after installation are also important, so that the measures can be refined if required.

Emergency vehicles do not use fixed routes in the same way as buses, and therefore any additional maintenance costs due to road humps would be difficult to establish. It can be assumed that emergency vehicles may exceed the desirable hump crossing speed while responding to an emergency call, and this could lead to damage in the long term.

Emergency vehicle operators claim that road humps cause unnecessary discomfort and damage to vehicles (Anon, 1996). Broadbent and Salmon (1993) devised a chicane system after objections to humps from the fire service claimed that the suspension could be affected and equipment could be dislodged while on an emergency call.

Some sources have suggested that a road hump will add 10 seconds to response time for emergency vehicles (Bulpitt, 1995), although it has been shown elsewhere (Layfield, 1994) that fire tenders and ambulances can achieve speeds of 38 mph and 24 mph respectively over narrow speed cushions on emergency runs. Cars generally cross narrow cushions at just under 20 mph and buses at just over 20 mph

7 Summary and conclusions

With the introduction of the UK National Air Quality Strategy, some local authorities will be required to draw up an air quality management plan which will lead to air quality objectives being met. Traffic management is one tool that may help authorities meet the objectives, although information on the relative impact of alternative schemes on air quality is limited and imprecise at present.

This Review has described the main stages in the assessment of the changes in vehicle emissions associated with the implementation of a particular type of traffic management: traffic calming. The areas that have been examined include traffic calming measures, changes in behaviour imposed by traffic calming schemes, and factors affecting emissions from road vehicles in the context of traffic calming. A summary has also been presented of case studies in which the effects of traffic calming on emissions have been determined by either direct measurement or the use of emission models/databases. An additional Chapter has been included to identify some of the problems that traffic calming introduces for public and emergency service vehicle operators.

In the UK, the 6 most common traffic calming measures (by number of schemes implemented) were found to be 75 mm high flat-top humps, 75 mm high round-top humps, speed cushions, single-lane-working chicanes, thermoplastic humps ('Thumps') and two-way-working chicanes. Schemes comprising mainly road humps are currently the most common type, although the proportion of schemes containing speed cushions is increasing.

Descriptions of driver behaviour include both detailed data on parameters relating to vehicle control, such as speed and gear selection, and information on trips such as journey purpose, duration, mode, time of day and time of year. It has been proposed that the factors influencing vehicle control include personal characteristics (such as gender, attitudes and age), the vehicle interior environment, vehicle performance, the road environment, the traffic situation, and other factors relating to the trip (e.g. available time, time of day, weather, commercial pressures). The relative importance of these factors is unknown at present, and there is little quantitative data on how they might be influenced by traffic calming.

Work relating to driver behaviour has usually been concerned with its relationship not to vehicle emissions, but rather to accident causation. Consequently, existing studies invariably relate to speed selection, and not necessarily to other parameters known to affect emission rates (e.g. acceleration rates, gear selection, pedal operation). This was also found to be true for assessments of the changes in driver behaviour associated with traffic calming.

The relationships between vehicle speeds and hump spacing, together with speeds at humps, are well documented for 75 mm humps (and 'thumps'). Similar relationships for cushions and chicanes are more complicated because the number of variables involved are greater. It appears that 1800-1900 mm wide cushions give comparable crossing speeds to road humps of a similar height, whereas narrower cushions have crossing speeds

about 5 mph higher. Cushions are generally straddled centrally by buses, and approximately half of cars, at sites where parking does not cause obstruction. The effectiveness of single-lane-working chicanes is dependent on the traffic flow along the road, and in non free-flow conditions speeds can be reduced by a further 10 mph.

Although vehicle speeds at given points are one of the most frequently measured parameters in the assessment of traffic calming schemes, it is knowledge of continuous driver behaviour, and changes in traffic flow and composition, that are fundamental requirements for accurately determining changes in vehicle emissions on this scale. However, it is precisely this kind of continuous information that is not widely available.

A review of previous case studies led to the conclusion that there is only limited agreement on the effects of traffic calming on vehicle emissions. The area-wide studies reviewed all showed a decrease in NO_x emissions as a result of calming. However, these studies were less conclusive in terms of the changes in emissions of CO and HC.

The studies of the effects of traffic calming based on single sections of road have produced a wide range of results. This is particularly evident in the case of NO_x, for which some studies have shown decreases of up to 30%, whilst others have shown large increases. It is not immediately obvious why this is the case, nor why discrepancies have arisen between the 'single-road' studies and the area-wide studies. The single-road studies did show a consistent increase in fuel consumption and emissions of CO and HC due to traffic calming, although the HC data is limited and wide variations in the changes in CO emissions were recorded. The variation in these results may be due in parts to both the variability of emission measurements performed on test vehicles (including those used to develop models) and the different modelling techniques employed in the studies reported.

The number of traffic calming measures employed on a given length of road should be an important factor in determining changes in emissions, since whatever effect one measure has on emissions, the effect will be magnified if more measures are employed. Höglund (1995) did predict that the introduction of 10 road humps (spaced at 150 metre intervals) along a section of road would produce a change in emissions approximately 10 times greater than that caused by the installation of a single hump, but there is a need for further evidence to substantiate this hypothesis. With the large hump spacings envisioned by Höglund and employed in the Austrian study, drivers would be able to accelerate up to a speed level similar to that which they would have chosen had the humps not been installed, even with comparatively low acceleration rates. These studies, where several widely-spaced humps have been employed, appear to have produced the largest increases in emissions.

Most of the information on emissions that has been presented in these case studies has been obtained through the use of emission models or databases. The results of a few studies in which measurements have actually been taken have often been used to make general predictions about the effects of traffic calming on emissions. However,

there is a need for much more empirical information at a more detailed level, and on a wider variety of schemes.

Claims relating to increased vehicle maintenance costs have been made by some bus companies, but it has also been reported that local authorities have reduced the severity of ramps to assist the bus companies. Much of the information on the damage that traffic calming measures can cause is anecdotal and therefore difficult to integrate into a framework for the assessment of schemes that is based on quantitative evidence.

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9 References

- Abbot P G, Hartley S, Hickman A J, Layfield R E, McCrae I S, Nelson P M, Phillips S M and Wilson J L (1995)** *The Environmental Assessment of Traffic Management Schemes*. Department of Transport. TRL Report 174. Transport Research Laboratory, Crowthorne.
- Abdel-Aty M A, Vaughan K M, Kitamura R, Jovanis P and Mannering F L (1994)**. *Models of commuters' information use and route choice: initial results based on Southern California commuter route choice survey*. Transportation Research Record (1453), pp46-55. National Academy Press, Washington D.C.
- AIT/FIA (1994)**. *Power and speed of vehicles: speed humps cause ten times more air pollution*. AIT/FIA Traffic Commission meeting. Munich, September 6. Federation Internationale de l'Automobile. Paris.
- Amundsen F H (1984)**. *Speed reducing measures in residential areas. Traffic operation and management*. Proceedings of Seminar L. PTRC Transport and Planning 12th Summer Annual Meeting. Volume p254, pp91-99. PTRC Education and Research Services Ltd., Glenthorne House, Hammersmith Grove, London.
- Anon (1996)**. *Calming success*. Highways, December 1996.
- Baguley C J (1981)**. *Speed control humps - Further public road trials*. Department of Transport, TRRL Report LR1017, Transport and Road Research Laboratory, Crowthorne.
- Barbosa H M (1995)** *Impacts of traffic calming measures on speeds on urban roads*. PhD Thesis. Institute of Transport Studies, Department of Civil Engineering, University of Leeds, Leeds.
- Bicknell D (1993)**. *Traffic calming*. Proceedings of the Institution of Civil Engineers, 98, March, pp13-19.

Boulter P G (1997). *Environmental traffic management: A review of factors affecting cold start emissions.* TRL Report 270. Transport Research Laboratory, Crowthorne.

Broadbent K and Salmon A M (1993). *An alternative to road humps.* Highways and Transportation, August 1993.

Brown I D (1993). *How is driver behaviour acquired?* From *Behavioural Research in Road Safety IV*. Proceedings of a seminar at Brunel University, 6-7 September. Ed. G B Grayson. PA3035/94. Transport Research Laboratory, Crowthorne.

Bulpitt M (1995). *Traffic calming - have we given everyone the hump, or is it just a load of chicanery?* Highways and Transportation, December 1995.

Buxton J and Newby L (1995). *Driver reaction to traffic calming. A survey of the effects of road humps on driver acceleration and braking.* Produced by Environ Research. Report No. 21. February 1995.

Collins M S (1990). *Traffic calming and environmental management. Environmental issues.* Proceedings of Seminar B. PTRC Transport and Planning 18th Summer Annual Meeting. Volume p329, pp25-35. PTRC Education and Research Services Ltd., Glenthorne House, Hammersmith Grove, London.

County Surveyors' Society (1994). *Traffic calming in practice.* County Surveyors' Society, Landor Publishing Ltd., London.

Craus J, Polus A, Livneh M, Gutman L and Ruhm K (1993). *Geometric aspects of traffic calming in shared streets.* ITE Compendium of Technical Papers. 63rd Annual Meeting. Institute of Transportation Engineers. The Hague. The Netherlands. September 19-22.

Danish Road Directorate (1993). *An improved traffic environment, a catalogue of ideas.* Road Data Laboratory, Road Standards Division Report 106, Danish Road Directorate, Stationsalle/en 42, DK-2730 Herlev.

Davies D G, Ryley T J, Taylor S B and Halliday M E (1997). *Cyclists at road narrowings.* TRL Report 241. Transport Research Laboratory, Crowthorne.

De Wit T and Slop M (1984). *Traffic humps as recommended by SVT: Design and effects.* Traffic Operation and Management. Proceedings of Seminar L. PTRC Transport and Planning 18th Summer Annual Meeting. Volume p254, pp101-110. PTRC Education and Research Services Ltd., Glenthorne House, Hammersmith Grove, London.

Department of the Environment, Scottish Office and Welsh Office (1996a). *The United Kingdom National Air Quality Strategy - Consultation Draft.* Published by the Department of the Environment.

Department of the Environment, Scottish Office and Welsh Office (1997). *The United Kingdom National Air Quality Strategy.* Published by the Stationary Office Limited, PO Box 276, London.

Department of the Environment, Department of Transport, Scottish Office and Welsh Office (1996b). *Local Authority circular on air quality and traffic management.* Draft Consultation Paper.

Department of Transport (1991). *20 mph speed limit zones.* Traffic Advisory Leaflet 7/91. Driver Information and Traffic Management Division, 2 Marsham Street, London.

Department of Transport (1994a). *Entry treatments.* Traffic Advisory Leaflet 2/94. Driver Information and Traffic Management Division, 2 Marsham Street, London.

Department of Transport (1994b). *Fire and ambulance services. Traffic calming: A code of practice.* Traffic Advisory Leaflet 3/94. Driver Information and Traffic Management Division, 2 Marsham Street, London.

Department of Transport (1994c). *Speed cushions.* Traffic Advisory Leaflet 4/94. Driver Information and Traffic Management Division, 2 Marsham Street, London.

Department of Transport (1994d). *'Thumps' Thermoplastic road humps.* Traffic Advisory Leaflet 7/94. Driver Information and Traffic Management Division, 2 Marsham Street, London.

Department of Transport (1994e). *Horizontal deflections.* Traffic Advisory Leaflet 9/94. Driver Information and Traffic Management Division, 2 Marsham Street, London.

Department of Transport (1996). *Highways (Road Humps) Regulations 1996.* Traffic Advisory Leaflet 7/96. Driver Information and Traffic Management Division, 2 Marsham Street, London.

Devon County Council (1991). *Traffic calming guidelines.* Engineering and Planning Department Devon County Council.

Döldissen A (1990). *Town traffic and the environment.* From the congress *Living and Moving in Cities*, Paris 29-31 January. Centre D'Études des Transports Urbains (CETUR), 8 Avenue Aristide Briand, 92220 Bagneux, France.

Durkin M and Pheby T (1992). *York: aiming to be the UK's first traffic calmed city.* Proceedings of Seminar G. PTRC European Transport, Highways and Planning 20th Summer Annual Meeting. Volume p359, pp73-90. PTRC Education and Research Services Ltd., Glenthorne House, Hammersmith Grove, London.

Eggleston H S, Gaudiso D, Gorissen N, Joumard R, Rijkeboer R C, Samaras Z and Zierock K-H (1993). *CORINAIR Working group on emission factors for calculating 1990 emissions from road traffic. Volume 1: methodology and emission factors.* B4-3045 (91) 10PH, Commission of the European Communities, Brussels.

ETSC (1994). *Reducing traffic injuries resulting from excess and inappropriate speed.* European Transport Safety Council, Rue du Cornet 34, B-1040 Brussels.

European Commission Directorate General for Transport (1996) COST 319: Estimation of pollutant emissions from road transport. Proceedings of the workshop, 27-28 November 1995. Interim report of the Action. CEC/DGVII, Brussels. 170p.

Evans L (1991). *Traffic safety and the driver.* Chapman and Hall, 2-6 Boundary Row, London.

Evans L (1996). *Traffic safety measures, driver behaviour responses, and surprising outcomes.* Journal of Traffic Medicine, Vol 24, No 1-2, pp5-15. International Association for Accident and Traffic Medicine (IAATM), Kizilirmak Cad 53/5, Kocatepe, Ankara, 06640, Turkey.

Evans L and Rothery R (1976). *Comments on effects of vehicle type and age on driver behaviour at signalised intersections.* Ergonomics, 19, pp559-570.

Ferguson N S (1996). *Traffic behaviour on the road network connected to an urban motorway.* Roadsafte '96 International Conference: 'Influences on driver behaviour'. Conference Report. Association of London Borough road Safety Officers.

Finch D J, Kompfner P, Lockwood C R and Maycock G (1994). *Speed, speed limits and accidents.* Department of Transport. TRL Project Report 32. Transport Research Laboratory, Crowthorne.

Fuller R (1993). *The management of driver behaviour.* From *Behavioural Research in Road Safety IV*. Proceedings of a seminar at Brunel University, 6-7 September. Ed. G B Grayson. PA3035/94. Transport Research Laboratory, Crowthorne.

Fwa T F and Liaw C Y (1992). *Rational approach for geometric design of speed-control road humps.* Transportation Research Record, 1356, pp66-72. Transportation Research Board, 2101 Constitution Avenue, NW, Washington, DC, 20418, USA.

Galin D (1981). *Speeds on two-lane rural roads - a multiple regression analysis.* Traffic Engineering and Control, 22, pp453-460.

Gassmann S and Breuer B (1989). *Effect of final drive ratio on driver's behaviour and fuel consumption in real urban traffic.* European Automobile Engineers Cooperation. Second International Conference on New Developments in Powertrain and Chassis Engineering. Strasbourg 14-16 June. Institution of Mechanical Engineers.

German Federal Ministries of Planning, Transport and Environment (1992). *Forschungsvorhaben, Flächenhafte verkehrsberuhigung, Folgerungen für die Praxis (Area-wide traffic calming: results and guidelines).* Bundesministerium für Raumordnung, Bauwesen und Städtebau; Bundesministerium für Verkehr; Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Bonn.

Grime G (1987). *Handbook of road safety research.* Butterworths. London.

Groeger J A and Clegg B A (1994). *Novice drivers' judgement of traffic scenes.* From *Behavioural Research in Road Safety V*. Proceedings of a seminar at Nottingham University, 6-7 September. Ed. G B Grayson. PA3081/95. Transport Research Laboratory, Crowthorne.

Hansen J Q, Winther M and Sorenson S C (1995). *The influence of driving patterns on petrol passenger cars.* Science of the Total Environment, 169, pp129-139. Elsevier Science.

Harré N, Field J and Kirkwood B (1996). *Gender differences and areas of common concern in the driving behaviours and attitudes of adolescents.* Journal of Safety Research, 27(3), pp163-173. Elsevier Science Ltd.

Hassel D (1996). *Gradient influence on emission and consumption behaviour of light and heavy duty vehicles.* COST 319: Estimation of pollutant emissions from road transport. Proceedings of the workshop, 27-28 November 1995. Interim report of the Action. CEC/DGVII, Brussels.

Hass-Klau C and Nold I (1994). *Horizontal traffic calming measures- alternatives to road humps?* Environmental Transport and Planning, 9 South Road, Brighton.

Hass-Klau C, Nold I, Bocker G and Crampton G (1992). *Civilised streets: a guide to traffic calming.* Environmental Transport and Planning, 9 South Road, Brighton.

Herrstedt L (1988). *Environmentally adapted through-road in Vinderup: effect evaluation.* Proceedings of Seminar P. 16th PTRC Transport and Planning summer Annual Meeting. Vol. P311, pp157-81. PTRC Education and Research Services Ltd., Glenthorne House, Hammersmith Grove, London.

Herrstedt L (1992). *Traffic calming design - a speed management method.* Danish experiences on environmentally adapted through roads. Accident Analysis and Prevention, 24(1), pp3-16. Pergamon Press.

- Hickman A J, André M, Hammarström U and Kyriakis N (1997).** *Road traffic characteristics for estimating pollutant emissions.* MEET Deliverable No. 4. Transport Research Laboratory, Crowthorne.
- Highways Act 1980.** ISBN 0 10 546680 8. HMSO, London.
- Highways Agency, The Scottish Office Development Department, The Welsh Office, The Department of the Environment for N. Ireland and The Department of Transport (1996)** *Design Manual for Roads & Bridges.* Vol.13, Economic assessment of road schemes: COBA manual. HMSO, London.
- Highways (Road Humps) Regulations 1990.** *Statutory Instrument No. 703.* HMSO, London.
- Highways (Traffic Calming) Regulations 1993.** *Statutory Instrument No. 1849.* HMSO, London.
- Highways (Road Humps) Regulations 1996.** *Statutory Instrument No. 1483.* HMSO, London.
- Hill J (1996).** *Getting the hump.* New Civil Engineer, 4(11), April.
- Hodge A R (1992).** *A review of the 20 mph speed zones: 1991.* Traffic Engineering and Control, October, pp545-547.
- Höglund P G (1995).** *Estimating traffic related exhaust emissions and immissions at road- and street intersections.* 12 s. Esitelmä: KFB & VTI Research Information Days, Linköping, Sweden. January 10-11.
- Holzmann E (1988).** *Flächenhafte Verkehrsberuhigung in Buxtehude: Auswirkungen der Massnahmen zu Tempo 30 auf die Umweltsituation (Area-wide traffic calming in Buxtehude).* BfLR (Hrsg.), 4. Kolloquium Flächenhafte Verkehrsberuhigung, am 26/27. 5.88 in Buxtehude, Tagungsband. Bonn.
- Huttunen I (1995).** *The effects of traffic calming on the dynamics of a vehicle.* Helsinki University of Technology. ISSN 0788-3722.
- Hydén C, Odelid K and Várhelyi A (1995).** *The effects of general speed calming in built-up areas.* Results of a large scale experiment in Växjö: 1 Main report. Institutionen för Trafikteknik, Lunds Tekniska Högskola, Box 118. 221 00 Lund. (in Swedish)
- Jarvis J R and Giummara G (1992).** *Humps for use on bus routes.* Road and Transport Research, Australia.
- Jensen (1995).** *Driving patterns and emissions from different types of road.* Science of the Total Environment, 169, pp123-128. Elsevier Science.
- Jones S M and Farmer S A (1993).** *Pedestrian ramps in Central Milton Keynes: a case study.* Traffic Engineering and Control, March 1993.
- Jørgensen F and Polak J (1993).** *The effect of personal characteristics on drivers' speed selection: an economic approach.* Journal of Transport Economics and Policy, 27(3), pp237-252.
- Jost P, Hassel D and Weber F-J (1992).** *Emission and fuel consumption modelling based on continuous measurements.* Deliverable No.7 of the DRIVE Project V1053. TÜV Rheinland, Cologne.
- Joumard R, Jost P and Hickman J (1995).** *Influence of instantaneous speed and fuel acceleration on hot passenger car emissions and fuel consumption.* SAE Paper 950928. Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, Pennsylvania, USA.
- Layfield R E (1994).** *The effectiveness of speed cushions as traffic calming devices.* Proceedings of Seminar J. 22nd PTRC European Transport Forum. Volume p381, pp29-40. PTRC Education and Research Services Ltd., Glenthorne House, Hammersmith Grove, London.
- Lichtenstein S, Slovic P, Fishhoff B, Layman M and Combs B (1978).** *Judged frequency of lethal events.* Journal of Experimental Psychology: Human Learning and Memory, (4), pp551-577.
- Mayhew N (1995).** *A419(P) Norwich Road, Cromer, Norfolk, Urban Traffic Calming.* The Third UK National Traffic Calming Conference 18 October 1995.
- Moses P J (1988).** *Traffic management and safety in Europe and North America 1988 - A study tour.* Main Roads Department, Waterloo Crescent, East Perth, Western Australia 6001, GPO Box x2255.
- Nottinghamshire County Council (1994).** *Monitoring of non-standard road humps - Bagnall Road, Nottingham.* Nottinghamshire CC.
- PACTS (1996).** *Taking action on speeding.* Parliamentary Advisory Council for Transport Safety, St Thomas' Hospital, Lambeth Palace Road, London.
- Parry D I and Layfield R E (1997).** *Traffic calming - Speed cushion schemes.* TRL Project Report PR/TT/088/97. Transport Research Laboratory, Crowthorne. (Unpublished report available on direct personal application only).
- Pearce T C and Davies G P (1990).** *The efficiency of automotive exhaust catalysts and the effects of component failure.* TRRL Research Report 287. Transport and Road Research Laboratory, Crowthorne.
- Pharoah T and Russel J (1989).** *Traffic calming: policy and evaluations in three European countries.* Occasional Paper 2/1989. Faculty of the Built Environment, South Bank Polytechnic, Wandsworth Road, London.

Potter C J and Savage C A (1982). *The determination of in-service vehicle gaseous emissions over a wide range of road operating conditions.* Warren Spring Laboratory Report LR 442 (AP).

Quimby A R and Watts G R (1981). *Human factors and driving performance.* TRRL Laboratory Report LR 1004. Transport and Road Research Laboratory, Crowthorne.

Road Traffic Act 1991. ISBN 0 10 544091 4. HMSO, London.

Rothengatter T (1993). *How is behaviour modified? From Behavioural Research in Road Safety IV.* Proceedings of a seminar at Brunel University, 6-7 September. Ed. G B Grayson. PA3035/94. Transport Research Laboratory, Crowthorne.

Sayer I A and Parry D I (1994). *Speed control using chicanes- A trial at TRL.* Project Report PR 102, Transport Research Laboratory, Crowthorne.

Sayer I A and Parry D I (1996). *Traffic calming - An assessment of selected on-road chicane schemes.* Project Report PR/TT/014/96, Transport Research Laboratory, Crowthorne. (Unpublished report available on direct personal application only).

Stephens B W (1986). *Road humps for the control of vehicular speeds and traffic flow.* Public Roads, Vol 50, No.3, December 1986.

Stonham P (1992). *Traffic calming: councils step up the efforts to tame the traffic tiger.* The Urban Street Environment, December/January, pp18-21.

Sumner R and Baguley C (1979). *Speed control humps on residential roads.* TRRL Report 878. Transport and Road Research Laboratory, Crowthorne.

SWOV and DVV (1985). *Reclassification and construction of urban roads in the Netherlands, effects on safety, the environment and commerce.* Institute for Road Safety Research (SWOV), Road Safety Directorate (DVV), P.O. Box 170, 2260 AD Leidschendam, Netherlands.

Thorne R (1993). *Town design that puts buildings before traffic.* Architectural Journal. 197(2). p23. Architectural Press Ltd., 33-39 Bowling Green Lane, London.

Tolley R (1989). *Calming traffic in residential areas.* Breffi Press, Plas y Gorwydd, Llanddewi Breffi, Tregaron, Dyfed.

Traffic Calming Act 1992. ISBN 0 10 543092 7. HMSO, London.

Transnet (1992). *Traffic calming.* Transport Innovation: 1992 spring, 21, pp1-4. Transnet (London Transport and Technology Network Ltd), 16 Warren Lane, London.

Trench S and Ball R (1995). *Buses and traffic calming.* Current issues in planning. Chapter 11, Volume 2, pp 98-110. Ashgate Publishing Ltd, Aldershot.

Van Every B and Holmes M (1992). *Local area traffic management: effects on the environment.* Engineering and Environment. Local Government Engineering Conference. Adelaide 18-19 March. South Australian Department of Road Transport, PO Box 1, Walkerville, South Australia 5081.

Velasco A (1996). *Traffic management strategies to reduce traffic air pollution.* COST 319: Estimation of pollutant emissions from road transport. Proceedings of the workshop, 27-28 November 1995. Interim report of the Action. CEC/DGVII, Brussels.

Wasielowski P (1984). *Speed as a measure of driver risk: observed speeds versus driver and vehicle characteristics.* Accident Analysis and Prevention, 16(2), pp89-103. Pergamon Press Ltd.

Waters M H L (1992). *Road vehicle fuel economy.* TRRL State of the Art Review/3. HMSO, PO Box 276, London.

Webster D C (1993a). *Road humps for controlling vehicle speeds.* Department of Transport, Project Report 18, Transport Research Laboratory, Crowthorne.

Webster D C (1993b) *Effect of traffic calming schemes on vehicle emissions.* Transport Research Laboratory Project Report PR/TF/13/93. Transport Research Laboratory, Crowthorne. (Unpublished report available on direct personal application only).

Webster D C (1994). *Speeds at 'thumps' and low height road humps.* Department of Transport, Project Report 101, Transport Research Laboratory, Crowthorne.

Webster D C (1995). *Traffic calming - four schemes on distributor roads.* Department of Transport, TRL Report 182, Transport Research Laboratory, Crowthorne.

Webster D C and Layfield R E (1993). *An assessment of rumble strips and rumble areas.* Department of Transport, TRL Report 186, Transport Research Laboratory, Crowthorne.

Webster D C and Layfield R E (1996). *Traffic calming - Road hump schemes using 75 mm high humps.* Department of Transport. TRL Report 186. Transport Research Laboratory, Crowthorne.

Webster D C and Mackie A M (1996). *Review of traffic calming schemes in 20 mph zones.* Department of Transport. TRL Report 215. Transport Research Laboratory, Crowthorne.

Wheeler A H, Taylor M and Payne A (1993). *The effectiveness of village 'gateways' in Devon and Gloucestershire.* Department of Transport. TRL Project Report 35. Transport Research Laboratory, Crowthorne.

Wheeler A H, Abbott P G, Godfrey N S, Lawrence D J and Phillips S M (1996). *Traffic calming on major roads: the A49 trunk road at Craven Arms, Shropshire.* TRL Report 212. Transport Research Laboratory, Crowthorne.

Wheeler A H, Abbott P G, Godfrey N S, Phillips S M and Stait R (1997). *Traffic calming on major roads: the A47 trunk road at Thorney, Cambridgeshire.* TRL Report 238. Transport Research Laboratory, Crowthorne.

Williams A F, Paek N and Lund A K (1995). *Factors that drivers say motivate safe driving practices.* Journal of Safety Research, 26(2), pp119-124. Elsevier Science Ltd.

Winnett M (1994). *A review of speed camera operations in the UK.* PTRC 22nd European Transport Forum. Vol. P381. PTRC Education and Research Services Ltd., Glenthorne House, Hammersmith Grove, London.

Appendix A: A brief chronology of recent traffic calming legislation

Although UK traffic calming legislation has tended to be more rigid than in some other European countries, it has evolved during the 1990s and now allows highway authorities to implement a wider range of measures. The various changes in legislation are outlined below.

Highways (Road Humps) Regulations 1990

Compared with earlier legislation, the 1990 Regulations provide increased flexibility in the siting and shaping of road humps. Certain requirements of the regulations can be relaxed when humps are introduced in 20 mph zones. The Regulations define the dimensions, siting, signing and lighting of road humps for use on the Highway. Both flat-top (including raised junctions) and round-top humps are permitted, and humps may be of any height between 50 mm and 100 mm.

Road Traffic Act 1991

The Act amended Sections 90A(1) and 90B(1) of the Highways Act 1980, clarifying the powers of the Secretary of State to authorise the use of road humps which do not conform to the 1990 Regulations, and on roads having speed limits of 30 mph or less.

Traffic Calming Act 1992

This amends the Highways Act 1980, and makes the first specific references in legislation to traffic calming. The 1992 Act removes doubts which existed over the legality of some traffic calming devices. This allows the Secretary of State to make regulations giving clear legal authority to construct a wide range of horizontal deflection features (Department of Transport, 1994e).

Highways (Traffic Calming) Regulations 1993

The 1993 Regulations provide local authorities with the necessary powers to construct particular measures for traffic calming purposes which are not otherwise clearly authorised. Traffic calming measures permitted by this legislation cannot be used to prevent access where this is not lawfully prohibited (Department of Transport, 1994a).

Highways (Road Humps) Regulations 1996

The very prescriptive 1990 Regulations have been replaced by the very much simplified Highways (Road Humps) Regulations 1996, leaving the actual design and location of road humps as a matter for local highway authorities to determine (Department of Transport, 1996). The only dimensions now constrained by the Regulations are: maximum and minimum heights of 100 mm and 25 mm respectively, a minimum length of 900 mm, and no vertical face to exceed 6 mm in height. Authorities have considerable flexibility concerning the implementation of humps, but need to ensure that an adequate duty of care has been exercised.

Abstract

Traffic calming is now a well known concept in the UK and it has proved successful in reducing the number of accidents where schemes have been installed. This Literature Review identifies the most frequently implemented traffic calming measures in the UK. Road humps are still the most popular calming measures but other measures can provide acceptable speed reductions for higher flow roads. With the introduction of the National Air Quality Strategy, some authorities may have to take remedial action where air quality objectives are not likely to be met. Such action may include the better management of traffic. Traffic calming has been identified as an approach that may influence emissions from road vehicles, and the Review describes the main steps in the assessment of the impact of traffic calming on vehicle emissions. This includes an examination of the changes in driver behaviour imposed by schemes, and a summary of research on the changes in emissions associated with traffic calming. There is currently only limited agreement on the effects of traffic calming schemes on vehicle emissions. The problems that traffic calming can introduce for public service vehicle operators and the emergency services are also mentioned briefly.

Related publications

- PR174 *The environmental assessment of traffic management schemes: A literature review* by P G Abbott, S Hartley, A J Hickman, R E Layfield, I S McCrae, P M Nelson, S M Phillips and J L Wilson. 1995 (price code L, £40).
- TRL180 *Traffic calming: Vehicle noise emissions alongside speed control cushions and road humps* by P G Abbott, J Tyler and R E Layfield. 1995 (price code H, £30).
- TRL186 *Traffic calming — Road hump schemes using 75mm high humps* by D C Webster and R E Layfield. 1996 (price code H, £30).
- TRL235 *Traffic calming: Vehicle generated ground-borne vibration alongside speed control cushions and road humps* by G R Watts, G J Harris and R E Layfield. 1997 (price code H, £30).
- TRL270 *Environmental traffic management: A review of factors affecting cold start emissions* by P G Boulter. 1997 (price code H, £30).

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