The impacts of traffic calming measures on vehicle exhaust emissions

Prepared for Charging and Local Transport Division,

Department of the Environment, Transport and the Regions

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Executive Summary

Traffic calming has been found to be particularly effective at reducing vehicle speeds and the frequency and severity of accidents. However, there is little information on the effects of different traffic calming measures on vehicle exhaust emissions and the concentrations of pollutants in the atmosphere. In order to provide more robust information and guidance for local authorities, the Charging and Local Transport Division of DETR commissioned TRL to conduct a three-year study of the impacts of traffic calming on exhaust emissions.

The main objectives of the study were to investigate the effects of different traffic calming measures on the exhaust emissions from passenger cars, and to develop a system of performance indicators for the measures. These indicators included the impacts on emissions, speed, safety, and delays to emergency service vehicles.

The following nine types of traffic calming measure were selected for investigation:

A 75mm-high flat-top road humps
B 80mm-high round-top road humps
C 1.7m-wide speed cushions
D A combined pinch point and speed cushion
E 100mm-high raised junctions
F A chicane
G A build-out
H A mini-roundabout
I 1.9m-wide speed cushions

The speed-time profiles of vehicles passing through each of these schemes were measured using an unobtrusive remote technique based on a LIDAR (Light Detection And Ranging) system. For measures F to I, speed measurements could not be obtained on the same road before and after calming. The profiles, together with gear selections obtained using instrumented cars, were used to formulate driving cycles to represent vehicle operation.

The impacts of each measure on emissions were determined by AEA Technology using the driving cycles and a chassis dynamometer. Twelve in-service petrol cars and three in-service diesel cars were selected by AEA. The petrol cars were categorised according to the level of emission control (*i.e.* whether or not the car was equipped with a catalyst) and engine size. A total of 542 individual emission tests were conducte, with fuel consumption and exhaust emissions of four pollutants (CO, HC, NO_x, and CO_2) being recorded in each test. Total particulate matter was recorded during the diesel vehicle tests.

Traffic flows were recorded where possible. At each site most of the traffic flow consisted of passenger cars and light goods vehicles. Very few heavy goods vehicles and buses were observed. There was no strong tendency for the composition of the traffic to be affected by the introduction of traffic calming, although the balance between medium-size and large cars shifted slightly in favour of the latter after calming.

There were some differences between the six sites where remote speed measurements were measured before calming - the mean speed of passenger cars varied between 38 km/h (24 mph) and 53 km/h (33 mph). The speed reduction after calming ranged between 10 km/h (6 mph) and 19 km/h (12 mph). There was no evidence to suggest that passenger car size had an impact on speed before or after calming, or on the magnitude of the speed reduction. Consequently, one driving cycle was considered sufficient to represent all three sizes of car. For most of the schemes the standard deviation of the speed increased after calming. This reflects the tendency of drivers to accelerate and decelerate between discrete traffic calming measures.

The results of the study clearly indicate that traffic calming measures increase the emissions of some pollutants from passenger cars. For petrol non-catalyst, petrol catalyst, and diesel cars, mean emissions of CO per vehicle-km increased by 34%, 59%, and 39% respectively. For all three vehicle categories the increase in mean HC emissions was close to 50%. Emissions of NO_x from petrol vehicles increased only slightly, but NO_x emissions from diesel vehicles increased by around 30%. Emissions of CO_2 from each the three vehicle categories increased by between 20% and 26%. Emissions of particulate matter from the diesel vehicles increased by 30%.

Although petrol catalyst cars tended to have the lowest absolute emission rates, they also had the most variable emission rates and generally showed the greatest sensitivity to traffic calming. However, whilst large increases in emissions from catalyst cars can occur as a result of calming, the overall results indicate that, for the vehicle fleet in the UK, the larger impacts of traffic calming on emissions recorded in some previous studies are not likely to be typical.

In spite of the variability in the results, particularly for petrol catalyst cars, the understanding of the general effects of traffic calming on passenger car emissions is improving. The overall percentage changes in CO emissions found in this study show quite a good agreement with those calculated using an average speed model (MEET), with those found in previous TRL traffic calming studies using an instantaneous emission model (MODEM), and with TRL remote sensing measurements. The changes in HC emissions fall within the overall range reported previously, though they do not concur with those quoted in any single study. The NO_x results tend to show more similarity to the predictions of MODEM than to the results of on-board measurements. For CO_2, there is a good level of agreement between different studies. However, the impacts of individual types of measure are more difficult to predict. Comparisons at this level between the percentage impacts measured in this study and those calculated using MEET suggest that the model cannot be used with confidence to rank different types of traffic calming measures according to their impact on emissions. It remains to be seen whether this can be achieved with other models, such as MODEM.

A statistical method - the Student-Newman-Keuls (SNK) test - was used to examine the differences between the impacts of the nine schemes on emissions. The SNK test grouped the schemes according to whether significant differences existed between the mean percentage changes. In general, there was a great deal of overlap between the groups of traffic calming measures, though for some vehicle category-pollutant combinations a clear hierarchy emerged. However, the more 'severe' traffic calming measures (*e.g*. road humps) tend to result in the greatest speed reductions, the greatest accident savings, and some of the largest increases in emissions.

Urban traffic calming measures have been mainly introduced on residential roads with low traffic flows. Consequently, even though traffic calming generally increases emissions per vehicle it is very unlikely that it would result in poor local air quality. The atmospheric pollutant concentrations associated with the types of scheme and levels of traffic flow considered in this report were calculated using a dispersion model, and were found to be well below the 2000 Air Quality Strategy standards. Furthermore, the improving performance of emission control technology means that, in the future, breaches of the standards would be even less likely to occur as a result of traffic calming. However, the increases in vehicle emissions associated with traffic calming would need to be given particular attention in Air Quality Management Areas, where air pollution standards are frequently breached.

A short experiment was conducted to estimate the delays imposed on a fire tender by different traffic calming measures. The results indicated that the speed reduction caused by the speed cushions was significantly smaller than that caused by the chicane which, in turn, was significantly smaller than that caused by the flat top humps. However, the time delay per measure was relatively small, and unless a large number of calming measures is encountered, it is unlikely that emergency fire tender response times would increase significantly.

The main findings of the study, together with relevant information from other sources, were used to develop performance indicators for different traffic calming measures. These were distilled into a simple set of guidelines which can be used by local authorities during the selection of appropriate traffic calming measures. The guidance identifies the type of traffic calming measure likely to achieve a specific reduction in speed, as well as the likely effects of each measure on accidents, delays to emergency service vehicles, and emissions.

1 Introduction

1.1 Background

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. Section 82(1) of Part IV of the Act also laid the foundations for a nation-wide system of local air quality management. Local authorities were presented with new responsibilities, including obligations to perform periodic reviews and assessments of the quality of the air in their areas, and to assess current and likely future air quality against standards and objectives which were set out in regulation. These obligations fell to district and unitary authorities in England, and to all local authorities in Scotland and Wales. The Government's standards and objectives were detailed in the National Air Quality Strategy (NAQS) (Department of the Environment *et al.*, 1997), and covered the pollutants carbon monoxide (CO), nitrogen dioxide (NO_2), lead, ozone, sulphur dioxide (SO_2), the hydrocarbons benzene and 1,3-butadiene, and particulate matter of aerodynamic diameter less than 10mm (PM_{10}). Since the publication of the NAQS, the original air quality standards and objectives have been revised (DETR *et al*., 2000).

The Government expected local authorities to have completed their initial review and assessment of local air quality by April 1999. In areas where the assessment showed that air quality objectives would probably not be met by 2005, the authority was required to designate an Air Quality Management Area (AQMA) and to draw up an air quality management plan which would lead to the objectives being met on time.

Given that road vehicles are a major source of some of the pollutants given priority in the NAQS, such as CO, PM_{10}, NO_2, and hydrocarbons (HC) including the two compounds identified above, the achievement of the air quality objectives, and continued compliance with the standards, requires substantial reductions in emissions from the road transport sector. The Environment Act has confirmed that traffic regulation orders, and hence management schemes, may be used for air quality management purposes. One form of traffic management - traffic calming - has been found to be particularly effective at reducing vehicle speeds, as well as the frequency and severity of accidents. However, although it is necessary for local authorities to be aware of any air quality impacts resulting from their traffic calming operations, there is little information relating to the effects of different traffic calming measures on vehicle exhaust emissions and the concentrations of pollutants in the atmosphere.

A review of case studies by Boulter and Webster (1997) concluded that the changes in vehicle operation effected by traffic calming tend to give rise to an increase in fuel consumption and emissions of carbon dioxide (CO_2), CO, and HC per vehicle-km on the affected roads, though the size of the increase can be highly variable. Data also exist for NO_x emissions, but there is no apparent trend in either the size or direction of the change caused by traffic calming. The results from some of these case studies, and from two more recent studies conducted by TRL, are given in Table 1.

It is likely that the variability of the impacts is linked to several factors, including the method of assessment, the types of vehicle considered, the configuration of the road, and the arrangement of the traffic calming scheme. For example, the methods available for estimating emissions can all produce different results, partly due to the variable performance of the test vehicle(s), and also the type of subjects selected to drive. Two of the studies listed in Table 1 involved direct measurement of the emissions from a single vehicle, one involved remote sensing of the emissions from a large number of vehicles, whilst the remainder relied upon emission models based on tests on a sample of vehicles. Also, older vehicles without emission control could be expected to exhibit moderate changes in emissions around a relatively high baseline, whereas newer technology vehicles equipped with an engine management system and catalyst would tend to have low baseline emissions. For these newer vehicles some modes of operation, such as rapid accelerations (which may occur on some roads with traffic calming), can result in fuelling conditions which deviate from those required for the optimum control of pollutants. Any such deviation can result in a momentary emission rate that is an order of magnitude higher than the baseline rate. In addition, aspects of the site, such as the presence of parked cars or pedestrians, traffic volume, the severity and spacing of the traffic calming measures, and the speeds before and after calming, will strongly influence the impacts on emissions.

In order to provide more robust information and guidance for local authorities, the Charging and Local Transport (CLT) Division of the Department of the

Table 1 Effects of traffic calming on emissions per vehicle-km

				Effects on emissions per vkm (% change)			
Study	*Measures*	*Assessment method*	*Vehicle type*[1]	*CO*	*HC*	*NO_x*	*CO_2/ FC*
GFMPTE (1992)	Area-wide calming	Dynamometer tests	PNC	+7 to +71	-23 to +10	-60 to -38	+7 to +19
Webster (1993a)	Road humps	Emission model	PNC/PC	+70 to +90	+70 to +120	-20 to 0	+50 to +60
H‘glund (1995)	Road humps	Emission model	PNC	+100	N/A	+200	+51
			PC	+200	N/A	+200	+37
Zhger and Blessing (1995)	Road humps	On-board measurement	PC	+160	N/A	+900	+25
Cloke *et al.* (1999)	Speed cushions	Emission model	UK fleet	+8 to +43	+10 to +42	-19 to -6	-10 to +27
Boulter (1999)	Road humps/ speed cushions	Remote sensing	Local fleet	+50 to +73	N/A	N/A	N/A

[1] *PNC=petrol non-catalyst; PC = Petrol catalyst.*

Environment, Transport and the Regions (DETR) commissioned TRL to conduct a three-year study of the impacts of traffic calming on exhaust emissions. The study was the most detailed and extensive of its kind to date, and the findings of the research are presented in this Report.

The main objectives of the study were:

- To investigate the effects of different traffic calming measures on the exhaust emissions from passenger cars.
- To develop a system of performance indicators for different traffic calming measures. These indicators would account for effects on emissions from all road traffic, and would demonstrate how the impacts on emissions compared with other impacts.

Nine types of traffic calming measure were selected for investigation. These were:

- 75mm-high flat-top road humps.
- 80mm-high round-top road humps.
- 100m-high raised junctions.
- 1.9m-wide speed cushions.
- 1.7m-wide speed cushions.
- A chicane.
- A build-out.
- A combined pinch point and speed cushion.
- A mini-roundabout.

These measures were primarily selected according a list of those most frequently implemented (Boulter and Webster, 1997). However, the selection was also governed, to some extent, by the types of measure employed in the traffic calming schemes which were actually installed by local authorities during the experimental phase of the project, as well as the practicality of conducting the appropriate measurements at potential sites.

There are clearly a number of difficulties associated with comparing the emission measurements relating to different traffic calming schemes. Consequently, in this study the effects of the selected traffic calming measures were assessed using, as far as possible, a common and consistent methodology so that the variation in the results could be minimised. A broad outline of the study methodology is presented in the following section of the Report. More detailed accounts of the experimental procedure adopted at each stage of the study are presented in the subsequent chapters.

1.2 Outline methodology

The exhaust emissions produced by a stream of traffic depend principally on the volume of the traffic, the types of vehicle present, and the emission rates of each type of vehicle. Vehicle emission rates depend to a large extent on the way in which the vehicles are operated. This consideration is particularly important in the assessment of traffic calming, since its very rationale is to improve safety via the control of vehicle operation. Gas sampling equipment and analysers can be fitted to individual vehicles to enable on-road exhaust emission rates to be measured. However, it is not cost-effective to extend this approach to the wide range of vehicle types and operating conditions encountered in reality. Consequently, a surrogate indicator of vehicle operation is usually employed in order to characterise the emissions from a representative sample of vehicles driven under representative operating conditions.

Currently, the most widely used surrogate indicator is vehicle speed, and the characteristic variation of emissions with average trip speed is well known. For CO, HC, particulate matter, and other products of incomplete combustion, the highest emissions per vehicle-km occur at the lowest average speeds, whereas NO_x emissions per vehicle-km generally increase with an increase in average speed. It has also been observed that accelerations and decelerations contribute to emission rates. A vehicle will tend to emit higher levels of pollutants when it is driven over a transient cycle than when it is driven over a cycle with the same average speed but less speed variation.

Once the speed-time profiles of vehicles in a traffic stream are known, it is possible to estimate their emissions by either driving the profiles in similar vehicles on a chassis dynamometer and measuring them directly, or by using the profiles as an input to a suitable emissions model. In this study, driving cycles have been formulated to characterise vehicle operation before and after the installation of each of the traffic calming measures listed in section 1.1. It was specified beforehand that the speed data used to develop the driving cycles for the traffic calming measures would be derived using a method of measurement which would not affect the behaviour of drivers as they negotiated the actual schemes. The speed-time profiles of the vehicles passing through each scheme were therefore measured using an unobtrusive remote technique.

It was initially proposed that a separate set of speed profile measurements, obtained using instrumented cars driven through the same schemes by selected subjects, would be used to determine the gear-change points across the operating speed ranges. Each speed profile measured using the remote technique and the instrumented cars would be characterised using statistical descriptors of the speed data, thus defining several modes of vehicle operation. A sample of speed profiles, reflecting the range of vehicle operation through the schemes, would then be taken from the remote measurements and used to select corresponding speed profiles (with associated gear selections) from the instrumented car measurements. The latter profiles would be combined to form a driving cycle representing the range of vehicle operation on the section of road at the time the speed measurements were taken. This process was adopted in the study, though in a simplified form after the early stages.

The proposed methodology relied in part on the matching of the speed profiles obtained by remote measurement with those measured using the instrumented cars. Tests were required to confirm that the speed profiles measured using these techniques were directly comparable. These tests were conducted at the TRL site. Details of the three measurement techniques, the test procedure employed, and the results, are provided in chapter 2. In order to establish the feasibility of the proposed methodology in a real-world situation, a field trial was conducted on a stretch of road along which traffic calming measures had already been installed. Chapter 2 of the Report also includes the details and results of this trial.

The completion of the study was dependent upon the appropriate measures being implemented well within its three-year time scale. From the outset it was considered that close liaison with local councils would be of paramount importance throughout, both to ensure that suitable sites were chosen and to confirm that it would be practical to take measurements before and after the introduction of traffic calming measures. The traffic calming measures investigated during the study are described in detail in chapter 3.

In-situ surveys of vehicle speed were conducted before and after the installation of each of the first five traffic calming measures under investigation. Two-way 24-hour traffic flows were recorded using automatic counters, vehicle speed profiles were determined using a remote measurement system, and information on traffic composition was derived from a video record. During the experimental phase of the study it was not possible to identify sites where a chicane, a build-out, or a mini-roundabout would have been introduced early enough for the measures to be included within the study, and where the layout was suitable for remote speed measurement. Consequently, the speed measurements designed to reflect vehicle operation after calming were obtained at sites where these measures had already been introduced. Also, for the 1.9m-wide speed-cushions, changes to the timetable for scheme implementation dictated that remote speed measurements had to be conducted on one road before calming, but on a different road after calming. The results of the traffic surveys are presented in chapter 4.

So that the impacts of each traffic calming measure on emissions could be determined using a chassis dynamometer under controlled laboratory conditions, driving cycles were formulated to represent vehicle operation before and after the introduction of the schemes, based on the vehicle speed surveys. The development of the driving cycles is described in chapter 5. A total of 22 different passenger cars were then submitted to exhaust emission testing. The tests were conducted by AEA Technology in the company's Vehicle Emissions Laboratory. Chapter 6 of the Report describes the selection of vehicles for testing and the test procedure, and includes a summary of the results.

Although the emergency services are usually consulted before the introduction of traffic calming measures, there is little quantitative evidence relating to the delays imposed on their vehicles by traffic calming. In addition to the experimental work relating to exhaust emissions, a short experiment was conducted with the aim of estimating the delays imposed on a fire tender by different traffic calming measures. The experiment is described in chapter 7.

One of the main objectives of the research was to develop a system of performance indicators for the different traffic calming measures. These indicators would have to account for how vehicle speed and emissions were affected, and would demonstrate how speed reduction and minimisation of emissions could be balanced against other requirements. The main findings of the study, as well as any relevant information drawn from other sources, have been used to develop guidance on the implementation of traffic calming measures. The methods by which these performance indicators were developed, the results for the traffic calming measures, and the guidance for local authorities, are presented in chapter 8 of the Report.

The impacts of the different schemes on ambient air pollution levels were not measured in the study, but the implications of the results for local air quality have been assessed using a dispersion model in chapter 9.

2 Speed measurement

The proposed methodology relied in part on a statistical method for matching the speed profiles obtained by remote measurement with those measured using instrumented cars. Tests were required to confirm that the speed profiles measured using these techniques were directly comparable. These tests were conducted at the TRL site, on a 200m section of road featuring two flat-top road humps.

The speed of a vehicle passing along the road section was monitored using three techniques simultaneously: one on-board instrument and two external methods of measurement (a laser-based system and road tubes). Details of the three measurement techniques, the test procedure employed, and the results of the tests are provided in sections 2.1 and 2.2.

2.1 Speed measurement techniques

Instrumented car

During this preliminary assessment an optical speed sensor was fixed to the side of a Ford Escort. The sensor, which was directed so that it faced the road surface, emitted a microwave beam. As the sensor was moved parallel to the surface the Doppler shift in the reflected signal was measured, and from this the road speed of the vehicle could be calculated every second. The system could measure the speed of the vehicle up to 180 mph (290 km/h), and to an accuracy of $\pm$ 0.5%.

As a longer-term arrangement, a PC-based data acquisition system was fitted inside the passenger compartment of a Ford Mondeo to enable its road speed and engine speed to be logged every second. An encoder was mounted in line with the vehicle's speedometer cable and connected to a data logger. The encoder generated a number of electrical pulses for each revolution of the speedometer cable. In order to derive calibration factors, the vehicle was driven several times over a fixed route of known length. This gave a speed resolution of 1.4 km/h. A hand control, operated by a navigator, was used to start and stop logging at the beginning and end of each trip and to mark specific node points during the trip.

LIDAR

A laser-based LIDAR (LIght Detection And Ranging) instrument, which was operated from a vehicle parked at the roadside, was used to measure speeds remotely. The instrument allowed the operator to isolate a single vehicle within the traffic and, whilst tracking it manually, to log both its speed and distance continuously on a portable computer. The instrument was capable of measuring a wide range of vehicle speeds to an accuracy of ± 1.6 km/h, and the distance to the target vehicle could be measured to an accuracy of ± 0.3 m. For a target travelling at 100 km/h the data acquisition time was 0.3 seconds. The LIDAR detector required a few seconds to 'lock on' to the target vehicle, by which time the vehicle had usually travelled 20-30 metres. As with conventional RADAR equipment, the LIDAR system was subject to a cosine error when monitoring along a direction that deviated from the true direction of travel of the target vehicle. The magnitude of this error was less than 1% at angles below 8^o, and less than 3% for angles under 14^o.

When using the LIDAR, a clear line of sight to the target vehicle had to be available during the entire measurement period. Intervening objects such as signposts, tree branches, cyclists, pedestrians, and other vehicles would interrupt the measurement and an incomplete speed profile would be logged. In a convoy of closely-spaced vehicles only the speed profile of the last vehicle could be recorded. Measurement would also be interrupted if the target vehicle stopped moving. The manufacturers claimed that rain, smoke, fog and airborne dust particles adversely affected operation, but the instrument was found to operate satisfactorily under a range of conditions.

Synchronised road tubes

A system has been developed by Leeds University for continuously measuring the speeds of vehicles in traffic over a distance of around 100m. The system contained four main components: 16 road tubes equipped with transducers, a laptop computer, a data logger, and data transmission cables. At TRL the road tubes were installed along the stretch of road at known distances apart. Each time a vehicle wheel passed over one of the tubes a pressure pulse arrived at a transducer which sent an electrical signal down the transmission cables to the data logger. The logger >time stamped= the event and passed the channel number plus event time to the computer. The resolution of the time data was 1 millisecond. The precise timing of the pulses from each of the 16 tubes was sufficient to calculate the speed and acceleration of a vehicle at various points along the road. However, no software was available to interpret the output for a complex traffic situation.

2.2 Comparison of techniques

The LIDAR was placed in an appropriate position to measure vehicle speed over the section of road on which the tubes had been installed. The Ford Escort equipped with the microwave Doppler sensor was driven over the road section several times in each direction, whilst its speed was recorded using all three systems simultaneously. Figure 1 shows that there was a good agreement between the speed profiles measured by all three devices, including those profiles exhibiting a large variation in speed. However, it is not certain which, if any, of the profiles was the most accurate representation of actual vehicle speed. Largely because of its ease of installation, ease of use, and less conspicuous nature, the LIDAR system was selected in preference to the road tubes as the means by which remote measurements would be obtained during the study.

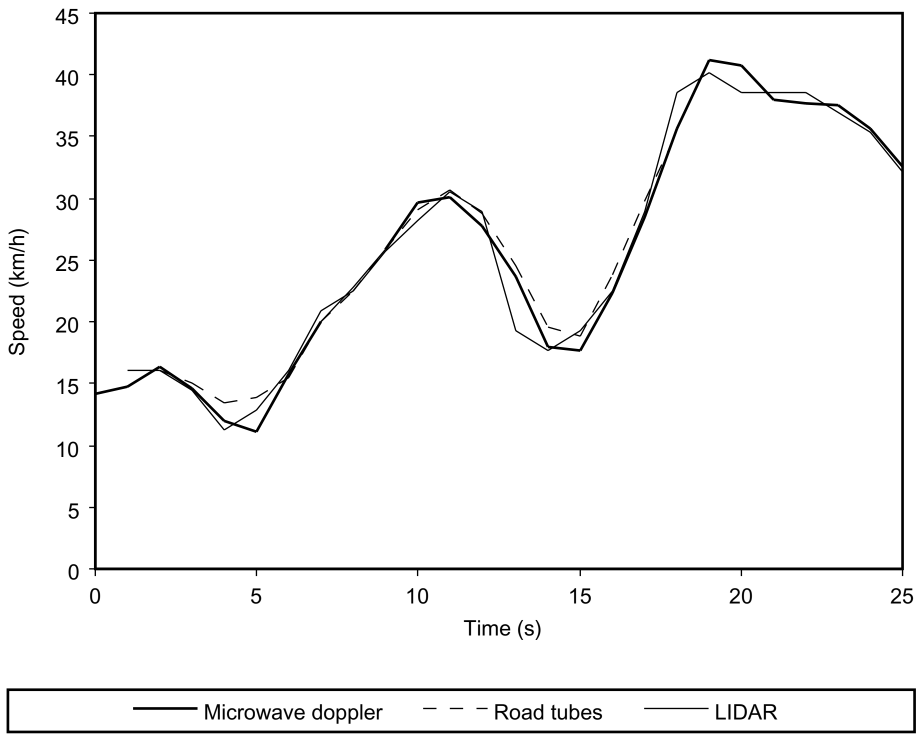


Figure 1 Comparison of speed measurement techniques

2.3 Field trial

In order to establish the feasibility of the proposed methodology in a real-world situation, a field trial was conducted on a stretch of road along which traffic calming measures had already been installed. The location for the trial was chosen according to its suitability for the measurement process, which in practical terms meant finding a site at which interruptions to the LIDAR beam would be minimised. The road had to be straight, unobstructed by parked vehicles, relatively flat, and possess a suitable location for monitoring traffic without interfering with moving vehicles or pedestrians. Even for this preliminary study, difficulties arose in finding a suitably straight stretch of road where speeds could be measured over distances of more than 200m.

The site selected for the field trial was a section of Owlsmoor Road in Sandhurst which featured round-top road humps. Around one and a half days were spent measuring speeds remotely using the LIDAR system, which was positioned in a Renault Espace with the laser beam directed through the rear window. The laser was manually directed at each target vehicle as it passed through the traffic calming scheme. The speed of, and distance to, the vehicle were recorded every second on a data logger, which was periodically downloaded to a portable computer. The time of the measurement and the registration number of each target vehicle were recorded on video so the vehicle specification could be cross-referenced with the recorded data. Other vehicles passing through the scheme were also recorded on video.

Mounting the LIDAR system and video equipment in the Renault Espace was considered to be impractical on a long-term basis. Therefore, after the field trial a small van was used as a dedicated housing for the LIDAR system. The comparatively small width of the van enabled it to be parked on a pavement or verge without causing a major obstruction to the traffic. A frame and shelving system were bolted to the interior of the van to support the various components of the remote measurement system. The laser unit and video camera were fixed together on a bracket and aligned, and the bracket was attached to a pan-and-tilt head which was in turn fixed to the frame. Figure 2 depicts the general arrangement of the remote measurement system when used at the roadside, and Figure 3 shows the system installed in the van. The rear door of the van was closed during operation, and the rear window was blacked out except for a small aperture through which the laser beam and video camera could be directed.

Figure 3 LIDAR system

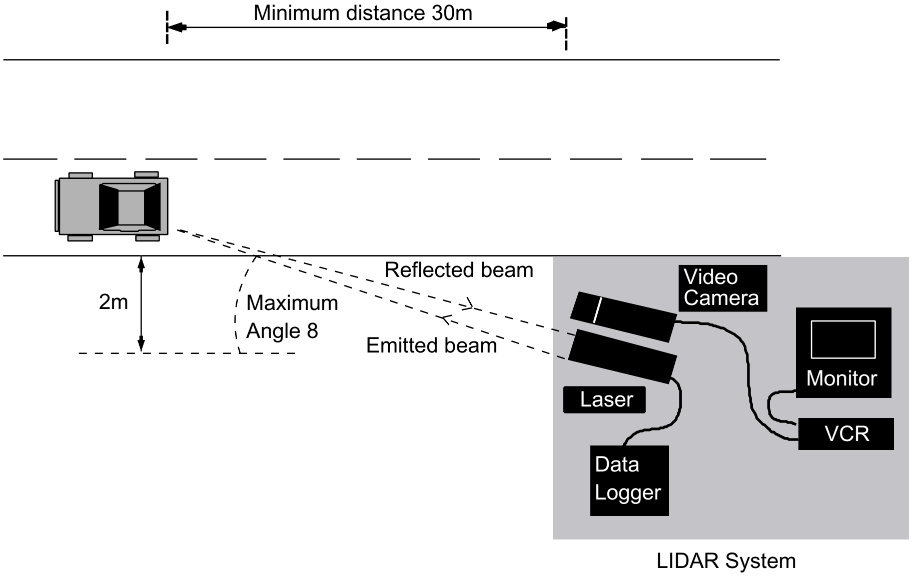


Figure 2 General arrangement of LIDAR system

Initially, in order to gain familiarity with the measurement procedure and to determine the feasibility of the methodology, TRL employees were asked to drive the Ford Escort equipped with the microwave Doppler sensor through the scheme. In a more thorough experiment that represented the intended approach during the study, twelve external subjects, selected from a large TRL database containing a representative cross-section of UK drivers, were asked to drive the instrumented Ford Mondeo thorough the scheme. It was assumed that the Ford Escort represented a typical medium-sized car, whilst the Ford Mondeo represented a typical large car. Each speed-time profile for the road section was characterised by the mean and the standard deviation (*i.e.* variability) of the second-by-second data comprising it. The overall mean speed, and the overall standard deviation of speed (both averaged over all speed profiles) for the instrumented cars were compared with those of the remote measurements.

As stated earlier, the proposed methodology relied in part on the matching of speed profiles obtained by remote measurement and those measured using an instrumented car. It was therefore important that the comparatively small number of instrumented car profiles, which would be used to construct the final driving cycle, exhibited a sufficiently wide range of speeds to reflect the speed range of the LIDAR measurements. A *t*-test confirmed that the overall mean speeds obtained using the two instrumented cars were different from the mean speed recorded using the LIDAR system at the 95% confidence level. It can be seen from Figure 4 that the mean speed of the Escort was somewhat lower, and that of the Mondeo higher, than the mean speed of the vehicles measured by the LIDAR. Figure 4 also shows that large differences in the overall standard deviations of speed were apparent. The speed profiles measured using the LIDAR had a lower overall standard deviation than those measured using either of the instrumented cars.

These results were not particularly surprising, and there were probably a number of reasons for there being differences in mean speeds measured by the two techniques. These included the following:

- The subjects driving the instrumented cars were aware that they were being monitored. They might therefore have altered their natural driving style, whereas the LIDAR measurements were unobtrusive.
- The performance and handling of the TRL instrumented cars may not have been typical of the vehicles in the area.
- The subjects used to drive the instrumented vehicles were unfamiliar with the area.
- The LIDAR system stopped logging once a vehicle came to rest during measurement, and the speed profile had be rejected. Consequently, no LIDAR profiles included a speed recording of zero. The data logger in the instrumented car, however, continued to operate when the car stopped, and so the zero values were included in the calculation of the mean speed of the associated profile. In the absence of other factors, this would have resulted in a general tendency for the overall mean speed of all the instrumented car profiles to have been lower than that of the LIDAR profiles.
- If a vehicle was travelling at low speed, there was a tendency for other vehicles to queue behind it. This occasionally led to the interruption of the LIDAR beam and the subsequent rejection of the speed profiles for some vehicles.

The distributions of the measurements are also shown in Figure 4 (each horizontal bar relates to a single speed profile). If the LIDAR measurements accurately reflected the range of real-world vehicle operation, then the results showed that in an experiment of this kind, where an attempt is being made to determine representative speed profiles over specific, and comparatively short sections of road, the use of a single instrumented car may produce unrepresentative results. The representativeness of the final driving cycles should therefore be improved if the instrumented car profiles comprising them are selected using the LIDAR measurements, as proposed.

As the range of the combined instrumented car measurements reflected the majority of the LIDAR measurements, it was considered that the trial confirmed the overall feasibility of applying the proposed methodology to a real-world situation. It was thought that the speed of a particular vehicle passing through a traffic calming scheme might well be affected by its characteristics, such as its performance, its wheel-base, the stiffness of its suspension, and the general ride comfort. Therefore, it was considered that the possibility of covering the entire speed range observed in the remote measurements could be increased by using three instrumented cars. Subsequently, a Ford Fiesta, a Ford Escort, and a Ford Mondeo were instrumented for this purpose. It was anticipated that the data collected using these three vehicles could be used to develop driving cycles applicable to small, medium and large cars.

3 The schemes

3.1 Scheme A: 75mm flat-top road humps

As part of Surrey County Council’s Accident Reduction Programme, an Area Road Safety Study was undertaken in a residential area of Walton-on-Thames. The Safety Study revealed that 150 personal injury accidents (PIAs) had occurred within the area between January 1989 and December 1991. Fifty per cent of the accidents involved vulnerable road users such as pedestrians, children, the disabled, the elderly, cyclists, and motorcyclists. Vehicle speeds were found to be inappropriate for the type of roads in the area, and traffic flows along the main roads in the area confirmed their use as ‘rat runs’ (Stillwell Bell and Elmbridge Borough Council, 1994).

In order to address these problems, Elmbridge Borough Council proposed a package of traffic calming measures for the area. The traffic calming measures were designed to reduce the risk of accidents, to emphasise the needs of vulnerable road users, to improve the environment, to achieve lower vehicle speeds, and to direct vehicles onto preferred routes. The proposed package included road humps, chicanes, pedestrian refuges, traffic islands, entry

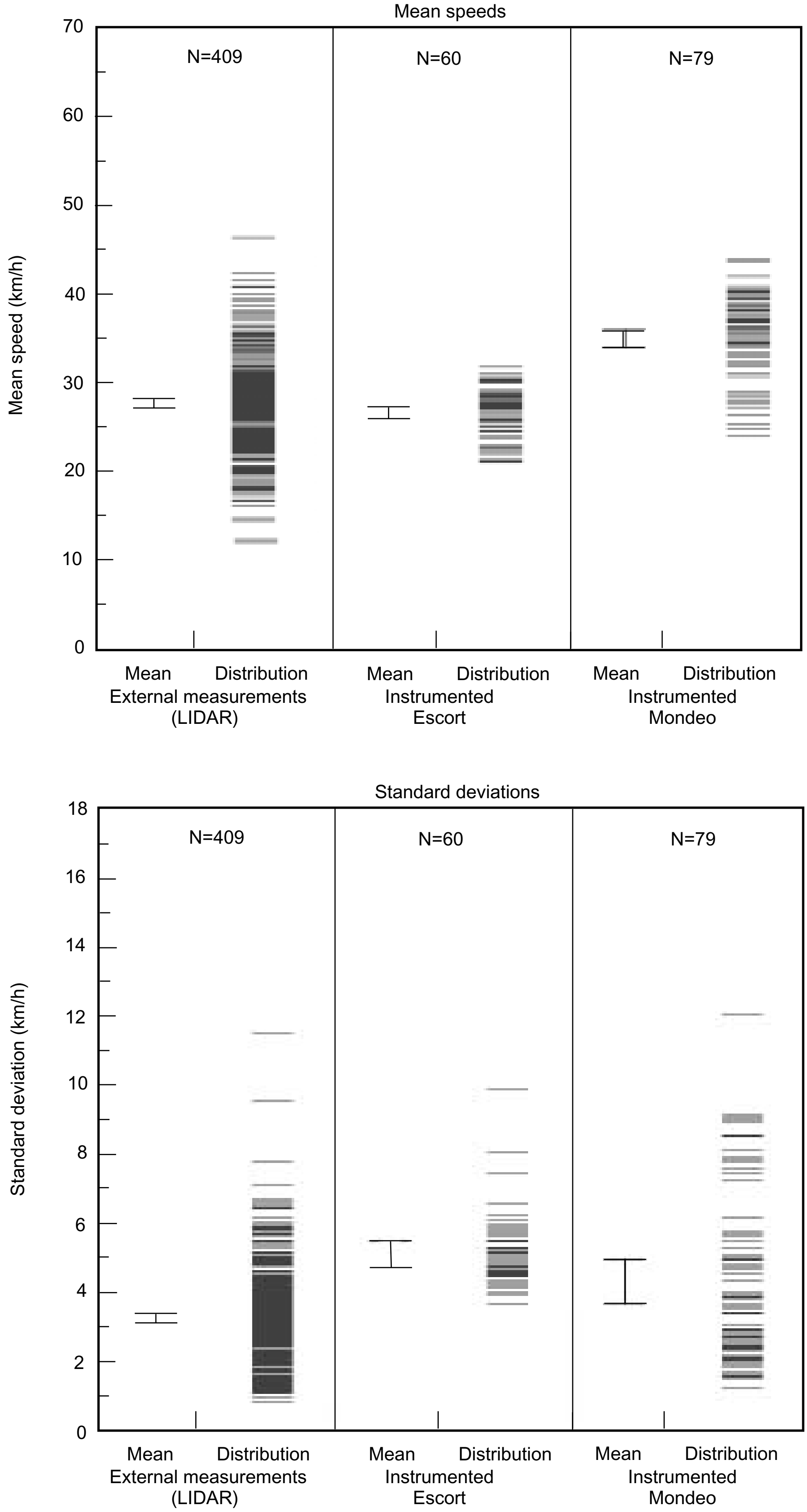


Figure 4 Mean speeds and standard deviations of profiles measured using LIDAR and two instrumented cars. The I-beams represent 95% confidence intervals, and the horizontal bars in the distributions correspond to individual speed profiles N = number of measurements

treatments, raised junctions, narrowings, parking management, one-way streets, road closures, and restricted turns.

Flat-top humps installed on Ambleside Avenue, one of which is depicted in Figure 5, were among the first features to be implemented in the Safety Study area. They were introduced in November 1997. The humps, being of a standard design, were 75mm high, with an overall length of 8.5m and a plateau length of 6m (giving a ramp gradient of 1:15). There was a distance of approximately 90m between the humps. The layout of the road section investigated by TRL is represented in Figure 6.

3.2 Scheme B: 80mm round-top road humps

In January 1998 the London Borough of Sutton introduced five road humps on Milton Road, a residential road in the Beddington area, in response to the problems of vehicle speed and traffic flow perceived by residents. The road humps, shown in Figure 7, were constructed of hot rolled asphalt. They were 80mm high, with a round-top profile, tapered edges, and appropriate white lining. The humps were spaced at intervals of, on average, around 60m. The layout of the section of Milton Road investigated by TRL is represented in Figure 8.

3.3 Scheme C: 1.7m wide speed cushions

In 1997 The London Borough of Harrow embarked on a programme of traffic calming. A points allocation system was applied for the purposes of prioritising roads for traffic calming. The system took into account reported PIAs, traffic speed, traffic volume and composition, and land use. Welbeck Road, which is a residential road in the Borough, was one of the roads given priority. Between January 1995 and August 1997 seven PIAs were reported on the road. As a result of the accident record, speed cushions were installed in January 1998. The cushions, which were constructed of hot rolled asphalt, were arranged in ‘in-line’ groups of three (Figure 9), spaced at an average interval of around 75m. Each cushion was 80mm high, had an overall length of 2.5m, an overall width of 1.7m, a plateau width of 0.75m, and a ramp gradient in the direction of travel of 1:8. The layout of the section of Milton Road investigated by TRL is represented in Figure 10.

3.4 Scheme D: combined pinch point and speed cushion

Slough Borough Council introduced a 20 mph zone in the Upton Lean area of Slough in June 1998. The introduction of the scheme provided the opportunity for TRL to monitor the effects on speed of a combined pinch point and speed cushion. Four pinch point/speed cushion combinations were installed at intervals of between 90 and 100 metres on Broadmark Road. One of these measures is depicted in Figure 11.

The effective carriageway width at each pinch point was around 3.3 m, and in each case the pinch point was accompanied by a single speed cushion located directly between the kerb build-outs. The speed cushions were constructed of hot rolled asphalt. They were 75 mm high, 3.7 m long, and 1.6 m wide. The locations of the measures on Broadmark Road are indicated in Figure 12.

3.5 Scheme E: raised junction

The introduction of the 20 mph zone in the Upton Lean area of Slough also provided an opportunity to investigate the effects of raised junctions. Two such measures were introduced on Carlton Road, and the implementation date broadly coincided with that of the measures described in section 3.4.

One of the junctions is depicted in Figure 13. The plateau of each raised junction was 100mm high and constructed of block paving, with the ramps being formed from rolled asphalt. One of the raised junctions was 22m long in the direction of travel (including the ramps), whilst the other was 17m long. Each plateau extended approximately 5m into the side road, and the centre-to-centre distance between the two raised junctions was approximately 70m. The locations of the measures on Carlton Road are indicated in Figure 14.

3.6 Scheme F: chicane

The site selected for the study of a chicane was located on Great Hollands Road in Bracknell, and the actual chicane investigated is pictured in Figure 15. Several measures of this type were introduced on the road in 1994 to reduce vehicle speeds and traffic flow. At the narrowest point of the chicane the road width was 3.7 metres. Illuminated bollards were placed either side of the road narrowing, and also on traffic islands located in the centre of the road at the entrance and exit of the chicane. Hatching was also used at the traffic islands to define the layout of the chicane. The overall length of the measure, including the traffic islands but excluding the hatching, was 28 metres. The distance between the chicanes on Great Hollands Road was comparatively large, and therefore the spacing has not been reported.

3.7 Scheme G: build-out

Owlsmoor Road in Sandhurst was used as the site for the field trial described in section 2.3. In order to reduce vehicle speeds in the vicinity of a secondary school on Owlsmoor Road, a variety of traffic calming were introduced in November of 1991. Round-top road humps (50mm-high and 75mm-high) were installed along a large section of the road, a single build-out was constructed near the entrance to the school, and a mini-roundabout was introduced at the junction with Yeovil Road.

The build-out (Figure 16) was selected as the seventh traffic calming measure in the TRL study. The build-out extended 1.5 m into the northbound carriageway, resulting in an effective road width of 3.9 m. Drivers in the northbound carriageway were forced to give priority to oncoming vehicles. Although road humps featured prominently on Owlsmoor road, none were installed in the immediate vicinity of the build-out.

Figure 5 Flat-top road hump: Ambleside Avenue, Walton-on-Thames

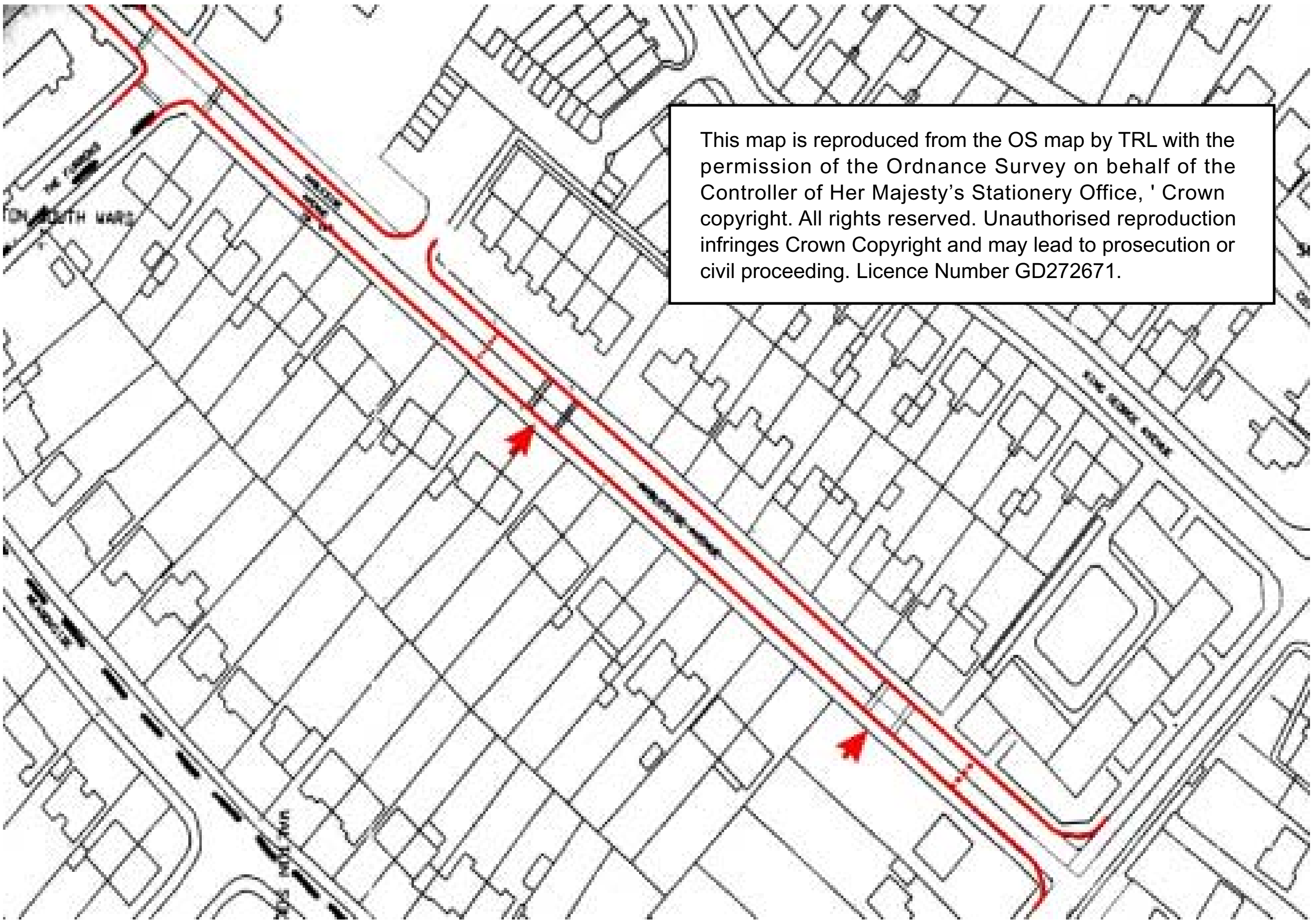


Figure 6 Site map: Ambleside Avenue, Walton-on-Thames. The red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone

Figure 7 Round-top road hump: Milton Road, Sutton

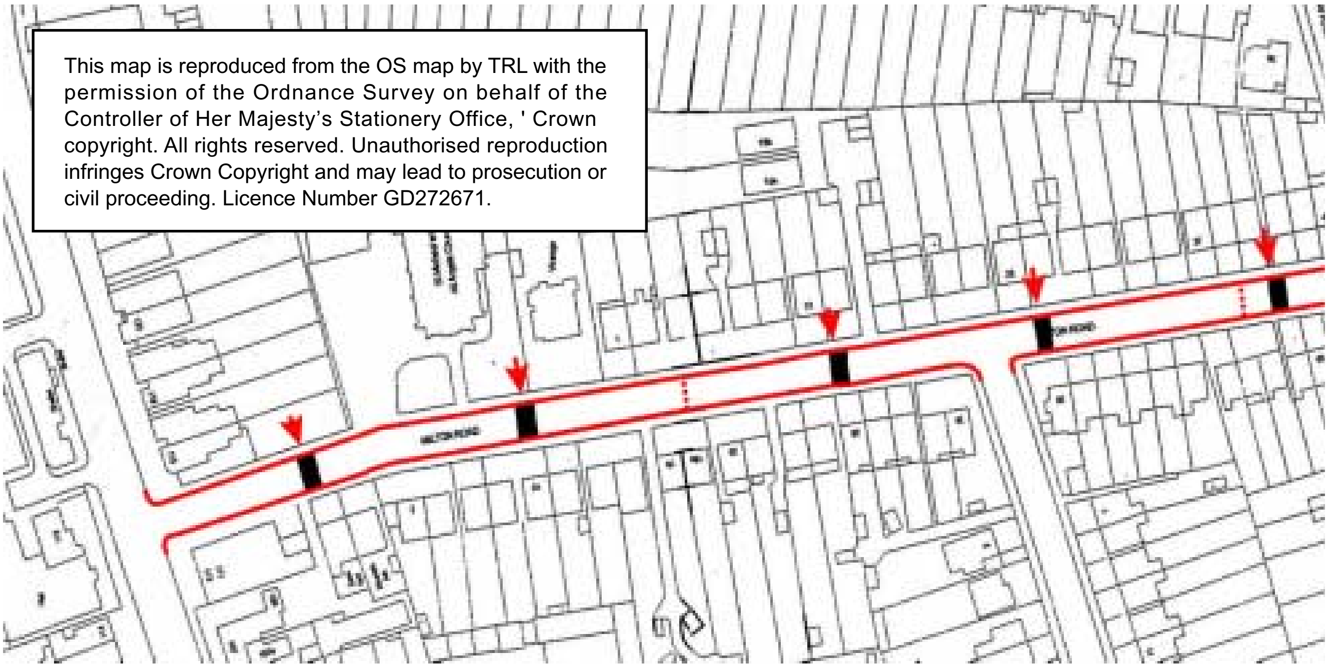


Figure 8 Site map: Milton Road, Sutton. The red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone

Figure 9 1.7m-wide speed cushions: Welbeck Road, Harrow

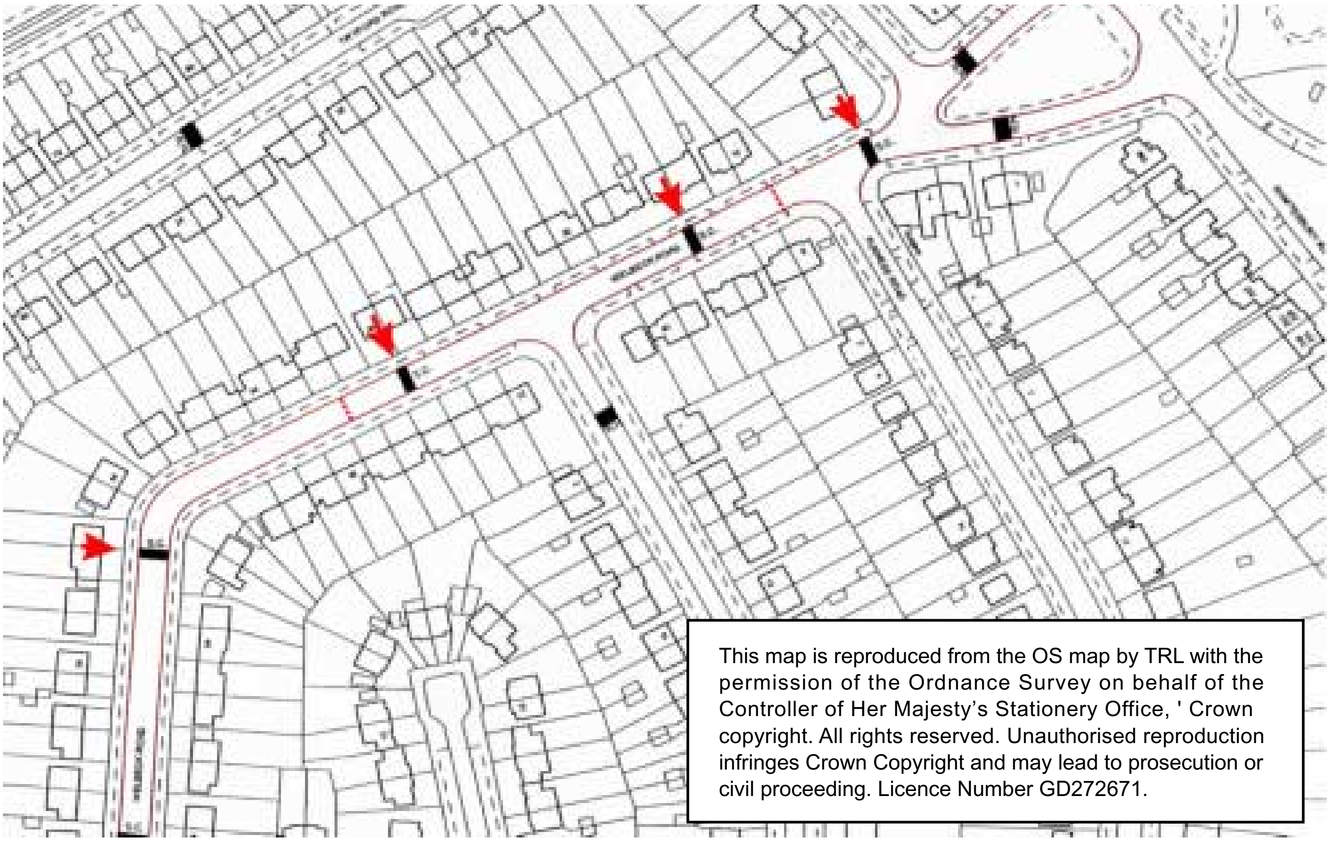


Figure 10 Site map: Welbeck Road, Harrow. The red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone

Figure 11 Combined pinch point and speed cushion: Broadmark Road, Slough

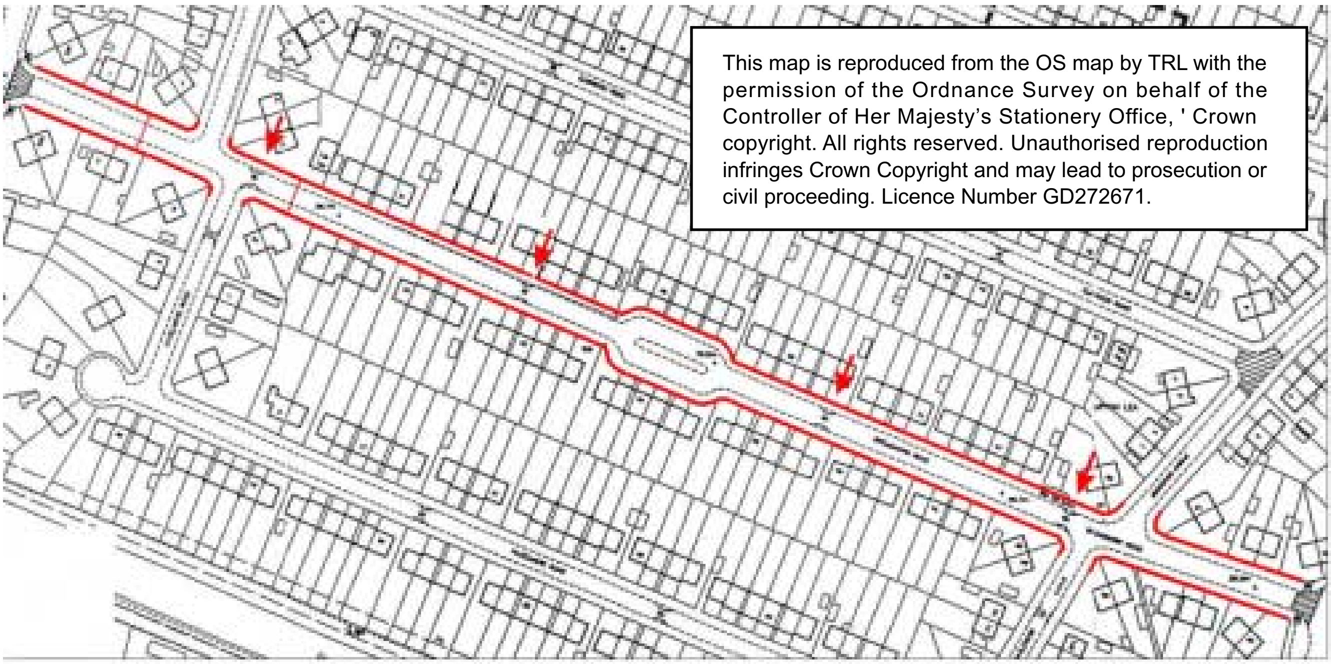


Figure 12 Site map: Broadmark Road, Slough. The red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone

Figure 13 Raised junction: Carlton Road, Slough

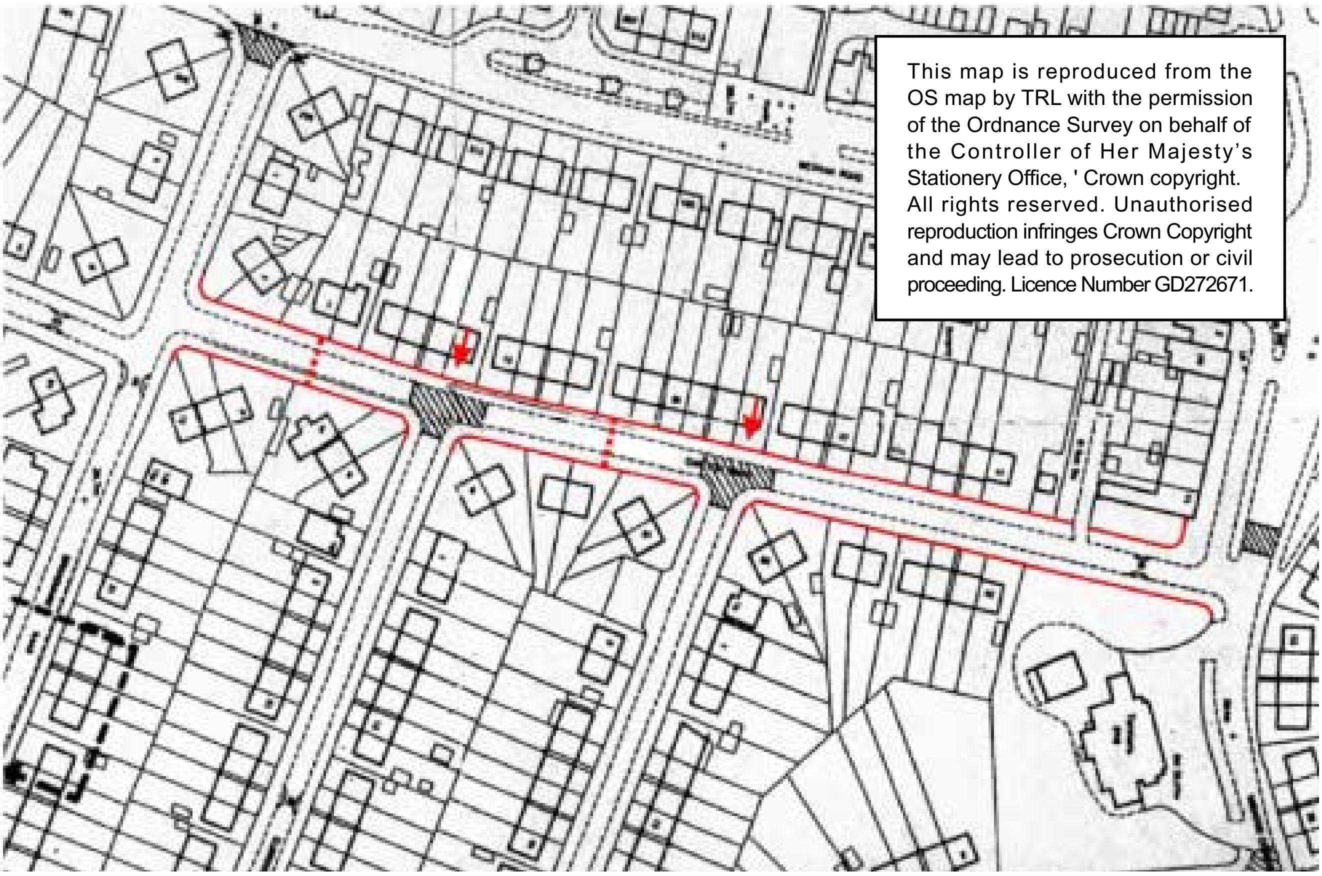


Figure 14 Site map: Carlton Road, Slough. The red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone

Figure 15 Chicane: Great Hollands Road, Bracknell

Figure 16 Build-out: Owlsmoor Road, Sandhurst

3.8 Scheme H: mini-roundabout

The mini-roundabout installed on Owlsmoor Road in Sandhurst (at the junction with Yeovil Road) was also selected as an appropriate measure for inclusion in the TRL study. The measure is depicted in Figure 17.

3.9 Scheme I: 1.9m wide speed cushions

West Grove is a residential road in Walton-on-Thames, though it is one of the main traffic routes between the A244 Hersham road and the A317 Queens Road/Hersham Bypass. Elmbridge Borough Council introduced traffic calming measures on West Grove in 1997 in an attempt to reduce vehicle speeds and traffic volume from levels which were inappropriate for the road. Because the route is also used by the emergency services, the Council opted mainly for speed cushions.

The speed cushions were installed in pairs, and were constructed of hot rolled asphalt to a height of 75 mm. They were 1.9 m wide and 1.9 m long in the direction of travel. The plateau of each cushion was 1.3 m wide and 0.7m long, giving a ramp gradient in the direction of travel of 1:8, and a side-ramp gradient of 1:4. In each cushion pair there was a gap of 1.2 m between the outer edges of the cushions and the kerb, and also a gap of 1.2 m between the inner edges of the two cushions. The speed cushion pairs, pictured in Figure 18, were installed at intervals of, on average, approximately 50 metres. The layout of the section of West Grove investigated by TRL is represented in Figure 19.

4 Traffic flow, composition and speed

4.1 Field measurements

The dates of all the main surveys conducted during the study are given in Table 2. Surveys were conducted before and after the installation of each of the first five traffic calming schemes listed in chapter 3. Two-way 24-hour traffic flows were recorded using automatic counters, vehicle speed profiles were determined using the LIDAR system, and information on traffic composition was derived from the video record of the LIDAR measurements. For the first scheme only, instrumented car measurements were also undertaken before and after calming, with the information being used to derive gear selection patterns for the driving cycles. The instrumented cars were not employed at the other sites for reasons which will be explained later. During the experimental phase of the study it was not possible to identify sites where a chicane (scheme F), a build-out (scheme G), or a mini-roundabout (scheme H) would have been introduced early enough for the measures to be included, and where the layout was suitable for remote speed measurement. Consequently, the speed measurements designed to reflect vehicle operation after the installation of these measures were obtained at sites where they had already been introduced. The traffic flows after calming at the three sites were estimated using the video record of the remote speed measurements.

For the 1.9m-wide speed-cushions (scheme I), remote speed measurements were conducted on one road before calming, but on a different road after calming. As part of the package of traffic calming measures proposed by Elmbridge Borough Council for the area of Walton-on-Thames

Figure 17 Mini-roundabout: Owlsmoor Road, Sandhurst

Figure 18 1.9m-wide speed cushions: West Grove, Walton-on-Thames

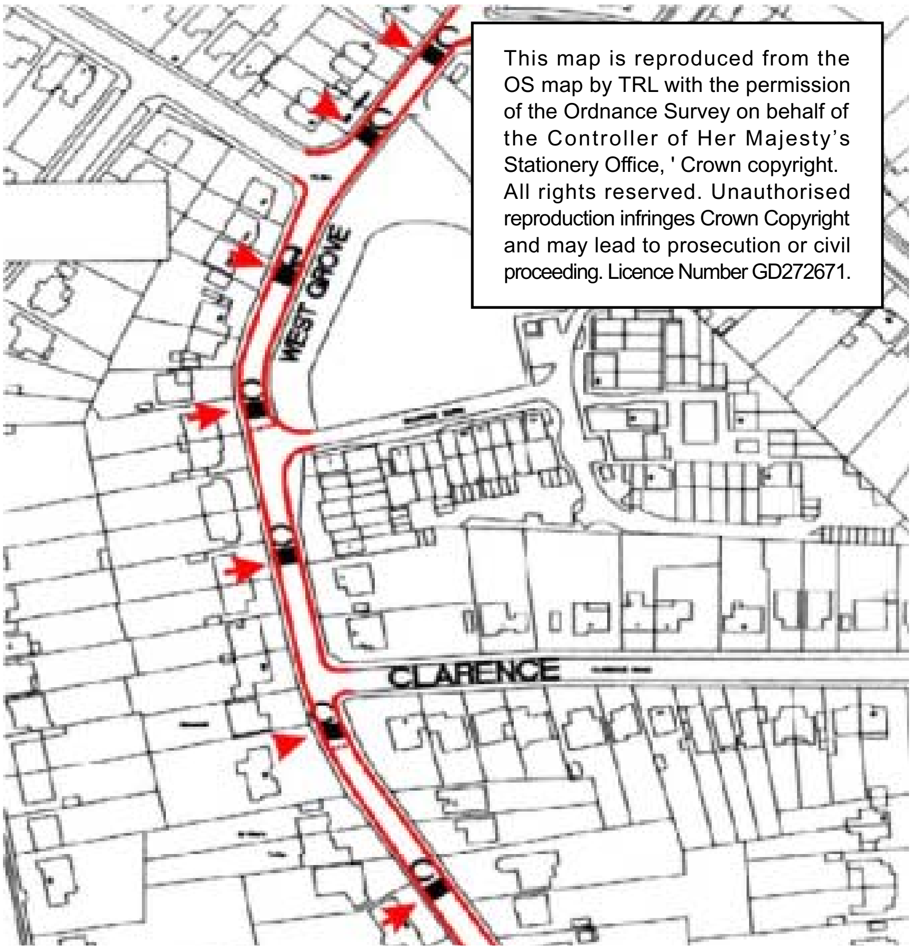


Figure 19 Site map: West Grove, Walton-on-Thames. The red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone

Table 2 Surveys undertaken during the study

Scheme	Traffic calming measure	*Remote speed measurements* Before calming	After calming	*Traffic flow measurements* Before calming	After calming
A	75mm-high flat-top road humps	7/97	11/97	7/97	11/97
B	80mm-high round-top humps	10/97	4/98	10/97	6/98
C	1.7m-wide speed cushions	1/98	3/98	11/95	1/98
D	Pinch point and speed cushion	2/98	8/98	4/98	4/99
E	10mm-high raised junction	2/98	7/98	4/98	4/99
F	Chicane	No survey	11/98	No survey	11/98 [1]
G	Build-out	No survey	6/98	No survey	6/98 [1]
H	Mini-roundabout	No survey	7/98	No survey	9/98 [1]
I	1.9m-wide cushions	7/97	1/99	No survey	No survey

[1] *Flow estimated from video record.*

described in section 3.1, there was an intention to include 1.9 m-wide speed cushions on one of the roads. However, the cushions were not installed early enough for measurements to be conducted by TRL. A nearby road, which already featured 1.9 m-wide speed cushions, was therefore adopted as an alternative.

At the sites where remote speed measurements could be obtained, the surveys were conducted between 06:00-11:00, 11:00-15:00, and 15:00-20:00, on a Tuesday, Wednesday and Thursday respectively. Monitoring was also conducted on a Saturday and Sunday between 09:00 and 15:00. A complementary video record of the traffic was obtained on each day. The periods of monitoring were designed to account for potential changes in the mean speed, or variability in speed, of vehicles at different times of day. It was assumed that the speeds measured during a particular time period on any particular day would be representative of those during the same period on other days of the week. Attempts were made to monitor speeds away from junctions, and in both directions along the stretch of road under investigation.

The speed profile of each vehicle recorded using the LIDAR as it passed through the traffic calming section was classified in terms of its mean speed and the standard deviation of the second-by-second speed measurements. All the vehicles monitored using the LIDAR were classified according to their type and direction of travel. Passenger cars were identified by model, and subsequently categorised according to size and level of emission control. In emission test work, the size of light-duty vehicles is usually defined in terms of engine capacity. However, because engine capacities could not be determined from the video record, passenger car size was defined in terms of vehicle length (>small= = shorter than 3.81m, >medium= = 3.81m to 4.19m, >large= = longer than 4.19m) which was, in turn, determined by make and model. The level of emission control (the presence or absence of a catalytic converter) was loosely defined in terms of year of registration.. The exhaust emission legislation which effectively required most petrol cars in the UK to be fitted with a catalyst (EC Directive 91/441/EEC) came into effect on January 1 1993. It was assumed that all petrol cars registered after August 1 1993 (*i.e.* 'L' registration or after) were equipped with a catalyst, and that all petrol cars registered before this date (*i.e.* pre- 'L') were not. However, it should be noted that no distinction could be made between petrol and diesel cars from the video analysis, and it can only be assumed that the ratio between non-catalyst and catalyst petrol cars would not have changed had such a distinction been possible. Those commercial vehicles having a weight less than 3.5 tonnes were labelled as light goods vehicles (LGVs), and commercial vehicles having a weight greater than 3.5 tonnes were identified as heavy goods vehicles (HGVs). All buses were combined in a single category.

The LIDAR measurements and video data were analysed to established whether significant differences existed between the speed profiles measured for different sizes of vehicle, at different times of day, and in different directions of travel. Differences in the speed profiles of convoy and non-convoy vehicles were also examined. This was thought to be an important consideration, as any variation in the ease with which different types of vehicle could be tracked with the LIDAR could have led to a sampling bias.

During the investigation of the first scheme (scheme A - 75mm flat-top road humps), twelve people were asked to drive the instrumented cars along a route in Walton-on-Thames that included the section of road of interest. Each subject drove along the route in the instrumented car which corresponded most closely to their own car in terms of size and engine capacity. The driving sessions were conducted over a period of three days. The results of these instrumented car measurements, and their role in the process of developing gear selection patterns for the driving cycles, are presented in the next chapter of the Report.

4.2 Traffic flow

It has been shown that traffic calming tends to result in the diversion of traffic away from the affected roads (*e.g.* Webster and Mackie, 1996; Webster and Layfield, 1996). Traffic flows were therefore recorded in the study where possible, so that the overall effect of each scheme on emissions from the traffic on the affected roads could be calculated. The traffic flows recorded during the study are presented in Table 3. Automatic 24-hour counts were only undertaken for schemes A-E, with the information being supplied by the appropriate local authorities. No automatic counts were available for schemes F-I, though for schemes F, G and H an estimate of traffic flow after calming was made using the video record.

Table 3 Mean 24 hour traffic flows at each site

				Traffic flow (number of vehicles per day)			
Scheme	*Traffic calming measure*	*Stage*	*Direction*	*Weekdays*	*Saturdays*	*Sundays*	*Weekly total (2-way)*
A	75mm flat-top road humps	Before calming	Westbound	3477	2924	2338	45981
			Eastbound	3541	3183	2446	
		After calming	Westbound	2591	2253	1820	36298
			Eastbound	2894	2689	2111	*(-21%)*
B	80mm round-top humps	Before calming	Northbound	694	526	289	8023
			Southbound	600	529	210	
		After calming	Northbound	788	673	442	10248
			Southbound	843	546	431	*(+28%)*
C	1.7m-wide speed cushions	Before calming	Westbound	1232	1094	970	15886
			Eastbound	1126	1107	925	
		After calming	Westbound	1294	1236	957	18073
			Eastbound	1417	1281	1044	*(+14%)*
D	Pinch point/speed cushion	Before calming	Eastbound	2356	2061	1267	31164
			Westbound	2478	2287	1379	
		After calming	Eastbound	2219	1843	1719	31976
			Westbound	2546	2380	2209	*(+3%)*
E	Raised junction	Before calming	Northbound	733	708	430	9776
			Southbound	777	710	369	
		After calming	Northbound	699	703	668	10485
			Southbound	845	741	656	*(+7%)*
F	Chicane	Before calming			Not available		
		After calming	Northbound	3924*		Not available	
			Southbound	2654*			
G	Build-out	Before calming			Not available		
		After calming	Northbound	2235*		Not available	
			Southbound	2242*			
H	Mini-roundabout	Before calming			Not available		
		After calming	Northbound	1670*		Not available	
			Southbound	1575*			
I	1.9m-wide speed cushions	Before calming			Not available		
		After calming			Not available		

** Approximate 12-hour count multiplied by a factor of 1.27 to covert to 24-hour count.*

The numbers in brackets in the last column of Table 3 indicate the percentage change in flow after calming. Although the flow of traffic through scheme A (75mm flat-top road humps) was found to have decreased, it actually increased through schemes B, C, D and E. The largest increase occurred at scheme B (80mm round-top road humps), where the total weekly two-way flow increased by 28% after calming. In some cases factors other than the traffic calming measures, such as seasonal variations and general growth in traffic, may have contributed to the observed changes in flow. Ideally, traffic counts would have been conducted immediately before and after the installation of each scheme. However, scheme implementation can often be subject to unforeseen delays, and this was one reason for the extended periods between the flow measurements at some of the sites.

4.3 Traffic composition

The percentages of the traffic flow in each vehicle category before and after installation of the traffic calming measures are shown in Table 4. In general, most of the traffic flows comprised passenger car and light goods vehicles. Very few HGVs and buses were observed on the roads investigated.

Where information on traffic composition was available before and after calming, there was generally a good agreement between the proportions of vehicles in each category. However, there were a number of discrepancies which cannot easily be explained. For example, there was a substantial difference between the proportion of medium-size cars in the ‘Pre-L’ category before and after the introduction of the raised junction. The main exception was scheme I, for which the large discrepancies were probably due to the surveys before and after calming having been conducted on different roads.

Table 4 Percentage of vehicles observed by category during video monitoring at each site

				Percentage of traffic flow in category										
				Small cars		*Medium cars*		*Large cars*		*LGVs*				
Scheme	*Traffic calming measure*	*Stage*	*Number of vehicles*	*Pre-'L'*	*'L' and after*	*Pre-'L'*	*'L' and after*	*Pre-'L'*	*'L' and after*	*Pre-'L'*	*'L' and after*	*HGVs*	*Buses*	*Total %*
A	75mm flat-top road humps	Before calming	2049	18.2	7.1	36.5	15.3	6.9	2.4	7.3	3.1	1.0	2.2	100
		After calming	1632	15.9	8.0	37.5	17.0	8.4	2.6	4.6	2.8	1.0	1.6	100
B	80mm round-top humps	Before calming	845	15.0	4.0	40.2	14.9	8.4	4.1	7.6	5.0	0.4	0.4	100
		After calming	403	17.1	6.5	39.0	13.9	7.2	2.2	8.2	5.0	0.2	0.7	100
C	1.7m-wide speed cushions	Before calming	688	14.2	7.6	42.9	13.7	4.9	7.6	7.0	4.5	2.0	0.6	100
		After calming	650	14.0	5.7	35.1	11.9	10.0	3.7	8.9	6.7	0.8	3.2	100
D	Pinch point/speed cushion	Before calming	487	10.5	6.0	38.0	15.6	11.5	3.7	7.8	4.9	1.0	1.0	100
		After calming	1282	11.8	8.4	36.0	16.5	10.1	2.5	4.5	6.2	0.9	3.1	100
E	Raised junction	Before calming	341	15.3	7.3	42.8	12.6	10.5	1.2	6.2	3.2	0.3	0.6	100
		After calming	285	13.0	8.0	22.8	4.9	30.2	11.6	4.6	3.9	1.0	0.0	100
F	Chicane	Before calming	Not available											
		After calming	640	10.8	11.6	17.5	10.3	18.6	16.3	4.4	7.7	1.4	1.6	100
G	Build-out	Before calming	Not available											
		After calming	672	13.1	9.4	21.1	9.8	20.5	15.6	3.7	4.6	1.0	1.0	100
H	Mini-roundabout	Before calming	Not available											
		After calming	215	7.0	8.4	15.4	14.9	10.7	10.2	7.4	13.5	3.7	8.8	100
I	1.9m-wide speed cushions	Before calming	861	18.5	9.1	35.0	17.9	7.6	2.9	5.8	2.7	0.1	0.5	100
		After calming	363	9.9	13.0	14.0	14.0	17.1	18.5	5.5	8.0	0.0	0.0	100

Because older vehicles are continually being replaced, there should have been a general trend towards an increase in the proportion of cars and LGVs in the 'L and after' category. In fact, this only occurred in just over half of the reported cases.

There is a possibility that the introduction of traffic calming could cause a change in the composition of the traffic on a particular road. For example, the drivers of heavy goods vehicles might be inclined to adopt an alternative route in order to avoid road humps. Figure 20 shows the average percentage of traffic flow in each vehicle category before and after calming. The data for schemes F-I are excluded from this calculation. The results relate to measurements on a small number of schemes, but they do suggest that there was no strong tendency for the composition of the traffic to be affected. However, it could be argued that the balance between medium-size and large cars had shifted slightly in favour of the latter after calming.

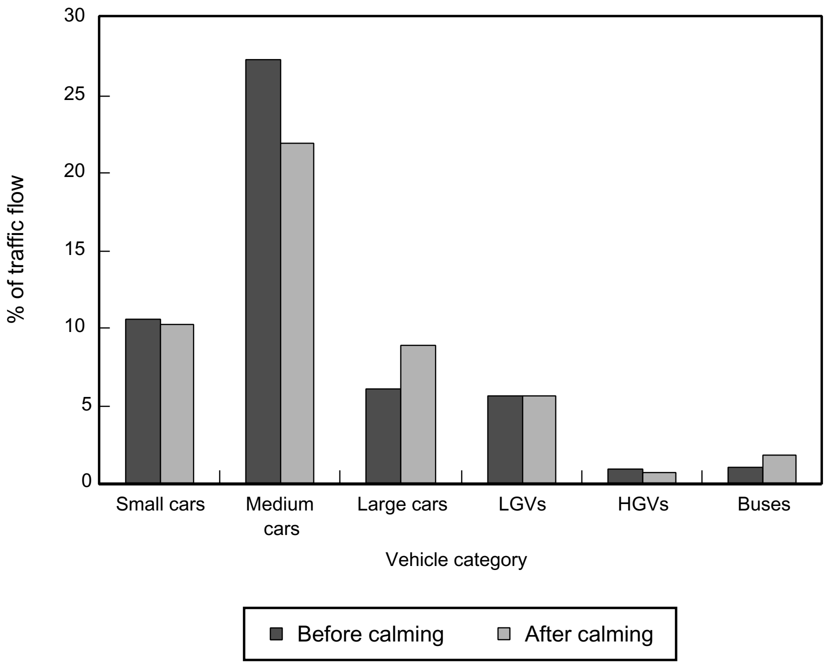


Figure 20 Average proportion of traffic flow in each vehicle category before and after the introduction of traffic calming (schemes A-E only)

4.4 Vehicle speed

Statistics relating to the mean speed, and the mean standard deviation of speed, of the profiles for the vehicle categories targeted using the LIDAR are shown in Tables 5 and 6. For each scheme and vehicle category the sample sizes can be inferred from the information presented in Table 4.

At the six sites where remote speed measurements were obtained before calming, the mean speed of passenger cars varied between 38 km/h (24 mph) and 53 km/h (33 mph). This suggests that, even though each road was in a residential area and had a 30mph speed limit, there were some differences in the nature of the sites monitored. The differences in the speeds before calming may have been attributable to factors which could not be controlled, such as carriageway width, the extent of on-road parking, and pedestrian activity. The speeds of passenger cars after calming varied between 23 km/h (14 mph) and 42 km/h (26 mph), with the actual speed reduction, excluding the three sites for which no measurements were obtained before calming, ranging from 10 km/h (6 mph) to 19 km/h (12 mph). The extent of the speed reduction effected by each traffic calming measure was much larger than the error on the speed measurements. The largest speed reductions were observed for scheme I, and once again this was probably due in part to the surveys before and after calming having been conducted on different roads. There was no evidence to suggest that passenger car size had an impact on speed before or after calming, or on the magnitude of the speed reduction achieved.

The speeds of LGVs changed from between 36 km/h (22 mph) and 50 km/h (31 mph) before calming to between 20 km/h (12 mph) and 42 km/h (26 mph) after calming, with a speed reduction of between 10 km/h (6 mph) and 17 km/h (11 mph). As with passenger cars, the extent of the speed reduction effected by each traffic calming measure was much larger than the error on the speed measurements.

The effects of traffic calming on the speeds of HGVs and buses were more variable, but this was probably due in part to the small sample sizes. The relatively low number of measurements for these vehicle categories also produced a larger degree of uncertainty on each mean value, a point that is illustrated by the larger confidence limits in Table 5.

The mean standard deviation of the speed measurements in the profiles of vehicles travelling through most of the schemes tended to increase after calming. These increases reflect the tendency of drivers to accelerate between

Table 5 Mean speeds of the vehicles measured using the LIDAR before and after the installation of traffic calming measures at each site

			Mean speed of vehicles in category in km/h, with 95% confidence intervals in brackets					
Scheme	*Traffic calming measure*	*Stage*	*Small cars*	*Medium cars*	*Large cars*	*LGVs*	*HGVs*	*Buses*
A	75mm flat-top road humps	Before calming	52.1 (±0.6)	52.2 (±0.4)	52.5 (±1.0)	50.0 (±1.0)	45.6 (±2.4)	48.8 (±2.4)
		After calming	34.9 (±0.7)	36.8 (±0.5)	36.6 (±1.1)	33.1 (±1.3)	25.9 (±1.5)	28.5 (±2.7)
		Change (km/h)	-17.2	-15.4	-15.9	-16.9	-19.7	-20.3
B	80mm round-top humps	Before calming	42.7 (±1.2)	41.7 (±0.7)	42.5 (±1.5)	41.6 (±1.5)	34.9(±9.2)	34.0(±9.2)
		After calming	28.1 (±1.0)	27.7 (±0.6)	28.0 (±1.5)	26.7 (±1.3)	25.3 (±2.4)	23.0 (N/A)
		Change (km/h)	-13.4	-14.0	-14.5	-14.9	-9.6	-11.0
C	1.7m-wide speed cushions	Before calming	45.4 (±1.4)	43.5 (±0.8)	44.3 (±1.6)	44.2 (±1.7)	43.3 (±4.0)	42.5 (±5.1)
		After calming	28.2 (±1.3)	31.2 (±0.7)	32.1 (±1.9)	33.3 (±1.5)	42.4 (±5.7)	29.4 (±3.7)
		Change (km/h)	-17.2	-12.3	-12.2	-10.9	-0.9	-13.1
D	Pinch point/speed cushion	Before calming	45.2 (±1.9)	47.1 (±1.0)	47.4 (±2.1)	47.1 (±2.2)	41.1 (±6.7)	36.7 (±1.8)
		After calming	35.1 (±1.1)	35.5 (±0.6)	36.4 (±1.3)	37.4 (±1.5)	36.3 (±3.4)	34.4 (±2.0)
		Change (km/h)	-10.1	-11.6	-11.0	-9.7	-4.8	-2.3
E	Raised junction	Before calming	38.9 (±1.5)	38.3 (±1.1)	37.9 (±2.0)	35.6 (±2.7)	39.5 (N/A)	33.9 (N/A)
		After calming	23.8 (±1.3)	23.1 (±1.1)	23.9 (±0.9)	20.3 (±1.5)	19.6 (±1.3)	N/A
		Change (km/h)	-15.1	-15.2	-14.0	-15.3	-19.9	N/A
F	Chicane	Before calming	Not available					
		After calming	42.1 (±1.0)	41.8 (±1.0)	42.4 (±0.8)	41.6 (±1.5)	29.6 (±3.5)	32.4 (±5.0)
		Change (km/h)	Not available					
G	Build-out	Before calming	Not available					
		After calming	34.7 (±0.9)	35.1 (±0.7)	35.7 (±0.8)	33.2 (±1.5)	28.5 (±2.2)	26.4 (±2.2)
		Change (km/h)	Not available					
H	Mini-roundabout	Before calming	Not available					
		After calming	30.9 (±1.7)	29.5 (±1.2)	31.5 (±1.6)	28.6 (±1.8)	22.9 (±1.9)	21.3 (±1.2)
		Change (km/h)	Not available					
I	1.9m-wide speed cushions	Before calming	51.0 (±1.0)	52.8 (±0.8)	51.6 (±1.6)	49.4 (±2.2)	36.2 (±5.7)	45.3 (N/A)
		After calming	33.6 (±1.5)	33.7 (±1.4)	34.4 (±1.2)	32.6 (±2.3)	Not available	
		Change (km/h)	-17.4	-19.1	-17.2	-16.8	Not available	

Table 6 Mean speed standard deviation of the vehicles measured using the LIDAR before and after the installation of traffic calming measures at each site

			Standard deviation of speed of vehicles in category in km/h, with 95% confidence intervals in brackets					
Scheme	*Traffic calming measure*	*Stage*	*Small cars*	*Medium cars*	*Large cars*	*LGVs*	*HGVs*	*Buses*
A	75mm-high flat-top road humps	Before calming	1.6 (±0.1)	1.6 (±0.1)	1.5 (±0.2)	1.7 (±0.2)	1.7 (±0.4)	2.0 (±0.3)
		After calming	3.1 (±0.2)	2.9 (±0.1)	2.9 (±0.2)	3.8 (±0.3)	3.9 (±0.6)	5.5 (±0.7)
		Change (km/h)	+1.5	+1.3	+1.4	+2.1	+2.2	+3.5
B	80mm round-top humps	Before calming	3.4 (±0.3)	3.4 (±0.2)	3.5 (±0.4)	3.4 (±0.4)	3.5 (±2.3)	7.1 (±2.3)
		After calming	3.0 (±0.3)	3.3 (±0.2)	3.3 (±0.4)	3.3 (±0.3)	4.4 (±0.8)	4.8 (N/A)
		Change (km/h)	-0.4	-0.1	-0.2	-0.1	+0.9	-2.3
C	1.7m-wide speed cushions	Before calming	3.4 (±0.4)	3.3 (±0.2)	2.9 (±0.5)	3.8 (±0.4)	3.6 (±1.0)	4.0 (±0.8)
		After calming	5.2 (±0.4)	4.4 (±0.2)	4.6 (±0.5)	4.2 (±0.4)	4.1 (±0.8)	3.6 (±0.8)
		Change (km/h)	+1.8	+1.1	+1.7	+1.4	+0.5	-0.4
D	Pinch point/speed cushion	Before calming	3.2 (±0.5)	2.7 (±0.2)	2.6 (±0.3)	2.7 (±0.4)	2.2 (±1.0)	1.0 (±0.1)
		After calming	3.4 (±0.2)	3.5 (±0.2)	3.6 (±0.3)	3.5 (±0.4)	2.9 (±0.6)	2.9 (±0.8)
		Change (km/h)	+0.2	+0.8	+1.0	+0.8	+0.7	+1.9
E	Raised junction	Before calming	3.4 (±0.5)	3.4 (±0.3)	2.9 (±0.6)	3.4 (±0.5)	3.1 (N/A)	4.2 (N/A)
		After calming	3.5 (±0.3)	3.4 (±0.2)	3.8 (±0.2)	3.8 (±0.5)	3.2 (±0.6)	N/A
		Change (km/h)	+0.1	0.0	+1.1	+0.4	+0.1	N/A
F	Chicanes	Before calming	Not available					
		After calming	3.0 (±0.3)	2.8 (±0.2)	3.0 (±0.2)	3.1 (±0.4)	5.2 (±1.7)	3.7 (±0.9)
		Change (km/h)	Not available					
G	Build-out	Before calming	Not available					
		After calming	2.9 (±0.3)	2.6 (±0.2)	2.6 (±0.2)	3.1 (±0.4)	3.7 (±0.9)	4.9 (±1.1)
		Change (km/h)	Not available					
H	Mini-roundabout	Before calming	Not available					
		After calming	3.2 (±0.7)	2.8 (±0.5)	2.7 (±0.4)	3.5 (±0.5)	2.8 (±0.6)	3.5 (±0.7)
		Change (km/h)	Not available					
I	1.9m-wide speed cushions	Before calming	2.7 (±0.3)	2.7 (±0.2)	2.8 (±0.5)	3.1 (±0.5)	2.7 (±0.7)	3.1 (N/A)
		After calming	3.1 (±0.4)	2.8 (±0.3)	2.8 (±0.3)	3.3 (±0.6)	Not available	
		Change (km/h)	+0.4	+0.1	0	+0.2	Not available	

discrete traffic calming measures. The main exception was scheme B (round-top road humps), where the speed standard deviation of most vehicles decreased after calming. The reason for this is unclear.

4.5 Implications for emission test programme

Only small differences were observed between the means and standard deviations of the small, medium, and large car categories before calming. Larger, but still small, differences were apparent after calming. The main issue concerning these measurements was not whether statistically significant differences in speed existed among the three car categories, but whether these differences would be significant when translated to emissions. In practice, quite large differences in speed would be necessary to show significant differences in emission rates, since emission measurements tend to show poor repeatability. For these reasons, one driving cycle was considered sufficient to represent all three categories of cars.

An assessment of the means and standard deviations of the speed profiles for each category of vehicle indicated that there were only small differences between those travelling in a convoy and those not in a convoy. Small differences were also observed between the means and standard deviations of the profiles obtained during different periods of the week. Once again, it has been assumed that the effects of these differences on emissions would have been minimal.

5 Driving cycles

So that the impacts of each traffic calming measure on emissions could be determined under controlled laboratory conditions, driving cycles were formulated to represent vehicle operation before and after the introduction of the schemes. For the reasons expressed in section 4.5, each driving cycle was used to test all the vehicles included in the emission measurement programme.

For the first scheme investigated in the study (scheme A: 75mm flat-top road humps), the speed profiles of around 500 cars were measured using the LIDAR before and after calming. The speed profile of each vehicle was characterised by its mean speed and standard deviation of speed, and the vehicle itself was classified according to its direction of travel and the size criteria given in chapter 4. From each of these sets of measurements, a random sample of around 100 profiles was selected. An equivalent number of instrumented car speed profiles, each having mean and standard deviation values matching those of one of the LIDAR profiles, were then identified from the instrumented car measurements. These instrumented car ‘mini-cycles’, containing road speed and engine speed data, were combined to form the two final driving cycles for the scheme, one representing vehicle operation before calming and one representing operation after calming.

Each final driving cycle was constructed by matching the ends of the 100 mini-cycles in a way that maximised the number included, although a number of artificial joining sections had to be employed. These joining sections were only inserted to ensure a smooth transition between some of the mini-cycles, and their total duration was short compared to the duration of the entire driving cycle.

The drivability of these first two cycles on a chassis dynamometer was tested at AEA Technology in Harwell. The tests showed that, although the cycles were drivable, they tended to have an ‘unnatural’ feel. This was attributed to the short, but rapid, accelerations and decelerations required to follow the cycle at some points. The coarse resolution of the speed measurements was considered to be responsible for this problem. Subsequently, a ‘moving average’ smoothing function was applied to the driving cycle data, and further dynamometer tests showed that the resulting cycle was much easier to drive. This smoothing function took the form $s_t' = (s_{t-1} + (2s_t) + s_{t+1})/4$, where s_t is the speed at time t, and s_t' is the smoothed speed at time t. The function was applied to all the driving cycles developed during the study.

In each mini-cycle contributing to a final driving cycle, every value of road speed was accompanied by a value denoting engine speed, and for each pair of readings in the final driving cycle, an overall gear ratio (km/h per 1000 rev/min) was calculated. In order to determine gear selection patterns for small, medium, and large cars, it was then necessary to determine the gear selection corresponding to each gear ratio value for the three instrumented cars. Using over four hours of second-by-second data for each instrumented car from the scheme A study, frequency distributions of gear ratio were obtained.

The example provided in Figure 21 illustrates the shape of the gear ratio distributions obtained for the Ford Fiesta before and after calming. The figure shows that the second and third gears were used more frequently after calming than before calming. From the distribution for each vehicle, it was possible to estimate a range of gear ratios corresponding to each gear selection. A change from one gear to the next was defined as the minimum frequency value between peaks. For example, for the Fiesta the range of gear ratios corresponding to fourth gear was taken to be 23.4 to 31.9. For each instrumented car, the ranges of gear ratio thus obtained were then used as the criteria by which the gear-selection pattern of the driving cycle was determined.

However, the application of this approach resulted in a series of gear selections which were unlikely to have occurred in reality, in terms of both their nature and frequency. Two main reasons were identified for this problem:

1 The driving cycles incorporated road speed and engine speed data for three different vehicles, each with their own characteristic gear ratios. This was caused by the amalgamation of the data from the three instrumented cars. Therefore, the criteria used to determine gear selections were being applied to incompatible engine speed data.

2 A large number of short mini-cycles (5-7 seconds duration) were linked to form the driving cycles. This meant that there were many instances where the data associated with one driver were joined to the data from

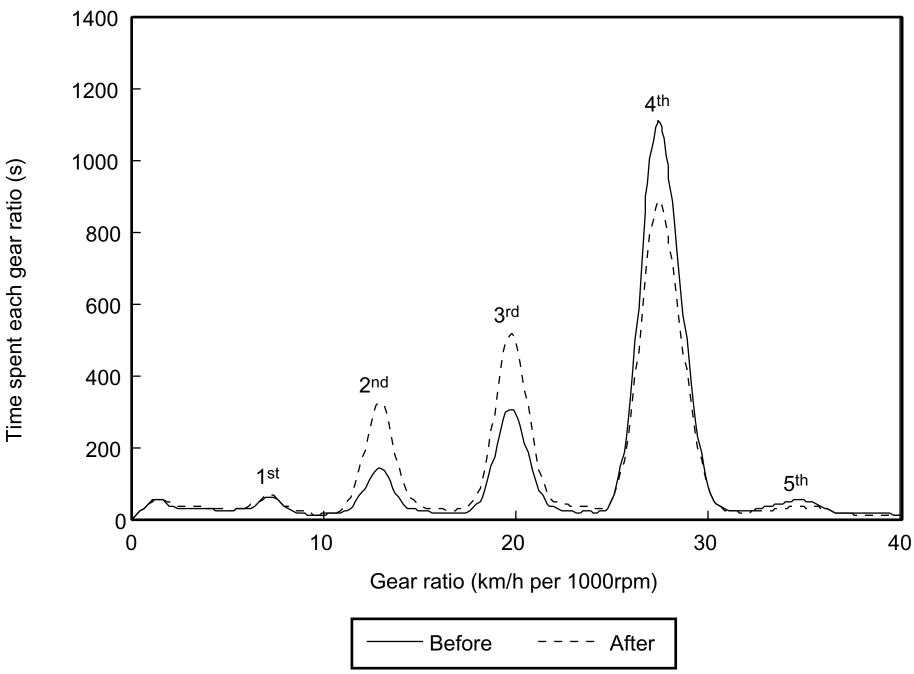


Figure 21 Gear ratio distribution: Ford Fiesta before and after calming

another. For example, a particular mini-cycle from one driver could end at 40 km/h in third gear. The subsequent mini-cycle could come from another driver and, although starting at 40 km/h, could be associated with fifth gear. This resulted in a gear change (third to fifth) in the final driving cycle which would not have occurred in reality. Additionally, it was considered that such a pattern of gear selections, when combined with a complex driving cycle, would prove difficult to follow on the chassis dynamometer.

Consequently, an alternative approach was adopted in order to determine a gear selection pattern for the driving cycles. This entailed the determination of a pattern of gear selections based on the typical speed associated with each gear change. From the large data set used to determine the ranges of gear ratios associated with each gear, the mean speeds associated with each gear change were determined. Only changes between adjacent gears were considered, and the range conditions were separated according to acceleration and deceleration phases. The peak corresponding to fifth gear was poorly defined for all three vehicles. An analysis of the gear selections through the study section showed that the usage of fifth gear was minimal, and this gear was therefore omitted from the driving cycle development.

The differences between the gear change speeds for the three vehicles were small, as were the differences before and after calming. Therefore, a single set of mean gear-change speeds was adopted for use with all vehicles and all driving cycles. As a result, the instrumented cars were no longer required for the other traffic calming measures, and the LIDAR speed profiles alone were used to construct the final driving cycles. These profiles were selected at random from the larger sample of measured profiles. The overall mean speeds associated with each gear change are given in Table 7. It was assumed that when decelerating a driver would remain in gear until either the speed attained during the deceleration phase coincided with one of the change-down speeds in Table 7 or, to maintain drivability, an acceleration was required from a speed lower than a change-up speed. A period of two seconds was allowed for each gear change. This is the same time period that is allowed for a change of gear during the ECE-15 legislative test cycle.

Table 7 Mean speed associated with each gear change: all vehicles

Gear change	*Mean speed of gear change (km/h)*
1-2	23.78
2-3	37.38
3-4	46.63
4-3	26.87
3-2	16.97
2-1	6.69

Using this approach, driving cycles were developed to represent vehicle operation before and after calming for schemes A-E. For schemes F, G and H, remote speed measurements could only be obtained after the traffic calming measures had been installed. Consequently, substitute cycles representing vehicle operation before the introduction of these measures were developed from the cycles constructed for some of the other schemes.

For scheme F (chicane), it was assumed that the last 90 seconds of the ‘before calming’ cycle for scheme D (pinch point/speed cushion) would provide the most accurate representation of vehicle operation before calming on Great Hollands Road. This portion of driving cycle was selected because it had an average speed which corresponded to the typical speed at chicane schemes before calming. This typical speed was reported by Sayer *et al.* (1998) to be around 56 km/h (35 mph), based on spot speed measurements at a number of locations. It should be noted that the resulting cycle was unique in the study, in that no gear changes were required. However, this was probably a fair reflection of the real world situation given that the road was comparatively wide, with an open aspect and a low volume of traffic.

A similar process was used to develop ‘before calming’ driving cycles for schemes G (build-out) and H (mini-roundabout). For these two schemes, the same cycle was used. The cycle was a shortened version of that used for scheme B (round-top road hump). Because no spot speed measurements were available for these two traffic calming measures, the cycle was selected because it had an average speed which was close to the average speed of all the other ‘before calming’ driving cycles.

The final driving cycles representing vehicle operation at all schemes before and after calming, including the associated patterns of gear selections, are illustrated in Figures 22-30. Statistics relating to each driving cycle are provided in Table 8.

6 Exhaust emissions

Exhaust emission measurements were conducted by AEA Technology, based on the driving cycles supplied by TRL. This chapter of the Report includes details of the vehicles subjected to emissions testing and the test procedure, and summarises the test results.

6.1 Vehicle selection and test procedure

At the start of the study, twelve in-service petrol cars and three in-service diesel cars were selected from a variety of sources by AEA for the emission test work. The petrol cars were categorised according to the level of emission control (*i.e.* whether or not the car was equipped with a catalyst) and vehicle size. The distinction between ‘small’, ‘medium’, and ‘large’ cars was defined in terms of engine size, rather than the vehicle length criteria used during the speed measurements. No size differentiation was applied to the diesel cars. The distribution of the test cars between the categories is shown in Table 9.

Although an effort was made to ensure that the same fifteen vehicles were used throughout the entire study, this could not be achieved in practice and several changes were required. When a vehicle had to be withdrawn from the test programme, it was replaced by a vehicle which fitted

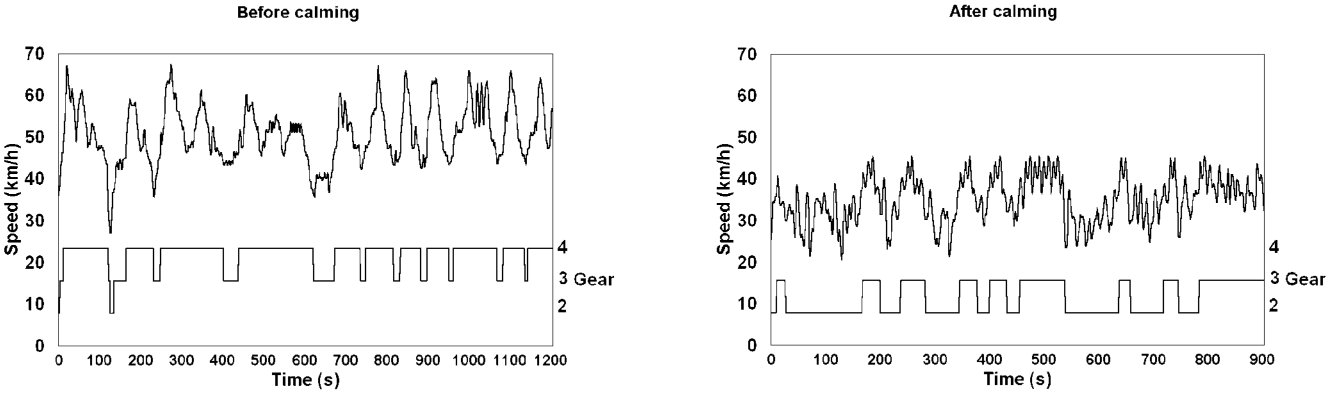


Figure 22 Driving cycles—Scheme A: 75mm flat-top road humps

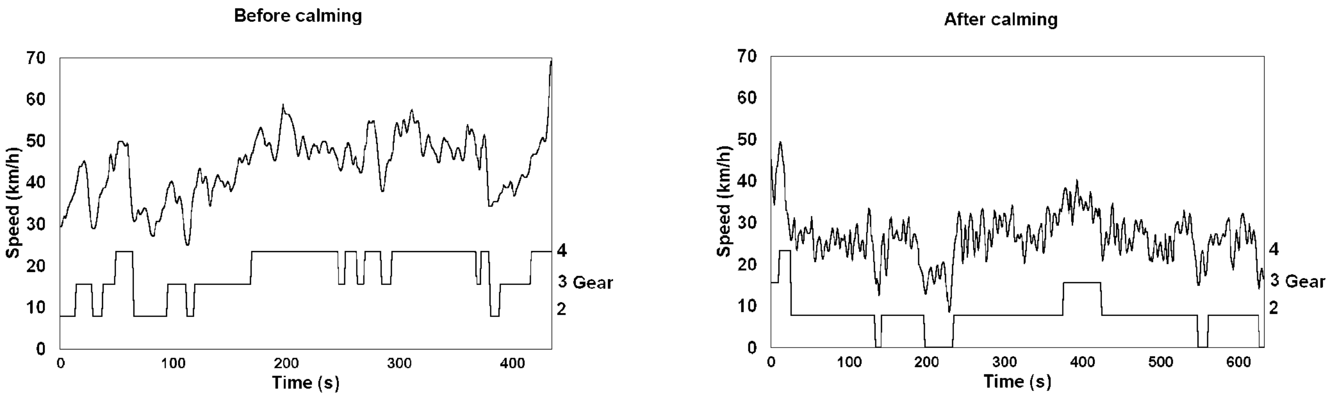


Figure 23 Driving cycles—Scheme B: 80mm round-top road humps

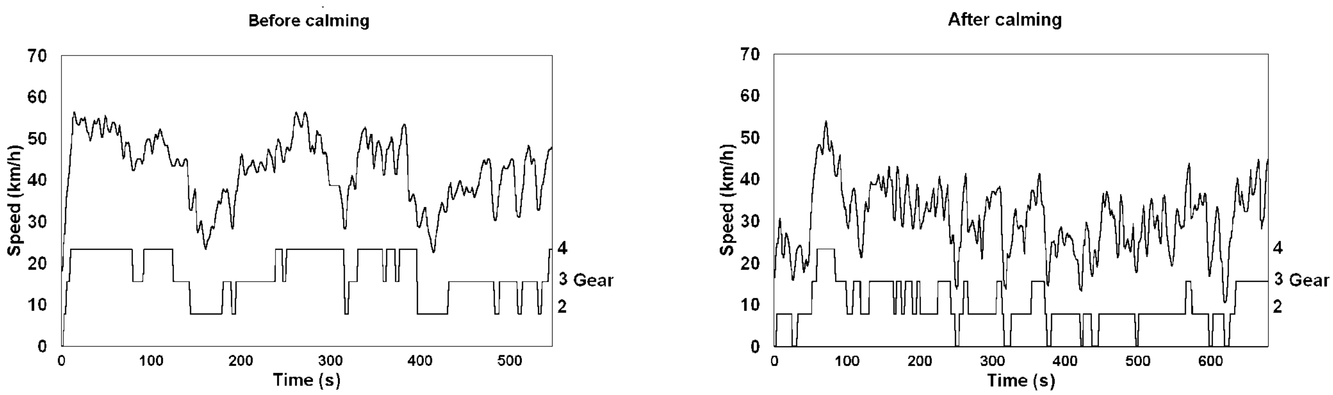


Figure 24 Driving cycles—Scheme C: 1.7m-wide cushions

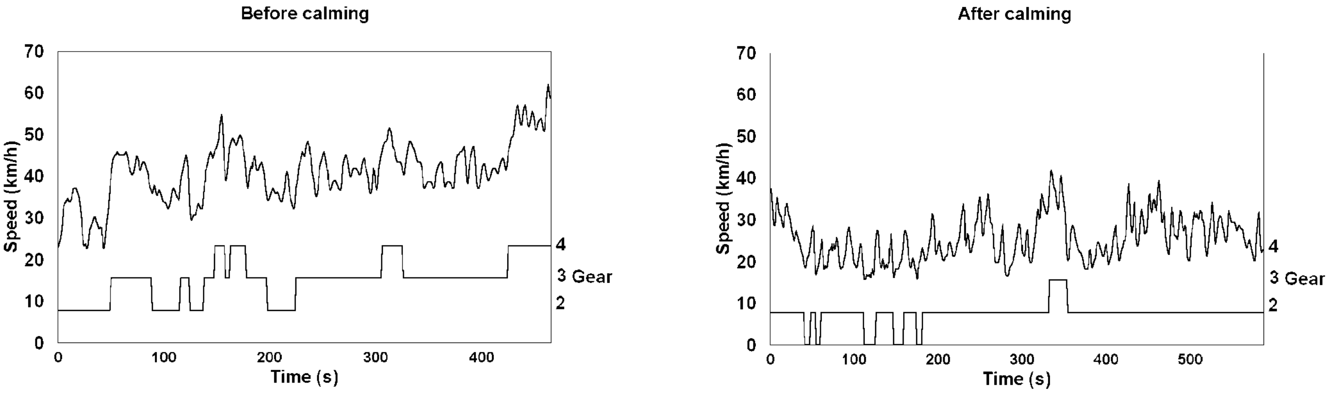


Figure 25 Driving cycles—Scheme D: combined pinch point and speed cushion

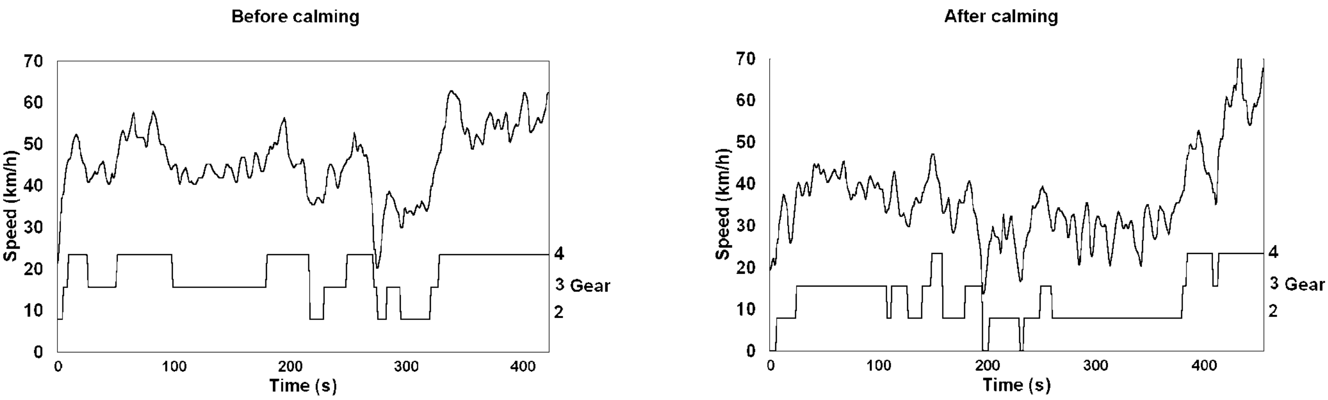


Figure 26 Driving cycles—Scheme E: raised junction

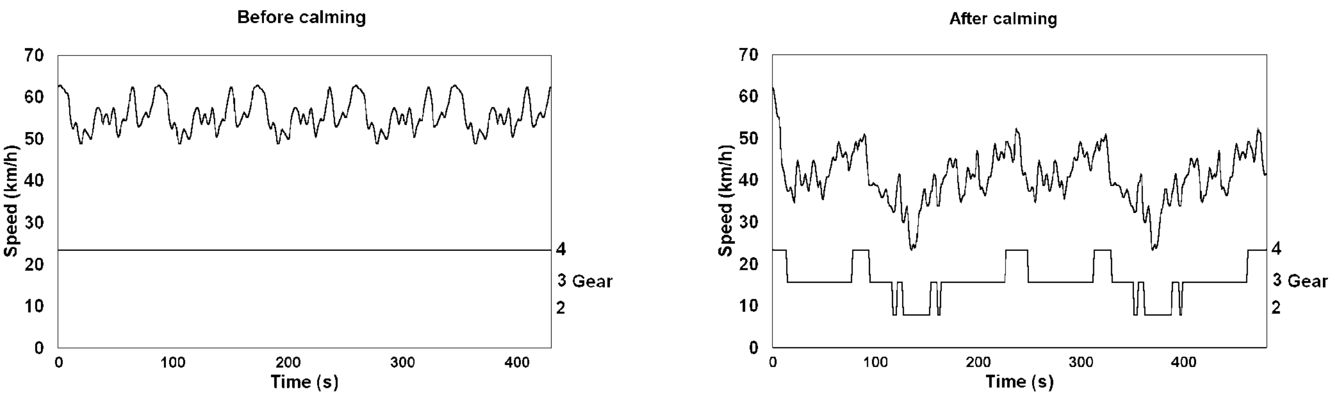


Figure 27 Driving cycles—Scheme F: chicane

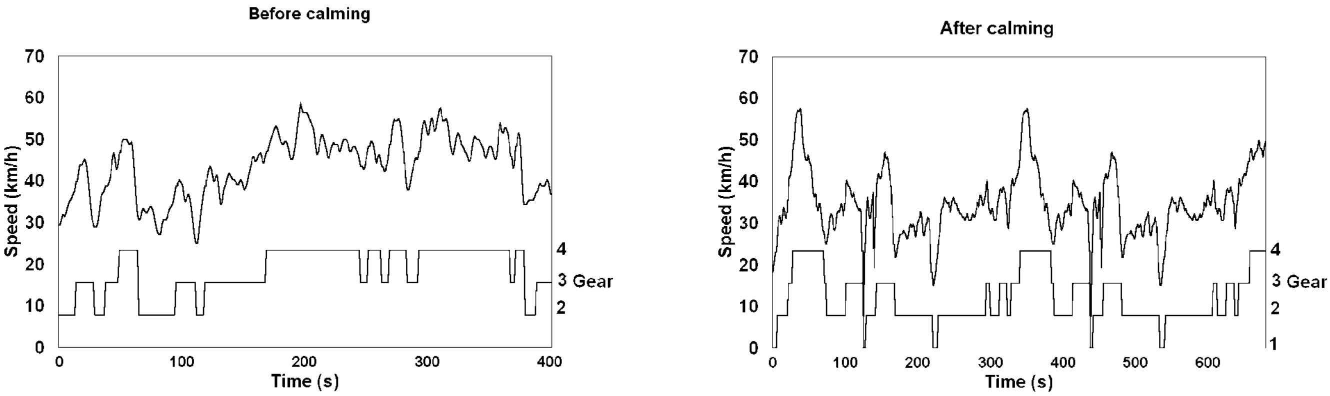


Figure 28 Driving cycles—Scheme G: build out

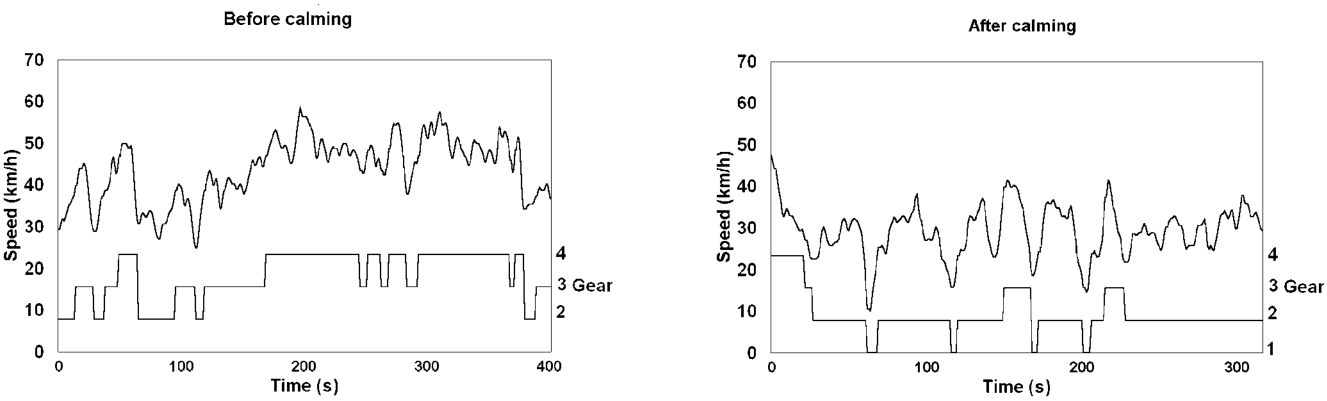


Figure 29 Driving cycles—Scheme H: mini-roundabout

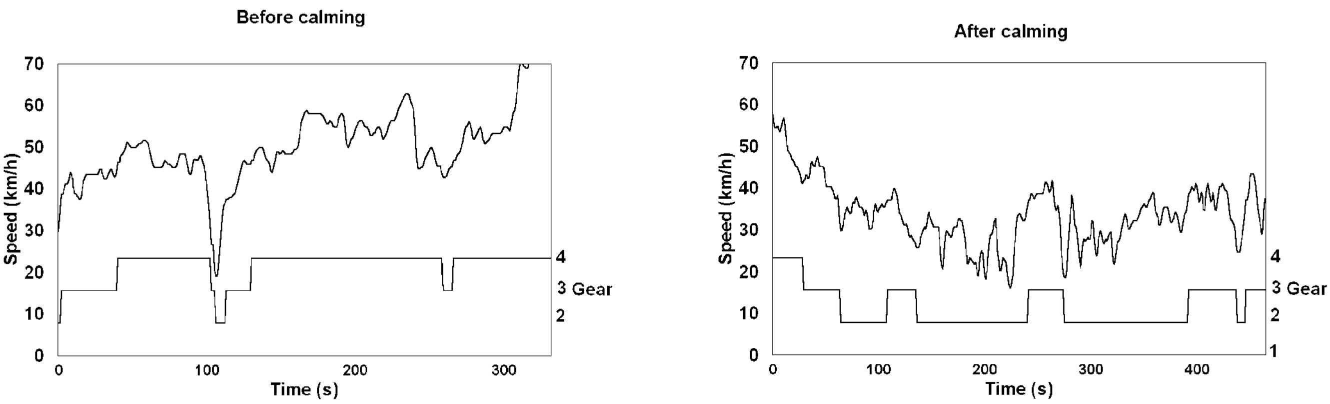


Figure 30 Driving Cycles—Scheme I 1.9m-wide cushions

Table 8 Driving cycle characteristics

			Driving cycle				
				Speed (km/h)			
Scheme	*Traffic calming measure*	*Stage*	*Duration (s)*	*Mean*	*St.Dev.*	*Maximum*	*Minimum*
A	75mm flat-top road humps	Before calming	1204	50.71	6.95	67.36	26.98
		After calming	903	34.97	5.44	45.33	20.51
B	80mm round-top road humps	Before calming	434	43.91	7.52	69.19	24.94
		After calming	632	26.65	5.85	49.48	8.45
C	1.7m-wide speed cushions	Before calming	547	42.46	8.06	56.32	18.10
		After calming	678	30.53	7.98	53.90	10.46
D	Pinch point/speed cushion	Before calming	422	46.05	8.10	62.75	20.11
		After calming	454	36.39	10.21	72.41	13.68
E	Raised junction	Before calming	465	41.08	6.92	61.95	22.53
		After calming	587	25.56	5.43	41.82	15.68
F	Chicanes	Before calming	429	55.61	3.76	62.75	48.67
		After calming	480	40.73	6.19	61.95	23.33
G	Build-out	Before calming	401	43.64	7.46	58.73	24.94
		After calming	679	34.43	7.96	57.52	7.64
H	Mini-roundabout	Before calming	401	43.64	7.46	58.73	24.94
		After calming	316	29.27	6.07	47.47	10.06
I	1.9m-wide speed cushions	Before calming	331	50.20	9.24	76.83	18.93
		After calming	464	33.77	7.50	57.52	16.09

Table 9 Vehicle categories in emission test programme

Engine size	*Petrol non-catalyst (pre-91/441/EEC)*	*Petrol catalyst (91/441/EEC and after)*	*Diesel*
Small (<1.4 litres)	2	2	
Medium (1.4 to 1.7 litres)	2	2	3
Large (>1.7 litres)	2	2	

in the same category. Consequently, some vehicles were used throughout the emission test programme, whilst others were only used with some of the schemes. The make, model, classification, registration year, engine size, and initial mileage of the vehicles used in the test programme are listed in Table 10.

NB: *It is not assumed that emission rates measured for each of these particular models are related to the model itself or the manufacturer, simply that that they are examples of in-service vehicles in the selected categories.*

In order to check that the vehicles were in a reasonable condition, and to ensure basic catalyst function where appropriate, they were subjected to the normal garage MoT emissions test (conforming to Regulation 92/55/EEC) prior to being driven over the traffic calming cycles. They were also subjected to basic safety checks to ensure their suitability for dynamometer operation. No adjustments were made and the vehicles were tested ‘as received’.

Equipment approved by the Vehicle Certification Agency was used for all tests. The cars were mounted on a standard chassis dynamometer, with the exhaust being connected to a constant volume sampling (CVS) system fitted with an 8"(200mm) diameter dilution tunnel. To determine the cycle average emissions, exhaust gas samples were collected in standard 60-litre tedlar bags. On completion of the driving cycle the sample was passed through a chemiluminescence analyser to determine NO_x concentrations, and non-dispersive infra-red (NDIR) analysers to determine CO and CO_2. The concentration of total hydrocarbons (THC) was determined using a flame ionisation detector (FID). For the diesel vehicles, particulate mass samples were collected on 47mm teflon-coated filter papers using a regulation sample train approved by the Vehicle Certification Agency, and hydrocarbons were measured using an on-line FID.

In addition to the bag sampling, emissions were logged on a continuous basis, with the regulation analyser suite being fed with a sample from the dilution tunnel and the output signals recorded on a PC-based logger. However, the continuous emission data are not included in this Report.

Four tests (*i.e.* two ‘calmed’ and two ‘uncalmed’) were conducted on each of the fifteen vehicles used in conjunction with a particular scheme. Each emission test was conducted with the engine and catalyst of the vehicle at their full operational temperatures prior to the first test.

Table 10 Details of vehicles tested

Vehicle reference number	Make	Model	Fuel type	Catalyst	Emission control level	Size/ class	Year	Engine size (l)	Mileage*
1	Ford	Fiesta	Petrol	No	83/351/EEC	Small	1990	1.1	86,000
2	Ford	Fiesta			(ECE Reg. 15.04)	Small	1991	1.1	98,000
3	Fiat	Panda				Small	1987	1.0	92,000
4	Rover	Metro				Small	1991	1.1	26,000
5	Rover	214Si				Medium	1990	1.4	100,000
6	Bedford	Astra				Medium	1987	1.6	21,000
7	Ford	Scorpio				Large	1987	2.9	111,000
8	Renault	Savanna				Large	1990	1.7	84,000
9	VW	Polo	Petrol	Yes	91/441/EEC	Small	1993	1.1	57,000
10	Rover	Metro			(EURO 1)	Small	1992	1.1	43,000
11	Vauxhall	Corsa				Small	1993	1.2	79,000
12	Nissan	Micra				Small	1996	1.0	9,000
13	Rover	214Si				Medium	1993	1.4	N/A
14	Ford	Mondeo				Medium	1993	1.6	43,000
15	Ford	Mondeo				Medium	1995	1.6	N/A
16	Ford	Mondeo				Medium	1993	1.6	N/A
17	Vauxhall	Astra				Medium	1996	1.6	27,000
18	Volvo	940				Large	1991	2.0	95,000
19	Saab	900SE				Large	1996	2.0	26,000
20	Rover	Montego	Diesel	No	88/436 and 91/441/EEC	No size	1991	2.0	170,000
21	Peugeot	405DT			(EURO 1)	discrimination	1992	1.9	112,000
22	Peugeot	306Dt					1996	1.9	26,000

** Mileage at start of test programme (to nearest 1,000 miles)*
N/A = Not available

In order to warm up these components, a ‘preconditioning’ regulation EUDC cycle was driven until a target oil temperature of 90ºC was attained. The first test cycle was then started with minimal delay in order to ensure a consistent starting temperature. Two test cycles were driven, and then the bag samples were analysed. The vehicle was again warmed up over the EUDC cycle, and the two remaining tests and analyses were completed. However, some alterations were made to the order of the ‘calmed’ and ‘uncalmed’ tests during the test programme, and later in the programme the EUDC cycle was replaced as the means of achieving engine and catalyst warm-up by a 120km/h steady-speed cycle.

These changes in the preconditioning and test sequence increased the variability of the results in general, and for petrol catalyst cars in particular. Subsequent testing by AEA Technology has indicated that the nature of the preconditioning cycle, and any time gaps introduced during the testing, can influence the emission values obtained. However, the problem has not been entirely resolved, and the analysis of the data at this level of detail is beyond the scope of this Report.

6.2 Emission test results

A total of 542 individual emission tests were conducted by AEA Technology, with fuel consumption and exhaust emissions of four pollutants (CO, HC, NO_x, and CO_2) being recorded in each test. Total particulate matter was also recorded during the tests involving diesel vehicles. The results of the tests are listed by pollutant, scheme, and vehicle in Appendix A. For each pair of tests associated with a given pollutant, vehicle, and driving cycle, the emission values were averaged. The overall impact of a particular scheme, in terms of the percentage change in emissions, was then determined.

6.2.1 Emissions by vehicle type and by vehicle

The overall effects of all the traffic calming measures on the mean emissions of each pollutant from the petrol non-catalyst, petrol catalyst, and diesel vehicle samples, are illustrated in Figure 31. Clearly, emissions of all pollutants tended to be higher over the driving cycles designed to reflect vehicle operation after calming than over the cycles representing operation before calming. The percentage increases in the mean emission levels after calming are given in Table 11. The asterisks against some of the changes in Table 11 indicate where paired-sample *t*-tests showed that the increase in emissions was significant at the 95% confidence level.

Table 11 Percentage increases in mean emissions due to traffic calming

	Percentage increase in mean emission				
Vehicle category	CO	HC	NO_x	CO_2	PM
Petrol non-catalyst	34%*	50%*	1%	20%*	N/A
Petrol catalyst	59%*	54%*	8%	26%*	N/A
Diesel	39%*	48%*	28%*	26%*	30%*

** Change significant at 95% confidence level*
N/A = Not available

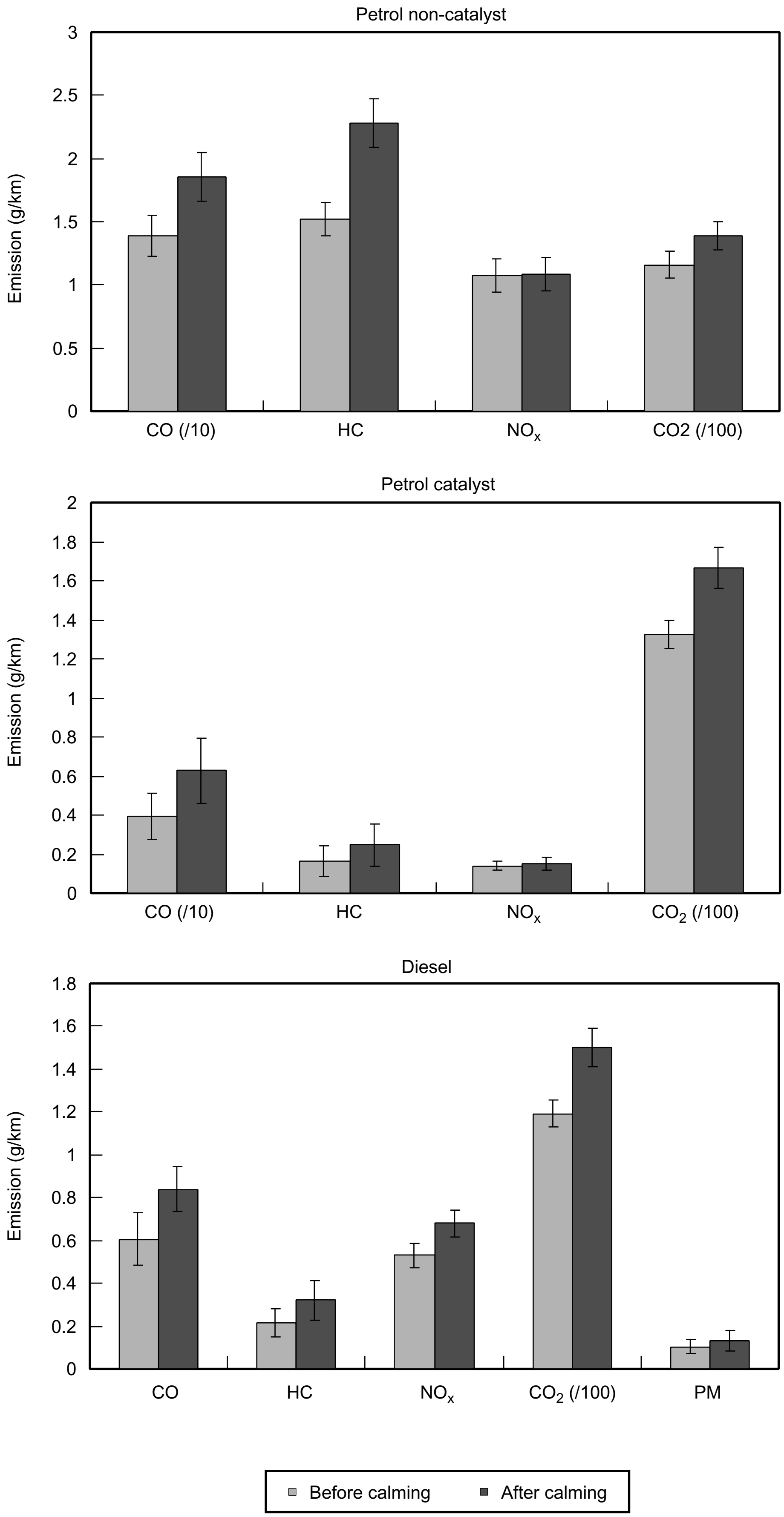


Figure 31 Mean emissions of CO, HC, NO_X, and CO_2 before and after calming for the three categories of vehicle. The I-beams represent the 95% confidence intervals on the means. For diesel cars, emissions of total particulate matter are also plotted

For petrol non-catalyst, petrol catalyst, and diesel cars, the increases in the mean emissions of CO were 34%, 59%, and 39% respectively. In each case, the increase in emissions was significant at a high level of confidence. For each vehicle category the increase in mean HC emissions was close to 50%, and again the increases were statistically significant. The mean emissions of NO_x from petrol vehicles increased slightly, but the change was not significant at the selected confidence level. NO_x emissions from diesel vehicles increased by around 30%. Emissions of CO_2 increased by 20-26%, and the increase was significant for each type of vehicle. For diesel vehicles, emissions of total particulate matter increased by 30%. These are some of the most important results of the study, since they appear to indicate that, for the vehicle fleet in the UK, the larger impacts of traffic calming on emissions recorded in some of the previous studies (see Table 1) are not likely to be typical.

For each vehicle tested, the mean emissions and fuel consumption after calming were plotted against the mean emissions and fuel consumption before calming in order to examine the consistency of the data. Some examples of these plots for petrol non-catalyst cars are shown in Figure 32. Similar plots for petrol catalyst and diesel cars are presented in Appendix B.

In most cases there was a reasonably good correlation between emissions before calming and emissions after calming, and the fitting of a quadratic regression function (forced through the origin) to the experimental data often resulted in a high R^2 value. For petrol non-catalyst cars the R^2 values for CO, HC, and NO_x ranged between 0.76 and 0.88. For the same pollutants, the range of R^2 values for petrol catalyst vehicles was 0.72-0.75, whilst for diesel vehicles the range was 0.82-0.91. For the fuel consumption and emissions of CO_2 of petrol vehicles there was a good correlation between the values before and after calming, with the R^2 equal to 0.91-0.95. For diesel cars the R^2 values for CO_2 and fuel consumption were 0.84 and 0.80 respectively. Emissions of particulate matter from diesel vehicles after calming were also well correlated with emissions before calming, with the relationship being characterised by an R^2 value of 0.81. The shapes of the fitted curves suggest that there was a slight tendency for the proportional increase in emissions associated with traffic calming to be slightly lower for vehicles which had high emissions before calming, and which might therefore be described as habitual high emitters. However, it should be noted that in some cases the R^2 value was highly influenced by a few high or low emitters. For example, for petrol catalyst cars the R^2 value for CO was reduced from 0.72 to 0.57 when the results for the two highest emitters were removed. For the individual vehicles within a particular category, the range of impacts of traffic calming on emissions of CO, HC, and NO_x was particularly wide. The ranges were largest for petrol catalyst cars. For these vehicles emissions of CO changed by between -30% and +639%, and HC emissions changed by between -91% and +285%.

The general representativeness of the absolute emission rates measured in the study was assessed by comparing

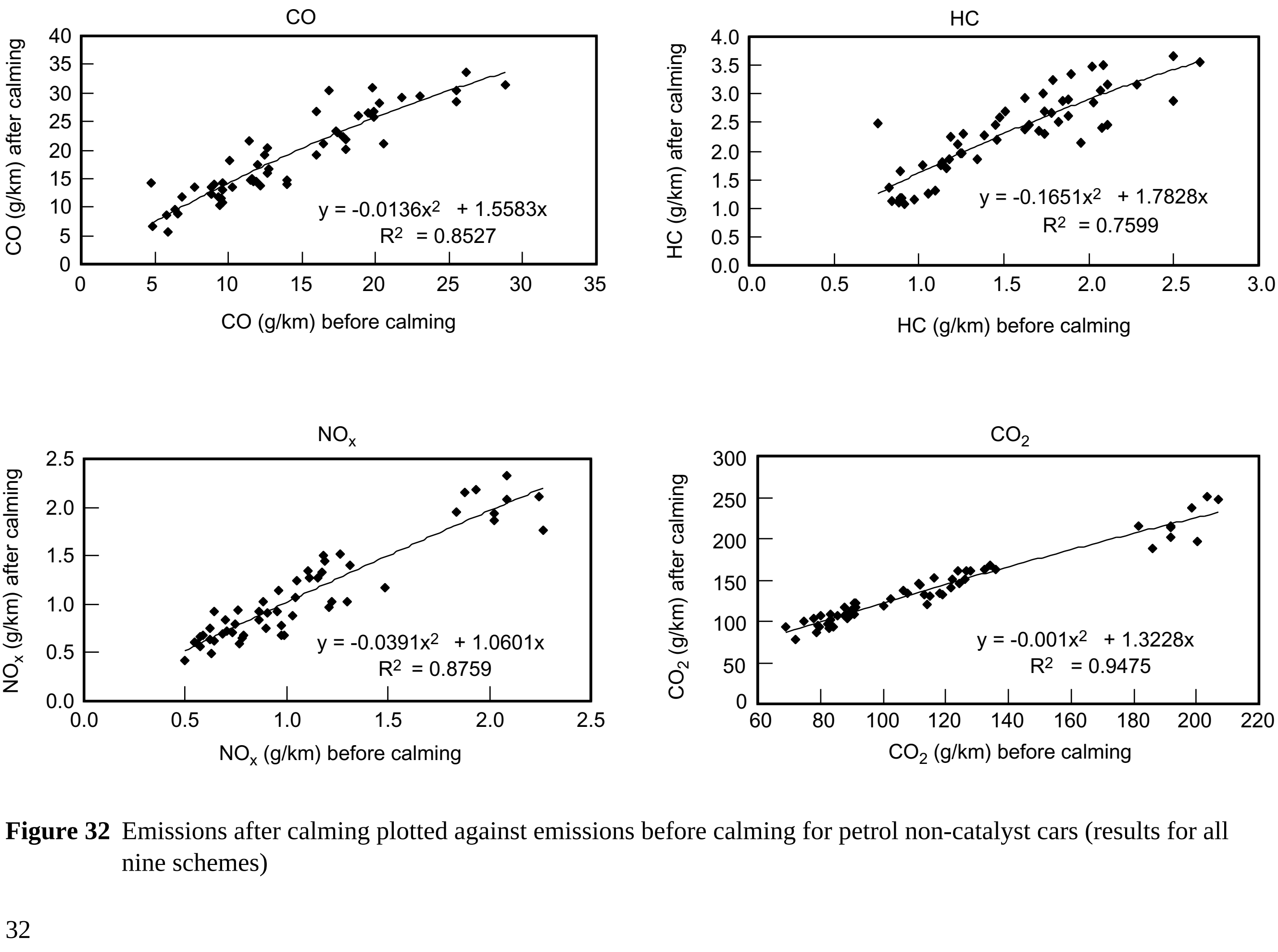


Figure 32 Emissions after calming plotted against emissions before calming for petrol non-catalyst cars (results for all nine schemes)

them with the results from a large-scale survey. It was noted in the outline of the study methodology that vehicle speed is currently the most widely used surrogate indicator for emissions, and that the characteristic variation of emissions with average trip speed is well known. Up-to-date speed-dependent emission functions (based on polynomial regression) for European road vehicles were developed in the European Commission's 4th Framework MEET project (European Commission, 1999). The mean emission rates measured in the TRL study are compared with the equivalent MEET emission rates in Table 12. The TRL and MEET emission rates were calculated in the same way; emission rates were determined for each cycle, and the nine values for a given pollutant, vehicle type, and situation (i.e. before or after calming) were then averaged). Where equations are provided in the MEET report for different engine size bands, the emission rates were weighted according to the distribution of engine sizes in the TRL vehicle sample. Although the emission rates in the TRL study (both before and after calming) were of the same order of magnitude as those in the MEET Report, there was generally only a fair level of agreement between the two. The observed differences are not particularly surprising given the variability of the MEET emission data and the relatively small vehicle sample in the TRL study. The variability of the MEET emission data was particularly high for petrol catalyst cars (equations fitted to the measurements for CO, HC, and NO_x were characterised by R^2 values of between 0.014 and 0.207). In addition, the relationships between speed and emissions described in MEET do not relate specifically to the modes of vehicle operation associated with traffic calming. Typical examples illustrating the discrepancies between the absolute emission rates measured in the TRL study and those provided in MEET is shown in Figure 33.

It could be argued that there tended to be a fairly good agreement between the overall percentage impacts recorded in the TRL study and those calculated using the MEET equations. These comparisons suggest that the average speed modelling approach used in MEET does, to a first approximation, give a good indication of the relative impacts of traffic calming on emissions per vehicle, though the reliability of the comparison between the different vehicle samples is somewhat hindered by the differences in absolute emission rates. Further comparisons between the percentage impacts calculated using the MEET emission functions and the TRL emission data at the level of individual schemes generally revealed a poor level of agreement.

The mean emission levels of each test vehicle before and after calming were also calculated. Some of the results for petrol catalyst cars are presented in Figure 34. No confidence limits could be plotted for vehicles 9, 10, 14, 15, and 16 because each of these vehicles was only tested over the cycles for one scheme. The variation in the absolute emission rates of individual vehicles was most pronounced for this category. For example, there was a difference of two orders of magnitude between the HC output of the highest and lowest emitters. The CO and HC emission levels of vehicle 10 appear to have been particularly high. This vehicle, which was equipped with a catalyst and a carburettor (rather than a fuel injection system), may therefore have had a disproportionate influence on the effects on petrol catalyst cars reported for scheme B (80mm round-top hump). There was less variation in the mean emission levels of the different petrol non-catalyst and diesel vehicles tested (see Appendix C).

6.2.2 Emissions by scheme

The mean emission rates of the petrol catalyst vehicles tested over the cycles for each scheme are presented in Figure 35. The equivalent plots for petrol non-catalyst and diesel cars are shown in Appendix D. It should again be noted that the vehicle sample changed during the test

Table 12 Mean emission rates in TRL traffic calming tests compared with emission rates for equivalent vehicle categories in EC MEET Report (all correct to 3 significant figures)

		Before calming		*After calming*		*% change in emissions*	
Vehicle category	*Pollutant*	*TRL (g/km)*	*MEET (g/km)*	*TRL (g/km)*	*MEET (g/km)*	*TRL*	*MEET*
Petrol non-catalyst	CO	13.9	8.00	18.5	11.1	+34%	+40%
	HC [1]	1.52	1.34	2.28	1.73	+50%	+29%
	NO_x [2]	1.08	2.02	1.08	1.84	+1%	-9%
	CO_2 [2]	116	142	139	168	+20%	+19%
Petrol catalyst	CO [2]	3.95	2.11	6.26	3.87	+59%	+83%
	HC [1,2]	0.13	0.19	0.20	0.27	+54%	+40%
	NO_x [2]	0.09	0.35	0.09	0.38	+8%	+9%
	CO_2 [2]	132	172	167	219	+26%	+28%
Diesel	CO [3]	0.61	0.42	0.84	0.63	+39%	+49%
	HC [1,3]	0.22	0.09	0.32	0.12	+48%	+44%
	NO_x [3]	0.53	0.67	0.68	0.81	+28%	+22%
	CO_2 [3]	119	159	150	191	+26%	+20%
	PM [3]	0.10	0.10	0.13	0.12	+30%	+30%

[1] Stated as VOC in MEET.
[2] MEET emission rates weighted according to engine size distribution in TRL vehicle sample.
[3] MEET emission rates weighted according to technology level in TRL vehicle sample.

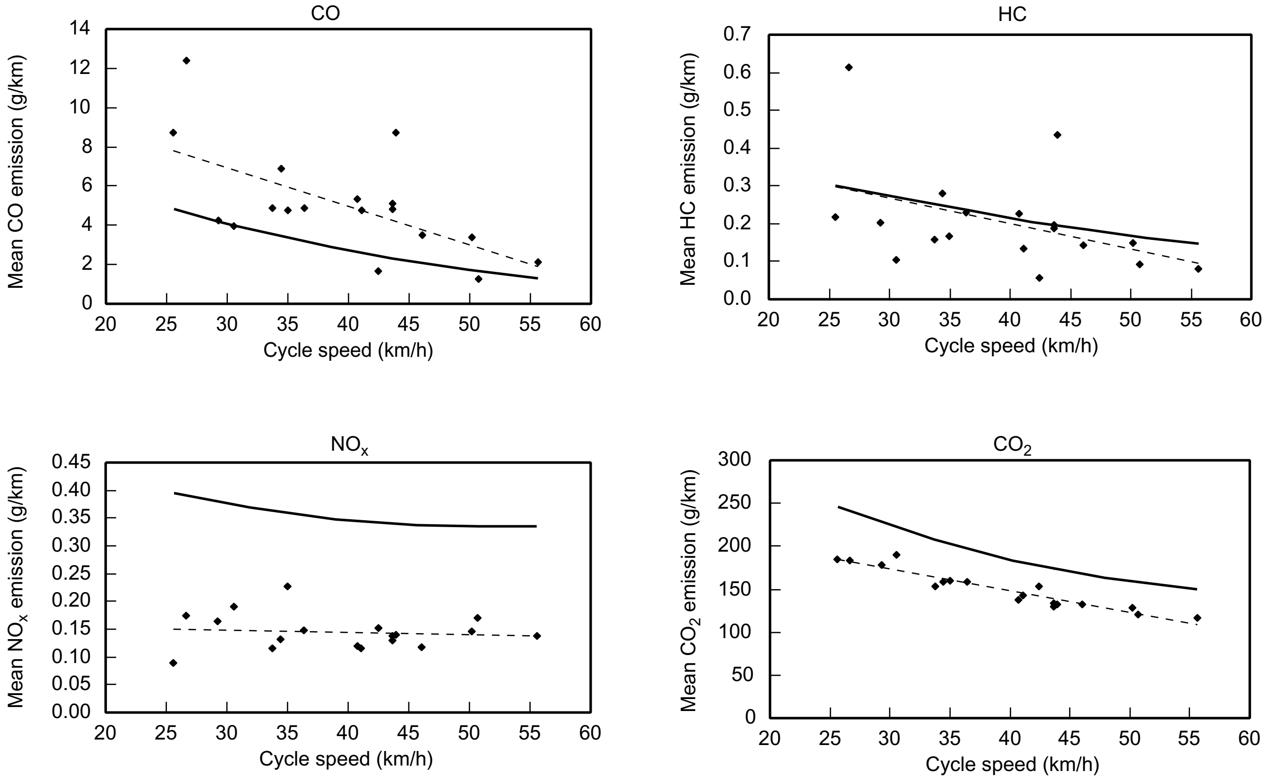


Figure 33 Speed dependency of absolute emission rates in TRL study and MEET model for petrol catalyst cars. The solid lines are derived from the MEET emission functions. The data points are average emission values over each TRL driving cycle, and the dotted line is a linear regression fit to the data points

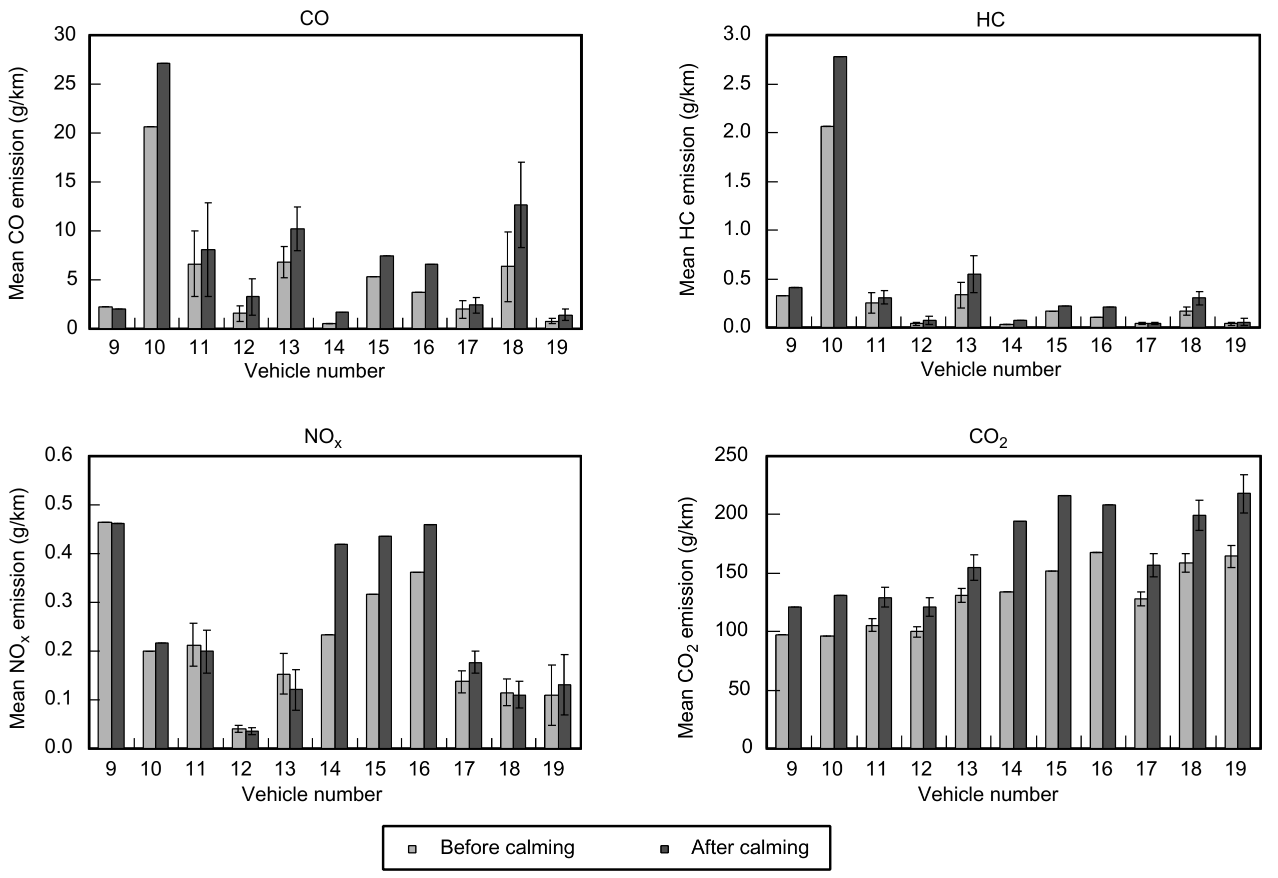


Figure 34 Emissions before calming and after calming for individual petrol catalyst cars. The emission levels have been averaged over all the schemes for which a vehicle was tested. The I-beams represent the 95% confidence intervals on the means. Where there are no confidence intervals, the vehicle was only tested on one scheme

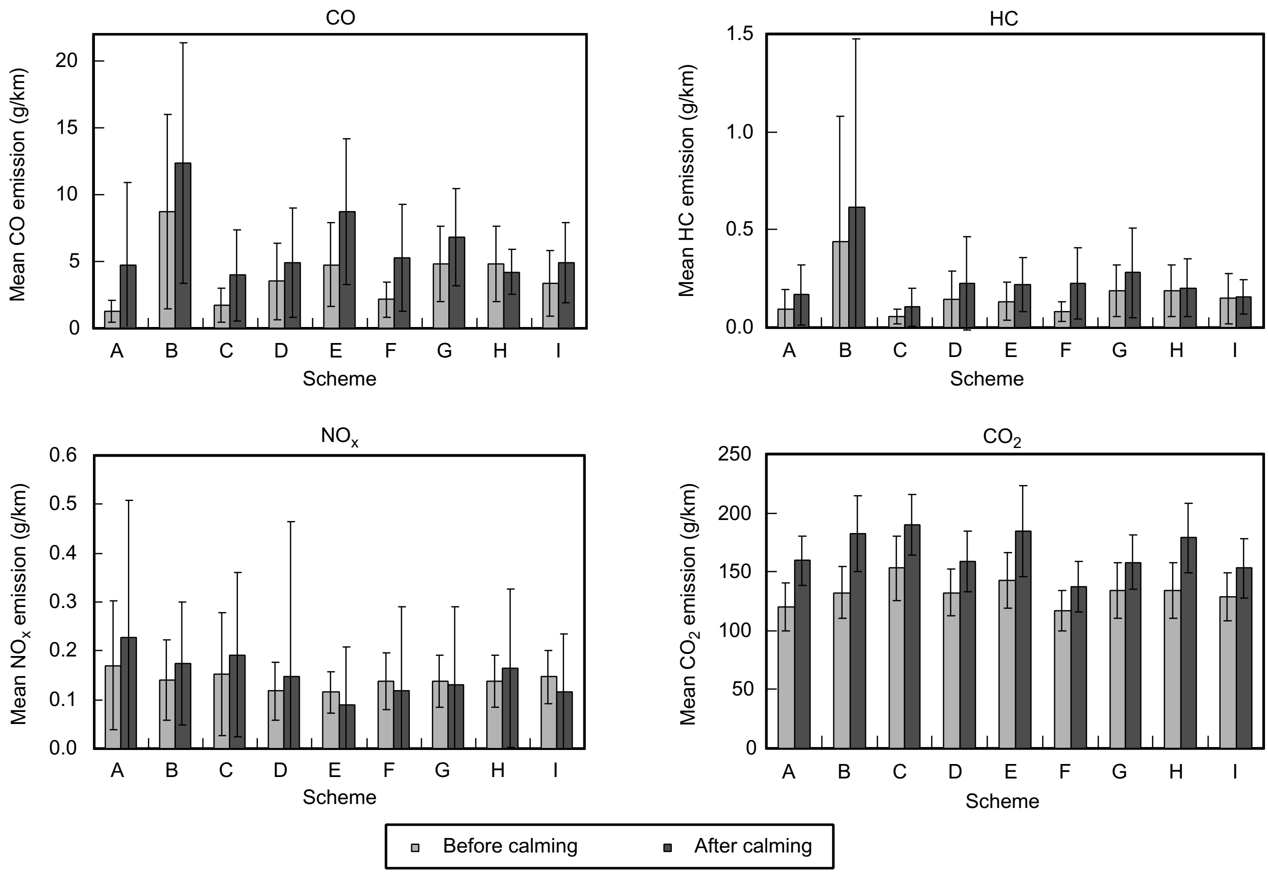


Figure 35 Emissions from petrol catalyst cars before calming and after calming for individual schemes. The emission levels have been averaged over all the vehicle tested for a particular scheme. The I-beams represent the 95% confidence intervals on the means

programme, although for each scheme six petrol non-catalyst, six petrol catalyst and three diesel vehicles were tested. As before, the results for the petrol catalyst vehicles showed the most variation, and this is reflected in the wide confidence intervals for CO, HC, and NO_x in Figure 35. The impact of vehicle 10 on the mean absolute CO and HC emission values and confidence intervals for scheme B (80mm round-top road humps) is also evident. However, it appears that the percentage impacts of scheme B on emissions of the various pollutants were not exceptional.

6.3 Statistical analysis of emission data

6.3.1 Within-scheme comparisons

For each combination of pollutant, vehicle category, and scheme, paired sample *t*-tests were conducted in order to determine whether the mean emission of the vehicle sample after calming was significantly different from the mean emission before calming at the 95% confidence level. The results of this analysis are presented in Table 13. It should be noted, once again, that the vehicle samples differed between the schemes.

For petrol non-catalyst cars the changes in emissions of CO, HC, and CO_2 were statistically significant for all schemes, whilst the changes in NO_x were only significant for selected schemes. The results were rather different for petrol catalyst cars, for which the measured emission rates were more variable. Although the changes in CO_2 emissions were significant for all schemes, the changes in CO and HC were generally not significant. The change in NO_x emissions from petrol catalyst cars was not statistically significant for any scheme. For diesel cars, the significant changes tended to occur for NO_x and CO_2. The changes in CO and HC emissions were generally not significant, and emissions of particulate matter did not change significantly for any scheme.

6.3.2 Between-scheme comparisons

The main objective of the study was to develop a system of comparative emission performance indicators for the different traffic calming measures. The development of these indicators, and the determination of an appropriate hierarchy for each vehicle type and pollutant, are described in chapter 8 of the Report. However, the impacts of the different schemes had to be compared statistically in order to assess the relevance of the hierarchy in each case. This assessment was more complex than that reported in the previous section, since the variation in the whole emission data set was due not only to the between-vehicle variability of emission levels, but also to the between-scheme variability. Furthermore, the fact that the vehicle sample changed during the emission test programme would have introduced variation into the data that was unrelated to the effects of the traffic calming measures. In order to assess the impacts of the schemes relative to one another, all between-vehicle variability in emission levels had to be taken into account.

Table 13 Pollutants, vehicle categories, and schemes for which the mean emission after calming was different from the mean emission before calming at the 95% confidence level

Scheme	*Traffic calming measure*	*Petrol non-catalyst*	*Petrol catalyst*	*Diesel*
A	75mm-high flat-top road humps	CO,HC,NO_x,CO_2	CO_2	NO_x,CO_2
B	80mm-high Round-top humps	CO,HC,CO_2	CO,CO_2	NO_x,CO_2
C	1.7m-wide speed cushions	CO,HC,NO_x,CO_2	CO_2	NO_x,CO_2
D	Pinch point/speed cushion	CO,HC,CO_2	CO_2	HC,NO_x, CO_2
E	Raised junction	CO,HC,CO_2	CO,HC,CO_2	CO,NO_x,CO_2
F	Chicane	CO,HC,NO_x,CO_2	CO_2	CO,NO_x,CO_2
G	Build-out	CO,HC,CO_2	CO,CO_2	NO_x,CO_2
H	Mini-roundabout	CO,HC,CO_2	CO_2	NO_x,CO_2
I	1.9m-wide cushions	CO,HC,NO_x,CO_2	CO_2	

The results in Table 12 indicated that the mean absolute emission levels recorded in the study did not correspond particularly well with the mean absolute emission levels of a larger sample of vehicles, though there was a fairly good level of agreement between the percentage impacts. Consequently, all the statistical tests were conducted on the *percentage changes* in emissions. In other words, for the purpose of the statistical tests the percentage change in the emission level of each vehicle (for a given vehicle category and pollutant) was calculated, and then the resulting values were averaged. Therefore, any further reference to 'means' in this section relates to the percentage change in the mean emission level associated with a given scheme, pollutant, and vehicle category. Elsewhere in the Report, the calculated impacts relate to the *percentage change in the mean* of the pooled 'before calming' and pooled 'after calming' values, as this method gives results which are more likely to be representative of the impacts on fleet emissions.

Because more than two (in this case 9) means were being compared for each pollutant and vehicle type, an Analysis of Variance (ANOVA) F-test was initially conducted in order to establish whether the means were significantly different from each other. However, the F-test did not explain which means differed from which other means. Multiple pairwise comparison methods provide more detailed information about the differences between the means. In this study, the Student-Newman-Keuls (SNK) test (described in Miller, 1981) was used. The SNK test grouped schemes according to whether significant differences existed between the means. The test ensures that the experimentwise error rate is held to a constant significance level regardless of how many comparisons are being made. The results of the tests are presented in Tables 14-18. For example, the results for CO presented in Table 14 indicate that for petrol non-catalyst cars only the impact of scheme F (chicane) was significantly different to the impacts of all the remaining schemes. The CO results for petrol catalyst cars show that the schemes could be separated into two groups, but also that there was a considerable amount of overlap between the groups. The inference from such an outcome would be that the differences between the impacts of all the schemes were slight.

NB: *It is important to note that ordering of the schemes in Tables 14-18 is slightly different to the order presented in chapter 8 because of the different calculation method. The results have only been used to determine whether the impacts of the different schemes are statistically distinguishable. In chapter 8, the results have been used to assess, in general terms, whether an ordering for a particular vehicle category and pollutant category is appropriate.*

In general, there was a great deal of overlap between the impacts of the different traffic calming measures. The extreme examples of this were the cases where there were no significant differences between the impacts of the different measures (petrol catalyst HC / NO_x, and diesel HC). The most distinct differences between schemes tended to occur with the petrol non-catalyst cars.

7 Delays to an emergency service vehicle

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

In fact, there is little quantitative evidence relating to the delays imposed on emergency service vehicles by traffic calming. Coleman (1997) described a study in the United States in which an assessment was made of the effects of traffic calming measures on the response of fire service vehicles. The study was conducted in the autumn of 1995 by the City of Portland Fire Bureau, and the Bureau of Traffic Management. Six different types of fire vehicle were driven on streets featuring roundabouts, flat-top road humps, and round-top road humps. A total of 36 drivers participated in the tests. The time required to travel a length of street without traffic calming was compared with the time required on the same length of road with traffic calming, and the results were used to determine a delay for each device. Delays per device were calculated for desirable response speeds of 25, 30, 35, and 40 mph. Depending on the type of fire vehicle and the desirable response speed, the delays imposed by the roundabouts, flat-top road humps, and round-top road humps were 1.3-10.7 seconds, 0.0-9.2 seconds, and 1.0-9.4 seconds respectively.

Table 14 Student-Newman-Keuls (SNK) test results: carbon monoxide

Scheme — ← *Decreasing impact* … *Increasing impact* →

Petrol non-catalyst

SNK group	I	H	G	C	D	E	A	B	F
I	X	X	X	X	X	X	X	X	
II									X

Petrol catalyst

SNK group	D	H	B	G	E	I	C	F	A
I	X	X	X	X	X	X	X	X	
II			X	X	X	X	X	X	X

Diesel

SNK group	D	C	H	G	F	A	E	I	B
I	X	X	X	X	X	X			
II		X	X	X	X	X	X		
II			X	X	X	X	X	X	X

Table 15 Student-Newman-Keuls (SNK) test results: hydrocarbons

Scheme — ← *Decreasing impact* … *Increasing impact* →

Petrol non-catalyst

SNK group	G	C	D	H	I	E	A	B	F
I	X	X	X	X	X	X			
II		X	X	X	X	X	X	X	
II							X	X	X

Petrol catalyst

SNK group	D	H	C	I	E	G	B	A	F
I	X	X	X	X	X	X	X	X	X

Diesel

SNK group	D	E	C	G	H	F	B	I	A
I	X	X	X	X	X	X	X	X	X

Table 16 Student-Newman-Keuls (SNK) test results: oxides of nitrogen

Scheme — ← *Decreasing impact* … *Increasing impact* →

Petrol non-catalyst

SNK group	I	F	G	E	H	D	B	C	A
I	X	X							
II			X						
III				X	X	X	X		
IV								X	X

Petrol catalyst

SNK group	E	F	I	G	H	D	C	A	B
I	X	X	X	X	X	X	X	X	X

Diesel

SNK group	G	I	F	D	C	H	A	E	B
I	X	X	X	X	X				
II						X	X	X	X

Table 17 Student-Newman-Keuls (SNK) test results: carbon dioxide

Scheme — ← *Decreasing impact* … *Increasing impact* →

Petrol non-catalyst

SNK group	F	I	D	G	C	E	H	B	A
I	X								
II		X							
III			X	X					
IV					X	X			
V						X	X		
VI							X	X	X

Petrol catalyst

SNK group	F	G	I	D	C	E	A	H	B
I	X	X	X	X	X				
II						X	X	X	
III							X	X	X

Diesel

SNK group	I	G	F	D	C	H	B	E	A
I	X	X	X	X	X				
II		X	X	X	X	X	X		
III					X	X	X	X	
IV								X	X

Table 18 Student-Newman-Keuls (SNK) test results: particulate matter

Scheme — ← *Decreasing impact* … *Increasing impact* →

Diesel

SNK group	I	B	E	D	G	H	C	F	A
I	X	X	X	X	X	X	X	X	
II									X

However, it has been shown in the UK that fire tenders and ambulances can achieve speeds of 38 mph and 24 mph respectively over narrow speed cushions on emergency runs (Layfield, 1994). Cars generally cross narrow cushions at just under 20 mph, and buses at just over 20 mph.

In this study there was scope for providing further information on delays to emergency service vehicles. Thus, in addition to the experimental work relating to exhaust emissions, a short experiment was conducted with the aim of estimating the delays imposed on a single fire tender by different traffic calming measures. In the experiment the speed of a fire tender was logged continuously as it was driven around a road circuit in the residential Old Dean estate of Camberley, Surrey.

7.1 Location and experimental method

The road circuit used in the tests featured a wide variety of vertical and horizontal traffic calming measures. These included seven speed cushions, a mini roundabout, a flat top hump, a combined flat top hump and chicane, and a combined 'fake' hump and chicane. The circuit also included a large roundabout, several junctions, and straight stretches of road without any traffic calming measures. A plan of the road circuit, including the traffic calming measures (numbered 1-11) and the sections of road with no traffic calming (labelled A1, A2, B1, and B2), is shown in Figure 36.

Surrey Fire & Rescue Service provided a test driver and fire tender for the tests. The fire tender was loaded up to its normal running weight of 11600 kg using sandbags and personnel, and was instrumented so that its speed could be measured continuously using a microwave Doppler shift speed sensor connected to a laptop computer. The sensor was identical to the one used in the field trial described in chapter 2.

The maximum distance over which the vehicle's road speed could be logged with an adequate spatial resolution (5m) was approximately 2km. Therefore, the circuit was divided into two 'runs', labelled 'A' and 'B'. These runs are indicated in Figure 36. The fire tender was driven over run A whilst its speed was measured and logged. At the end of run A the vehicle was brought to a halt to allow data to be downloaded to a laptop computer, and the logger was reset. This procedure was then repeated over run B. A total of 12 full circuits were driven in this manner so that sufficient data could be obtained to evaluate typical speeds over each traffic calming section. The speed at each measure was calculated as an average of the three consecutive speed readings obtained at the appropriate location.

Details of the traffic calming measures, and the distances of the measures from the starting point of each run, are provided in Table 19.

Table 19 Traffic calming measures on the road circuit

Run A		*Run B*	
Traffic calming measure (number)	*Distance from start (m)*	*Type of calming measure (number)*	*Distance from start (m)*
Start of run	0	***Start of run***	0
Speed cushions (1)	45	Mini roundabout	195
Speed cushions (2)	214	Flat top hump (7)	238
'Fake' hump and chicane (3)	286	Speed cushions (6)	327
Flat top hump and chicane (4)	364	Speed cushions (5)	405
Speed cushions (5)	425	Flat top hump and chicane (4)	466
Speed cushions (6)	505	'Fake' hump and chicane (3)	544
Flat top hump (7)	593	Speed cushions (8)	723
Mini Roundabout	643	Speed cushions (9)	792
End of run	1337	Speed cushions (10)	879
		Speed cushions (11)	916
		End of run	1448

7.2 Results

The average speed at each individual traffic calming measure, together with the 95% confidence intervals are shown in Figure 37. Some traffic calming measures, for which the speed may have been greatly influenced by other factors (such as junctions), have been excluded from the analysis.

In Figure 37 the measures have been separated into groups and arranged (approximately) in order of increasing speed. The speed of the vehicle was lowest at the flat top hump (26.4 kph) and the flat top hump in combination with a chicane (27.0 kph), both of which gave lower average speeds than a chicane in isolation (32.0 kph). The cushions gave a wide range of average speeds (35.1 kph), and these appear to be separated into higher and lower speed groups. Two out of the three cushions in the former group were positioned so that the fire engine had a long unobstructed stretch of road prior to encountering the measures, which may explain the higher speeds. The average speed measured at the unobstructed sections of road (37.6 kph) was higher than the mean speed of the low-speed cushion cluster, but similar or slightly lower than the mean speed of the high-speed cushion cluster. Further statistical analysis would be required to distinguish significant differences between the humps and humps/chicane, and between 'no measures' and the high-speed group of the speed cushions.

The overall mean speeds and confidence levels associated with the different types of measure are illustrated in Figure 38. Since only one flat top hump and one chicane were included in the road circuit, these are represented by the average value only. Statistical tests showed that the speeds measured over the uncalmed sections were significantly higher than the speeds measured at the cushions at the 99% confidence level.

Figure 38. Average speed of fire tender at each type of traffic calming measure.

The time taken to pass over each traffic calming measure was calculated from the average speed at each traffic calming measure and the distance over which the speed was measured. By subtracting the time taken to pass through an equivalent distance of an uncalmed road, it was possible to calculate the time delay caused by each traffic calming measure. The time delays, in increasing order, were 0.14 seconds for a chicane, 0.21 seconds for a speed cushion, 0.38 seconds for a flat top hump/chicane, and 0.39 seconds for a flat top hump.

An alternative method of calculating a typical delay time would be to simply subtract the time taken to travel over a calmed portion of road by the time taken to travel over an equivalent distance of uncalmed portion of road and divide by the number of traffic calming measures. Using stretches A1, A2, B1 and B2 for the uncalmed part and the remaining route for the calmed part of the route, the delay time per scheme was calculated to be 1.25 seconds per measure when including the mini roundabout as a calming measure, or 1.40 seconds per measure excluding it. The large differences between the times calculated by using this method and by the previous one are discussed in the following paragraph.

The effect of a single traffic calming measure on speed is very difficult to determine since it is common practice, particularly in the case of road humps and speed cushions, to position several traffic calming measures in proximity to one another, this may result in a different average speed than if they were used in isolation. Moreover, it is also difficult to define the precise start and end of a traffic calming section since the influence of speed from one traffic calming measure can become superimposed upon the influence of the next. Many variables, other than traffic

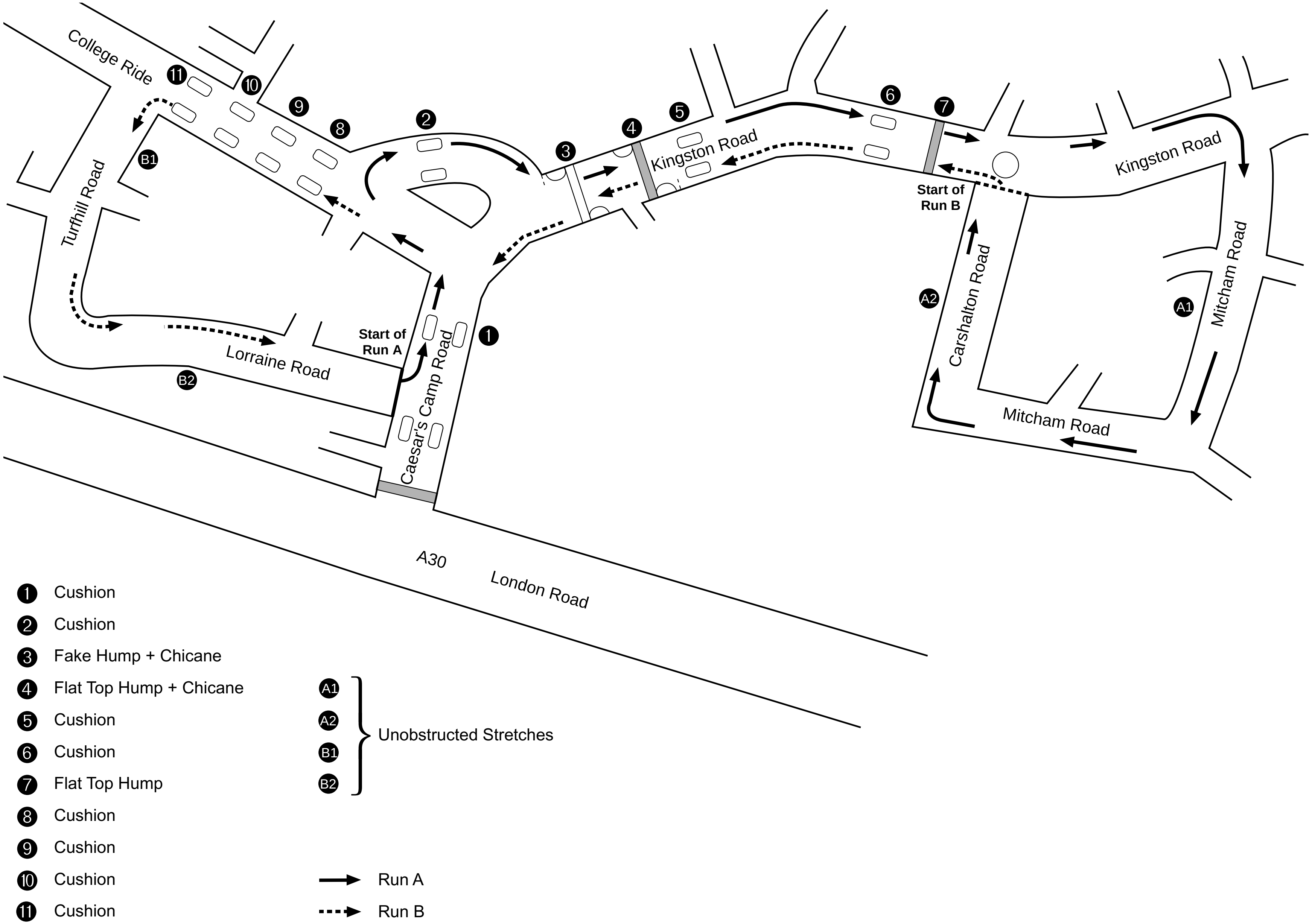


Figure 36 Road circuit used in experiment

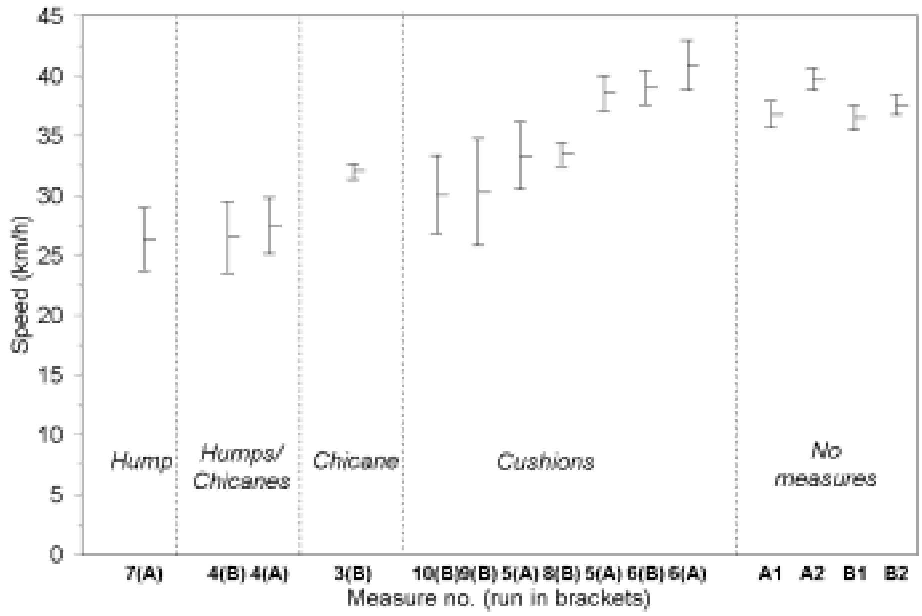


Figure 37 Average speed of fire tender at each traffic calming measure investigated

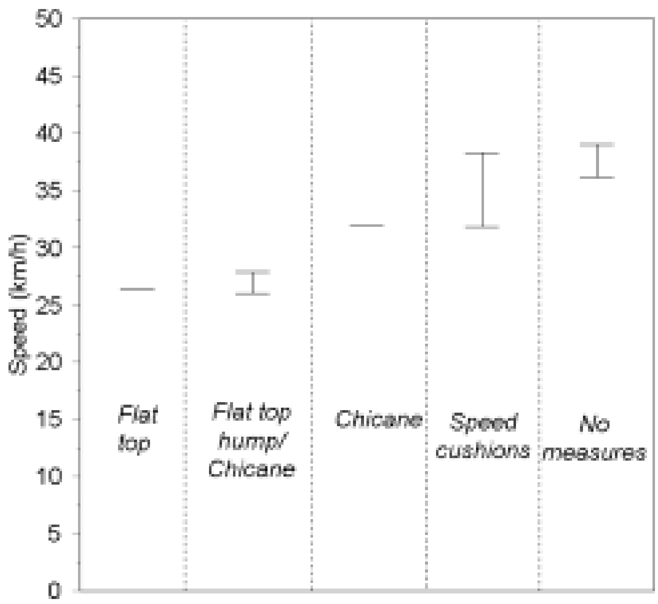


Figure 38 Average speed of fire tender at each type of traffic calming measure

calming, influence road speed. Therefore, the results from measurements using one type of scheme in one environment cannot always be translated to another even if the scheme layout is identical. With regard to these specific tests it must also be noted that only one type of vehicle and one driver were used for the tests, and these speeds were taken in an experimental, non-emergency situation.

Taking into account these factors, this type of experiment can only provide a general guide to which type of measures would be more likely to reduce fire tender speeds than others, and the order of magnitude of the speed reduction or time delay which is likely.

The experiment indicated that the speed reduction effected by the speed cushions was significantly smaller than the speed reduction effected by the chicane which, in turn, was significantly smaller than the reduction effected by the flat top humps. This would be expected, since speed cushions are usually designed so that the front wheels of a large emergency vehicle such as a fire tender can straddle them without major interference.

The time delays caused by the speed reductions were much smaller than expected, ranging between 0.14 seconds and 0.39 seconds per measure. Clearly, the assumed distance of each measure is an important criterion when calculating this figure, and it is possible that too small a distance (10m) was chosen for the influence of the measures. The second method of calculating time delays is probably more realistic in that it takes account of how the measures affect speed in combination, but it may be highly specific to the type of measures, the way they were combined, and the characteristics of the uncalmed road. The time delay of 1.25 -1.40 seconds per measure is still probably relatively small and unless large numbers of calming measures were used it is unlikely that fire tender response times in an emergency situation would increase significantly.

8 Performance indicators and guidance on scheme implementation

One of the main objectives of the research was to develop a system of comparative performance indicators for different traffic calming measures. These indicators would have to account for how vehicle speed and emissions were affected, and would indicate how speed reduction and minimisation of emissions could be balanced against other requirements. The methods by which these indicators were developed are presented in this chapter of the Report, with the input data being derived from the results presented in the previous chapters and from other existing information.

8.1 Construction of indicators

8.1.1 Speed

The speed reduction that is likely to be achieved after the introduction of traffic calming measures will vary from site to site, and will mainly depend upon the type of traffic calming measure, the mean 'before' speed, and the spacing between measures. The speeds before calming and the spacing between measures varied between the sites in this study and, in order to provide a consistent basis for comparison, the speed reduction indicators were based on a common mean 'before' speed of 30 mph and a common separation between measures of 80m. The speed reduction data were obtained from a range of TRL studies at a large number of sites (Webster, 1993b; Webster and Layfield, 1996; Layfield and Parry, 1998; Cloke *et al*., 1999; Sayer *et al*., 1998).

8.1.2 Accidents

Traffic calming measures are often introduced as part of an area-wide safety scheme, and there is a large body of research which indicates that, for most locations, the frequency of injury accidents is likely to be reduced (Evans, 1994; Amis, 1995; Hampshire County Council, 1996; Webster and Mackie, 1996; Sayer *et al*., 1998; Wheeler and Taylor, 2000). The mechanism for this accident reduction is thought to mainly result from the reduction in average speeds, which acts to reduce the likelihood of a collision and to reduce the severity of injury if a collision occurs.

Webster and Mackie (1996) reported reductions in injury accidents of around 60% after the introduction of 20mph zones using mainly road humps to reduce mean speeds (by about 9mph) and flows (by about 20%). While the overall effects of the introduction of traffic calming measures are well documented, the relative effects of different traffic calming measures are less well established due to the small numbers of accidents recorded in surveys conducted before and after the introduction of individual traffic calming schemes, and the use of several different types of traffic calming measure within individual schemes.

An indication of the relative effect of the different types of traffic calming measure on injury accident frequency can be obtained by considering the likely reduction in mean speed that will be achieved at each type of traffic calming measure and applying established relationships between changes in speed and accidents (Taylor *et al*., 2000). Taylor *et al.* estimate that, for vehicles travelling on urban roads at a mean speed of about 25 mph (average of 'before' and 'after' speeds), a 5% reduction in injury accidents can be expected, on average, per 1 mph reduction in mean speed. Because the accident reductions at the different types of traffic calming are based on reductions in speed, the order of the different measures in terms of their accident reduction impact will be the same as the order in terms of their speed reduction impact.

8.1.3 Unweighted passenger car emissions

The traffic calming measures were ranked, by vehicle type and pollutant, in accordance with their percentage impacts on emissions per vehicle-km. The statistical tests reported in section 6.3 have been used to assess the robustness of the rankings.

8.1.4 Weighted traffic emissions

The unweighted passenger car emission impacts do not account for the composition of the UK vehicle fleet, and how the composition is likely to change in the future. Therefore, aggregate emission indicators, which combined the vehicle emission test data and fleet composition data, were constructed to describe the expected changes in emissions of CO, HC, NO_x, and CO_2 from road traffic after the installation of the different traffic calming measures. Also, because the effects of traffic calming on emissions are different for different types of vehicle, the overall effect at a given site will vary with the year of implementation.

A weighted impact was determined for the reference year 1998 using existing fleet information. Forecasts of future vehicle stock were used to estimate the effects of the schemes on emissions in two other reference years: 2000 and 2005. The overall breakdown of the fleet is given in Table 20. The breakdown by vehicle class was based on the proportion of kilometres travelled by each vehicle class on unclassified roads in urban areas. The origin of the more detailed fleet breakdown within each vehicle class, and any other information used in the weightings, is described in the following paragraphs.

Passenger cars

The emission test data for passenger cars were weighted according to the composition of the UK fleet in terms of

Table 20 UK Fleet composition on unclassified urban roads in 1998, 2000, and 2005

Fuel	*Size*	*Emission control*	*% of fleet in each category* 1998	2000	2005
Passenger cars					
Petrol	Small	Non-catalyst (pre EURO 1)	6.49	3.59	0.44
	(<1.2l)	Catalyst (EURO 1)	5.41	3.91	1.60
		Catalyst (EURO 2)	3.78	6.36	3.35
		Catalyst (EURO 3)	–	–	6.42
	Medium	Non-catalyst (pre EURO 1)	17.61	11.14	1.49
	(1.2-1.8l)	Catalyst (EURO 1)	14.67	12.15	5.47
		Catalyst (EURO 2)	10.27	19.74	11.45
		Catalyst (EURO 3)	–	–	21.90
	Large	Non-catalyst (pre EURO 1)	6.80	4.34	0.64
	(>1.8l)	Catalyst (EURO 1)	5.66	4.74	2.36
		Catalyst (EURO 2)	3.96	7.70	4.93
		Catalyst (EURO 3)	–	–	9.44
Diesel	All	Uncontrolled	1.90	1.29	0.24
		Controlled EURO 1	5.58	4.38	2.27
		Controlled EURO 2	3.68	7.21	4.52
		Controlled EURO 3	–	–	9.26
LGVs					
Petrol	All	Non-catalyst (pre EURO 1)	2.52	1.48	0.17
		Catalyst (EURO 1)	0.35	0.26	0.09
		Catalyst (EURO 2)	0.17	0.44	0.26
		Catalyst (EURO 3)	–	–	0.52
Diesel	All	Uncontrolled	2.09	1.57	0.44
		Controlled EURO 1	2.18	1.74	0.96
		Controlled EURO 2	1.39	3.13	1.91
		Controlled EURO 3	–	–	4.35
HGVs					
Diesel	Rigid	88/77 and before	1.10	0.62	0.05
		EURO 1	0.79	0.69	0.23
		EURO 2	0.71	1.29	1.01
		EURO 3	–	–	1.30
	Articulated	88/77 and before	0.04	0.03	-
		EURO 1	0.08	0.06	0.01
		EURO 2	0.07	0.12	0.07
		EURO 3	–	–	0.12
Buses					
All	All	All categories	1.60	1.60	1.60
Motorcycles					
All	All	All categories	1.10	1.10	1.10
Total			100.00	100.00	100.00

Sources: Salway et al. (1997), Department of Transport (1997), European Commission (1999)

fuel type, emission control level, and engine size to produce indicators which were representative of UK national vehicle use. The proportions of the passenger car fleet in each category (petrol non-catalyst, petrol catalyst, and diesel) in the three reference years were not specific to urban minor roads, but were based on total vehicle kilometres travelled nationally. It was assumed that this was not a significant source of error.

For the years 2000 and 2005, a weighted reduction factor was applied to the absolute emission rates of CO, HC and NO_x for catalyst cars. This factor was derived from the proportions given above and the expected emissions reductions given in Table 21. It was assumed that all catalyst cars undergoing the dynamometer tests met the EURO 1 emissions standard. Due to the smaller sample size for diesel vehicles, adjustments for future emissions standards have not been applied.

Table 21 Scaling (reduction) factors: future standards for petrol cars

Pollutant	*EURO 1 to EURO 2*	*EURO 1 to EURO 3*
CO	0.95	0.76
HC	0.60	0.39
NO_x	0.45	0.27

Source: European Commission (1999)

The distribution of engine sizes within the UK petrol car fleet was estimated using a simple trend analysis of new registration data and total stock. The analysis demonstrated an increase in engine size, as catalyst-equipped vehicles become widespread and vehicles in general become larger and equipped with more energy-consuming accessories. This would tend to lead to increased fuel consumption and emissions of CO_2, though it is recognised that any such increases will probably be offset by the introduction of new technologies, as manufacturers strive to improve fuel efficiency. Diesel vehicles were not weighted by size. Also, a sub-division of diesel vehicles by emissions standards was not used. For technical reasons, particulate emissions from petrol vehicles were not measured during the dynamometer tests. Consequently, no weighted emission estimates were calculated.

LGVs

The mean speeds observed before and after calming at each scheme were used to derive emission rates using TRL speed-emission relationships based on previous vehicle measurements. For simplicity, a single medium-sized LGV (1250-1700kg) was chosen to derive the indicators. The emissions for various van types were combined to a single index using forecasts of fleet vehicle kilometres prepared by Salway *et al.*, (1997). This composition is shown in Table 20.

HGVs

The emissions from HGVs before and after traffic calming were calculated using speed-emission relationships developed by TRL from previous emission tests. Mean vehicle speeds before and after calming for each scheme were used to derive emissions estimates for both rigid and articulated HGVs. As before, future emissions were calculated using emission reduction factors (Table 22). The basic emissions rates were assumed to be for vehicles meeting the 88/77 standard. Total emissions were derived by weighting these figures by the proportions of rigid and articulated vehicles in the HGV fleet on unclassified urban roads (92% rigid, 8% articulated; source: Salway *et al.*,1997).

Table 22 Emission reduction rates (HGVs)

	CO	*HC*	*NO_x*	*PM*
88/77 to Euro 1	0.9	0.9	0.7	0.8
88/77 to Euro 2	0.8	0.8	0.6	0.3
88/77 to Euro 3	0.8	0.8	0.4	0.2

Source: European Commission (1999)

Buses

Contributions for bus emissions were calculated in a similar manner to those for HGVs. Mean vehicle speeds before and after implementation of traffic calming from the on-site measurements were used to calculate emissions using relationships supplied by TRL and derived from previous emission tests. Again, reduction rates for future emissions standards were applied to absolute emission rates (calmed and uncalmed) for future years. These were identical to those used for HGVs.

8.1.5 Delays to emergency service vehicles

The results of the fire tender experiment in chapter 7 were used to derive a ranking hierarchy for the delays imposed by different traffic calming measures (grouped according to type) on emergency service vehicles. The impacts of round-top road humps, raised junctions, build-outs and mini-roundabouts were not quantified in the experiment. Hence, the effects of these measures have been ranked according to their anticipated effects.

8.2 Results

8.2.1 Speed and accidents

The speed and accident impacts of the different schemes are presented in Table 23. These impacts are based on the generalised speed-reduction data and the speed-accident relationships referred to in section 8.1. The relative impacts of the traffic calming measures generally correspond to what might have been expected given their severity.

Table 23 Speed and accident reduction impacts

Impact	*Scheme*	*Traffic calming measure*	*Absolute speed reduction mph (km/h)*	*Accident reduction (%)*
Largest	E	100mm-high raised junction	12 (19)	60
●	A	75mm flat-top humps	10 (16)	50
●	B	80mm round-top hump	10 (16)	50
●	I	1.9m speed cushions	9 (14)	45
●	H	Mini-roundabout	8 (13)	40
●	C	1.7m-wide speed cushions	8 (13)	40
●	D	Pinch point/speed cushion	7 (11)	35
●	F	Single-lane-working chicane	7 (11)	35
Smallest	G	Build-out	5 (8)	25

8.2.2 Unweighted vehicle emissions

The percentage impacts of the different schemes on the average emission levels of the three categories of vehicle are presented in Tables 24-26. The reasons for use of the percentage impact as a basis for ordering the schemes was discussed in section 6.3.2.

Table 24 Unweighted emission impacts: petrol non-catalyst cars

	Scheme and mean % change in emissions per vehicle-km			
Impact	*CO*	*HC*	*NO_x*	*CO_2*
Smallest	I (+19%)	G (+19%)	I (-21%)	F (+7%)
●	G (+21%)	C (+41%)	F (-17%)	I (+10%)
●	H (+22%)	D (+45%)	G (-10%)	G (+15%)
●	C (+24%)	H (+46%)	E (0%)	D (+16%)
●	D (+34%)	I (+50%)	H (+3%)	C (+22%)
●	E (+39%)	A (+69%)	D (+6%)	E (+24%)
●	B (+43%)	B (+71%)	B (+7%)	H (+25%)
●	A (+44%)	E (+77%)	A (+19%)	A (+28%)
Largest	F (+70%)	F (+87%)	C (+19%)	B (+28%)

Shaded columns indicate where the scheme order for a given vehicle category and pollutant was considered to be statistically robust

Key

Scheme	*Traffic calming measure*		
A	*75mm-high flat-top road humps*	*F*	*Chicane*
B	*80mm-high round-top humps*	*G*	*Build-out*
C	*1.7m-wide speed cushions*	*H*	*Mini-roundabout*
D	*Pinch point and speed cushion*	*I*	*1.9m-wide cushions*
E	*100mm-highRaised junction*		

Table 25 Unweighted emission impacts: petrol catalyst cars

	Scheme and mean % change in emissions per vehicle-km			
Impact	*CO*	*HC*	*NO_x*	*CO_2*
Smallest	H (-13%)	I (+6%)	E (-22%)	F (+18%)
●	D (+39%)	H (+7%)	I (-21%)	G (+18%)
●	G (+41%)	B (+41%)	F (-14%)	I (+19%)
●	B (+42%)	G (+48%)	G (-5%)	D (+20%)
●	I (+45%)	D (+61%)	H (+18%)	C (+24%)
●	E (+84%)	E (+62%)	B (+25%)	E (+30%)
●	C (+135%)	A (+79%)	D (+25%)	A (+32%)
●	F (+147%)	C (+87%)	C (+26%)	H (+33%)
Largest	A (+270%)	F (+186%)	A (+34%)	B (+38%)

Shaded columns indicate where the scheme order for a given vehicle category and pollutant was considered to be statistically robust

Key

Scheme	*Traffic calming measure*		
A	*75mm-high flat-top road humps*	*F*	*Chicane*
B	*80mm-high round-top humps*	*G*	*Build-out*
C	*1.7m-wide speed cushions*	*H*	*Mini-roundabout*
D	*Pinch point and speed cushion*	*I*	*1.9m-wide cushions*
E	*100mm-highRaised junction*		

Clearly, the impact of a given scheme varied with the vehicle type and pollutant being considered, and it was therefore difficult to discern general trends. However, with some exceptions, it could be argued that for petrol cars schemes G (build-out) and I (1.9m-wide speed cushions) tended to be have a relatively low impact, whereas schemes A (flat-top hump) and B (round-top hump) tended to have a high overall impact. The relative impacts of the remaining schemes tended to vary. For diesel cars, schemes D (pinch point/speed cushion) and scheme G (build-out) tended to have a lower impact than the other schemes, and scheme A (flat-top hump) tended to have a

Table 26 Unweighted emission impacts: diesel cars

	Scheme and mean % change in emissions per vehicle-km				
Impact	*CO*	*HC*	*NO_x*	*CO_2*	*PM*
Smallest	D (+19%)	E (+21%)	I (+17%)	I (+15%)	D (-1%)
●	C (+26%)	D (+28%)	G (+19%)	G (+19%)	G (+2%)
●	H (+31%)	C (+38%)	D (+20%)	F (+20%)	B (+21%)
●	G (+34%)	G (+39%)	F (+20%)	D (+23%)	I (+27%)
●	A (+42%)	B (+57%)	C (+26%)	C (+24%)	E (+31%)
●	F (+43%)	H (+59%)	A (+37%)	B (+30%)	H (+35%)
●	I (+44%)	F (+70%)	H (+37%)	H (+30%)	C (+46%)
●	E (+55%)	I (+80%)	B (+38%)	E (+32%)	F (+49%)
Largest	B (+56%)	A (+109%)	E (+39%)	A (+40%)	A (+82%)

Shaded columns indicate where the scheme order for a given vehicle category and pollutant was considered to be statistically robust

Key

Scheme	*Traffic calming measure*				
A	*75mm-high flat-top road humps*	*D*	*Pinch point and speed cushion*	*G*	*Build-out*
B	*80mm-high round-top humps*	*E*	*100mm-highRaised junction*	*H*	*Mini-roundabout*
C	*1.7m-wide speed cushions*	*F*	*Chicane*	*I*	*1.9m-wide cushions*

high impact. Again, the relative impacts of the remaining schemes were more variable. There was a general but weak trend for the impacts of the traffic calming measures incorporating vertical deflections (*i.e.* road humps and raised junction) to be higher than those incorporating horizontal deflections or a requirement to give way. This observation may be related to the fact that in the second instance the measures were studied in isolation, whereas the vertical deflections were repeated at fairly regular intervals. A further point to note is that the passenger car fleet will eventually be dominated by petrol cars equipped with a catalyst, and therefore the results in Table 25 are of most interest

Given the extensive within-vehicle and between-vehicle variation in the emission data, the ordering of the impacts of the different schemes should only be considered in the light of the statistical analysis of the results presented in section 6.3. For example, the variability of emissions means that it is conceivable that the effect of a scheme listed as having a low impact in Tables 24-26 may not be significantly different to the effect of a scheme listed as having a high impact. The scheme order for a given vehicle category and pollutant was accepted if the following criteria were met:

- The effects of most individual schemes were statistically significant (see Table 13).
- Several groups (with minimal overlapping) were identifiable in the ANOVA and multiple comparison tests (see Tables 14-18). This was partly a subjective judgement.

The few cases for which these criteria were met are shaded in Tables 24-26. This outcome does not necessarily mean that the percentage changes and the order for the remaining cases were invalid or inappropriate, merely that the vehicle sample sizes were not large enough for any significant differences between the impacts of the different schemes to be observable.

It is worth noting again at this point the poor level of agreement, at the level of individual schemes, between the percentage changes in emissions calculated using the MEET functions and those measured in this study (see section 6.2.1). This effectively suggests that the MEET model cannot be used with confidence to predict the relative ordering of the different schemes, as shown in Tables 24-26.

8.2.3 Weighted traffic emissions

The weighted traffic emissions in the three reference years are presented in Tables 27-29. It is important to note that the impacts of the different schemes still only relate to the percentage change in emissions per vehicle-km, and that there will be a gradual reduction in the absolute emission levels of all road traffic between 1998 and 2005. In Figure 39 this gradual reduction is illustrated in the values for CO and NO_x averaged over all schemes. In 1998 the CO emission per vehicle-km on the roads before the introduction of traffic

Table 27 Weighted emission impacts: reference year 1998

	Scheme and % change in emissions per vehicle-km			
Impact	*CO*	*HC*	*NO_x*	*CO_2*
Smallest	H (+10%)	G (+21%)	I (-6%)	F (+11%)
●	I (+26%)	C (+28%)	F (-2%)	G (+13%)
●	G (+27%)	H (+35%)	G (-1%)	I (+13%)
●	C (+35%)	I (+36%)	H (+8%)	D (+15%)
●	B (+41%)	D (+42%	B (+10%)	C (+19%)
●	D (+46%)	E (+54%)	D (+11%)	H (+22%)
●	E (+52%)	B (+57%)	C (+16%)	B (+30%)
●	A (+66%)	A (+65%)	E (+23%)	A (+31%)
Largest	F (+86%)	F (+81%)	A (+35%)	E (+32%)

Shaded columns indicate where the scheme order for a given vehicle category and pollutant was considered to be statistically robust

Key

Scheme	*Traffic calming measure*		
A	*75mm-high flat-top road humps*	*F*	*Chicane*
B	*80mm-high round-top humps*	*G*	*Build-out*
C	*1.7m-wide speed cushions*	*H*	*Mini-roundabout*
D	*Pinch point and speed cushion*	*I*	*1.9m-wide cushions*
E	*100mm-highRaised junction*		

Table 28 Weighted emission impacts: reference year 2000

	Scheme and % change in emissions per vehicle-km			
Impact	*CO*	*HC*	*NO_x*	*CO_2*
Smallest	H (+5%)	G (+24%)	I (-3%)	F (+12%)
●	I (+30%)	C (+29%)	F (+1%)	G (+14%)
●	G (+31%)	H (+32%)	G (+2%)	I (+14%)
●	B (+41%)	I (+32%)	H (+10%)	D (+15%)
●	C (+43%)	D (+42%	B (+13%)	C (+19%)
●	D (+56%)	E (+54%)	D (+13%)	H (+22%)
●	E (+58%)	B (+55%)	C (+17%)	B (+31%)
●	A (+82%)	A (+65%)	E (+28%)	A (+31%)
Largest	F (+95%)	F (+80%)	A (+37%)	E (+32%)

Shaded columns indicate where the scheme order for a given vehicle category and pollutant was considered to be statistically robust

Key

Scheme	*Traffic calming measure*		
A	*75mm-high flat-top road humps*	*F*	*Chicane*
B	*80mm-high round-top humps*	*G*	*Build-out*
C	*1.7m-wide speed cushions*	*H*	*Mini-roundabout*
D	*Pinch point and speed cushion*	*I*	*1.9m-wide cushions*
E	*100mm-highRaised junction*		

calming varied, according to the scheme, by between 4.0 and 7.8 grammes. The corresponding CO emission before calming in 2005 is expected to vary between 1.2 and 4.0 grammes. Also, the rankings do not account for any differences that may exist between the impacts of the different schemes on traffic flow along the roads.

The validity of the unweighted emission indicators, and the information relating to how the passenger car fleet will change between 1998 and 2005, have been used to assess the validity of the weighted emission indicators. Consequently, it has been assumed that the ordering of the impacts of the different schemes may only be statistically valid for CO_2 given the vehicle sample sizes used in the study.

Table 29 Weighted emission impacts: reference year 2005

	Scheme and % change in emissions per vehicle-km			
Impact	*CO*	*HC*	*NO_x*	*CO_2*
Smallest	H (-9%)	H (+21%)	I (+6%)	F (+13%)
●	G (+39%)	I (+21%)	G (+9%)	G (+14%)
●	B (+40%)	G (+35%)	F (+10%)	I (+15%)
●	I (+41%)	C (+36%)	H (+17%)	D (+16%)
●	E (+75%)	D (+41%	C (+19%)	C (+20%)
●	C (+79%)	B (+48%)	D (+20%)	H (+23%)
●	D (+91%)	E (+55%)	B (+22%)	B (+32%)
●	F (+126%)	A (+67%)	E (+39%)	A (+32%)
Largest	A (+157%)	F (+72%)	A (+42%)	E (+33%)

Shaded columns indicate where the scheme order for a given vehicle category and pollutant was considered to be statistically robust

Key

Scheme	*Traffic calming measure*		
A	*75mm-high flat-top road humps*	*F*	*Chicane*
B	*80mm-high round-top humps*	*G*	*Build-out*
C	*1.7m-wide speed cushions*	*H*	*Mini-roundabout*
D	*Pinch point and speed cushion*	*I*	*1.9m-wide cushions*
E	*100mm-highRaised junction*		

8.2.4 Delays to emergency service vehicles

The rankings of the measures according to their impact on the response times of emergency service vehicles are provided in Table 30.

Because of the rather limited nature of the experiment, the delay times obtained are probably not representative of an emergency situation. Hence, the generic groups of measures have been awarded star ratings, with the measures causing the least delay being awarded three stars, and those causing the longest delay one star. Although delays to ambulances were not determined in the experiment, it likely that the relative rankings of the generic groups will also apply to these vehicles.

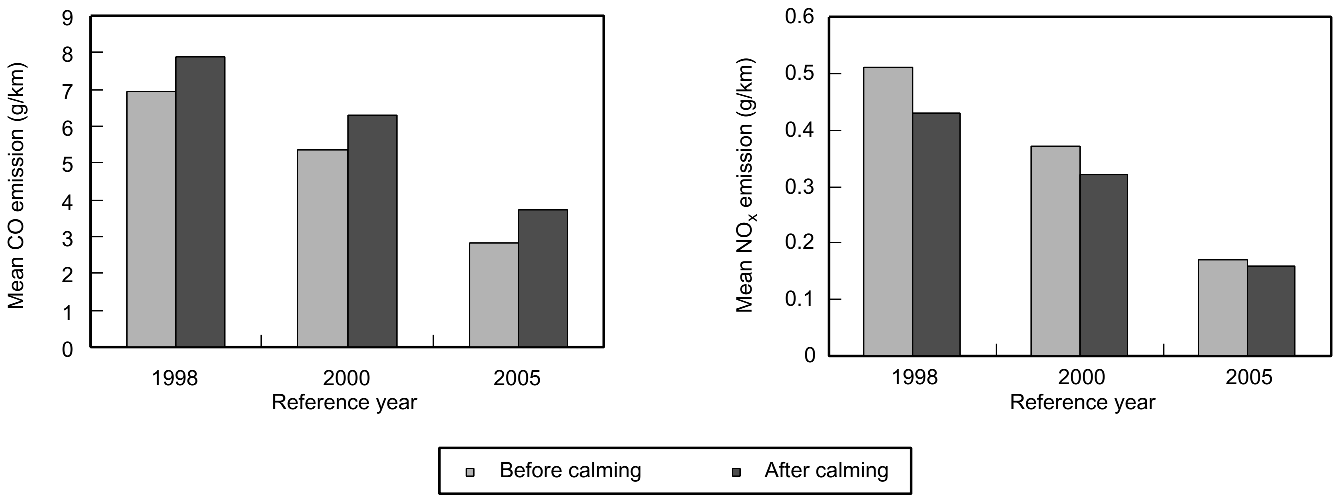


Figure 39 Emissions of CO and NO_X before and after calming in the reference years 1998, 2000, and 2005 (averaged over all nine schemes)

Table 30 Delays to emergency services

Impact (✶✶✶= shortest delay)	*Scheme*	*Traffic calming measure*	*Generic group*
✶✶✶	F	Chicane	'Chicanes'
	G	Build-out	
	H	Mini-roundabout	
✶✶	C	1.7m-wide speed cushions	'Speed cushions'
	D	Pinch point/speed cushion	
	I	1.9m speed cushions	
✶	A	75mm flat-top humps	'Humps'
	B	80mm round-top hump	
	E	Raised junction	

[1] *Speeds after calming measured on different road to speeds before calming*
[2] *Based on an estimated mean speed before calming*

8.3 Guidance on scheme implementation

A large amount of information relating to the various impacts of traffic calming has been generated in the study. In this chapter of the Report, the information has been distilled into a simple set of guidelines, in the form of a general set of performance indicators, which can be used by local authorities during the process of selecting appropriate traffic calming measures to implement.

The general performance indicators for the nine types of traffic calming measure investigated in the study are summarised in Table 31. The format of the table is based on the assumption that a local authority will hope to improve safety by achieving a specific reduction in vehicle speeds through the introduction of traffic calming. Consequently, the first column of Table 31 lists a number of possible target speed reduction values, based on a mean speed before calming of 30 mph (48 km/h). The second column of the table identifies the type of traffic calming measure likely to achieve a specific reduction in speed, and the remaining columns give the likely effects of each measure on accidents, delays to emergency service vehicles, and emissions. The weighted emission estimates for the reference year 2000 have been used to reflect the current traffic composition. Because of the large amount of variation in the measured emission rates, and the resulting uncertainty in the comparison of the impacts of the different schemes, a star rating system has been adopted. The relative importance of the individual effects may be defined by each local authority according to prevailing circumstances.

9 Impacts on local air quality

The National Air Quality Strategy (NAQS) (Department of the Environment *et al.*, 1997) details the Government's policies with respect to the management of local air pollution in the UK. Air quality objectives have been set for the pollutants carbon monoxide, nitrogen dioxide, lead, ozone, sulphur dioxide, the hydrocarbons benzene and 1,3-butadiene, and particulate matter of aerodynamic

Table 31 Summary of performance indicators for the nine traffic calming measures investigated

Target speed reduction mph (km/h)†	*Type of measure likely to achieve target speed reduction (scheme)*		*Likely accident reduction (%)*	*Delays to emergency services (✶✶✶ = shortest)*	*Effect on traffic exhaust emissions (per average vkm) for the year 2000 (☆☆☆ = lowest impact)*									
					CO		*HC*		*NO_x*		*CO_2*		*PM**	
12 (19)	100mm Raised junction	(E)	60	✶	☆	(+58%)	☆	(+54%)	☆	(+28%)	☆	(+32%)	☆☆	(+31%)
10 (16)	75mm flat-top road humps	(A)	50	✶	☆	(+82%)	☆	(+65%)	☆	(+37%)	☆	(+31%)	☆	(+82%)
	80mm round-top humps	(B)		✶	☆☆	(+41%)	☆	(+55%)	☆☆	(+13%)	☆	(+31%)	☆☆	(+21%)
9 (14)	1.9m-wide cushions	(I)	45	✶✶	☆☆	(+30%)	☆☆	(+32%)	☆☆☆	(-3%)	☆	(+14%)	☆☆	(+27%)
8 (13)	Mini-roundabout	(H)	40	✶✶✶	☆☆☆	(+5%)	☆☆	(+32%)	☆☆	(+10%)	☆☆	(+22%)	☆☆	(+35%)
	1.7m-wide speed cushions	(C)		✶✶	☆☆	(+43%)	☆☆☆	(+29%)	☆☆	(+17%)	☆☆	(+19%)	☆	(+46%)
7 (11)	Pinch point and speed cushion	(D)	35	✶✶	☆	(+56%)	☆☆	(+42%)	☆☆	(+13%)	☆☆☆	(+15%)	☆☆☆	(-1%)
	Single-lane working chicane	(F)		✶✶✶	☆	(+95%)	☆	(+80%)	☆☆☆	(+1%)	☆☆☆	(+12%)	☆	(+49%)
5 (8)	Build-out	(G)	25	✶✶✶	☆☆	(+31%)	☆☆☆	(+24%)	☆☆☆	(+2%)	☆☆☆	(+14%)	☆☆☆	(+2%)

* *Based on unweighted emission test results for diesel cars only.*
† *Based on a mean speed before calming of 30 mph (48 km/h).*

diameter less than 10mm (PM_{10}). The original objectives have been subject to revision (DETR *et al*., 2000), and the new objectives for the pollutants which are relevant to this Report are summarised in Table 32. The objectives apply in non-occupational near-ground-level locations where people might be exposed over the relevant averaging period.

Ideally, the impact of each traffic calming measure on ambient air pollution would also have been measured in the study. However, the impacts on local air pollution would have been difficult to detect, given the normal variation in concentrations. Consequently, the minimum and maximum traffic-weighted changes in emissions determined in the study were used in conjunction with the DMRB dispersion model (Highways Agency *et al*., 1996) in order to predict how local air quality would be affected. The percentage changes in local atmospheric concentrations of carbon monoxide, benzene, 1,3-butadiene, and NO_2 were simulated by changing the traffic flow according to the changes in the primary source emissions. No calculation could be undertaken for PM_{10}, as no emission values were recorded for petrol-engined cars. An average hourly traffic flow and average HGV component were estimated from the data presented in Tables 3 and 4.

Figures 40-43 show the calculated concentrations of CO, benzene, 1,3-butadiene, and NO_2 at various distances from the centre of the road in the three reference years. It should be noted that the scales on the vertical axes do not start at zero. For the four pollutants all the calculated concentrations (at distances at and beyond 10m from the road centre) were well below the NAQS objective, and it is very unlikely that the observed increases in emissions would have resulted in poor local air quality. There are a number of explanations for this outcome. For example, given the volume of traffic on each of the roads in question air pollution would probably not have been a major problem either before or after calming. Furthermore, local emissions from traffic on the road of interest are superimposed on a background concentration that includes emissions from traffic in surrounding areas, and a wide range of non-traffic phenomena also affect atmospheric concentrations of pollutants. Therefore, concentrations will tend to show a damped response to any localised changes in vehicle emissions. This effect is illustrated by the comparatively small changes in pollutant concentrations shown in Table 33. It was found that the percentage changes in atmospheric concentrations due to traffic calming would tend to decrease with time, due to the increasing numbers of catalyst-equipped vehicles in the passenger car fleet resulting in a reduced contribution of traffic to local air pollution.

Table 33 Changes in the concentration of each pollutant 10m from the road centre

	% change in concentration					
	1998		*2000*		*2005*	
Pollutant	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*
CO	+0.9	+8.0	+0.4	+6.7	-0.5	+5.1
Benzene	+1.4	+11.9	+2.7	+10.1	+1.2	+7.7
1,3-butadiene	+2.9	+11.2	+2.7	+9.5	+1.2	+7.2
NO_2	-1.2	+5.1	-0.4	+4.3	+0.5	+3.3

10 Summary and discussion of results

10.1 Background

In order to provide robust information on the impacts of traffic calming on vehicle emissions, as well as guidance for local authorities, the Charging and Local Transport Division of DETR commissioned TRL to conduct a three-year study of the impacts of traffic calming on exhaust emissions. The main objectives of the study were:

- To investigate the effects of different traffic calming measures on the exhaust emissions from passenger cars.
- To develop a system of performance indicators for different traffic calming measures. These indicators would account for effects on emissions from all road traffic, and would demonstrate how the emission impacts compared with impacts on speed, safety, and delays to emergency service vehicles.

Nine types of traffic calming measure were selected for investigation. These were:

A 75mm-high flat-top road humps.
B 80mm-high round-top road humps.
C 1.7m-wide speed cushions.
D A combined pinch point and speed cushion.
E 100mm-high raised junctions.
F A chicane.
G A build-out.
H A mini-roundabout.
I 1.9m-wide speed cushions.

Table 32 Revised objectives in the 2000 National Air Quality Strategy

	Objective		
Pollutant	*Concentration*	*Measured as*	*Date to be achieved by*
Carbon monoxide	11.6mg/m³ (10ppm)	Running 8-hour mean	December 31, 2003
Benzene	16.25:µg/m³ (5ppb)	Running annual mean	December 31, 2003
1,3-butadiene	2.25:µg/m³ (1ppb)	Running annual mean	December 31, 2003
Nitrogen dioxide	40:µg/m³ (21ppb)	Annual mean	December 31, 2005
	200:µg/m³ (105ppb)	1-hour mean not to be exceeded more than 18 times a year	December 31, 2005
PM_{10}	40:µg/m³ (1ppb)	Annual mean	December 31, 2004
	50:µg/m³ (1ppb)	24-hour mean not to be exceeded more than 35 times a year	December 31, 2004

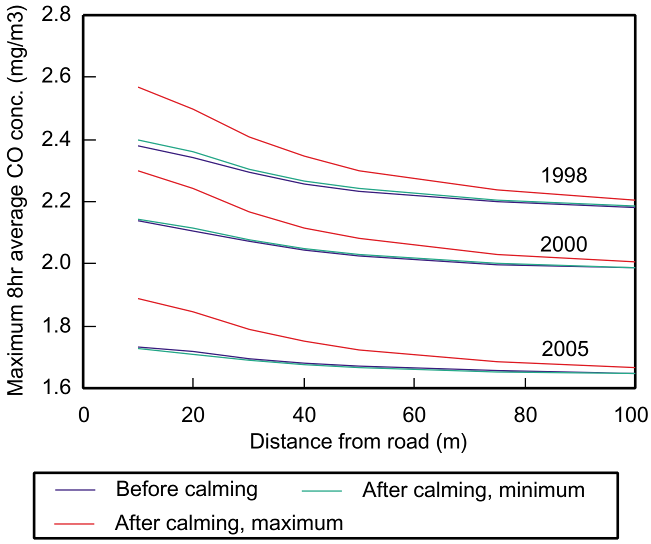


Figure 40 CO concentrations at various distances from the road centre in the reference years 1998, 2000, and 2005

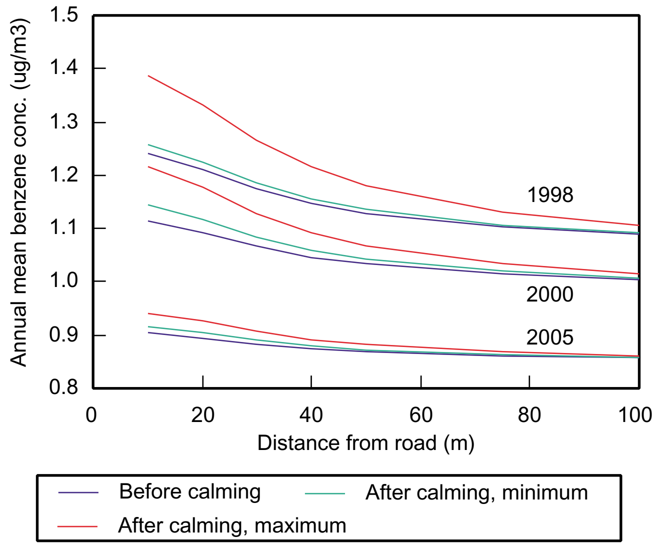
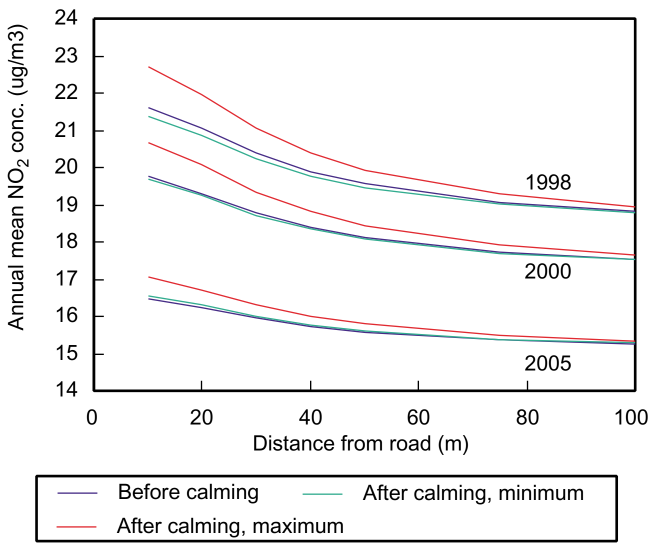


Figure 41 Benzene concentrations at various distances from the road centre in the reference years 1998, 2000, and 2005



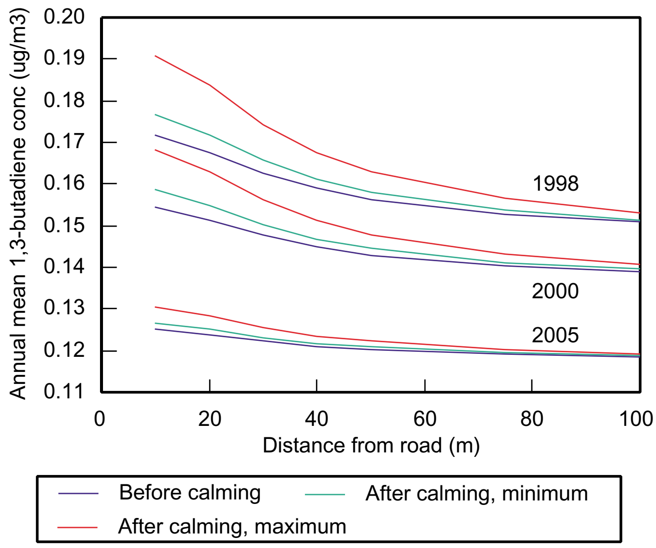


Figure 42 1,3-butadiene concentrations at various distances from the road centre in the reference years 1998, 2000, and 2005

Figure 43 NO_2 concentrations at various distances from the road centre in the reference years 1998, 2000, and 2005

10.2 Study methodology

So that the impacts of each traffic calming measure on emissions could be determined using a chassis dynamometer under controlled laboratory conditions, driving cycles were formulated to represent vehicle operation before and after the introduction of the schemes, based on *in situ* traffic survey data.

It was specified beforehand that the speed data used to develop the driving cycles for the traffic calming measures would be derived using a method of measurement which would not affect the behaviour of drivers as they negotiated the actual schemes. The speed-time profiles of the vehicles passing through each scheme were therefore measured using an unobtrusive remote technique. It was initially proposed that a separate set of speed profile measurements, obtained using instrumented cars driven through the same schemes by selected subjects, would be used to determine the gear-change points across the operating speed ranges. Each speed profile measured using the remote technique and the instrumented cars at a particular scheme would be characterised using statistical descriptors of the speed data, thus defining several modes of vehicle operation. A sample of speed profiles, reflecting the range of vehicle operation through the scheme, would then be taken from the remote measurements and used to select corresponding speed profiles (with associated gear selections) from the instrumented car measurements. The latter profiles would be combined to form a driving cycle representing the range of vehicle operation on the section of road at the time the speed measurements were taken. This process was adopted in the study, but it was simplified in the early stages.

10.3 Speed measurement techniques

The proposed methodology relied in part on a statistical method for matching the speed profiles obtained by remote measurement with those measured using the instrumented cars. Tests were required to confirm that the speed profiles measured using these approaches were directly comparable. The speed of a vehicle passing along a section of road at the TRL site featuring road humps was monitored simultaneously using three techniques: one on-board instrument and two external methods of measurement (a laser-based LIDAR system and road tubes). There was found to be a good agreement between the speed profiles measured by all three devices, including those profiles exhibiting a large variation in speed. Mainly because of its ease of installation, ease of use, and less conspicuous nature, the LIDAR system was selected in preference to the road tubes as the means by which remote measurements would be obtained during the study.

In order to establish the feasibility of the proposed methodology in a real-world situation, a field trial was conducted on a stretch of road along which traffic calming measures had already been installed. The overall mean speed, and the overall standard deviation of speed (both averaged over all speed profiles) from two instrumented cars (one ‘medium’, one ‘large’) were compared with those of the remote measurements. It was important that the comparatively small number of instrumented car profiles, which would be used to construct the final driving cycle, exhibited a sufficiently wide range of speeds to reflect the speed range of the LIDAR measurements. It was found that the mean speeds of the two instrumented cars were significantly different from the mean speed recorded using the LIDAR system (one was higher, one lower). Large differences in the overall standard deviation of speed were also apparent. The speed profiles measured using the LIDAR had a lower overall standard deviation than those measured using either of the instrumented cars. If the LIDAR measurements accurately reflected the range of real-world vehicle operation, then the results showed that in an experiment of this kind, where an attempt is being made to determine representative speed profiles over specific, and comparatively short sections of road, the use of a single instrumented car may produce unrepresentative results. However, as the ranges of the combined instrumented car measurements reflected the majority of the LIDAR measurements, it was considered that the trial confirmed the overall feasibility of applying the proposed methodology to a real-world situation. It was thought that the speed of a particular vehicle passing through a traffic calming scheme might well be affected by its characteristics, such as its performance, its wheel-base, the stiffness of its suspension, and the general ride comfort. Therefore, it was considered that the possibility of covering the entire speed range observed in the remote measurements could be increased by including a third instrumented car.

10.4 Traffic flow, composition and speed

Traffic surveys were conducted before and after the installation of each of the first five traffic calming measures under investigation (schemes A-E). During the experimental phase of the study it was not possible to identify sites where a chicane, a build-out, or a mini-roundabout would have been introduced early enough for the measures to be included within the study, and where the layout was suitable for remote speed measurement. Consequently, the speed measurements designed to reflect vehicle operation after calming were obtained at sites where these measures had already been introduced. Also, practical considerations dictated that for the 1.9m-wide speed-cushions remote speed measurements were conducted on one road before calming, but on a different road after calming.

Traffic flow

Traffic flows were recorded where possible, so that the overall effect of each scheme on emissions from the traffic on the affected roads could be calculated. Automatic 24-hour counts were only undertaken for schemes A-E, with the information being supplied by the appropriate local authorities. No automatic counts were available for schemes F-I, though for schemes F, G and H an estimate of traffic flow after calming was made using the video record.

Although the flow of traffic through scheme A (75mm flat-top road humps) was found to have decreased, it actually increased at schemes B-E. The largest increase occurred at scheme B (80mm round-top road humps), where the total weekly two-way flow increased by 28% after calming. However, the counts were not conducted immediately before and after the introduction of each scheme, and any changes in flow due to the schemes are probably masked by seasonal differences, and possibly by a general increase in overall traffic during the intervening periods. Scheme implementation can often be subject to unforeseen delays, and this was one reason for the extended periods between the flow measurements at some of the sites.

Traffic composition

At each site, most of the traffic flows comprised passenger cars and light goods vehicles. Very few HGVs and buses were observed on the roads investigated. Where information on traffic composition was available before and after calming, there was generally a good agreement between the proportions of vehicles in each category. The main exception was scheme I, for which the large discrepancies were probably due to the surveys before and after calming having been conducted on different roads.

There is a possibility that the introduction of traffic calming could cause a change in the composition of the traffic on a particular road. For example, the drivers of heavy goods vehicles might be inclined to adopt an alternative route in order to avoid road humps. However, the data for schemes A-E indicated that there was no strong tendency for the composition of the traffic to be affected, although the balance between medium-size and large cars had shifted slightly in favour of the latter after calming.

Vehicle speed

At the six sites where remote speed measurements were obtained before calming, the mean speed of passenger cars varied between 38 km/h (24 mph) and 53 km/h (33 mph). This implies that, even though each road was in a residential area and had a 30mph speed limit, there were some differences in the nature of the sites monitored. The differences in the speeds before calming may have been attributable to factors which could not be controlled, such as carriageway width, the extent of on-road parking, and pedestrian activity. The speeds of passenger cars after calming varied between 23 km/h (14 mph) and 42 km/h (26 mph), with the actual speed reduction, excluding the three sites for which no measurements were obtained before calming, ranging from 10 km/h (6 mph) to 19 km/h (12 mph). The largest speed reductions were observed for scheme I (1.9m-wide speed cushions), and once again this was probably due in part to the surveys before and after calming having been conducted on different roads. There was no evidence to suggest that passenger car size had an impact on speed before or after calming, or on the magnitude of the speed reduction achieved. The speeds of LGVs changed from between 36 km/h (22 mph) and 50 km/h (31 mph) before calming to between 20 km/h (12 mph) and 42 km/h (26 mph) after calming, with a speed reduction of between 10 km/h (6 mph) and 17 km/h (11 mph). The effects of traffic calming on the speeds of HGVs and buses were more variable, but this was probably due in part to the small sample sizes. As the mean speeds reported in this study were calculated from second-by-second LIDAR profiles, they are not directly comparable to the spot speed measurements at traffic calming schemes reported elsewhere.

The mean speed standard deviation per profile generally increased after calming. These increases reflect the tendency of drivers to accelerate and decelerate between discrete traffic calming measures. The main exception was scheme B (round-top road humps) where, for reasons which are not clear, the speed standard deviation of most vehicles decreased after calming.

One of the disadvantages of using the LIDAR system was that it failed to record a speed of zero. This meant that idling will have been under-represented in some of the measurements, and hence in some of the driving cycles. The effect would have been most pronounced on the roads where periods of idling might have occurred more frequently, or on roads where the traffic calming measures would usually have resulted in periods of idling. For example, some vehicles would have been stationary at the mini-roundabout and the build-out, with drivers being forced to give priority. On Owlsmoor road, round-top road humps had also been installed in addition to the measures of specific interest. Although vehicle speeds were measured away from the road humps, it is possible that they affected speeds in the vicinity of the build-out and mini-roundabout.

Implications for emission test programme

Only small differences were observed between the means and standard deviations of the speeds of the small, medium, and large car categories before calming. Larger, but still small, differences were apparent after calming. In practice, quite large differences in speed would be necessary to show significant differences in emission rates, since emission measurements tend to show poor repeatability. Therefore, one driving cycle was considered sufficient to represent all three sizes of car.

An assessment of the means and standard deviations of the speed profiles for each category of vehicle indicated that there were only small differences between those travelling in a convoy and those not in a convoy. Small differences were also observed between the mean and standard deviation of the profiles obtained during different periods of the week. Once again, it has been assumed that the effects of these differences on emissions would have been minimal. In any case, the cycles were constructed from random sets of profiles which included all of this potential variation.

10.5 Driving cycles

For the first scheme in the study (scheme A: 75mm-high flat-top road humps) the driving cycles were derived from a combination of remote speed measurements obtained using a LIDAR device, and speed and gear-change data recorded using instrumented cars. The feasibility of selecting a number of instrumented car speed profiles to correspond to a representative sample of LIDAR profiles was confirmed both in tests at TRL and in real traffic. It was found that the range of instrumented car measurements covered the range of the LIDAR measurements if the results from two different instrumented cars were used. However, although the LIDAR system was capable in principle of measuring 'real' driver behaviour, certain aspects of its operation indicated that it was probably not the definitive technique.

The amalgamation of short instrumented car cycles resulted in driving cycles which were difficult to follow on the dynamometer, and had unrealistic gear-change patterns. Consequently, a smoothing function was applied to the speed data to make the cycle more drivable, and gear changes were simply set to occur at given speeds. As gear-selection measurements were no longer required for the remaining schemes, the LIDAR speed profiles alone were be used to construct the driving cycles.

Using this approach, driving cycles were developed to represent vehicle operation before and after calming for schemes A-E and scheme I. For schemes F, G and H, remote speed measurements could only be obtained after the traffic calming measures had been installed. Consequently, substitute cycles representing vehicle operation before the introduction of these measures were developed from the cycles constructed for some of the other schemes.

10.6 Exhaust emissions

Exhaust emission measurements were conducted by AEA Technology, based on the driving cycles supplied by TRL. At the start of the study, twelve in-service petrol cars and three in-service diesel cars were selected from a variety of sources by AEA for the emission test work. The petrol cars were categorised according to the level of emission control (*i.e.* whether or not the car was equipped with a catalyst) and engine size. No differentiation was applied to the diesel cars. Some vehicles were withdrawn by their owners during the test programme. Although replacement vehicles were introduced, the changes in the vehicle samples for the different schemes inevitably introduced an additional element of variability into the results.

A total of 542 individual emission tests were conducted by AEA, with fuel consumption and exhaust emissions of four pollutants (CO, HC, NO_x, and CO_2) being recorded in each test. Total particulate matter was also recorded during the tests involving diesel vehicles. For each pair of tests associated with a given pollutant, vehicle, and driving cycle, the emission values were averaged.

Overall effects of traffic calming by vehicle type

For the petrol non-catalyst, petrol catalyst, and diesel vehicle samples, the overall effects of all the traffic calming measures on the mean emissions of each pollutant per vehicle-km were determined. For each vehicle category emissions were higher over the driving cycles designed to reflect vehicle operation after calming than over the cycles representing operation before calming. For petrol non-catalyst, petrol catalyst, and diesel cars, the increases in the mean emissions of CO were 34%, 59%, and 39% respectively. In each case, the increase in emissions was significant at a high level of confidence. For each vehicle category the increase in mean HC emissions was close to 50%, and again the increases were statistically significant. The mean emission of NO_x from petrol vehicles increased slightly, but the change was not significant at the 95% confidence level. In contrast, NO_x emissions from diesel vehicles increased by around 30%. Emissions of CO_2 increased by 20-26%, with the increase being significant for each type of vehicle. For diesel vehicles, emissions of particulate matter increased by 30%.

These were some of the most important results of the study, since they appeared to indicate that, for the vehicle fleet in the UK, the larger impacts of traffic calming on emissions recorded in some previous studies are not likely to be typical. For example, Zhger and Blessing (1995) found that the CO and NO_x emissions from a single catalyst-equipped petrol car increased by 160% and 900% respectively after the introduction of road humps. Here, a more extensive test programme revealed that although catalyst cars tended to have the lowest *absolute* emission rates, they also had the most variable emission rates and generally showed the greatest sensitivity to traffic calming. For example, there was a difference of two orders of magnitude between the HC output of the highest and lowest emitters. Emissions of CO from catalyst-equipped vehicles changed by between -30% and +639% as a result of calming, and HC emissions changed by between -91% and +285%. For NO_x emissions in particular, where a large increase had occurred, the emission rate before calming tended to be very low. There was less variation in the mean emission levels and percentage impacts of the petrol non-catalyst and diesel vehicles tested. However, whilst it was found that large increases in emissions can occur for catalyst cars as a result of calming (*i.e.* over 600% in the case of CO, and around 160% in the case of NO_x), such effects do not appear to be dominant.

Given the inevitable variation between the findings from different studies of this kind (due to the different assessment methods and scenarios employed, as well as the general variability of exhaust emissions), and the tendency to quote wide ranges in the results, the overall results for CO show quite a good agreement with those from previous TRL studies using the MODEM model (Cloke *et al*., 1999) and remote sensing (Boulter, 1999), and fall within the range of results reported by GFMPTE (1992) for a petrol non-catalyst car. The mean HC results fall within the overall range of those reported previously, though they do not concur with those quoted in any single study. As implied above, the NO_x results tended to show more similarity to the predictions of the MODEM model (Webster, 1993a; Cloke *et al*., 1999) than to the results of the on-board measurements conducted by Zhger and Blessing (1995). For CO_2, there was a better level of agreement between the studies. In the study by Cloke *et al*. (1999), where MODEM was used to estimate impacts, a range of vehicle operating conditions (*i.e*. different roads) were assessed. The results of the current study appear to agree quite well with the largest increases in CO, HC, and CO_2 reported by Cloke *et al*., and the smallest decrease in NO_x.

Clearly, some catalyst-equipped cars exhibit substantially higher emissions over traffic calming cycles than the other catalyst cars. Evidence suggests that catalysts tend to exhibit on/off control, and emission levels from catalyst-equipped vehicles are much more sensitive to operating conditions than those from non-catalyst vehicles. For particular operating conditions the catalyst may be operating at its maximum efficiency, but for slightly different conditions the conversion efficiency may be low. For example, measurements by Joumard *et al*. (1998) have shown that for engine loads (the actual power divided by the maximum power at a given engine speed) greater than 75%, instantaneous CO emissions can be 20,000 times higher than for lower loads (Figure 44). Over an entire motorway driving cycle around 90% of the total CO emissions occurred during only 15% of the time. This feature of catalyst operation would have contributed to the observed sensitivity.

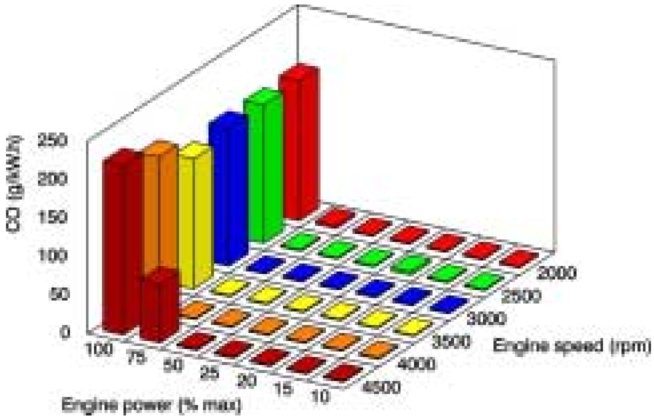


Figure 44 Instantaneous CO emissions from a catalyst car versus engine speed and load over a motorway cycle (Journard *et al*., 1998)

The general representativeness of the absolute emission rates measured in the study was assessed by comparing them with the up-to-date speed-dependent emission functions developed in the European Commission's 4th Framework MEET project. Although the emission rates in the TRL study (both before and after calming) were of the same order of magnitude as those in the MEET Report, there was generally only a fair level of agreement between the two. However, there tended to be a fairly good agreement between the percentage impacts recorded in the TRL study and those calculated using the MEET equations. These comparisons suggest that the average speed modelling approach used in MEET does, to a first approximation, give a good indication of the relative impacts of traffic calming on emissions per vehicle, though the comparison between the different vehicle samples is somewhat hindered by the differences in absolute emission rates. Further comparisons between the percentage impacts calculated using the MEET emission functions and the TRL emission data at the level of individual schemes generally revealed a poor level of agreement. This suggested that the MEET model cannot be used with confidence to order different types of traffic calming scheme according to their impact on emissions.

Emissions by scheme

The mean emission rates of all the vehicles tested over the cycles for each scheme were also determined. For each combination of pollutant, vehicle category, and scheme, paired sample *t*-tests were conducted in order to determine whether the mean emission of the vehicle sample after calming was significantly different from the mean emission before calming at the 95% confidence level. For petrol non-catalyst cars the changes in emissions of CO, HC, and CO_2 were statistically significant for all schemes, whilst the changes in NO_x were only significant for selected schemes. The results were rather different for petrol catalyst cars. Although the changes in CO_2 emissions were significant for all schemes, the changes in CO and HC were generally not significant. The change in NO_x emissions from petrol catalyst cars was not statistically significant for any scheme. For diesel cars, the significant changes tended to occur for NO_x and CO_2. The changes in CO and HC emissions were generally not significant, and emissions of particulate matter did not change significantly for any scheme.

The main objective of the study was to develop a system of comparative emission performance indicators for the different traffic calming measures. However, the impacts of the different measures had to be compared statistically in order to assess the relevance of the scheme order for each vehicle category and pollutant. All the statistical tests were conducted on the *percentage changes* in emissions. In other words, for the purpose of the statistical tests the percentage change in the emission level of each vehicle (for a given vehicle category and pollutant) was calculated, and then the resulting values were averaged. A multiple pairwise comparison method (the Student-Newman-Keuls (SNK) test) was used to examine the differences between the scheme means. The SNK test enabled schemes to be grouped according to whether significant differences existed between the means. In general, there was a great deal of overlap between the impacts of the grouped traffic calming measures. The extreme examples of this were the cases where there were no significant differences between the impacts of any of the different measures (*i.e.* petrol catalyst HC / NO_x, and diesel HC). The most distinct differences between schemes tended to occur with the petrol non-catalyst cars.

10.7 Delays to an emergency service vehicle

Although the emergency services are usually consulted before the introduction of traffic calming measures, there is little quantitative evidence relating to the delays imposed on their vehicles by traffic calming. In addition to the experimental work relating to exhaust emissions, a short experiment was conducted with the aim of estimating the delays imposed on a fire tender by different traffic calming measures. The results of the experiment indicated that the speed reduction effected by the speed cushions was significantly smaller than the speed reduction effected by the chicane which, in turn, was significantly smaller than the reduction effected by the flat top humps. However, the delays per measure were relatively small, and unless large numbers of traffic calming measures are encountered, it is unlikely that fire tender response times in an emergency situation would increase significantly.

10.8 Performance indicators and guidance

One of the main objectives of the research was to develop a system of performance indicators for the different traffic calming measures. The main findings of the study, as well as any relevant information drawn from other sources, were used to generate these indicators, as well as guidance on the implementation of traffic calming measures. The indicators were speed reduction, accident reduction, vehicle emissions, traffic emissions, and delays to emergency service vehicles.

The speed reduction that is likely to be achieved after the introduction of traffic calming measures will vary from site to site, and will mainly depend upon the type of traffic calming measure, the mean 'before' speed, and the spacing between measures. The speeds before calming and the spacing between measures varied between the sites in this study and, in order to provide a consistent basis for comparison, the speed reduction indicators were based on a common mean 'before' speed of 30 mph and a common separation between measures of 80m. The speed reduction data were obtained from a range of TRL studies at a large number of sites

An indication of the relative effect of the different types of traffic calming measure on injury accident frequency was obtained by considering the likely reduction in mean speed that will be achieved at each type of traffic calming measure and applying established relationships between changes in speed and accidents.

The resulting information was distilled into a simple set of guidelines, in the form of a general set of performance indicators, which can be used by local authorities during the process of selecting appropriate traffic calming measures to implement. The guidance is based on the assumption that a local authority will hope to improve safety be achieving a specific reduction in vehicle speeds through the introduction of traffic calming, and identifies the type of traffic calming measure likely to achieve a specific reduction in speed, as well as the likely effects of each measure on accidents, delays to emergency service vehicles, and emissions. The relative importance of the individual effects may be defined by each local authority according to prevailing circumstances.

The performance indicators demonstrate that the more severe ‘hump-type’ traffic calming measures tend to result in the largest speed reductions and hence the greatest reduction in accidents and the longest delays to emergency service vehicles. These measures also tend to result in the largest increases in emissions. The measures incorporating speed cushions and/or horizontal deflections tend to result in smaller speed reductions and smaller increases in emissions than the hump-type measures.

10.9 Local air quality

The impacts of the different schemes on ambient air pollution levels were not measured in the study, but the implications of the results on the ambient concentrations of CO, benzene, 1,3-butadiene, and NO_2 near the road were assessed using a dispersion model. For the four pollutants all the calculated concentrations (at distances at and beyond 10m from the road centre) were well below the NAQS objective, and it is unlikely that the observed increases in emissions would have resulted in poor local air quality.

11 Conclusions

TRL has conducted a three-year study of the impacts of traffic calming on exhaust emissions, the most detailed and extensive of its kind to date. Nine different types of measure were investigated, and the results have been used to develop guidance on scheme implementation for local authorities. The main conclusions of the research are presented as follows:

1 The results of the study clearly indicate that traffic calming measures increase the emissions of some pollutants from passenger cars. For the petrol non-catalyst, petrol catalyst, and diesel cars tested, the mean emissions of CO, HC, and CO_2 increased by between 20 and 60 percent. For NO_x emissions, only the diesel cars showed a substantial increase (about 30 percent). The increases in NO_x emissions for petrol non-catalyst and petrol catalyst cars were much smaller, and not statistically significant. Emissions of total particulate mater from the diesel cars increased by 30 percent.

2 Although the catalyst-equipped petrol cars tended to have the lowest *absolute* emission rates, they also had the most variable emissions and some vehicles exhibited a particular sensitivity to traffic calming. Whilst it was found that large increases in emissions can occur for some catalyst cars, such effects do not appear to be dominant, and it is unlikely that the very large impacts of traffic calming on emissions recorded in some previous studies are typical of the UK vehicle fleet.

3. The more ‘severe’ traffic calming measures (*e.g.* road humps) tend to result in the greatest speed reductions, the greatest accident savings, and some of the largest increases in emissions. It will therefore be necessary for local authorities to adopt a balanced approach to the implementation of traffic calming, whereby the potential benefits of reduced speeds and fewer accidents are weighed against the possible adverse impacts of increased emissions.

4 Urban traffic calming measures have been mainly introduced on residential roads with low traffic flows. Consequently, even though traffic calming generally results in increased emissions per vehicle it is very unlikely that that it would result in poor local air quality. Indeed, the atmospheric pollutant concentrations associated with the types of scheme and levels of traffic flow considered in this report were calculated using a dispersion model, and were found to be well below the 2000 Air Quality Strategy standards. Furthermore, the improving performance of emission control technology with time means that, in the future, breaches of the standards would be even less likely to occur as a result of traffic calming. However, in Air Quality Management Areas, where air pollution standards are frequently breached, particular attention would need to be given to the balance between reductions in injury accidents and increases in vehicle emissions.

5 In spite of the variability in the results, particularly for petrol catalyst cars, the understanding of the general effects of traffic calming on passenger car emissions is now improving. The *overall* percentage changes in CO vehicle emissions found in this study show quite a good agreement with those calculated using an average speed model (MEET), and with those found in previous TRL traffic calming studies using an instantaneous emission model (MODEM), and TRL remote sensing measurements. The changes in HC emissions fall within the overall range of those reported previously, though they do not concur with those quoted in any single study. The NO_x results tend to show more similarity to the predictions of the MODEM model than to the results of on-board measurements. For CO_2, there is a good level of agreement between different studies. However, the impacts of individual types of measure are more difficult to predict. Comparisons at this level between the percentage impacts measured in this study and those calculated using MEET have suggested that the model cannot be used with confidence to rank different types of traffic calming measures according to their impact on emissions. It remains to be seen whether this can be achieved with other models, such as MODEM.

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13 References

Amis G (1995). *Traffic calming in Cambridgeshire. Effects on accident frequency at calmed sites and on surrounding roads.* Cambridge County Council.

Boulter P G (1999). *Remote sensing of vehicle emissions near two traffic calming measures in Gloucester*. TRL Report TRL423. TRL Limited, Crowthorne.

Boulter P G and Webster D C (1997). *Traffic calming and vehicle emissions: a literature review*. TRL Report TRL307. TRL Limited, Crowthorne.

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

Cloke J, Webster D, Boulter P, Harris G, Stait R, Abbott P and Chinn L (1999). *Traffic calming: Environmental assessment of Leigh Park Area Safety Scheme in Havant.* TRL Report TRL397, TRL Limited, Crowthorne.

Coleman M A (1997). *The influence of traffic calming devices upon fire vehicle travel times.* Institute of Transportation Engineers 67th Annual Meeting. Boston, 3-7 August . Institute of Transport Engineers, Washington D.C.

Department of the Environment, The Scottish Office and The Welsh Office (1997). *The United Kingdom National Air Quality Strategy*. The Stationery Office, London.

Department of the Environment, Transport and the Regions (1997). *Transport Statistics Great Britain 1997 Edition*. The Stationery Office, London.

Department of Transport (1994). *Fire and ambulance services. Traffic calming: a code of practice*. Traffic Advisory Leaflet 3/94.

Department of Transport (1997). *Vehicle licensing statistics: 1996*. The Stationery Office, London

Department of the Environment, Transport and the Regions, the Scottish Executive, the National Assembly for Wales, and the Department of the Environment in Northern Ireland (2000). *The air quality strategy for England, Scotland, Wales, and Northern Ireland.* Cm4548. Department of the Environment, Transport and the Regions, London.

EC Directive 91/441/EEC (1991). *Council Directive of 26 June 1991 amending Directive 70/220/EEC on the approximation of the laws of the Member States relating to measures to be taken against air pollution by emissions from motor vehicles*. Official Journal of the European Communities, Legislation, Volume 34, Part 242. Brussels.

European Commission (1999). *MEET - Methodology for calculating transport emissions and energy consumption.* Office for Official Publications of the European Communities, L-2985 Luxembourg.

Evans D (1994). *Traffic calming: the first five years and the Oxfordshire experience.* Proceedings of ICE. *Municipal Engineer* 1994-03.

GFMPTE (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 (German Federal Ministries of Planning, Transport & Environment), Bonn.

Hampshire County Council (1996). *Traffic calming in Hampshire.* Report of the County Surveyor, 29th April 1996.

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 and Bridges (DMRB).*

Höglund P G (1995). *Estimating traffic related exhaust emissions and immisions at road and street intersections.* Esitelmä: KFB & VTI Research Information Days, Linköping, Sweden. January 10-11, pp9-11. Department of Infrastructure and Planning, Division of Traffic and Transport Planning, Royal Institute of Technology, Stockholm, Sweden.

Joumard R, Philippe F and Vidon R (1998). *Reliability of the current models of instantaneous pollutant emissions. Science of the Total Environment*, 235 (1999), pp133-142. Elsevier Science.

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.

Layfield R E and Parry D I (1998). *Traffic calming-speed reduction schemes*. TRL Report TRL312. TRL Limited, Crowthorne.

Miller R G jr. (1981). *Simultaneous Statistical Inference*. Springer-Verlag, New York.

Salway A G, Eggleston H S, Goodwin J W L, and Murrells T P (1997). *National Atmospheric Emissions Inventory (NAEI). UK Emissions of Air Pollutants 1970-1995*. National Environmental Technology Centre (NETCEN), Culham, Abingdon.

Sayer I A, Parry D I and Barker J K (1998). *Traffic calming - an assessment of selected on-road chicane schemes*. TRL Report TRL313. TRL Limited, Crowthorne.

Stilwell Bell and Elmbridge Borough Council (1994). *Drawing No. SB/EBC/7000/13. Options for improvement - Rydens Road and Ambleside Avenue*. Stilwell Bell Safety Traffic and Highway Engineering Partnership, Frimley.

Taylor M C, Lynam D A and Baruya A (2000). *The effects of divers' speed on the frequency of road accidents*. TRL Report TRL421. TRL Limited, Crowthorne.

Webster D C (1993a). *Effect of traffic calming schemes on vehicle emissions*. Project Report PR/TF/13/93, p8. TRL Limited, Crowthorne. *(Unpublished report available on direct personal application only)*

Webster D C (1993b). *Road humps for controlling vehicle speeds*. Project Report PR18. TRL Limited, Crowthorne. *(Unpublished report available on direct personal application only)*

Webster D C and Layfield R E (1996). *Traffic calming - Road hump schemes using 75mm high humps*. TRL Report TRL186, TRL Limited, Crwothorne.

Webster D C and Mackie A M (1996). *Review of traffic calming schemes in 20mph zones*. TRL Report TRL215. TRL Limited, Crowthorne.

Wheeler A H and Taylor M C (2000). *Changes in accident frequency following the introduction of traffic calming in villages*. TRL Report TRL452. TRL Limited, Crowthorne.

Zhger P and Blessing R (1995). *Emissions nocives du traffic*. Les mefaits des embouteillages et des gendarmes couches. TOURING: Journal du Touring Club Suisse. No.1 January 12.

Appendix A: Emission test results

Table A1 Carbon monoxide (g/km): Petrol non-catalyst cars

		Vehicle size and reference number							
Traffic calming measure		*Small*				*Medium*		*Large*	
Stage		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Scheme A: Flat-top road humps									
Before calming	Test results	4.944	–	6.968	–	7.179	16.154	6.751	10.967
		4.728	–	5.820	–	6.025	21.475	6.348	14.351
	Mean	4.836	–	6.394	–	6.602	18.815	6.550	12.659
After calming	Test results	6.727	–	10.213	–	9.751	25.044	9.208	19.461
		6.721	–	9.050	–	7.774	26.950	8.358	21.327
	Mean	6.724	–	9.632	–	8.763	25.997	8.783	20.394
	% change in mean	*+39*	–	*+51*	–	*+33*	*+38*	*+34*	*+61*
Scheme B: Round-top humps									
Before calming	Test results	8.615	–	15.301	–	9.562	25.729	9.914	16.302
		9.140	–	9.582	–	9.083	26.656	9.326	15.678
	Mean	8.878	–	12.442	–	9.323	26.193	9.620	15.990
After calming	Test results	13.038	–	23.531	–	13.431	35.789	12.981	27.547
		13.884	–	14.798	–	9.895	31.319	13.144	26.009
	Mean	13.461	–	19.165	–	11.663	33.554	13.063	26.778
	% change in mean	*+52*	–	*+54*	–	*+25*	*+28*	*+36*	*+67*
Scheme C: 1.7m-wide speed cushions									
Before calming	Test results	10.755	–	11.710	20.351	9.885	29.803	9.127	16.256
		9.733	–	7.402	15.270	9.327	27.851	8.545	24.273
	Mean	10.244	–	9.556	17.811	9.606	28.827	8.836	20.265
After calming	Test results	13.361	–	11.543	23.123	11.341	27.056	11.938	25.755
		13.600	–	11.618	21.625	10.261	35.550	12.723	30.620
	Mean	13.481	–	11.580	22.374	10.801	31.303	12.331	28.188
	% change in mean	*+32*	–	*+21*	*+26*	*+12*	*+9*	*+40*	*+39*
Scheme D: Pinch point/speed cushion									
Before calming	Test results	6.450	–	10.345	–	9.618	21.360	11.683	18.440
		7.190	–	13.071	–	8.499	22.201	12.648	21.390
	Mean	6.820	–	11.708	–	9.059	21.781	12.166	19.915
After calming	Test results	11.455	–	13.082	–	14.220	29.288	13.309	25.559
		11.969	–	15.988	–	13.673	29.330	14.021	25.905
	Mean	11.712	–	14.535	–	13.947	29.309	13.665	25.732
	% change in mean	*+72*	–	*+24*	–	*+54*	*+35*	*+12*	*+29*
Scheme E: Raised junction									
Before calming	Test results	–	17.380	13.879	–	6.784	23.794	11.707	21.430
		–	17.318	10.020	–	4.756	22.257	11.580	18.185
	Mean	–	17.349	11.950	–	5.770	23.026	11.644	19.808
After calming	Test results	–	24.369	18.162	–	8.507	29.866	15.264	33.945
		–	22.276	16.879	–	8.678	28.964	14.476	28.083
	Mean	–	23.323	17.521	–	8.593	29.415	14.870	31.014
	% change in mean	–	*+34*	*+47*	–	*+49*	*+28*	*+28*	*+57*
Scheme F: Chicane									
Before calming	Test results	–	17.885	10.370	–	5.267	17.105	12.097	11.024
		–	16.866	9.793	–	4.164	16.546	10.944	11.854
	Mean	–	17.375	10.081	–	4.176	16.826	11.520	11.439
After calming	Test results	–	21.866	17.847	–	14.740	30.039	15.212	19.795
	Mean	–	22.972	18.161	–	14.297	30.330	14.844	21.683
	% change in mean	–	*+32*	*+80*	–	*+203*	*+80*	*+29*	*+90*

Continued ....

Table A1 (Continued) Carbon monoxide (g/km): Petrol non-catalyst cars

Traffic calming measure		*Vehicle size and reference number*							
		Small				*Medium*		*Large*	
Stage		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Scheme G: Build-out									
Before calming	Test results	–	18.285	13.304	–	7.340	26.953	13.122	19.901
		–	17.580	11.929	–	8.113	24.104	14.785	–
	Mean	–	17.932	12.616	–	7.727	25.529	13.954	19.901
After calming	Test results	–	17.143	16.578	–	12.809	29.166	12.321	26.787
		–	22.875	15.258	–	14.376	27.546	15.586	
	Mean	–	20.009	15.918	–	13.593	28.356	13.954	26.787
	% change in mean	–	*+12*	*+26*	–	*+76*	*+11*	*0*	*+35*
Scheme H: Mini-roundabout									
Before calming	Test results	–	18.285	12.570	–	10.780	26.953	13.122	21.500
		–	17.580	12.890	–	8.010	24.104	14.785	17.400
	Mean	-–	17.932	12.730	–	9.395	25.529	13.954	19.450
After calming	Test results	–	21.565	16.420	–	9.110	32.233	14.711	23.690
		–	22.144	16.820	–	11.610	28.823	14.855	29.330
	Mean	–	21.584	16.620	–	10.360	30.528	14.783	26.510
	% change in mean	-	*+22*	*+31*	–	*+10*	*+20*	*+6*	*+36*
Scheme I: 1.9m-wide speed cushions									
Before calming	Test results	–	15.534	9.361	–	6.590	21.407	13.710	16.210
		–	16.406	9.857	–	5.192	19.678	10.028	16.619
	Mean	–	15.970	9.609	–	5.891	20.543	11.869	16.414
After calming	Test results	–	20.098	14.269	–	5.899	21.366	14.647	22.041
		–	18.371	14.328	–	5.496	20.880	14.342	20.099
	Mean	–	19.235	14.299	–	5.698	21.123	14.494	21.070
	% change in mean	–	*+20*	*+49*	–	*-3*	*+3*	*+22*	*+28*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A2 Carbon monoxide (g/km): Petrol catalyst cars

		Vehicle size and reference number										
Traffic calming measure		*Small*				*Medium*					*Large*	
Stage		*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Scheme A: Flat-top road humps												
Before calming	Test results	2.268	–	–	0.363	–	0.563	–	–	1.368	2.075	0.152
		2.100	–	–	0.424	–	0.554	–	–	1.784	3.467	0.282
	Mean	2.184	–	–	0.394	–	0.559	–	–	1.576	2.771	0.217
After calming	Test results	2.014	–	–	1.483	–	1.202	–	–	2.147	15.996	0.881
		1.965	–	–	0.893	–	2.254	–	–	2.774	24.969	0.473
	Mean	1.990	–	–	1.188	–	1.728	–	–	2.461	20.483	0.677
	% change in mean	*-9*	–	–	*+202*	–	*+209*	–	–	*+56*	*+639*	*+212*
Scheme B: Round-top humps												
Before calming	Test results	–	21.706	–	2.478	–	–	3.399	–	1.629	17.212	0.851
		–	19.668	–	4.794	–	–	7.270	–	1.514	22.632	1.442
	Mean	–	20.687	–	3.636	–	–	5.335	–	1.572	19.922	1.147
After calming	Test results	–	28.816	–	9.039	–	–	7.413	–	3.312	25.282	1.461
		–	25.439	–	5.700	–	–	7.583	–	5.144	27.171	2.092
	Mean	–	27.128	–	7.370	–	–	7.798	–	4.228	26.227	1.777
	% change in mean	–	*+31*	–	*+103*	–	–	*+41*	–	*+169*	*+32*	*+55*
Scheme C: 1.7m-wide speed cushions												
Before calming	Test results	–	–	–	0.909	–	–	–	3.535	0.353	2.448	0.701
		–	–	–	0.754	–	–	–	3.896	0.491	3.070	0.764
	Mean	–	–	–	0.832	–	–	–	3.715	0.422	2.759	0.733
After calming	Test results	–	–	–	0.810	–	–	–	5.957	1.519	7.424	1.126
		–	–	–	0.828	–	–	–	7.265	1.798	11.633	1.471
	Mean	–	–	–	0.819	–	–	–	6.611	1.658	9.529	1.298
	% change in mean	–	–	–	*-2*	–	–	–	*+78*	*+293*	*+245*	*+77*
Scheme D: Pinch point/speed cushion												
Before calming	Test results	–	–	1.490	1.043	3.972	–	–	–	0.783	3.937	0.276
		–	–	4.184	1.256	10.568	–	–	–	0.831	13.264	0.562
	Mean	–	–	2.837	1.150	7.270	–	–	–	0.807	8.600	0.419
After calming	Test results	–	–	3.423	1.411	8.374	–	–	–	1.076	8.425	0.507
		–	–	3.899	1.427	11.866	–	–	–	1.025	16.374	0.802
	Mean	–	–	3.661	1.419	10.120	–	–	–	1.051	12.400	0.655
	% change in mean	–	–	*+29*	*+23*	*+39*	–	–	–	*+30*	*+44*	*+56*
Scheme E: Raised junction												
Before calming	Test results	–	–	4.708	0.825	3.737	–	–	–	1.202	4.205	0.554
		–	–	18.173	6.190	4.568	–	–	–	2.516	9.680	0.539
	Mean	–	–	11.441	3.508	4.153	–	–	–	1.859	6.943	0.547
After calming	Test results	–	–	13.829	3.886	5.056	–	–	–	1.709	8.467	0.445
		–	–	23.794	13.163	12.595	–	–	–	2.623	18.430	0.910
	Mean	–	–	18.812	8.525	8.826	–	–	–	2.166	13.453	0.678
	% change in mean	–	–	*+64*	*+143*	*+113*	–	–	–	*+17*	*+94*	*+24*
Scheme F: Chicane												
Before calming	Test results	–	–	1.362	0.974	1.973	–	–	–	0.469	3.693	0.428
		–	–	5.180	0.750	7.008	–	–	–	0.792	2.230	0.899
	Mean	–	–	3.271	0.862	4.490	–	–	–	0.631	2.962	0.664
After calming	Test results	–	–	3.859	2.902	9.953	–	–	–	0.981	6.358	0.923
		–	–	7.218	2.651	17.501	–	–	–	0.335	9.891	1.158
	Mean	–	–	5.539	2.776	13.727	–	–	–	0.658	8.125	1.041
	% change in mean	–	–	*+69*	*+222*	*+206*	–	–	–	*+4*	*+174*	*+57*

Continued ....

Table A2 (Continued) Carbon monoxide (g/km): Petrol catalyst cars

Traffic calming measure		*Vehicle size and reference number*										
		Small				*Medium*					*Large*	
Stage		*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Scheme G: Build-out												
Before calming	Test results	-	-	3.767	0.763	7.277				1.798	1.565	0.568
				16.074	2.208	8.776				4.512	8.726	2.080
	Mean	-	-	9.921	1.486	8.027	-	-	-	3.155	5.146	1.324
After calming	Test results	-	-	6.587	1.763	12.71				3.197	6.951	2.372
				15.082	4.301	12.374				3.400	11.349	2.433
	Mean	-	-	10.835	3.032	12.542	-	-	-	2.999	9.150	2.403
	% change in mean	-	-	*+9*	*+104*	*+56*	-	-	-	*+5*	*+78*	*+81*
Scheme H: Mini-roundabout												
Before calming	Test results	-	-	3.767	0.763	7.277				1.798	1.565	0.568
				16.074	2.208	8.776				4.512	8.726	2.080
	Mean	-	-	9.921	1.486	8.027	-	-	-	3.155	5.146	1.324
After calming	Test results	-	-	4.410	2.093	8.422				2.733	3.663	3.258
				9.518	1.375	3.427				2.305	6.301	3.113
	Mean	-	-	6.964	1.734	5.925	-	-	-	2.519	4.982	3.186
	% change in mean	-	-	*-30*	*+17*	*-26*	-	-	-	*-20*	*-3*	*+41*
Scheme I: 1.9m-wide speed cushions												
Before calming	Test results	-	-	2.625	0.407	4.510				1.355	3.521	0.442
				2.165	1.186	13.223				7.957	1.921	1.142
	Mean	-	-	2.395	0.797	8.867	-	-	-	4.656	2.721	0.792
After calming	Test results	-	-	2.773	1.676	6.030				2.679	6.946	0.636
				2.806	3.083	13.969				4.952	11.573	1.734
	Mean	-	-	2.790	2.380	9.999	-	-	-	3.816	9.260	1.185
	% change in mean	-	-	*+16*	*+198*	*+13*	-	-	-	*-18*	*+240*	*+50*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A3 Carbon monoxide (g/km): Diesel cars

Traffic calming measure		Vehicle size and reference number		
		No size discrimination		
Stage		20	21	22
Scheme A: Flat-top road humps				
Before calming	Test results	1.062	0.433	0.492
		0.965	0.433	0.512
	Mean	1.014	0.433	0.502
After calming	Test results	1.126	0.676	1.001
		1.058	0.709	0.965
	Mean	1.092	0.693	0.983
	% change in mean	*+8*	*+60*	*+96*
Scheme B: Round-top humps				
Before calming	Test results	1.264	0.342	0.507
		1.227	0.375	0.462
	Mean	1.246	0.359	0.485
After calming	Test results	1.479	0.691	1.051
		1.435	0.824	1.031
	Mean	1.457	0.758	1.041
	% change in mean	*+17*	*+111*	*+115*
Scheme C:1.7m-wide speed cushions				
Before calming	Test results	1.156	0.392	0.548
		1.063	0.377	0.557
	Mean	1.110	0.385	0.553
After calming	Test results	1.245	0.568	0.811
		1.162	0.571	0.803
	Mean	1.203	0.570	0.807
	% change in mean	*+8*	*+48*	*+46*
Scheme D: Pinch point/speed cushion				
Before calming	Test results	1.246	0.369	0.391
		1.177	0.407	0.436
	Mean	1.212	0.388	0.414
After calming	Test results	1.245	0.531	0.593
		1.274	0.543	0.586
	Mean	1.260	0.537	0.590
	% change in mean	*+4*	*+38*	*+43*
Scheme E: Raised junction				
Before calming	Test results	0.706	0.365	0.629
		0.947	0.337	0.697
	Mean	0.826	0.351	0.516
After calming	Test results	1.147	0.504	0.850
		1.067	0.527	0.855
	Mean	1.107	0.663	0.852
	% change in mean	*+34*	*+89*	*+65*
Scheme F: Chicane				
Before calming	Test results	0.889	0.296	0.437
		0.913	0.254	0.427
	Mean	0.901	0.275	0.287
After calming	Test results	1.156	0.372	0.598
		1.148	0.304	0.617
	Mean	1.152	0.432	0.510
	% change in mean	*+28*	*+57*	*+77*

Continued ...

Table A3 (Cont'd) Carbon monoxide (g/km): Diesel cars

Traffic calming measure		Vehicle size and reference number		
		No size discrimination		
Stage		20	21	22
Scheme G: Build-out				
Before calming	Test results	1.062	0.372	0.399
		1.037	0.304	0.405
	Mean	1.050	0.338	0.402
After calming	Test results	1.118	0.598	0.726
		1.074	0.617	0.677
	Mean	1.096	0.608	0.702
	% change in mean	*+4*	*+80*	*+75*
Scheme H: Mini-roundabout				
Before calming	Test results	1.062	0.372	0.399
		1.037	0.304	0.405
	Mean	1.050	0.338	0.402
After calming	Test results	1.026	0.515	0.828
		1.017	0.539	0.777
	Mean	1.021	0.527	0.802
	% change in mean	*-3*	*+56*	*+100*
Scheme I: 1.9m-wide speed cushions				
Before calming	Test results	0.945	0.260	0.341
		0.919	0.269	0.314
	Mean	0.932	0.264	0.328
After calming	Test results	0.956	0.559	0.689
		0.950	0.574	0.666
	Mean	0.953	0.567	0.678
	% change in mean	*+2*	*+115*	*+106*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A4 Total hydrocarbons (g/km): Petrol non-catalyst cars

Traffic calming measure		Vehicle size and reference number							
		Small				Medium		Large	
Stage		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Scheme A: Flat-top road humps									
Before calming	Test results	0.863	–	1.417	–	0.862	1.730	0.914	1.192
		0.915	–	1.352	–	0.780	1.738	0.845	1.186
	Mean	0.889	–	1.385	–	0.821	1.734	0.880	1.189
After calming	Test results	1.567	–	2.283	–	1.360	3.110	1.128	2.224
		1.714	–	2.277	–	1.351	2.890	1.091	2.261
	Mean	1.641	–	2.280	–	1.356	3.000	1.110	2.243
	% change in mean	*+85*	–	*+65*	–	*+_65*	*+73*	*+26*	*+89*
Scheme B: Round-top humps									
Before calming	Test results	1.244	–	1.926	–	1.221	1.932	0.861	1.701
		1.270	–	1.649	–	1.307	1.851	0.898	1.548
	Mean	1.257	–	1.788	–	1.246	1.892	0.880	1.625
After calming	Test results	2.134	–	3.564	–	1.941	3.392	1.087	3.025
		2.453	–	2.911	–	1.966	3.300	1.152	2.853
	Mean	2.294	–	3.238	–	1.954	3.346	1.120	2.939
	% change in mean	*+82*	–	*+81*	–	*+55*	*+77*	*+27*	*+81*
Scheme C: 1.7m-wide speed cushions									
Before calming	Test results	1.174	–	1.878	2.423	1.345	1.859	0.906	1.606
		1.144	–	1.606	2.144	1.340	1.785	0.769	1.868
	Mean	1.159	–	1.742	2.284	1.342	1.822	0.838	1.737
After calming	Test results	1.748	–	2.271	3.262	1.964	2.391	1.021	2.449
		1.651	–	2.345	3.052	1.762	2.646	1.250	2.938
	Mean	1.700	–	2.308	3.157	1.863	2.519	1.136	2.693
	% change in mean	*+47*	–	*+32*	*+38*	*+39*	*+38*	*+36*	*+55*
Scheme D: Pinch point/speed cushion									
Before calming	Test results	1.091	–	1.566	–	1.331	1.693	1.177	1.559
		1.164	–	1.848	–	1.026	1.774	1.016	1.681
	Mean	1.128	–	1.708	–	1.179	1.784	1.097	1.620
After calming	Test results	1.737	–	2.124	–	1.954	2.606	1.291	2.585
		1.784	–	2.578	–	1.783	2.711	1.344	2.156
	Mean	1.761	–	2.351	–	1.869	2.659	1.317	2.371
	% change in mean	*+56*	–	*+38*	–	*+59*	*+49*	*+20*	*+46*
Scheme E: Raised junction									
Before calming	Test results	–	2.660	2.159	–	1.043	2.108	0.937	1.978
		–	2.640	1.883	–	0.995	2.023	0.858	1.787
	Mean	–	2.650	2.021	–	1.019	2.066	0.898	1.883
After calming	Test results	–	3.703	3.510	–	1.672	3.097	1.202	2.947
		–	3.420	3.428	–	1.838	3.045	1.129	2.873
	Mean	–	3.562	3.469	–	1.755	3.071	1.166	2.910
	% change in mean	–	*+34*	*+72*	–	*+72*	*+49*	*+30*	*+55*
Scheme F: Chicane									
Before calming	Test results	–	2.070	1.520	–	0.765	1.518	0.993	1.636
		–	2.130	1.423	–	0.745	1.505	0.830	1.664
	Mean	–	2.086	1.472	–	0.755	1.152	0.911	1.650
After calming	Test results	–	3.361	2.586	–	3.057	2.683	1.130	2.351
		–	3.660	2.596	–	1.925	2.721	1.024	2.573
	Mean	–	3.510	2.591	–	2.491	2.072	1.077	2.462
	% change in mean	–	*+68*	*+76*	–	*+230*	*+79*	*+18*	*+49*

Continued ....

Table A4 (Continued) Total hydrocarbons (g/km): Petrol non-catalyst cars

Traffic calming measure		*Vehicle size and reference number*							
		Small				*Medium*		*Large*	
Stage		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Scheme G: Build-out									
Before calming	Test results	–	2.308	2.093	–	1.190	2.187	1.008	2.025
		–	2.683	2.067	–	1.730	2.031	1.097	1.880
	Mean	–	2.496	2.080	–	1.460	2.109	1.053	1.953
After calming	Test results	–	2.786	2.395	–	1.787	2.452	1.332	2.108
		–	2.949	2.433	–	2.587	2.481	1.163	2.157
	Mean	–	2.868	2.414	–	2.187	2.467	1.248	2.133
	% change in mean	–	*+15*	*+16*	–	*+50*	*+17*	*+19*	*+9*
Scheme H: Mini-roundabout									
Before calming	Test results	–	2.308	1.960	–	1.410	2.187	1.008	2.090
		–	2.683	1.730	–	1.090	2.031	1.097	1.960
	Mean	–	2.496	1.845	–	1.250	2.109	1.053	2.025
After calming	Test results	–	3.473	2.810	–	1.970	3.364	1.251	2.570
		–	3.830	2.960	–	1.960	2.967	1.269	3.110
	Mean	–	3.651	2.885	–	1.965	3.166	1.260	2.840
	% change in mean	–	*+46*	*+56*	–	*+57*	*+50*	*+19*	*+40*
Scheme I: 1.9m-wide speed cushions									
Before calming	Test results	–	1.952	1.262	–	0.897	1.542	1.046	1.165
		–	1.810	1.194	–	0.875	1.365	0.893	1.105
	Mean	–	1.881	1.228	–	0.886	1.454	0.970	1.135
After calming	Test results	–	2.682	2.110	–	1.251	2.549	1.185	1.974
		–	2.550	2.115	–	1.121	2.383	1.096	1.620
	Mean	–	2.616	2.113	-	1.186	2.466	1.140	1.797
	% change in mean	–	*+39*	*+72*	–	*+34*	*+70*	*+18*	*+58*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A5 Total hydrocarbons (g/km): Petrol catalyst cars

Traffic calming measure		*Vehicle size and reference number*										
		Small				*Medium*					*Large*	
Stage		*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Scheme A: Flat-top road humps												
Before calming	Test results	0.291	–	–	0.019	–	0.027	–	–	0.028	0.143	0.015
		0.359	–	–	0.007	–	0.038	–	–	0.041	0.133	0.023
	Mean	0.325	–	–	0.013	–	0.033	–	–	0.035	0.138	0.019
After calming	Test results	0.454	–	–	0.032	–	0.062	–	–	0.032	0.350	0.046
		0.367	–	–	0.028	–	0.085	–	–	0.043	0.483	0.024
	Mean	0.411	–	–	0.030	–	0.074	–	–	0.038	0.417	0.035
	% change in mean	*+26*	–	–	*+131*	–	*+126*	–	–	*+9*	*+250*	*+84*
Scheme B: Round-top humps												
Before calming	Test results	–	2.091	–	0.043	–	–	0.062	–	0.023	0.145	0.027
		–	2.033	–	0.078	–	–	0.273	–	0.016	0.403	0.042
	Mean	–	2.062	–	0.061	–	–	0.168	–	0.020	0.274	0.035
After calming	Test results	–	2.955	–	0.135	–	–	0.169	–	0.043	0.465	0.041
		–	2.609	–	0.088	–	–	0.280	–	0.068	0.470	0.056
	Mean	–	2.782	–	0.112	–	–	0.225	–	0.056	0.468	0.049
	% change in mean	–	*+35*	–	*+84*	–	–	*+34*	–	*+185*	*+71*	*+41*
Scheme C: 1.7m-wide speed cushions												
Before calming	Test results	–	–	–	0.054	–	–	–	0.100	0.013	0.094	0.013
		–	–	–	0.023	–	–	–	0.102	0.018	0.118	0.021
	Mean	–	–	–	0.038	–	–	–	0.101	0.016	0.106	0.017
After calming	Test results	–	–	–	0.021		–	–	0.175	0.025	0.227	0.017
		–	–	–	0.013	–	–	–	0.243	0.031	0.262	0.022
	Mean	–	–	–	0.017	–	–	–	0.209	0.028	0.245	0.020
	% change in mean	–	–	–	*-55*	–	–	–	*+107*	*+79*	*+130*	*+13*
Scheme D: Pinch point/speed cushion												
Before calming	Test results	–	–	0.064	0.019	0.361	–	–	–	0.031	0.132	0.022
		–	–	0.143	0.020	0.589	–	–	–	0.014	0.292	0.016
	Mean	–	–	0.103	0.020	0.475	–	–	–	0.023	0.212	0.019
After calming	Test results	–	–	0.226	0.026	0.643	–	–	–	0.010	0.230	0.011
		–	–	0.251	0.019	0.910	–	–	–	0.017	0.381	0.011
	Mean	–	–	0.239	0.023	0.777	–	–	–	0.014	0.305	0.011
	% change in mean	–	–	*+131*	*+15*	*+63*	–	–	–	*-40*	*+44*	*-42*
Scheme E: Raised junction												
Before calming	Test results	–	–	0.213	0.040	0.078	–	–	–	0.034	0.158	0.043
		–	–	0.449	0.141	0.098	–	–	–	0.044	0.312	0.003
	Mean	–	–	0.331	0.091	0.088	–	–	–	0.039	0.235	0.023
After calming	Test results	–	–	0.323	0.141	0.109	–	–	–	0.021	0.283	0.000
		–	–	0.528	0.313	0.364	–	–	–	0.053	0.476	0.004
	Mean	–	–	0.425	0.227	0.237	–	–	–	0.037	0.380	0.002
	% change in mean	–	–	*+29*	*+151*	*+169*	–	–	–	*-5*	*+61*	*-91*
Scheme F: Chicane												
Before calming	Test results	–	–	0.099	0.050	0.090	–	–	–	0.038	0.154	0.003
		–	–	0.146	0.026	0.209	–	–	–	0.022	0.105	0.007
	Mean	–	–	0.123	0.038	0.150	–	–	–	0.030	0.130	0.005
After calming	Test results	–	–	0.301	0.070	0.464	–	–	–	0.041	0.223	0.003
		–	–	0.468	0.066	0.690	–	–	–	0.038	0.350	0.007
	Mean	–	–	0.385	0.068	0.577	–	–	–	0.040	0.287	0.005
	% change in mean	–	–	*+214*	*+79*	*+286*	–	–	–	*+32*	*+121*	*0*

Continued ....

Table A5 (Continued) Total hydrocarbons (g/km): Petrol catalyst cars

Traffic calming measure		*Vehicle size and reference number*										
		Small				*Medium*					*Large*	
Stage		*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Scheme G: Build-out												
Before calming	Test results	–	–	0.203	0.028	0.422	–	–	–	0.029	0.077	0.044
		–	–	0.557	0.058	0.404	–	–	–	0.101	0.231	0.110
	Mean	–	–	0.380	0.043	0.413	–	–	–	0.065	0.154	0.077
After calming	Test results	–	–	0.183	0.040	0.977	–	–	–	0.056	0.188	0.218
		–	–	0.481	0.102	0.673	–	–	–	0.049	0.285	0.100
	Mean	–	–	0.332	0.071	0.825	–	–	–	0.053	0.236	0.159
	% change in mean	–	–	*-13*	*+64*	*+100*	–	–	–	*-19*	*+54*	*+106*
Scheme H: Mini-roundabout												
Before calming	Test results	–	–	0.203	0.028	0.422	–	–	–	0.029	0.077	0.044
		–	–	0.557	0.058	0.404	–	–	–	0.101	0.231	0.110
	Mean	–	–	0.380	0.043	0.413	–	–	–	0.065	0.154	0.077
After calming	Test results	–	–	0.143	0.048	0.513	–	–	–	0.088	0.133	0.163
		–	–	0.343	0.040	0.578	–	–	–	0.030	0.188	0.153
	Mean	–	–	0.243	0.044	0.546	–	–	–	0.059	0.160	0.158
	% change in mean	–	–	*-36*	*+1*	*+32*	–	–	–	*-9*	*+4*	*+105*
Scheme I: 1.9m-wide speed cushions												
Before calming	Test results	–	–	0.163	0.018	0.336	–	–	–	0.015	0.107	0.053
		–	–	0.232	0.033	0.567	–	–	–	0.130	0.055	0.068
	Mean	–	–	0.197	0.025	0.451	–	–	–	0.072	0.081	0.061
After calming	Test results	–	–	0.223	0.050	0.243	–	–	–	0.026	0.183	0.033
		–	–	0.219	0.088	0.410	–	–	–	0.068	0.220	0.123
	Mean	–	–	0.221	0.069	0.327	–	–	–	0.047	0.202	0.078
	% change in mean	–	–	*+12*	*+172*	*-28*	–	–	–	*-35*	*+148*	*+29*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A6 Total hydrocarbons (g/km): Diesel cars

Traffic calming measure		Vehicle size and reference number: No size discrimination		
Stage		*20*	*21*	*22*
Scheme A: Flat-top road humps				
Before calming	Test results	0.120	0.077	0.047
		0.038	0.061	0.049
	Mean	0.079	0.069	0.048
After calming	Test results	0.221	0.090	0.100
		0.212	0.104	0.092
	Mean	0.217	0.097	0.096
	% change in mean	*+175*	*+41*	*+99*
Scheme B: Round-top humps				
Before calming	Test results	0.493	0.027	0.080
		0.489	0.048	0.073
	Mean	0.491	0.038	0.077
After calming	Test results	0.693	0.046	0.147
		0.763	0.098	0.155
	Mean	0.728	0.072	0.151
	% change in mean	*+24*	*+53*	*+46*
Scheme C: 1.7m-wide speed cushions				
Before calming	Test results	0.239	0.015	0.043
		0.255	0.016	0.044
	Mean	0.247	0.016	0.043
After calming	Test results	0.330	0.023	0.064
		0.342	0.020	0.064
	Mean	0.336	0.021	0.064
	% change in mean	*+36*	*+34*	*+49*
Scheme D: Pinch point/speed cushion				
Before calming	Test results	0.315	0.521	–
		0.358	0.514	0.377
	Mean	0.337	0.518	0.377
After calming	Test results	0.435	0.653	0.455
		0.446	0.650	0.504
	Mean	0.441	0.652	0.479
	% change in mean	*+31*	*+26*	*+27*
Scheme E: Raised junction				
Before calming	Test results	0.504	0.280	0.061
		0.521	0.270	0.059
	Mean	0.513	0.275	0.060
After calming	Test results	0.785	0.151	0.111
		0.771	0.122	0.117
	Mean	0.778	0.136	0.114
	% change in mean	*+52*	*-50*	*+90*
Scheme F: Chicane				
Before calming	Test results	0.283	0.022	0.235
		0.282	0.020	0.216
	Mean	0.283	0.021	0.225
After calming	Test results	0.411	0.034	0.422
		0.427	0.035	0.464
	Mean	0.419	0.035	0.443
	% change in mean	*+48*	*+64*	*+96*

Continued ...

Table A6 (Cont'd) Total hydrocarbons (g/km): Diesel cars

Traffic calming measure		Vehicle size and reference number: No size discrimination		
Stage		*20*	*21*	*22*
Scheme G: Build-out				
Before calming	Test results	0.427	0.315	0.030
		0.462	0.252	0.036
	Mean	0.444	0.284	0.033
After calming	Test results	0.590	0.419	0.046
		0.609	0.397	0.049
	Mean	0.599	0.408	0.047
	% change in mean	*+35*	*+44*	*+41*
Scheme H: Mini-roundabout				
Before calming	Test results	0.427	0.315	0.030
		0.462	0.252	0.036
	Mean	0.444	0.284	0.033
After calming	Test results	0.665	0.479	0.057
		0.681	0.490	0.054
	Mean	0.673	0.484	0.055
	% change in mean	*+51*	*+71*	*+65*
Scheme I: 1.9m-wide speed cushions				
Before calming	Test results	0.415	0.149	0.056
		0.414	0.174	0.046
	Mean	0.414	0.162	0.051
After calming	Test results	0.668	0.349	0.103
		0.659	0.382	0.092
	Mean	0.664	0.366	0.098
	% change in mean	*+60*	*+126*	*+92*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A7 Total NO_x (g/km): Petrol non-catalyst cars

Traffic calming measure		Vehicle size and reference number							
		Small				*Medium*		*Large*	
Stage		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Scheme A: Flat-top road humps									
Before calming	Test results	1.191	–	0.878	–	1.182	0.641	1.939	1.161
		1.170	–	0.843	–	1.033	0.642	1.924	1.068
	Mean	1.181	–	0.861	–	1.108	0.642	1.932	1.115
After calming	Test results	1.557	–	0.911	–	1.368	0.879	2.205	1.287
		1.448	–	0.931	–	1.329	0.958	2.163	1.242
	Mean	1.503	–	0.921	–	1.349	0.919	2.184	1.265
	% change in mean	*+27*	–	*+7*	–	*+22*	*+43*	*+13*	*+13*
Scheme B: Round-top humps									
Before calming	Test results	1.186	–	0.623	–	0.901	0.602	1.950	0.795
		1.123	–	0.621	–	0.865	0.635	1.729	0.781
	Mean	1.155	–	0.622	–	0.883	0.619	1.840	0.788
After calming	Test results	1.270	–	0.615	–	1.031	0.722	1.936	0.670
		1.277	–	0.653	–	1.024	0.792	1.978	0.678
	Mean	1.274	–	0.634	–	1.028	0.757	1.957	0.674
	% change in mean	*+10*	–	*+2*	–	*+16*	*+22*	*+6*	*-14*
Scheme C: 1.7m-wide speed cushions									
Before calming	Test results	1.276	–	1.134	0.622	1.237	0.745	1.911	1.072
		1.259	–	0.970	0.768	1.136	0.771	1.851	0.853
	Mean	1.267	–	1.052	0.695	1.187	0.758	1.881	0.962
After calming	Test results	1.553	–	1.207	0.814	1.480	1.011	2.154	1.175
		1.475	–	1.288	0.858	1.416	0.861	2.165	1.102
	Mean	1.514	–	1.247	0.836	1.448	0.936	2.160	1.139
	% change in mean	*+19*	–	*+19*	*+20*	*+22*	*+23*	*+15*	*+18*
Scheme D: Pinch point/speed cushion									
Before calming	Test results	1.008	–	0.706	–	0.906	0.578	2.137	0.807
		1.072	–	0.655	–	0.898	0.543	2.034	0.685
	Mean	1.040	–	0.681	–	0.902	0.561	2.086	0.746
After calming	Test results	1.093	–	0.709	–	0.903	0.607	2.348	0.828
		1.046	–	0.668	–	0.923	0.585	2.300	0.776
	Mean	1.070	–	0.689	–	0.913	0.596	2.324	0.802
	% change in mean	*+3*	–	*+1*	–	*+1*	*+6*	*+11*	*+8*
Scheme E: Raised junction									
Before calming	Test results	–	0.579	0.820	–	1.281	0.676	2.149	1.036
		–	0.588	0.911	–	1.338	0.725	2.028	1.020
	Mean	–	0.584	0.866	–	1.310	0.701	2.089	1.028
After calming	Test results	–	0.639	0.789	–	1.383	0.698	2.053	0.880
		–	0.708	0.875	–	1.410	0.733	2.089	0.874
	Mean	–	0.674	0.832	–	1.397	0.716	2.076	0.877
	% change in mean	–	*+15*	*-4*	–	*+7*	*+2*	*-1*	*-15*
Scheme F: Chicane									
Before calming	Test results	–	0.491	0.966	–	1.449	0.778	2.299	1.261
		–	0.508	0.980	–	1.526	0.754	2.188	1.181
	Mean	–	0.500	0.973	–	1.488	0.766	2.243	1.221
After calming	Test results	–	0.435	0.696	–	1.148	0.613	2.153	1.080
		–	0.408	0.666	–	1.192	0.574	2.068	0.971
	Mean	–	0.422	0.681	–	1.170	0.594	2.110	1.026
	% change in mean	–	*-16*	*-30*	–	*-21*	*-22*	*-6*	*-16*

Continued ...

Table A7 (Continued) Total NO_x (g/km): Petrol non-catalyst cars

Traffic calming measure		*Vehicle size and reference number*							
		Small				*Medium*		*Large*	
Stage		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Scheme G: Build-out									
Before calming	Test results	–	0.603	0.788	–	1.160	0.568	1.992	0.943
		–	0.489	0.776	–	1.257	0.575	2.056	0.852
	Mean	–	0.546	0.782	–	1.209	0.572	2.024	0.898
After calming	Test results	–	0.660	0.641	–	0.992	0.558	1.835	0.782
		–	0.546	0.658	–	0.938	0.570	1.893	0.733
	Mean	–	0.603	0.649	–	0.965	0.564	1.864	0.758
	% change in mean	–	*+10*	*-17*	–	*-20*	*-1*	*-8*	*-16*
Scheme H: Mini-roundabout									
Before calming	Test results	–	0.603	0.780	–	1.130	0.568	1.992	0.910
		–	0.489	0.690	–	1.220	0.575	2.056	0.990
	Mean	–	0.546	0.735	–	1.175	0.572	2.024	0.950
After calming	Test results	–	0.657	0.680	–	1.360	0.668	1.929	1.020
		–	0.546	0.740	–	1.300	0.662	1.938	0.820
	Mean	–	0.602	0.710	–	1.330	0.665	1.934	0.920
	% change in mean	–	*+10*	*-3*	–	*+13*	*+16*	*-4*	*-3*
Scheme I: 1.9m-wide speed cushions									
Before calming	Test results	–	0.636	1.023	–	1.328	0.662	2.296	0.985
		–	0.617	0.950	–	1.275	0.667	2.229	0.963
	Mean	–	0.626	0.986	–	1.301	0.644	2.262	0.974
After calming	Test results	–	0.491	0.674	–	1.041	0.592	1.807	0.771
		–	0.489	0.678	–	1.023	0.652	1.721	0.778
	Mean	–	0.490	0.676	–	1.032	0.622	1.764	0.775
	% change in mean	–	*-22*	*-31*	–	*-21*	*-3*	*-22*	*-20*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A8 Total NO_x (g/km): Petrol catalyst cars

		Vehicle size and reference number										
Traffic calming measure		*Small*				*Medium*					*Large*	
Stage		*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Scheme A: Flat-top road humps												
Before calming	Test results	0.377	–	–	0.014	–	0.206	–	–	0.112	0.158	0.029
		0.551	–	–	0.021	–	0.260	–	–	0.104	0.158	0.044
	Mean	0.464	–	–	0.018	–	0.233	–	–	0.108	0.158	0.037
After calming	Test results	0.476	–	–	0.035	–	0.425	–	–	0.149	0.152	0.088
		0.450	–	–	0.034	–	0.413	–	–	0.214	0.192	0.104
	Mean	0.463	–	–	0.035	–	0.419	–	–	0.182	0.172	0.096
	% change in mean	*0*	–	–	*+94*	–	*+80*	–	–	*+69*	*+9*	*+159*
Scheme B: Round-top humps												
Before calming	Test results	–	0.209	–	0.039	–	–	0.263	–	0.125	0.003	0.034
		–	0.191	–	0.046	–	–	0.371	–	0.134	0.171	0.087
	Mean	–	0.200	–	0.043	–	–	0.317	–	0.130	0.087	0.061
After calming	Test results	–	0.248	–	0.041	–	–	0.415	–	0.189	0.107	0.055
		–	0.186	–	0.032	–	–	0.454	–	0.194	0.097	0.067
	Mean	–	0.217	–	0.037	–	–	0.435	–	0.192	0.102	0.061
	% change in mean	–	*+8*	–	*-14*	–	–	*+37*	–	*+48*	*+17*	*0*
Scheme C: 1.7m-wide speed cushions												
Before calming	Test results	–	–	–	0.028	–	–	–	0.370	0.233	0.131	0.026
		–	–	–	0.005	–	–	–	0.351	0.209	0.128	0.042
	Mean	–	–	–	0.016	–	–	–	0.361	0.221	0.130	0.034
After calming	Test results	–	–	–	0.041	–	–	–	0.454	0.218	0.143	0.058
		–	–	–	0.011	–	–	–	0.468	0.237	0.180	0.104
	Mean	–	–	–	0.026	–	–	–	0.460	0.228	0.162	0.081
	% change in mean	–	–	–	*+63*	–	–	–	*+27*	*+3*	*+25*	*+138*
Scheme D: Pinch point/speed cushion												
Before calming	Test results	–	–	0.246	0.028	0.173	–	–	–	0.079	0.099	0.035
		–	–	0.220	0.032	0.144	–	–	–	0.128	0.168	0.069
	Mean	–	–	0.233	0.030	0.159	–	–	–	0.104	0.133	0.052
After calming	Test results	–	–	0.263	0.010	0.153	–	–	–	0.145	0.160	0.116
		–	–	0.307	0.024	0.225	–	–	–	0.204	0.128	0.048
	Mean	–	–	0.285	0.017	0.189	–	–	–	0.175	0.144	0.082
	% change in mean	–	–	*+22*	*-43*	*+19*	–	–	–	*+68*	*+8*	*+58*
Scheme E: Raised junction												
Before calming	Test results	–	–	0.208	0.049	0.158	–	–	–	0.116	0.092	0.029
		–	–	0.160	0.047	0.151	–	–	–	0.144	0.137	0.093
	Mean	–	–	0.184	0.048	0.155	–	–	–	0.130	0.115	0.061
After calming	Test results	–	–	0.160	0.029	0.126	–	–	–	0.195	0.063	0.043
		–	–	0.121	0.031	0.069	–	–	–	0.156	0.036	0.052
	Mean	–	–	0.141	0.030	0.098	–	–	–	0.176	0.050	0.048
	% change in mean	–	–	*-23*	*-38*	*-37*	–	–	–	*+35*	*-57*	*-21*
Scheme F: Chicane												
Before calming	Test results	–	–	0.251	0.033	0.246	–	–	–	0.138	0.092	0.116
		–	–	0.208	0.047	0.171	–	–	–	0.129	0.072	0.159
	Mean	–	–	0.230	0.040	0.208	–	–	–	0.134	0.082	0.138
After calming	Test results	–	–	0.256	0.028	0.093	–	–	–	0.152	0.071	0.133
		–	–	0.223	0.033	0.031	–	–	–	0.267	0.077	0.069
	Mean	–	–	0.240	0.030	0.062	–	–	–	0.210	0.074	0.101
	% change in mean	–	–	*+4*	*-25*	*-70*	–	–	–	*+57*	*-10*	*-27*

Continued ....

Table A8 (Continued) Total NO_x (g/km): Petrol catalyst cars

Traffic calming measure		*Vehicle size and reference number*										
		Small				*Medium*					*Large*	
Stage		*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Scheme G: Build-out												
Before calming	Test results	–	–	0.224	0.055	0.085	–	–	–	0.096	0.071	0.259
		–	–	0.157	0.073	0.113	–	–	–	0.185	0.117	0.223
	Mean	–	–	0.191	0.064	0.099	–	–	–	0.141	0.094	0.241
After calming	Test results	–	–	0.173	0.035	0.083	–	–	–	0.125	0.107	0.200
		–	–	0.181	0.050	0.125	–	–	–	0.132	0.119	0.247
	Mean	–	–	0.177	0.042	0.104	–	–	–	0.129	0.113	0.224
	% change in mean	–	–	*-7*	*-34*	*+5*	–	–	–	*-9*	*+20*	*-7*
Scheme H: Mini-roundabout												
Before calming	Test results	–	–	0.224	0.055	0.085	–	–	–	0.096	0.071	0.259
		–	–	0.157	0.073	0.113	–	–	–	0.185	0.117	0.223
	Mean	–	–	0.191	0.064	0.099	–	–	–	0.141	0.094	0.241
After calming	Test results	–	–	0.197	0.042	0.144	–	–	–	0.137	0.063	0.254
		–	–	0.208	0.067	0.221	–	–	–	0.100	0.102	0.430
	Mean	–	–	0.203	0.054	0.183	–	–	–	0.119	0.083	0.342
	% change in mean	–	–	*+6*	*-16*	*+84*	–	–	–	*-16*	*-12*	*+42*
Scheme I: 1.9m-wide speed cushions												
Before calming	Test results	–	–	0.236	0.046	0.244	–	–	–	0.132	0.164	0.069
		–	–	0.255	0.038	0.146	–	–	–	0.122	0.124	0.186
	Mean	–	–	0.245	0.042	0.195	–	–	–	0.127	0.144	0.128
After calming	Test results	–	–	0.151	0.039	0.119	–	–	–	0.149	0.093	0.115
		–	–	0.155	0.043	0.066	–	–	–	0.219	0.090	0.157
	Mean	–	–	0.153	0.041	0.093	–	–	–	0.184	0.092	0.136
	% change in mean	–	–	*-38*	*-2*	*-52*	–	–	–	*+44*	*-36*	*+7*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A9 Total NO_x (g/km): Diesel cars

Traffic calming measure		Vehicle size and reference number: No size discrimination		
Stage		*20*	*21*	*22*
Scheme A: Flat-top road humps				
Before calming	Test results	0.738	0.327	0.453
		0.692	0.318	0.401
	Mean	0.715	0.322	0.427
After calming	Test results	0.967	0.459	0.630
		0.911	0.447	0.600
	Mean	0.939	0.453	0.615
	% change in mean	*+31*	*+41*	*+44*
Scheme B: Round-top humps				
Before calming	Test results	0.630	0.379	0.397
		0.612	0.377	0.396
	Mean	0.621	0.378	0.397
After calming	Test results	0.770	0.604	0.573
		0.773	0.555	0.581
	Mean	0.772	0.580	0.577
	% change in mean	*+24*	*+53*	*+45*
Scheme C: 1.7m-wide speed cushions				
Before calming	Test results	0.625	0.413	0.383
		0.613	0.401	0.366
	Mean	0.619	0.407	0.374
After calming	Test results	0.771	0.508	0.485
		0.745	0.531	0.486
	Mean	0.758	0.519	0.485
	% change in mean	*+22*	*+28*	*+30*
Scheme D: Pinch point/speed cushion				
Before calming	Test results	0.743	0.264	0.520
		0.761	0.234	0.487
	Mean	0.752	0.249	0.504
After calming	Test results	0.869	0.331	0.636
		0.869	0.291	0.621
	Mean	0.869	0.311	0.629
	% change in mean	*+16*	*+25*	*+25*
Scheme E: Raised junction				
Before calming	Test results	0.610	0.577	0.560
		0.776	0.574	0.561
	Mean	0.693	0.576	0.561
After calming	Test results	0.985	0.800	0.778
		0.945	0.822	0.754
	Mean	0.965	0.811	0.766
	% change in mean	*+39*	*+41*	*+37*
Scheme F: Chicane				
Before calming	Test results	0.637	0.433	0.402
		0.677	0.434	0.414
	Mean	0.657	0.434	0.408
After calming	Test results	0.764	0.552	0.472
		0.773	0.554	0.484
	Mean	0.769	0.553	0.478
	% change in mean	*+17*	*+27*	*+17*

Continued ....

Table A9 (Cont'd) Total NO_x (g/km): Diesel cars

Traffic calming measure		Vehicle size and reference number: No size discrimination		
Stage		*20*	*21*	*22*
Scheme G: Build-out				
Before calming	Test results	0.757	0.482	0.509
		0.743	0.476	0.498
	Mean	0.75	0.479	0.504
After calming	Test results	0.848	0.603	0.614
		0.850	0.600	0.60
	Mean	0.849	0.602	0.612
	% change in mean	*+13*	*+26*	*+21*
Scheme H: Mini-roundabout				
Before calming	Test results	0.757	0.482	0.509
		0.743	0.476	0.498
	Mean	0.750	0.479	0.504
After calming	Test results	0.943	0.649	0.770
		0.942	0.669	0.762
	Mean	0.943	0.659	0.766
	% change in mean	*+26*	*+38*	*+52*
Scheme I: 1.9m-wide speed cushions				
Before calming	Test results	0.807	0.474	0.497
		0.799	0.462	0.509
	Mean	0.803	0.468	0.503
After calming	Test results	0.812	0.604	0.648
		0.804	0.617	0.656
	Mean	0.808	0.611	0.652
	% change in mean	*+1*	*+30*	*+30*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A10 Total CO_2 (g/km): Petrol non-catalyst cars

Traffic calming measure		Vehicle size and reference number							
		Small				*Medium*		*Large*	
Stage		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Scheme A: Flat-top road humps									
Before calming	Test results	75.900	–	70.500	–	108.000	91.600	188.000	126.800
		73.400	–	67.200	–	105.100	89.700	174.700	121.300
	Mean	74.650	–	68.850	–	106.550	90.650	181.350	124.050
After calming	Test results	99.900	–	93.000	–	135.300	121.000	221.300	165.100
		98.800	–	92.300	–	138.700	124.200	209.600	157.400
	Mean	99.350	–	92.650	–	137.000	122.600	215.450	161.250
	% change in mean	*+33*	–	*+35*	–	*+29*	*+35*	*+19*	*+30*
Scheme B: Round-top humps									
Before calming	Test results	92.270	–	81.720	–	118.870	110.290	209.470	130.360
		90.370	–	78.950	–	113.950	112.920	197.780	134.580
	Mean	91.320	–	80.335	–	116.410	111.605	203.625	132.470
After calming	Test results	120.890	–	107.330	–	153.660	144.520	249.340	160.510
		121.520	–	107.480	–	153.070	146.610	251.010	165.330
	Mean	121.205	–	107.405	–	153.365	145.565	250.175	162.920
	% change in mean	*+33*	–	*+34*	–	*+32*	*+30*	*+23*	*+23*
Scheme C: 1.7m-wide speed cushions									
Before calming	Test results	88.782	–	88.308	89.317	123.543	108.156	212.420	140.342
		87.826	–	83.045	90.908	120.755	107.563	201.930	131.325
	Mean	88.304	–	85.676	90.113	122.149	107.859	207.175	135.834
After calming	Test results	109.705	–	105.487	107.992	151.849	133.914	245.660	163.091
		106.565	–	108.226	108.713	150.175	133.801	250.770	161.676
	Mean	108.135	–	106.857	108.352	151.012	133.858	248.215	162.383
	% change in mean	*+22*	–	*+25*	*+20*	*+24*	*+24*	*+20*	*+20*
Scheme D: Pinch point/speed cushion									
Before calming	Test results	90.510	–	84.22	–	113.150	100.640	195.991	127.190
		87.130	–	80.13	–	113.400	99.690	187.982	121.800
	Mean	88.82	–	82.175	–	113.275	100.165	191.986	124.495
After calming	Test results	103.450	–	99.000	–	129.830	118.050	217.877	144.720
		102.030	–	94.620	–	134.030	118.890	213.945	146.180
	Mean	102.74	–	96.810	–	131.930	118.470	215.911	145.450
	% change in mean	*+16*	–	*+18*	–	*+16*	*+18*	*+12*	*+17*
Scheme E: Raised junction									
Before calming	Test results	–	90.560	90.12	–	125.880	101.490	203.380	134.200
		–	92.020	89.69	–	127.700	103.860	193.410	134.230
	Mean	–	91.290	89.905	–	126.790	102.675	198.395	134.215
After calming	Test results	–	115.060	113.380	–	160.890	127.830	239.220	164.990
		–	118.000	113.340	–	161.550	127.910	235.930	171.100
	Mean	–	116.530	113.360	–	161.220	127.870	237.575	168.045
	% change in mean	–	*+28*	*+26*	–	*+27*	*+25*	*+20*	*+25*
Scheme F: Chicane									
Before calming	Test results	–	78.703	72.429	–	113.750	83.770	188.964	117.230
		–	78.404	71.677	–	114.500	84.740	182.671	112.460
	Mean	–	78.554	72.053	–	114.125	84.255	185.818	114.845
After calming	Test results	–	86.583	77.565	–	121.020	93.310	189.688	132.920
		–	84.814	77.275	–	120.010	93.280	188.228	129.570
	Mean	–	85.698	77.420	–	120.515	93.295	188.958	131.245
	% change in mean	–	*+9*	*+7*	–	*+6*	*+11*	*+2*	*+14*

Continued ....

Table A10 (Continued) Total CO_2 (g/km): Petrol non-catalyst cars

Traffic calming measure		Vehicle size and reference number							
		Small				*Medium*		*Large*	
Stage		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Scheme G: Build-out									
Before calming	Test results	–	84.851	79.893	–	115.650	90.080	195.020	126.630
		–	81.562	78.658	–	120.660	85.090	188.710	125.820
	Mean	–	83.207	79.276	–	118.155	87.585	191.865	126.225
After calming	Test results	–	101.420	92.973	–	136.520	108.220	199.270	148.340
		–	100.800	97.946	–	132.010	106.540	204.780	153.420
	Mean	–	101.110	95.459	–	134.265	107.380	202.025	150.880
	% change in mean	–	*+22*	*+20*	–	*+14*	*+23*	*+5*	*+20*
Scheme H: Mini-roundabout									
Before calming	Test results	–	84.851	79.250	–	110.160	90.080	195.020	124.890
		–	81.562	76.950	–	113.740	85.090	188.710	131.090
	Mean	–	83.207	78.100	–	111.950	87.585	191.865	127.990
After calming	Test results	–	109.420	103.880	–	114.350	117.240	210.950	161.550
		–	109.009	102.960	–	144.310	115.660	216.600	160.180
	Mean	–	109.214	103.420	–	144.330	116.450	213.775	160.865
	% change in mean	–	*+31*	*+32*	–	*+29*	*+33*	*+11*	*+26*
Scheme I: 1.9m-wide speed cushions									
Before calming	Test results	–	82.270	81.287	–	119.067	90.193	206.791	123.060
		–	83.236	78.281	–	119.034	91.263	193.850	120.088
	Mean	–	82.753	79.784	–	119.050	90.728	200.321	121.574
After calming	Test results	–	91.735	94.253	–	129.753	106.300	199.868	142.173
		–	92.128	91.773	–	134.354	110.070	194.367	140.466
	Mean	–	91.932	93.013	–	132.054	108.185	197.118	141.320
	% change in mean	–	*+11*	*+17*	–	*+11*	*+19*	*-2*	*+16*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A11 Total CO_2 (g/km): Petrol catalyst cars

Traffic calming measure		*Vehicle size and reference number*										
		Small				*Medium*					*Large*	
Stage		*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Scheme A: Flat-top road humps												
Before calming	Test results	93.000	–	–	89.300	–	134.6	–	–	112.600	147.400	148.300
		101.800	–	–	86.900	–	133.0	–	–	108.500	147.300	144.900
	Mean	97.400	–	–	88.100	–	133.8	–	–	110.550	147.350	146.600
After calming	Test results	120.700	–	–	116.400	–	197.9	–	–	141.600	177.600	196.500
		121.400	–	–	112.500	–	191.0	–	–	140.900	196.100	202.500
	Mean	121.050	–	–	114.450	–	194.45	–	–	141.250	186.850	199.500
	% change in mean	*+24*	–	–	*+30*	–	*+45*	–	–	*+28*	*+27*	*+36*
Scheme B: Round-top humps												
Before calming	Test results	–	103.650	–	102.000	–	–	153.99	–	135.000	152.060	148.260
		–	88.530	–	98.640	–	–	149.69	–	132.720	149.690	172.270
	Mean	–	96.090	–	100.320	–	–	151.84	–	133.860	150.875	160.265
After calming	Test results	–	137.810	–	128.680	–	–	217.34	–	172.400	209.090	244.460
		–	123.250	–	128.370	–	–	215.83	–	169.190	204.150	242.780
	Mean	–	130.530	–	128.525	–	–	216.58	–	170.795	206.620	243.620
	% change in mean	–	*+36*	–	*+28*	–	–	*+43*	–	*+28*	*+37*	*+52*
Scheme C: 1.7m-wide speed cushions												
Before calming	Test results	–	–	–	108.582	–	–	–	169.042	136.034	181.814	177.923
		–	–	–	105.894	–	–	–	166.662	134.337	174.314	175.786
	Mean	–	–	–	107.238	–	–	–	167.832	135.185	178.064	176.854
After calming	Test results	–	–	–	124.966	–	–	–	208.529	165.135	224.017	234.083
		–		–	126.339	–	–	–	208.505	163.389	210.693	235.885
	Mean	–	–	–	125.653	–	–	–	208.517	164.262	217.355	234.98
	% change in mean	–	–	–	*+17*	–	–	–	*+24*	*+22*	*+22*	*+33*
Scheme D: Pinch point/speed cushion												
Before calming	Test results	–	–	114.310	99.790	129.910	–	–	–	132.030	166.668	165.790
		–	–	108.480	100.820	127.420	–	–	–	130.850	150.736	163.300
	Mean	–	–	111.395	100.305	128.665	–	–	–	131.440	158.702	164.545
After calming	Test results	–	–	134.570	117.450	152.040	–	–	–	154.210	195.356	205.720
		–	–	132.620	117.580	152.050	–	–		153.950	188.053	200.680
	Mean	–	–	133.595	117.515	152.045	–	–	–	154.080	191.705	203.200
	% change in mean	–	–	*+20*	*+17*	*+18*	–	–	–	*+17*	*+21*	*+23*
Scheme E: Raised junction												
Before calming	Test results	–	–	119.590	104.960	141.870	–	–	–	140.670	178.900	179.900
		–	–	105.050	110.380	145.590	–	–	–	135.930	170.600	174.670
	Mean	–	–	112.320	107.670	143.730	–	–	–	138.300	174.750	177.285
After calming	Test results	–	–	143.870	146.060	177.230	–	–	–	178.990	232.420	247.620
		–	–	134.380	139.970	169.410	–	–	–	175.960	227.830	243.980
	Mean	–	–	139.125	143.015	173.320	–	–	–	177.475	230.125	245.800
	% change in mean	–	–	*+24*	*+33*	*+21*	–	–	–	*+28*	*+32*	*+39*
Scheme F: Chicane												
Before calming	Test results	–	–	95.910	87.390	124.811	–	–	–	115.110	140.016	125.620
		–	–	92.400	91.203	118.445	–	–	–	117.700	139.992	153.740
	Mean	–	–	94.155	89.297	121.628	–	–	–	116.405	140.004	139.68
After calming	Test results	–	–	112.670	103.389	137.219	–	–	–	134.620	167.998	168.980
		–	–	110.200	102.672	130.530	–	–	–	134.320	162.433	182.840
	Mean	–	–	111.435	103.030	133.875	–	–	–	134.470	165.216	175.910
	% change in mean	–	–	*+18*	*+15*	*+10*	–	–	–	*+16*	*+18*	*+26*

Continued ....

Table A11 (Continued) Total CO_2 (g/km): Petrol catalyst cars

Traffic calming measure		Vehicle size and reference number										
		Small				Medium					Large	
Stage		9	10	11	12	13	14	15	16	17	18	19
Scheme G: Build-out												
Before calming	Test results	–	–	110.800	106.920	133.200	–	–	–	133.790	163.623	173.110
		–	–	94.720	99.624	128.963	–	–	–	131.170	151.041	183.250
	Mean	–	–	102.760	103.272	131.082	–	–	–	132.480	157.332	178.180
After calming	Test results	–	–	127.230	112.189	149.698	–	–	–	152.510	191.665	197.840
		–	–	121.570	118.401	157.783	–	–	–	153.740	188.403	223.980
	Mean	–	–	124.400	115.295	153.741	–	–	–	153.125	190.034	210.910
	% change in mean	–	–	*+21*	*+12*	*+17*	–	–	–	*+16*	*+21*	*+18*
Scheme H: Mini-roundabout												
Before calming	Test results	–	–	110.800	106.920	133.200	–	–	–	133.790	163.623	173.110
		–	–	94.720	99.624	128.963	–	–	–	131.170	151.041	183.250
	Mean	–	–	102.760	103.272	131.082	–	–	–	132.480	157.332	178.180
After calming	Test results	–	–	142.670	133.207	166.894	–	–	–	169.790	217.916	223.780
		–	–	137.430	128.871	168.403	–	–	–	169.280	221.283	264.540
	Mean	–	–	140.050	131.039	167.649	–	–	–	169.535	219.600	244.160
	% change in mean	–	–	*+36*	*+27*	*+28*	–	–	–	*+28*	*+40*	*+37*
Scheme I: 1.9m-wide speed cushions												
Before calming	Test results	–	–	110.737	99.663	132.216	–	–	–	122.798	158.677	166.598
		–	–	105.581	98.822	122.628	–	–	–	119.504	161.842	145.868
	Mean	–	–	108.159	99.243	127.422	–	–	–	121.151	160.260	156.233
After calming	Test results	–	–	129.855	112.859	150.901	–	–	–	141.604	188.651	193.355
		–	–	126.325	110.322	145.353	–	–	–	142.862	185.808	211.692
	Mean	–	–	128.090	111.590	148.127	–	–	–	142.233	187.230	202.524
	% change in mean	–	–	*+18*	*+12*	*+16*	–	–	–	*+17*	*+17*	*+30*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A12 Total CO_2 (g/km): Diesel cars

		Vehicle size and reference number		
Traffic calming measure		*No size discrimination*		
Stage		*20*	*21*	*22*
Scheme A: Flat-top road humps				
Before calming	Test results	95.176	107.387	118.925
		91.567	104.049	113.244
	Mean	93.371	105.718	116.085
After calming	Test results	129.869	152.000	164.708
		124.615	153.304	160.579
	Mean	127.242	152.652	162.644
	% change in mean	*+36*	*+44*	*+40*
Scheme B: Round-top humps				
Before calming	Test results	104.400	136.600	134.800
		103.100	138.200	135.700
	Mean	103.750	137.400	135.250
After calming	Test results	133.000	187.300	179.800
		129.300	181.500	169.070
	Mean	131.150	184.400	174.435
	% change in mean	*+26*	*+34*	*+29*
Scheme C: 1.7m-wide speed cushions				
Before calming	Test results	108.975	134.368	135.422
		107.472	135.167	133.794
	Mean	108.223	134.767	134.608
After calming	Test results	131.262	170.422	169.283
		129.840	173.257	165.563
	Mean	130.551	171.840	167.423
	% change in mean	*+21*	*+28*	*+24*
Scheme D: Pinch point/speed cushion				
Before calming	Test results	105.740	128.334	130.100
		105.690	130.094	130.407
	Mean	105.715	129.214	130.254
After calming	Test results	123.240	158.986	159.390
		123.640	168.441	161.740
	Mean	123.440	163.713	160.567
	% change in mean	*+17*	*+27*	*+23*
Scheme E: Raised junction				
Before calming	Test results	77.990	144.065	143.785
		107.077	147.351	148.280
	Mean	92.534	145.708	146.033
After calming	Test results	130.436	191.700	184.984
		128.125	190.049	187.285
	Mean	129.281	190.875	186.134
	% change in mean	*+40*	*+31*	*+27*
Scheme F: Chicane				
Before calming	Test results	86.110	114.020	116.416
		91.940	117.120	114.874
	Mean	89.025	115.570	115.645
After calming	Test results	105.320	140.650	136.915
		107.500	145.220	133.758
	Mean	106.410	142.935	135.336
	% change in mean	*+20*	*+24*	*+17*

Continued ....

Table A12 (Cont'd) Total CO_2 (g/km): Diesel cars

		Vehicle size and reference number		
Traffic calming measure		*No size discrimination*		
Stage		*20*	*21*	*22*
Scheme G: Build-out				
Before calming	Test results	102.387	127.106	132.100
		101.107	123.035	131.492
	Mean	101.747	125.070	131.796
After calming	Test results	119.473	153.416	159.727
		118.365	148.893	154.505
	Mean	118.919	151.154	157.116
	% change in mean	*+17*	*+21*	*+19*
Scheme H: Mini-roundabout				
Before calming	Test results	102.387	127.106	132.100
		101.107	123.035	131.492
	Mean	101.747	125.070	131.796
After calming	Test results	128.063	158.885	180.455
		127.185	162.213	175.742
	Mean	127.624	160.549	178.098
	% change in mean	*+25*	*+28*	*+35*
Scheme I: 1.9m-wide speed cushions				
Before calming	Test results	103.437	124.748	131.971
		101.597	123.858	131.576
	Mean	102.517	124.303	131.774
After calming	Test results	113.390	146.582	150.750
		111.217	149.138	155.691
	Mean	112.303	147.860	153.220
	% change in mean	*+10*	*+19*	*+16*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A13 Total particulate matter (g/km): Diesel cars

Traffic calming measure / Stage		Vehicle size and reference number: No size discrimination 20	21	22
Scheme A: Flat-top road humps				
Before calming	Test results	0.203	0.047	0.038
		0.176	0.049	0.036
	Mean	0.190	0.048	0.037
After calming	Test results	0.354	0.075	0.073
		0.350	0.081	0.069
	Mean	0.352	0.078	0.071
	% change in mean	*+85*	*+63*	*+92*
Scheme B: Round-top humps				
Before calming	Test results	0.246	0.069	0.053
		0.323	0.060	0.056
	Mean	0.285	0.065	0.055
After calming	Test results	0.354	0.083	0.066
		0.351	0.056	0.072
	Mean	0.353	0.070	0.069
	% change in mean	*+24*	*+8*	*+25*
Scheme C: 1.7m-wide speed cushions				
Before calming	Test results	0.240	0.058	0.048
		0.255	0.049	0.044
	Mean	0.248	0.053	0.046
After calming	Test results	0.370	0.062	0.068
		0.389	0.065	0.062
	Mean	0.380	0.063	0.065
	% change in mean	*+53*	*+19*	*+41*
Scheme D: Pinch point/speed cushion				
Before calming	Test results	0.228	0.047	0.033
		0.292	0.040	0.387
	Mean	0.260	0.044	0.210
After calming	Test results	0.418	0.059	0.045
		0.391	0.058	0.044
	Mean	0.405	0.059	0.045
	% change in mean	*+56*	*+34*	*-79*
Scheme E: Raised junction				
Before calming	Test results	0.179	0.036	0.039
		0.186	0.032	0.035
	Mean	0.182	0.034	0.037
fter calming	Test results	0.275	0.040	0.043
		0.226	0.038	0.040
	Mean	0.250	0.039	0.042
	% change in mean	*+37*	*+15*	*+14*
Scheme F: Chicane				
Before calming	Test results	0.220	0.030	0.021
		0.215	0.031	0.023
	Mean	0.217	0.030	0.022
After calming	Test results	0.334	0.044	0.033
		0.314	0.047	0.031
	Mean	0.324	0.046	0.032
	% change in mean	*+49*	*+53*	*+45*

Continued ....

Table A13 Total particulate matter (g/km): Diesel cars

Traffic calming measure / Stage		Vehicle size and reference number: No size discrimination 20	21	22
Scheme G: Build-out				
Before calming	Test results	0.170	0.036	0.033
		0.183	0.027	0.034
	Mean	0.177	0.032	0.033
After calming	Test results	0.160	0.040	0.049
		–	0.040	0.045
	Mean	0.160	0.040	0.047
	% change in mean	*-10*	*+25*	*+42*
Scheme H: Mini-roundabout				
Before calming	Test results	0.170	0.036	0.033
		0.183	0.027	0.034
	Mean	0.177	0.032	0.033
After calming	Test results	0.240	0.047	0.048
		0.233	0.039	0.047
	Mean	0.236	0.043	0.048
	% change in mean	*+34*	*+34*	*+44*
Scheme I: 1.9m-wide speed cushions				
Before calming	Test results	0.158	0.027	0.047
		0.158	0.029	0.037
	Mean	0.158	0.028	0.042
After calming	Test results	0.235	0.029	0.044
		0.207	0.026	0.036
	Mean	0.221	0.028	0.040
	% change in mean	*+40*	*-1*	*-4*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A14 Total FC (l/100km): Petrol non-catalyst cars

Traffic calming measure		*Vehicle size and reference number*							
		Small				*Medium*		*Large*	
Stage		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Scheme A: Flat-top road humps									
Before calming	Test results	3.729	–	3.708	–	5.266	5.284	8.694	6.378
		3.615	–	3.481	–	5.051	5.563	8.063	6.369
	Mean	3.672	–	3.595	–	5.159	5.424	8.389	6.374
After calming	Test results	4.980	–	5.018	–	6.686	7.347	10.328	8.748
		4.955	–	4.909	–	6.696	7.581	9.762	8.546
	Mean	4.968	–	4.964	–	6.691	7.464	10.045	8.647
	% change in mean	*+35*	–	*+38*	–	*+30*	*+38*	*+20*	*+36*
Scheme B: Round-top humps									
Before calming	Test results	4.740	–	4.830	–	5.940	6.770	9.830	6.960
		4.690	–	4.280	–	5.710	6.930	9.290	7.080
	Mean	4.715	–	4.555	–	5.825	6.850	9.560	7.020
After calming	Test results	6.390	–	6.720	–	7.810	9.130	11.790	9.210
		6.520	–	6.040	–	7.550	8.900	11.880	9.290
	Mean	6.455	–	6.380	–	7.680	9.015	11.835	9.250
	% change in mean	*+37*	–	*+40*	–	*+32*	*+32*	*+24*	*+32*
Scheme C: 1.7m-wide speed cushions									
Before calming	Test results	4.721	–	4.862	5.566	6.185	6.942	9.910	7.378
		4.606	–	4.305	5.252	6.026	6.774	9.400	7.568
	Mean	4.664	–	4.584	5.409	6.106	6.858	9.655	7.473
After calming	Test results	5.879	–	5.646	6.675	7.590	7.940	11.550	9.119
		5.747	–	5.779	6.575	7.417	8.546	11.850	9.455
	Mean	5.813	–	5.712	6.625	7.504	8.243	11.700	9.287
	% change in mean	*+25*	–	*+25*	*+22*	*+23*	*+20*	*+21*	*+24*
Scheme D: Pinch point/speed cushion									
Before calming	Test results	4.490	–	4.550	–	5.720	6.040	9.410	6.950
		4.410	–	4.600	–	5.610	6.050	9.108	6.940
	Mean	4.450	–	4.575	–	5.665	6.045	9.259	6.945
After calming	Test results	5.480	–	5.450	–	6.830	7.440	10.480	8.330
		5.460	–	5.520	–	6.950	7.490	10.366	8.360
	Mean	5.470	–	5.485	–	6.890	7.465	10.423	8.345
	% change in mean	*+23*	–	*+20*	–	*+22*	*+23*	*+13*	*+20*
Scheme E: Raised junction									
Before calming	Test results	–	5.450	5.130	–	6.030	6.280	9.700	7.500
		–	5.510	4.810	–	5.970	6.270	9.250	7.270
	Mean	–	5.480	4.970	–	6.000	6.275	9.475	7.385
After calming	Test results	–	7.210	6.610	–	7.220	7.970	11520	9.820
		–	7.070	6.510	–	7.810	7.900	11.320	9.680
	Mean	–	7.095	6.560	–	7.515	9.935	11.420	9.750
	% change in mean	–	*+29*	*+32*	–	*+25*	*+58*	*+21*	*+32*
Scheme F: Chicane									
Before calming	Test results	–	4.892	4.037	–	5.370	4.980	9.110	6.030
		–	4.815	3.952	–	5.320	4.980	8.738	5.880
	Mean	–	4.854	3.994	–	5.345	4.980	8.924	5.955
After calming	Test results	–	5.679	4.911	–	6.640	6.430	9.371	7.400
		–	5.794	4.943	–	6.380	6.470	9.244	7.540
	Mean	–	5.737	4.927	–	6.510	6.450	9.307	7.470
	% change in mean	–	*+29*	*+22*	–	*+25*	*+58*	*+21*	*+32*

Continued ....

Table A14 (Continued) Total FC (l/100km): Petrol non-catalyst cars

Traffic calming measure		*Vehicle size and reference number*							
		Small				*Medium*		*Large*	
Stage		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Scheme G:Build-out									
Before calming	Test results	–	5.219	4.636	–	5.650	6.101	9.440	7.090
		–	5.079	4.486	–	5.990	5.580	9.300	5.690
	Mean	–	5.149	4.561	–	5.820	5.795	9.370	6.390
After calming	Test results	–	5.941	5.464	–	7.000	6.980	9.620	8.510
		–	6.305	5.594	–	7.030	6.800	10.050	6.910
	Mean	–	6.123	5.529	–	7.015	6.890	9.835	7.710
	% change in mean	–	*+19*	*+21*	–	*+21*	*+19*	*+5*	*+21*
Scheme H: Mini-roundabout									
Before calming	Test results	–	5.219	4.540	–	5.010	6.010	9.440	7.130
		–	5.079	4.430	–	5.600	5.580	9.300	7.100
	Mean	–	5.149	4.485	–	5.305	5.795	9.370	7.115
After calming	Test results	–	6.660	5.980	–	7.120	7.710	10.270	8.930
		–	6.730	5.990	–	7.280	7.350	10.530	9.330
	Mean	–	6.695	5.985	–	1.200	7.530	10.400	9.130
	% change in mean	–	*+30*	*+33*	–	*+36*	*+30*	*+11*	*+28*
Scheme I: 1.9m-wide speed cushions									
Before calming	Test results	–	3.815	4.315	–	5.707	5.554	9.995	6.568
		–	4.952	4.210	–	5.608	5.459	9.166	6.460
	Mean	–	4.384	4.262	–	5.658	5.507	9.581	6.514
After calming	Test results	–	5.689	5.324	–	6.170	6.385	9.779	7.899
		–	5.570	5.221	–	6.323	6.492	9.509	7.646
	Mean	–	5.630	5.727	–	6.247	6.438	9.644	7.773
	% change in mean	–	*+28*	*+24*	–	*+10*	*+17*	*+1*	*+19*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A15 Total FC (l/100km): Petrol catalyst cars

		Vehicle size and reference number										
Traffic calming measure		*Small*				*Medium*					*Large*	
Stage		*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Scheme A: Flat-top road humps												
Before calming	Test results	4.207	–	–	3.882	–	5.848	–	–	4.953	6.518	6.409
		4.584	–	–	3.779	–	5.783	–	–	4.809	6.61	6.274
	Mean	4.396	–	–	3.831	–	5.816	–	–	4.881	6.556	6.342
After calming	Test results	5.408	–	–	5.127	–	8.631	–	–	6.259	8.796	8.546
		5.421	–	–	4.920	–	8.405	–	–	6.273	10.219	8.773
	Mean	5.415	–	–	5.024	–	8.518	–	–	6.266	9.508	8.660
	% change in mean	*+23*	–	–	*+31*	–	*+46*	–	–	*+28*	*+45*	*+37*
Scheme B: Round-top humps												
Before calming	Test results	–	6.230	–	4.570	–	–	6.880	–	5.940	77.500	6.460
		–	5.430	–	4.590	–	–	6.990	–	5.830	8.050	7.540
	Mean	–	5.830	–	4.580	–	–	6.935	–	5.885	7.900	7.000
After calming	Test results	–	8.310	–	6.180	–	–	9.900	–	7.670	10.800	10.650
		–	7.400	–	5.940	–	–	9.860	–	7.660	10.720	10.620
	Mean	–	7.855	–	6.060	–	–	9.880	–	7.665	10.760	10.635
	% change in mean	–	*+35*	–	*+32*	–	–	*+42*	–	*+30*	*+36*	*+52*
Scheme C: 1.7m-wide speed cushions												
Before calming	Test results	–	–	-	4.754	–	–	–	7.547	5.895	8.024	7.726
		–	–		4.623	–	–	–	7.467	5.832	7.746	7.639
	Mean	–	–	-	4.689	–	–	–	7.507	5.864	7.885	7.683
After calming	Test results	–	–	-	5.450	–	–	–	9.425	7.231	10.200	10.179
		–	–		5.509	–	–	–	9.522	7.176	9.916	10.280
	Mean	–	–	-	5.479	–	–	–	9.474	7.204	10.058	10.230
	% change in mean	–	–	-	*+17*	–	–	–	*+26*	*+23*	*+28*	*+33*
Scheme D: Pinch point/speed cushion												
Before calming	Test results	–	–	5.040	4.380	5.920	–	–	–	5.750	7.476	7.180
		–	–	5.350	4.440	6.300	–	–	–	5.700	7.443	7.090
	Mean	–	–	5.195	4.410	6.110	–	–	–	5.725	7.460	7.135
After calming	Test results	–	–	6.070	5.170	7.220	–	–	–	6.730	9.032	8.910
		–	–	6.020	5.170	7.490	–	–	–	6.710	9.276	8.710
	Mean	–	–	6.045	5.170	7.355	–	–	–	6.720	9.154	8.810
	% change in mean	–	–	*+16*	*+17*	*+20*	–	–	–	*+17*	*+23*	*+23*
Scheme E: Raised junction												
Before calming	Test results	–	–	5.510	4.590	6.390	–	–	–	6.160	8.030	7.810
		–	–	5.830	5.200	6.610	–	–	–	6.040	8.060	7.570
	Mean	–	–	5.670	4.895	6.500	–	–	–	6.100	8.045	7.690
After calming	Test results	–	–	7.190	6.580	8.003	–	–	–	7.840	10.640	10.710
		–	–	6.280	6.970	8.210	–	–	–	7.780	11.150	10.590
	Mean	–	–	6.735	6.775	8.107	–	–	–	7.810	10.895	10.650
	% change in mean	–	–	*+19*	*+38*	*+25*	–	–	–	*+28*	*+35*	*+38*
Scheme F: Chicane												
Before calming	Test results	–	–	4.240	3.844	5.531	–	–	–	5.000	6.313	5.450
		–	–	4.360	3.990	5.614	–	–	–	5.140	6.206	6.700
	Mean	–	–	4.300	3.917	5.573	–	–	–	5.070	6.259	6.075
After calming	Test results	–	–	5.160	4.667	6.659	–	–	–	5.880	7.710	7.350
		–	–	5.310	4.619	6.913	–	–	–	5.820	7.727	7.970
	Mean	–	–	5.235	4.643	6.786	–	–	–	5.850	7.719	7.660
	% change in mean	–	–	*+22*	*+19*	*+22*	–	–	–	*+15*	*+23*	*+26*

Continued ....

Table A15 (Continued) Total FC (l/100km): Petrol catalyst cars

Traffic calming measure		*Vehicle size and reference number*										
		Small				*Medium*					*Large*	
Stage		*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Scheme G: Build-out												
Before calming	Test results	–	–	5.060	4.669	6.300	–	–	–	5.900	7.177	7.510
		–	–	5.250	4.456	6.215	–	–	–	5.980	7.140	8.060
	Mean	–	–	5.155	4.563	6.258	–	–	–	5.940	7.158	7.785
After calming	Test results	–	–	5.960	4.966	7.455	–	–	–	6.800	8.767	8.730
		–	–	6.330	5.414	7.739	–	–	–	6.870	8.938	9.840
	Mean	–	–	6.145	5.190	7.597	–	–	–	6.835	8.852	9.285
	% change in mean	–	–	*+19*	*+14*	*+21*	–	–	–	*+15*	*+24*	*+19*
Scheme H: Mini-roundabout												
Before calming	Test results	–	–	5.060	4.669	6.300	–	–	–	5.900	7.177	7.510
		–	–	5.250	4.456	6.215	–	–	–	5.980	7.140	8.060
	Mean	–	–	5.155	4.563	6.258	–	–	–	5.940	7.158	7.785
After calming	Test results	–	–	6.470	5.896	7.842	–	–	–	7.520	9.669	9.900
		–	–	6.620	5.659	7.578	–	–	–	7.460	10.001	11.650
	Mean	–	–	6.545	5.778	7.710	–	–	–	7.490	9.835	10.775
	% change in mean	–	–	*+27*	*+27*	*+23*	–	–	–	*+26*	*+37*	*+38*
Scheme I: 1.9m-wide speed cushions												
Before calming	Test results	–	–	4.978	4.330	6.057	–	–	–	5.392	7.100	7.226
		–	–	4.734	4.349	6.265	–	–	–	5.714	7.121	6.381
	Mean	–	–	4.856	4.340	6.161	–	–	–	5.553	7.110	6.803
After calming	Test results	–	–	5.821	4.990	6.953	–	–	–	6.295	8.636	8.390
		–	–	5.671	4.981	7.275	–	–	–	6.509	8.832	9.268
	Mean	–	–	5.746	4.986	7.114	–	–	–	6.402	8.734	8.829
	% change in mean	–	–	*+18*	*+15*	*+15*	–	–	–	*+15*	*+23*	*+30*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Table A16 Total FC (l/100km): Diesel cars

Traffic calming measure		Vehicle size and reference number		
		No size discrimination		
Stage		20	21	22
Scheme A: Flat-top road humps				
Before calming	Test results	3.690	4.090	4.530
		3.550	3.970	4.320
	Mean	3.620	4.030	4.420
After calming	Test results	5.020	5.800	6.300
		4.820	5.850	6.140
	Mean	4.920	5.820	6.220
	% change in mean	*+36*	*+44*	*+41*
Scheme B: Round-top humps				
Before calming	Test results	4.080	5.190	5.140
		4.030	5.250	5.170
	Mean	4.055	5.220	5.155
After calming	Test results	5.20	7.130	6.796
		5.060	6.920	6.396
	Mean	5.130	7.025	6.596
	% change in mean	*+27*	*+35*	*+28*
Scheme C: 1.7m-wide speed cushions				
Before calming	Test results	4.217	5.105	5.157
		4.157	5.134	5.096
	Mean	4.187	5.120	5.127
After calming	Test results	5.076	6.479	6.456
		5.019	6.586	6.315
	Mean	5.047	6.533	6.385
	% change in mean	*+21*	*+28*	*+25*
Scheme D: Pinch point/speed cushion				
Before calming	Test results	4.110	4.821	4.943
		4.110	4.888	5.001
	Mean	4.110	4.855	4.972
After calming	Test results	4.790	5.977	6.116
		4.800	6.331	6.210
	Mean	4.795	6.154	6.163
	% change in mean	*+17*	*+27*	*+24*
Scheme E: Raised junction				
Before calming	Test results	3.015	5.468	5.474
		4.118	5.600	5.645
	Mean	3.566	5.534	5.559
After calming	Test results	5.034	5.468	7.062
		4.941	7.310	7.151
	Mean	4.987	6.389	7.107
	% change in mean	*+40*	*+15*	*+28*
Scheme F: Chicane				
Before calming	Test results	3.340	4.330	4.447
		3.560	4.450	4.386
	Mean	3.450	4.390	4.417
After calming	Test results	4.100	5.350	5.264
		4.180	5.520	5.150
	Mean	4.140	5.435	5.207
	% change in mean	*+20*	*+24*	*+18*

Continued ....

Table A16 (Con't) Total FC (l/100km): Diesel cars

Traffic calming measure		Vehicle size and reference number		
		No size discrimination		
Stage		20	21	22
Scheme G: Build-out				
Before calming	Test results	3.983	4.863	5.066
		3.937	4.698	4.995
	Mean	3.960	4.781	5.030
After calming	Test results	4.697	5.917	6.093
		4.656	5.742	5.881
	Mean	4.677	5.829	5.987
	% change in mean	*+18*	*+22*	*+19*
Scheme H: Mini-roundabout				
Before calming	Test results	3.983	4.863	5.066
		3.937	4.698	4.995
	Mean	7.490	9.835	10.775
After calming	Test results	4.962	6.080	6.878
		4.930	6.209	6.702
	Mean	3.960	4.781	5.030
	% change in mean	*+25*	*+29*	*+35*
Scheme I: 1.9m-wide speed cushions				
Before calming	Test results	3.969	4.694	4.957
		3.899	4.664	4.940
	Mean	3.934	4.679	4.948
After calming	Test results	4.372	5.551	5.685
		4.289	–	5.867
	Mean	4.331	5.551	5.776
	% change in mean	*+10*	*+19*	*+17*

For consistent formatting all emission rates are quoted to three decimal places. The emission rates should not be considered accurate to more than three significant figures.

Appendix B: Emissions by vehicle type

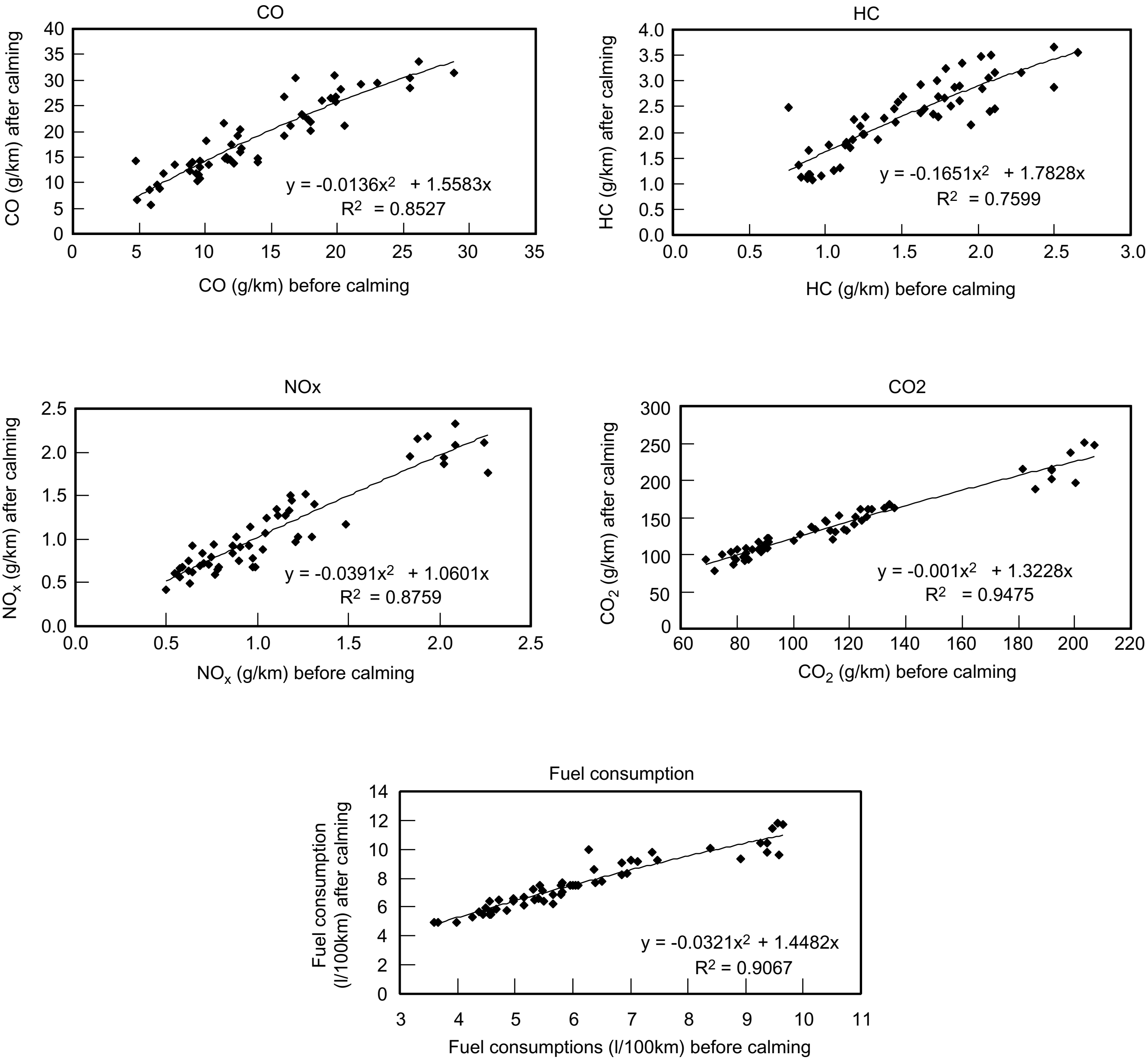

Figure B1 Emissions and fuel consumption after calming plotted against emissions before calming for petrol non-catalyst cars (results for all nine schemes)

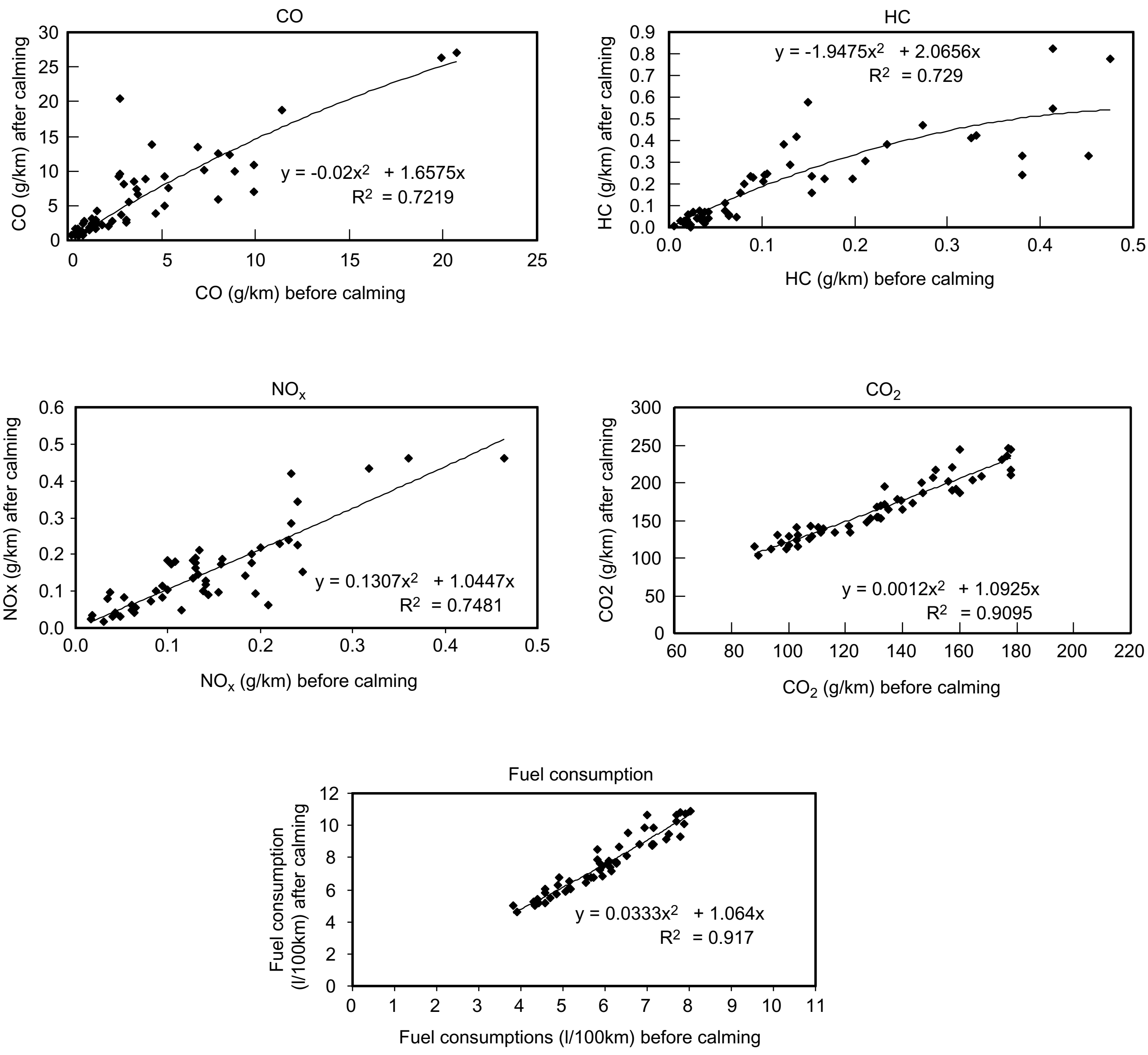

Figure B2 Emissions and fuel consumption after calming plotted against emissions and fuel consumption before calming for petrol catalyst cars (results for all nine schemes)

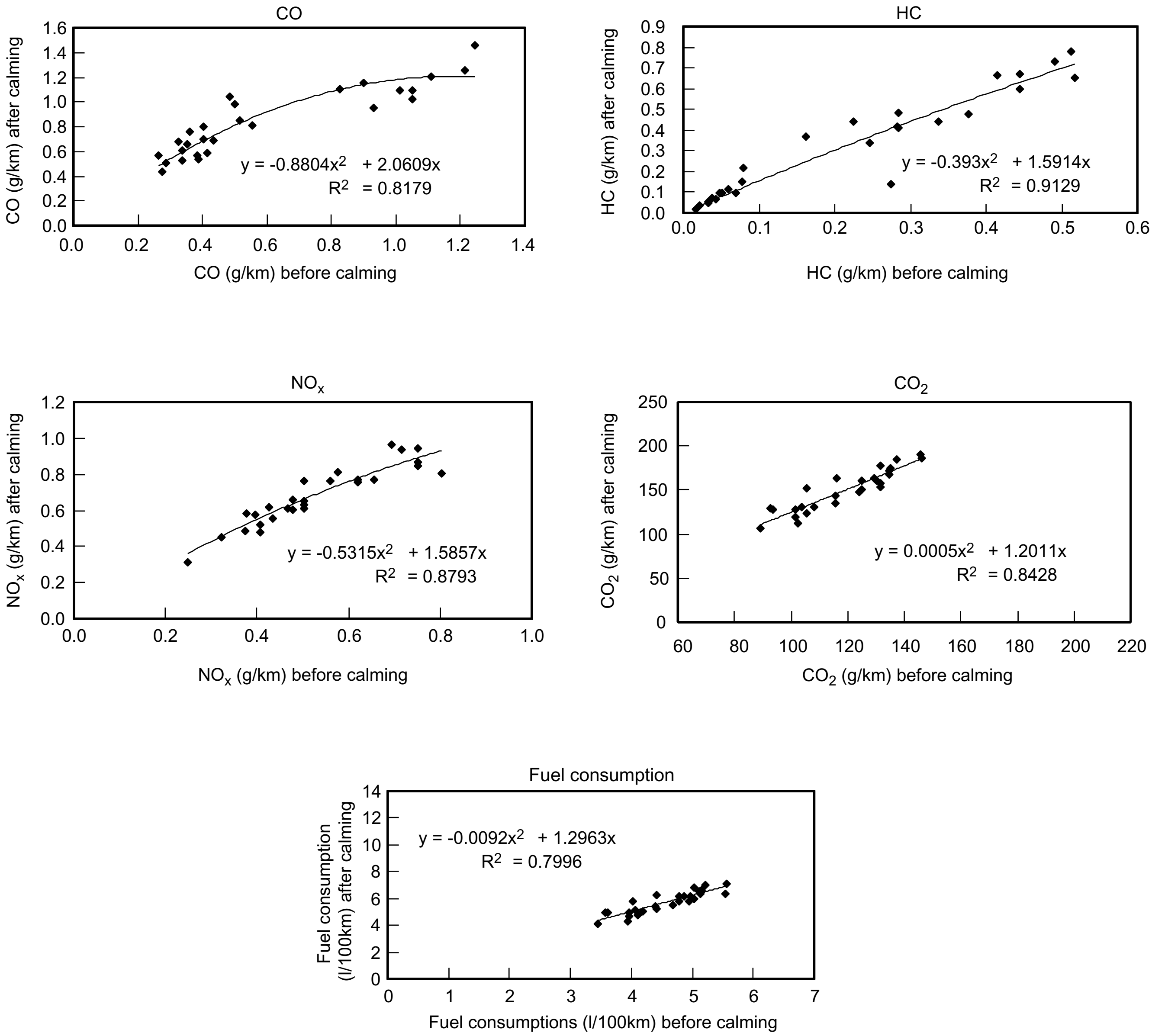

Figure B3 Emissions and fuel consumption after calming plotted against emissions and fuel consumption before calming for diesel cars (results for all nine schemes)

Appendix C: Emissions by vehicle

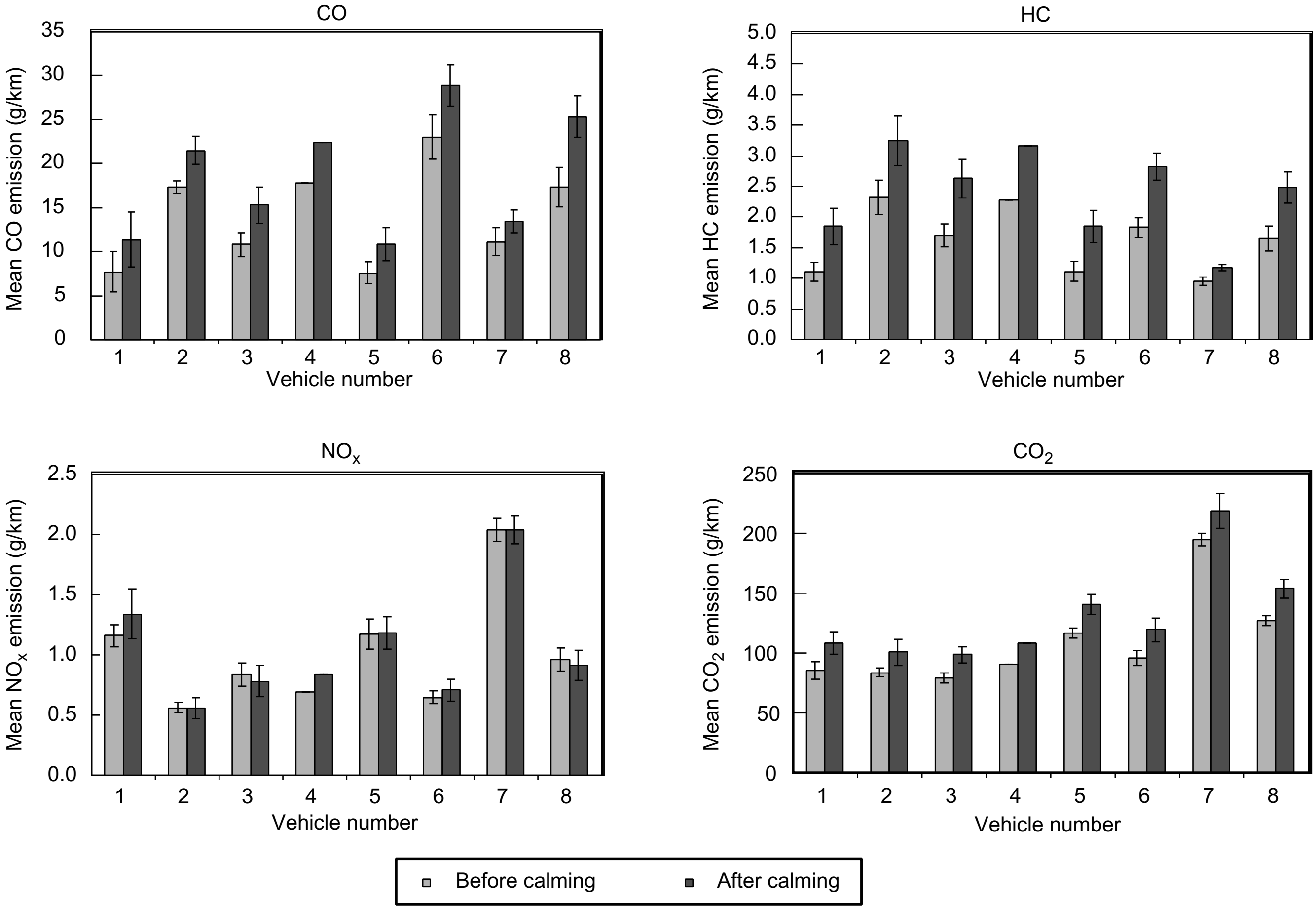

Figure C1 Emissions before calming and after calming for individual petrol non-catalyst cars. The emission levels have been averaged over all the schemes for which a vehicle was tested. The I-beams represent the 95% confidence intervals on the means. Where there are no confidence intervals, the vehicle was only tested on one scheme

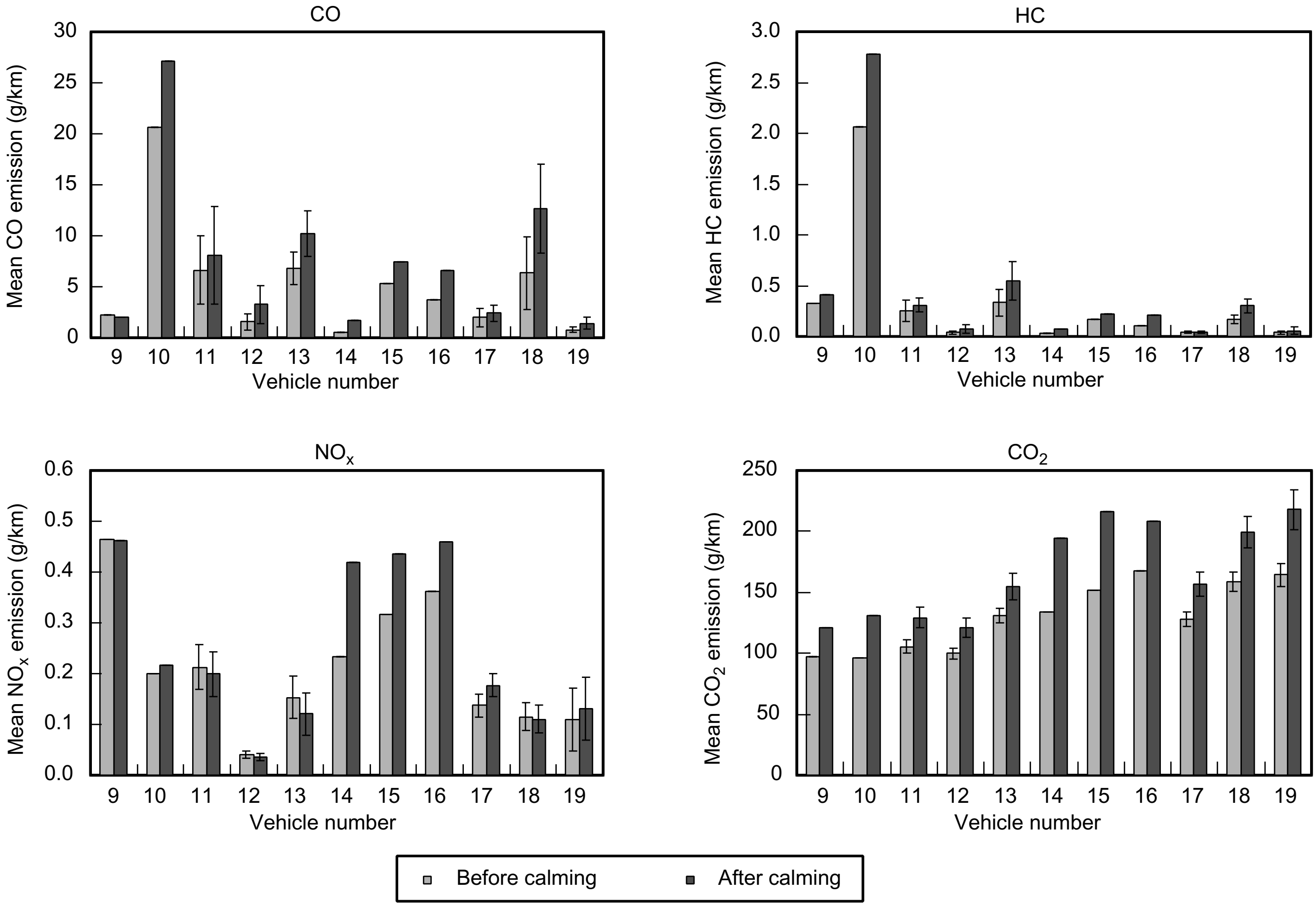

Figure C2 Emissions before calming and after calming for individual petrol catalyst cars. The emission levels have been averaged over all the schemes for which a vehicle was tested. The I-beams represent the 95% confidence intervals on the means. Where there are no confidence intervals, the vehicle was only tested on one scheme

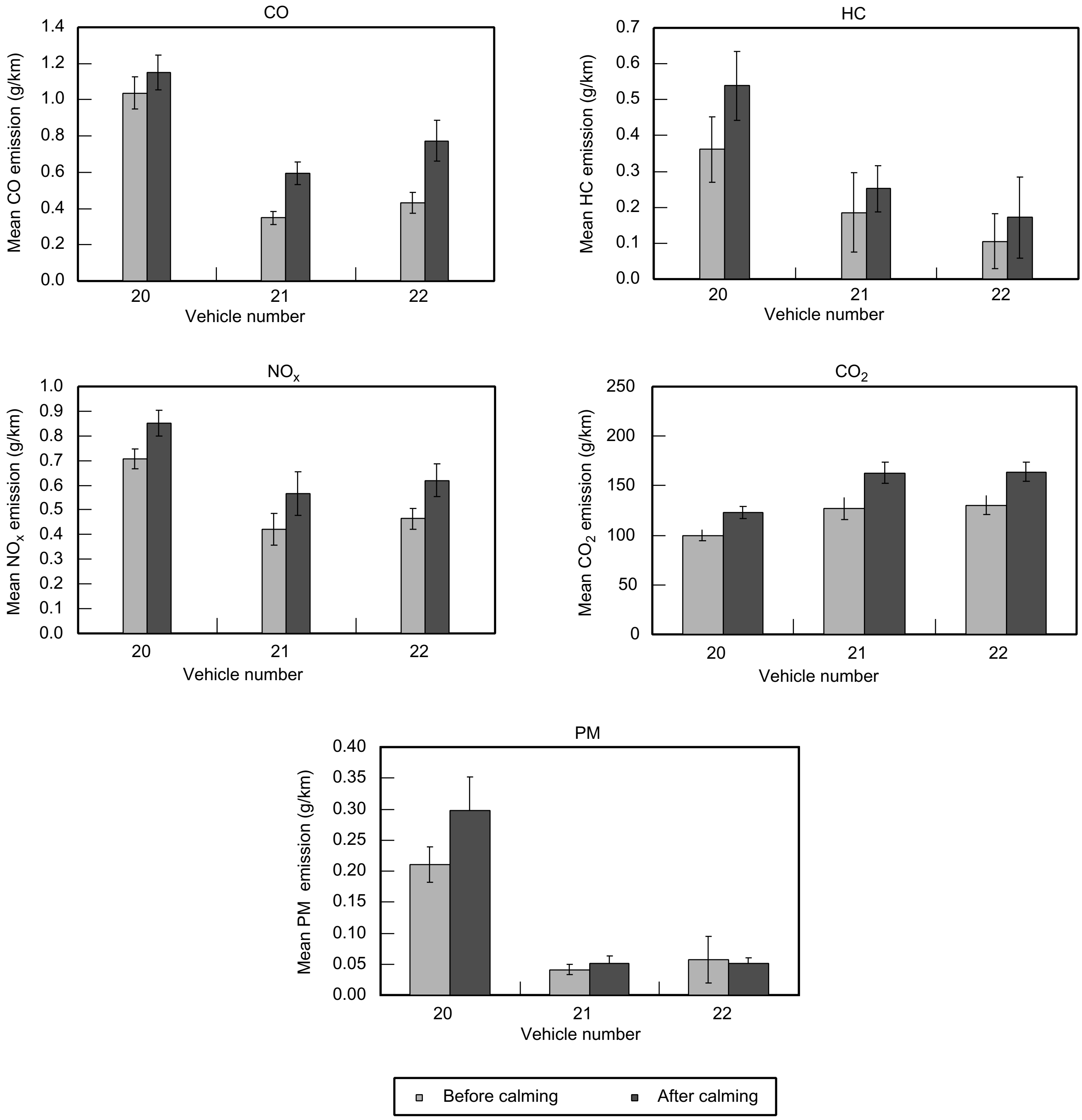

Figure C3 Emissions before calming and after calming for individual diesel cars. The emission levels have been averaged over all the schemes for which a vehicle was tested. The I-beams represent the 95% confidence intervals on the means. Where there are no confidence intervals, the vehicle was only tested on one scheme

Appendix D: Emissions by scheme

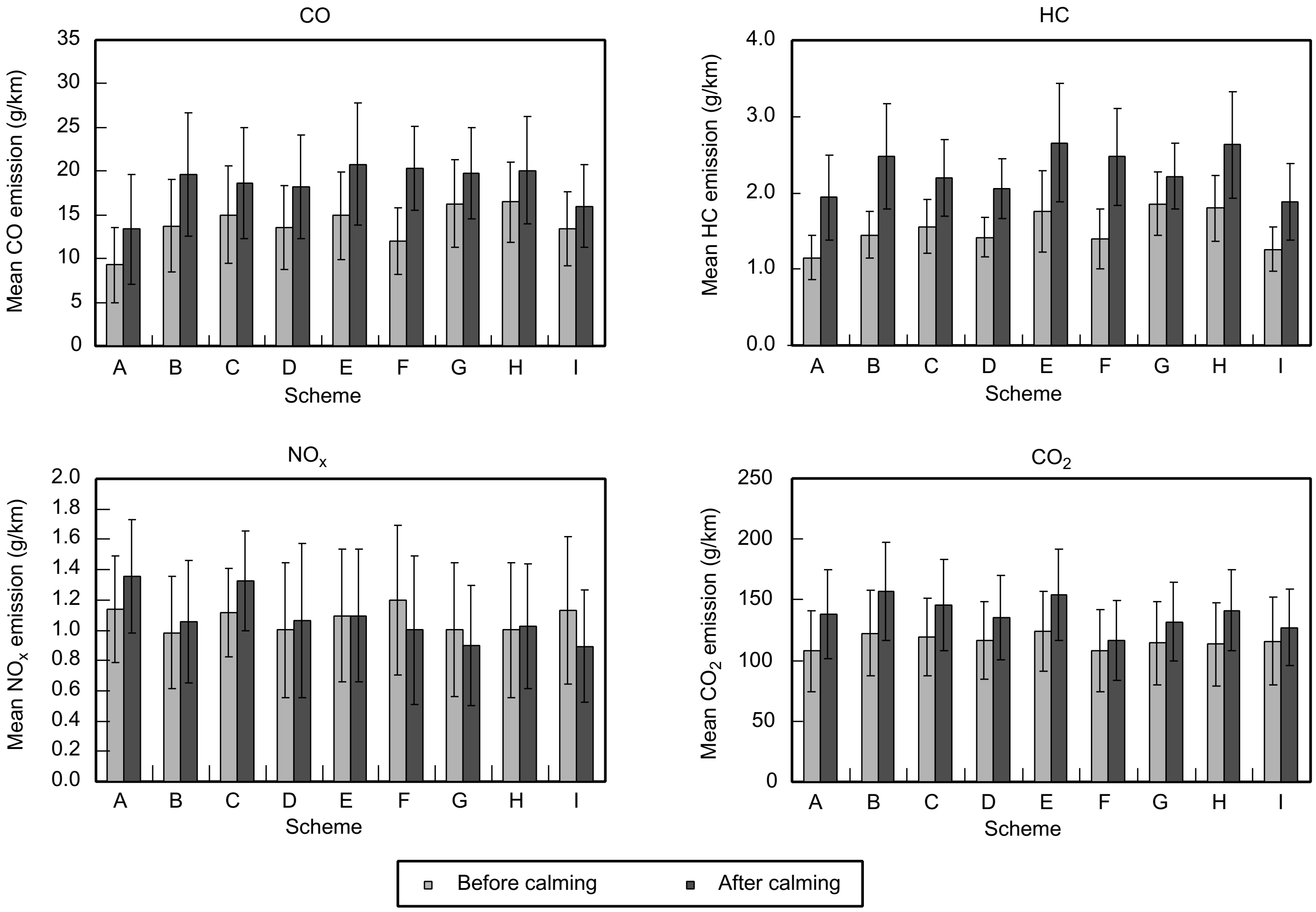

Figure D1 Emissions from petrol non-catalyst cars before calming and after calming for individual schemes. The emission levels have been averaged over all the vehicle tested for a particular scheme. The I-beams represent the 95% confidence intervals on the means

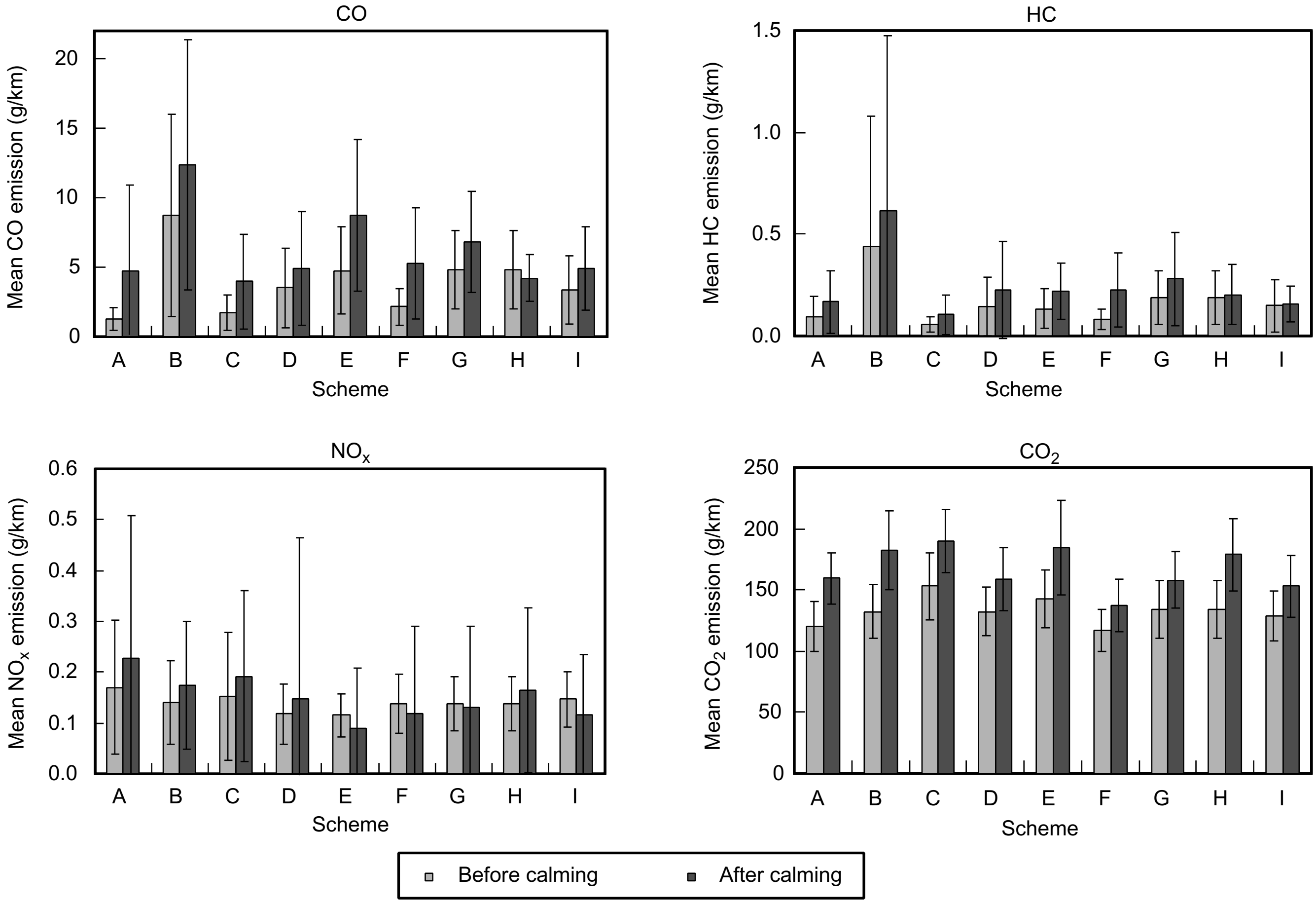

Figure D2 Emissions from petrol catalyst cars before calming and after calming for individual schemes. The emission levels have been averaged over all the vehicle tested for a particular scheme. The I-beams represent the 95% confidence intervals on the means

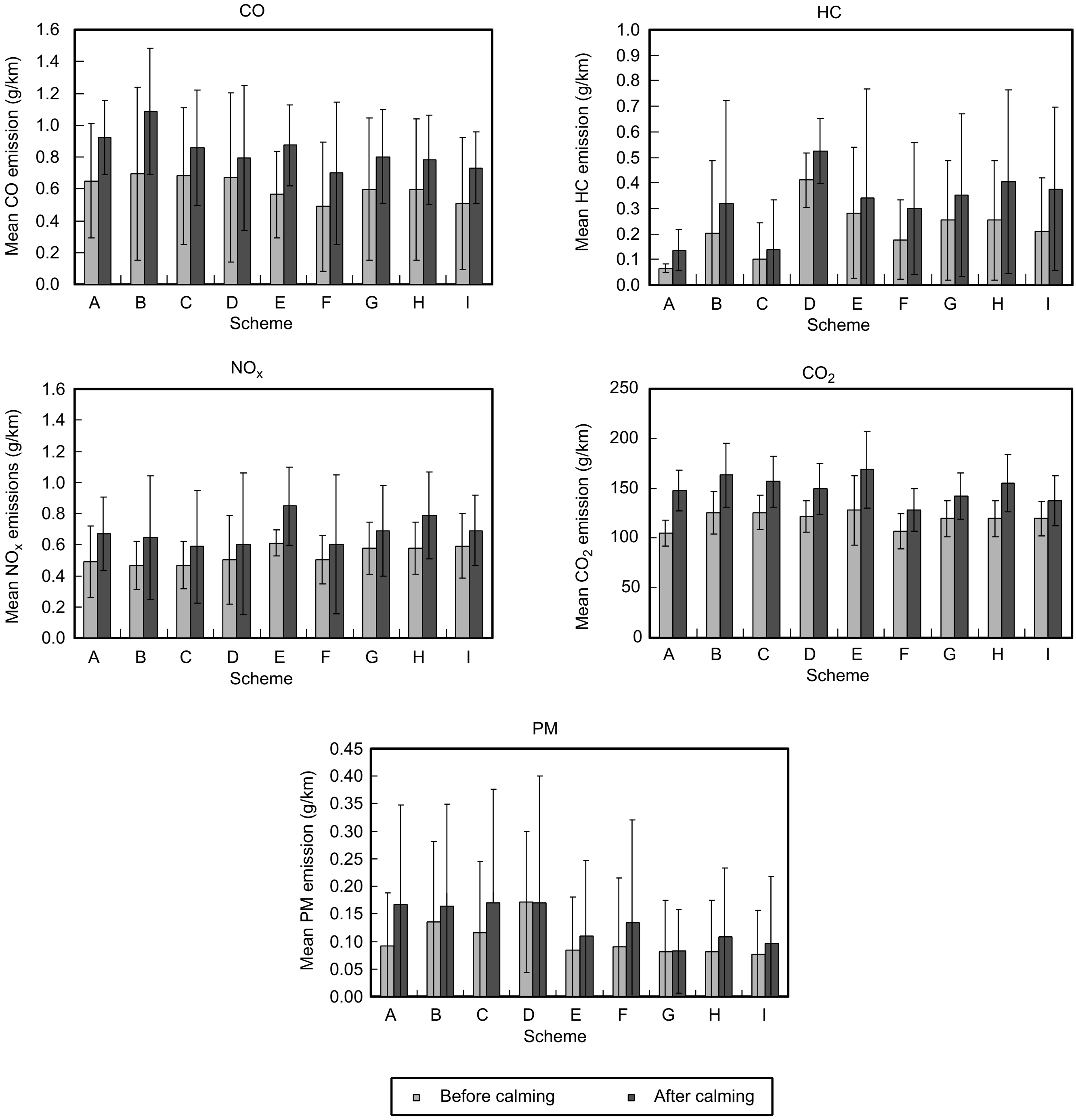

Figure D3 Emissions from diesel cars before calming and after calming for individual schemes. The emission levels have been averaged over all the vehicle tested for a particular scheme. The I-beams represent the 95% confidence intervals on the means

Abstract

The Environment Act 1995 has confirmed that traffic regulation orders, and hence traffic management schemes, may be used for the purposes of air quality management. One form of traffic management - traffic calming - has been found to be particularly effective at reducing vehicle speeds, as well as the frequency and severity of accidents. However, there is little information relating to the effects of different traffic calming measures on vehicle exhaust emissions and ambient air pollution. In order to provide information and guidance for local authorities, TRL was commissioned to undertake a study on behalf of the Charging and Local Transport Division of DETR. The main objectives of the study were to investigate the effects of nine different types of traffic calming measure on the exhaust emissions from passenger cars, and to develop a system of performance indicators for the measures. These indicators accounted for effects on emissions from all road traffic, and demonstrated how emission impacts compared with impacts on speed, safety, and delays to emergency service vehicles. Driving cycles were formulated to represent vehicle operation before and after the introduction of the measures, based on *in situ* traffic survey data, and the emissions from a range of passenger cars were then recorded as they were driven over the cycles on a chassis dynamometer. The mean emission rates of CO, HC, NO_x, and CO_2 from petrol non-catalyst, petrol catalyst, and diesel cars increased by up to 60% following the introduction of traffic calming measures. However, it was estimated that the increased emission rates were unlikely to have resulted in poor local air quality.

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