THE IMPACTS OF TRAFFIC CALMING MEASURES ON VEHICLE EXHAUST EMISSIONS

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A Thesis submitted to Middlesex University
in partial fulfilment of the requirements for the degree of
Doctor of Philosophy

October 2001

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ACRONYMS AND ABBREVIATIONS

AQMA	Air Quality Management Area
AQS	Air Quality Strategy
CEDIA	Centre d'Etude et de Développement en Ingénierie Acoustique
CO	Carbon monoxide
CO_2	Carbon dioxide
CNG	Compressed Natural Gas
COPERT	Computer model to calculate emissions from road transport
COST	European co-operation in the field of scientific and technical research
CVS	Constant volume sampler
DETR	Department of the Environment, Transport and the Regions
DGV	Digitised Graz method
DMRB	Design Manual for Roads and Bridges
DVLC	Driver and Vehicle Licensing Agency
EC	European Commission
ELPI	Electrical low pressure impactor
EUDC	Extra-Urban Driving Cycle
ETSU	Energy Technology Support Unit
FEAT	Fuel Efficiency Automobile Test
FID	Flame Ionisation Detector
HBEFA	Handbook of emission factors
HC/THC/VOC	Hydrocarbons/ total hydrocarbons/ volatile organic compounds
HGV	Heavy goods vehicle
INRETS	Institut National de Recherche sur les Transports et leur sécurité
LGV	Light goods vehicle
LIDAR	Light detection and ranging
MEET	Methodologies for Estimating Emissions from Transport
MODEM	Modelling of emissions and consumption in urban areas
MoT	Motor test
NAQS	National Air Quality Strategy
NDIR	Non-dispersive infra red
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides ($NO + NO_2$)
PIA	Personal injury accident
PM	Particulate matter
PM_{10}	Particulate matter with an aerodynamic diameter less than 10μm
RADAR	Radio detection and ranging
SO_2	Sulphur dioxide
SMPS	Scanning mobility particle sizer
SNK	Student-Newman-Keuls
TEOM	Tapered element oscillating microbalance
TNO	Nederlandse Organisatie voor Toegepastnatuurvetenschappelijk Onderzoek (Netherlands Organisation for Applied Scientific Research)
TRL	Transport Research Laboratory
UV	Ultra violet
VCA	Vehicle Certification Agency
VITO	Vlaamse Instelling voor Technologisch Onderzoek (Flemish Institute for Technological Research)
Vkm	Vehicle-kilometres

ACKNOWLEGDEMENTS

I would like to express my gratitude to the following organisations and people, without whom this work would not have reached completion:

- TRL, for allowing me the opportunity to embark on a doctoral programme of research, and for funding all activities within that programme. On the administrative side, I would like to thank Dr Phil Bly, Mr Bill Newton, and the staff in TRL's Personnel Department.

- The many members of staff in TRL's Environment Department who have provided invaluable advice and encouragement on a regular basis. Foremost among these is Mr John Hickman, Senior Research Fellow in vehicle emissions and air pollution, and my PhD supervisor at TRL. I would also like to thank Dr Paul Nelson, Mr Stephen Latham, Dr Jane Cloke, Dr Tim Barlow, and Dr Ian McCrae for advice relating to various aspects of the research. On a more practical level, additional recognition is due to Dr Barlow and Dr McCrae for the assistance they provided during the remote sensing surveys, to Dr Barlow for installing speed measurement equipment in test vehicles, and to Mr Michael Ainge for designing and constructing a housing for the LIDAR system.

- Staff either working in other TRL departments. I owe a debt of gratitude to Mr Roger Layfield in the Safety Group, who is an international expert in the field of traffic calming, and has been a constant source of helpful advice. All staff working at TRL Library, and in particular Mrs Sarah Groombridge and Miss Heather Johns, must be thanked for their knowledgeable and prompt assistance throughout. I would like to thank Mr Michael Smith, Mr David Jenkins and Mr Colin Davies for transcribing the numerous and lengthy video recordings from the remote sensing surveys, all the drivers, navigators, and LIDAR operators who helped out during the site surveys, and Mr Barry Sexton who provided statistical advice during the work.

- Professor Donald Stedman of the University of Denver for his helpful comments relating to the remote sensing aspects of the research. Thanks are also due to the emissions laboratory staff at AEA Technology, in particular Mr Philip Whiteman, Mr Tony Reading, Dr David Blaikley, and Dr Andy Feest, to Mr Paul Davison at ETSU, and to all the local

authorities who provided information relating to their traffic calming schemes.

- All the staff of Middlesex University who have had involvement. More specifically, Dr Ian Williams, my supervisor, for his learned and constructive criticism and advice throughout the work.

- My family for their patience and support.

Paul Boulter
Crowthorne, 15 October 2001.

ABSTRACT

This Thesis describes a study of the impacts of traffic calming on exhaust emissions, the most detailed and extensive of its kind to date. The main objectives of the work were to measure the effects of different types of traffic calming measure on vehicle emissions, to develop a system of comparative performance indicators and guidance for local authorities, and to assess and improve the performance of an existing micro-scale emission model in traffic calming applications. There were several elements to the research which have not previously been reported, including the development of driving cycles for traffic calming based on external speed measurements, and the use of remote sensing to assess the impacts of traffic calming on emissions *in situ.*

Nine different types of measure were investigated, including a mixture of vertical deflections (*e.g.* road humps, speed cushions) and horizontal deflections (*e.g.* chicanes). Driving cycles were formulated to represent vehicle operation before and after the introduction of the schemes, based on traffic speeds measured using both an instrumented car and an external method (LIDAR). Fuel consumption and emissions of CO, HC, NO_x, and CO_2 from a total of 22 cars (including petrol non-catalyst, petrol catalyst, and diesel vehicles) were measured on a chassis dynamometer using the cycles. Emissions of total particulate matter were also recorded from the diesel vehicles.

The results from the laboratory emission tests were used to compare the performance of an 'average speed' emission model (MEET) and a 'modal' emission model (MODEM). Also, an attempt was made to improve the accuracy of MODEM model in such applications by developing a variant model (MODEM-TC) for use in traffic calming applications. In MODEM-TC the original MODEM emission matrices were replaced with ones derived from the laboratory test results.

The emission tests indicated that traffic calming increases exhaust emissions. For the three types of car tested, emissions of CO, HC, and CO_2 increased by between 20% and 60%. Only the diesel cars showed a substantial (30%) and statistically significant increase in NO_x emissions. Emissions of total particulate matter from diesel cars also increased by 30%. The more 'severe' traffic calming measures (*e.g.* road humps) tended to result in the greatest speed reductions and some of the largest increases in emissions.

The 50-73% increase in mass emissions of CO per kilometre (for all vehicles) determined by remote sensing agreed reasonably well with the range of impacts measured in the laboratory emission tests, but the remote sensing HC results were less conclusive.

For almost all combinations of vehicle type and pollutant, the MEET model provided a more reliable indication of the likely impact of traffic calming than the MODEM and MODEM-TC models, in spite of the fact that the latter employ a more detailed mechanism for representing vehicle operation. It was concluded that the most fundamental problem with modal models is that the analyser emission signals on which they are based are delayed and damped relative to the 'true' signal. It appears that further advances in the field of modal emission modelling will not be forthcoming until realistic continuous emission data are available. Other workers are currently developing a mathematical model of the measurement system which can be used to reconstruct the original emission signal in the exhaust pipe from the one measured at the analyser.

CHAPTER 1 INTRODUCTION

1.1 The National Air Quality Strategy and the role of traffic management

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 air quality 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 10μm (PM_{10}). Since the publication of the NAQS, the original air quality standards and objectives have been revised in the UK Air Quality Strategy (AQS) (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.

Because road vehicles are a major source of some of the pollutants given priority in the NAQS and AQS, particularly 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. Accordingly, the Government set out the four key principles that it would follow to secure reductions in air pollution resulting from road transport (Department of the Environment *et al.*, 1997). These were:

(i) Improvements in vehicle and fuel technology to reduce emissions.

(ii) Tighter controls on the existing vehicle fleet, its management, and its operation.

(iii) Development of environmental responsibilities by fleet operators, particularly public service fleet operators, and by the public at large, in transport and vehicle use.

(iv) Changes in planning and transport policy which would reduce the need to travel and reduce reliance on the car.

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

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

The Environment Act 1995 also confirmed that traffic management schemes could be used for air quality management purposes. Plans drawn up by local authorities under Section 84(2) of the Act could include alterations to existing schemes, or the development of new schemes, on air quality grounds. Where local authorities considered that traffic management could make an appropriate contribution to improving air quality, they were advised to consider and carefully evaluate all the opportunities available to them, and set out a balanced and integrated approach tailor-made to their specific local circumstances (Department of the Environment *et al.*, 1996b).

The introduction of the NAQS meant that local authorities had to be aware of any air quality impacts resulting from their traffic management operations. However, at the time the Strategy was drawn up there was little information relating to the effects of different traffic management schemes on vehicle exhaust emissions and air quality. Therefore, in order to facilitate the approach proposed by the Government, Abbott *et al.* (1995) suggested that:

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

At the time the NAQS was published, the investigation of the relationships between traffic management and its environmental impacts was a relatively new and inexact science. Consequently, the extent to which schemes brought about environmental improvements or otherwise was difficult to quantify. The Government commissioned an extensive programme of work aimed at improving the level of understanding. A large proportion of the work programme was, and is still being, conducted at the Transport Research Laboratory (TRL). The environmental appraisals undertaken at TRL have been spread over number of projects, and have covered a range of subject areas. These subject areas have included noise, vibration, vehicle emissions, air pollution, and perceived impacts.

This Thesis incorporates a large proportion of the TRL research relating to the impacts of a particular type of traffic management - traffic calming - on vehicle emissions and air quality.

1.2 Research objectives

Traffic calming schemes, which generally incorporate physical measures such as road humps, chicanes, and road narrowings, are designed primarily to reduce vehicle speeds. Indeed, they have been found to be particularly effective in this respect, and have also been successful at reducing the frequency and severity of accidents. As with other types of traffic management scheme, there is little information relating to the effects of traffic calming on emissions and air quality. Thus, in order to guide local authorities in their traffic calming operations, the emissions impacts of various traffic calming schemes were subjected to extensive investigation.

The main objectives of the research undertaken for the PhD programme were:

(i) To review the existing level of understanding regarding traffic calming and emissions.

(ii) To determine the effects of different types of traffic calming measure on exhaust emissions, primarily from passenger cars but also from goods vehicles and buses. Subordinate objectives in this respect included:

- To assess the impact of traffic calming on vehicle speed profiles.
- To develop driving cycles using external speed measurement techniques.
- To determine the impact of traffic calming on emissions from passenger cars, based on the driving cycles.
- To measure emissions from large numbers of vehicles on the road using remote sensing in the vicinity of traffic calming measures.

(iii) To develop a system of comparative performance indicators and guidance for local authorities which would enable them to predict the effects of their proposed traffic calming schemes.

(iv) To assess the performance of an existing micro-scale emission model in traffic calming applications, and to explore the ways in which its performance could be enhanced.

A general procedure for assessing the environmental impact of all traffic management schemes was proposed by Abbott *et al.* (1995). For traffic calming schemes, this procedure is characterised by the following five stages:

(i) The imposition of a traffic calming scheme will introduce changes to the traffic which need to be defined accurately so that environmental appraisal can proceed to the next stage. Drivers will respond to controls by modifying their behaviour. Such changes may include modifications to average and maximum speeds, rates and numbers of accelerations and decelerations, gear changing, *etc.* Trip lengths, traffic flows, traffic composition, and modal split may also be affected.

(ii) Changes in driver behaviour will result in modified patterns of vehicle operation. These are specified by various engine and vehicle parameters like engine speed, engine load, engine temperature, and exhaust temperature, as well as their rates of change.

(iii) These changes will influence emissions rates.

(iv) If vehicle emissions are affected then local levels of air pollution exposure will also be affected.

(v) Finally, the impact of changes in exposure on people in different community settings must be adequately assessed. This would complete the connection between the introduction of a traffic calming scheme and the environmental impact that the resulting traffic changes have on people whether they are drivers, pedestrians, or at home.

The primary aim of the research was to gain an insight into the effects of traffic calming on vehicle emissions; stage (iv) of this procedure was not considered in detail, and stage (v) was not considered at all.

1.3 Thesis structure

The logical progression of the research, and the structure of the Thesis, are illustrated in Figure 1.1. The time scale of the programme of research is given in Table 1.1. From Table 1.1 it can be seen that some of the work presented in this Thesis was conducted by the author before the official registration date. This work is included to clarify the progression of the work. The remaining Section of Chapter 1 lists publications and conferences attended by the author.

Chapter 2 contains a literature review which is a condensed version of TRL Report 307 (Boulter and Webster, 1997). The aim of the review was to summarise existing knowledge of the effects, or potential effects, of traffic calming on vehicle emissions. A brief outline of the philosophy of traffic calming, and short descriptions of the engineering measures employed to calm traffic, are followed by a discussion of the first step in the assessment procedure: driver behaviour and the changes in behaviour imposed by traffic calming schemes. The review also deals with the factors affecting emissions from road vehicles in the context of traffic calming, and includes a summary of previous case studies relating to emissions impacts.

Chapter 3 describes the research methods and tools that are available for determining the impacts of traffic calming schemes on emissions. These include the appropriate techniques for evaluating driver behaviour, and techniques for measuring and modelling emissions. At the end of the Chapter, recommendations are provided on the design of an appropriate experimental methodology.

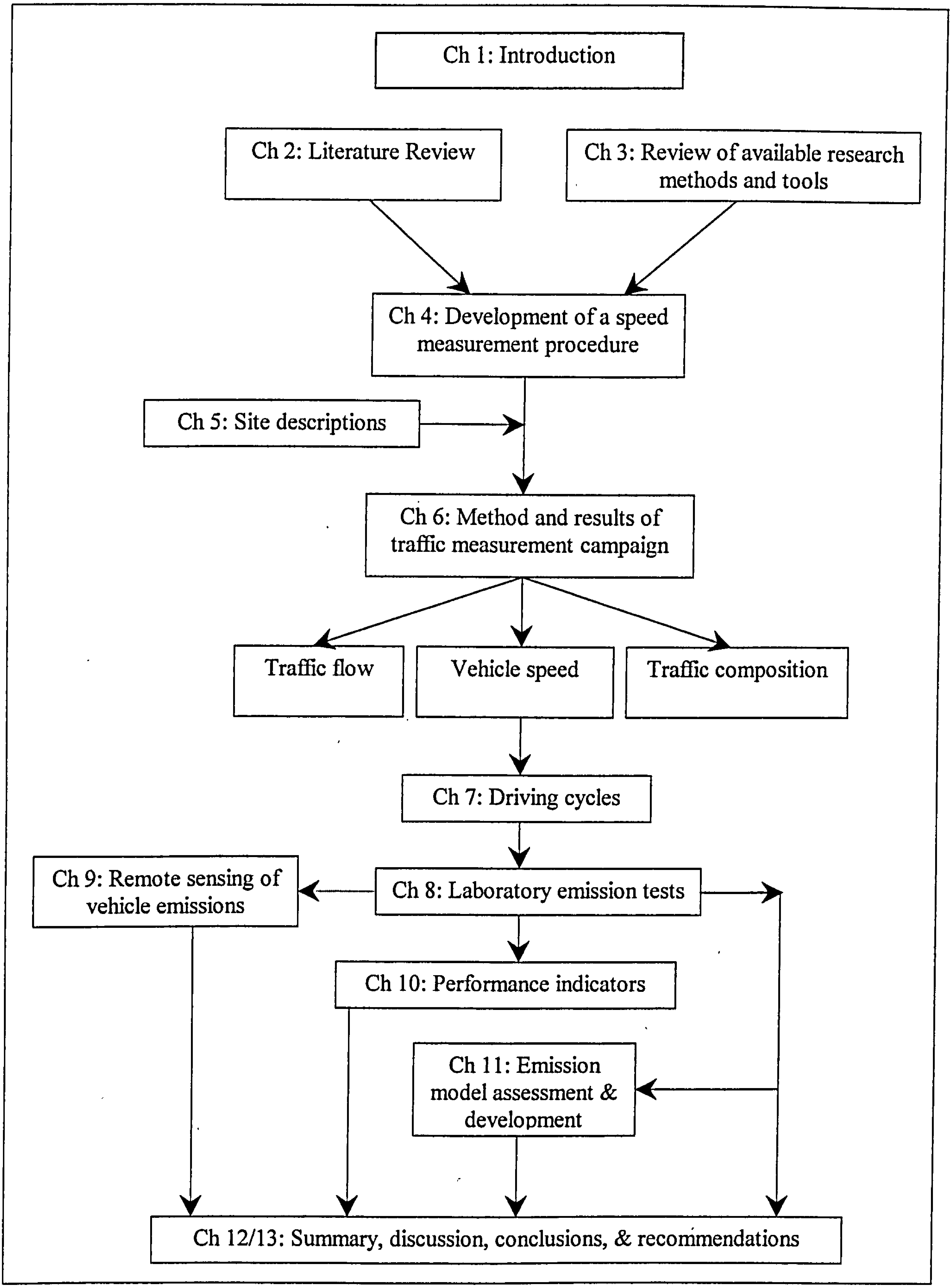

Figure 1.1 Progression of research and Thesis structure.

Table 1.1 Gantt chart illustrating the time scale of the programme of research.

Task						Year 1												Year 2												Year 3												Year 4											
	1997												1998												1999												2000												2001				
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Literature review			▨	▨	▨	▨	▨	▨	▨	▨																																											
Speed measurement tests	▨																																																				
Speed measurement field trial		▨	▨	▨	▨																																																
Site selection					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																																		
Traffic and vehicle surveys							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																												
Development of driving cycles											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																											
Emission measurements															▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																										
Analysis of emission test data																			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																			
Development of indicators																																			▨	▨																	
Remote sensing surveys												▨									▨																																
Analysis of remote sensing data																							▨	▨	▨																												
Emission model development																																					▨	▨	▨	▨	▨	▨	▨	▨	▨								
Thesis preparation																																									▨	▨	▨	▨	▨	▨	▨	▨	▨				
Publications												*			*					*	*								*			*	*	*	*					*	*	*			*				*				

The main focus of the methodology was the determination of the impacts of traffic calming schemes on emissions from *passenger cars*. The methodology involved the development of driving cycles to represent vehicle operation (speeds, accelerations, and gear selections) before and after the introduction of a traffic calming, with the cycles subsequently being used to measure emissions from a sample of passenger cars on a chassis dynamometer. The driving cycles were based on real-world measurements of vehicle speed. The development of a speed measurement procedure is described in Chapter 4, the traffic calming measures investigated during the study are described in Chapter 5, and the method and results of the speed measurement campaign are presented in Chapter 6. The development of the driving cycles, based on the speed data, is described in Chapter 7.

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 8 of the Thesis describes the selection of vehicles for testing and the test procedure, and includes a summary of the results.

In order to determine whether the emission behaviour of the sample of vehicles tested over specific cycles on the dynamometer could be related more generally to the emission behaviour of large numbers of vehicles on the road, remote sensing surveys were conducted in the vicinity of two traffic calming measures. The method, results, and conclusions of this on-road study are presented in Chapter 9.

One of the objectives of the research was to develop a system of performance indicators for 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 different types of traffic calming measure, and the guidance for local authorities, are presented in Chapter 10.

Modelling emissions is a cost-effective alternative to direct measurement. Estimating changes in emissions on the spatial scale of a traffic calming scheme probably requires the use of a micro-scale emission model, in which vehicle emissions are related to a detailed vehicle operation profile. Such applications represent the state of the art in emission modelling, and at present they are few in number. One model, MODEM (Jost *et al.*, 1992), has been shown to underestimate the changes in emissions arising from the introduction of traffic calming measures (Sturm *et al.*, 1998). However, Sturm *et al.* only reported emission test results for a single vehicle. The results from the experimental work presented in this Thesis were used firstly to assess the performance of the model in more detail, and secondly to examine how its performance in traffic calming applications might be improved. The MODEM model, and the assessment and development of the model for use in traffic calming applications, are described in Chapter 11.

Chapter 12 contains a summary and discussion of the research. The conclusions and recommendations for future work are presented in Chapter 13.

1.4 Associated publications and conferences attended

Publications

- Boulter, P. G., Hickman, A.J., Latham, S., Layfield, R., Davison, P. (AEA Technology), & Whiteman, P. (AEA Technology) (2001). 'The impacts of traffic calming measures on vehicle exhaust emissions'. TRL Report 482. Transport Research Laboratory, Crowthorne.

- Boulter, P. G. (2000). 'Remote sensing of vehicle emissions near traffic calming measures'. Proceedings of 9th international symposium on Transport and Air Pollution, Avignon, France, 5-8 June, ISBN 2-85782-533-1, pp529-534.

- Green, J. & Boulter, P.G. (2000).'Traffic management: an evaluation of parking duration and vehicle exhaust emissions using remote sensing techniques'. TRL Report 469. Transport Research Laboratory, Crowthorne.

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- Sturm, P. J., Boulter, P., de Haan, P., Joumard, R., Hausberger, S., Hickman, A. J., Keller, M., Niederle, W., Ntziachristos, L., Reiter, C., Samaras, Z., Schinagl, G., Schweizer, T. & Pischinger, R. (1998). 'Instantaneous emission data and their use in estimating passenger car emissions'. EC MEET Project Deliverable no. 6. Task 1.1: Instationary vehicle emissions. Published by the Technical University of Graz, Institute for Internal Combustion Engines and Thermodynamics, A-8010 Graz Inffeldgasse 25, Austria, Editor Univ.-Prof. Dr. R. Pischinger.

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- Cloke, J., Boulter, P. G., Davies, G., Hickman, A. J., Layfield, R. E., McCrae, I. S., & Nelson, P. M. (1997). 'Traffic management and air quality research programme'. TRL 327.

Transport Research Laboratory, Crowthorne.

- Boulter, P. G. & Webster, D. C. (1997). 'Traffic calming and vehicle emissions: a literature review'. TRL 307. Transport Research Laboratory, Crowthorne.

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

Conferences, workshops, and meetings attended

- TRAMAQ (Traffic Management and Air Quality) meeting. DETR, 7 November 2000.

- 9th International Scientific Symposium on Transport and Air Pollution. Avignon, France, 5-8 June 2000. Poster presentation: *Remote sensing of vehicle emissions near traffic calming measures.*

- Workshop on Particles Research. DETR, 24 May 2000.

- TRAMAQ (Traffic Management and Air Quality) meeting. DETR, 4 November 1999.

- Final meeting of the EC MEET project and COST 319 Action (Estimation of Pollutant Emissions from Transport), Graz, Austria, 18 June 1998.

- 6th International Highway and Urban Pollution Symposium, Baveno, Italy, 18-22 May 1998. Oral presentation: *Driving cycles for measuring passenger car emissions on roads with traffic calming measures.*

- National Society for Clean Air and Environmental Protection Spring Workshop. 15/16 April 1997. 'Air Quality Management'. Abingdon, Oxfordshire. Oral presentation: *Traffic management and vehicle emissions.*

CHAPTER 2 TRAFFIC CALMING: A REVIEW OF MEASURES AND EFFECTS

2.1 Traffic calming

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

Changes in traffic speed have been shown to be related to changes in accident occurrence. By examining the results from studies on various types of road in several countries, Finch *et al.* (1994) found that a 1 mph reduction in mean vehicle speed gave a 5% reduction in accidents. A similar relationship has been observed for 20 mph zones, where it has been demonstrated that the same reduction in mean vehicle speed equates to a 6.2% reduction in accidents (Webster and Mackie, 1996). More recent research by TRL (Taylor *et al.*, 2000) has both confirmed an expanded on these findings, and it is clear that such results have encouraged the use of physical engineering measures - or 'traffic calming' - to reduce speeds.

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

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

It was acknowledged by Pharoah and Russell that the principal objectives vary from scheme to scheme, but generally include reduction of accidents, reclamation of space for non-traffic activities, promotion of greater feelings of security (particularly among residents, pedestrians, cyclists, and others engaged in non-traffic activities), creation of environmental improvements, and promotion of local economic activity.

Since traffic calming works by adapting the characteristics of traffic to the functions of the streets through which it passes (Devon County Council, 1991), it follows that different approaches will be required for different sections of the road network. For example, vehicle speeds must be kept low throughout an urban residential 20 mph zone. The position in the road hierarchy that a 20 mph zone occupies ensures that vehicles entering the zone are not travelling at particularly high speeds, and consequently fairly severe traffic calming measures can be employed. In contrast, vehicles entering a rural village on a main road will be travelling at higher speeds, and the proportion of HGVs in the traffic will be considerably greater. The design of any traffic calming measures employed to reduce speeds through such a village would need to take these factors into account.

In order to inform local authorities of the recommended procedures and legislative requirements concerning the implementation of schemes, the Government has published an extensive series of Traffic Advisory Leaflets (*e.g.* Department of Transport, 1996). The publications mentioned at the start of this Chapter also offer advice on implementation. Descriptions of the more important traffic calming measures are provided in the following Sections of the Review, but for a more in-depth view these publications should be consulted. Photographs of typical examples of some of these measures can be found in Chapter 5 of the Thesis.

2.2 Specific traffic calming measures

The rules governing the design of traffic calming measures were relaxed with the introduction of the Highways (Road Humps) Regulations 1996 (for a brief chronology of traffic calming legislation, refer to Appendix A). This has led to the implementation of a diverse range of measures on UK roads, although many of the measures now seen in the UK have been used extensively on the continent for several years. The main traffic calming measures currently in use in the UK are described in the following Sections. They have been separated into three categories: measures which result in a vertical deflection in vehicle path, measures which result in a horizontal deflection in vehicle path, and other measures.

Measures may be implemented individually, but it is increasingly common for authorities to implement a combination of measures in area-wide schemes. Indeed, this approach has been encouraged for a number of years. For example, Devon County Council (1991) have regarded the list of available measures as a 'palette' to be used in combination to meet specific objectives.

2.2.1 Vertical deflections

2.2.1.1 Road humps

A road hump is a raised portion of carriageway laid at right angles to the direction of traffic. Humps generally have either a circular (round-top) profile, or a trapezoidal (flat-top) profile with ramps leading up to and down from a plateau. Road humps are the most commonly used traffic calming measure in Britain (Hass-Klau *et al.*, 1992), and this is no doubt due to their effectiveness as speed-reducing devices. Round-top humps were first used in the UK in the 1980s (Baguley, 1981), though their design was tightly controlled. Flat-top humps made their first appearance in the UK during the 1990s. It is common to see the latter used in conjunction with a Pelican or Zebra Crossing. The most effective humps at reducing vehicle speeds are 100 mm high but, because of passenger discomfort or grounding, they are not usually suitable for use on bus routes, or on routes which are frequented by the emergency services. The use of 75 mm humps can substantially lessen the likelihood of grounding with little or no erosion in the speed reduction obtained using 100 mm humps (Webster and Layfield, 1996). Where the higher humps would have been unacceptable to the emergency services, bus operators, and residents, humps with lower profiles and shallower gradients have been implemented.

2.2.1.2 Speed cushions

As Layfield (1994) indicated, one of the main problems with road humps is that the effect on larger vehicles such as buses, mini-buses, and emergency vehicles is more severe than for cars, and therefore the discomfort for passengers in larger vehicles can be more pronounced. Road humps can also cause delays for emergency vehicles, and can be uncomfortable for cyclists. On the continent, and more recently in Britain, the solution to these problems has taken the form of speed cushions.

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

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

2.2.1.3 Raised junctions

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

2.2.1.4 Thumps

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

2.2.1.5 Rumble devices

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

2.2.2 Horizontal deflections

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

2.2.2.1 Build-outs/Half-chicanes

A build-out consists of a feature which extends into the road to narrow the existing carriageway. Build-outs can be constructed in various ways; they may be introduced as pavement extensions, as planted areas, or in the form of plant pots or tubs. The narrowed carriageway, even if reduced to a single lane, still allows most vehicles to be driven relatively quickly through the available gap, unless there is opposing traffic to prevent this (Department of Transport, 1994e).

2.2.2.2 Full Chicanes

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

2.2.2.3 Pinch points

Pinch points are created when two build-outs are constructed on directly opposite sides of the carriageway, thus reducing the width of both lanes over a distance of around 5-10 metres. The form and shape of pinch points can vary substantially, and the distinction between pinch points and chicanes is often blurred. By implementing this measure the carriageway width can be restricted so that only one vehicle at a time can negotiate the point (when the width is around 2.8-3.2 metres), or so that two cars can pass each other slowly (when the width is around 4.6-4.8 metres). If rat-running traffic is the problem, rather than excessive traffic speed, reducing the carriageway to one lane by using pinch points can be effective at deterring through traffic by causing delays (Hass-Klau *et al.*, 1992).

2.2.2.4 Carriageway narrowing

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

2.2.2.5 Traffic islands/Pedestrian refuges

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

2.2.3 Other devices

2.2.3.1 Roundabouts

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

2.2.3.2 Road markings/Surface treatments

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

2.2.3.3 Entrance treatments

Entrance treatments are features designed to make car drivers more aware when they are entering a traffic calmed area, or to generally mark the beginning of an area where reduced speed is required (Hass-Klau and Nold, 1994). Hence, they can be an effective means of identifying the beginning of a 20 mph zone. Entrance treatments have been developed for use at side roads so that drivers leaving a major road are in no doubt that they are entering a road of different character. They may be used alone, generally to indicate to a driver that he is about to encounter other traffic calming measures, or may be combined with traffic calming measures themselves. The design of an entrance treatment can itself incorporate a wide variety of features, including build-outs, pinch points, changes in surface texture or colour, vertical deflections, and planting (Department of Transport, 1994a).

2.2.3.4 Gateways

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

2.2.3.5 Road closure

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

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

2.2.4 Area-wide traffic calming

As stated above, car drivers who have been forced to give up one rat-run because it has been traffic calmed often switch to another. This can be avoided by area-wide calming, and the best results can be achieved through the implementation of a combination of traffic calming measures. During the design phase of the scheme it has to be made clear how emergency services would be affected if they had to get to a location in the middle of a network of streets featuring traffic calming, and it is important to consider the comfort of patients being carried in ambulances (Hass-Klau *et al.*, 1992).

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

2.2.5 Speed limits

2.2.5.1 Speed cameras

Speed cameras have become an increasingly common sight along main and local distributor roads in urban areas in the UK, but their effects on speed tend to be very localised. Abbott *et al.* (1995) observed that the development of speed-enforcement technology that can detect excessive speeds along a route rather than excessive speeds at particular locations may give speed-enforcement technology a greater role in accident reduction and traffic calming. Cameras operating on this principle - called 'SPECS' - are already on trial in the UK (Totton, 2000).

2.2.5.2 20 mph speed limits and zones

The use of signing alone to define a 20 mph speed limit is most appropriate where the 85th percentile speeds are already low, and further traffic calming measures are not needed (DETR, 1999).

DETR (1999) advises that 20 mph zones are most appropriate in areas where there is a record of accidents to children, or where concentrations of pedestrians and/or cyclists are anticipated. The zone itself will normally be residential in character. Until June 1999, specific consent from the Secretary of State for Transport was required. The legislation has now been changed, and local authorities no longer need to obtain consent before implementing 20mph speed limits and zones. Previously, in order that zones did not become too large, no road within it could be more than one kilometre from the boundary of the zone. This no longer applies, but it remains sound general advice (DETR, 1999). Hodge (1992) noted an apparent lack of variation in the type of measure implemented in 20 mph zones. Flat-top humps appeared to be the device most frequently used.

2.2.6 Most frequently implemented types of measure in the UK

The traffic calming measures to be included in the PhD research programme were selected according to their popularity (in terms of how many had already been implemented by local authorities). The types of traffic calming measure most frequently implemented in the UK (as of 1997) are listed in Table 2.1. The ranking is based on details of schemes authorised by the Road Safety Division of DETR, a number of TRL reports, and the personal knowledge of TRL staff. Each measure has been evaluated according to the percentage of schemes implemented in which that particular measure was the most prevalent device. The percentage values presented are very approximate, since some of the features listed are often used in combination with each other or with mini-roundabouts. The relative positions of the measures in the list are changing constantly, and regional disparities in the ranking will also exist. The main point to note is that, up to 1997, schemes comprised mainly of road humps were by far the most common type, although the proportion of schemes containing speed cushions was increasing.

Table 2.1 Most frequently implemented traffic calming measures in the UK by 1997.

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

[a] Cushion width can vary from 1600 to 1900 mm.

2.3 Traffic calming and driver behaviour

The first main stage in the determination of the environmental impact of a traffic calming scheme (see Section 1.2) is an assessment of the modifications to driver behaviour imposed by the scheme, and a common approach is to consider behaviour before and after implementation. The following Section is mainly concerned with the factors which influence driver behaviour in urban areas in general, since in this context traffic calming has not been studied in detail.

2.3.1 What is driver behaviour ?

Defining driver behaviour precisely is not a straightforward task. Two basic types of information that describe it were identified by the COST 319 Action, 'Estimation of Pollutant Emissions from Transport' (European Commission Directorate General for Transport, 1996). These are:

(i) Vehicle operation/control data. These include detailed data on parameters such as speed and gear selection

(ii) Activity data. These include information on trips such as journey purpose, duration, mode, time of day, time of year.

'Vehicle operation' data describe the driver's choice of speed and driving style. In urban traffic drivers normally have a choice of possible gear, clutch, brake, and accelerator positions. They thereby determine the operating parameters of their engines, and consequently the fuel consumption and exhaust emissions of their vehicles. The variety of possible control options means that measurements of parameters that are dependent on these options are likely to be quite variable. For example, Waters (1992) stated that different drivers can obtain substantially different fuel consumption figures in the same model of car. When nine drivers were asked to drive the same car around a TRL test route, Waters reported that there was a large difference (50%) between the least economical and most economical drivers.

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

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

Although there is no single effective overall model of how people drive, Evans (1991) has noted that a great deal has been learned about various specific aspects of the driving task. The techniques for studying driver capabilities and performance have included observing actual drivers in traffic, experiments using instrumented vehicles, and studies using driving simulators of varying degrees of complexity and realism. Work relating to driver behaviour has usually been concerned with its relationship with accident causation rather than with accidents. Consequently, existing studies invariably relate to speed selection and not necessarily to the other parameters known to affect emission rates (*e.g.* vehicle type, acceleration rates, gear selection, pedal operation).

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

(i) Personal characteristics: *e.g.* gender, attitudes, age and experience, reaction times, and vehicle ownership.

(ii) The vehicle environment: *e.g.* factors relating to the interior layout, ergonomics (such as actuating forces of the steering wheel, foot pedals, and gear lever) and comfort, and factors relating to vehicle performance (such as available power).

(iii) The road environment: *e.g.* gradient, width, lateral slope, curvature, surface quality, speed limit, adjacent land use, number of pedestrians.

(iv) The traffic environment: *e.g.* volume of traffic, behaviour of other drivers.

(v) Other factors relating to the trip: *e.g.* available time, time of day, weather and light level, commercial pressures.

These distinctions appear to fit in reasonably well with the way in which information on vehicle operation has been reported. For example, Jørgensen and Polak (1993) observed that the topic of drivers' speed selection is one that has attracted considerable research effort in recent decades, with most of the work having concentrated on the relationship between speed selection and the characteristics of the road (alignment, number of lanes, surface condition, *etc.*) or the vehicle (type, age, engine capacity, *etc.*). Researchers have also sought to develop a better understanding of the factors affecting speed selection by extending the scope of analysis to include drivers' personal characteristics and attitudes (*e.g.* Quimby and Watts, 1981). Such work has established the importance of a number of factors, including drivers' perception of safety, their sensitivity to the perceived cost implications of alternative speeds, and the availability and comprehension of information regarding speed limits. Rothengatter (1993) noted that the relative importance of the different factors underlying specific behaviour is still largely uncharted territory and requires further study, since these determine to a large extent the efficacy of the various behaviour modification approaches.

In-depth summaries of the five factors listed above would be too large to warrant inclusion in this review. The report by Boulter and Webster (1997) includes more detailed coverage.

In the context of the type of research presented in this Thesis, the term 'activity data' relates to the type of data obtained from traffic counts and travel surveys, such as the volume and composition of traffic and on different roads, the lengths of trips, the time elapsing between successive trips, and the origin, destination and chosen route, all as a function of the hour, day, month, season, or year.

Whereas vehicle operation defines, to some extent, emission rates, activity data are required to determine scaling factors which can then be used to calculate the total emissions from traffic associated with a given scenario. For example, in the case of traffic calming, the types of activity data required to determine the impact of a given scheme on emissions include traffic composition and traffic flow, both along the calmed section and along potential diversionary routes before and after the implementation of the scheme. For the specific purpose of determining the emissions associated with a particular scenario, it is also important to disaggregate the activity data in terms of the characteristics of vehicles which affect emissions, such as engine type and the level of emission control. There is clearly some degree of overlap between this type of information and that relating to vehicle operation.

2.3.2 Effects of traffic calming on driver behaviour

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

According to Devon County Council (1991), the immediate environment of urban roads needs to convey to the motorist that it would be wholly inappropriate and anti-social to drive at high speed. For Pharoah and Russell (1989), the measures or factors which create a direct and perceived risk or discomfort to the driver are the most effective at ensuring slow speeds. The same authors feared, however, that very low speeds could create driver frustration, and thus greater dangers, where they are required over long distances. It was suggested that drivers might be more likely to reduce their speed if schemes were more varied. Driver acceptance of, and compliance with, low speeds might depend not only on the physical measures themselves, but also on the visual appearance of the street as a 'living area' rather than a 'traffic road'.

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

Although the interactions between the factors listed in Section 2.3.1 are complex, when combined they manifest themselves in the form of measurable vehicle and traffic parameters. The most obvious examples are the route choice and the speed profile (with associated gear selections) of a given driver between two points, and changes in traffic flow and composition on all affected roads. Knowledge of this continuous vehicle operation, as well as changes in traffic flow and composition, are fundamental requirements for accurately determining changes in vehicle emissions along the roads with traffic calming, as well as any other affected roads. However, although vehicle speeds at given points are one of the most frequently measured parameters in the assessment of traffic calming schemes, it is precisely this kind of continuous information that is not widely available.

Much work has been done on the optimum spacing of road humps to reduce speeds. Webster and Layfield (1996) derived empirical relationships between the speed between humps, V (mph), their spacing S (m), and the speed before the measures were installed, V_b (mph). For 75 -100mm high round-top and flat-top humps the relationship is given by:

$$V = 3.9 + 0.057S + 0.40V_b$$

According to Fwa and Liaw (1992), drivers will usually decelerate on the approach to a hump and accelerate after crossing the hump. Driver behaviour on calmed roads in Leicester was evaluated subjectively by Buxton and Newby (1995) and drivers were categorised in terms of their acceleration and braking at the humps. These observations indicated that, for most drivers, the road humps were associated with only slight acceleration and braking. In a Finnish study (Huttenen, 1995), the height and separation of the road humps were found to influence deceleration and acceleration, although the mean rates were again comparatively low. Average decelerations were in the range 0.43 - 0.77 m/s^2 and acceleration values were 0.49 - 0.85 m/s^2.

De Wit and Slop (1984) observed that the effect of a traffic calming hump extends along a length of about 50m before to 60m after. Webster and Layfield (1996) showed that a hump spacing of less than 70m is required to achieve a speed difference of less than 5 mph between the mean speed at the humps and the mean speed mid-way between the humps. A more even speed profile might be obtained by using less severe measures (*e.g.* lower height humps) at closer spacing, but such an arrangement might raise problems of public acceptability regarding the effectiveness and number of the measures within an area.

2.4 Factors affecting vehicle emissions

In order to determine the impact of traffic calming schemes on exhaust emissions, it is important to understand, as fully as possible, the complex relationships between traffic characteristics, vehicle operation, and rates of emission. This Section of the Thesis presents an overview of the factors known to affect the emission rates of individual vehicles.

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

(i) Technical factors relating to the design and engineering of the vehicle: its weight, engine type, exhaust after-treatment, aerodynamic properties, *etc.*;

(ii) Operational factors relating to the way in which the vehicle is used: its speed, rate of acceleration, maintenance, road gradient, *etc.*

Of these two groups, the factors most likely to be influenced by traffic calming schemes are those relating to vehicle operation (*e.g.* speed, acceleration). Indeed, it should be clear from the preceding Sections of the Thesis that changing vehicle operation is the primary objective of traffic calming. Consequently, more attention has paid to the dependency of emissions on vehicle operation in this Review. Technical factors affecting vehicle emissions have been summarised in less detail, since traffic calming does not usually influence these unless it leads to the exclusion of certain vehicle types. However, in any assessment of road traffic emissions the differences between the emission rates of different vehicle types must be appreciated.

2.4.1 Technical factors

The emissions that a vehicle produces are influenced, to an extent, by all aspects of its design and construction. The fundamental differences between vehicles are very significant in accounting for variations in their emission rates (Abbott *et al.*, 1995). Some of the technical factors that are known to affect vehicle emissions are listed in Table 2.2.

Table 2.2 Some technical factors affecting vehicle emissions.

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

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

2.4.1.1 Engine type

Most road vehicles are powered by either a petrol or diesel engine. Petrol and diesel have a similar chemical composition, and so when they are combusted the exhaust products, or types of pollutant, are similar. However, the differences in their combustion are sufficient to make a sizeable difference to pollutant emission rates. Table 2.3 is taken from Abbott *et al.* (1995), and gives an indication of the relative pollutant emission rates for petrol and diesel passenger cars under typical urban driving conditions.

Table 2.3 Comparison of emission rates for some pollutants from petrol (non-catalyst) and diesel cars (adapted from Abbott *et al.*, 1995).

Pollutant	Emission rate (g/km)	
	Petrol	Diesel
Oxides of nitrogen	2	0.8
Hydrocarbons	4	0.3
Carbon monoxide	40	1
Methane	0.1	0.03
Sulphur dioxide	0.1	0.5
Lead	0.02	-
Particulates	0.02	0.5

2.4.1.2 Engine management systems

Emission rates are strongly dependent on the combustion conditions in the engine, and the optimal settings to achieve the desired performance and minimise emission rates vary according to operation. Mechanically-timed systems cannot modify the timing over as wide a range of operating conditions as an electronic system. Emission rates therefore tend to be higher for mechanically-timed engines. It should be noted that neither system responds well to rapid changes in operation (*e.g.* during acceleration), and it is during these conditions that the highest emission rates are observed.

2.4.1.3 Shape, size, and weight

The physical characteristics of a vehicle, such as aerodynamic properties, size and weight can affect its emission rates. More power is needed to move a large, heavy vehicle than one that is smaller and lighter, and hence fuel consumption increases systematically with increasing vehicle weight (Bleijenberg and Rutten, 1991).

2.4.1.4 Engine capacity

Engine capacity has been found to be an important parameter affecting pollutant emission rates for petrol passenger cars (Samaras *et al.* 1997a). For modern petrol cars equipped with catalysts it was found that vehicle engine capacity affected CO and HC emissions only at low speeds, and NO_x emissions only at high speeds. For non-catalyst petrol cars, engine capacity correlated well with NO_x emissions in all speed ranges, and also with CO and HC emissions at higher speeds.

2.4.1.5 Age and mileage

From their statistical analysis of emissions data from European laboratories, Samaras *et al.* (1997a) found that vehicle mileage had a strong influence on the emissions of all pollutants for modern petrol cars equipped with a catalyst, but not for older petrol cars. This is likely to be a result of the gradual degradation of the catalyst with accumulating mileage.

2.4.1.6 Exhaust after treatment

Pollutant emission rates can be reduced by treating the exhaust after it leaves the engine. Generally, methods of after treatment can be categorised according to the three technologies identified below. The applicability of each technology is strongly dependent on the type of engine and fuel.

(i) Three-way catalysts which, when used on petrol vehicles, can remove most of the CO, HC and NO_x. Emission rates of these pollutants are typically an order of magnitude lower than those given for non-catalyst cars in Table 2.3.

(ii) Oxidation catalysts, which can be used on both petrol and diesel-engined vehicles (but are generally fitted to diesel vehicles) and remove CO and HC, but not NO_x

(iii) Particulate traps, which are used solely on diesel vehicles. The most recent systems have been shown to remove 90 per cent or more of the exhaust particles (by mass).

2.4.1.7 Maintenance level

The control of emissions from an in-service vehicle is the responsibility of the owner, and there is evidence that emission rates and fuel consumption of in-service vehicles are worse than when they are new (Hickman, 1994). The most common way of investigating the influence of vehicle maintenance on rates of emission has been to conduct tests before and after the tuning of vehicles in normal service. In an investigation of 204 passenger cars by Williams and Everett (1983), emissions of CO before tuning were much higher than the type approval levels, but those of NO_x were lower. After tuning, all emission rates were much closer to the legislative limits. Joumard *et al.* (1990) carried out a similar study of 50 petrol and 5 diesel cars, and found that, after tuning, CO emission rates were reduced to 78-85% of the pre-tuning value for petrol cars (84-97% for diesel cars), and total particulates were reduced to 64-75% for diesel cars. Latham and Davies (1991) suggested that half of the heavy-duty vehicles in the UK were emitting smoke levels above specified limits, again based on tests carried out before and after tuning. It was estimated that these vehicles were responsible for approximately 80% of total smoke emissions.

2.4.2 Operational factors

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

2.4.2.1 Average speed

The most common way of representing vehicle emission rates has been as a function of average speed and, for passenger cars at least, the characteristic variation of emissions with speed is well known. The average speed is determined from the time taken, including stops, to cover a driving cycle of a given length. Typical emission rates for passenger cars as a function of average speed are shown in Figure 2.1. The presentation of emissions data in this way became customary during the early 1980s (Abbott *et al.*, 1995).

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

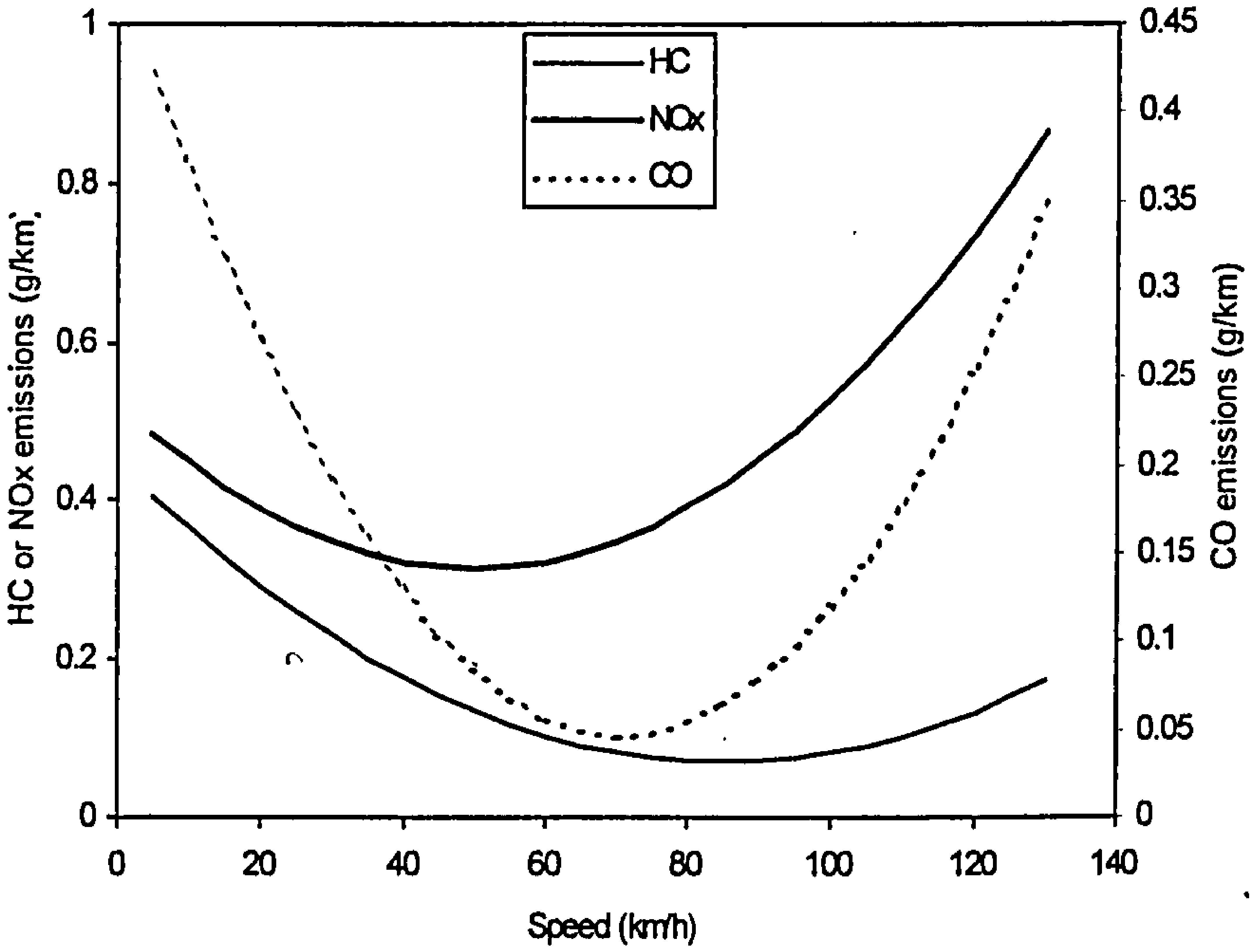

Figure 2.1 Emissions of CO, HC, and NO_X as a function of average speed for petrol catalyst cars with an engine size between 1.4l and 2.0l (adapted from Ntziachristos *et al.*, 1999).

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

Driver behaviour through traffic calming schemes has usually been represented in terms of mean vehicle speed. However, it is obvious that there are substantial problems involved in using average speed/emission relationships to establish the impact of traffic calming schemes on emissions. Speeds before and after calming often conform to significantly different operational regimes. Although schemes are usually successful in reducing vehicle speeds, calming often appears to have had the additional effect of increasing speed variation, and the pattern of gear changes may be affected significantly. For example, Hansen *et al.* (1995) noted that as the flow of traffic becomes limited by either traffic regulation or congestion, it is expected that the variability of the traffic speed will increase as the number of accelerations and decelerations increases. When the authors normalised both the average speed and the standard deviation of speed for a trip along a given road to the rated speed of the road, they observed a clear trend of increasing speed variation as the average trip speed decreased. Also, during emission tests the average speed is almost invariably the overall mean speed of the vehicle for the complete test. However, surveys of traffic speeds are often made at individual locations on the road network, and then the average speed represents not that of a vehicle during a journey, but the average of all vehicles at one point of their journeys. Depending on the location of the observation the two could be quite different (Hickman *et al.*, 1997).

2.4.2.2 Average speed and speed variation

An improved representation of exhaust emissions should result if variations in speed around a mean are also taken into account. Hickman *et al.* (1997) showed that the description of a trip in terms of its basic driving modes (*e.g.* acceleration, deceleration, cruising and idling) could be used to calculate overall emissions as the sum of those produced when driving in each mode.

Hansen *et al.* (1995) also considered the relationships between statistical descriptors of driving patterns and emissions. The authors measured emissions from a number of passenger cars using driving cycles selected to represent a wide range of average trip speed and speed variation. The parameter chosen to represent speed variation was the standard deviation of the instantaneous driving speed over the entire driving cycle. Average trip speeds ranged between 10 and 90 km/h, and standard deviations from 0-20 km/h. The results for both catalyst and non-catalyst petrol cars showed similar trends. For CO and HC the average trip speed was seen to be the most significant factor, though at the lowest and highest speeds emissions increased with increasing speed variation. Speed variation had little effect on emissions at the intermediate speeds. For HC emissions the effect of speed variation was generally smaller than for CO. For NO_x the lowest emissions were observed at the lowest speeds and lowest speed variation, while the highest emissions were found for cycles with lowest speeds and highest variations. In general, it was noted that for CO and HC, trip speed was the more dominant factor in determining emissions, with speed variation playing a lesser role. In the case of NO_x, the relative effects of speed and deviation were more equal.

2.4.2.3 Instantaneous speed and acceleration

According to Joumard *et al.* 1995, the acceleration rate of a vehicle is a direct measure of the variation in speed and is therefore an important parameter to consider. However, the operation of a vehicle's engine necessary to achieve a certain rate of acceleration also depends on the vehicle's speed. For a given engine input, a slow moving vehicle will accelerate at a considerably higher rate than a fast moving vehicle. A better indication of the power demand on the engine, which ultimately determines the rate of emission, is given by the product of the vehicle speed and acceleration, as instantaneous parameters. If the emissions and fuel consumption recorded at one second intervals can be successfully related to the corresponding driving and operating conditions (through detailed modal analysis), then it is possible to present emissions and fuel consumption as functions of instantaneous speed and acceleration in order to characterise driver behaviour (Jost *et al.*, 1992). Examples of instantaneous emission rates are presented in Figure 2.2.

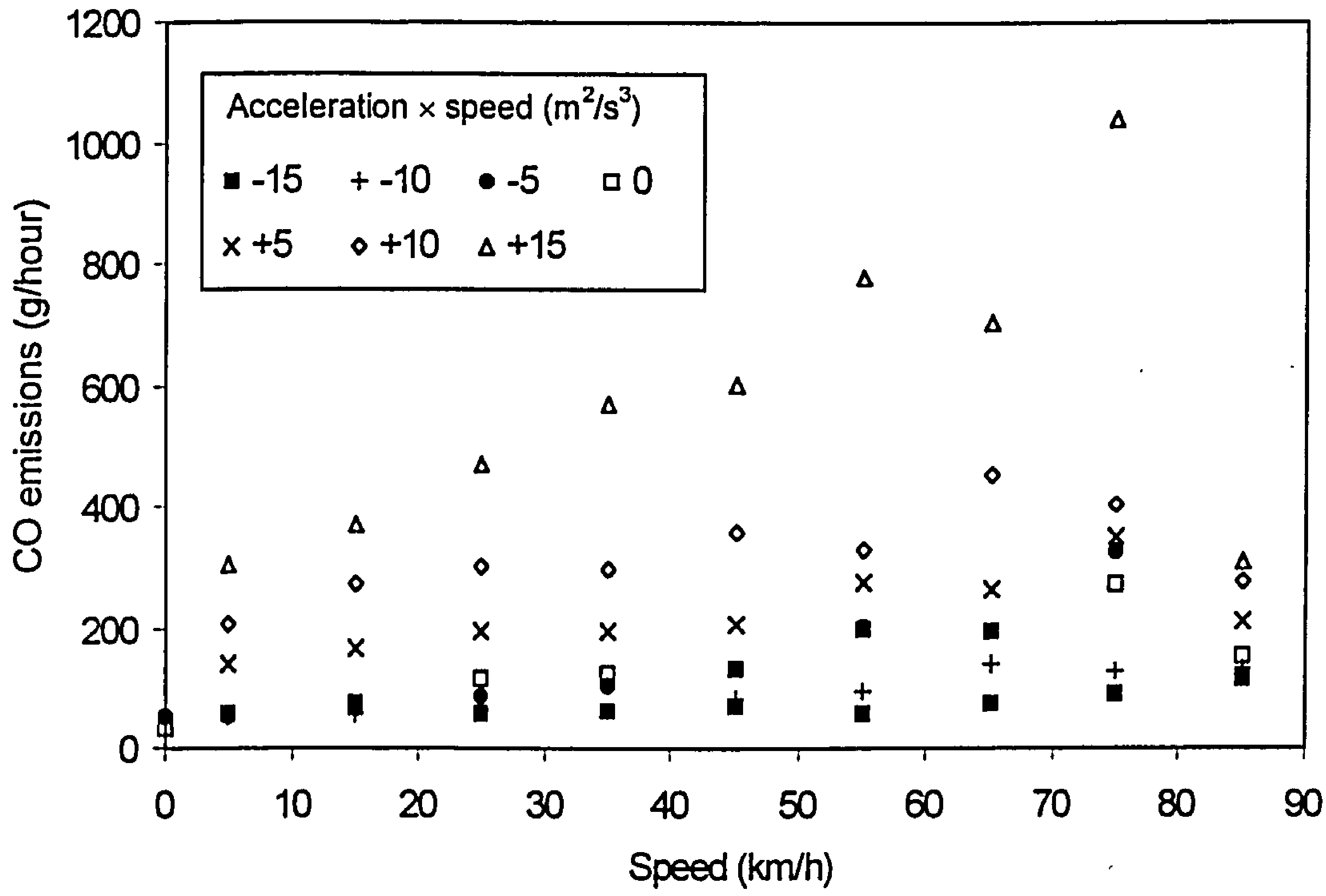

Figure 2.2 CO emissions per hour as a function of instantaneous speed and acceleration for petrol catalyst cars with an engine size between 1.4 and 2.0 litres (Jost *et al.*, 1992).

2.4.2.4 Other operational parameters

Gear selection

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

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

Gradient

The power required to propel any vehicle at a given speed will increase or decrease according to the inclination of the road on which it is travelling. During on-road driving, it was observed by Potter and Savage (1982) that hill ascents produced consistently high NO_x emission rates, whilst descents resulted in low NO_x emissions. However, it was noted by Hassel (1996) that it cannot be assumed that the extra emission when travelling uphill is fully compensated by a corresponding reduction in emissions when travelling downhill. Hassel calculated gradient factors that reflected the change in emissions along roads with a range of gradients compared to the case of a flat road.

The effects of gradient are greatest for heavy-duty vehicles, although Hickman *et al.* (1997) argued that road gradient could be an important factor governing emissions from catalyst cars if the necessary performance of the engine is outside the range for which the engine management system is optimised.

Altitude

When a vehicle with a normally-aspirated engine operates at high altitude, the lower air density means that there is a reduction in the mass of air entering the combustion chamber. This leads to enrichment of the air/fuel mixture. For petrol-engined vehicles driven at an altitude of 3000m, Sorrels *et al.* (1974) found that emissions of CO and HC were approximately twice as high, and NO_x half as high, than at sea level.

Cold start emissions

The operational effects mentioned so far have all related to 'hot' engines working at around 80-90°C. This Section summarises the factors affecting cold start emissions. A more detailed and technical discussion of the definition, measurement, and modelling of cold starts can be found in the review by Boulter (1997).

The term 'cold start' is used to describe the portion of a journey which is driven with the engine operating below its design temperature. During the cold start period, fuel consumption and emissions of the main gaseous pollutants (CO, HC, NO_x, and CO_2) are generally elevated. This originates as a result of the problems associated with the combustion process. The normal operational temperature of an engine is greater than the ambient temperature, and because fuel condenses on cold metal surfaces in the engine during the warm-up phase, extra fuel must be delivered to the engine to prevent misfire and maintain driveability. However, as the engine is running 'rich', emissions of CO and HC are elevated accordingly. Emissions of NO_x tend not to be as elevated during the cold start period.

For cars equipped with a three-way catalyst, running rich is still the primary reason for the elevated CO and HC emission levels associated with cold starting, since the efficient conversion of pollutants cannot be achieved with a fuel-rich exhaust gas. In addition, the catalyst operates inefficiently at temperatures below what is termed the 'light-off' temperature (generally around 300°C).

Absolute values of cold start emissions tend to be highest for petrol non-catalyst cars, followed by petrol catalyst cars, and then diesel cars. However, for CO and HC the ratio of cold start to hot start emissions is greater for petrol cars with a catalyst than for petrol cars without a catalyst. This is mainly because the emissions from a catalyst-equipped car are particularly low during hot operation. Cold start emissions of NO_x from all categories of car are usually small.

Limited data exist for heavy-duty diesel vehicles, but the evidence suggests that (excess) cold start emissions are quite low. The ratios of cold start to hot start emissions for several vehicle categories and pollutants are shown in Table 2.4.

Table 2.4 Ratio of cold-start to hot-start emissions for light-duty vehicles and heavy-duty vehicles (adapted from Pavlidis and Joumard, 1995; Holman, 1996).

	Ratio of cold start to hot start emissions				
	CO_2	CO	HC	NO_x	PM
Light-duty vehicles:					
Petrol, three-way catalyst	1.1	5.1	7.1	1.9	-
Petrol, non-catalyst	1.1	3	3.3	0.8	-
Diesel	1.2	1.6	1.8	1.1	1.6
Heavy-duty diesel vehicles	1.0	1.2	1.0	0.9	1.2

Low engine and/or catalyst temperature is the fundamental cause of cold start emissions. The rate at which an engine warms up may be dependent on how the vehicle is operated (*i.e.* the pattern of speed and gear selection), but an engine will generally be 'hot' after around 8 minutes or 3-6 km of driving (Joumard *et al.*, 1995b). It appears that the catalyst reaches its full operational temperature well before the engine, but emissions will not be minimised until the engine ceases to run rich.

The temperature of the engine and catalyst at the outset of a journey will also affect the duration of the cold start period and cold start emissions. When a vehicle is parked and remains inoperative, the engine cools down. The relationship between the length of time a vehicle has been left to cool down and cold start emissions is, in turn, affected by the prevailing weather conditions, and possibly engine size. As ambient temperature decreases, the rate of cooling increases, so that the time between successive cold starts is shorter. A small engine should cool at a faster rate than a large engine, indicating that the time between cold starts may be shorter. However, there is little information relating to cold start emissions at engine and catalyst temperatures which are between the ambient temperature and the temperatures at which they normally operate.

Cold starts pose a particular problem during the assessment of emission changes associated with traffic calming since, in the residential areas where calming is employed, car engines will frequently be running cold. At present, there is little information relating to the impact of detailed vehicle operation on cold start emissions, and it is therefore unclear how the such emissions are affected by traffic calming.

Evaporative emissions

Apart from the incomplete combustion of fuel, hydrocarbon emissions may arise by evaporation from the fuel systems of vehicles. The largest evaporative losses occur from petrol-fuelled vehicles. Evaporative emissions occur as a result of the volatility of the fuel and the variations in both the ambient temperature and the temperature of the fuel system during a journey. Four types of evaporative loss can occur:

(i) Filling losses due to the displacement of vapour-saturated air when the fuel tank is filled.

(ii) Diurnal losses resulting of the expansion and contraction of the contents of the fuel tank during the daily temperature cycle.

(iii) Hot soak emissions arising from the evaporation of fuel after the engine is switched off.

(iv) Running losses resulting from the evaporation of fuel during operation of the vehicle.

Filling losses, however, are generally not regarded as vehicle emissions, but are considered as an emission which arises during fuel handling and distribution.

Evaporative losses from vehicles are dependent upon four major factors (Samaras *et al.*, 1997b):

(i) Vehicle technology. Although there are little data on the effectiveness of carbon canisters in preventing evaporative losses, modelling procedures suggest losses can be reduced to between 10 and 70 % of uncontrolled emissions.

(ii) The diurnal variation of ambient temperature.

(iii) The volatility of the fuel. The presence of lighter hydrocarbons causes petrol to have a relatively high volatility compared to diesel. Petrol-engined vehicles are consequently a greater source of evaporative emissions.

(iv) Driving conditions (average trip length, parking time, *etc.*).

Barlow (1993) estimated that 45 per cent of hydrocarbon emissions derived from road vehicles in the UK are produced by evaporation, and found that diurnal emissions tend to increase with both vehicle size (*i.e.* engine size, vehicle weight, and fuel tank capacity) and age. The factors affecting diurnal losses appear to have little effect on hot soak losses. Barlow suggested that many factors could lead to the variations in the evaporative emissions from different vehicles, including differences in the fuel and carburation, and faulty components.

As significant amounts of evaporative emissions can be produced by vehicles with hot engines after they are switched off, this type of emission should be taken into account when evaluating traffic management schemes that induce changes in the frequency and duration of car parking. Evaporative emissions are less likely to be an important consideration in the evaluation of traffic calming schemes.

2.5 Traffic calming schemes and vehicle exhaust emissions: case studies

2.5.1 Background

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

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

Because the environmental impacts of traffic calming have not previously been a major consideration in the design of schemes, there is little information on the impacts of different measures on vehicle emissions. This has not, however, prevented authors from airing their views on the subject. Many have remained optimistic about the potential benefits of traffic calming in terms of environmental improvement in general, and in relation to vehicle emissions in particular:

> *'Traffic calming techniques...can directly improve the safety and environmental quality of streets in built-up areas and, in combination with other policies, can help to limit the growth of traffic and promote the use of alternative means of travel with the associated environmental benefits'* (Devon County Council, 1991)
>
> *'The benefits of reducing the speed and dominance of traffic include...reducing noise and air pollution...'* (Durkin and Pheby, 1992)

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

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

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

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

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

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

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

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

The idea of a smooth driving espoused by Döldissen (also referred to earlier in the review as a 'calm driving style') is a common theme in strategies to reduce the environmental impact of traffic. Döldissen believed that this idea should be used to influence the placement of new traffic calming measures, in that measures should not be placed so far apart that the result is high speeds between measures followed by abrupt braking.

Since the effects of traffic calming on vehicle emissions have not been studied in great detail, any claims concerning its benefits or drawbacks in terms of air pollution appear to be somewhat speculative and premature. There has not yet been a detailed study of the effects of traffic calming on vehicle emissions and/or air pollution. The remainder of Section 2.5 is dedicated to existing studies of the changes in vehicle emissions associated with traffic calming schemes that incorporate physical engineering measures. Some of these studies relate to the changes in emissions associated with area-wide schemes, whilst others relate to single sections of road. The studies included here have been categorised according to the country of origin, and a summary of the results is provided at the end of the Chapter.

2.5.2 Case studies

2.5.2.1 Results by country

Germany

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

Buxtehude is a medium-sized town (population 30,000) lying 35 km west of Hamburg. The northern half of the town was chosen for area-wide traffic calming. The scheme has been acclaimed as achieving all-round benefits at reasonable cost (Krause, 1986; Holzmann, 1988). The area-wide scheme was implemented in two stages. In October 1983 the first stage was implemented at low cost. This included a change of speed limit from 50 km/h ('Tempo 50') to 30 km/h ('Tempo 30'), a change of priority rule at junctions, and some narrowing of carriageways using temporary objects. Stage 2 involved more permanent measures to create a self-enforcing speed limit of 30 km/h. This included the provision of new surfaces and lighting at all entrances, footpath and cycle crossings at important junctions, carriageway narrowing, re-designed on-street parking, road width restrictions, road humps, and gateways. This work was completed in November 1986. A planned third stage, designed to exclude through traffic by road closures and barriers, turned out to be unnecessary. The 'after' study of the environmental effects of the second phase was completed in October 1987 (Holzmann, 1988).

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

Holzmann (1988) also showed that the nature of the speed reduction measures, and the styles of driving which they generated, were important factors in determining the impact on emissions. If drivers were encouraged to adopt a calmer driving style, further improvements could be achieved. The calm driving style was also simulated in the emission tests. This calm style implied an earlier changing-up of gear, and always using the highest possible gear (*i.e.* driving at low rpm). Under these test conditions, emissions per vehicle-km of NO_x, CO, and HC were reduced by 50%, 25% and 25% respectively, and fuel consumption was reduced by 10%. It was noted by Holzmann that these results contradicted the usual assumption that slowing down traffic can be expected to result in a general worsening of emissions. The Buxtehude study is therefore regularly cited as an example of traffic calming being beneficial in terms of vehicle emissions. These results formed the basis of Döldissen's argument (Section 2.5.1).

Results from the other demonstration projects have not been as widely reported. In Esslingen, where only three small 30 km/h zones were established, the measurement of emissions was only carried out over short distances. The results indicated a significant decrease in NO_x and a significant increase in CO. In Mainz the 30 km/h zone incorporated single, severe (though infrequent) traffic calming measures. This led to local speed reductions and an uneven driving pattern, although reductions in NO_x emissions per vehicle-km (-22% to -5%) were recorded. The effects on emissions of HC and CO (HC, -23% to +1%; CO, -16% to +28%) were less clear. In Berlin, where extensive traffic calming resulted in low vehicle speeds, emissions of NO_x and HC were found to have decreased significantly. Emissions of CO_2 and fuel consumption were found to have increased (German Federal Ministries of Planning, Transport and Environment, 1992).

Overall, the emission results were variable, with consistent decreases in NO_x, but with increases and decreases in fuel consumption and emissions of CO, HC, and CO_2. The variation reflected the local differences in the type and extent of the physical traffic calming measures that were used to control speed (German Federal Ministries of Planning, Transport and Environment, 1992).

Holland

Two areas in the Dutch towns of Eindhoven and Rijswijk were selected as sites for an experiment to investigate the effects of urban restructuring. The areas contained three types of traffic calming on residential roads. The most limited 'Option I' measures included the introduction of one-way streets, road humps, and parking bays. The 'Option II' and 'Option III' measures were progressively more extensive. In addition to the Option I measures, Option II also included raised junctions and the realignment of the road axis. In Option III, partial pedestrianisation, narrowing of the carriageway, and other features were also added.

The effects of the three Options on air pollution were ascertained by measuring exhaust gas emissions on a number of test trips (SWOV/ DVV, 1985). Although the type of vehicle used in the measurement campaign was not specified, judging by the date of the report it is likely that these results relate only to petrol non-catalyst cars. Also, the changes in emissions were only expressed qualitatively. The measurements showed that emissions of CO per vehicle-km increased slightly in Option II streets. Emissions of NO_x decreased, and HC emissions remained unchanged. In Option III streets, emissions of CO and HC per vehicle-km also increased, whereas NO_x emissions decreased. The increase in CO emissions in Option III streets was thought to be due to the road axis realignments, which caused drivers to release and then depress the accelerator frequently. Because of the halving of traffic flow in Option III streets, total emissions of each pollutant decreased (SWOV/ DVV, 1985).

United Kingdom 1

Webster (1993b) constructed speed profiles for hypothetical traffic calming schemes that had either round-top or flat-top road humps placed at 50, 75, and 100 metre intervals on a 300 metre stretch of road. 'Sawtooth' speed profiles were derived using empirical relationships between the speed at, and between, humps and hump separation. These speeds were based on large numbers of measurements conducted at a range of sites.

It was assumed that vehicles accelerated for two thirds of the distance between the humps, and decelerated for the remaining third. The speed profiles associated with a scheme with a 75 metre hump spacing had an average speed of 15-17 mph (24-27 km/h), accelerations of 0.2-0.3 m/s^2, and decelerations of 0.5-0.7 m/s^2.

Using these profiles, Webster calculated the emissions of CO, HC, NO_x, and CO_2 from petrol catalyst and non-catalyst cars of two engine sizes. The emissions data used in the estimates, which had been collected by Jost *et al.*(1992) and were subsequently used in the MODEM emissions model, were based on tests on a large number of vehicles. Emission rates were also obtained by Webster for steady-speed profiles at 20, 25, and 30 mph (32, 40, and 48 km/h) over the same stretch of road, in order to give an impression of the emissions before calming.

The calculated emissions for schemes with flat-top humps and circular-profile humps were found to be similar for each engine size. When these were compared with emissions at a constant speed of 30 mph, petrol non-catalyst cars showed increases in CO and HC of 70-90% and 70-120% respectively, and an increase in CO_2 of 50-60%. NO_x emissions were predicted to be 0-20% lower than the level before calming. Petrol cars with catalysts showed an increase in CO of 125-160% and an increase in CO_2 of 90%, but no change in HC or NO_x. For both types of car, fuel consumption increased by between 50 and 60%. For a constant speed of 25 mph before calming, the increases in CO, HC and CO_2 were predicted to be lower, and NO_x emissions were calculated to be reduced by about a further 20%.

In order to examine the effect of 'smoother' driving after the installation of humps, Webster also calculated the change in emissions associated with changing from a constant speed of 30 mph before calming to a constant speed of 20 mph after calming. For this scenario, CO and HC were now found to have increased by around 40-80%, and CO_2 increased by 30-40%. Emissions of NO_x, however, were also found to have increased by around 20-30%.

United Kingdom 2

Using the same emission model employed by Webster (1993b), the emission changes resulting from the implementation of a traffic calming scheme in York, featuring road humps and speed cushions, were estimated by Boulter (1996). The evaluation was based on mean speeds measured at a number of points along the calmed section, both before and after the introduction of the scheme. The speed profile before calming was fairly smooth, with an average speed of around 30 mph. The 'after' profile had an average speed of about 20 mph, but speeds varied between 15 and 24 mph. The calculated changes in emissions exhibited some similarities to those obtained by Webster (1993b), although they were generally smaller. For example, for non-catalyst petrol cars CO and HC emissions per vehicle-km were predicted to increase by 30-60% and NO_x emissions reduced by around 30%. For catalyst-equipped petrol cars, CO and HC emissions per vehicle-km were predicted to increase by up to 30%, although the change in NO_x emissions was less certain.

United Kingdom 3

The environmental impacts of an area-wide traffic calming scheme, introduced in the Leigh Park area of Havant, Hampshire were studied by Cloke *et al.* (1999). The study covered the impact of the scheme of vehicle emissions, air quality, noise, vibration, and public perception.

Leigh Park was identified in 1992 as having a high level of casualties to vulnerable road users. In order to reduce road casualties, Hampshire County Council implemented a comprehensive traffic calming scheme in January 1997. The scheme comprised speed cushions, humped pelican crossings, a raised junction, pedestrian refuges, gateways at the entrances to the area, build-outs to protect on-street parking spaces, and mini-roundabouts.

The measures were successful at reducing vehicle speeds and discouraging through traffic from using the residential streets. The cushions, raised junction, and mini-roundabout were the most effective, giving average two-way speed reductions of 11-12 mph (18-19 km/h) at the measure. Average daily flows were reduced on the roads with cushions by 15-35%. A smaller flow reduction (10%) was seen where only traffic islands had been installed. There was some diversion of flow within the scheme onto roads with fewer or less effective measures, and some transfer of traffic (around 600 vehicles per day) onto roads outside the scheme.

Exhaust emissions were estimated using the MODEM model for passenger cars, and speed-dependent emission functions for heavy-duty vehicles. The introduction of speed cushions on a particular stretch of road led to a change in driving pattern, and an estimated increase in emissions of CO, HC, and CO_2 per vehicle-km, but a decrease in NO_x. However, when changes in flow within, and away from, the scheme were taken into account, the total daily emissions of all the modelled pollutants were reduced. Daily emissions of CO were reduced by 6%, and emissions of HC, NO_x, and CO_2 were reduced by 5%, 15%, and 8% respectively. Finally, when changes in the vehicle fleet (*i.e.* the introduction of more vehicles equipped with a catalytic converter during the 'after' period) were taken into account, then a greater percentage reduction in the emissions of all pollutants was observed. Traffic diverting onto roads outside a traffic calming scheme could have an adverse effect on emissions on these roads, but in this scheme the volume of diverted traffic was relatively small and any increase in emissions is unlikely to have had a significant effect on air quality on these roads.

Benzene and NO_2 concentrations were measured at eight locations where traffic was directly affected by the measures installed as part of the safety scheme. Air quality surveys carried out before and after implementation of the safety scheme indicated that modest reductions in NO_2 and benzene concentrations had occurred. Following implementation of the scheme, concentrations of benzene and NO_2 in the Leigh Park area were found to be lower by about 5% and 1% respectively. These changes were, however, not statistically significant. The largest (and only significant) reductions in pollutant concentration occurring as a result of individual measures were seen for the roads where speed cushions have been installed, and then only for NO_2.

Sweden

Höglund (1995) modelled the changes in emission associated with a small number of alternative and idealised scenarios involving the placement of road humps on a section of road. The Nordic Calculation Model for Vehicle Exhaust Pollution was used to estimate emissions.

Höglund firstly considered the effects of introducing road humps on vehicle speed profiles. Four scenarios were assumed for a 1.5 km section of road:

(i) No humps, with a constant vehicle speed (50 km/h). This was taken to represent the situation before calming.

(ii) One hump, resulting in a speed change of 50 km/h to 30 km/h before the hump, and then back up to 50 km/h after the hump.

(iii) Ten humps, resulting in ten of the speed changes described in scenario (ii).

(iv) Ten humps, but only one decrease in speed (50-30 km/h) at the beginning of the road and one increase (30-50 km/h) at the end. A constant speed of 30 km/h was assumed for the mid-section.

The percentage changes in fuel consumption and emissions of CO and NO_x per vehicle-km associated with calming were calculated by comparing each of the 'after' scenarios (ii, iii and iv) with the 'before' scenario (i). The results generated by the emission model were presented for both non-catalyst and catalyst-equipped cars.

It was found that the introduction of a single hump increased emissions per kilometre along the section of road by up to 20%, and fuel consumption by around 5%. The predicted increases in emissions were magnified when ten humps were introduced. The transient profile (scenario iii) resulted in a 200% increase in CO emissions per vehicle-km, and a 300% increase in NO_x emissions, from both types of vehicle, and increases in fuel consumption of 40-50%. However, the rates of both acceleration and deceleration were assumed by Höglund to be a constant 1.5 m/s^2, a value which is somewhat larger than those used in the modelling exercise conducted by Webster (1993b) and those measured by Huttunen (1995) (see Section 2.3.2). Even so, Höglund argued that, in normal braking, a deceleration of 1.9 m/s^2 would be typical, but hard braking can result in a deceleration rate of 3.5-4.5 m/s^2 and, in first or second gear, accelerations are normally between 1.8 and 2.7 m/s^2. Because the acceleration and deceleration values used were limited by the lack of emission data for more rapid changes, it was concluded that real changes in emissions could actually be greater than those predicted by the model. Höglund predicted that the adoption of a constant speed of 30 km/h over the humps would result in a smaller increase (up to 50%).

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

Denmark

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

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

The atmospheric concentrations of lead, CO, and NO_2 were studied before and after the conversions in the three towns. The lead content of the air was determined by means of biological monitoring. The CO and NO_2 concentrations were calculated using a Scandinavian air pollution model (Herrstedt, 1992). In the outer zones of Vinderup, where speeds had been reduced by almost 10 km/h whilst flow remained smooth, lead concentrations were reduced, but the lower speed resulted in a very small increase in CO and NO_2. The fuel consumption of the through traffic had decreased by 9% after the conversion. There was no reported change in the daily traffic flow (Herrstedt, 1988). In Skærbæk, air pollution was unchanged on the central part of the stretch of road. Lead concentrations dropped on the edges of town, while the quantities of CO and NO_2 rose slightly. In Ugerløse, lead pollution reduced slightly in the central part of town, while it increased at the newly-installed roundabouts.

The overall conclusion from the studies of traffic calming in Denmark was that, in most cases, the ensuing reduction in vehicle speed would have had no great influence on air pollution, and any adverse impacts on emissions could be reduced if a more 'even' driving pattern could be employed (Danish Road Directorate, 1993).

Austria

On-road measurements using an individual catalyst-equipped petrol car have shown NO_x emissions to increase dramatically after the introduction of road humps (Züger and Blessing, 1995). The test vehicle, which was equipped with emission analysers, was driven over a 1.5 km stretch of road featuring six road humps spaced at 200 metre intervals. Emissions were measured for three different vehicle operating profiles.

The speed of the vehicle was limited to 30 km/h. In the first test the driver slowed down to 15 km/h at the humps and accelerated to 30 km/h after the humps. In the second test, the driver almost came to a halt at each hump before accelerating to 30 km/h. In order to determine what the emission level of the vehicle would have been before calming, a third test was conducted in which the vehicle was driven at a constant speed of 30 km/h.

When the results of the first test where compared with the results of the third test, it was found that traffic calming had caused NO_x emissions per kilometre to increase by an order of magnitude. Emissions of NO_x during the test were eight times higher than during the third test. Both CO_2 emissions and fuel consumption per kilometre were found to have risen by around 25% with the humps in place, whilst CO emissions increased by 160%. The equipment employed was not sensitive enough to measure hydrocarbon emissions.

Australia

Van Every and Holmes (1992) calculated passenger car fuel consumption on a 500 metre calmed stretch of a local street system using a theoretical model. The model was used to calculate fuel consumption for three scenarios: five road humps spaced at 100 metre intervals, five flat-top road humps spaced at 100 metre intervals and two roundabouts spaced at 250 metre intervals. The average speed before calming was assumed to be 50 km/h. The assumed average speeds at, and between, the measures are given in Table 2.5.

Table 2.5 Assumed speeds associated with traffic calming measures (Van Every and Holmes, 1992).

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

The model predicted that fuel consumption per vehicle-km would increase after the implementation of the round-top humps, flat-top humps and roundabouts by 73%, 36%, and 33% respectively.

2.5.2.2 Review of case studies

The results from the case studies that have been reviewed here are summarised in Table 2.6. The percentage changes in the Table relate to changes in emissions per vehicle-km, and do not take into account changes in traffic flow.

The studies have generally indicated that fuel consumption and emissions of CO, HC, and CO_2 per vehicle-km increase after the introduction of traffic calming, although the range of results for each pollutant is rather wide. For NO_x, both increases and decreases in emissions have been observed, and the variability in impacts was the most pronounced of any pollutant. One study has shown a decrease in NO_x emissions of 60%, whilst another has shown an increase of 900%. Unfortunately, no further information has been made available to suggest why the large increases in NO_x emissions obtained in the Austrian study (Züger and Blessing, 1995) were so great.

It is likely that the variability of the impacts is related to a number of factors. These include:

(i) The method of assessment.

Some of the studies listed in Table 2.6 involved the direct measurement of emissions from a single vehicle or a small sample of vehicles (both on the road and in the laboratory), whilst others relied upon an emission model based on tests on a sample of vehicles.

(ii) The types of vehicle considered.

Older petrol-engined 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. With these newer vehicles, some modes of operation, such as rapid accelerations, can result in fuelling conditions that deviate from those required for the optimum control of pollutants. Any deviation from optimum conditions can result in a momentary emission rate that is an order of magnitude higher than the baseline rate. However, the limited results in Table 2.6 appear to indicate that there are no clear differences between the percentage effects of traffic calming on emissions from petrol non-catalyst cars, and the effects on emissions from petrol catalyst cars. A controlled experiment is required to examine this hypothesis further.

(iii) The nature of the traffic calming.

The severity and spacing of the traffic calming measures, as well as speeds before and after calming, will strongly influence the impacts on emissions. The number of traffic calming measures employed on a given length of road should be an important factor in determining changes in emissions, since whatever effect one measure has on emissions, the effect will be magnified if more measures are employed. Höglund (1995) predicted that the introduction of ten road humps (spaced at 150 metre intervals) along a section of road would produce a change in emissions approximately ten times greater than that caused by the installation of a single hump on the same road, but again there is a need for further evidence to substantiate this hypothesis. With large hump spacings, such as those used by Höglund and employed in the study by Züger and Blessing (1995), drivers would be able to accelerate up to a speed level similar to that which they would have chosen had the humps not been installed, even with comparatively low acceleration rates. These studies, where several widely-spaced humps have been employed, appear to have produced the largest increases in emissions. However, there is no conclusive evidence to support the suggestion that hump spacing is an important factor.

(iv) The configuration of the road and prevailing traffic conditions.

It is possible that the large changes in NO_x emissions by observed Züger and Blessing may have arisen because of the particularly low speeds and the deceleration and acceleration rates. These were described as 'rapid' by, but no values were quoted. The relationships between vehicle speed and emissions per kilometre are not linear, and the change in emissions associated with two different speeds depends greatly on the speeds themselves, and hence the road layout prevailing traffic characteristics. In the low-speed region (below around 30 km/h), the emission rate per kilometre increases rapidly, and approaches infinity as speed approaches zero (see Figure 2.1). In addition, emissions tend to be very variable in this low-speed region. Therefore, when comparing the emissions associated with two driving cycles, it is likely that a large change in emissions will be observed if one of these cycles is in the low-speed region. The speed at the road humps was 15 km/h (9 mph), and therefore well into this region. Further on-road tests of this type need to be conducted at speeds which are more representative of driver behaviour in the vicinity of traffic calming measures.

Table 2.6. Summary of results from case studies.

Country and reference	Measures	Mean speed (km/h)		Acceleration Range (m/s^2)	Assessment method for emissions	Vehicle type[a]	Effect on emissions and fuel consumption per vkm (%)				
		Before calming	After calming				CO	HC	NO_x	CO_2	F.C.
Germany (GFMTPE, 1992)	Extensive traffic calming	N/A			Dynamometer Tests	PNC	+7 to +71	-23 to +10	-60 to -38	+7 to +19	N/A
	30 km/h zone						-20 to +28	-23 to +2	-31 to -5	-6 to +14	
Holland SWOV/ DVV (1985)	Various traffic calming	N/A			On-board measurement	PNC	Slight increase	No change	Decrease	N/A	N/A
	Extensive traffic calming, and partial pedestrianisation						Increase	Increase	Decrease		
UK 1 Webster (1993)	Road humps	48	39-43	-0.7 to +0.3	Emission model	PNC	+70 to +90	+70 to +120	-20 to 0	+50 to +60	+50 to +60
						PC	+125 to +160	0	0	+90	
UK 2 Boulter (1996)	Road humps and speed cushions	48	32	N/A	Emission model	PNC	+31 to +58	+37 to +59	-34 to -10	+9 to +26	+12 to +29
						PC	+5 to +33	0 to +30	-21 to +5	+15 to +34	+15 to +34
						Diesel	+13 to +34	+73 to +111	-8 to +22	-5 to +11	-5 to +12
UK 3 Cloke *et al.* (1999)	Speed cushions	N/A			Emission model	UK fleet	+8 to +43	+10 to +42	-19 to -6	-10 to +27	N/A
Sweden Höglund (1995)	1 road hump per 1.5 km	50	30 at humps	+/- 1.5 at humps	Emission model	PNC	+11	N/A	+22	N/A	+5
						PC	+20	N/A	+18		+4
	10 road humps per 1.5 km					PNC	+200	N/A	+300		+51
						PC	+200	N/A	+300		+37
Denmark Herrstedt (1992)	40 km/h limit, various calming	N/A			N/A	N/A	N/A	N/A	N/A	N/A	-9%
Austria Züger and Blessing (1995)	6 road humps per 1.5 km	30	15 at humps	N/A	On-board measurement	PC	+160	N/A	+900	+25	+25
Australia Van Every and Holmes (1992)	5 road humps per 0.5 km	50	15-25	N/A	Fuel consumption model	N/A	N/A	N/A	N/A	N/A	+36 to +73
	2 roundabouts per 0.5 km		25-40			N/A	N/A	N/A	N/A	N/A	+33

[a] PNC=petrol non-catalyst PC=petrol catalyst N/A = not available F.C.=fuel consumption

2.6 Summary and conclusions of literature review

This literature review has described the main stages in the assessment of how traffic calming schemes affect vehicle emissions. The topics covered include specific traffic calming measures, the changes in driver behaviour imposed by traffic calming schemes, and the factors affecting emissions from road vehicles in the context of traffic calming. A summary has also been presented of case studies in which the effects of traffic calming on emissions have been determined, either by direct measurement or by the use of emission models and databases.

The review has provided information on the most common traffic calming measures in the UK. These were found to be 75 mm high flat-top humps, 75 mm high round-top humps, speed cushions, single lane working chicanes, thermoplastic humps ('thumps') and 2-way working chicanes. Schemes featuring road humps are currently the most common type, although the proportion of schemes containing speed cushions in increasing. This information was used as the basis for the selection of schemes to be investigated in the research.

It was noted in the review that descriptions of driver behaviour include both detailed data on parameters relating to vehicle operation, such as speed and gear selection, and information on trips such as journey purpose, duration, mode, time of day, and time of year. The factors influencing vehicle operation are numerous, and the relative importance of these factors is unclear at present. There are also few quantitative data relating to how emissions might be influenced by traffic calming. Work relating to driver behaviour has usually been concerned with its relationship to accident causation, rather than to vehicle emissions. Consequently, existing studies usually relate to speed selection, and rarely to other parameters known to affect emission rates (*e.g.* acceleration rates, gear selection).

Average vehicle speed at specific locations on a road is one of the most frequently measured parameters in the assessment of traffic calming schemes. However, emission impacts could be determined more accurately if data on continuous vehicle operation were available. Also, changes in traffic flow and composition are required to determine the overall impact of a traffic calming scheme, especially where a diversion of traffic has occurred.

A review of previous case studies led to the conclusion that, to date, there has been only limited agreement on the effects of traffic calming on vehicle emissions. This is particularly evident in the case of NO_x, for which some studies have shown decreases of up to 60%, whilst one study has shown a dramatic increase. It is likely that the variability of the impacts is related to a number of factors, including the method of assessment, the types of vehicle considered, the configuration of the road, and the arrangement of the traffic calming scheme.

Most of the information on emissions that has been presented in these case studies has been obtained through the use of emission models or databases. The results of a few studies in which measurements have actually been taken have often been used to make general predictions about the effects of traffic calming on emissions. However, there is a need for more empirical information, gathered at a more detailed level, and derived using a consistent method at a wider variety of schemes. The research presented in this Thesis has been designed to address this issue.

CHAPTER 3 RESEARCH TOOLS AND METHODS

A general procedure for assessing the environmental impact of all traffic management schemes was described in the introduction. The procedure requires that any changes in driver behaviour and vehicle operation are accurately defined before the appraisal can proceed to the next stage - the assessment of emissions. This Chapter of the Thesis covers the experimental techniques and models which are available for use in the assessment of driver behaviour and vehicle emissions. A summary at the end of the Chapter includes recommendations for the design of the experimental work.

3.1 Recording driver behaviour

It was noted in Chapter 2 that there are two basic types of information which describe driver behaviour. These are 'vehicle operation data' (including data on parameters such as speed, acceleration, and gear selection), and 'activity data' (including information on trips such as journey purpose, duration, mode, time of day, time of year). Methods for recording these aspects of driver behaviour are discussed in the following paragraphs.

3.1.1 Vehicle operation data

3.1.1.1 Vehicle speed and acceleration

The results in Table 2.6 indicate that vehicle emissions can be rather sensitive to the modes of vehicle operation which are associated with traffic calming. In order to accurately determine changes in vehicle emissions on the spatial scale of traffic calming schemes, these operational modes must be identified, and continuous measurement of vehicle speed (from which acceleration can subsequently be derived) is therefore required. Consequently, any technique which is only capable of recording speed at a unique point on a road, such as a radar speed gun, has not been considered here.

Essentially, there are three techniques for measuring and logging vehicle speeds continuously over a section of road. These techniques are described in the following paragraphs.

Instrumented car

Microwave Doppler devices for measuring vehicle road speed are commercially available. The devices employ a sensor which is attached to the side of the vehicle and directed so that it faces the road surface. The sensor emits and receives microwaves and, as it is moved parallel to the surface, the Doppler shift in the reflected signal is measured. From this, the road speed of the vehicle can be calculated. Such systems can measure the speed of the vehicle up to 180 mph (290 km/h), and to an accuracy of ± 0.5% (Datron-Messtechnik, 1994).

There are also a number of ways in which a data acquisition system can be fitted inside a car to record vehicle operation parameters on a continuous basis. TRL has developed a PC-based system which can be fitted inside the passenger compartment of a vehicle to enable its road speed and engine speed to be logged every second. A commercially available shaft encoder has been mounted in line with the vehicle's speedometer cable and connected to a data logger. The encoder generates a number of electrical pulses for each revolution of the speedometer cable. In order to derive calibration factors, the vehicle is usually driven several times over a fixed route of known length. This generally gives a speed resolution of 1.4 km/h. A hand control is also connected to the data logger. This hand control, operated by a navigator, features an on/off toggle switch used to start and stop logging at the beginning and end of each trip, and a press button for marking specific node points during the trip. TRL has previously measured typical speed profiles on roads with traffic calming using this system in traffic (Cloke *et al.*, 1999). However, there were concerns that awareness of the measurements on the part of the driver could mean that this approach does not always give representative results. Therefore, in this research it was likely that speed data would have to be collected using a method of measurement that does not affect the behaviour of drivers. Two potential techniques are identified below.

LIDAR

LIDAR (LIght Detection And Ranging) devices for measuring vehicle speed are also commercially available. These allow the operator to isolate a single vehicle within the traffic, and to measure both its speed and distance continuously. When the trigger on the instrument is pulled, hundreds of pulses of infrared light are emitted every second. The light, collimated into a narrow beam, is reflected from part of the vehicle. As each pulse is emitted, a timer is started and, when a reflected pulse of light is detected by the sensor, the timer is stopped. From the time elapsing between the emission and detection of each pulse, the distance to the target can be calculated. If the target is moving with respect to the instrument, an algorithm is used to derive its speed from a successive number of range calculations. The speed and range values are displayed continuously on the instrument, and recorded on a data logger.

Such instruments can measure a wide range of vehicle speeds to an accuracy of ±1.6 km/h, and the distance to the target vehicle can be measured to an accuracy of ±0.3 m. For a target travelling at 100 km/h the data acquisition time is 0.3 seconds. The LIDAR detector requires a few seconds to 'lock on' to the target vehicle, by which time the vehicle has usually travelled 20-30 metres. As with conventional RADAR equipment, the LIDAR system is subject to a cosine error when monitoring along a direction that deviates from the true direction of travel of the target vehicle. The magnitude of this error is less than 1% at angles below 8°, and less than 3% for angles under 14°.

An important factor in selecting a suitable location is that a clear line of sight to the target vehicle must be available during the entire measurement period. Intervening objects such as signposts and tree branches, as well as other vehicles, cyclists, and pedestrians will interrupt the measurement. The manufacturers claim that rain, smoke, fog and airborne dust particles adversely affect operation, but tests at TRL have shown that the devices operate satisfactorily under a range of conditions.

Synchronised road tubes

A system has been developed by Leeds University for continuously measuring the speed of vehicles in traffic over a distance of around 100m. The system contains four main components: 16 road tubes equipped with transducers, a laptop computer, a data logger, and data transmission cables. The road tubes are installed along the stretch of road at known distances apart. Each time a vehicle wheel passes over one of the tubes a pressure pulse arrives at a transducer which sends an electrical signal down the transmission cables to the data logger. The logger 'time stamps' the event and passes the channel number plus event time to the computer. The resolution of the time data is 1 millisecond. The precise timing of the pulses from each of the 16 tubes is sufficient to calculate the speed and acceleration of a vehicle at various points along the road, once the wheelbase of each passing vehicle has been determined. The first two tubes of the system are placed one metre apart, and the average spot speed is obtained from the difference between the passing times of the first axle over the two tubes, and from the difference between the passing times of the second axle over the two tubes. The wheelbase is then calculated as the mean difference in passing times of the first and second axles multiplied by the spot speed. In order to ensure that the data are correctly interpreted, there must be a synchronous complementary record (*e.g.* video) of unexpected events such as parked vehicles, overtaking, conflicts, and incomplete journeys (Barbosa, 1995). There appears to be no software available to interpret the output for a complex traffic situation.

3.1.1.2 Gear selection

Gear selection is an important determinant of fuel consumption and emissions. The most straightforward method of logging gear use on a section of road is by manual observation. However, such a method is cumbersome if gear changes are frequent, and the accuracy with which the time of each gear change is determined may be poor.

Alternatively, instrumentation installed in vehicles to measure speed continuously may also be adapted for the determination of gear selection patterns. For example, the on-board equipment used by TRL can also be used to measure and record engine speed. The combination of road speed and engine speed data for the same points in time enables the user to identify the gear.

3.1.2 Activity data

In the context of this research, the term 'activity data' relates to the volume and composition of the traffic on the roads affected by traffic calming. For the specific purpose of determining the emissions associated with a particular scenario, it is also important to disaggregate this information in terms of the characteristics of vehicles that affect emissions, such as engine type and emission control technology.

3.1.2.1 Traffic flow

Traffic flows may be determined manually or automatically. The manual method is used either where the flow is low, the count is of short duration, or if the data needed are difficult to gather automatically (*e.g.* turning counts). There are a number of automatic counting devices which provide information with varying degrees of accuracy and reliability (OECD, 1979). These include:

(i) Pressure detection (pneumatic tubes)
(ii) Magnetic detection
(iii) Inductive loop detection
(iv) Sonic detection
(v) Optical detection

For the type of traffic counts required in the research (*i.e.* short-term automatic counts), pneumatic tubes are generally favoured.

3.1.2.1 Traffic composition

For the assessment of emissions, as much information as possible is required on the composition of the traffic. This includes vehicle type (passenger cars, LGVs, HGVs, buses, *etc.*), engine size, fuel type, and emission control level (catalyst, non-catalyst, *etc.*). Because all this information cannot be recorded manually, or by the use of conventional automatic counters, the most effective method of determining the composition of the traffic is the use of video recording. If the registration plates of vehicles can be recorded, then extensive information on the vehicles may be provided by DVLC or DETR. Magnetic systems are also available for identifying vehicle types according to the 'signature' waveform they present at a detector whilst passing. However, such system may not be able to identify vehicles according to the criteria required in the assessment of emissions.

3.2 Measurement of vehicle emissions

3.2.1 Background

The engines used in light- and heavy-duty vehicles are designed to comply with legal limits for exhaust emissions. A manufacturer must demonstrate during the type approval test that an example of a particular model satisfies the necessary requirements before the model can be marketed. Production vehicles are also required to undergo 'conformity of production' tests to ensure that the standards that are achieved during type approval are maintained during mass production. Once a vehicle is purchased and is in service, emissions are only checked during the annual MoT, and then only for vehicles older than three years.

Type approval, conformity of production, and experimental tests are performed under standardised laboratory conditions to maximise repeatability. A number of experimental on-board systems also exist for measuring emissions during normal driving. An additional experimental technique, the remote measurement of vehicle emissions, has been developed comparatively recently. These various methods of measurement are described in the following Sections.

3.2.2 Laboratory testing

3.2.2.1 Exhaust emissions

Type approval and conformity of production tests are required by law for all new vehicles. It was noted in Section 2.4.2 that a single vehicle of a particular type will display wide variations in emissions depending on its operation, and so the best way to ensure that an emission test is reproducible is to perform it under standardised laboratory conditions.

Pollutant sampling and analysis

The procedures for the collection and analysis of the pollutants specified in the type approval and conformity of production tests have largely been standardised. For gases (*i.e.* HC, NO_x, and CO) there are two main methods by which sampling and analysis may be conducted.

Throughout the test a constant proportion of the diluted exhaust gas can be collected, via a constant volume sampler (CVS), in a bag made from an inert material. The gases are analysed later (infra red absorption for CO, flame ionisation for HC, and chemiluminescence for NO_x) to provide average values for the whole of the test cycle. Alternatively, the sample may be introduced directly to analysers that give a continuous reading of pollutant concentrations in the exhaust. For particulate matter, a probe continuously extracts a sample of the diluted exhaust gas, and the sample is drawn through a pre-weighed filter. The change in mass of the filter allows the total amount of particulate matter, and hence the rate of emission, to be calculated.

Bag sampling has the advantage of relative simplicity, but it provides average values that cannot be directly related to detailed vehicle operation. Bag sampling is also unsuitable for the analysis of hydrocarbons in diesel exhaust, as non-volatile compounds tend to condense on the surface.

Continuous sampling and analysis requires that the analysers be physically attached to the exhaust. The data from continuous sampling must be interpreted carefully if they are to be evaluated in relation to the vehicle's operating conditions on a short time scale. The sampling system and each of the gas analysers used will have a characteristic response time that may be of the order of a few seconds to a minute. Thus, a result measured at a particular moment may well be a damped and delayed response to an event some time earlier (Abbott *et al.*, 1995).

Some pollutants, including PM_{10}, 1,3-butadiene, and benzene are not regulated by law, and there are no standardised measurement procedures. The determination of benzene emissions could be achieved relatively easily using gas chromatography or IR absorption spectroscopy. Emissions of 1,3-butadiene may also be determined by gas chromatography, but this could be problematic on account of its low concentration in vehicle exhaust. Some form of pre-concentration (such as cryogenic trapping) would be required to ensure values above instrument detection limits.

The characterisation of vehicle particulate emissions, including size distribution, has been investigated in detail in recent years (*e.g.* Kittleson and Abdul-Khalek, 1998; Shi *et al.*, 1999). Moon and Donald (1997) considered a number of techniques that could be used to determine the size distribution of particles in vehicle exhaust in terms of mass and number. The Scanning Mobility Particle Sizer (SMPS) and the Electrical Low Pressure Impactor (ELPI) techniques were considered to be the most useful. The former measures number-size distributions, and the latter can be used in both mass and number modes. Both techniques give real-time data for number-size distributions. The Anderson Impactor may also be a useful instrument providing mass distributions for sizes greater than 0.4μm, although not in real time. The use of the Tapered Element Oscillating Microbalance (TEOM), as used in the DETR air quality monitoring network), was not recommended for use in monitoring particulates in vehicle exhausts. Further evaluation of both the ELPI and SMPS were recommended.

Moon and Donald (1997) also found that the use of the CVS system may lead to a loss in particles, particularly those above 2-3μm in diameter. Consequently, the emission measurements made for regulatory purposes are likely to be dominated by particles with a diameter of less than 5μm. This may mean that any emission factors derived from these measurements would underestimate the true impact of vehicles on airborne particulate concentrations. Amongst their recommendations for future research, it was suggested that further work could focus on the sampling efficiency of the CVS for vehicle exhaust particles.

Driving cycles

Laboratory tests involve the operation of the vehicle or engine on power-absorbing apparatus such as a chassis dynamometer for light-duty petrol and diesel vehicles, or an engine test-bed for heavy-duty diesel engines.

With a chassis dynamometer, the drive wheels are positioned so that they are in contact with rollers. The rollers can be adjusted to simulate friction losses and aerodynamic resistance. The sampling of emissions is performed as the vehicle progresses through a pre-defined driving cycle constructed to represent the speeds, accelerations, and gear changes associated with normal driving patterns. Figure 3.1 shows the driving cycle used in the European test for light-duty vehicles.

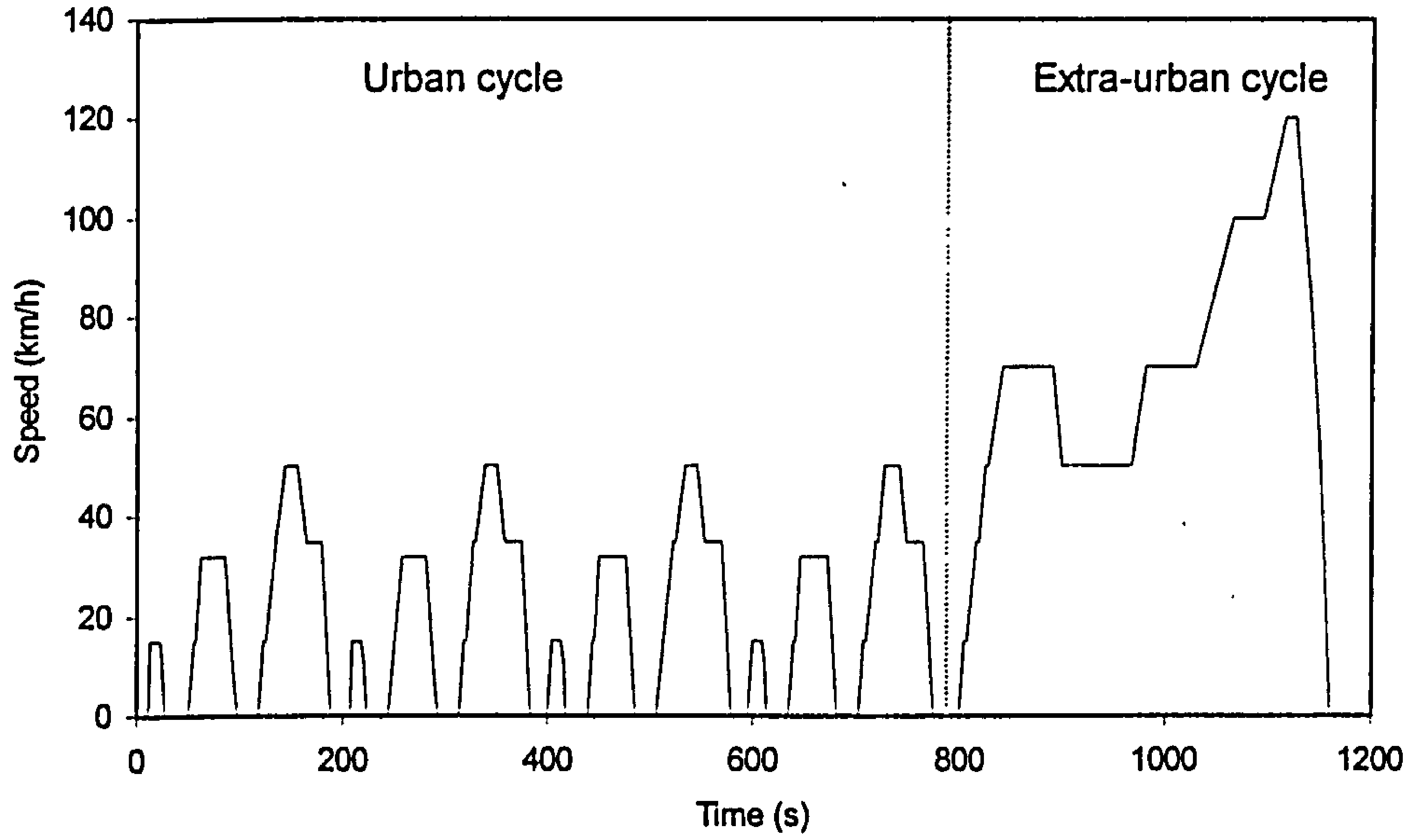

Figure 3.1 The ECE driving cycle for light-duty vehicles.

Type-approval emission tests for heavy-duty vehicle engines are usually performed on engine test beds using the ECE 13-mode cycle (ECE Reg.49). Emissions from the engine under test are sampled at three engine speeds (idle, intermediate, and rated), and under six load conditions. Emissions are then calculated using an equation which applies different weighting factors to the emissions from each of the test modes. The EC emissions legislation for heavy-duty vehicles applies to lorries, buses, and coaches of weight greater than 3.5 tonnes.

3.2.2.2 Evaporative emissions

The standard European test procedure for the measurement of evaporative emissions (EC Directive 91/441/EEC) is carried out by placing the test vehicle in a gas-tight measuring chamber equipped with sensors to monitor the temperature and HC concentration. 'Cold soak' emissions are determined from the quantity of HC emitted during the period when the temperature of the fuel tank is increased gradually from 14°C to 30°C. 'Hot soak' emissions are determined from the quantity of HC emitted during a period of one hour when the vehicle is allowed to cool down after having undergone the EC cold start urban and the extra-urban drive cycles.

As with exhaust emissions, there is no standard procedure for measuring evaporative emission rates of benzene and 1,3-butadiene. Gas chromatography could be used for both, but again this would require some pre-concentration, particularly for 1,3-butadiene.

3.2.2.3 Problems associated with laboratory testing

It should be noted that vehicle exhaust emission rates are inherently very variable, and repeat tests on a single vehicle can give results that differ by tens of percent; tests on different vehicles of the same type may vary by a factor of ten (Abbott *et al.*, 1995). This variability will be encountered whatever measurement technique is employed, although laboratory conditions provide the best way to control repeatability. However, recent evidence suggests that even average emission measurements for pollutants can vary considerably between laboratories (Samaras *et al.*, 1997a).

There is also concern that tests carried out in the laboratory do not accurately reflect the emission rates encountered on the road. Emission rates are dependent on the operation of the vehicle, and this may not be adequately represented by standardised cycles. For example, Bang *et al.* (1993) suggested that emission rates for heavy-duty vehicles measured during the ECE 13-mode test are a good approximation of those from heavy-duty vehicles engaged in suburban and rural driving. However, the test is not at all representative of the driving cycles, and hence the emissions, from buses on scheduled routes in towns. Other difficulties are encountered when using the engine test data to represent emissions from in-service vehicles. Engine tests cannot account for factors such as chassis/body weight and aerodynamic performance.

Emission levels from a public service vehicle could also vary substantially according to its level of occupancy. Therefore, the emission rates measured in Type Approval tests cannot be easily converted to real-world emission rates. Also, it is likely that well-maintained vehicles will be over-represented in the tests carried out in the laboratory.

There is considerable interest in the development of driving cycles for both light- and heavy-duty vehicles that reflect operation in urban areas more adequately than the type approval test. Examples of alternative cycles include those developed by BP (Reynolds *et al.*, 1992) and TNO (Van de Weijer *et al.*, 1993). Both were developed from measurements of bus operating patterns, but are quite different in nature (Figure 3.2). However, comparisons between bus operation in Southampton and both the BP and TNO cycles have shown that the cycles do not simulate well the speeds and accelerations attained in normal service (TRL *et al.*, 1997). Two further cycles were developed by TRL for bus operations in Southampton, one each for the diesel and CNG fuelled buses, to take into account the different engine capabilities.

Because of these difficulties and uncertainties, alternatives to laboratory-based emission tests have been the focus of interest for a number of years. The following two Sections examine two on-road measurement techniques that have been developed. These are on-board sampling and remote sensing at roadside locations.

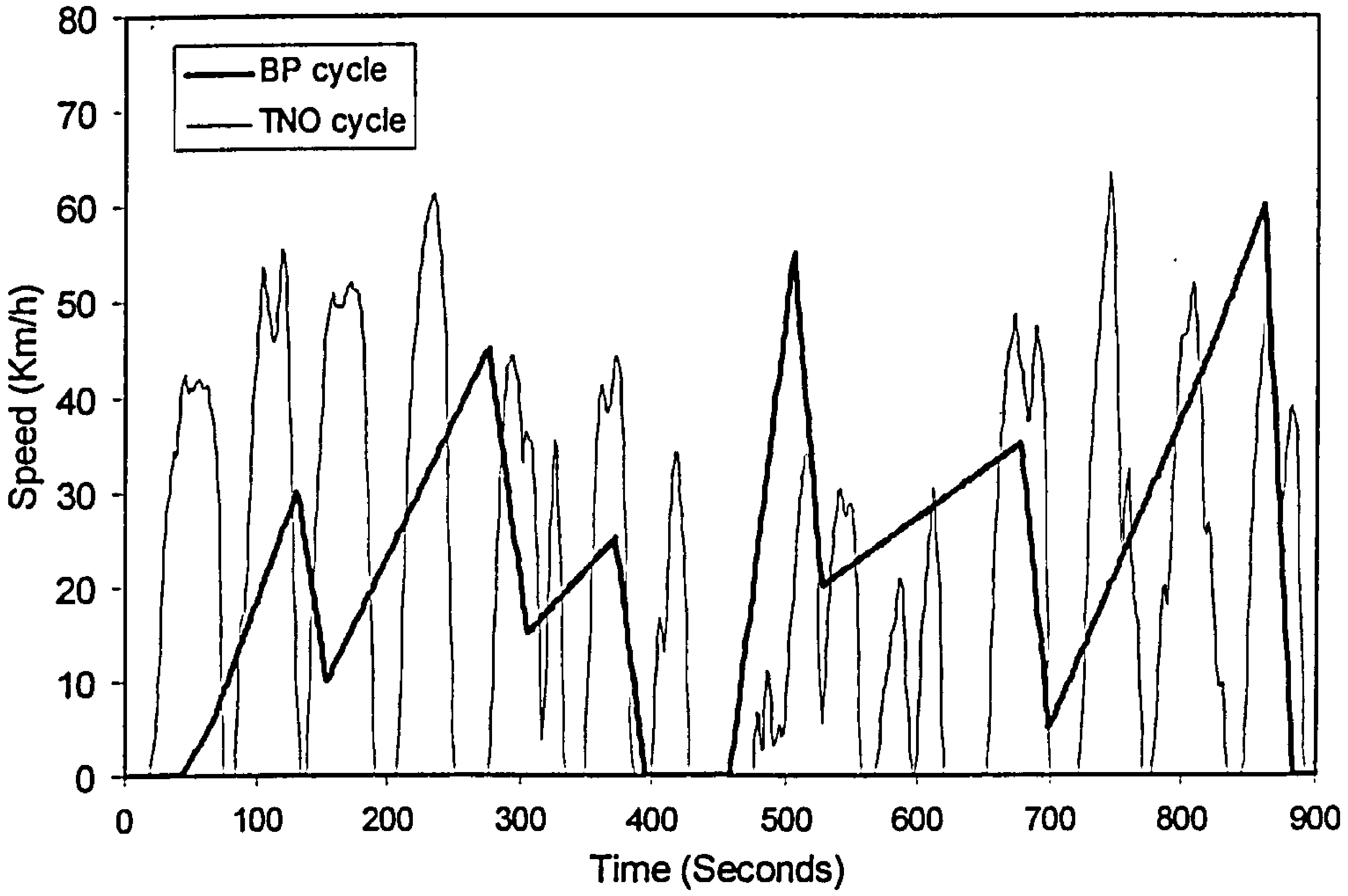

Figure 3.2 BP and TNO bus cycles.

3.2.3 On-board emissions measurement

When vehicle emissions are measured under standardised conditions during laboratory tests, the measurements do not cover the variety of operational modes encountered in real-world driving. Realistic vehicle operation is most easily achieved during an on-road test, where it is usually only necessary to drive the vehicle in a normal way in the traffic. However, because there is considerable variation in traffic conditions, both diurnally and from location to location, it is not possible to provide highly repeatable test conditions.

A number of on-board techniques exist for making emission measurements during normal driving, and systems are available from institutions in several different countries. One such example is the system developed and evaluated by the Warren Spring Laboratory (Potter *et al.*, 1986; Potter and Savage, 1982). With this system, a proportional sampler (Plate 3.1) attached to the exhaust pipe of a vehicle enables emissions to be measured while the vehicle is being driven on the road.

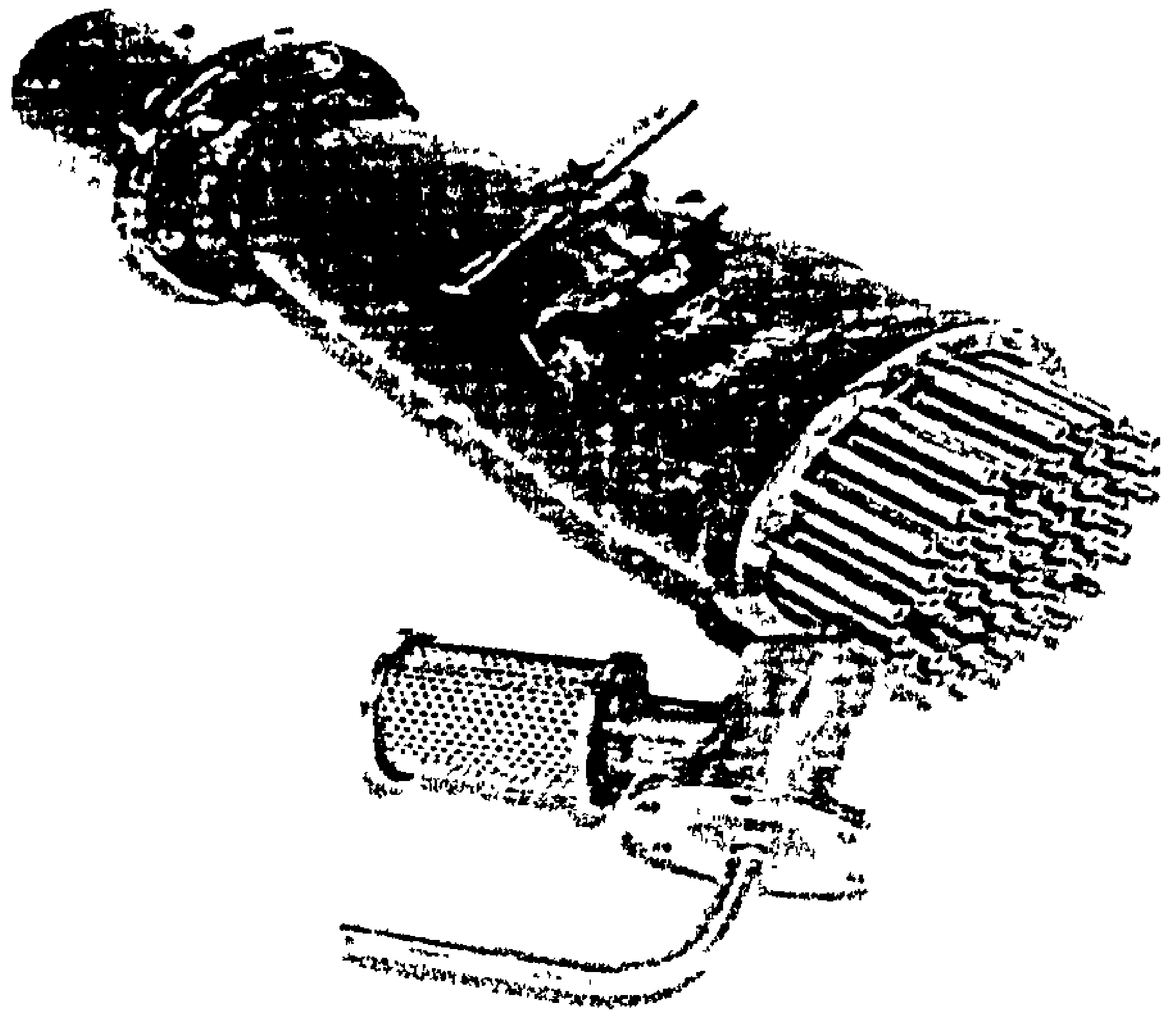

Plate 3.1 Warren Spring Laboratory exhaust sampler.

The sampler is essentially a scaled-down version of the CVS used in laboratory tests. It is therefore known as a 'mini-CVS'. The mini-CVS sampling system relies on an exhaust splitter, which is a passive device used to divide the total exhaust gas flow through a number of identical tubes each having the same nominal flow resistance. The exhaust gas sample is drawn from one of the tubes and then diluted with air. A sub-sample of the diluted flow is pumped to a bag made from inert material, where it is stored for analysis in the laboratory. Exhaust particles may also be sampled using a filter. Because it is much smaller than the sampling system used in laboratory tests, the device can be used to sample emissions over the range of operating conditions encountered in urban, rural, and motorway driving.

Several years ago, TRL developed an on-board electronic sampling system which automatically controls a sample of exhaust gas in proportion to the exhaust flow. This was achieved using two flow meters, one measuring the engine air intake flow rate and another measuring a sample of exhaust taken from the exhaust tailpipe. A servo-assisted valve was used to control the sample flow in proportion to the air intake flow; further calculations were required to adjust for the small discrepancy between the engine intake air flow rate and the exhaust flow rate. The device was primarily used for particulate sampling; gaseous emissions were sampled and measured separately by using conventional gas analysers mounted in the vehicle.

The Flemish Institute for Technical Research (VITO) has also developed a system for obtaining on-road emission measurements, and Lenaers and de Vlieger (1996) have reported measurements on a small petrol car and two diesel buses. The sampling technique differs from the mini-CVS system in that the sample is drawn off from the main exhaust gas flow using a pump. The test vehicle is fitted with gas analysers so that emissions can be measured continuously. The effective surplus weight of the system is approximately equivalent to that of two people. The on-line collection of exhaust gas, the 'real-time' processing of measurements, and an automatic calculation of emissions on a g/km basis, are all featured.

For the laboratory measurement of CO_2, CO, HC, and NO_x from light-duty petrol vehicles over the European and US standard drive cycles, Warren Spring Laboratory and VITO have claimed that their on-board systems are accurate to within around 10% of full-size CVS/chassis dynamometer results. However, their accuracy on the road is likely to be poorer due to dynamic or aerodynamic effects (Whiteman, 1995). Systems to analyse benzene, 1,3-butadiene and PM_{10} have not specifically been developed for on-board measurements. However, in theory, the procedures suggested earlier may be adapted for this purpose.

3.2.4 Remote sensing

Remote sensing is an on-road emissions measurement technique which is non-intrusive and requires no participation from vehicle owners or operators. Vehicles can be monitored at a rate of more than 1000 per hour, and the technique can therefore be employed at a fraction of the cost that would be incurred using conventional, time-consuming measurement methods.

The first successful devices for remotely sensing the CO content of vehicle exhaust plumes were introduced at the University of Denver in 1987 (Bishop *et al.*, 1989), and at the General Motors Research and Development Centre in 1988 (Stephens and Cadle, 1991). By 1990 the sensors could also determine hydrocarbons concentrations. The Denver method was developed under a grant from the Colorado Office of Energy Conservation primarily as an energy conservation measure - identifying vehicles that were wasting fuel using CO emissions as an indicator. This explains the acronym by which the system is widely known: FEAT (Fuel Efficiency Automobile Test). Both the Denver and General Motors remote sensing devices operate on the same general principles of infra red spectrometry. Because the FEAT system was used in the traffic calming research programme, it is described in detail in the following Sections.

3.2.4.1 Equipment and principles of operation

The FEAT system consists of four main components: an infra red source, a detector, a computer, and a video system. Under the standard operating procedures the IR source is positioned on one side of a stream of traffic and the detector on the opposite side, so that the distance between the source and detector units is typically 6 to 15 metres. The general arrangement of the system when in use at the roadside is illustrated in Figure 3.3. The collimated IR beam, generated continuously by the source unit, is directed horizontally towards the detector. The beam is positioned around 25 cm above the road surface, a height which corresponds to the average position of light-duty vehicle exhaust pipes.

The FEAT system is based upon a conventional non-dispersive infra red (NDIR) gas analyser. The system relies on the principle that most species will absorb light at a particular wavelength. CO, CO_2 and HC will all absorb in the IR spectrum at wavelengths between 2.5 and 25 μm. Optical filters allow the specific measurement of CO at 4.6 μm, CO_2 at 4.3 μm, HC at 3.4 μm, and a background reference channel in a non-absorbing region at 3.9 μm.

The system operates by continuously measuring the intensity of the IR beam. Voltages from each of the signal channels (CO_2, CO, HC, and reference) are recorded before a car enters the beam. When a vehicle passes through the beam path the voltages recorded at the detector drop to zero. Correction voltages for each channel are acquired while the vehicle is completely blocking the beam, thus enabling the determination of background levels. This beam block triggers both the video system to record an image of the passing vehicle and the measurement procedure. When the vehicle passes the beam is reformed, and the change in intensity of the light due to the presence of the exhaust gas plume is recorded. Fifty independent measurements of CO, CO_2, and HC are recorded over a period of half a second. Data collection times longer than this provide little benefit, since dispersion of the exhaust plume is very rapid.

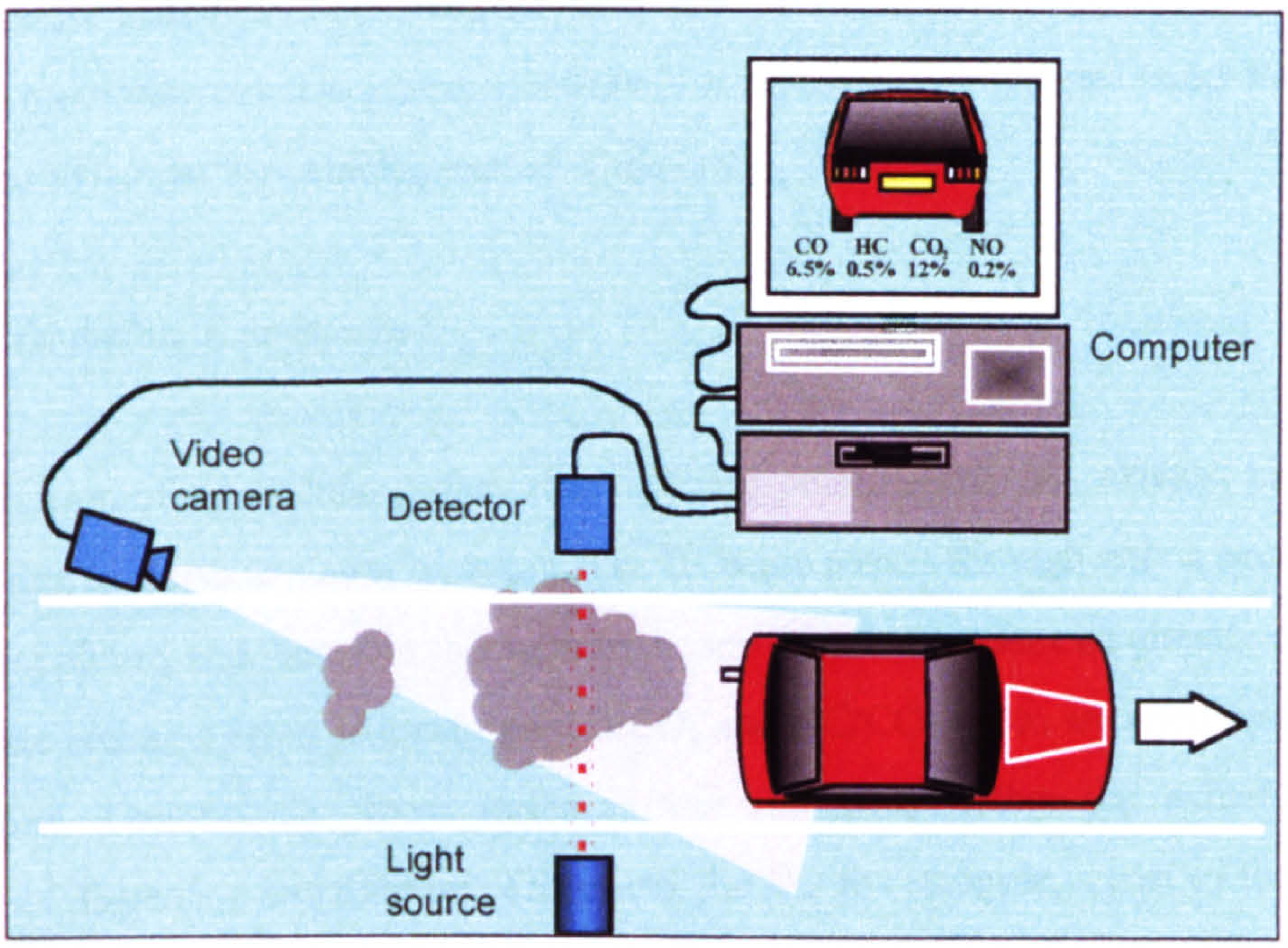

Figure 3.3 Remote sensing: arrangement at roadside.

There is some interference from water vapour in the measurement of hydrocarbons. Water vapour in the atmosphere can be ignored because it is accounted for in the background reading and does not fluctuate rapidly. Guenther *et al.* (1991) have also argued that water vapour in the exhaust causes little interference. However, water in the particulate phase in the exhaust gas is more problematic, particularly at low ambient temperatures where thick 'steam' plumes are observed (Bishop and Stedman, 1996).

The University of Denver has also added nitric oxide (NO) remote sensing to their instrument by attaching a co-linear UV source and detection system. Because 95% or more of the NO_x emitted by vehicles is NO, this is effectively a NO_x instrument (Zhang *et al.*, 1996).

The speed and acceleration of a vehicle at the time of a remote sensing measurement are obtained using two infra red detectors placed alongside the beam used to detect exhaust gas pollutants. An image of the rear of each target vehicle, including the registration plate, is stored on video tape along with the vehicle's emission measurements and the time and date at which it interrupted the beam. In addition, the emission data and associated beam block time details are recorded numerically onto computer media. Subsequently, information on the vehicle from the registration plate allows for correlation between emissions and make, model, and age. To date, the license plate numbers have been read manually from the video records. According to Cadle and Stephens (1994), this labourious process will be eliminated when a reliable automated licence plate reader becomes available. Also, research to develop practical methods for remotely measuring exhaust gas temperature is continuing. Exhaust gas temperature data could be used to screen for vehicles started while cold.

3.2.4.2 Calculation of emissions

The concentration of a particular pollutant at different points within any exhaust plume may vary widely due to dispersion after emission. The IR beam passes through only a small portion of the exhaust plume, and therefore the measured concentrations cannot be directly converted into aggregate emission rates. Instead, the CO/CO_2 and HC/CO_2 ratios are used to determine concentrations. Theoretically, these ratios remain the same within the exhaust plume, irrespective of dispersion and dilution. Therefore, for CO for example, a plot of the CO and CO_2 readings at the points measured within the plume gives a straight line through the origin. The slope of the linear regression fit to the data gives the CO/CO_2 ratio. A high ratio corresponds to a vehicle with high emissions, a low ratio to a cleaner vehicle.

Vehicle emission data are not normally reported in terms of the CO/CO_2 and HC/CO_2 ratios. It is more common to see percentage by volume concentrations (*e.g.* %CO), or mass emissions (per unit time or distance). The ratios can be readily converted to volumetric concentrations using equations describing combustion chemistry. The derivation of mass emission rates is more complicated, and the results are less certain (this will be discussed in more detail later in the Thesis). The mass of a pollutant emitted per unit of fuel burnt (*e.g.* grammes of CO per litre of fuel burnt) can be obtained by estimating the empirical formula and density of the fuel. However, information on fuel consumption is required in order to estimate the mass emitted per unit time or distance. The fuel consumption rate must be estimated from existing statistics.

Propane gas is used to calibrate the hydrocarbon channel, and therefore quoted %HC values are propane equivalents. Estimates of emissions per unit distance travelled can only be obtained for each vehicle using fuel economy figures, such as those reported by manufacturers. For example, Cadle and Stephens (1994) have reported conversion factors for 1% CO and 0.1% HC at 20 mpg of 17.4 g/mile and 2.73 g/mile, respectively. However, there is no way of knowing the fuel economy of the vehicle at the time of the remote sensing measurement and g/mile emission rates for individual vehicles are therefore highly uncertain.

The FEAT software operates a number of data rejection criteria. The two main criteria are insufficient change in the signal and excessive scatter in the data. In the first instance, the change in the signal received at the FEAT unit may be insufficient where the beam is blocked without the presence of exhaust gas (*e.g.* with pedestrians). In the second instance, as a large number of data points are recorded the software can interrogate the data scatter and reject entire vehicle data sets if the data scatter is excessive. Rejected beam blocks are recorded by the FEAT system as invalid data.

The accuracy and lower limit of detection of individual remote measurements depend on how the exhaust plume disperses and what part of the plume is intersected by the beam. Thus, it is difficult to give an absolute accuracy for remote sensing devices. Overall accuracies have been reported by the University of Denver as 5% and 15% for CO and HC respectively, and by General Motors as 15% for the CO/CO_2 and HC/CO_2 ratios.

3.2.4.3 The variability of emissions

The remote sensing technique provides only a 'snapshot' of the emissions from each vehicle at a single location, and during the measurement period a particular vehicle may be in any one of a number of operational modes. The operational dependency of emissions can be observed in remote sensing studies in which repeat tests have been made on the same vehicles. For example, Sadler *et al.* (1996) found only a slight correlation between repeat measurements of CO from the same vehicle; the Spearman's rank correlation coefficient varied between 0.50 and 0.71.

When a vehicle is operated over a complex driving pattern, its exhaust emission rates vary considerably. Part of the observed variability of remote sensing data will be a consequence of this operational dependency of emission rates. Depending on the instant at which a reading is taken, almost any vehicle can produce results indicating 'high' or 'low' emissions. Engine temperature can be a particularly important parameter in urban driving, and a vehicle in cold start mode would be identified as a high-emission vehicle. Vehicles under high load conditions, such as wide-open throttle accelerations, are designed to operate at rich air:fuel ratios, and CO emissions during this enrichment are very high. Alternatively, very rapid throttle closure can result in a flash of gasoline into the engine, and the resulting low air:fuel ratio and possible misfire may cause high emissions. Therefore, any single measurement made by remote sensing will give only an indication of a vehicle's emission behaviour at a particular point in time.

The ability of remote sensing to monitor a large number of vehicles allows the generation of emission distribution profiles. For CO, the distribution of instantaneous emission rates for both catalyst and non-catalyst petrol cars from remote sensing depart significantly from the normal distribution. Most vehicles tend to show mean emissions of 1% CO or less in the exhaust, although a few vehicles (termed 'gross polluters') are particularly polluting. Stedman *et al.* (1994) obtained emission distributions in 24 world cities. It was found that in Toronto half the emissions came from only 8% of the vehicles, whilst in Kathmandu half the emissions came from 25% of the vehicles. For CO in particular, the distribution can be described statistically as leptokurtic (more peaked than a normal distribution) with a high positive skew, and Zhang *et al.* (1994) have shown that it is well represented by a gamma distribution. Because of ongoing improvements in emission control technology, it appears that the newer the fleet, the more skewed the distribution (Peterson and Stedman, 1992). This is because many more of the fleet have near-zero emissions and thus a smaller number of gross polluters strongly dominate the fleet emissions (Zhang *et al.*, 1994).

For HC, the fleet emissions tend to be less skewed than for CO, with more vehicles contributing to the overall fleet emissions. Nevertheless, there still tends to be only a few gross polluters and many low emitters. For example, only four of the cities studied by Stedman *et al.* (1994) - Bangkok, Hong Kong, Kathmandu and Taipei - had half of the HC emissions produced by more than 15% of the fleet. Most of the same conclusions that are drawn regarding CO emissions and fleet characteristics hold true for HC emissions. This is because HC emissions increase as engine combustion gets richer and produces more CO (Stedman *et al.*, 1994).

3.2.5 In-service inspections

In the UK, emission checks have been included in the annual MoT test for light-duty vehicles since November 1991. The UK regulations cover light-duty vehicles over three years old and heavy-duty vehicles. For light-duty petrol vehicles emissions of carbon monoxide and hydrocarbons are measured at idle (and fast idle for catalyst-equipped petrol vehicles) against specified limits. For light-duty and heavy-duty diesels, the check is on visible smoke emissions during a free acceleration[1] operation.

As discussed earlier, conventional laboratory emission measurements involve the use of specialist and expensive equipment that is not appropriate for use in the average garage environment. In-service checks are therefore based on simplified operations of the vehicle, and make use of measuring equipment that is less precise and less expensive than that used in the laboratory. As a consequence, there is concern that the test does not reflect a vehicle's emissions when it is used on the road (Hickman and McCrae, 1995). The tests take place only once a year, and therefore it can be argued that they ensure only that the vehicle is operating satisfactorily at the time of the test. There is evidence that engine settings can drift over a much shorter time scale. Some vehicle operators may intentionally alter settings after a test because of a belief that the vehicle performs better if tuned differently. On average, in the year to March 1994, less that 8% of light-duty vehicles presented for annual inspection failed the emission test. Random roadside surveys, on the other hand, produced a failure rate of more than 35% (Hickman and McCrae, 1995). On behalf of DETR, TRL is examining the effectiveness of the current MoT emission tests, and specifically the failure trends in emission control equipment. The database will be based on the MoT emission tests conducted at around 200 garages throughout the UK, and other sources including roadside spot-checks.

3.3 Emissions modelling

3.3.1 General principles

The general principle underlying the estimation of pollutant emissions from road traffic is the summation of the product of an emission factor and the amount of traffic, for each type of vehicle and each type of vehicle operation, as expressed by the following equation (Hickman

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[1] A 'free acceleration' operation is one in which the engine speed of a stationary vehicle is increased continuously from idle.

et al., 1997):

$$E_i = \sum_{j=1}^{n} \sum_{k=1}^{n} e_{i,j,k} \times T_{j,k}$$

where:
E is the amount of pollutant i emitted
e is an emission factor
T is the amount of traffic
j identifies different types of vehicle
k identifies different types of vehicle operation.

This expression shows the broad categories of data that are required in emission modelling, but it hides the large number of variables within each category. For example, there are hundreds of types of vehicles in service, and each will have different characteristics in terms of emissions. The categories are therefore usually sub-divided, according to the characteristics of vehicles and vehicle operation that exert an influence on emission rates, as discussed in Section 2.4.

Methods of predicting the emissions of pollutants from road traffic have been the subject of extensive research and development. Traditionally, modelling has concentrated on hot exhaust emissions. More recently, procedures to estimate cold start and evaporative emissions have been developed. The following Sections describe the different approaches adopted in modelling hot, cold start, and evaporative emissions.

3.3.2 Modelling hot emissions

A recent survey conducted as part of the DRIVE II 'KITE' project identified around 30 models used throughout Europe to estimate hot emissions on a variety of spatial and temporal scales (Negrenti, 1995). These emission models can be divided into three basic groups of increasing complexity:

(i) emission factor models
(ii) average speed models
(iii) modal models.

3.3.2.1 Emission factor models

Emission factor models operate on the simplest level, with a single emission factor used to represent a particular type of vehicle and a very general type of driving (*e.g.* urban, rural, or motorway). The emission factors are calculated as mean values of repeat measurements over given driving cycles, and are usually stated in terms of the mass of pollutant emitted per unit distance (*e.g.* g/vehicle-km). These factors are useful in applications covering a large spatial scale, such as national and regional emissions inventories, where there is little detail on flows and operation. However, this approach probably has disadvantages in terms of predicting emissions on the microscale, such as with a traffic management scheme, not least because the emission factors are based on driving conditions which are not representative of traffic management.

3.3.2.2 Average speed models

Average speed emission models are, at present, the most common type in use. Emission rates are measured for a variety of trips, each with a different average speed, and this yields speed-dependent emission functions such as those shown in Figure 3.1. Examples of this type of model are COPERT (Eggleston *et al.*, 1993), DMRB (Highways Agency *et al.*, 1996), and MEET (European Commission, 1999). This approach is considered to be best suited to the compilation of emission inventories for road networks. Only limited variations in vehicle operation (*e.g.* changes in speed, cold starts) are accommodated in this type of model, and so their use in microscale applications is not really appropriate.

3.3.2.3 Modal emission models based on speed and acceleration

Modal emission models have been designed to provide an estimation technique which is applicable to a small spatial scale, and in this way complement the more simple models. Modal modelling improves on the average speed approach by relating the modes of vehicle operation encountered on a given trip, in terms of the phases of steady speed, acceleration, deceleration, and idling, to the emissions produced during those modes. The most complex modal models employ a matrix of combinations of instantaneous (*i.e.* second-by-second) speed/acceleration and emission rates. Such models can therefore be used to calculate the second-by-second emissions and fuel consumption for a particular vehicle type from a given driving cycle. Speed-acceleration modal emission models represent the state-of-the-art in emission modelling, but cannot yet take into account other important variables such as road gradient.

3.3.2.4 Modal emissions modelling based on engine power

The engine load, as described in Section 3.1, has a significant impact on emission rates. Emissions modelling based on engine power and speed may prove to be more effective than using relationships based on speed and acceleration, because effects such as gradient can be taken into account directly (Barth *et al.*, 1996). Such models are based on the engine power demand, and the emissions process is broken down into the physical parameters relating to vehicle operation. This type of model is undergoing development in the US and Australia (Barth *et al.*, 1996; Taylor, 1992), but its establishment as a research tool could be expensive because of the amount of data required.

3.3.3 Modelling cold start emissions

Cold start emission factors are usually incorporated into emission models that operate on a large spatial scale, where vehicle emissions are related to trip lengths and average speeds. In many models and inventories, the general approach towards introducing cold start emissions has been to apply a penalty (*e.g.* Eggleston *et al.*, 1993) to hot emission levels over the assumed cold start period, and to the number of vehicles assumed to be travelling in the cold start mode.

Modal emissions models have so far been developed only for vehicles with 'hot' engines. In order to calculate cold start emissions, the same penalty factors must be employed. This means that if modal models are to be used in urban scenarios, then the potential increase in accuracy that they afford can be somewhat negated by the need for these relatively crude conversion factors for cold start emissions. In addition, these conversion factors are usually derived from secondary testing on vehicles that have not been used to develop the modal models.

3.3.4 Modelling evaporative emissions

Models that estimate evaporative emissions generally split the processes into diurnal losses, hot (and warm) soak and hot (and warm) running losses as described in Section 3.1. The emission rates are then calculated according to equations involving fuel volatility, ambient temperature, temperature variation, and the presence of emission control systems. The more sophisticated procedures distinguish between hot and warm soak/running losses (dependent on trip length) and different parking duration.

3.3.5 Considerations when modelling traffic calming schemes

A primary consideration in the selection of an emission model to apply to a traffic management scheme is the spatial scale on which the scheme operates. It is rare to find a scheme that has clearly-defined spatial boundaries, and even those schemes that appear to operate on a relatively small section of the network can affect the volume or operation of traffic on adjacent roads. However, there are obvious differences between the spatial scale of, say, a park and ride scheme and that of a junction improvement.

It is generally rather easier to estimate emissions on a large spatial scale than on a small scale. Local variations in the composition and operation of traffic may be important factors in the immediate vicinity, but as the scale becomes larger there will be a tendency to approximate more closely to regional or national trends. Many types of traffic management schemes are intended to improve the circulation of traffic in a particular locality, and their effects on pollution are confined to that area. Schemes can influence the volume, composition and behaviour of the traffic, so their consequences for air pollution depend on departures of such parameters from normal, average conditions. It is usually insufficient, therefore, to base an assessment on generalised data (Abbott *et al.*, 1995). This rules out emission factor models for most traffic management applications.

However, the more complex approaches necessitate detailed and extensive input data which can limit their application. Even on the smallest of road sections, complete driving cycles for every vehicle can never be obtained, and therefore representative cycles must be determined. As Zachariadis and Samaras (1996) indicated, calculations of vehicle emissions along individual streets are associated with a high degree of uncertainty, and the representativeness of all input data is crucial.

Certain types of traffic management schemes, such as those that control parking, could influence the overall magnitude and spatial distribution of cold start and evaporative emissions in a particular area. It is therefore important that these aspects are modelled as accurately as possible. A further consideration in the selection of an appropriate model is its compatibility with the National Air Quality Strategy. As discussed in Section 4.1, few measurements of benzene, 1,3-butadiene and PM_{10} have been made largely because, in terms of exhaust emissions, they are not regulated pollutants.

3.3.6 Available models

Here, details of the main modal and average-speed emission models suitable for determining the impact of traffic management schemes are described. Emission factor models are not included, as they are only designed for use on spatial scales that are generally much larger than those covered by traffic management schemes. Whilst it is acknowledged that other emission models are available outside Europe, they are not suitable for use in the UK, largely because of the differences in emissions control legislation and, consequently, emission rates.

3.3.6.1 DMRB (Design Manual for Roads and Bridges)

Volume 11 of the Design Manual for Roads and Bridges (Highways Agency *et al.*, 1996) provides guidance on the environmental assessment of trunk road schemes. In Section 3 of the Manual, a step-by-step procedure is presented for the calculation of emissions from road transport. The average-speed emission factors are applicable to hot engines, and were derived from measurements made by TRL the members of the CORINAIR working group (Eggleston *et al.*, 1993).

3.3.6.2 COPERT (Computer Program to calculate Emissions from Road Traffic)

COPERT is the computer program developed by the CORINAR working group on behalf of the European Commission, and is mainly applied to medium- and large-scale emission estimates using average-speed emission factors for hot engines. The model also includes simple expressions for cold start and evaporative emissions, and takes into account national variations in parameters such as vehicle fleet, vehicle age, driving patterns, fuel composition and climate. A full explanation of the method of calculation is provided by Eggleston *et al.* (1993).

3.3.6.3 MEET

The MEET project (Methodologies for Estimating Emissions from Transport) was undertaken in order to provide a basic Europe-wide procedure for evaluation the impact of transport on air pollutant emissions and fuel consumption. It brings together the most comprehensive and up-to-date information on emission rates and activity statistics, and enables the estimation of the emissions resulting from virtually any transport operation. The road transport sub-model in MEET allows the estimation of emissions at various levels of detail, but essentially uses an average-speed approach.

3.3.6.4 MODEM

MODEM is a modal emission model that was produced from the data collected during the European Commission's DRIVE V1053 project, "Modelling of emissions and consumption in urban areas". One of the objectives of the research reported in this Thesis was to assess MODEM's accuracy in terms of predicting the emission impacts of traffic calming and to explore ways in which it could be improved for use in traffic calming applications. A more detailed description of the model, as well as details of the model assessment and development, are presented in Chapter 12.

3.3.6.5 Workbook of Emission Factors (HBEFA)

The Workbook was developed on behalf of the German Federal Environmental Agency and the Swiss Federal Ministry for the Environment, Forestry and Agriculture. It is based on chassis dynamometer measurements of hot reference emission functions for a representative sample of 286 passenger vehicles with petrol and diesel engines, 31 light-duty vehicles, 35 diesel engines from HGVs, and 40 motorcycles (Hassel *et al.*, 1993). Additional 'correction factors' were derived in order to take into account the effects of cold starting, gradient, altitude, special driving conditions, and degradation of emission control systems. In extensive additional studies, the behaviour of passenger car and HGV drivers were also recorded, and the two data sets were combined (Keller, 1996).

The different correction factors, which relate to the particular traffic conditions the user is interested in, are applied to the reference emission functions in order to generate appropriate emission estimates. In the Workbook, a specific set of driving patterns is associated with a particular set of traffic conditions. These traffic conditions are characterised by the features of the section of road concerned (*e.g.* 'motorway with 120 km/h limit'; 'main road outside built-up area'), and the driving patterns are defined in terms average speed and acceleration. The emission factors produced by the Workbook must then be further weighted by traffic flow and composition. The user is led through a selection procedure by different menus, and can select from several options, including:

(i) the type of emission factor (hot/cold/evaporative);
(ii) the type of vehicle (passenger car/HGV/motorcycle);
(iii) the year (to give traffic composition);
(iv) the pollutant;
(v) traffic situation (motorway, urban freeway, stop-go, roads in residential areas);
(vi) temperature, distribution of standing times; and
(vii) additional parameters for calculation of evaporative emissions.

3.3.6.6 Digitalised Graz Method (DGV)

The Graz model is used in Austria for small- and medium-scale operations. The model calculates emissions from passenger cars with the aid of instantaneous emission maps, although it is based on a database developed from measurements on just 12 cars. The emission maps were produced for each car, and describe the emissions (in mg/s) of CO, HC, NO_x, particulates and fuel consumption for a large combination of speeds and accelerations. Three maps were developed: one for non-catalyst (ECE 15/04) cars, one for petrol catalyst cars, and one for diesel cars. With the aid of these maps, an average emission map for any given vehicle fleet composition can be constructed. The emission maps apply to hot emissions, and cold start emissions are applied independently of the speed and acceleration sequence. These emission maps can be combined with real-world measurements of driving behaviour to produce instantaneous emission estimates (Sturm *et al.*, 1994a, 1994b; Sturm, 1996).

3.4 Summary and recommendations for experimental design

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 vehicle operation.

Apart from the MoT test which, it is acknowledged, does not provide a realistic estimate of on-road emissions, three types of emissions measurement techniques are currently in use: on-board sampling, laboratory sampling, and remote sensing. Gas sampling equipment and analysers can be fitted to individual vehicles to enable on-road exhaust emission rates to be measured under conditions which are representative of on-road operation. 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 the traffic 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.

The advantage of laboratory testing is the potential to achieve reproducible results. The main disadvantages of testing individual vehicles relate to the dependence of emission rates on vehicle type and operation; there are several hundred different types of vehicle on the road in the UK, and during any one journey vehicle operation can vary quite markedly. Remote sensing can be used to determine emissions from both individual vehicles and traffic and it is relatively inexpensive. However, it can only give a 'snapshot' of emissions at one particular monitoring point on the road network.

Given that emission test results can be highly variable, a high degree of repeatability was required in this study. Chassis dynamometer testing, which, though expensive, is conducted in a controlled environment, was therefore selected as the primary method by which emission rates would be established. Consequently, the effect of traffic calming on vehicle operation would have to be defined in the form of driving cycles which could be used on a dynamometer. Driving cycles would be formulated to characterise vehicle operation before and after the installation of the nine different traffic calming measures identified in Chapter 1. The cycles would have to represent the observed ranges of speed and acceleration on the road where each measure was introduced. This required the use of a non-intrusive method for determining vehicle speed and gear selection on a continuous basis. The techniques which were available included an instrumented car, a LIDAR system, and road tubes.

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 one of the external techniques 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 scheme, would then be taken from the external 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 simplified in the early stages of the study.

The proposed methodology would rely, in part, on the matching of speed profiles obtained by external measurement and those measured using instrumented cars. Preliminary 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 of the tests are provided in Chapter 4. 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 4 of the Thesis also includes the details and results of this trial.

Well established methods for determining traffic flow and composition would subsequently be used to weight the emission rates resulting from the chassis dynamometer measurements. In order to assess the representativeness of the emission test results, on-road measurements of emissions from a large number of vehicles would be conducted using a remote sensing system.

CHAPTER 4 SPEED MEASUREMENT

The proposed methodology for the development of driving cycles relied in part on a statistical method for matching the speed profiles obtained using instrumented cars with those measured externally. Tests were required to confirm that the speed profiles measured using these two types of technique 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 simultaneously the three techniques described in Section 3.1.2.1: on-board instrumentation and two external methods of measurement (a laser-based system and pneumatic road tubes). Details of the test procedure and the results are provided in Section 4.1. 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 where traffic calming measures had already been installed. The trial is described in Section 4.2.

4.1 Comparison of speed measurement techniques

The LIDAR was placed in an appropriate position to measure vehicle speed over the section of road on which the pneumatic tubes had been installed. A Ford Escort instrumented with a 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 4.1 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 technique provided the most accurate representation of true 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 external measurements would be obtained during the study.

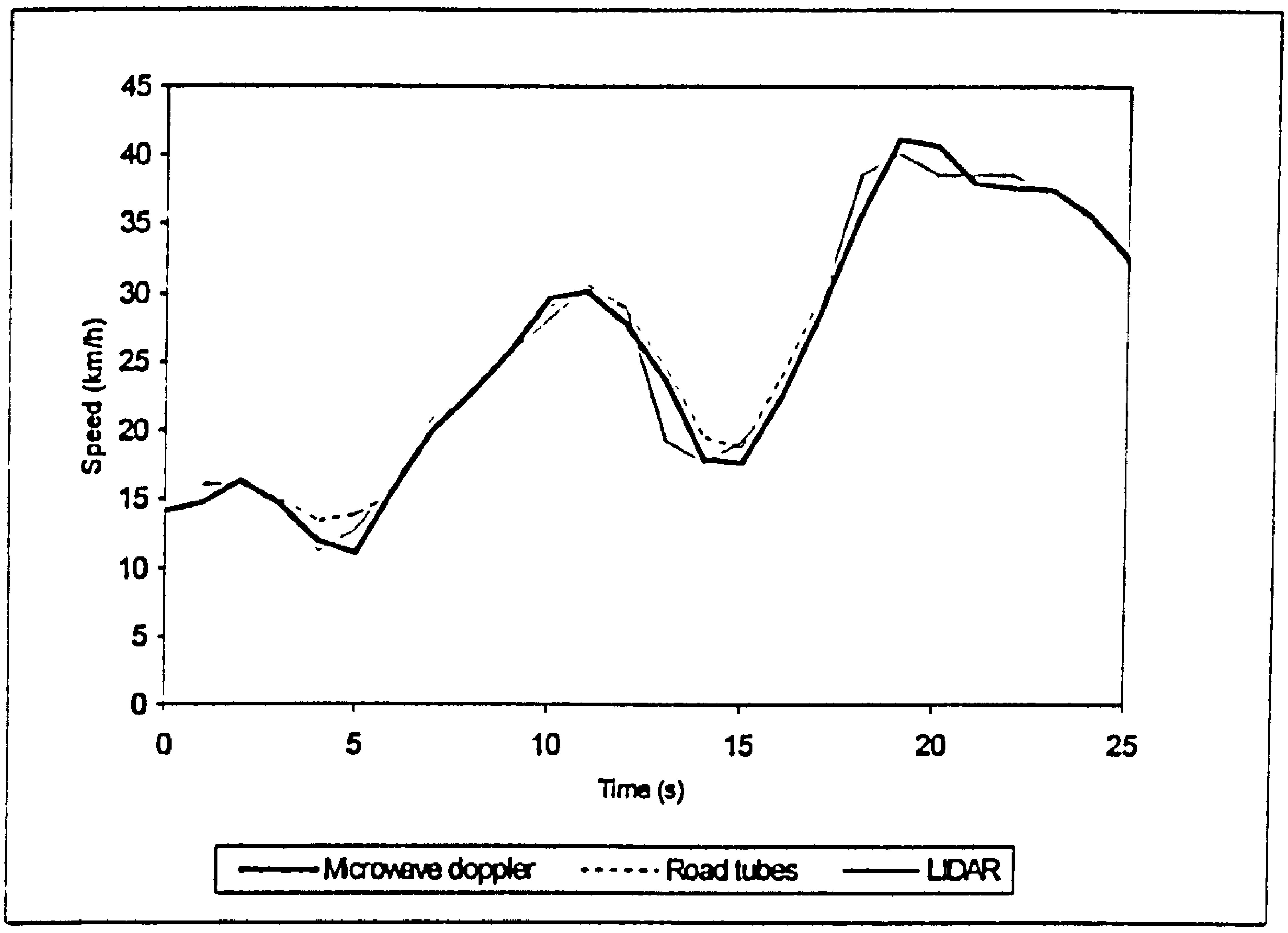

Figure 4.1 Comparison of speed measurement techniques.

4.2 Field trial

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 around 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 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, and the data were 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.

The mounting of 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 or pedestrians. A frame and shelving system were bolted to the interior of the van to support the various components of the external measurement system. The laser unit and video camera were fixed together on a bracket and aligned. The bracket was attached to a pan-and-tilt head which was, in turn, fixed to the frame. Figure 4.2 depicts the general arrangement of the external measurement system when used at the roadside, and Plate 4.1 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.

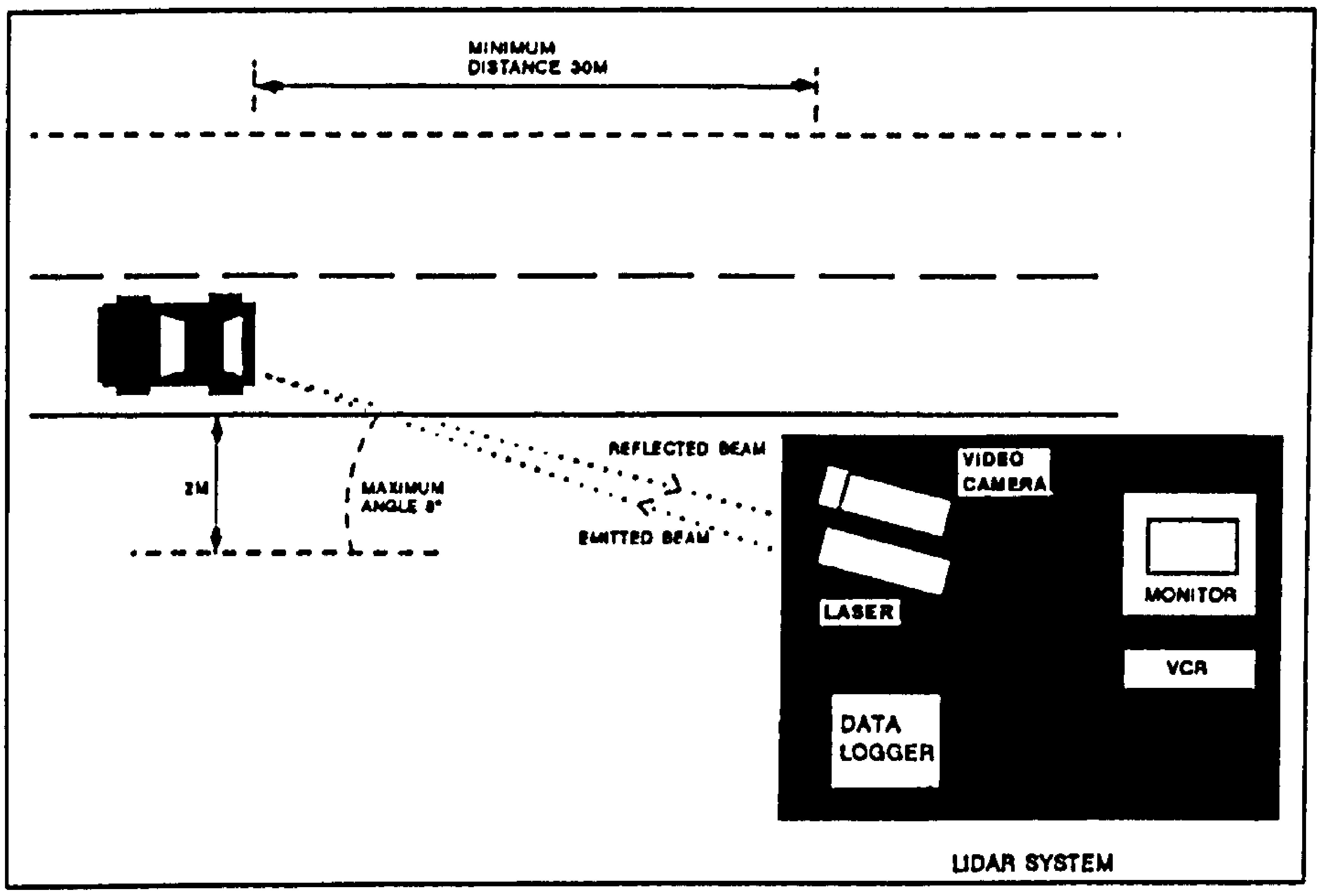

Figure 4.2 General arrangement of LIDAR system.

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 which 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 a Ford Mondeo fitted with internal instrumentation thorough the scheme. It was assumed that the Ford Escort represented a typical medium-size 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 external measurements.

Plate 4.1 LIDAR system.

As stated earlier, the proposed methodology relied in part on the matching of speed profiles obtained by external measurement with 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 and speed variation to reflect the speed range of the LIDAR measurements. *T*-tests 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 4.3 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 4.3 also shows that large differences in the overall standard deviation 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.

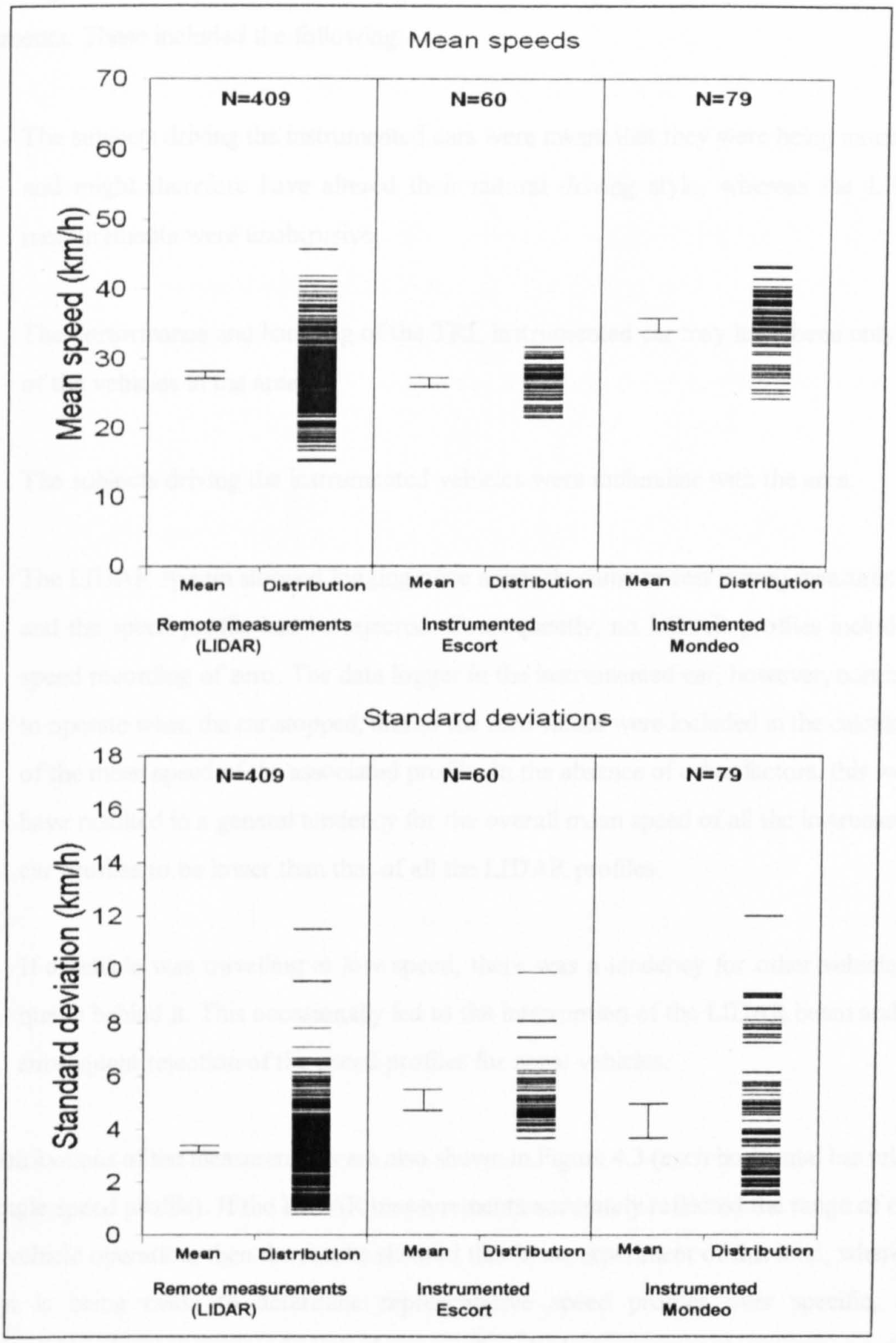

Figure 4.3 Mean speeds and standard deviations of profiles measured using LIDAR and two instrumented cars (the I-beams represent 95% confidence intervals, the horizontal bars in the distributions correspond to individual speed profiles, and N is the number of measurements).

These results were not particularly surprising, and there were probably a number of reasons for there being differences between the mean speeds measured using the LIDAR and the on-board instruments. These included the following:

(i) The subjects driving the instrumented cars were aware that they were being monitored and might therefore have altered their natural driving style, whereas the LIDAR measurements were unobtrusive.

(ii) The performance and handling of the TRL instrumented car may have been untypical of the vehicles in the area.

(iii) The subjects driving the instrumented vehicles were unfamiliar with the area.

(iv) 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 be lower than that of all the LIDAR profiles.

(v) 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 4.3 (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 external 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.

4.3 Summary

The methodology for the development of driving cycles relied on a statistical matching of the speed profiles measured internally (using an instrumented car) with those measured externally. The methodology was tested in two experiments: a basic comparison between different measurement techniques (at TRL), and a full field trial.

The experiment at TRL showed that was a good agreement between the speed profiles measured simultaneously using on-board instrumentation and two external methods of measurement (a LIDAR system and pneumatic road tubes). 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 external measurements would be obtained during the study.

The field trial was conducted on a public road featuring road humps. Drivers were asked to drive either a 'medium-size' or 'large' instrumented car thorough the scheme. The overall mean speed, and the overall standard deviation of speed for the instrumented cars were compared with those of the external measurements. 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. The mean speed of the medium-size car was lower, and that of the large car higher, than the mean speed of the vehicles measured by the LIDAR. Large differences in the overall standard deviation 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. The reasons for the differences between the internal and external measurements probably linked to the driving styles of the two samples, one being a small sample of drivers who were unfamiliar with the area, the other being a large sample of local drivers, as well the performance and handling of the instrumented cars compared with those of local vehicles, and limitations of the external measurement technique.

However, it was concluded that the representativeness of the final driving cycles should be improved if the instrumented car profiles comprising them are selected using the LIDAR measurements. 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 considered that the possibility of covering the entire speed range observed in the external measurements at all sites 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.

CHAPTER 5 SITE DESCRIPTIONS

Nine types of traffic calming measure were selected for investigation. These measures, which as described in this Chapter of the Thesis, were primarily selected according a list of those most frequently implemented (Table 2.1). 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 research, as well as the practicality of conducting the appropriate measurements at potential sites. A summary of the characteristics of the traffic calming measures is presented in Table 5.1 at the end of the Chapter.

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

The flat-top humps installed on Ambleside Avenue, one of which is depicted in Plate 5.1, 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 5.1.

5.2 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 Plate 5.2, 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 5.2.

5.3 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 accounted for 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 this 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 (Plate 5.3), spaced at an average (but rather variable) 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 Welbeck Road investigated by TRL is represented in Figure 5.3.

5.4 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 Plate 5.4.

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 5.4.

5.5 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 5.4.

One of the junctions is depicted in Plate 5.5. 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 5.5.

5.6 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 in pictured in Plate 5.6. 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. No map of the section of Great Hollands Road investigated by TRL was available.

5.7 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 measures 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 (Plate 5.7) was selected as the seventh traffic calming measure in the study. The build-out extended 1.5 m into the northbound carriageway, resulting in an effective road width of 3.9 m and, as a result, 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. No map of Owlsmoor Road was available for inclusion here.

5.8 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 Plate 5.8.

5.9 Scheme I: 1.9m-wide speed cushions

West Grove in Walton-on-Thames is one of the main traffic routes between the A244 and the A317, even though it is a residential road. 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 Plate 5.9, 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 5.6.

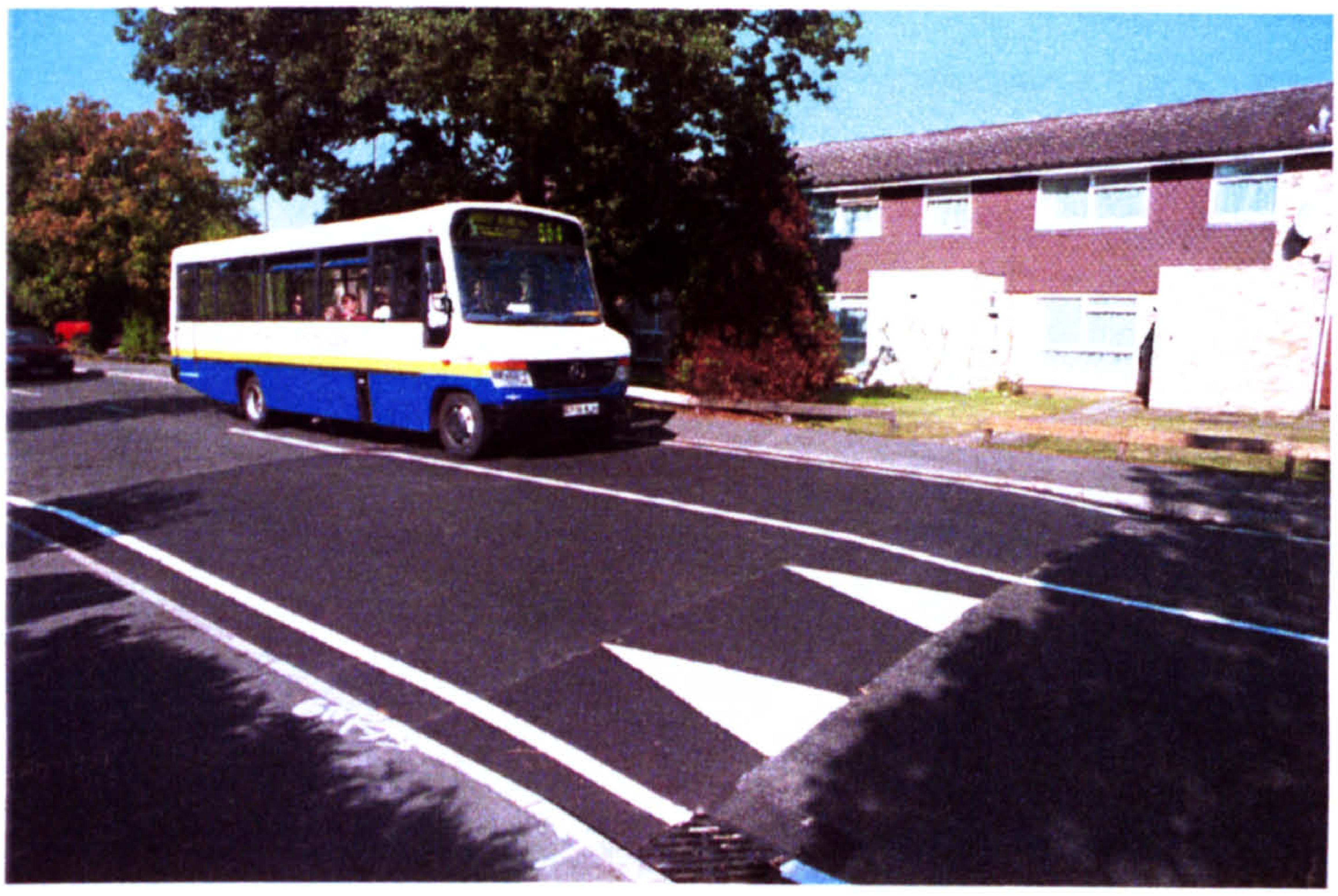

Plate 5.1 Flat-top road hump: Ambleside Avenue, Walton-on-Thames.

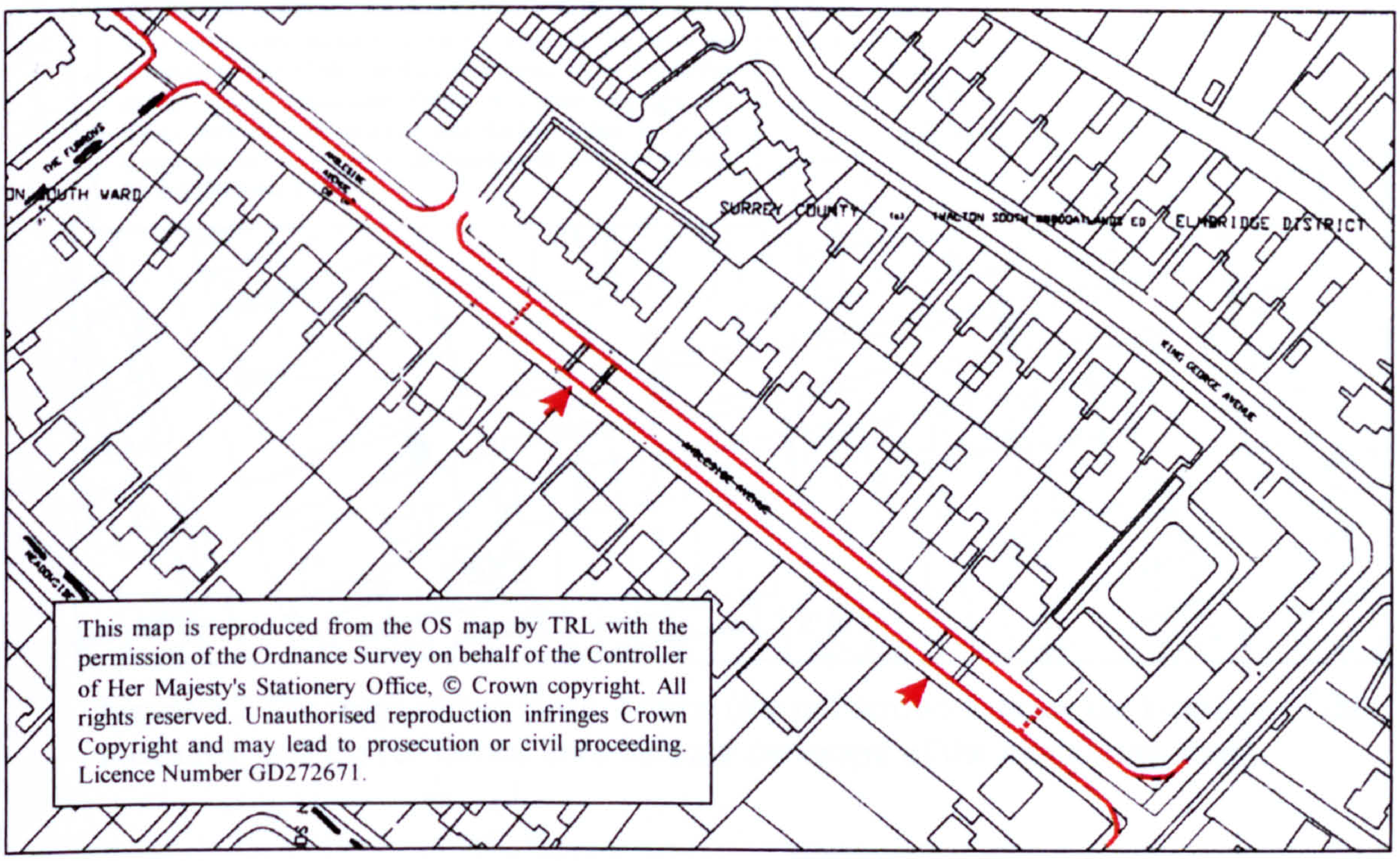

Figure 5.1 Site map: Ambleside Avenue, Walton-on-Thames (the red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone).

Plate 5.2 Round-top road hump: Milton Road, Sutton.

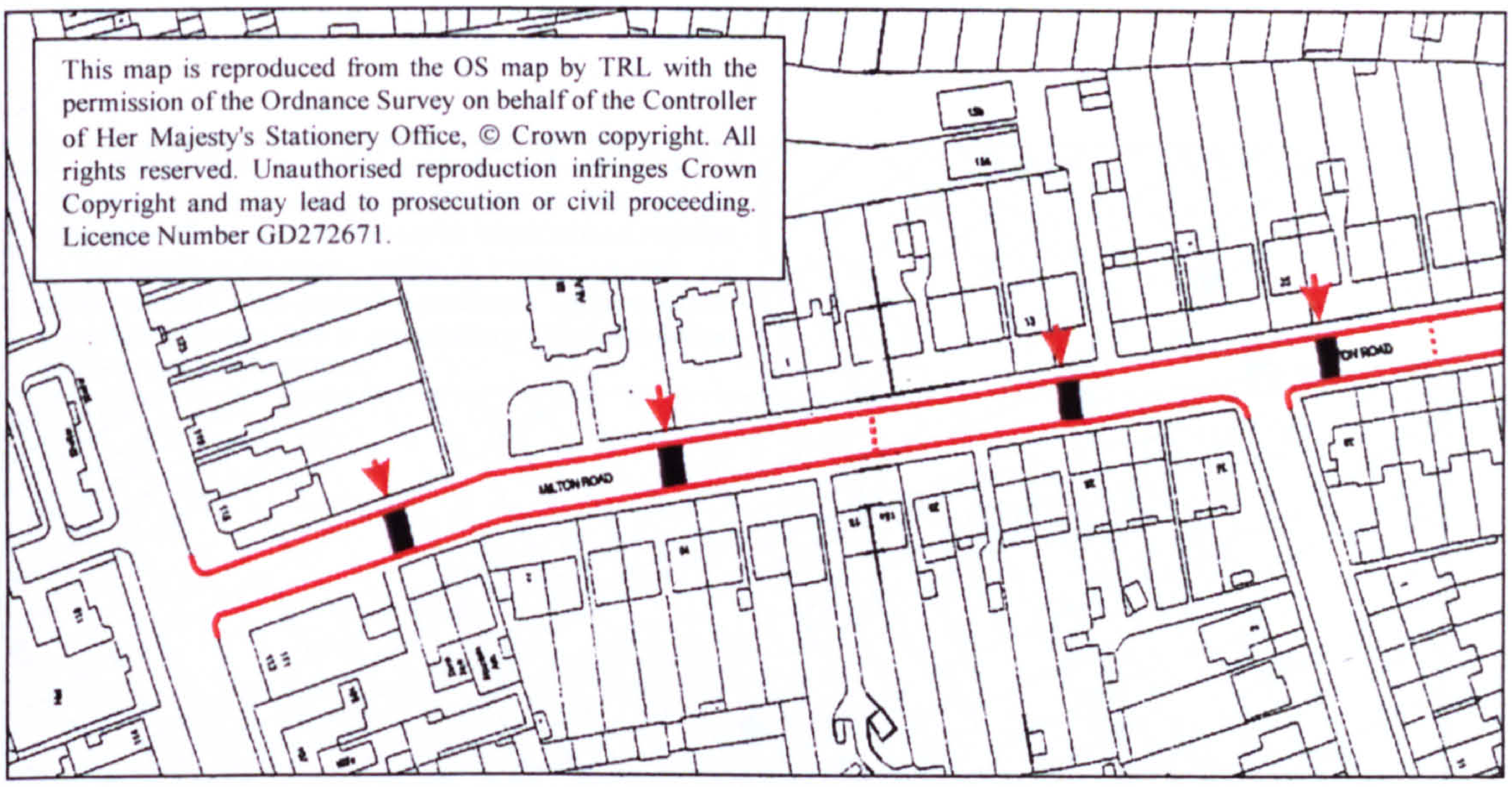

Figure 5.2 Site map: Milton Road, Sutton (the red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone).

Plate 5.3 1.7m-wide speed cushions: Welbeck Road, Harrow.

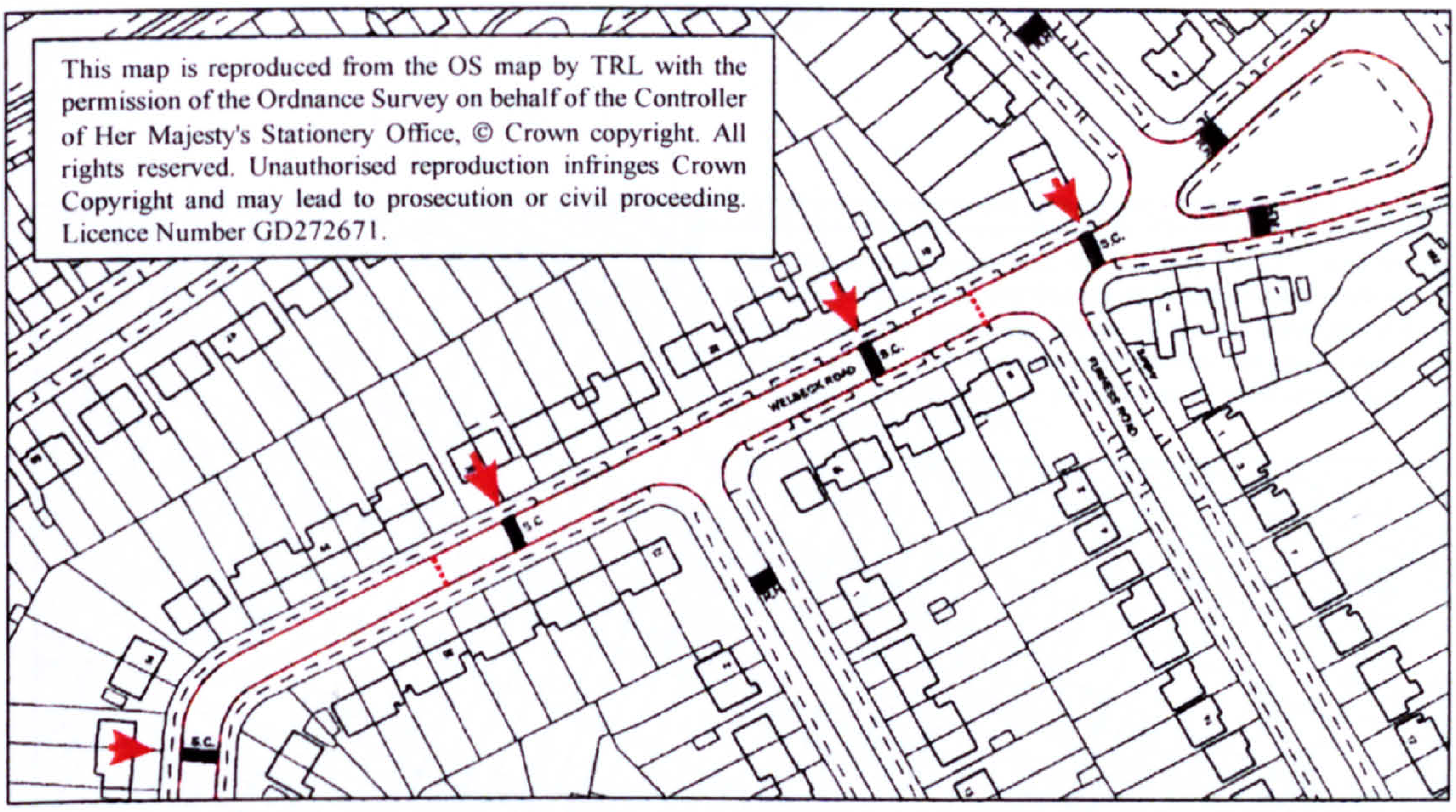

Figure 5.3 Site map: Welbeck Road, Harrow (the red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone).

Plate 5.4 Combined pinch point and speed cushion: Broadmark Road, Slough.

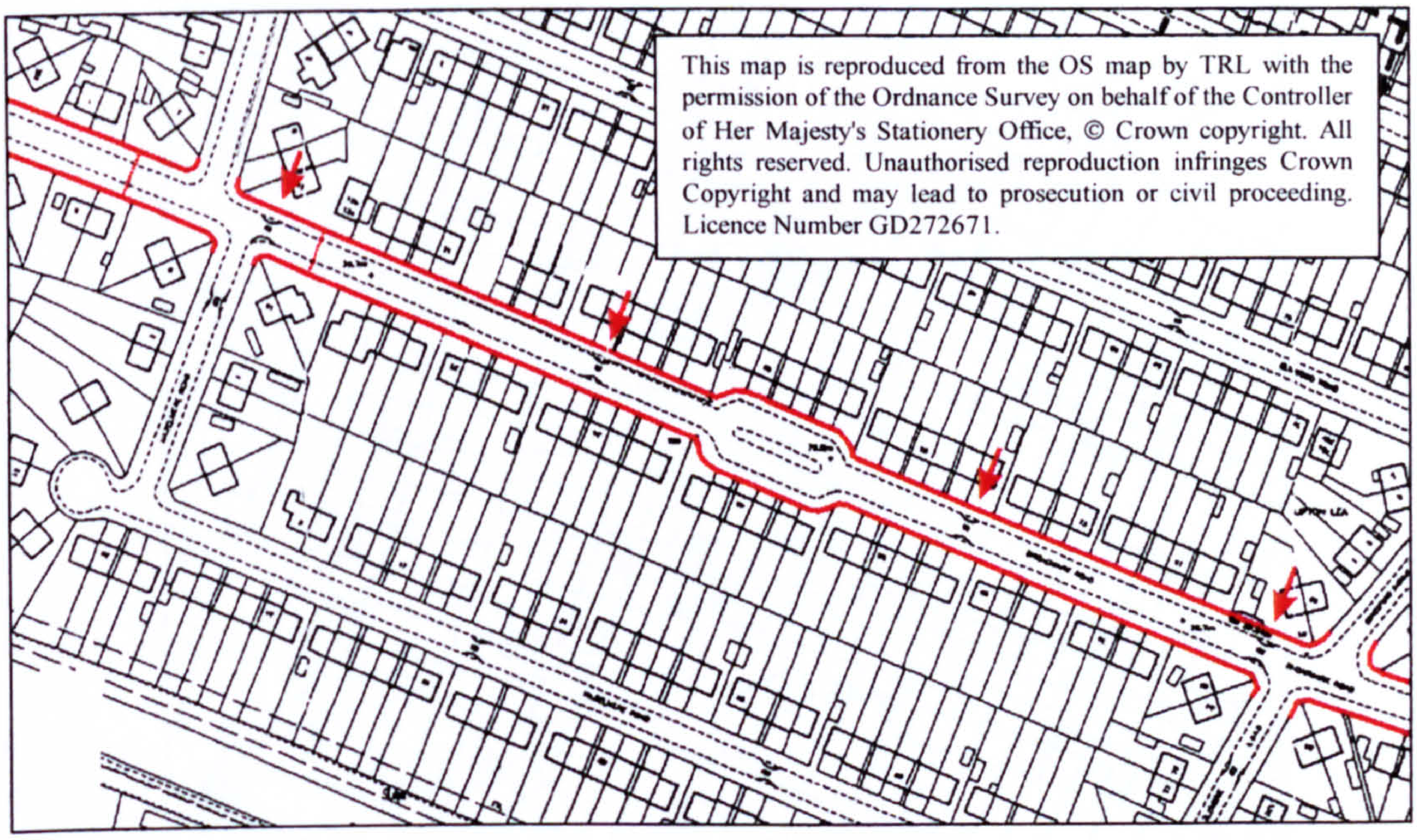

Figure 5.4 Site map: Broadmark Road, Slough (the red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone).

Plate 5.5 Raised junction: Carlton Road, Slough.

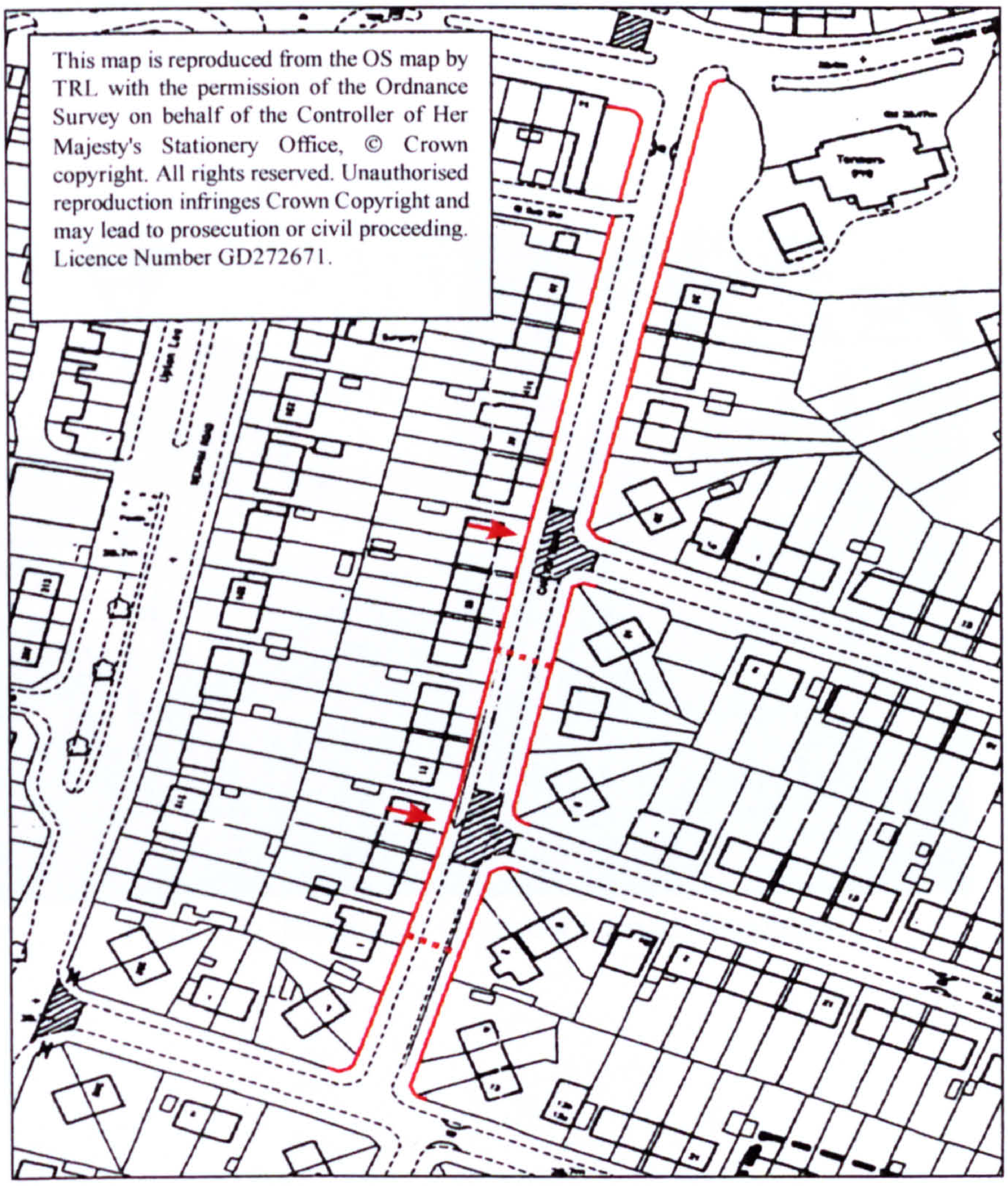

Figure 5.5 Site map: Carlton Road, Slough (the red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone).

Plate 5.6 Chicane: Great Hollands Road, Bracknell.

Plate 5.7 Build-out: Owlsmoor Road, Sandhurst.

Plate 5.8 Mini-roundabout: Owlsmoor Road, Sandhurst.

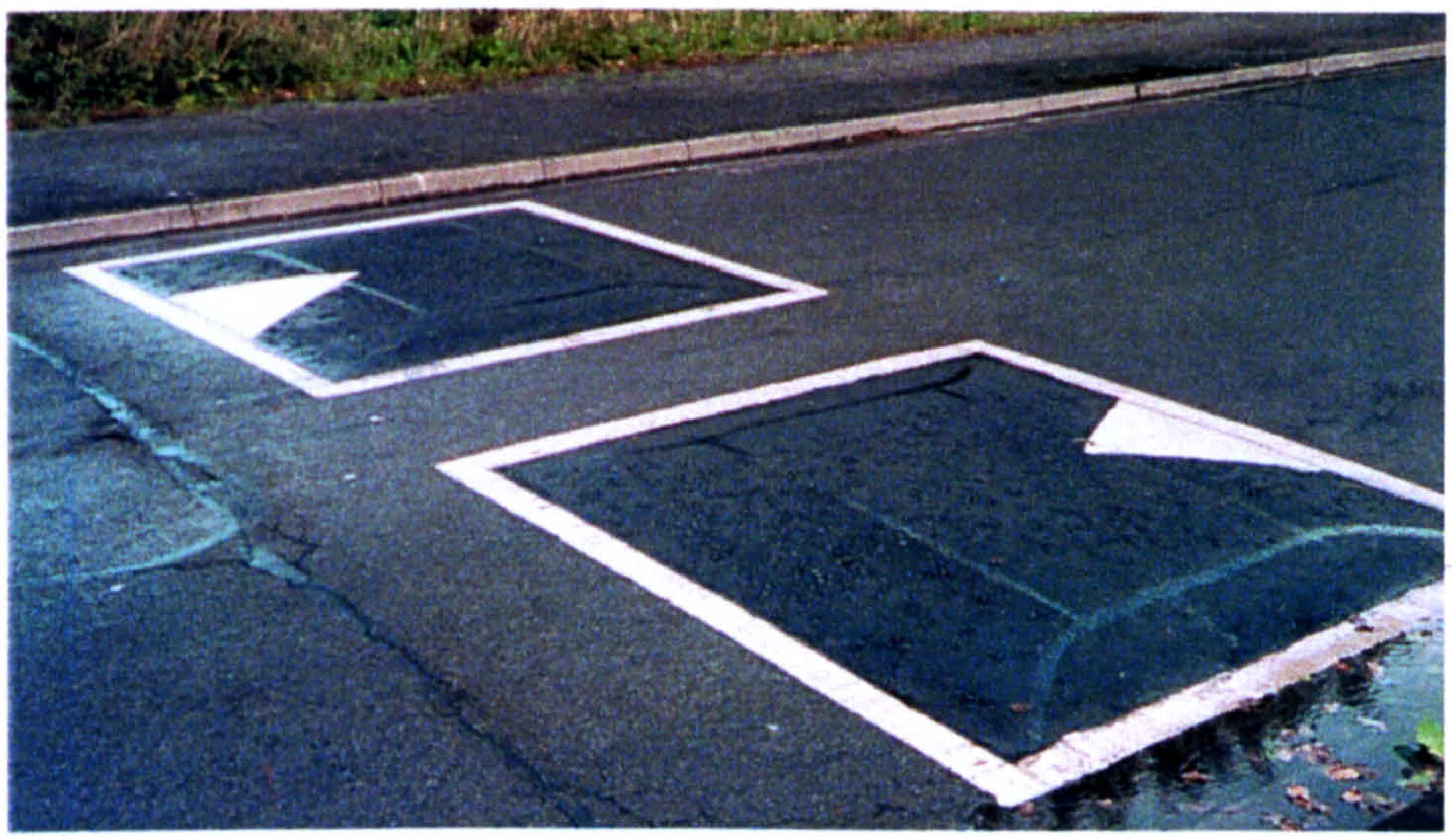

Plate 5.9 1.9m-wide speed cushions: West Grove, Walton-on-Thames.

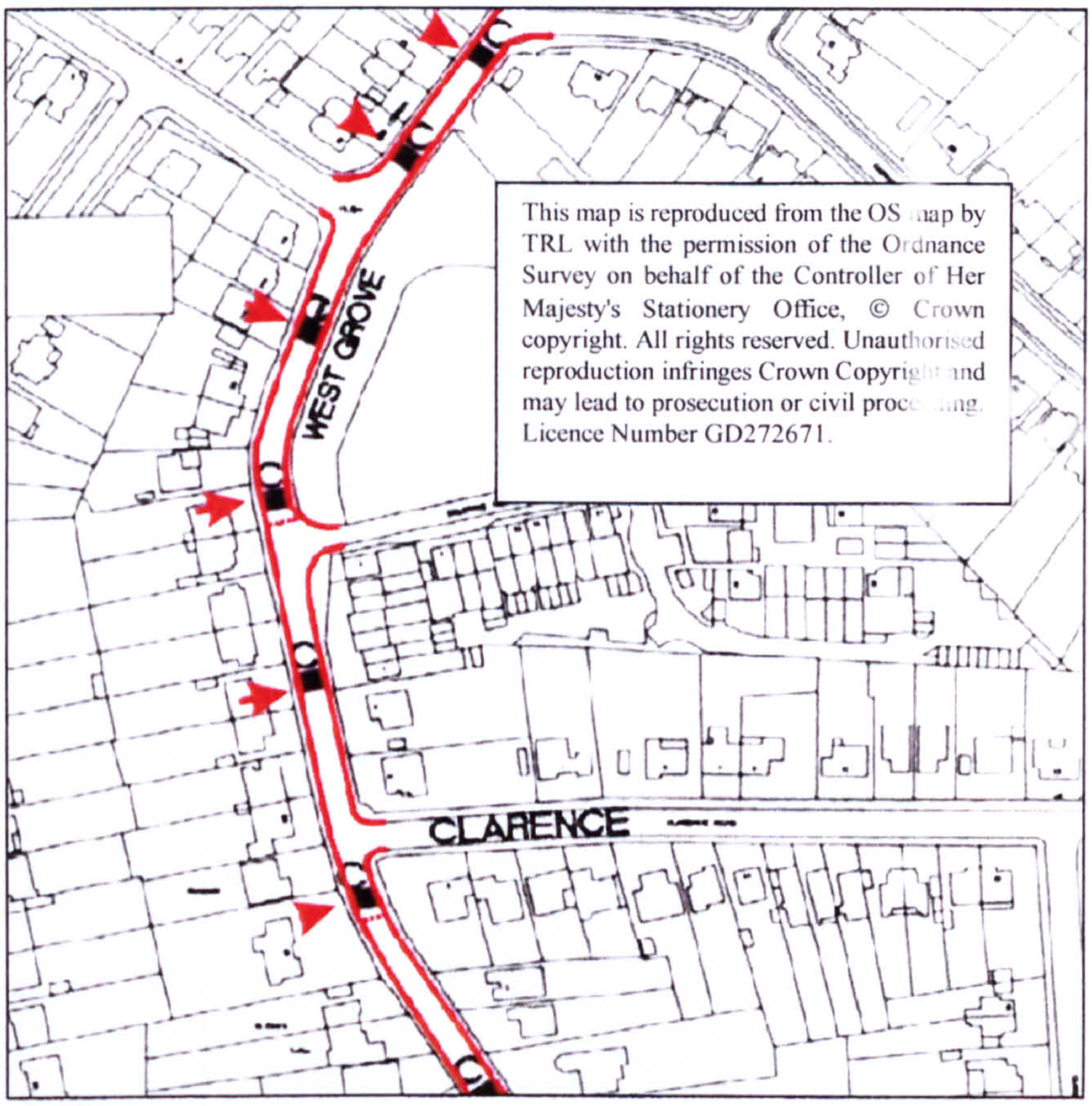

Figure 5.6 Site map: West Grove, Walton-on-Thames (the red arrows indicate the locations of the measures, and the red dotted lines indicate the extent of the monitoring zone).

Table 5.1 Characteristics of traffic calming measures (dashes indicate where no information was available or the parameter is not relevant).

Scheme	Measure	Location	Height (mm)	Overall length (m)	Plateau length (m)	Overall width (m)	On/off ramp gradient	Side ramp gradient	Approximate spacing (m)
A	Flat-top road humps	Walton-on-Thames	75	8.5	6.0	-	1:15	-	90
B	Round-top road humps	Sutton	80	-	-	-	-	-	60
C	Speed cushions[a]	Harrow	80	2.5	1.2	1.7	1:8	-	75
D	Pinch point / speed cushion	Slough	75[c]	3.7[c]	-	3.3[b] / 1.6[c]	-	-	90-100
E	Raised junction	Slough	100	17-22	-	-	-	-	70
F	Chicane	Bracknell	-	28	-	3.7[b]	-	-	-
G	Build-out	Sandhurst	-	-	-	3.9[b]	-	-	-
H	Mini-roundabout	Sandhurst	-	-	-	-	-	-	-
I	Speed cushions[d]	Walton-on-Thames	75	1.9	1.7	1.9	1:8	1:4	50

[a] Arranged in transverse 'in-line' groups of three. Dimensions relate to each cushion.

[b] Carriageway width.

[c] Cushion dimensions.

[d] Arranged in transverse 'in-line' groups of three. Dimensions relate to each cushion.

6 TRAFFIC FLOW, COMPOSITION AND SPEED

6.1 Field measurements

Where possible, vehicle speed profiles were measured before and after the introduction of the nine schemes identified in the previous Chapter. These speed profiles were subsequently used to develop driving cycles for use in laboratory emission tests. 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). In principle, diversions and any changes in traffic composition will also have an impact on overall emissions. Traffic flow and composition were also 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. However, consistent results were not obtained in practice.

The dates of the main traffic surveys conducted during the work are presented in Table 6.1. Speed and flow measurements were conducted before and after the installation of each of the first five traffic calming schemes listed in Chapter 5. Two-way 24-hour traffic flows were recorded using automatic counters. For scheme C, traffic flow data had already been collected by the local authority in 1995, prior to the introduction of the scheme. No subsequent traffic count was conducted at this site before calming. The flow counts for scheme C were therefore separated by 26 months, for schemes A, B, D, and E, the counts were separated by 4-12 months. Vehicle speed profiles were measured externally 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, or where the layout was suitable for external 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 external speed measurements.

For the 1.9m-wide speed-cushions (scheme I), external 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 described in Section 5.1, 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. A nearby road, which already featured 1.9 m-wide speed cushions, was therefore adopted as an alternative. Although traffic flows were recorded before the introduction of scheme I, the measurements were not used because of the change of site.

Table 6.1 Surveys undertaken during the study.

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

[a] Flow estimated from video record.

Where speed measurements could be conducted at the same site both before and after calming, the time period between the surveys varied from two to six months. Because of the difficulties associated with scheme I, there was an 18-month time gap between the before and after speed surveys. The external speed measurement 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 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 LIDAR speed profile of each vehicle passing through the traffic calming section was classified in terms of the mean and the standard deviation of the second-by-second speed measurements. All the vehicles measured 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, there are a few points to note concerning this system of classification. Firstly, many cars registered between January 1 1993 and August 1 1993 would have been equipped with a catalyst. Also, some manufacturers produced catalyst-equipped vehicles well before the date of the 91/441 legislation, and some manufacturers managed to produce vehicles after this date that were compliant with the pollutant limits but were not equipped with a catalyst. Finally, 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 which included the section of road of interest. Each subject was asked to drive an 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.

6.2 Traffic flow

The traffic flows recorded during the study are presented in Table 6.2. 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.

The numbers in brackets in the last column of Table 6.2 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 at 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.

Table 6.2 Mean 24 hour traffic flows at each site.

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

[a] Approximate 12-hour count multiplied by a factor for residential roads of 1.26 (Boulter and Cloke, 1996) to covert to 24-hour count.

6.3 Traffic composition

The percentages of the traffic flow in each vehicle category before and after the installation of the traffic calming measures are shown in Table 6.3. In general, most of the traffic flows comprised of passenger car and light goods vehicles. Very few HGVs and buses were observed on the roads investigated.

Table 6.3 Percentage of vehicles observed by category during video monitoring at each site.

Scheme	Traffic calming measure	Stage	Number of vehicles	Percentage of traffic flow in category										Total %
				Small cars		Medium cars		Large cars		LGVs		HGVs	Buses	
				Pre-'L'	'L' and after	Pre-'L'	'L' and after	Pre-'L'	'L' and after	Pre-'L'	'L' and after			
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

Where information on traffic composition was available before and after calming, there was generally 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 difference of 20 percentage points between the proportions 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.

Because older vehicles in the fleet 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 6.1 shows the average percentage of traffic flow in each vehicle category before and after calming.

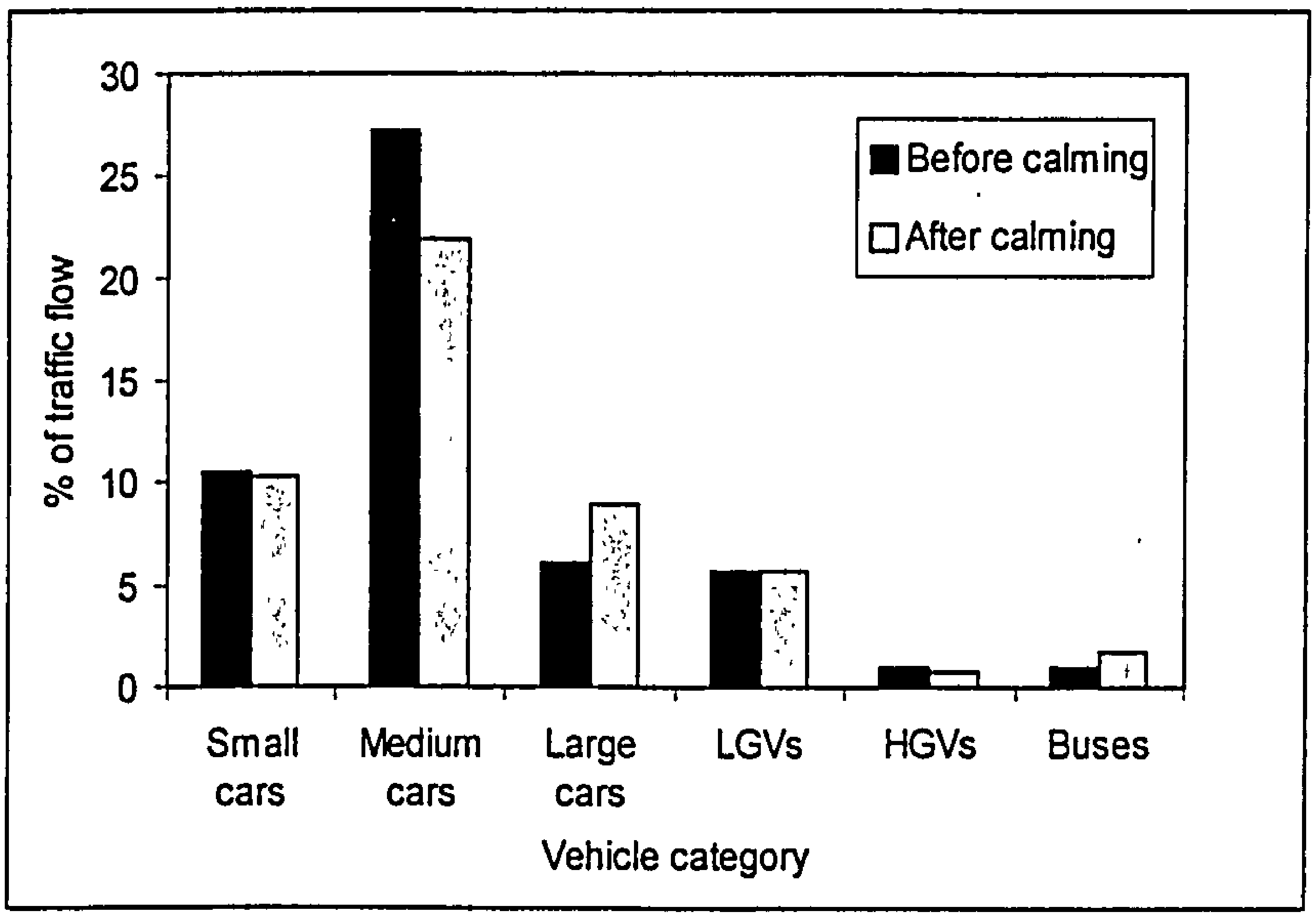

Figure 6.1. Average proportion of traffic flow in each vehicle category before and after the introduction of traffic calming (schemes A-E only).

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.

6.4 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 6.4 and 6.5. For each scheme and vehicle category the sample sizes can be inferred from the information presented in Table 6.3.

At the six sites where external speed measurements were obtained before calming, the mean speed of passenger cars varied between 38 km/h and 53 km/h. 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 and 42 km/h, with the actual speed reduction, excluding the three sites for which no measurements were obtained before calming, ranging from 10 km/h to 19 km/h. 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 and 50 km/h before calming to between 20 and 42 km/h after calming, with a speed reduction of between 10 and 17 km/h. 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 6.4.

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 and decelerate between 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.

6.5 Implications for emission test programme

Only small differences were observed between the means and standard deviations of the speed profiles for the small, medium, and large car categories before calming. Larger, but still small, differences were apparent after calming. The main issue concerning these measurements is not whether statistically significant differences in speed existed between the three car categories, but whether these differences would have been significant when translated to emissions. In practice, quite large differences in speed are necessary to show significant differences in emission rates, since emission measurements tend to show a large amount of variation and poor repeatability. For these reasons, one driving cycle was considered sufficient to represent all three categories 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 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, and as the cycles were built from random sets of profiles they would include all of this potential variation.

Table 6.4 Mean speeds of the vehicles measured using the LIDAR before and after the installation of traffic calming measures at each site.

Scheme	Traffic calming measure	Stage	Mean speed of vehicles in category in km/h, with 95% confidence intervals in brackets					
			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 6.5 Mean speed standard deviation of the vehicles measured using the LIDAR before and after the installation of traffic calming measures at each site.

Scheme	Traffic calming measure	Stage	Standard deviation of speed of vehicles in category in km/h, with 95% confidence intervals in brackets					
			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	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	

CHAPTER 7 DEVELOPMENT OF DRIVING CYCLES

7.1 Introduction

Laboratory emission tests for light-duty vehicles involve the operation of the vehicle on a power-absorbing chassis dynamometer. So that the impacts of each traffic calming measure on passenger 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 6.5, each driving cycle was used to test all the vehicles included in the emission measurement programme.

The development of the cycles took place at TRL over a 16-month period, though much of the effort was concentrated in the early stages, and thereafter the cycles were constructed intermittently, depending on when the speed data from the sites were available.

7.2 Construction of driving cycles

7.2.1 Original method

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 6. 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 corresponding to 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 driveability of these first two cycles on a chassis dynamometer was tested by AEA Technology in Harwell. The tests showed that, although the cycles were driveable, 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 revs/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 7.1 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 instrumented 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.

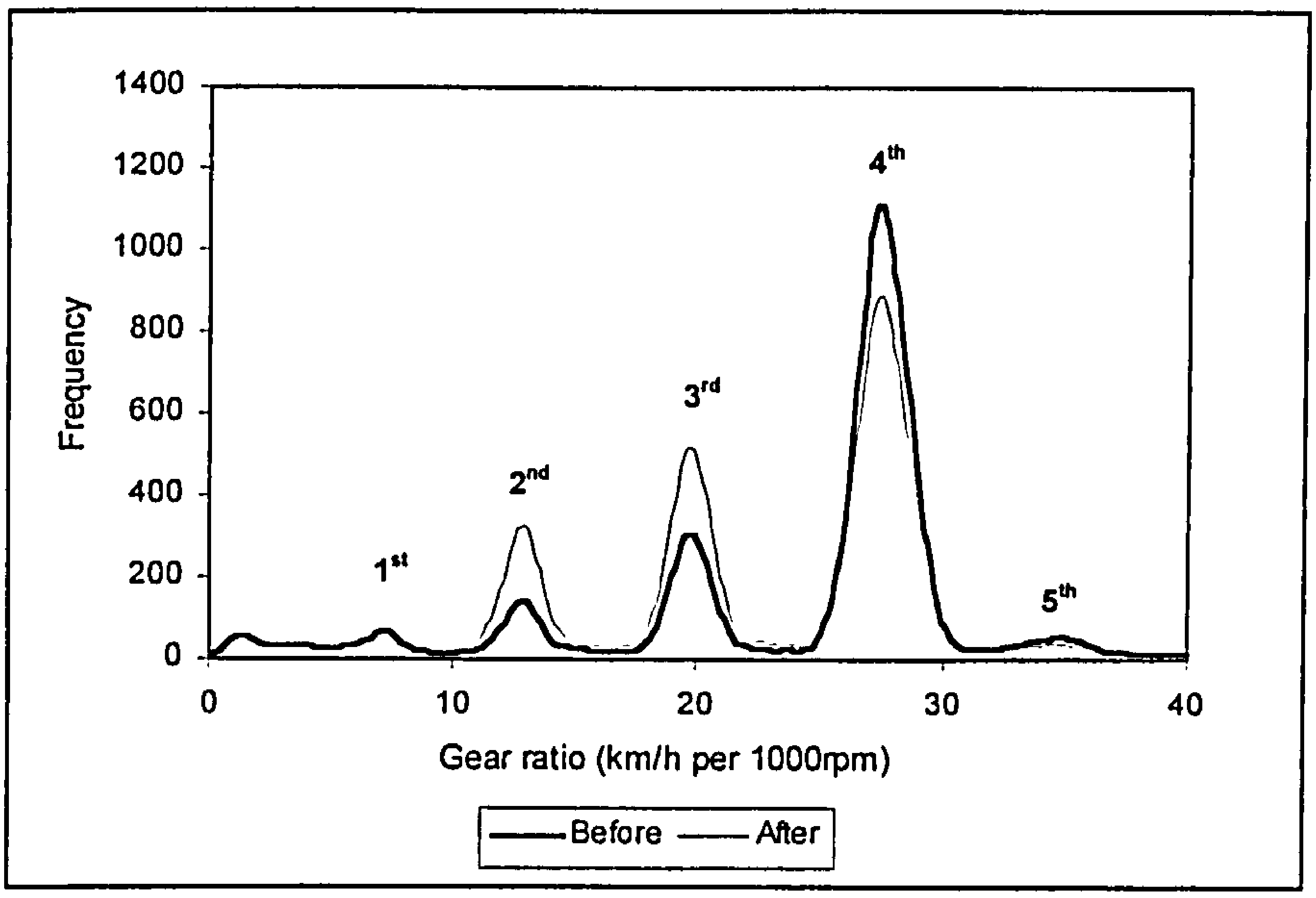

Figure 7.1 Gear ratio distribution: Ford Fiesta before and after calming.

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:

(i) 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.

(ii) 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 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 probably not have occurred often 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.

7.2.2 Simplified method

Because of the problems encountered when using the original approach for determining a gear-selection pattern for the driving cycles, an alternative approach was adopted. 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 instrumented vehicles. An analysis of the gear selections through the road section also showed that 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 7.1. 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 7.1, or until 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 7.1 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. Once the final method for constructing the cycles had been determined, each cycle could be constructed within two days following the reception of the speed data. For schemes F, G and H, external 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 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.

7.3 Driving cycle characteristics

The final driving cycles representing vehicle operation at all schemes before and after calming, including the associated patterns of gear selection, are illustrated in Figures 7.2-7.10. Statistics relating to each driving cycle are provided in Table 7.2.

Table 7.2 Driving cycle characteristics.

Scheme	Traffic calming measure	Stage	Driving cycle					
			Duration (s)	Speed (km/h)				Acceleration Range (m/s^2)
				Mean	St.Dev.	Max	Min	
A	75mm flat-top road humps	Before calming	1204	50.71	6.95	67.36	26.98	-1.5 to +1.0
		After calming	903	34.97	5.44	45.33	20.51	-1.7 to +1.4
B	80mm round-top road humps	Before calming	434	43.91	7.52	69.19	24.94	-1.9 to +1.5
		After calming	632	26.65	5.85	49.48	8.45	-1.6 to +1.2
C	1.7m-wide speed cushions	Before calming	547	42.46	8.06	56.32	18.10	-1.8 to +1.5
		After calming	678	30.53	7.98	53.90	10.46	-2.1 to +1.8
D	Pinch point/speed cushion	Before calming	422	46.05	8.10	62.75	20.11	-1.8 to +1.2
		After calming	454	36.39	10.21	72.41	13.68	-1.6 to +1.5
E	Raised junction	Before calming	465	41.08	6.92	61.95	22.53	-2.2 to +1.6
		After calming	587	25.56	5.43	41.82	15.68	-1.3 to +1.8
F	Chicanes	Before calming	429	55.61	3.76	62.75	48.67	-0.9 to +0.7
		After calming	480	40.73	6.19	61.95	23.33	-1.5 to +0.5
G	Build-out	Before calming	401	43.64	7.46	58.73	24.94	-1.9 to +1.2
		After calming	679	34.43	7.96	57.52	7.64	-1.7 to +1.4
H	Mini-roundabout	Before calming	401	43.64	7.46	58.73	24.94	-1.9 to +1.2
		After calming	316	29.27	6.07	47.47	10.06	-1.6 to +1.7
I	1.9m-wide speed cushions	Before calming	331	50.20	9.24	76.83	18.93	-1.8 to +1.7
		After calming	464	33.77	7.50	57.52	16.09	-1.2 to +1.2

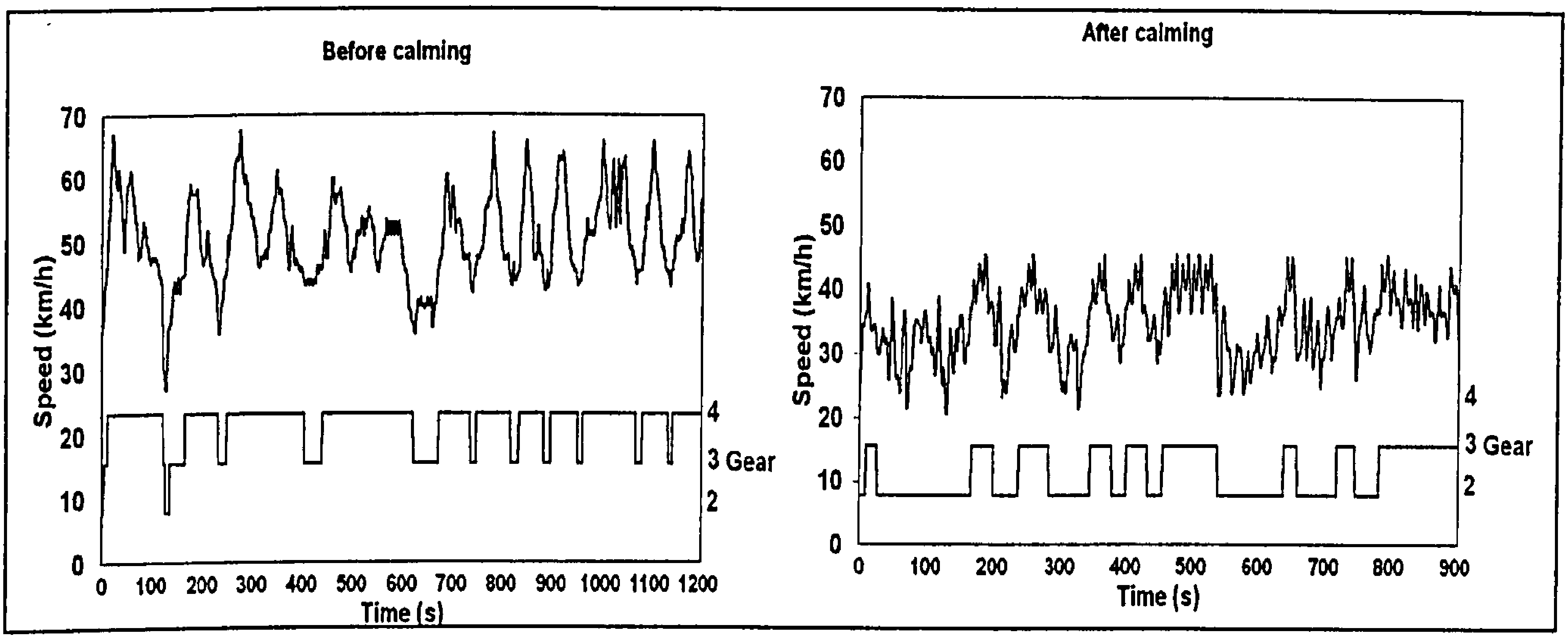

Figure 7.2 Driving cycles - Scheme A: 75mm flat-top road humps.

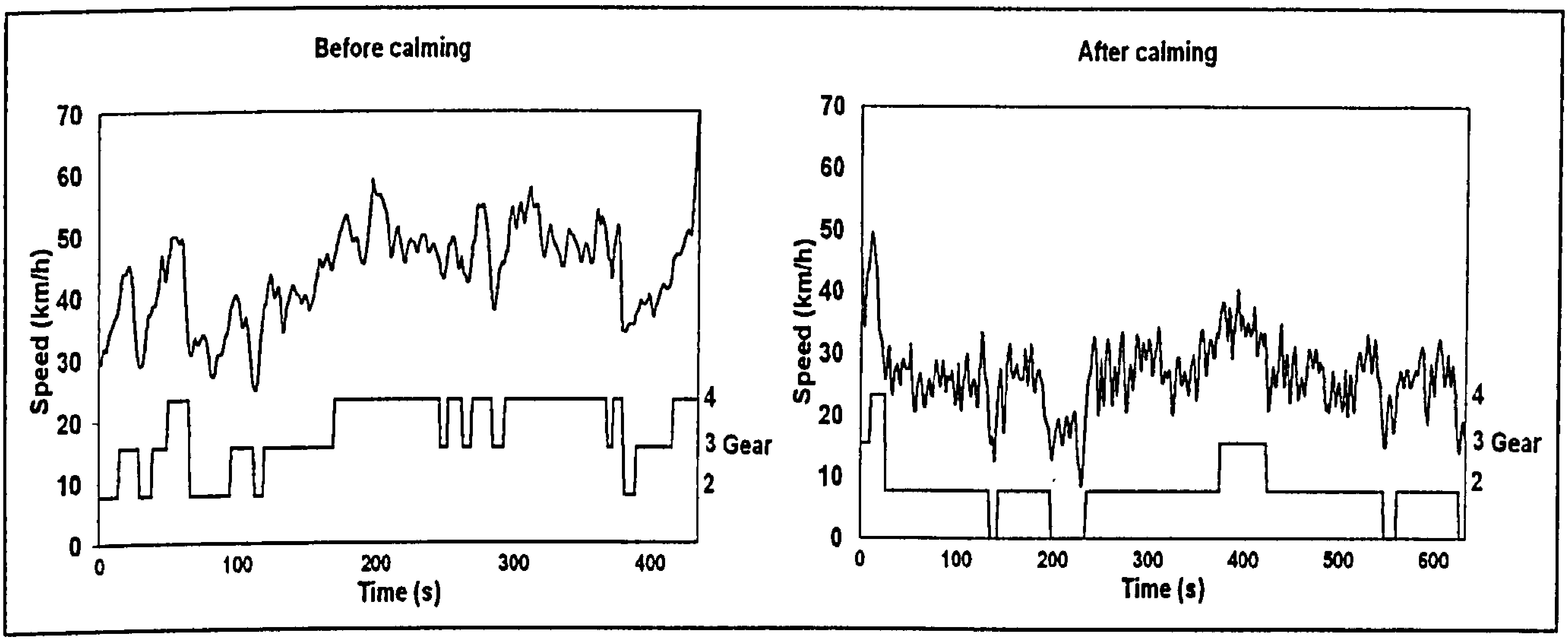

Figure 7.3 Driving cycles - Scheme B: 80mm round-top road humps.

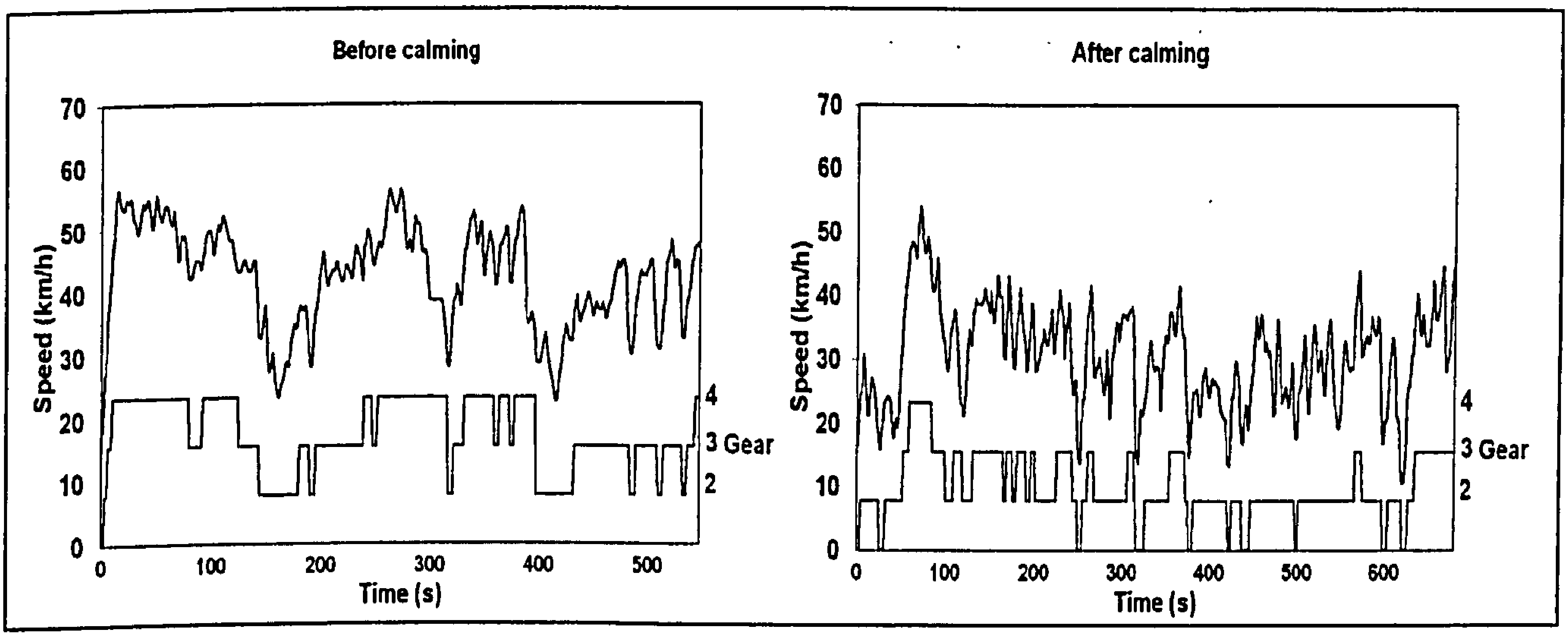

Figure 7.4 · Driving cycles - Scheme C: 1.7m-wide speed cushions.

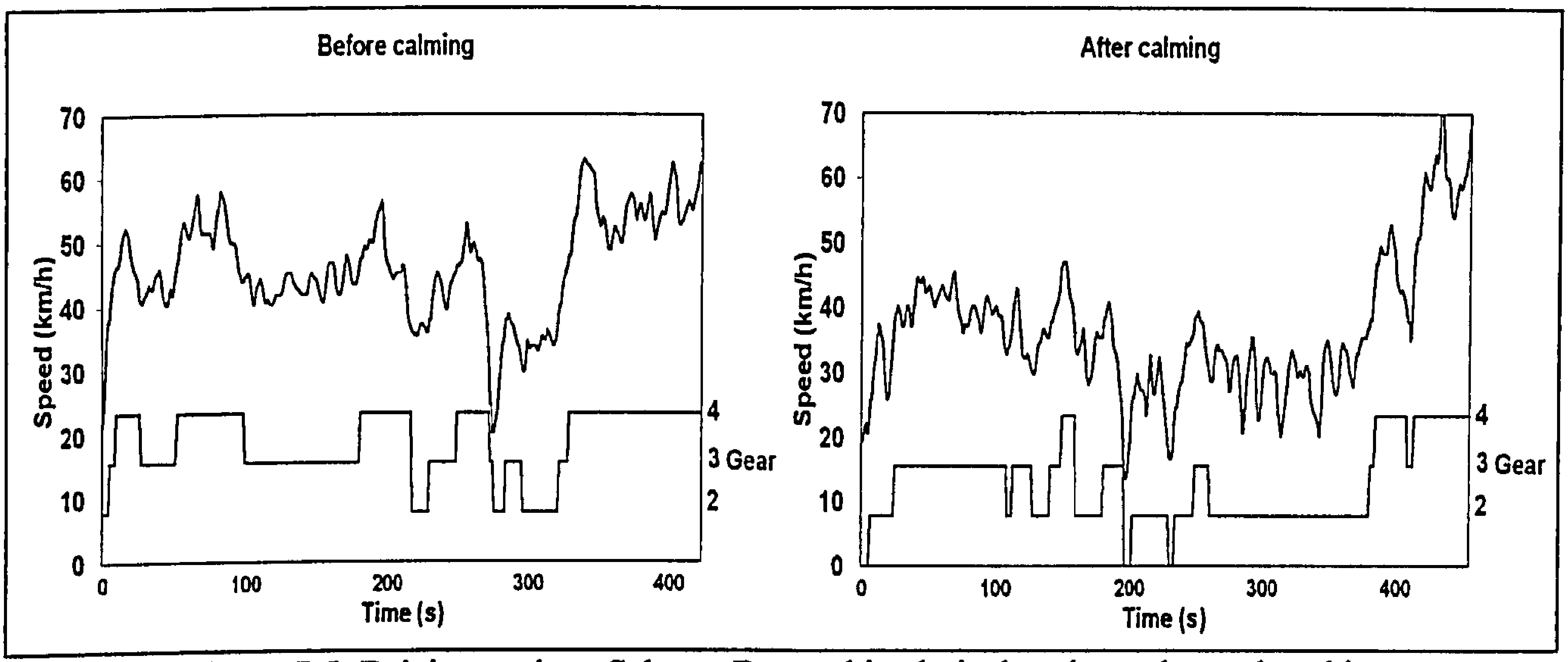

Figure 7.5 Driving cycles - Scheme D: combined pinch point and speed cushion.

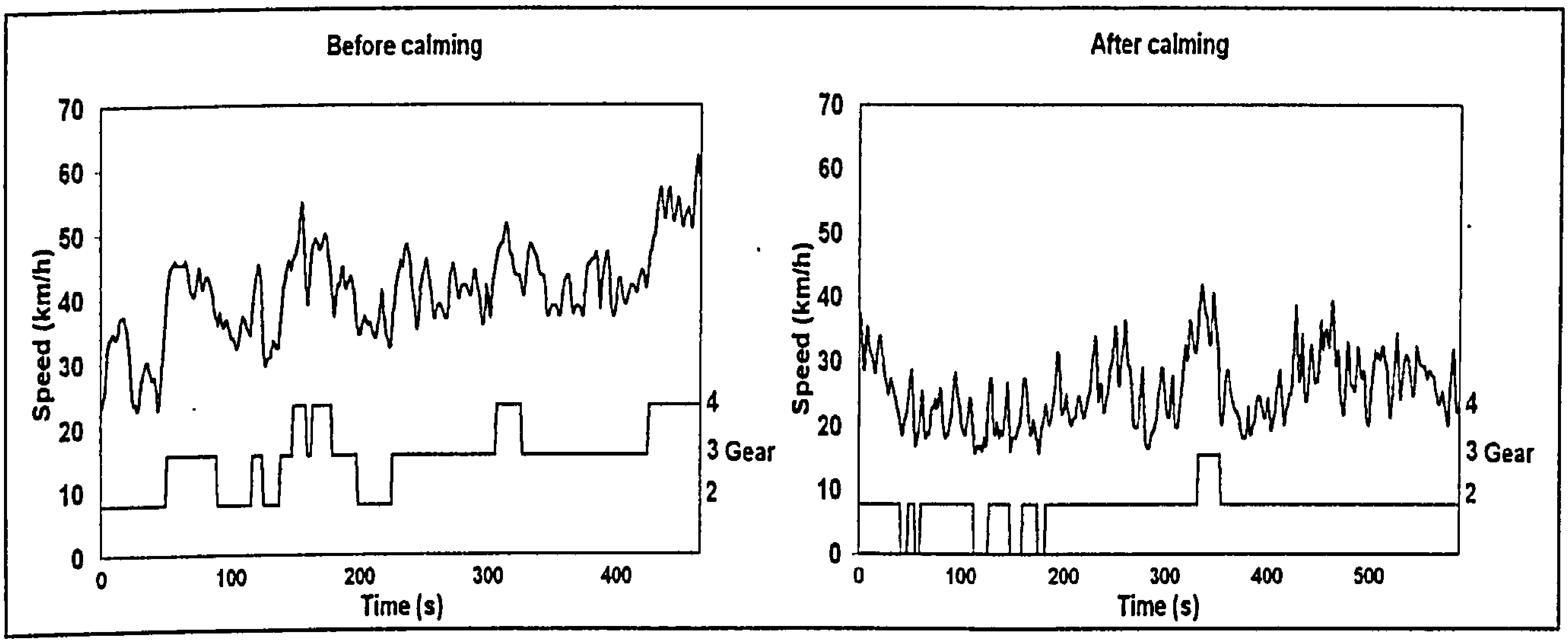

Figure 7.6 Driving cycles - Scheme E: raised junction.

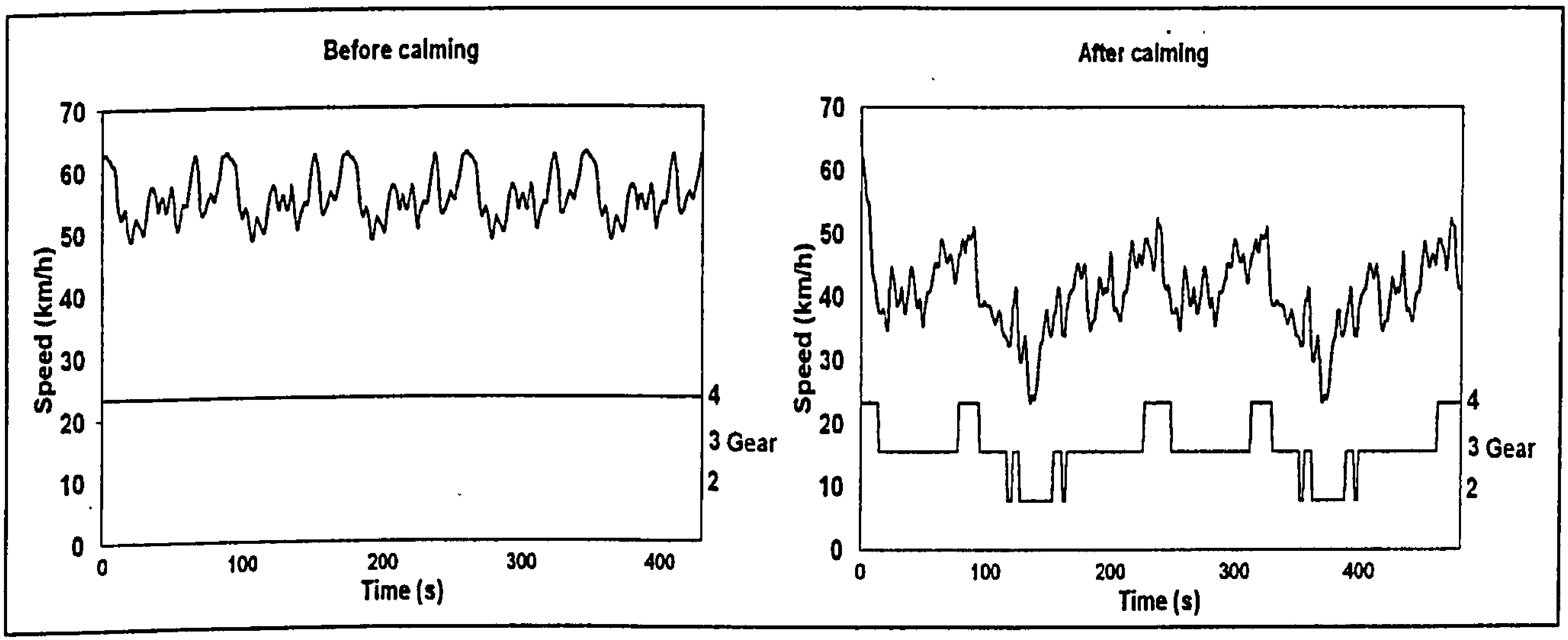

Figure 7.7 Driving cycles - Scheme F: chicane.

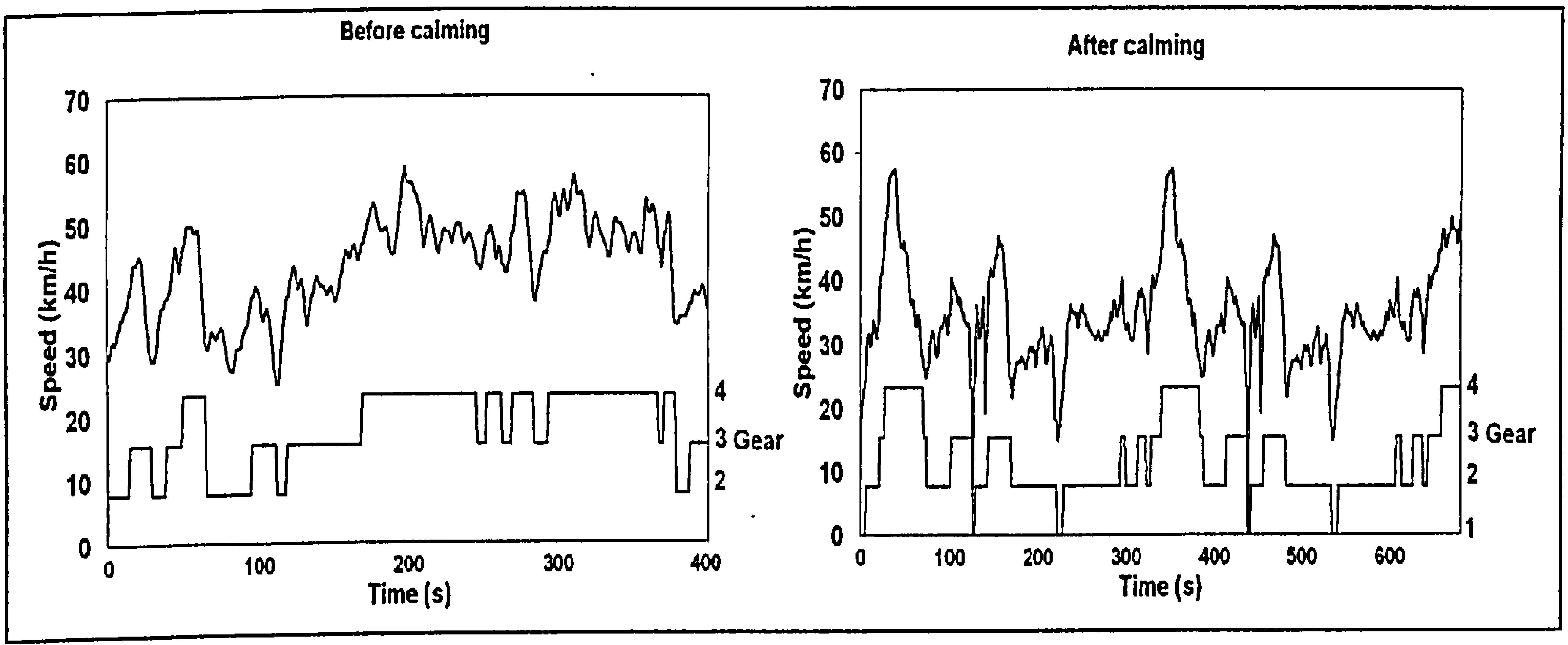

Figure 7.8 Driving cycles - Scheme G: build-out.

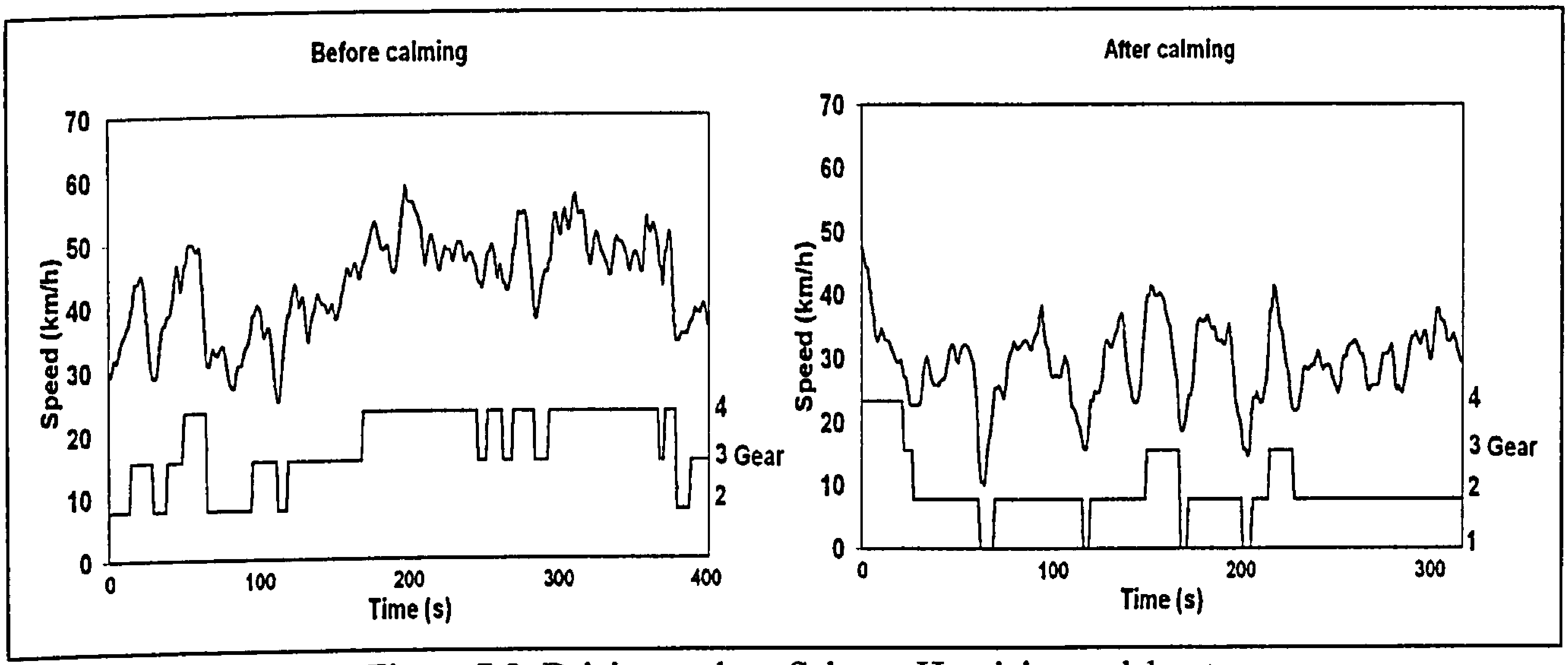

Figure 7.9 Driving cycles - Scheme H: mini-roundabout.

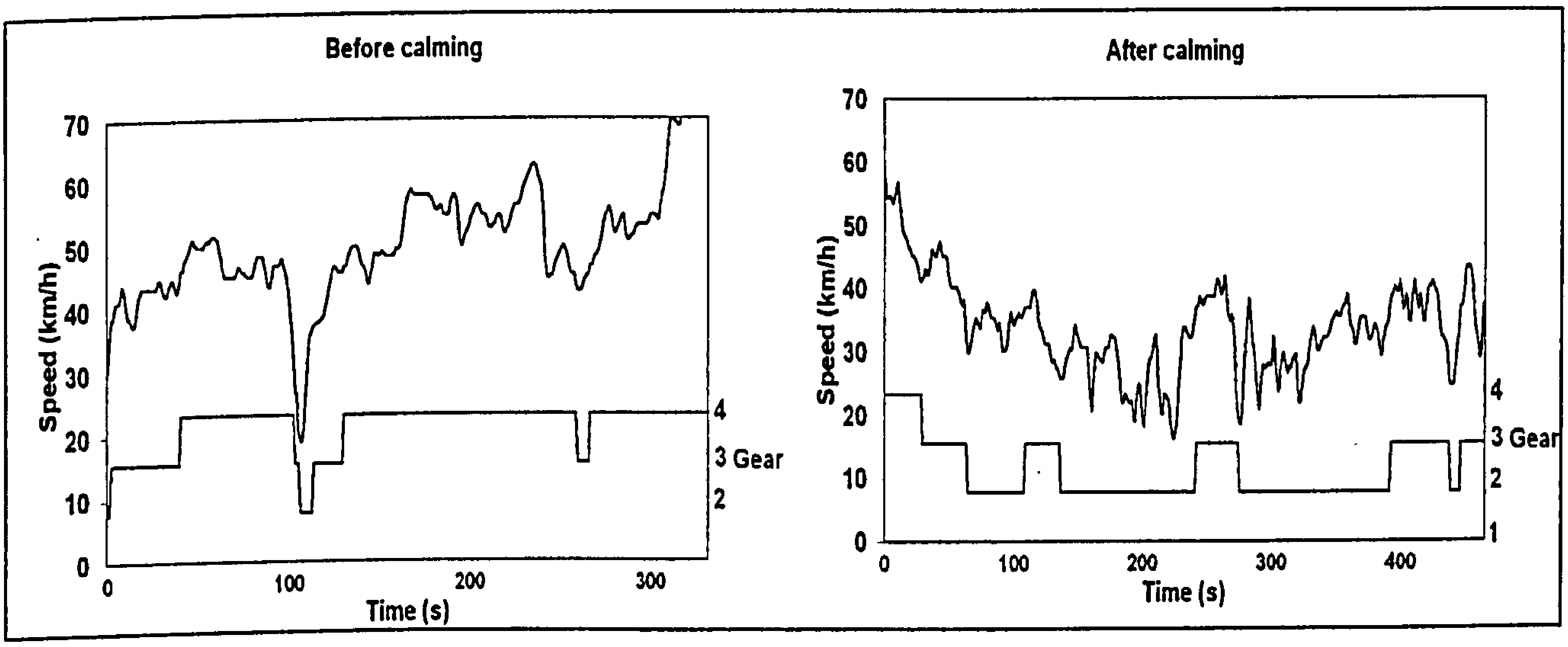

Figure 7.10 Driving cycles - Scheme I: 1.9m-wide speed cushions.

CHAPTER 8 EXHAUST EMISSIONS

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

8.1 Vehicle selection and test procedure

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, based on criteria defined by TRL. 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 8.1.

Table 8.1 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	3
Medium (1.4 to 1.7 litres)	2	2	
Large (>1.7 litres)	2	2	

Although an effort was made by AEA to ensure that the same fifteen vehicles were used throughout the entire test programme, this could not be achieved in practice and several changes were required. When a vehicle had to be withdrawn from the programme, it was replaced by a vehicle which fitted 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 characteristics of the vehicles used in the test programme are listed in Table 8.2. It was not assumed that the emission rates measured for each of these particular models were related to the model itself or the manufacturer, simply that they were 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) at AEA 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 (VCA) 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 a non-dispersive infra-red (NDIR) analyser 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 VCA, 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.

Four tests (*i.e.* two 'calmed' and two 'uncalmed') were carried out 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. In order to warm up these components, a regulation EUDC cycle was driven until a target oil temperature of 90°C was attained. This so-called 'preconditioning' of the vehicle is often employed in emission testing to avoid any variability in emissions arising from cold start effects.. 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. In the tests relating to schemes G and H, for which the same 'before calming' cycle was used, six tests (*i.e.* four 'calmed' and two 'uncalmed') were conducted on each vehicle, with the bag analysis taking place after the third and sixth tests. 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. The implications of these changes in the sampling procedure are discussed later in the Chapter.

Table 8.2. Details of Vehicles Tested.

Vehicle reference number	Make	Model	Fuel Type	Catalyst	Emission Control level	Size/ class	Year	Engine size (l)	Mileage[a]
1	Ford	Fiesta	Petrol	No	83/351/EEC (ECE Reg. 15.04)	Small	1990	1.1	86,000
2	Ford	Fiesta				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 (EURO 1)	Small	1993	1.1	57,000
10	Rover	Metro				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 (EURO 1)	No size discrimination	1991	2.0	170,000
21	Peugeot	405DT					1992	1.9	112,000
22	Peugeot	306Dt					1996	1.9	26,000

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

8.2 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 B. For each pair of tests associated with a given pollutant, vehicle, and driving cycle, the emission values were averaged by AEA, and the average values were used to determine the overall impact of a particular scheme in terms of the percentage change in emissions per vehicle-kilometre. All subsequent analysis of the emission test data was performed at TRL.

8.2.1 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 8.1. 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 8.3. The asterisks against some of the changes in Table 8.3 indicate where paired-sample *t*-tests showed that the increase in emissions was significant at the 95% confidence level.

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 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 which were recorded in some of the previous studies (see Table 2.6) 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 8.2. Similar plots for petrol catalyst and diesel cars are presented in Appendix C.

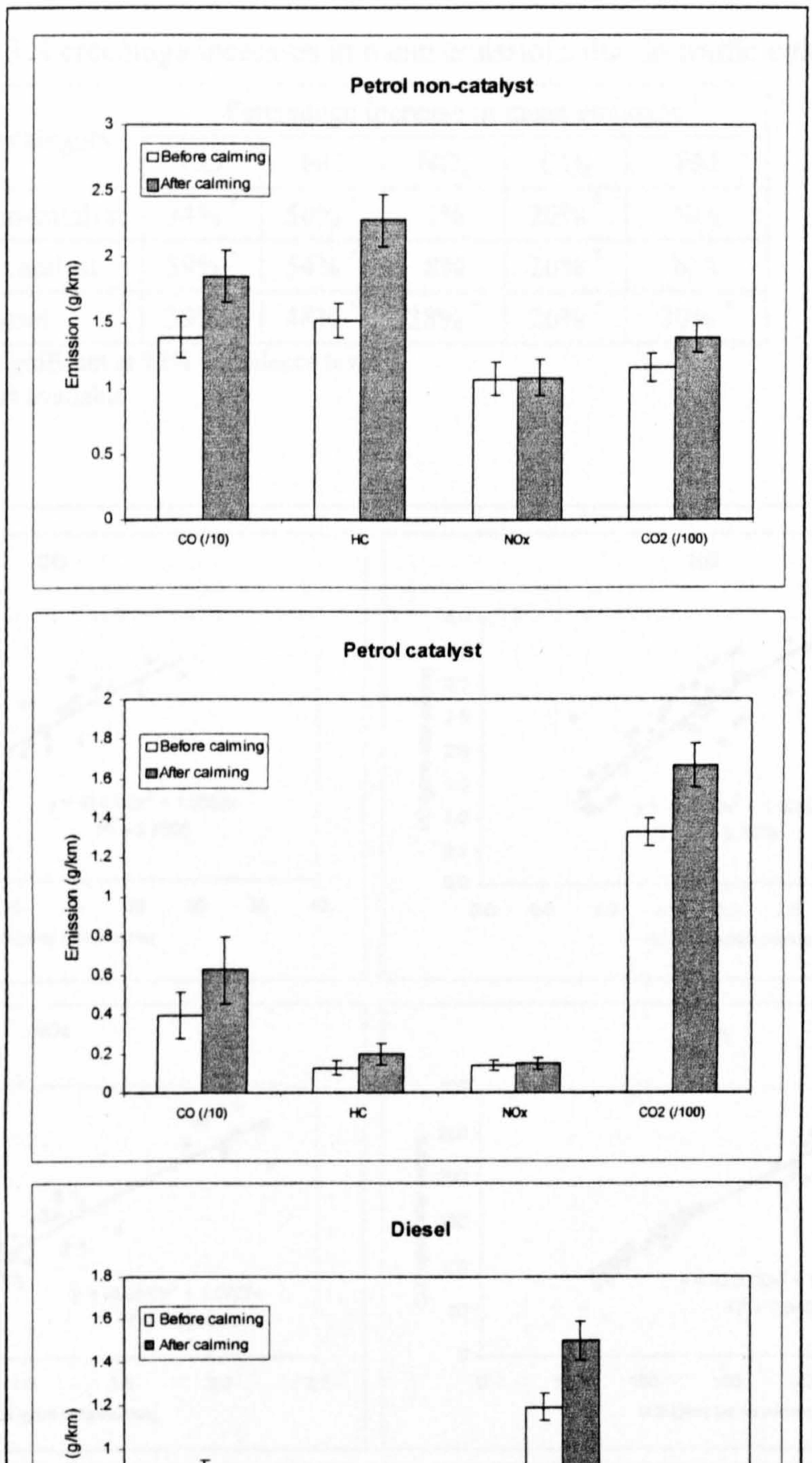

Figure 8.1 Mean emissions of CO, HC, NO_x, and CO_2 before and after calming for the three categories of vehicle (the I-beams represent the 95% confidence intervals on the means, and emissions of total particulate matter are also shown for diesel cars).

Table 8.3 Percentage increases in mean emissions due to traffic calming.

Vehicle category	Percentage increase in mean emission				
	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

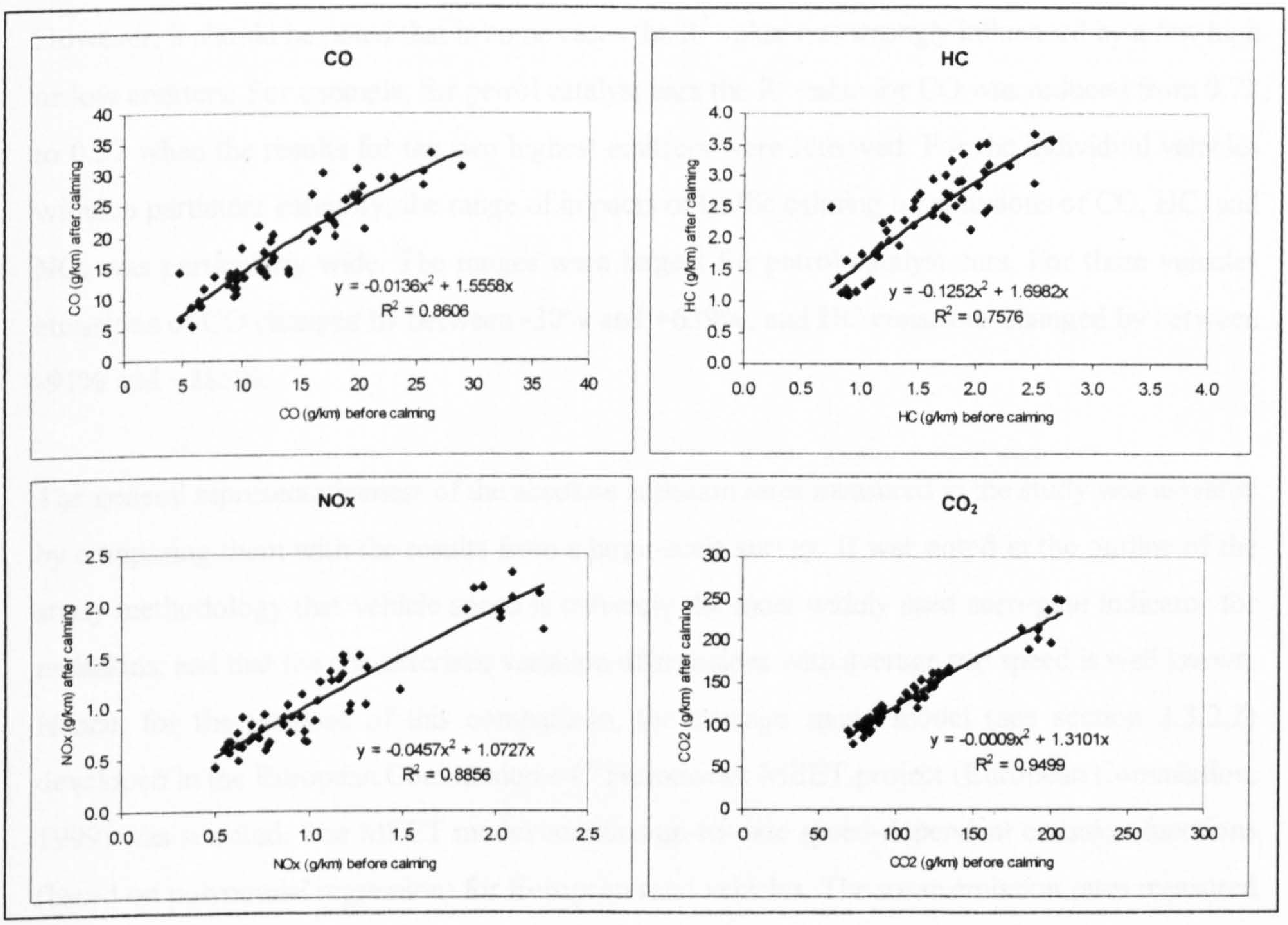

Figure 8.2. Emissions after calming plotted against emissions before calming for petrol non-catalyst cars (results for all nine schemes).

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 comparatively 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 value 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 'high emitters'.

However, it should be noted that in some cases the R^2 value was strongly 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 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. Hence, for the purpose of this comparison, the average speed model (see section 3.3.2.2) developed in the European Commission's 4th Framework MEET project (European Commission, 1999) was selected. The MEET model contains up-to-date speed-dependent emission functions (based on polynomial regression) for European road vehicles. The mean emission rates measured in the TRL study are compared with the equivalent MEET emission rates in Table 8.4. The TRL and MEET values have been calculated in the same way; an emission rate was 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 underlying MEET emission data (*i.e.* the data used to develop the regression equations) 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 are shown in Figure 8.3.

Table 8.4. 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).

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

[a] Stated as VOC in MEET.

[b] MEET emission rates weighted according to engine size distribution in TRL vehicle sample.

[c] MEET emission rates weighted according to technology level in TRL vehicle sample.

However, 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, but this is discussed in more detail in Chapter 11.

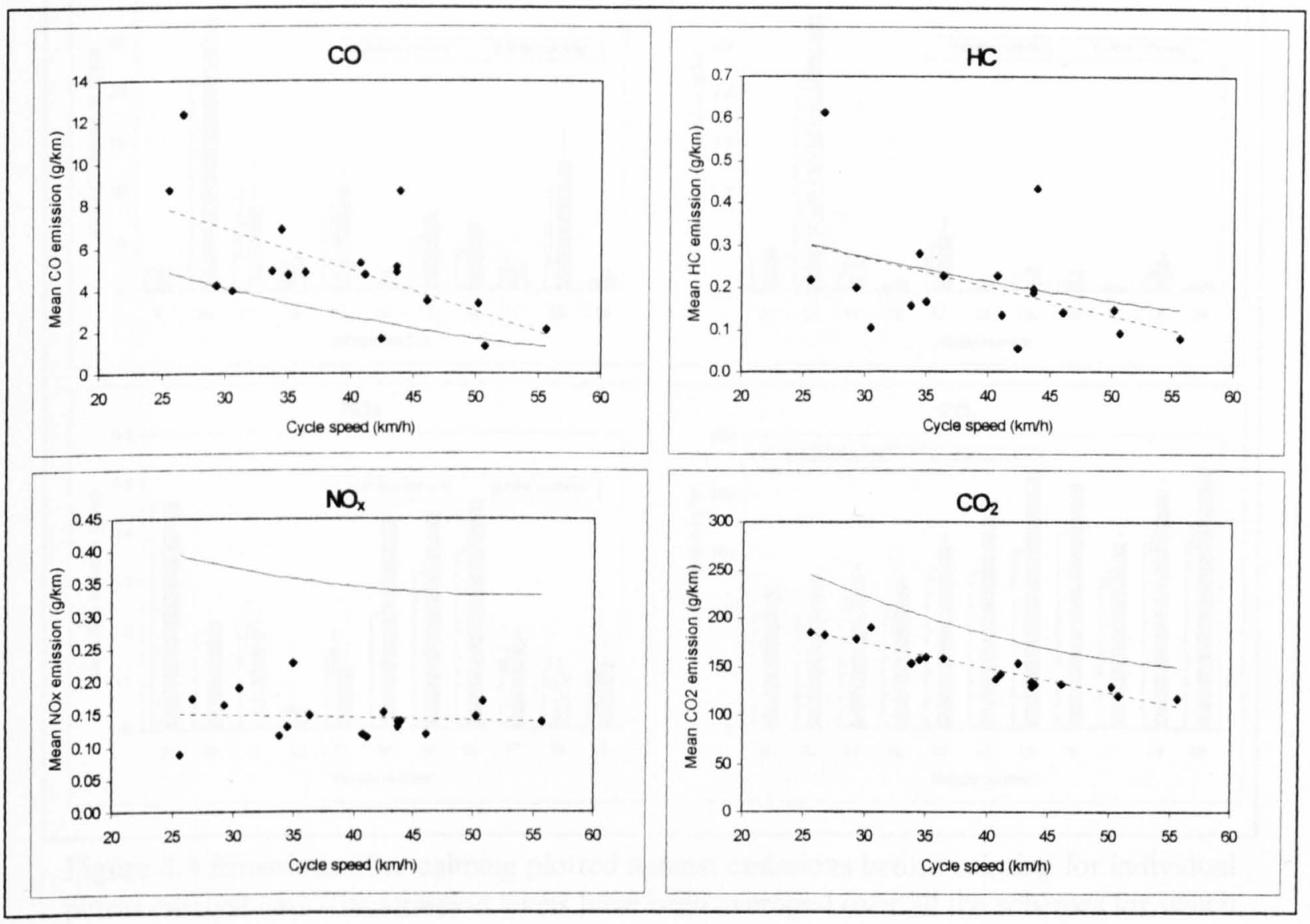

Figure 8.3 Speed dependency of absolute emission rates in TRL study and MEET model for petrol catalyst cars (the solid lines are derived from the MEET emission functions, the data points are average emission values over each TRL driving cycle, and the dotted line is a linear regression fit to the data points).

The mean emission levels of each test vehicle for all schemes before and after calming were also calculated. Some of the results for petrol catalyst cars are presented in Figure 8.4. 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 carburetor (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 D).

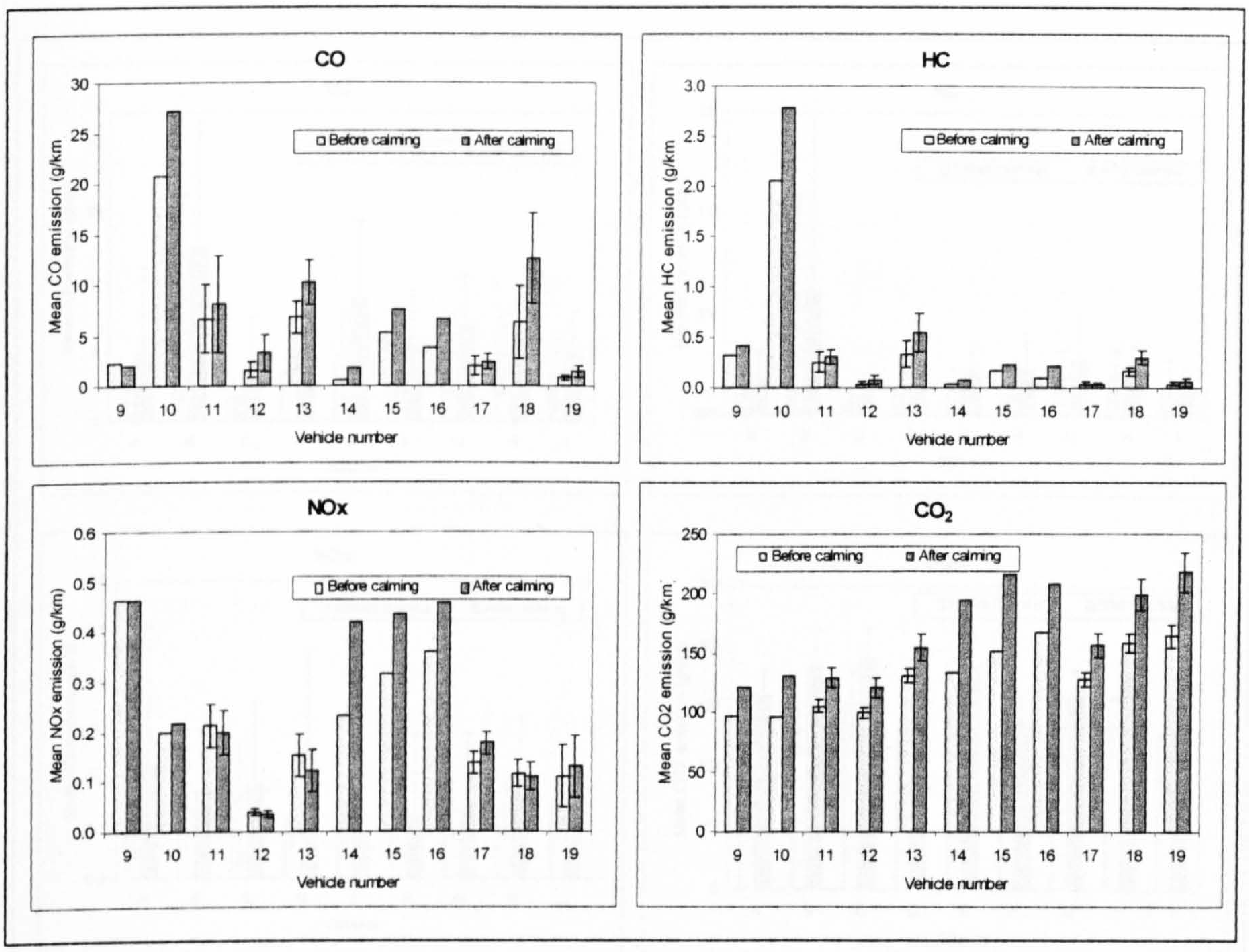

Figure 8.4 Emissions after calming plotted against emissions before calming for individual petrol catalyst cars (the emission levels have been averaged over all the schemes for which a vehicle was tested, and the I-beams represent the 95% confidence intervals on the means).

8.2.2 Emissions by scheme

The mean emission rates of all the petrol catalyst vehicles tested over the cycles for each scheme are presented in Figure 8.5. The equivalent plots for petrol non-catalyst and diesel cars are shown in Appendix E. It should again be noted that the vehicle sample changed during the test 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 8.5. 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.

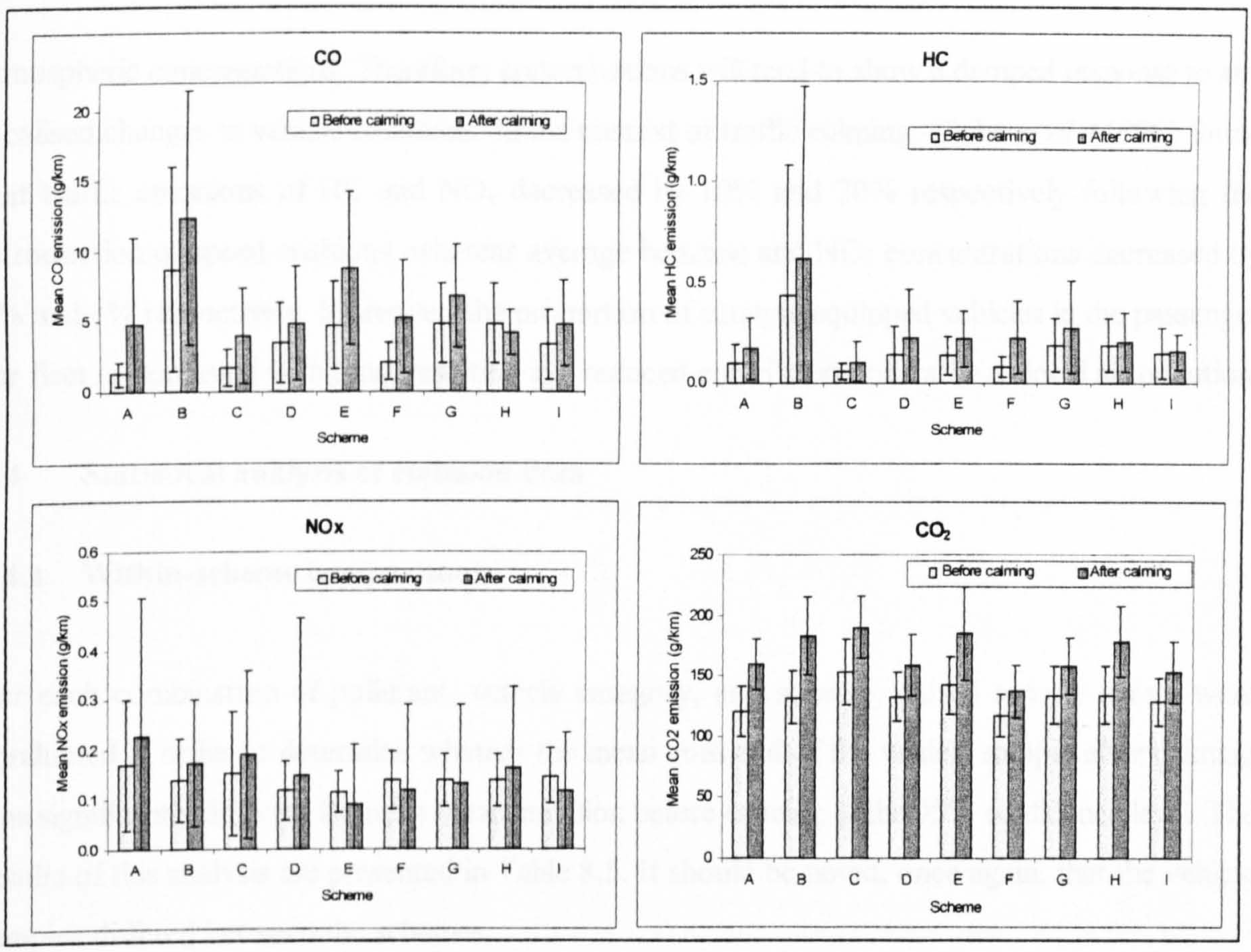

Figure 8.5 Emissions from petrol catalyst cars after calming plotted against emissions before calming for individual schemes (the emission levels have been averaged over all the vehicle tested for a particular scheme, and the I-beams represent the 95% confidence intervals on the means).

8.3 Implications of test results for local air quality

The UK Air Quality Strategy (Department of the Environment *et al.*, 1997) detailed 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 diameter less than 10μm (PM_{10}). The ambient concentrations of these pollutants were not measured at the study sites, nor was any pollutant dispersion modelling undertaken. However, a number of general observations suggest that the observed increases in traffic emissions would have been unlikely to have resulted in breaches of the air quality standards at the sites. Firstly, 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 pollutant emissions from traffic are superimposed on a background concentration that includes emissions from traffic in surrounding areas, and a range of sources and phenomena unrelated to traffic also affect atmospheric concentrations. Therefore, concentrations will tend to show a damped response to any localised changes in vehicle emissions. In the context of traffic calming, Cloke *et al.* (1999) found that traffic emissions of HC and NO_x decreased by 10% and 20% respectively following the introduction of speed cushions, whereas average benzene and NO_2 concentrations decreased by 5% and 1% respectively. Moreover, the proportion of catalyst-equipped vehicles in the passenger car fleet is increasing with time, resulting in a reduced contribution of traffic to local air pollution.

8.4 Statistical analysis of emission data

8.4.1 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 8.5. It should be noted, once again, that the vehicle samples differed between the schemes.

Table 8.5 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	

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.

8.4.2 Between-scheme comparisons

One of the objectives of the research 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 10 of the Thesis. 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 the one 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.

The results in Table 8.4 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, it was assumed that the percentage change in emissions would be a better indicator of 'impact' than the absolute change, and all the statistical tests were conducted on the percentage changes. 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 Thesis, 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. As the interpretation of the results of the statistical tests is somewhat subjective, this difference was not considered to be problematic.

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. For this purpose a multiple pairwise comparison method, 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 ensured that the experimentwise error rate was held to a constant significance level regardless of how many comparisons were being made. The results of the tests are presented in Tables 8.6-8.10. For example, the results for CO presented in Table 8.6 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.

The scheme order in each of Tables 8.6-8.10 is slightly different to that presented in Chapter 10, because of the differences in the calculation method explained previously. The results have only been used to determine whether the impacts of the different schemes are statistically distinguishable. In this Chapter, the results have been used to assess, in general terms, whether an ordering for a particular vehicle category and pollutant category is appropriate.

Table 8.6 Student-Newman-Keuls (SNK) test results: Carbon monoxide.

Vehicle category	SNK Group	Scheme ← Decreasing impact								Increasing impact →
Petrol non-catalyst		I	H	G	C	D	E	A	B	F
	I	▨	▨	▨	▨	▨	▨	▨	▨	
	II									▨
Petrol catalyst		D	H	B	G	E	I	C	F	A
	I	▨	▨	▨	▨	▨	▨	▨	▨	
	II			▨	▨	▨	▨	▨	▨	▨
Diesel		D	C	H	G	F	A	E	I	B
	I	▨	▨	▨	▨	▨	▨			
	II		▨	▨	▨	▨	▨	▨		
	II			▨	▨	▨	▨	▨	▨	▨

Table 8.7 Student-Newman-Keuls (SNK) test results: Hydrocarbons.

Vehicle category	SNK Group	Scheme								
		← Decreasing impact								Increasing impact →
Petrol non-catalyst		G	C	D	H	I	E	A	B	F
	I	▨	▨	▨	▨	▨	▨			
	II		▨	▨	▨	▨	▨	▨	▨	
	II							▨	▨	▨
Petrol catalyst		D	H	C	I	E	G	B	A	F
	I	▨	▨	▨	▨	▨	▨	▨	▨	▨
Diesel		D	E	C	G	H	F	B	I	A
	I	▨	▨	▨	▨	▨	▨	▨	▨	▨

Table 8.8 Student-Newman-Keuls (SNK) test results: Oxides of nitrogen.

Vehicle category	SNK Group	Scheme								
		← Decreasing impact								Increasing impact →
Petrol non-catalyst		I	F	G	E	H	D	B	C	A
	I	▨	▨							
	II			▨						
	III				▨	▨	▨	▨		
	IV								▨	▨
Petrol catalyst.		E	F	I	G	H	D	C	A	B
	I	▨	▨	▨	▨	▨	▨	▨	▨	▨
Diesel		G	I	F	D	C	H	A	E	B
	I	▨	▨	▨	▨	▨				
	II						▨	▨	▨	▨

Table 8.9 Student-Newman-Keuls (SNK) test results: Carbon dioxide.

Vehicle category	SNK Group	Scheme								
		← Decreasing impact								Increasing impact →
Petrol non-catalyst		F	I	D	G	C	E	H	B	A
	I	▨								
	II		▨							
	III			▨	▨					
	IV					▨	▨			
	V						▨	▨		
	VI							▨	▨	▨
Petrol catalyst		F	G	I	D	C	E	A	H	B
	I	▨	▨	▨	▨	▨				
	II						▨	▨	▨	
	III							▨	▨	▨
Diesel		I	G	F	D	C	H	B	E	A
	I	▨	▨	▨	▨	▨				
	II		▨	▨	▨	▨	▨	▨		
	III					▨	▨	▨	▨	
	IV								▨	▨

Table 8.10 Student-Newman-Keuls (SNK) test results: Particulate matter.

Vehicle category	SNK Group	Scheme ← Decreasing impact							Increasing impact →	
		I	B	E	D	G	H	C	F	A
Diesel	I	▨	▨	▨	▨	▨	▨	▨	▨	
	II									▨

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.

8.5 Influence of sampling conditions

The test procedure during the sampling of emissions was described in Section 8.1. It was found that the changes in the preconditioning and test sequence increased the variability of the results in general, and for petrol catalyst cars in particular. Figures 8.6, 8.7, and 8.8 show the mean emission rates of CO, HC, and NO_x from the three car categories when driven through the various test sequences. The letters 'U' and 'C' stand for 'uncalmed' and 'calmed' respectively. The sample of vehicles, the schemes included, and the number of vehicles tested, varied according to the test sequence. This accounts for the differences in the absolute emission rates between the sequences. The number of vehicles tested over each sequence is shown in Table 8.11.

Table 8.11 Numbers of vehicles tested by test sequence.

Preconditioning cycle	Test sequence	Percentage of all vehicle-cycle test combinations by test sequence and vehicle category		
		Petrol non-catalyst	Petrol catalyst	Diesel
EUDC	U-U-C-C	6%	11%	4%
	U-C-U-C	23%	15%	21%
	U-C-C-U	33%	23%	29%
	C-U-C-U	0%	2%	0%
120 km/h	C-U-U-C	2%	0%	0%
	U-C-C-U	30%	36%	33%
	U-C7-C8-C7-C8-U	6%	13%	13%
	Total	100%	100%	100%

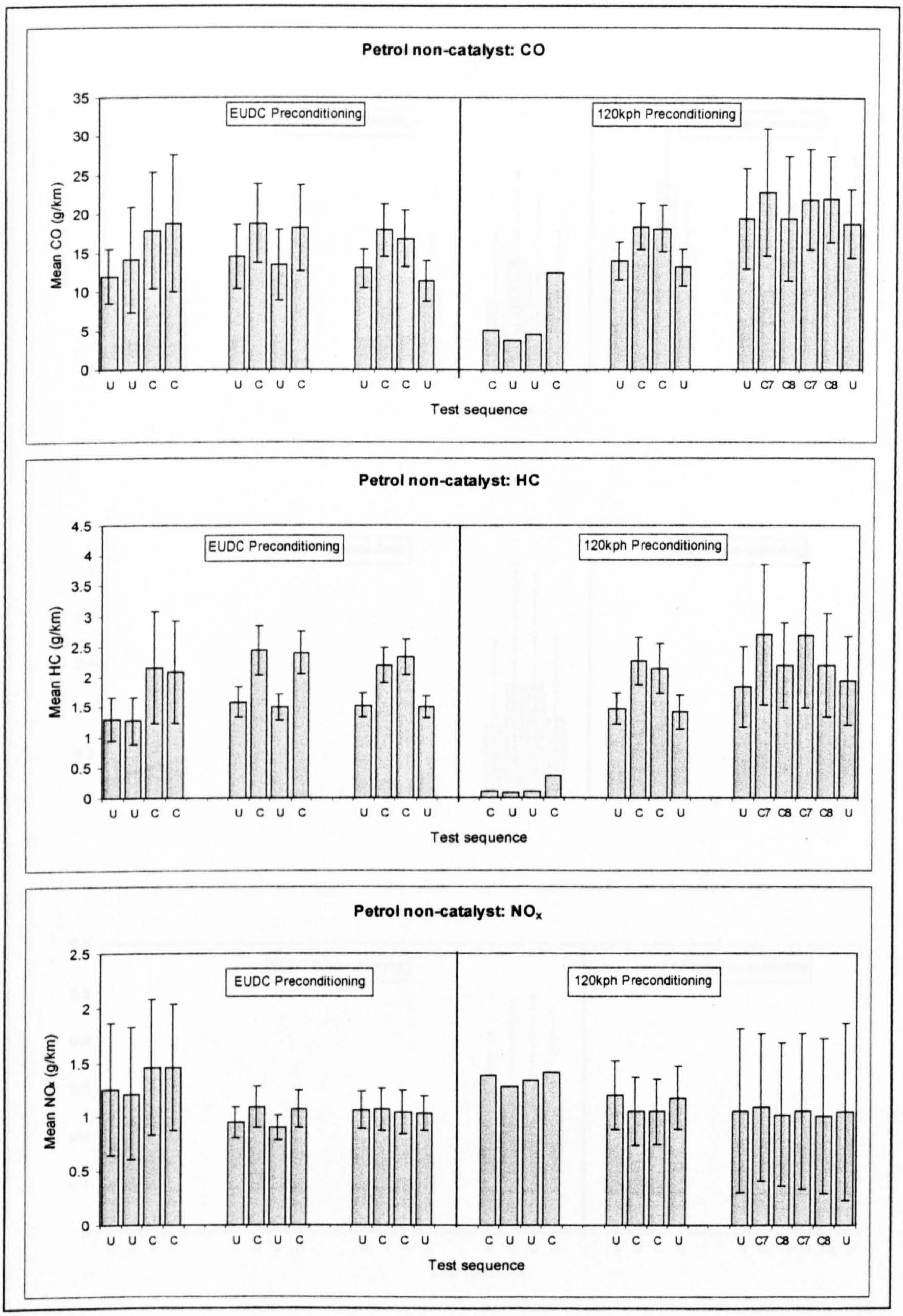

Figure 8.6 Emissions of CO, HC and NO_x from petrol non-catalyst cars over various test sequences (I-beams show 95% confidence intervals).

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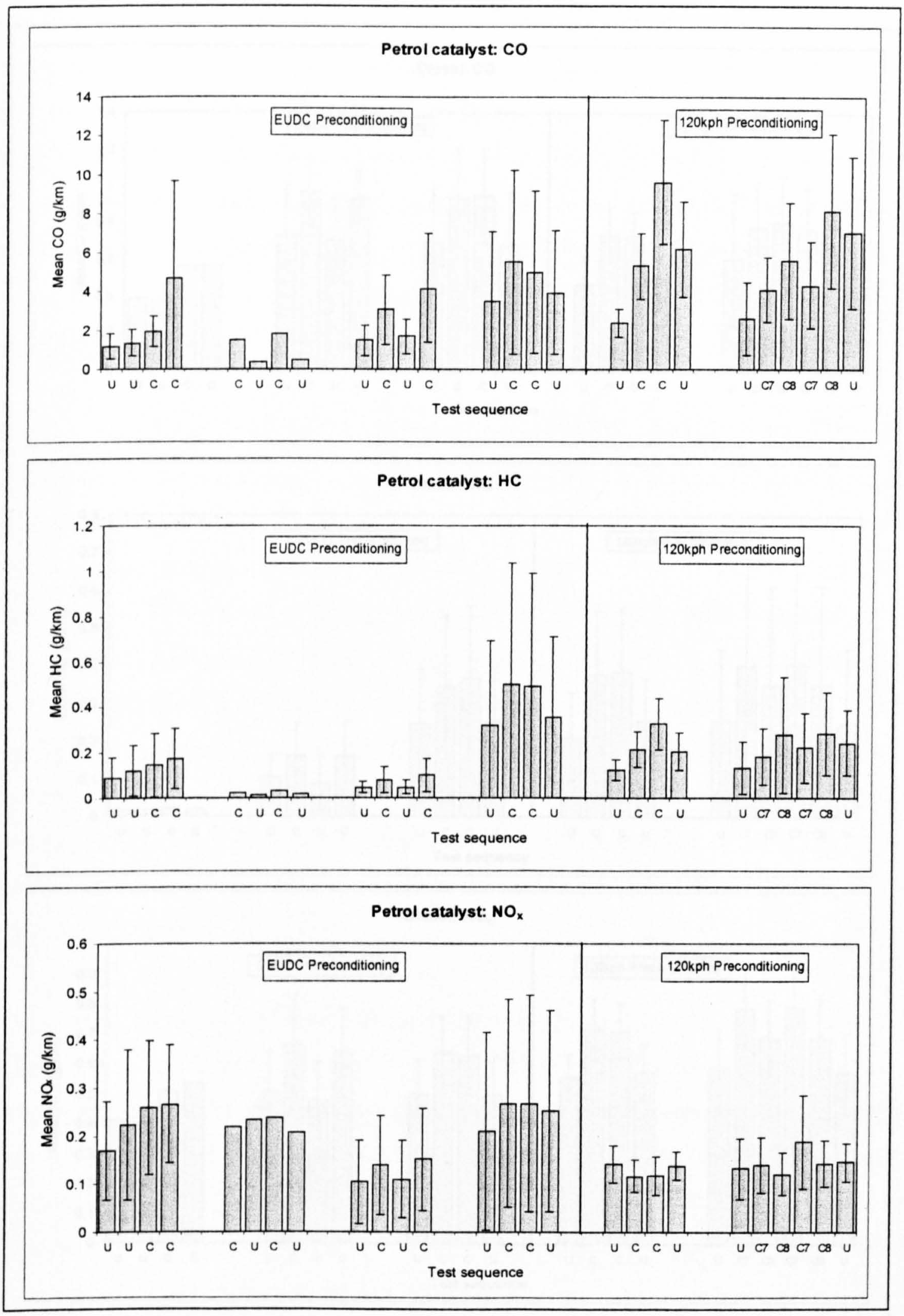

Figure 8.7 Emissions of CO, HC and NO_x from petrol catalyst cars over various test sequences (I-beams show 95% confidence intervals).

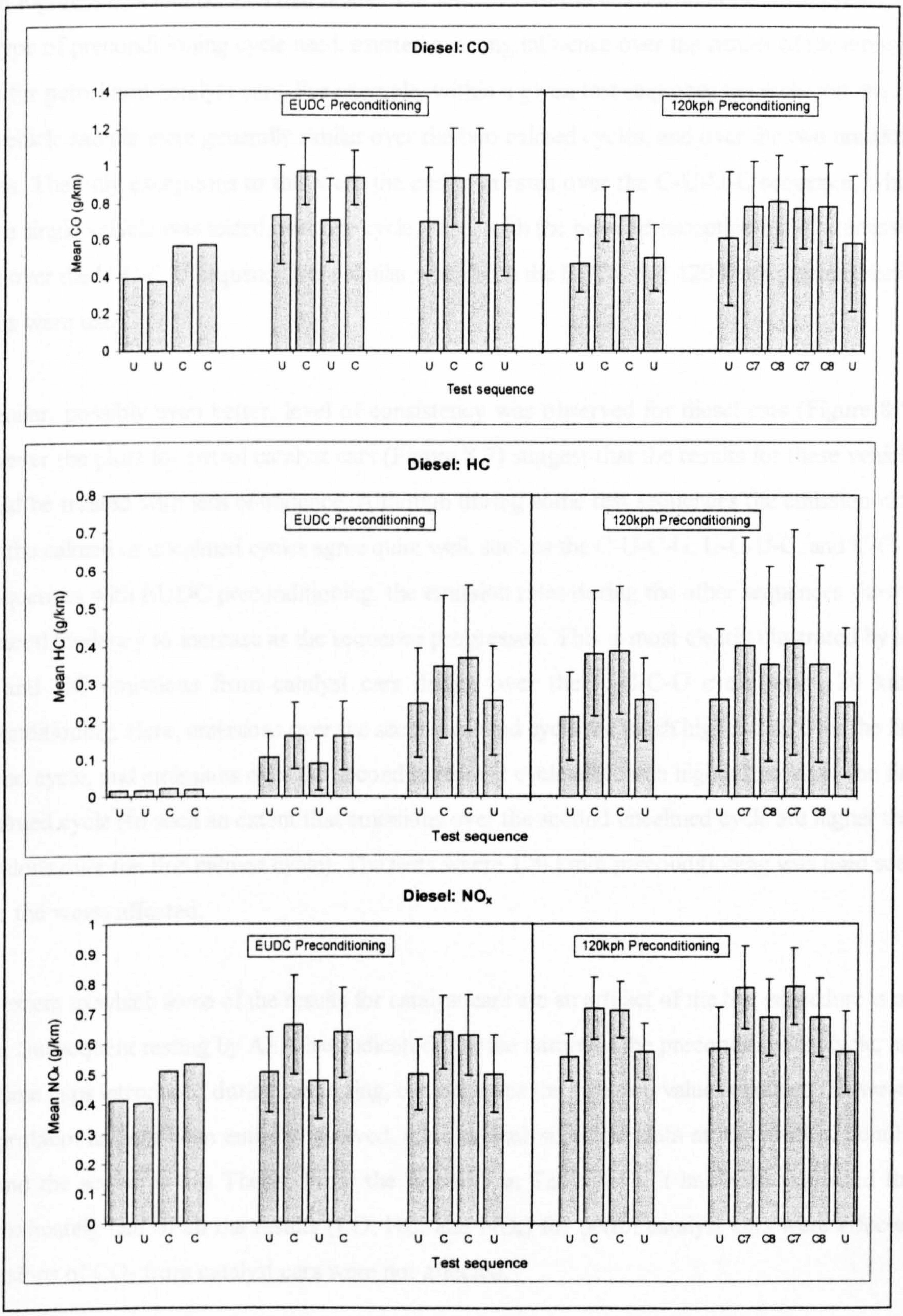

Figure 8.8 Emissions of CO, HC and NO_x from diesel cars over various test sequences (I-beams show 95% confidence intervals).

From Figure 8.6, it can be seen that neither the sequence of the calmed and uncalmed cycles, nor the type of preconditioning cycle used, exerted a strong influence over the results of the emission tests for petrol non-catalyst cars. For example, within a given test sequence the emission rates of the vehicle sample were generally similar over the two calmed cycles, and over the two uncalmed cycles. The only exceptions to this were the emission rates over the C-U-U-C sequence, where only a single vehicle was tested over one cycle. Also, with the possible exception of NO_x, emission rates over the U-C-C-U sequence were similar when both the EUDC and 120 km/h preconditioning cycles were used.

A similar, possibly even better, level of consistency was observed for diesel cars (Figure 8.8). However the plots for petrol catalyst cars (Figure 8.7) suggest that the results for these vehicles should be treated with less confidence. Although during some test sequences the emission rates over the calmed or uncalmed cycles agree quite well, such as the C-U-C-U, U-C-U-C, and U-C-C-U sequences with EUDC preconditioning, the emission rates during the other sequences showed a general tendency to increase as the sequence progressed. This is most clearly illustrated by the CO and HC emissions from catalyst cars driven over the U-C-C-U cycle with 120 km/h preconditioning. Here, emissions over the second calmed cycle are much higher than over the first calmed cycle, and emissions over the second uncalmed cycle are much higher than over the first uncalmed cycle (to such an extent that emissions over the second uncalmed cycle are higher than emissions over the first calmed cycle). The tests where 120 km/h preconditioning was used seem to be the worst affected.

The extent to which some of the results for catalyst cars are an artifact of the test procedure is not clear. Subsequent testing by AEA 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 Thesis. From the numbers in Table 8.11, it has been estimated that approximately half of all the results (CO, HC, and NO_x) for petrol catalyst cars were affected. Emissions of CO_2 from catalyst cars were not affected.

8.6 Summary

Exhaust emission measurements were conducted by AEA Technology, based on the driving cycles supplied by TRL. Twelve cars (6 petrol non-catalyst, 6 petrol catalyst, and 3 diesel) were tested over each cycle. 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 vehicle category emissions per kilometre were higher over the driving cycles designed to reflect 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. For each vehicle category the increase in mean HC emissions was close to 50%. The mean emission of NO_x from petrol vehicles increased slightly, whereas NO_x emissions from diesel vehicles increased by around 30%. Emissions of CO_2 increased by 20-26%. For diesel vehicles, emissions of particulate matter increased by 30%. These results 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, Züger 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), 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 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 Züger 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.

The mean emission rates measured in the study were also compared with those predicted by the MEET average-speed model. There was only a fair level of agreement between the absolute measured and modelled emissions. However, 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-kilometre. 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.

Although no study of ambient pollutant concentrations was undertaken, it was considered unlikely that the observed increases in emissions would have resulted in breaches of air quality standards at the study sites.

A multiple pairwise comparison method (the 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.

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. It was found that the changes in the preconditioning and test sequence increased the variability of the results in general, and for petrol catalyst cars in particular.

CHAPTER 9 ON-ROAD REMOTE SENSING MEASUREMENTS

The emission test results presented in the previous Chapter of this Thesis were based on a total sample of 22 passenger cars. This sample was less than one millionth of the number of light-duty vehicles on British roads. Clearly, there was a need to determine the extent to which the effects of traffic calming measured in the dynamometer tests were reflected in the emission behaviour of a larger number of vehicles. In response to this need for representative information, a remote sensing study was conducted near traffic calming measures in Gloucester to examine changes in the on-road emissions of a local fleet of vehicles. There appears to be no previous record in the literature of remote sensing techniques being used in this manner.

The study was conducted in the residential Longlevens area of Gloucester, and formed part of TRL's assessment of the DETR-funded Safer City Project. In the Safer City Project, a coherent range of road safety and traffic management measures are being implemented over a five year period, and in Longlevens the area-wide traffic calming approach was adopted. The remote sensing work is summarised in this Chapter. Further details can be obtained in a TRL report describing the study (Boulter, 1999).

9.1 Site selection

During the experimental design stage of the remote sensing study in the spring of 1997, the aim was to investigate the effects of two similar road humps. The actual traffic calming measures to be studied, and suitable sites for the 'before' surveys, were identified from plans of the scheme provided by Gloucester City Council, with particular consideration given to certain restrictions. For example, the road had to be comparatively narrow to limit attenuation of the light beam of the remote sensing system, the traffic flow had to be sufficient to generate a large sample size, and the traffic had to be free-flowing to maximise the effects of changes in operation.

Two suitable sites were identified. At these sites, on Longford Lane and Oxtalls Lane, flat-top road humps were due to be installed in November 1997. However, after the 'before calming' surveys had been completed (July 1997) the plans for part of Oxtalls Lane scheme were changed by the local authority. The authority decided not to proceed with the road hump on Oxtalls Lane, but to introduce a pair of speed cushions at a different location on the road. Consequently, the assessment on Oxtalls Lane focussed on the speed cushions.

Selection of the exact locations for the 1997 surveys was comparatively straightforward. It was assumed that once a vehicle was moving freely along the roads, its operation would be similar at different points. The exact locations for the surveys were therefore not considered critical. In fact, they were conducted near the proposed locations for the measures. Site selection was governed more by practical considerations, particularly the need to park the vehicle housing the FEAT system in a safe position.

However, selection of the locations for the 1998 'after calming' surveys was more difficult, since it was likely that the introduction of the traffic calming measures would cause vehicle operation to vary considerably at various points along the roads. The approach adopted was analogous to the one used commonly to measure the effects of traffic calming measures on vehicle speeds - that is to take measurements both near the measure and between measures (see, for example, Webster and Layfield (1996)). For the assessment of the road hump, the 'near hump' location was identical to the location of the 'before calming' survey. However, no suitable 'between humps' location could be found on Longford Lane, and a site on Innsworth Lane (actually between a hump and a raised junction) was used as an alternative. Suitable sites on Oxtalls Lane were found near and between the cushions. In this case, the 'between cushions' site was identical to the location of the 'before calming' survey, whilst a 'near cushion' site was found near the junction with Alder Close.

The road hump on Longford Lane had a nominal height of 75mm, with an overall length of 6.5m and a ramp gradient of 1:13.5. The centre of the hump was 150m from the junction with Innsworth Lane and Oxtalls Lane. The speed cushions on Oxtalls Lane were installed in pairs.

Each cushion was 75mm high, with an overall length of 3.5m and an overall width of 1.7m. The on-off ramp gradient was 1:10, and the side ramp gradient was 1:4. The cushions near the junction with Alder Close, and those near the junction with Bradley Close, were separated by a distance of 170m. At the Innsworth Lane site, the hump and the raised junction were separated by a distance of 106m.

The timetable for the experimental work is given in Table 9.1. The part of the Longlevens road network investigated in the study is depicted in Figure 9.1, and the layout of one of the survey sites (near speed cushions) is shown in Plate 9.1.

Table 9.1 Timetable for the experimental work.

Measure	Survey	Location	Survey date
Speed cushions	Before calming	Oxtalls Lane	22/7/97
	After calming: near cushions	Oxtalls Lane	21/9/98
	After calming: between cushions	Oxtalls Lane	22/9/98
Road hump	Before calming	Longford Lane	23/7/97
	After calming: near hump	Longford Lane	23/9/98
	After calming: between humps [a]	Innsworth Lane	24/9/98

[a] Actually between a flat-top hump and a raised junctions.

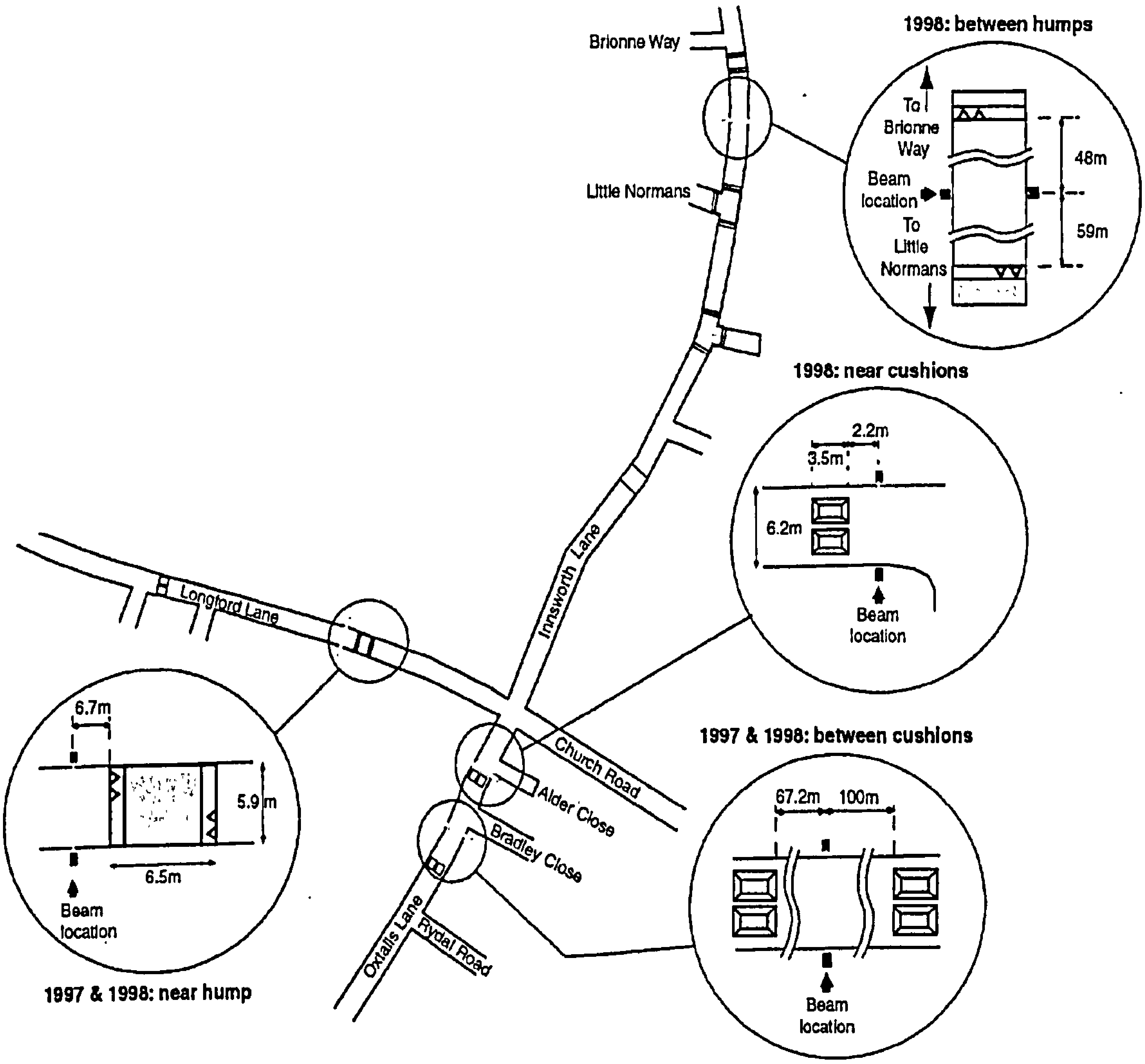

Figure 9.1 Study area and locations of survey sites (not to scale).

Plate 9.1 Survey at 'near cushions' site.

An additional site was employed in the 1998 survey in the hope that this would account for any changes in fleet emission levels resulting from changes in variables not related to vehicle operation (*e.g.* traffic composition and ambient temperature). An attempt was made to identify a suitable site in the study area which had a character similar to that of the calmed roads but was located away from any traffic calming measures. This proved to be difficult, and the only suitable site at which the character of the roads was retained, and where the other site selection criteria were satisfied, was located between two widely-spaced traffic calming measures on Longford Lane. The mean speed and CO level recorded at this site were similar to those recorded at the 'between hump' site on Longford Lane, and it was concluded that the site was too close to traffic calming measures to act as intended. Consequently, no further use was made of the data from the site.

9.2 Field measurements

The FEAT remote sensing system developed by the University of Denver (Section 3.2.4) was used to measure pollutant concentrations in the exhaust plumes of vehicles. Each remote sensing survey was conducted on a separate weekday, between approximately 08:30 and 18:30. During the surveys the detector unit of the FEAT system was placed on one side of the road, with the source unit located directly opposite so that vehicles in both lanes could be monitored. Concentrations (% by volume) of CO, CO_2, and HC in the exhaust plume of individual vehicles were measured using the remote sensing equipment. Although the FEAT equipment can measure NO, the NO channel of the TRL unit was inoperative at the time of the surveys. The speed and acceleration of each vehicle at the time of each FEAT recording were also recorded using two infra red detectors placed alongside the FEAT beam and 1m apart.

During the 1997 surveys a video recording was only obtained for one lane of traffic, since it was felt that the emission distributions would not be lane-specific. However, after the traffic calming had been introduced, it was felt that vehicle operation would be different in each lane. For example, in one lane vehicles would be approaching a measure and would generally slow down, whereas vehicles in the other lane would be departing from the measure and would tend to accelerate. Therefore, a second video camera was introduced for the 1998 surveys so that vehicles travelling in both lanes could be identified.

9.3 Analysis of FEAT data and video tapes

All emission measurements not rejected by the FEAT system were assumed to be valid (including negative values, which are discussed in more detail at the end of this Chapter). Very occasionally, incorrect speed and acceleration values were recorded. These values, which were caused mainly by extraneous reflections received by the sensors, were excluded from the analysis.

For two of the surveys conducted on Longford Lane - the before survey and the after survey near the hump - the video tapes were transcribed. The registration and direction of travel of each vehicle were noted down alongside the corresponding FEAT measurements. A note was also made of the type of vehicle. From the results of the video analysis the vehicles monitored by the FEAT system were separated by their direction of travel: the lane closest to the FEAT vehicle and detector unit was designated as 'lane 1', whilst the far-side lane was designated as 'lane 2'. In both the surveys conducted near the traffic calming measures, vehicles travelling in lane 1 were approaching the measure, whilst those in lane 2 were departing from it.

Vehicles were then separated according to three pre-defined emission categories. The emission categories were defined as follows:

(i) Passenger cars and light goods vehicles without a catalyst (taken to be all conforming vehicles registered before August 1 1993 - *i.e.* pre 'L' registration).

(ii) Passenger cars and light goods vehicles with a catalyst (taken to be all conforming vehicles registered after and including August 1 1993 - *i.e.* 'L' registration and later).

(iii) All other vehicles, including buses, heavy goods vehicles, medium goods vehicles, and motorcycles.

The classification of the first two categories in this way was discussed in Section 6.1

For each traffic calming measure and pollutant studied, a statistical test was conducted to examine the significance of the difference between the emission values before and after calming. Because the values recorded at each site were not normally distributed, the main assumptions underlying the use of the *t*-test were violated. Therefore a non-parametric test - the Mann-Whitney test - was used. All valid FEAT readings obtained at each site were used in the tests.

9.4 Results

9.4.1 Valid FEAT readings

All emission measurements that were not rejected by the FEAT software, and all valid speed and acceleration measurements were used. The numbers of valid data collected during each survey are summarised in Table 9.2. This data includes measurements for all vehicle types. It can be seen that several thousand valid remote sensing results were obtained in each of the surveys.

Similar numbers of beam interruptions were recorded on Oxtalls Lane and Longford Lane before and after calming (*i.e.* 3200-3400). Although inferences about traffic flow could be made from this information, there are inaccuracies that result from variations in the length of time for which the FEAT system was not operational (*e.g.* for re-calibration). Probably more reliable for assessing changes in traffic flow are the average daily flows on these roads recorded by Webster (1998) using automatic counters. The counters were located near to the FEAT survey sites. The daily flows on Oxtalls Lane and Longford Lane before implementation of the scheme were around 5700 and 5400 respectively. After the scheme had been implemented, the traffic flow was 7% lower on Oxtalls Lane, and 9% lower on Longford Lane. However, these changes were not statistically significant.

Table 9.2 Summary of the data collected.

Measure	Survey	Location	Beam interruptions	Valid CO	Valid CO2	Valid HC	Valid speed/ acceleration
Speed cushions	Before calming	Oxtalls Lane	3181 (291)[a]	2499	2519	1496	2830
	Near cushions	Oxtalls Lane	3308 (337)	2525	2550	1776	1080
	Between cushions	Oxtalls Lane	3560 (349)	2836	2843	1725	2648
Flat-top hump	Before calming	Longford Lane	3371 (331)	2424	2447	1253	3076
	Near hump	Longford Lane	3281 (322)	2627	2649	2045	408
	Between humps	Innsworth Lane	4559 (421)	3942	3984	2398	1717

[a] The figure in brackets is the average number of beam interruptions per hour.

The number of beam interruptions at the 'between hump' site on Innsworth Lane was considerably higher than at the other sites, at around 4500. No FEAT survey had been conducted on Innsworth Lane before calming. Webster recorded average daily flows on Innsworth Lane of 7768 before calming and 7090 after calming. This equated to a 9% reduction in traffic flow.

Repeated failure of the speed-measurement system during the after calming surveys resulted in the loss of large amounts of data, particularly near the flat-top hump. However, even the sample obtained in this survey was still large enough to give standard errors on the mean speeds of less than 4%.

9.4.2 Flat-top road humps

9.4.2.1 Traffic composition

The composition of the traffic on Longford Lane was determined from the video recordings for two of the surveys: (i) before calming and (ii) after calming near the hump. The composition was based on the vehicles in lane 1 that were identifiable, and the results are presented in Table 9.3. The results of manual classified traffic counts undertaken by Webster (1998) are included for comparison.

The two classification systems used were slightly different. The definitions used by Webster were those recommended by the Highways Agency *et al.* (1996). However, in the FEAT analysis broader categories were used. All light-duty vehicles (including passenger cars, mini-vans, pick-ups, four-wheel drive vehicles, and all commercial vehicles not powered by heavy-duty diesel engines) were included in the same category. Heavy goods vehicles were defined in the FEAT analysis as all vehicles powered by heavy-duty diesel engines. The vehicle categories used in the FEAT analysis that corresponded approximately to those used by Webster are shown in Table 9.3.

Table 9.3 Composition of 12-hour traffic flow on Longford Lane before and after calming.

Vehicle type (remote sensing classification)	FEAT surveys		Vehicle type (HA classification)	Webster (1998)	
	Before calming (July 1997) (%)	After calming (September 1998) (%)		Before calming (June 1997) (%)	After calming (July 1998) (%)
Cars and Light goods	92.2	91.7	Cars	84.0	80.0
			Light goods	8.7	8.5
Heavy goods	2.3	4.4	Medium goods and heavy goods	2.8	3.1
Buses/coaches	1.8	0.0	Buses/coaches	2.4	3.0
Motorcycles	1.3	1.4	Motorcycles	0.4	1.0
Pedal cycles	2.4	2.5	Pedal cycles	1.7	4.4
Total	100.0	100.0	Total	100.0	100.0

The most important point to note is that, irrespective of how the vehicles were classified, passenger cars and light goods vehicles formed around 90% of the identifiable vehicle fleet on Longford Lane before and after the introduction of the traffic calming scheme. As the FEAT system is optimised to measure emissions from passenger cars and light duty vehicles, it is clear that the emission values that were measured relate to a large proportion of the traffic flow. The proportion of passenger cars and light goods vehicles equipped with a catalyst was obtained based on the criteria given in Section 9.3. It was estimated that during the 1997 FEAT survey on Longford Lane around 32% of these vehicles had a catalyst. By the 1998 FEAT survey the proportion had increased to 39%. It is not clear why no buses were observed on the FEAT video recording for Longford Lane after calming. It may have been possible that during this survey the video camera was aligned in such that any bus interrupting the beam was out of picture when the image was frozen.

9.4.2.2 Speed and acceleration

The mean speeds and accelerations recorded before and after the introduction of the hump were normally distributed. The overall mean values for the three categories of vehicle identified in Section 9.3 are given in Table 9.4. Blank cells in the Table indicate where no video analysis was conducted to categorise vehicles. When the results for all vehicles travelling in both lanes were combined, the mean speed was found to have reduced from 45 km/h (28 mph) before calming to 33 km/h (21 mph) between humps, and 27 km/h (17 mph) near the hump. The mean acceleration rates were found to be small. There was only a slight difference between the mean acceleration rate measured before calming and that measured near the hump, with both surveys yielding a small net deceleration. With the results for all vehicles at the 'near hump' site separated according to direction of travel, the mean deceleration of vehicles in lane 1 (approaching the hump) was 1.3 m/s^2, whereas in lane 2 (departing from the hump) the mean acceleration was +0.6 m/s^2.

Table 9.4 Mean speeds and accelerations.

Vehicle type	Survey	Mean speed (km/h)			Mean acceleration (m/s^2)		
		Lane 1[a]	Lane 2[b]	Both lanes[c]	Lane 1	Lane 2	Both lanes
All vehicles	Before calming	44.7	44.9	44.5	-0.6	-0.5	-0.5
	After calming (near hump)	27.7	26.0	26.7	-1.3	+0.6	-0.4
	After calming (between humps)			32.5			+0.1
Cars: Pre 'L' reg. (*i.e.* non-catalyst)	Before calming	45.2			-0.5		
	After calming (near hump)	28.1	26.2		-1.3	+0.5	
	After calming (between humps)						
Cars: 'L' reg. and after (*i.e.* catalyst)	Before calming	45.0			-0.5		
	After calming (near hump)	28.3	26.8		-1.4	+0.6	
	After calming (between humps)						
All other vehicles	Before calming	41.4			-0.1		
	After calming (near hump)	24.9	23.7		-1.1	+0.9	
	After calming (between humps)						

[a] Lane 1 = near-side lane (approaching the hump in survey conducted near the hump).

[b] Lane 2 = far-side lane (departing from the hump in survey conducted near the hump).

[c] Including vehicles for which the direction of travel was not identified.

Only slight differences were apparent between the speeds of the three vehicle categories near the hump and the speeds before calming. There was also little difference between the effects of the hump on the acceleration and deceleration of non-catalyst and catalyst cars. All other types of vehicle (motorcycles, buses, medium goods vehicles and heavy goods vehicles) were treated as a single category. Other vehicles tended to decelerate before the hump at a slower rate, and accelerate away from the hump at a faster rate than passenger cars.

9.4.2.3 Carbon monoxide

Figure 9.2 shows the CO distributions recorded for all vehicles before and after the introduction of the road hump on Longford Lane. The negative CO values obtained during each survey are included, and the distributions are normalised for the number of valid readings obtained. The distributions are typical of those produced by remote sensing - they are highly skewed with large numbers of vehicles emitting a low amount of CO. It can be seen immediately that the three distributions are very similar in shape and location.

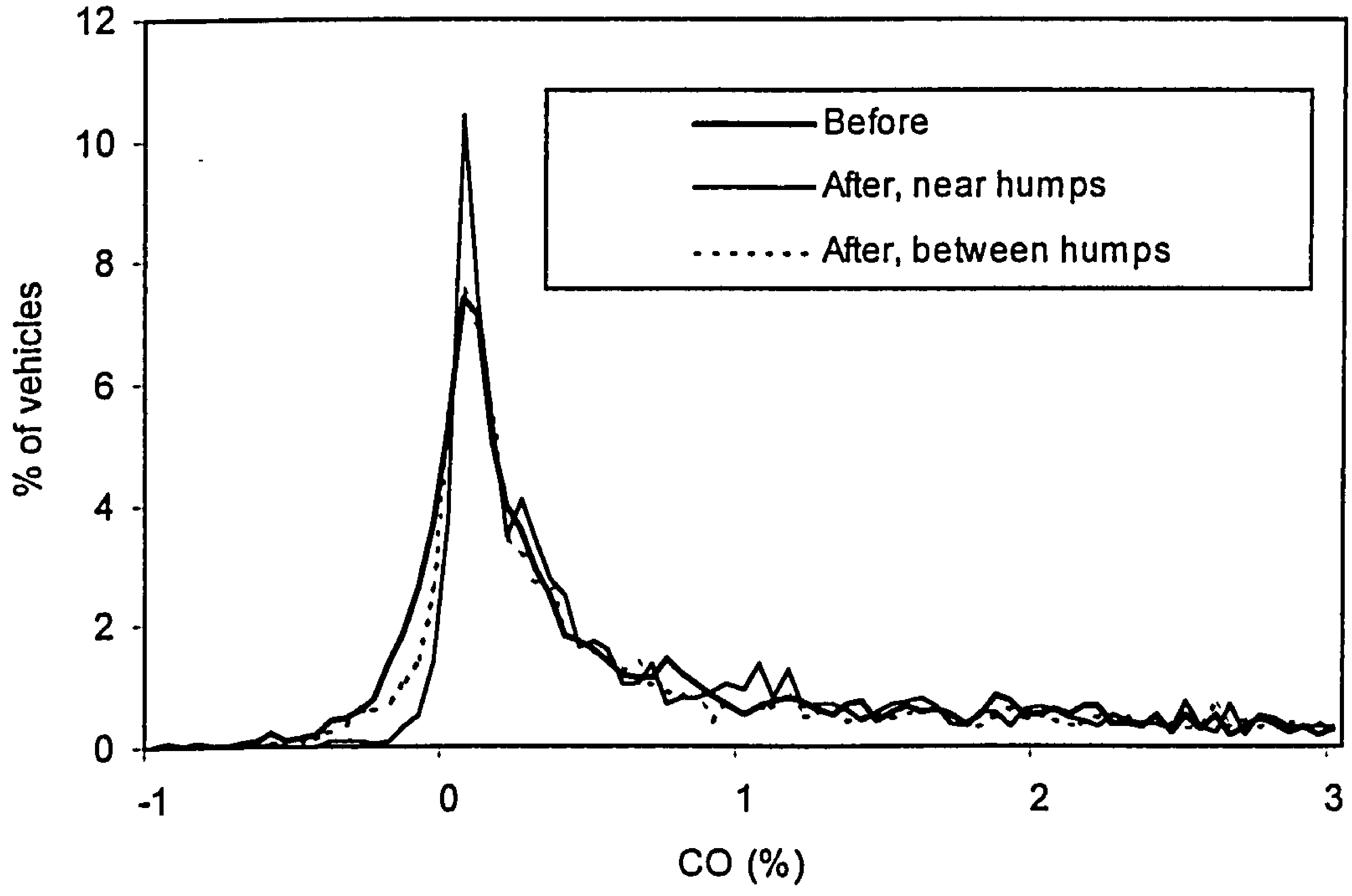

Figure 9.2 CO distributions, flat-top road humps.

The mean and median CO levels recorded before and after the introduction of the hump are given in Table 9.5. The median values are of interest because the skew in each distribution meant that more that 50% of the vehicles had a %CO value lower than the mean. In addition, statistical tests to determine the significance of any differences between the distributions related to the median values. Again, blank cells in the Table indicate where no video analysis was conducted to categorise vehicles.

Table 9.5 Mean and median levels of carbon monoxide in the exhaust plume.

Vehicle type	Survey	Mean CO (%)			Median CO (%)		
		Lane 1	Lane 2	Both lanes[a]	Lane 1	Lane 2	Both lanes[a]
All vehicles	Before calming	1.36	1.08	1.19	0.42	0.31	0.34
	After calming (near hump)	1.84	1.24	1.56	0.79	0.39	0.53
	After calming (between humps)			1.64			0.47
Cars: Pre 'L' reg. (*i.e.* non-catalyst)	Before calming	1.93			1.28		
	After calming (near hump)	2.78	1.82	2.22	2.13	1.11	1.51
	After calming (between humps)						
Cars: 'L' reg. and after (*i.e.* catalyst)	Before calming	0.36			0.06		
	After calming (near hump)	0.57	0.46	0.51	0.18	0.10	0.13
	After calming (between humps)						
All other vehicles	Before calming	0.91			0.12		
	After calming (near hump)	1.57	0.81	1.09	0.64	0.10	0.20
	After calming (between humps)						

[a] Including vehicles for which the direction of travel was not identified.

For all vehicles travelling in both lanes, the mean level of CO in the exhaust gas recorded near the hump and between humps was higher than the level recorded before calming by 30% and 38% respectively. The equivalent increases in the median levels were 56% and 38%. Mann-Whitney tests conducted on these results showed that the observed increase in the median CO level near the hump and between humps was significant at a confidence level greater than 99%. The results of the tests are given in Appendix F. At the 'near hump' site the increase in the mean and median was absolutely and proportionately larger for lane 1 (approaching the hump, net deceleration) than for lane 2 (departing from the hump, net acceleration).

Prior to the experiment it was hoped that the disaggregated before data from lane 1 could also be used to represent the before situation in lane 2 for the different vehicle categories. However, the mean and median CO levels were consistently higher in lane 1 than in lane 2. This suggests that a comparison of lane 1 before data with lane 2 after data is probably not valid for the three vehicle categories. The disaggregated data for the different vehicle categories have only therefore been interpreted for lane 1. Based on the disaggregated data for lane 1 alone, the largest proportional increase in the mean CO level (73%) was observed for vehicles other than passenger cars. The mean CO level for non-catalyst cars increased by 44%, and that for catalyst-equipped cars by 60%.

9.4.2.4 Hydrocarbons

Figure 9.3 shows the HC distributions recorded for all vehicles before and after the introduction of the road hump on Longford Lane. Again, the distributions obtained have been normalised to the number of valid readings for each of the surveys. The mean and median HC concentrations are given in Table 5.6.

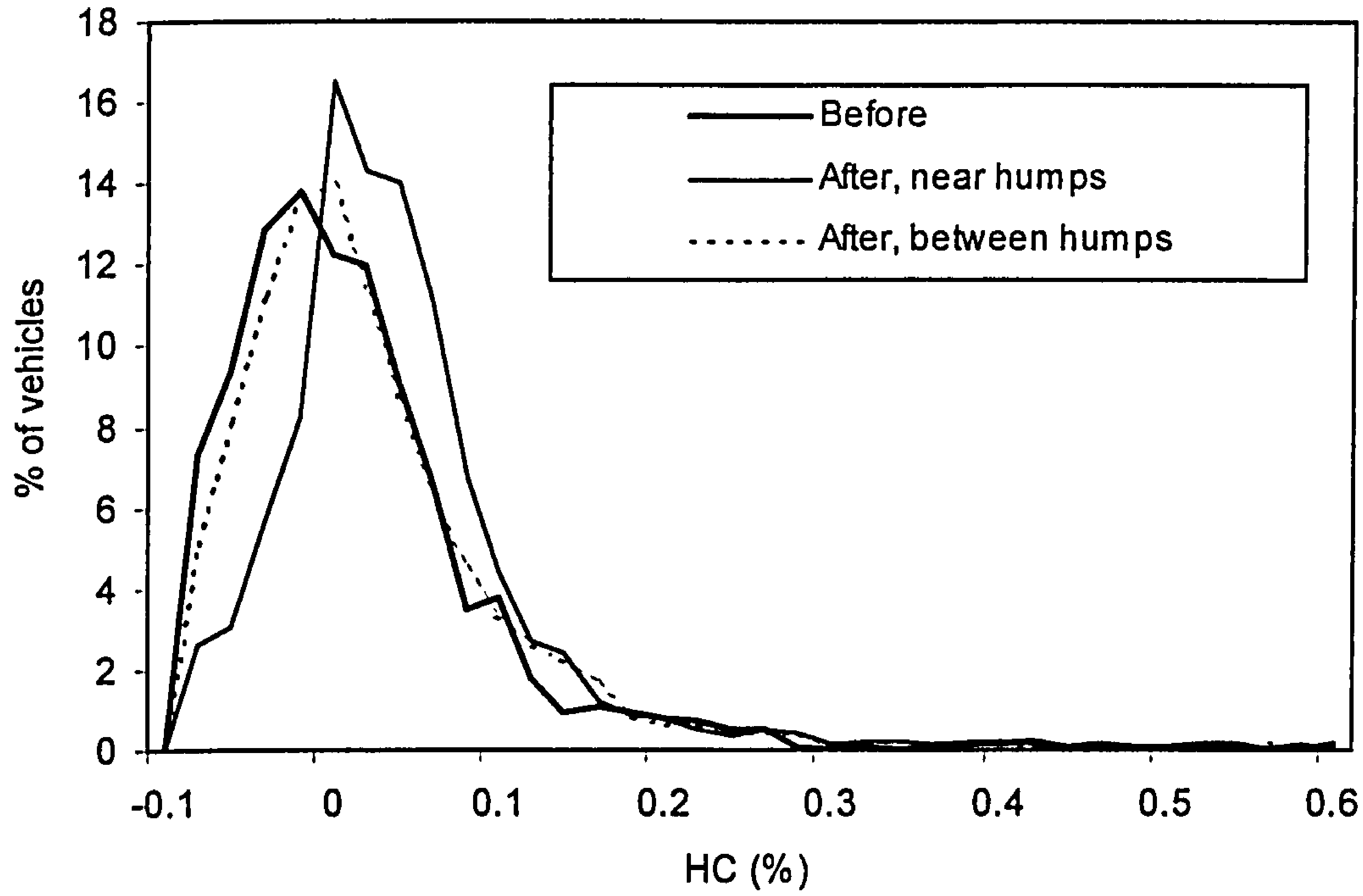

Figure 9.3 HC distributions, flat-top road humps.

The measurements showed that both overall mean and median hydrocarbon levels increased after the introduction of traffic calming. The tests in Appendix F show that the increase in the median level was significant at a confidence level greater than 99%. The HC distributions were far less skewed than the corresponding distributions for CO, though it can be seen that there were proportionally far more negative readings obtained for HC emissions. A further point that should be noted is that the HC concentrations are substantially lower (around a factor of 10) than those found for CO. The fact that the concentrations are comparatively weak probably accounts for the large number of negative readings observed. From these results it therefore appears that the instrument is unable to discriminate between the relatively weak absorption of the hydrocarbons in the exhaust plume and the inherent fluctuations of the measurement technique. The fact that the distributions shown in Figure 9.3, and the values given in Table 9.6, exhibit mean values very close to zero further underlines this particular point. It should be noted that HC distributions obtained at other sites using the same instrument have shown that a stronger signal can be obtained. However, at present it is unclear whether the differences are due to changes in the nature of the site or changes in the configuration of the instrument. TRL will be reassessing the HC channel in further experiments.

Table 9.6 Mean and median levels of hydrocarbons in the exhaust plume.

Vehicle type	Survey	Mean HC (%)			Median HC (%)		
		Lane 1	Lane 2	Both lanes[a]	Lane 1	Lane 2	Both lanes[a]
All vehicles	Before calming	0.02	0.01	0.01	-0.004	-0.012	-0.009
	After calming (near hump)	0.07	0.03	0.05	0.010	0.021	0.019
	After calming (between humps)			0.03			-0.004
Cars: Pre 'L' reg. (*i.e.* non-catalyst)	Before calming	0.047			0.001		
	After calming (near hump)	0.11	0.05	0.07	0.042	0.039	0.039
	After calming (between humps)						
Cars: 'L' reg. and after (*i.e.* catalyst)	Before calming	-0.03			-0.033		
	After calming (near hump)	-0.02	0.00	-0.01	-0.032	-0.004	-0.008
	After calming (between humps)						
All other vehicles	Before calming	0.07			0.009		
	After calming (near hump)	0.08	0.07	0.07	0.016	0.019	0.019
	After calming (between humps)						

[a] Including vehicles for which the direction of travel was not identified.

9.4.3 Speed cushions

Video recordings of the surveys carried out at, and between, the speed cushions located on Oxtalls Lane were not transcribed, since the similarity between the overall mean results from the two traffic calming measures suggested that this would yield no further information. At these sites it was assumed that all decelerating vehicles were approaching the speed cushions (*i.e.* in lane 1), and all accelerating vehicles were departing from the speed cushions (*i.e.* in lane 2). In other words, the mean acceleration of vehicles in lane one was calculated using all negative acceleration values, and the mean acceleration of vehicles in lane two was calculated using all positive acceleration values.

The validity of this approach was confirmed by examination of the Longford Lane acceleration data. The resulting disaggregation was further used to obtain speed and emission data for the vehicles travelling in each lane.

9.4.3.1 Traffic composition

Although no data on traffic composition was obtained from the FEAT surveys, the data recorded by Webster (1998) show that passenger cars and light goods vehicles formed over 90% of the traffic before and after calming.

9.4.3.2 Speed and acceleration

The overall mean speeds and accelerations measured before and after the introduction of the cushions are given in Table 9.7.

Table 9.7 Mean speeds and accelerations.

Vehicle type	Survey	Mean speed (km/h)			Mean acceleration (m/s^2)		
		Lane 1[a]	Lane 2[b]	Both lanes[c]	Lane 1	Lane 2	Both lanes
All vehicles	Before calming			43.3			+0.1
	After calming (near cushions)	25.22	23.20	24.0	-1.5	+1.8	+0.4
	After calming (between cushions)			35.6			+0.1

[a] Lane 1 = near-side lane (approaching the cushions in survey conducted near the cushions).
[b] Lane 2 = far-side lane (departing from the cushions in survey conducted near the cushions).
[c] Including vehicles for which the direction of travel was not identified.

The mean speeds measured before and after the introduction of the speed cushions were very similar to the corresponding speeds for the road hump. The mean speed was reduced from 43 km/h (27 mph) before calming to 36 km/h (22 mph) between cushions, and 24 km/h (15 mph) near the cushions, after calming. There was little difference in the speed of traffic in each lane near the cushion. The speed reduction at the cushion was greater than that observed at the road hump.

With the results for all vehicles at the 'near cushion' site separated according to direction of travel, the mean deceleration of vehicles in lane 1 (approaching the cushions) was 1.5 m/s^2, whereas in lane 2 (departing from the cushions) the mean acceleration was +1.8 m/s^2. These accelerations and decelerations were slightly larger than those recorded for the road hump. This was probably due in part to the way in which the data for each lane were defined (*i.e.* based on the assumption that there were no positive values in lane 1 and no negative values in lane 2).

9.4.3.3 Carbon monoxide

The CO distributions recorded for all vehicles before and after the introduction of the speed cushions on Oxtalls Lane were very similar to those obtained at the road hump sites. However, although the proportion of negative values obtained at the 'near cushion' site appears to be similar to the proportion obtained at the other sites on Oxtalls Lane, at the 'near hump' site on Longford Lane the proportion of negative values was lower than that obtained in the 'before' and 'between hump' surveys.

The mean and median %CO values recorded before and after the introduction of the cushions are given in Table 9.8.

Table 9.8 Mean and median carbon monoxide levels.

Vehicle type	Survey	Mean CO (%)			Median CO (%)		
		Lane 1	Lane 2	Both lanes[a]	Lane 1	Lane 2	Both lanes[a]
All vehicles	Before calming			1.30			0.45
	After calming (near cushions)	1.89	1.57	1.72	0.69	0.66	0.67
	After calming (between cushions)			1.55			0.46

[a] Including vehicles for which the direction of travel was not identified.

For all vehicles travelling in both lanes, the mean level of CO in the exhaust gas recorded near the cushions and between cushions was higher than the fraction recorded before calming by 32% and 20% respectively. The equivalent increases in the median %CO value were 47% and 2%. In both cases the increase in the median %CO value was statistically significant.

As with the road hump, the mean and median %CO values at the 'near cushion' site were higher for the vehicles lane 1 (approaching the cushions, net deceleration) than for those in lane 2 (departing from the cushions, net acceleration).

9.4.3.4 Hydrocarbons

The HC distributions recorded for all vehicles before and after the introduction of the speed cushions on Oxtalls Lane were also similar to those obtained at the road hump sties. Again, the distributions were less skewed than those for CO, and the proportion of negative values in each distribution was much higher. The mean HC levels recorded before and after the introduction of the cushions are given in Table 9.9.

Table 9.9 Mean and median hydrocarbon levels.

Vehicle type	Survey	Mean HC (%)			Median HC (%)		
		Lane 1	Lane 2	Both lanes[a]	Lane 1	Lane 2	Both lanes[a]
All vehicles	Before calming			0.02			-0.03
	After calming (near cushions)	0.11	0.08	0.10	0.035	0.033	0.036
	After calming (between cushions)			0.03			-0.006

[a] Including vehicles for which the direction of travel was not identified.

The effects of the speed cushions on hydrocarbon emissions were similar to those associated with the road hump. Overall mean and median HC concentrations were found to have increased after calming. The results in Appendix F show that the increase was significant near the cushions, but not between cushions. Again, the same provisos apply to quantifying the changes. That is to say, it appears that the instrument errors were similar in magnitude to the measured signals.

9.4.4 Relationships between emissions and speed/acceleration

The mass of CO emitted per unit distance or time is dependent upon the mass of fuel consumed. The relationship between the fuel consumption of a vehicle and speed therefore dictates, to some extent, the nature of the CO speed dependency (see Figures 2.1 and 2.2). The %CO values measured for different vehicles by remote sensing, on the other hand, are independent of fuel consumption.

The CO data obtained in each remote sensing survey were plotted as a function of speed and acceleration for individual vehicles. No significant relationship was observed between the %CO value and the speed or acceleration of individual vehicles. This is a common finding of remote sensing studies. For example, using data from 102 sites Walsh (1998) found that there was no statistically significant relationship between the mean %CO value at a site and the mean speed at the same site ($R^2 = 0.05$). A similar analysis, using individual %CO and speed readings at a single site, produced comparable results. Koplow *et al.* (1997) have found a similar lack of correlation between individual NO emissions measured by remote sensing and vehicle speed or acceleration. However, Koplow *et al.* did observe a clear correlation between the mean of the NO and acceleration values averaged at decile intervals ($R^2 = 0.87$).

However, the vehicle-to-vehicle variation in emissions resulted in a large degree of scatter. In order to investigate whether any underlying pattern in the data existed, the combined measurements for all sites before and after calming were ranked according to speed, and mean values were calculated for decile intervals. In the plot of decile mean %CO as a function of decile mean speed (Figure 9.4), it can be seen that the CO level in the exhaust gas remained relatively steady between speeds of around 10 km/h and 30 km/h, and decreased thereafter. Based on the reductions in speed at each site, the observed changes in the site mean %CO value could be accurately predicted using the polynomial curve-fit presented in Figure 9.4.

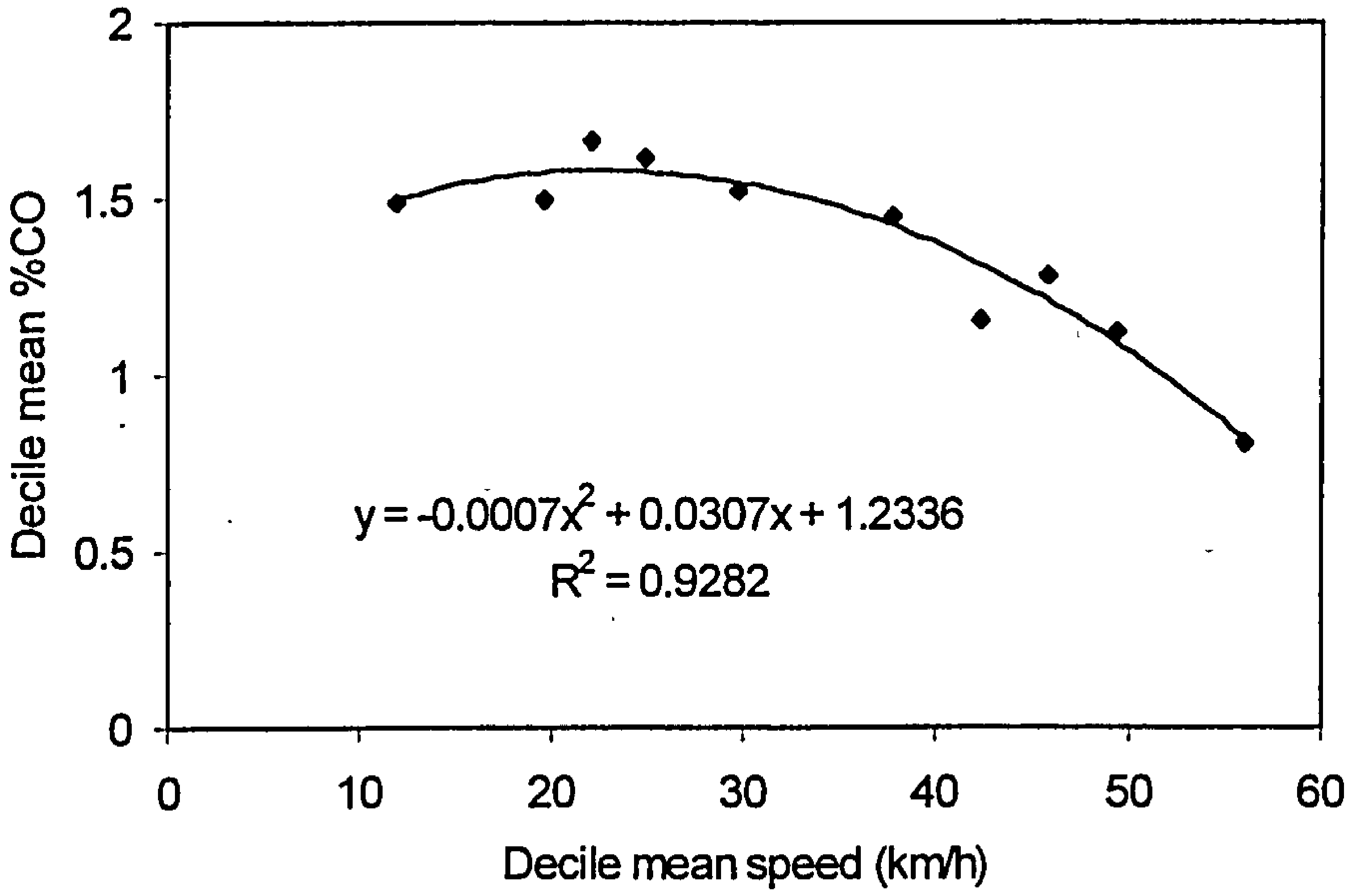

Figure 9.4 Decile mean %CO as a function of decile mean speed (all sites combined).

However, the relationship is based on the UK fleet in two particular years. If vehicle speeds are to be used to predict site mean CO levels at other sites, in other countries, or in other years where the fleet mix is different, more fundamental relationships are required that account for vehicle type and age. There was no obvious relationship between the %CO value and the acceleration of individual vehicles, or between the decile mean values.

9.4.5 Estimation of mass emission rates

Remote sensing measures the percentage by volume of a given pollutant in vehicle exhaust plumes. To enable a direct comparison to be made between the impacts of traffic calming measured on the AEA dynamometer and those measured by remote sensing, there was a need to derive mass-based information (*i.e.* g/km) on pollutant emissions from the remote sensing data.

A situation can be envisaged in which the CO level in the exhaust plume of a single vehicle is recorded using the FEAT system at two points in time. If the volume of fuel consumed by the vehicle per unit distance (*i.e.* l/km) does not change, but its mass emission rate (*i.e.* g/km) increases, the FEAT system will register an increase in the %CO value. However, if the volume of fuel consumed by the vehicle and the mass emission rate increase by the same percentage, then the FEAT system should, in theory, produce identical results for the two measurements since the proportion of CO by volume in the exhaust gas will not have changed. Therefore, in order to estimate the change in the mass of CO emitted by the vehicle using the FEAT system, it is essential to also have some indication of the change in the fuel consumption of the vehicles measured.

The changes in fuel consumption of the vehicles observed were not known. One way of deducing the change in fuel consumption is to use the results of other studies of traffic calming schemes where it has been measured. A large sample of vehicles (for which age, composition, and operation are constant) should give rise to the same distribution of %CO values in independent surveys, unless there has been a systematic change in the fuel consumption of the sample.

The dynamometer-based tests conducted by AEA showed that the fuel consumption (and therefore to a first approximation the volume of gas emitted) per kilometre of passenger cars increased by, on average, 25.4 ±0.8% as a result of traffic calming. The fuel consumption test data for petrol and diesel cars are shown in Figure 9.5. There was no significant difference between the mean percentage changes for the three different types of car. Consequently, this change in fuel consumption has been applied systematically to the FEAT results to provide a reasonable estimate of the change in the average mass of CO emitted per vehicle-km on the roads investigated. For this purpose, it was assumed that motorcycles, buses, medium goods vehicles, and heavy goods vehicles were effectively passenger cars, and the change in fuel consumption of each vehicle was also 25.4%. For these other types of vehicle the numbers observed were relatively small, and even fewer gave valid emission readings. It was therefore unlikely that this assumption would introduce a large error in the overall estimate.

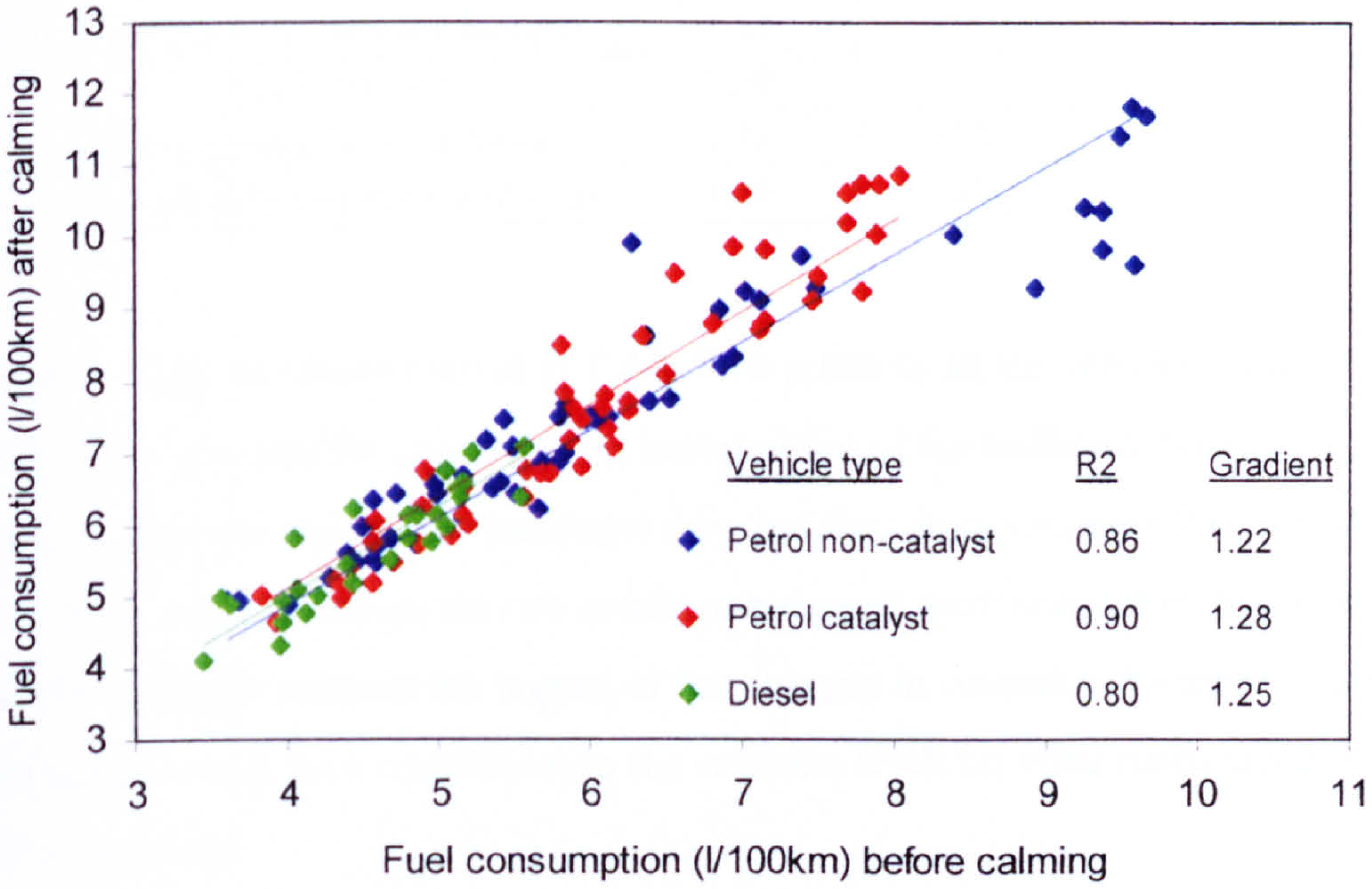

Figure 9.5 Fuel consumption after calming as a function of fuel consumption before calming for three categories of passenger car.

The change in the average mass of CO emitted per vehicle-km on each of the roads investigated was given by the equation:

$$\%\ change\ in\ CO\ mass\ emitted\ per\ km = x + y\left(\frac{x+100}{100}\right)$$

Where x is the % change in exhaust gas volume (with fuel consumption used as a proxy and assuming complete combustion of the fuel)

y is the percentage change in the measured %CO

The changes in mass emission calculated in this way for each type of measure are presented in Table 9.10. It can be seen that the results of the analysis indicate that traffic calming would cause the average mass of CO emitted per vehicle-km to increase by between 50% and 73%. However, this is only a broad estimate of the likely effect.

Table 9.10 Estimated changes in the mass of CO emitted.

Measure	Survey	Mean %CO (All vehicles)	Increase in mean %CO	Estimated increase in mass of CO per vehicle-km
Flat-top road humps	Before calming	1.19	-	-
	After calming (near hump)	1.56	30%	63%
	After calming (between humps)	1.64	38%	73%
Speed Cushions	Before calming	1.30	-	-
	After calming (near cushions)	1.72	32%	65%
	After calming (between cushions)	1.55	20%	50%

The increases in mass emissions quoted in Table 9.10 relate to all the vehicles travelling on each road studied. They accounts for changes in the composition of the traffic on those roads, including the introduction of newer and cleaner passenger cars, but they do not account for changes in traffic flow. On average, traffic flows on the two roads investigated were reduced by 8% after calming. This would have slightly reduced the impact of the changes in operation on these roads, though the diverted traffic would have contributed to the emission levels on other roads unless it had been suppressed completely.

9.5 Discussion

Remote sensing is potentially a useful tool for assessing the impact on emissions of changes in vehicle operation. However, there are currently a number of uncertainties relating to the interpretation of remote sensing data in any such assessment.

Four main sources of uncertainty were identified in this particular study:

(i) The effects of field calibration of different days.

(ii) The method of analysing the emission data, and in particular the treatment of negative values.

(iii) The calculation of changes in mass emission rates from existing fuel consumption data.

(iv) The impact of cold start emissions.

These problems are discussed in the following Sections.

9.5.1 Calibration

There are two separate calibration procedures performed on every remote sensing unit. The first procedure, which is conducted in the laboratory, establishes the fundamental sensitivity of each gas/filter combination to the gas of interest. During the second calibration, which is undertaken by the operator in the field at the start of each day's operation, known concentrations of CO, CO_2, propane, and NO are introduced into the path of the beam. The ratio readings from the instrument in the field are compared with those in the calibration mixture (Bishop and Stedman, 1996). In this study comparisons were made between the results of surveys conducted on different days, and this may have resulted in calibration errors. Bishop (1999) has estimated the error due to calibration on different days to be up to 10% of the measured ratios.

9.5.2 Treatment of emission data

A significant number of negative emission values were recorded during each survey. In principle, negative values are erroneous since they represent a condition where the concentration of a pollutant in the exhaust gas is lower than the recorded background. However, since the instrument itself will tend to produce fluctuations in the readings that are independent of the emissions that are being measured, it is reasonable to conclude that where the true result is close to zero on the scale, a negative reading is merely the result of system noise. By deduction, vehicles that produce negative readings can be assumed to be very low emitters (*i.e.* their effects on background concentrations are effectively negligible).

Negative exhaust pollutant concentrations have not been widely reported in the literature, and there is some confusion concerning how they should be treated in analyses. In previous remote sensing studies workers have tended to focus on identifying 'gross polluters' (*e.g.* Sjödin *et al.*, 1996) where, it is presumed, the signal-to-noise problem identified above has not posed a problem. However, negative values could introduce problems where the intention is to use the system to gain an insight into changes in average fleet emission levels, since they could affect the mean value of a sample, particularly where relatively small vehicle samples are being studied.

In the analysis reported here, the sample sizes were quite large, and so it is expected that the influence of negative values on the sample means would be small. Consequently, the data accepted by the FEAT system were used without further filtering or adjustment. However, the inclusion of negative values in the analysis of the distributions could be criticised from the standpoint that clearly in practice the concentrations of CO and HC in the exhaust plume should exceed the concentration in the ambient air. Alternative options would include omitting negative values, changing them to zero, or shifting the entire distribution in the positive direction by the most negative value (*i.e.* treating it as an offset). However, at this stage in the development of the method none of these approaches appears to offer a distinct advantage over simply using the raw data and accepting that the instrument itself will produce some degree of scatter which is independent of the concentrations being measured. The advantage of treating the data as recorded is that no arbitrary changes are made, and the interpretation of the results can be made from the data in its purest form.

A similar view has been stated by Stedman (1999). He has noted that negative values are a result of instrument noise and therefore cannot be excluded from the analysis. Provided the concentrations of pollutant are sufficient to give readings which are high enough to exceed the non-systematic random fluctuations in the system response then accurate and repeatable readings can still be obtained. For situations where the concentrations of pollutant are close to zero, then the system fluctuations may mask the measured effects, thus preventing any sensible measurements being taken. However, Stedman claims that system errors are relatively small so that in most cases, particularly where the system is being used to detect gross emitters, the signal-to-noise ratio will be high and the measurements reliable.

The other approaches to treating the emission data have also been proposed include normalising each distribution to, for example, the mean, and determining an offset for each individual instrument (Bishop, 1999). However, no detailed analysis has been conducted to suggest that either of these approaches is more appropriate or accurate than treating the data as recorded.

9.5.3 Mass emission rates

Two potential sources of error in the estimation of mass emission rates have been identified. These are errors due to the assumption of complete combustion, and errors associated with the use of pre-existing fuel consumption data to calculate mass emissions per kilometre.

The CO/CO_2 ratios measured by the FEAT system can be used, with only a small error in the conversion, to give the mass of CO per volume of fuel burnt. However, when a fuel is burnt the energy produced is proportional to the amounts of CO_2 and CO that are produced (and also the amounts of hydrocarbons, nitrogen oxides and other compounds, but these are generally much smaller and for this purpose may be neglected). Combustion to CO produces less energy per unit of fuel than complete combustion so, to perform the same work, more fuel must be used. Thus, for a conventional petrol engine, it is possible to relate the fuel consumption to the exhaust composition. When a catalyst is used, this modifies the exhaust composition by promoting the conversion of CO to CO_2. An estimate of fuel consumption based on the exhaust composition downstream of a catalyst is therefore uncertain because it is not known how much of the CO_2 results from primary combustion (and thus contributes to the energy produced by the engine) and how much results from the catalytic conversion of CO without supplying combustion energy to the vehicle. If the mass of CO emitted per unit of fuel burnt is to be determined by remote sensing data, it must be assumed at present that this latter effect is not significant. It should be a future undertaking to investigate this effect in greater depth.

In the current study, the need to use existing fuel consumption data to estimate mass emissions per vehicle-km introduced a further degree of uncertainty. This fuel consumption data was recorded in the laboratory using a comparatively small sample of vehicles and driving cycles which may not have been wholly representative of vehicles and driving behaviour on the roads investigated in Gloucester.

9.5.4 Cold start emissions

Differences in ambient temperature might also have affected the results of the surveys. In areas such as Longlevens cold start emissions are likely to be significant due to the presence of a substantial flow of residential traffic. Cold start emission rates have been shown to be dependent upon ambient temperature (*e.g.* Lenner, 1994), but at present the technology is not available to measure relevant parameters *in situ* by remote sensing. Because the surveys were conducted at different times of year, it is possible that the contribution of cold start emissions to total emissions would have been different in each survey. The mean temperature during the July 1997 survey was 23°C, whereas the mean temperature during the September 1998 survey was 18°C. Cold start emissions were therefore probably greater in the 1998 survey than in the 1997 survey because of the lower air temperature, and it is likely that part of the increases in the mass emissions of CO after calming would have been due to a larger contribution from cold start emissions during the 1998 survey.

It is difficult to quantify the extent to which any changes in cold start emissions would have contributed to the observed changes. From the linear regression equations presented by Sérié and Joumard (1997), which can be used to correct cold start emissions measured at 20°C for changes in ambient temperature, it can be shown that cold start emissions of CO (by mass) at 18°C are higher than those at 23°C by, on average, 25% for diesel cars and petrol cars without a catalyst, and 33% for petrol cars with a catalyst. However, these values assume that a vehicle is started at the ambient temperature and is driven over the entire cold start period (*i.e.* until the engine has warmed up). They therefore relate to the maximum effect of cold start operation.

Unfortunately, the fraction of vehicles operating in cold start mode on the roads investigated in Gloucester was not known. The fraction of vehicles operating in cold start mode on the two residential distributor roads studied in Gloucester can only be estimated from the results of other studies, such as those given in Table 9.11. However, it should be noted that these studies do not relate to traffic on UK roads.

If it is assumed that the majority of traffic is divided equally between the morning and evening peaks, then these studies suggest that during the course of the day 20-50% of all vehicles are operating in cold start mode. Given that the difference in air temperature would have resulted in an average increase in cold start emissions of CO of 25-30%, this indicates that changes in cold start emissions probably accounted for no more than around a third of the 50-73% changes in total CO emissions estimated earlier.

Table 9.11 Percentage of vehicles operating in cold start mode on residential roads.

Source	Road type description	Time of day	Percentage of vehicles operating in cold start mode.
Bendtsen and Thorsen (1995) (Denmark)	'Residential'	07:00-08:00	52
		08:00-09:00	36
		15:00-16:00	0
		16:00-17:00	0
Allen and Davies (1993) (United States)	'Urban local'	AM peak	64
		PM peak	31
	'Urban minor arterial'	AM peak	46
		PM peak	30

9.6 Summary

Apart from a few exceptions, most previous remote sensing surveys have been conducted across a single lane of traffic. In this study it was found that remote sensing surveys could be conducted across two lanes of traffic on narrow residential roads, though the selection of suitable sites was governed largely by the road layout. Vehicle speed, vehicle acceleration, and carbon monoxide and hydrocarbon emissions were recorded near and between two types of traffic calming measure (flat-top road humps and speed cushions).

The speeds, speed reductions, accelerations and decelerations observed in the remote sensing study were normal for traffic calming schemes. In the context of the case studies of emission impacts described in Section 2.5, the speeds were similar to those employed by Webster (1993) and Höglund (1995), but significantly higher than those used in the study by Züger and Blessing (1995).The acceleration values recorded were lower than those used by Höglund (1995), but higher than those used by Webster (1993).

The remote sensing instrument recorded a significant proportion of small negative CO values. It was decided that negative values occur as a result of the instrumentation errors associated with attempting to measure pollutant concentrations close to zero. It was decided, therefore, that all the recorded CO data should be used in the analysis without further filtering or adjustment. Alternative treatments, which included removing the negative values from the analysis and shifting the point corresponding to zero emissions, were considered but not used because they may have introduced a systematic bias in the results.

The mean percentages of carbon monoxide in the exhaust gas recorded near the hump and between humps were found to be higher than the level recorded before calming by 30% and 38% respectively. The corresponding median %CO values increased by 56% and 38%. The increases in the mean %CO near and between speed cushions were 32% and 20%, with corresponding increases in the median CO levels of 47% and 2%. In each case the increase in the median carbon monoxide level was statistically significant.

No relationship was observed between the %CO value for individual vehicles and either speed or acceleration. With the CO and speed data ranked and averaged at decile intervals, the CO level in the exhaust gas remained relatively constant up to a speed of around 30 km/h, and dropped thereafter. There was still no clear relationship between the CO and acceleration data averaged at decile intervals. However, measurements taken at both the road hump and speed cushion sites showed that the increase in the mean %CO after calming was absolutely and proportionately larger for vehicles having a net deceleration than for vehicles having a net acceleration.

Based on the disaggregated data for a single lane of traffic near a road hump, the largest proportional increase in the mean %CO (73%) was observed for vehicles other than passenger cars. The mean CO level for non-catalyst cars increased by 44%, and that for catalyst-equipped cars by 60%. These values for passenger cars are close to the changes in CO mass emissions measured in the laboratory tests (Table 8.3).

The level of instrument noise on the hydrocarbon emission measurements was considered too great for firm conclusions to be drawn for this pollutant. The fact that the distributions exhibited mean values very close to zero underlined this particular point. It was therefore unclear whether the differences in the mean %HC value were due to changes in the nature of the site or changes in the configuration of the instrument, and TRL will be reassessing the hydrocarbon channel in further experiments.

The emission tests conducted by AEA showed that passenger car fuel consumption per kilometre increases by, on average, 25% as a result of traffic calming. This change in fuel consumption was applied systematically to the remote sensing results for all vehicles to provide a reasonable estimate of the change in the total mass of CO emitted per vehicle-km by on each of the roads investigated. By using this estimate, it was found that traffic calming would cause the average mass of CO emitted per vehicle-km to increase by 50-73%. This estimate included the effects of changes in the composition of the traffic between the two surveys, but it did not account for changes in traffic flow. On average, traffic flows on the two roads investigated were reduced by 8% after calming. This would have slightly reduced the impact of the changes in operation on these roads, though the diverted traffic would have contributed to the emission levels on other roads unless it had been suppressed completely.

As the before and after surveys were conducted at different ambient temperatures, it was also possible that the contribution of cold start emissions to total emissions would have been different in each survey. However, the extent to which any changes in cold start emissions would have contributed to the observed changes could only be assessed by estimating both the effect of the change in ambient temperature on cold start emissions, and the proportion of vehicles operating in cold start mode. It was calculated that changes in cold start emissions of CO probably accounted for no more than around one third of the 50-73% change in mass emissions per vehicle-km.

Given the uncertainties in the remote sensing estimate, the 50-73% increase in mass emissions of CO per kilometre (for all vehicles) determined by remote sensing agrees reasonably well with the range of impacts measured in the laboratory emission tests, although the two sets of data were not wholly independent. In the laboratory tests, the mean CO emission of petrol non-catalyst, petrol catalyst, and diesel cars increased by 34%, 59%, and 39% respectively. However, the relatively high CO emission rate of petrol non-catalyst cars means that the effect on these vehicles would probably dominate the change in emissions of a stream of traffic.

CHAPTER 10 PERFORMANCE INDICATORS FOR TRAFFIC CALMING MEASURES

One of the 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 Thesis, with the input data being derived from the results presented in the previous Chapters and from other existing information.

10.1 Construction of indicators

10.1.1 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, geometry, and spacing of the measures, and the mean 'before' speed. 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).

10.1.2 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.

10.1.3 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.

10.1.4 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 10.1. 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 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 10.2. 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.

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.

Table 10.1 UK Fleet composition on unclassified urban roads in 1998, 2000, and 2005.

Vehicle class	Fuel	Size	Emission control	% of fleet in each category		
				1998	2000	2005
Passenger Cars	Petrol	Small (<1.2l)	Non-catalyst (pre EURO 1)	6.49	3.59	0.44
			Catalyst (EURO 1)	5.41	3.91	1.60
			Catalyst (EURO 2)	3.78	6.36	3.35
			Catalyst (EURO 3)	-	-	6.42
		Medium (1.2-1.8l)	Non-catalyst (pre EURO 1)	17.61	11.14	1.49
			Catalyst (EURO 1)	14.67	12.15	5.47
			Catalyst (EURO 2)	10.27	19.74	11.45
			Catalyst (EURO 3)	-	-	21.90
		Large (>1.8l)	Non-catalyst (pre EURO 1)	6.80	4.34	0.64
			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
Motorcycle	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).

Table 10.2 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)

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 10.1.

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 10.3). 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 10.3 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.

10.2 Results

10.2.1 Speed and accidents

The speed and accident impacts of the different schemes are presented in Table 10.4. 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 10.4 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

10.2.2 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 10.5-10.7. The reasons for use of the percentage impact as a basis for ordering the schemes was discussed in Section 8.3.2.

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 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 10.6 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 8.3. 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 10.5-10.7 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:

(i) The effects of most individual schemes were statistically significant (see Table 8.5).

(ii) Several groups (with minimal overlapping) were identifiable in the ANOVA and multiple comparison tests (see Tables 8.6-8.10). This was partly a subjective judgement.

The few cases for which these criteria were met are shaded in Tables 10.5-10.7. 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 8.2.1). 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 10.5 to 10.7.

10.2.3 Weighted traffic emissions

The weighted traffic emissions in the three reference years are presented in Tables 10.8-10.10. 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 10.1 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 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.

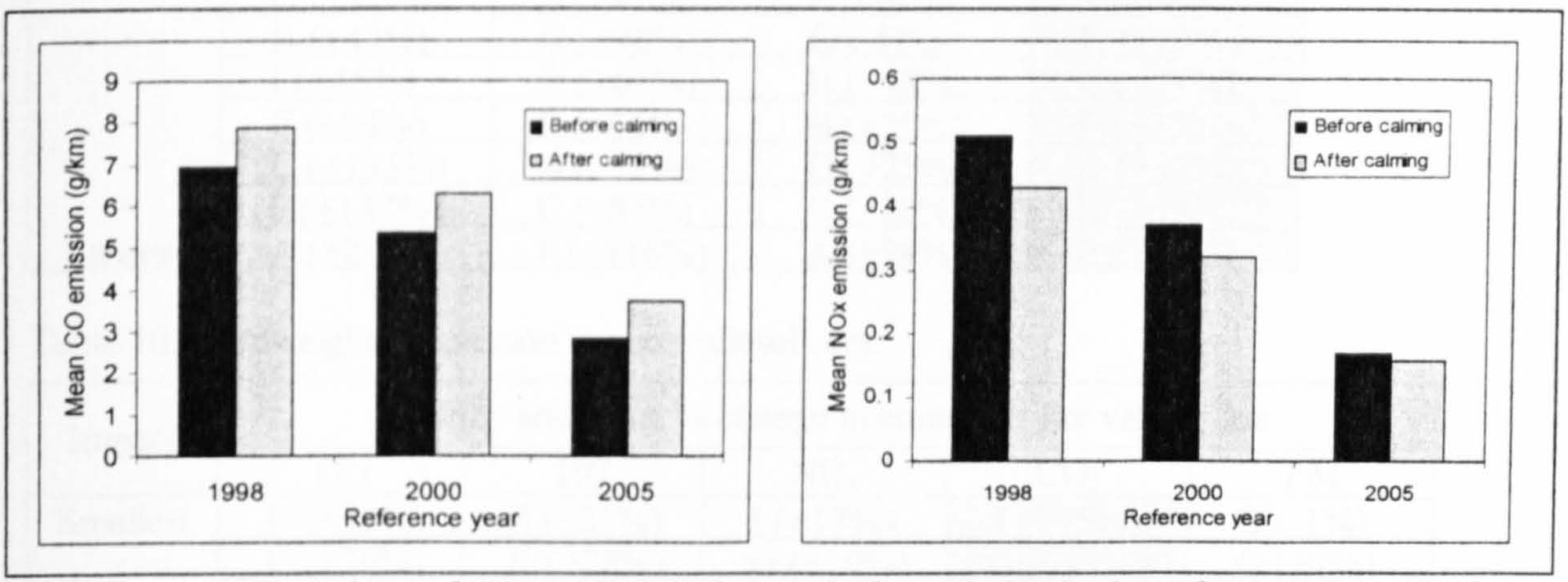

Figure 10.1 Emissions of CO and NO_x before and after calming in the reference years 1998, 2000, and 2005 (averaged over all nine schemes).

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, 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 10.5 Unweighted emission impacts: petrol non-catalyst cars.

Impact	Scheme and mean % change in emissions per vehicle-km			
	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%)

Table 10.6 Unweighted emission impacts: petrol catalyst cars.

Impact	Scheme and mean % change in emissions per vehicle-km			
	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%)

Table 10.7 Unweighted emission impacts: diesel cars.

Impact	Scheme and mean % change in emissions per vehicle-km				
	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	E (+39%)	A (+40%)	A (+82%)

	Scheme	Traffic calming measure	Scheme	Traffic calming measure
KEY	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-high raised junction		

NB The shaded columns indicate where the scheme order for a given vehicle category and pollutant was considered to be statistically robust.

Table 10.8 Weighted emission impacts: reference year 1998.

Impact	Scheme and % change in emissions per vehicle-km			
	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%)

Table 10.9 Weighted emission impacts: reference year 2000.

Impact	Scheme and % change in emissions per vehicle-km			
	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%)

Table 10.10 Weighted emission impacts: reference year 2005.

Impact	Scheme and % change in emissions per vehicle-km			
	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%)

	Scheme	Traffic calming measure	Scheme	Traffic calming measure
KEY	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-high raised junction		

NB The shaded columns indicate where the scheme order for a given vehicle category and pollutant was considered to be statistically robust.

10.3 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 10.11. 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 10.11 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 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.

It is important to note that the guidance provided here does not take into account the various other factors which may influence the success of a traffic calming scheme in terms of acceptability to, for example, pedestrians, residents, drivers, and the emergency services. Such factors include physical levels of noise and vibration, perceptions relating to the visual appearance of the road environment, perceptions of safety, perceptions of 'smoke', 'dirt', 'fumes', 'noise', 'odour', *etc.*, perceived damage to vehicles, and ride comfort. Information on the perceived effects of traffic calming is rather scarce; an overview of perceived environmental impacts in relation to traffic management compiled by Boulter (1998) contains some relevant information on the subject. For information on noise and vibration impacts, authorities are directed towards a number of TRL reports (*e.g.* Abbott *et al.*, 1995b and 1997; Harris *et al.*, 1999).

Table 10.11 Summary of performance indicators for the nine traffic calming measures investigated[a].

Target speed reduction Mph (km/h)[b]	Type of measure likely to achieve target speed reduction (scheme)	Likely accident reduction (%)	Effect on traffic exhaust emissions (per average vkm) for the year 2000 (☆☆☆ = lowest impact)				
			CO	HC	NO_x	CO_2	PM[c]
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%)

[a] The guidance provided here does not take into account other important factors, such as physical levels of noise and vibration, aesthetics, perceived safety, and perceptions of 'smoke', 'dirt', 'fumes', 'noise', 'odour'.

[b] Based on a mean speed before calming of 30 mph (48 km/h).

[c] Based on unweighted emission test results for diesel cars only.

CHAPTER 11 EMISSION MODEL ASSESSMENT AND DEVELOPMENT

Modelling the impacts of traffic management schemes on emissions is an inexpensive and flexible alternative to direct measurement. Some of the emission models available for this purpose were described in Chapter 3. In the most commonly used models, average vehicle speed is the only operational parameter used to estimate emission rates, and the emission values obtained over the traffic calming cycles were compared with the output from a model of this type (MEET) in Chapter 8. It was found that there was generally only a fair level of agreement between the overall absolute emission rates in the traffic calming study (both before and after calming) and those predicted by the MEET model. It is likely that this was mainly due to differences in the emission characteristics of the vehicles tested by AEA over the traffic calming cycles and those used in MEET, rather than to any inherent flaws in the average-speed modelling approach. However, there tended to be a fairly good agreement between the overall percentage impacts recorded in the traffic calming 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 overall indication of the percentage impacts of *traffic calming in general* on emissions per vehicle, though the assessment of the reliability of the comparison between the different vehicle samples was somewhat hindered by the differences in absolute emission rates. However, initial comparisons (described later in this Chapter) between the percentage impacts calculated using the MEET emission functions and the traffic calming emission data at the level *of individual types of scheme* generally revealed a poor level of agreement.

It is often assumed that, in order to estimate accurately the changes in emissions on the spatial scale of a traffic calming scheme, a modal emission model (otherwise known as a micro-scale or instantaneous model) is required, whereby vehicle emissions are related to a detailed vehicle operation profile. Such applications represent the state of the art in emission modelling , though one model, MODEM (Jost *et al.*, 1992), has already been found to underestimate the changes in emissions arising from the introduction of traffic calming measures (reported in Sturm *et al.*, 1998). However, at the time of the study emission test results relating to traffic calming were only available for a single vehicle.

In order to examine in greater depth whether the modal modelling approach was able to offer any improvements over the average-speed approach in the assessment of traffic calming, the results from the experimental work presented in the Thesis were used to compare the performance of the MEET and MODEM models. Also, an attempt was made to improve the accuracy of MODEM model in such applications by developing a variant model (MODEM-TC), and a re-appraisal of the variant model was undertaken.

11.1 The MODEM model

MODEM is the modal emission model that was produced from the data collected during the European Commission's DRIVE V1053 project, "Modelling of emissions and consumption in urban areas". Laboratory emission test data collected by various European laboratories - INRETS (France), TRL (UK), CEDIA (France), and TÜV RHINELAND (Germany) - form the basis of the model. Through the statistical analysis of a large-scale survey of the operating characteristics of vehicles in urban areas, INRETS developed a set of 14 drive cycles to be repeated on a chassis dynamometer (André *et al.*, 1991). Using these cycles, emission measurements were obtained for a representative sample of 150 cars of different types. The gear shift points for each vehicle were calculated with respect to the specific gear and axle ratios, rated power, and maximum engine speed (Jost *et al.*, 1992).

In the model the different types of car tested are grouped according to 'layers'. These layers, which represent given combinations of engine type, technology level, and engine size, are listed in Table 11.1. Petrol non-catalyst cars are divided into two groups according to compliance with emission control legislation ECE 15.03 (EC directive 78/665/EEC) and ECE 15.04 (EC directive 83/351/EEC). The vehicles tested by AEA over the traffic calming cycles are also matched to the corresponding MODEM layers in Table 11.1. It should be noted that no ECE 15.03 cars were tested by AEA. For each layer, the model is capable of estimating fuel consumption and emissions of CO, HC, NO_x, and CO_2 on a second-by-second basis. It does not provide estimates of cold start emissions, evaporative emissions, emissions from heavy-duty vehicles and motorcycles, or emissions of PM_{10}, benzene, and 1,3-butadiene (pollutants for which there are air quality standards in the UK; DETR *et al.*, 2000).

From the analysis of the emission data collected during the DRIVE project, the best indicators of instantaneous emissions, in terms of instantaneous driving parameters, were found to be vehicle speed and the product of the vehicle speed and acceleration (see Figure 2.2). In MODEM the emission functions for a particular layer and pollutant have therefore been defined in the form a two-dimensional matrix, with the columns representing speed intervals (km/h), and the rows representing the speed×acceleration intervals (m^2/s^3). For a particular test vehicle the emission rate recorded each second is entered into the cell of the matrix which corresponds to the speed and acceleration at the time of its measurement. The final emission function in a given cell of the matrix is calculated as the arithmetic mean of all the values entered in that cell (averaged over all cycles and appropriate vehicles). The CO emission matrix corresponding to Figure 2.2 is shown in Table 11.2

Table 11.1 Car category layers used in the MODEM model, and corresponding vehicles in dynamometer tests.

MODEM model				Corresponding vehicles in traffic calming tests
Layer	Engine type	Technology	Engine Size	
1	Petrol	Non-catalyst - ECE 15.03	< 1.4 l	None
2			1.4 - 2.0 l	
3			> 2.0 l	
4		Non-catalyst - ECE 15.04	< 1.4 l	1, 2, 3, 4
5			1.4 - 2.0 l	5, 6, 8
6			> 2.0 l	7
7		Catalyst - Euro 1	< 1.4 l	9, 10, 11, 12
8			1.4 - 2.0 l	13, 14, 15, 16, 17
9			> 2.0 l	18, 19
10[a]	Diesel	Euro 1	1.4 - 2.0 l	21, 22
11			1.4 - 2.0 l	
12			> 2.0 l	20

[a] As the majority of diesel cars have engine sizes >1400cc, layer 10 is identical to layer 11.

Table 11.2 MODEM emission factor matrix : CO emissions (g/h) from petrol catalyst vehicles (1.4-2.0l) as a function of instantaneous speed and acceleration (Jost *et al.*, 1992).

		Speed (km/h)									
		0	5	15	25	35	45	55	65	75	85
Speedxacceleration (m2/s3)	-15	-	-	66	56	63	69	59	76	92	115
	-10	-	-	57	61	63	84	94	141	129	134
	-5	-	53	53	73	85	102	130	204	194	325
	0	33	59	74	116	123	131	196	193	274	152
	5	-	142	163	192	192	207	275	263	350	211
	10	-	-	274	301	295	357	330	454	403	275
	15	-	-	-	469	568	603	779	706	1041	308

The model user inputs a driving cycle which describes vehicle speed as a function of time. From the input cycle the program evaluates the average speed and acceleration between each pair of adjacent speed readings, and the corresponding emission factor is then referenced for each vehicle category. Emissions over the entire driving cycle are calculated as the sum of the individual emission factors.

Occasionally, operating conditions will be encountered which are outside the speed-acceleration envelope of the MODEM model. In such cases, the model defaults to the nearest emission value (*i.e.* the highest or lowest) on the speed or speed × acceleration axis.

11.2 Model assessment and development: method

11.2.1 Model assessment

The output from the MEET model, based on the traffic calming driving cycles developed during the study, was presented in Chapter 8. The individual driving cycles were also used as an input to the MODEM model. Subsequently, the MEET and MODEM predictions were compared with the results of the dynamometer test programme for petrol non-catalyst, petrol catalyst, and diesel cars. For this purpose, the vehicles tested by AEA were assigned to the appropriate MODEM categories, as shown in Table 11.1. Comparisons were made between both the absolute emission rates before and after calming, and the associated percentage changes in emissions, both as average values for all schemes and for individual schemes. The MEET and MODEM predictions were weighted according to the engine sizes of the vehicles used in the traffic calming tests.

11.2.2 Development of MODEM-TC model

11.2.2.1 Options

A number of potential sources of error in the modal modelling approach have been identified. These sources of error are well documented (*e.g.* Joumard *et al.*, 1998; Sturm *et al.*, 1998; Latham *et al.*, 2000; Weilenmann *et al.*, 2000), and are not just confined to MODEM. Sturm *et al.*, 1998 summarised a number of studies relating to a number of these sources of error. The aspects of modal emission modelling which where covered included the following:

(i) The types of cycle used to create emission matrices

The experience gained during the development of various emission models suggests that they may not predict accurately the emissions associated with vehicle operations which are different to those used in their development. For example, Sturm *et al.* (1998) employ the term 'dynamics' to describe driving cycles. A cycle is described as having either 'low dynamics' or 'high dynamics' depending on the number of gear changes involved, and whether the cycle fills the cells of an emission matrix with low or high speed×acceleration values. Models are often based on cycles with 'low dynamics' (such as those defined in legislation), and might produce more accurate results if the emission database which it currently uses is replaced by ones based on the types of vehicle operation for which they are trying to predict

(ii) The parameters used to describe vehicle operation

Some modal models define the emission matrix according to speed and acceleration, whereas others use the parameters speed and speed × acceleration. Also, acceleration values can be calculated in a number of different ways from the speed profile.

(iii) The grid size in the emission matrix

Typical increments in an emission matrix are 5-10 km/h for speed, 0.1-0.4 m/s^2 for acceleration, and 1.3-5.0 m^2/s^3 for speed × acceleration. With smaller increments the operational conditions of the modelled driving cycle can be better represented, but proportionally more of the emission matrix cells will remain empty unless a wider variety of driving cycles are used in the development of the model. Larger increments allow more matrix cells to be filled with emission data, but subtle alterations in vehicle operation are not taken into account.

(iv) The type of interpolation scheme

Emission values are stored in a matrix with a given grid size, and the values in each cell relate to a range of operational conditions. An interpolation scheme can be used to calculate emission values for operational conditions which lie within this range. The way in which the emission values are interpolated between the matrix values can lead to different emission results. The version of the MODEM model described in this Thesis does not employ an interpolation scheme.

It was concluded by Sturm *et al.* (1998) that the choice of driving cycles used to develop emission matrices is an important determinant of a model's accuracy, but neither the parameters used to describe operation, the grid size, nor the use of an interpolation scheme resulted in any improvements in accuracy. Consequently, in the development of the MODEM-TC model, a decision was taken to concentrate on the driving cycle element. This was considered to be particularly appropriate for traffic calming, as it tends to impose a particular regime of low-speed operation with 'high dynamics', for which a specific emissions database might be more appropriate.

11.2.2.2 Construction of emission matrices

In the emission tests conducted by AEA, the volumetric concentrations of CO, HC, NO_x, and CO_2 in the exhaust gas, as well as vehicle speed, were recorded on a continuous basis. These measurements were used to develop emission matrices for the MODEM model for use in traffic calming applications. This version of the model was named MODEM-TC.

Around 1600 individual continuous emission profiles were recorded by AEA. This was out of a possible 2168 (4 pollutants, 542 tests). Of these 1600 profiles, 1088 could be used in the development of the new emission matrices. The criteria used to reject data are given later in this Section. The distribution of the 1088 profiles by vehicle and pollutant is shown in Table 11.3.

There were several stages involved in the development of the emission matrices for the MODEM-TC model. These are described in outline below.

Table 11.3 Valid emission profiles by vehicle, pollutant and scheme.

Vehicle category	Vehicle number	Pollutant				Schemes included
		CO	HC	NO_x	CO_2	
Petrol non-catalyst	1	11	10	12	12	B,C,D
	2	-	-	-	-	
	3	20	19	20	20	B,C,D,E,G,H
	4	6	5	7	7	B,C
	5	23	21	25	25	B,C,D,F,G,H,I
	6	21	23	25	24	B,C,D,E,F,G,H
	7	3	-	3	3	C
	8	49	48	51	50	B,C,D,E,F,G,H,I
Petrol catalyst	9	-	-	-	-	
	10	-	-	-	-	
	11	9	9	12	11	E,F,G,H
	12	9	7	6	8	B,C,D
	13	8	7	7	8	D,E
	14	-	-	-	-	
	15	2	1	2	1	B
	16	3	2	5	5	C
	17	18	17	25	25	B,C,D,E,F,G,H,I
	18	4	2	3	4	B
	19	15	8	16	18	B,C,D,E,F
Diesel	20	27	26	26	28	B,C,D,E,F,G,H,I
	21	15	14	23	24	B,C,D,E,F,G,H,I
	22	22	15	24	24	B,C,D,E,F,G,H,I

Correction of time lag

Because of the time required to transport the exhaust gas to the analysers, and the actual response time of the analysers themselves, the emission signals are delayed relative to the driving cycle. The time lag between an emission event occurring and it being recorded at the analyser was different for each pollutant. Consequently, each concentration profiles was shifted in time (*i.e.* corrected subjectively) so that the initial rise in concentration corresponded to the initial rise in speed. Other (preferred) methods for correcting the time lag have been developed. For example, TÜV Rhineland have developed a statistical method called 'Virtual Time Shift' in which the standard deviation of the values in each cell of the emission matrix is minimised (Hassel *et al.*, 1993). However, it was considered that, given the other sources of error in modal emission modelling, the application of this technique might only provide a small improvement in accuracy.

Conversion to mass emission rates

The volumetric concentrations recorded during the tests were converted to mass emission rates (g/h) for each second of an emission profile using the following equation:

$$\text{Mass emission rate (g/h)} = \frac{3600 \times C \times f \times M_r}{10^6 \times V_m}$$

Where: C is the pollutant concentration in ppm

f is the gas flow rate (193.33 l/s)

V_m is the molar gas volume (22.4 l)

M_r is the relative molecular mass of the pollutant - for CO = 28

for HC = 13.85 ($CH_{1.85}$)

for NO_x = 46 (NO_2)

for CO_2 = 44

Comparison of bag values with modal values

In order to determine the usability of modal emission data, a comparison is usually made between the sum of the instantaneous emission values over a given driving cycle with the corresponding bag value from the CVS test in which the dilute exhaust gas has been sampled in a bag. The bag sample measurements should, in general, correspond to the sum of the modal values, but due to restrictions in the measurement set-up and the accuracy of the analysers, differences between the two are inevitable. Sturm *et al.* (1998) reported that the differences vary with pollutant and vehicle type.

Comparisons between the bag values and aggregate modal values are shown in Figure 11.1. The best correlation between the bag and modal values was obtained for CO. There was also a good level of agreement for CO_2, though the modal data appear to be systematically higher than the bag data, with an offset of around 12 g/km. For HC and NO_x the relationships were poorer, and there appears to be a gradient factor. Because different measurement techniques were used, and either the bag samples or the modal sample could have been correct, no modal data were actually rejected.

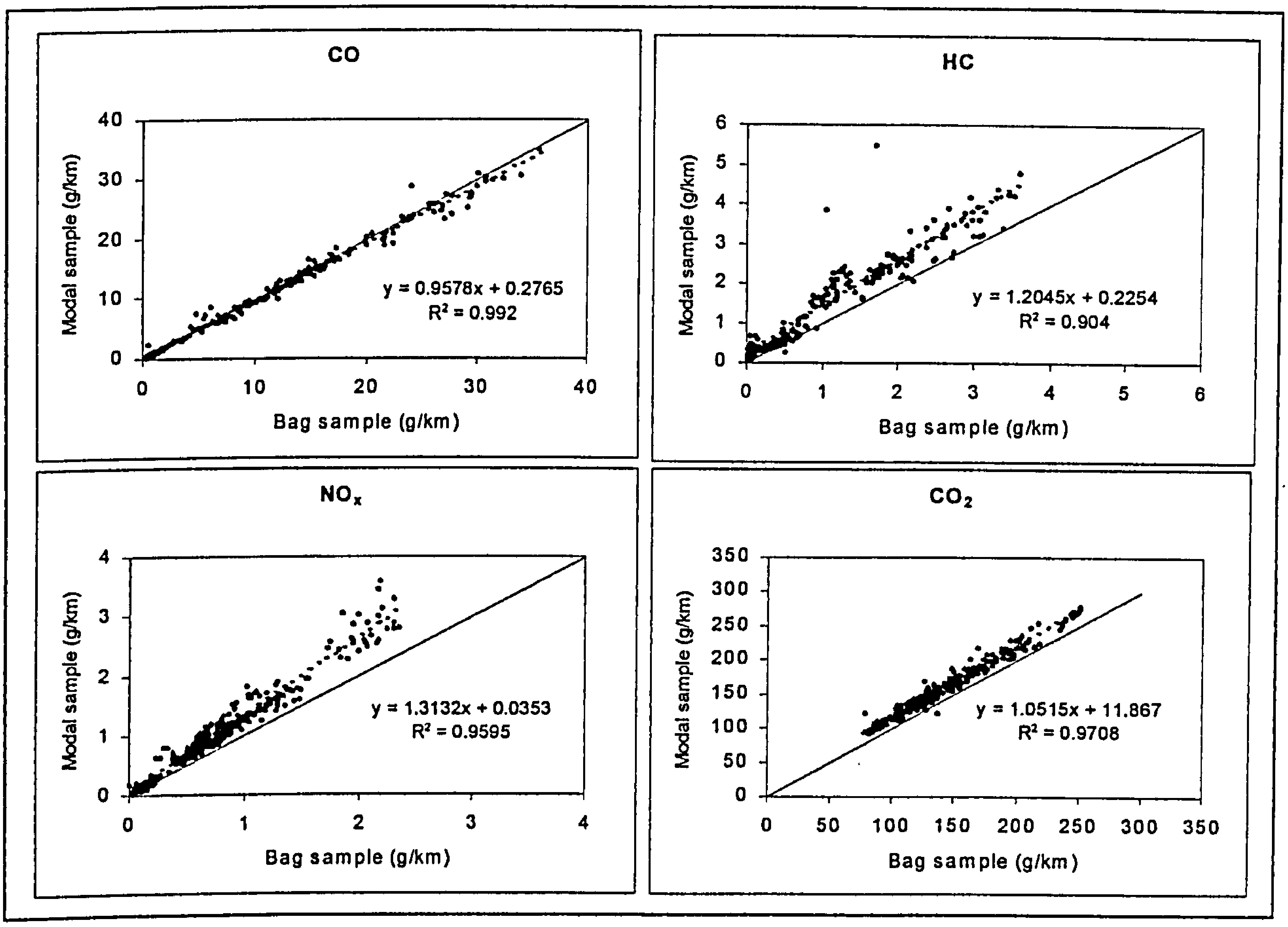

Figure 11.1 Comparison between bag values and aggregate modal values over all 'before calming' and 'after calming' driving cycles. The solid line represents a 1:1 ratio, and the dotted line is the linear regression fit to the data.

Data rejection criteria

Emission data were either accepted or rejected according to a number of criteria. The conditions which led to emission data being rejected were:

(i) Errors in the emission profile. Problems included no emission profile, partial emission profile, large offsets, signal drift, and an excessive noise-to-signal ratio. These were all judged subjectively.

(ii) Errors in the speed profile, whereby the measured speed profile did not correspond to the driving cycle used in the test. The errors included the absence of a speed signal (wholly or in part), and exceptionally high momentary speeds and accelerations.

(iii) Excessive time lag in the emission profile. This can lead to instability in the measured signal, and arises as a result of soiling or condensation in the analyser (Jost *et al.*, 1992).

(iv) Insufficient data in matrix cell. INFRAS (1998) found that a minimum number of 10 readings per matrix cell was necessary to minimise the standard deviation of the values without affecting the mean significantly, and Philippe (1996) suggested an optimum number of 30 values. Because only a relatively small sample of vehicles was tested over the traffic calming cycles, a limit of 20 values per cell was adopted, and any cells with less than 20 values were left blank. However, it should be noted that, where cells contained few values, this was due to the operation they represented occurring infrequently. Consequently, the removal of the values from such cells had little effect on the predicted emissions.

11.3 Model assessment and development: results

11.3.1 All schemes

The results of the assessment for all schemes are shown in Figures 11.2 and 11.3. Six data series are presented in each Figure.

The first three series (shown in blue) relate to measurements:

Series 1: The average of the bag values for all the tests conducted
Series 2: The average of the bag values for each emission trace used to develop MODEM-TC
Series 3: The average of the summated modal vales for each emission trace used in MODEM-TC

The second three series (shown in green) rate to model predictions:

Series 4: The average MEET prediction for all the test cycles
Series 5: The average MODEM prediction for all the test cycles
Series 6: The average MODEM-TC prediction for all the test cycles

The mean measured and modelled absolute emission rates are shown in Figure 11.2. There was generally good agreement between the bag values for all the tests (series 1) and the bag values of the tests used in development of MODEM-TC (series 2), with the latter tending to be slightly higher. This indicated that the emission characteristics of vehicle sample used in the development of MODEM-TC were fairly representative of those of the entire vehicle sample tested in the laboratory by AEA. The largest differences were observed for HC and NO_x emissions from petrol catalyst cars. The summated modal values (series 3) tended to be higher than both the series 1 and series 2 values, with the most pronounced differences occurring with HC emissions. Both the MEET and MODEM models exhibited a mixture of underestimation and overestimation compared with the series 1 results, though in some cases there was a good level of agreement between the measured and modelled values. MODEM-TC, on the other hand, overestimated bag emissions in almost all cases. The differences between the measured and predicted absolute emission rates are, one again, likely to reflect differences in the vehicle samples on which the results are based and, as such, are to be expected. As would also be expected, MODEM-TC model showed a better agreement with the MODEM-TC modal data, except in the case of HC emission from catalyst cars.

The overall percentage impacts of traffic calming measured in the dynamometer tests, and the overall percentage impacts predicted by MEET, MODEM, and MODEM-TC for the three vehicle categories, are shown in Figure 11.3. The series 1, 2 and 3 measurements showed a good level of agreement for petrol non-catalyst cars and diesel cars. However, the percentage changes for catalyst cars showed no consistent pattern. This follows on from the earlier observations relating to the variability of the emissions from these vehicles.

It has already been observed that the MEET model generally provided a good indication of the percentage change in emissions associated with traffic calming when assessed over a range of schemes, though the ability of MEET to predict these changes in emissions depends very much on the vehicle type and pollutant being considered. The percentage changes predicted by the MEET and MODEM models showed an unexpected pattern. For almost all combinations of vehicle type and pollutant, the MEET model provided a more reliable indication of the likely impact of traffic calming than the MODEM model, in spite of the fact that the latter employs a more detailed mechanism for representing vehicle operation.

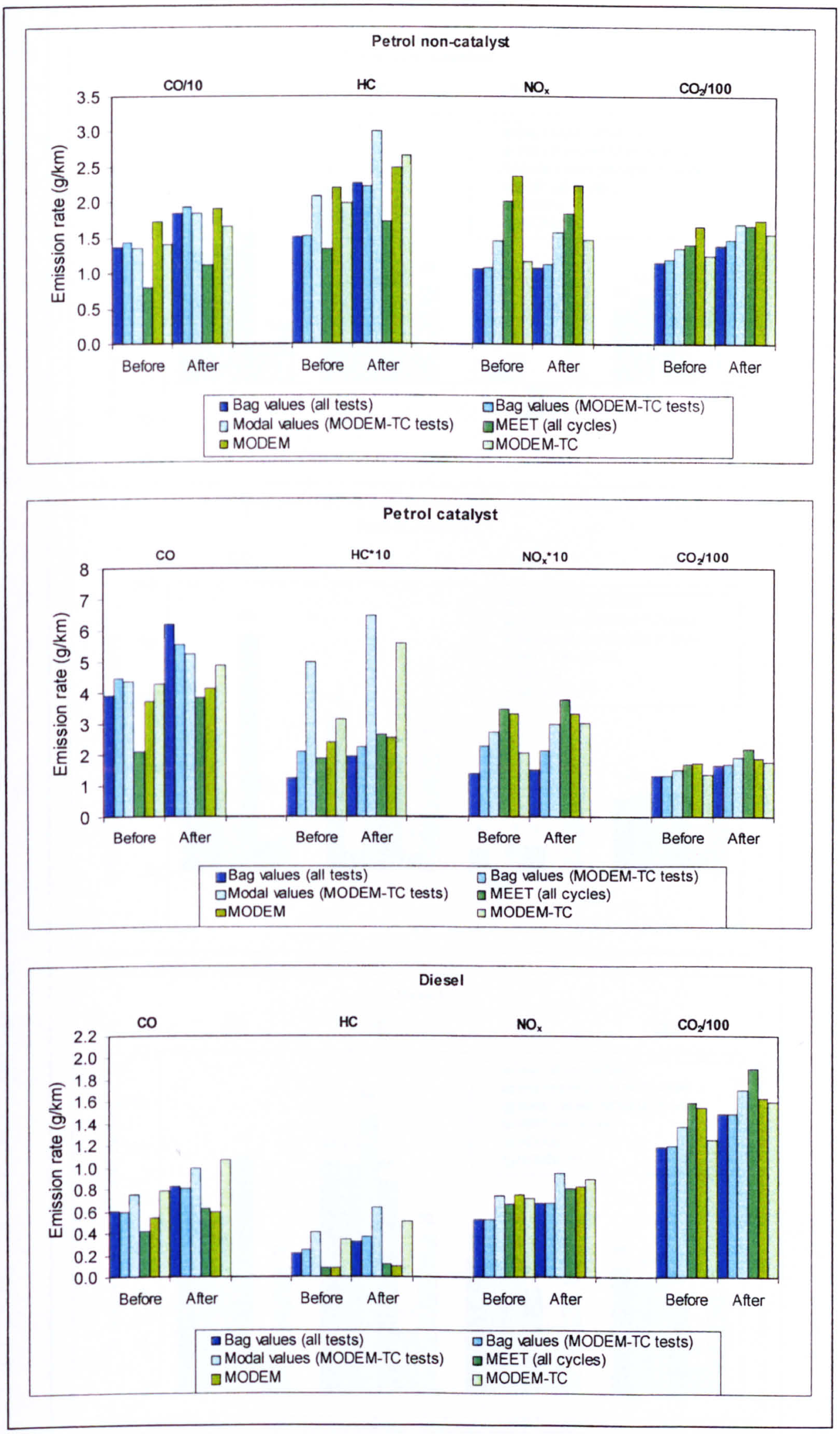

Figure 11.2 Mean dynamometer test results vs. weighted MEET and weighted MODEM predictions for petrol non-catalyst, petrol catalyst, and diesel cars.

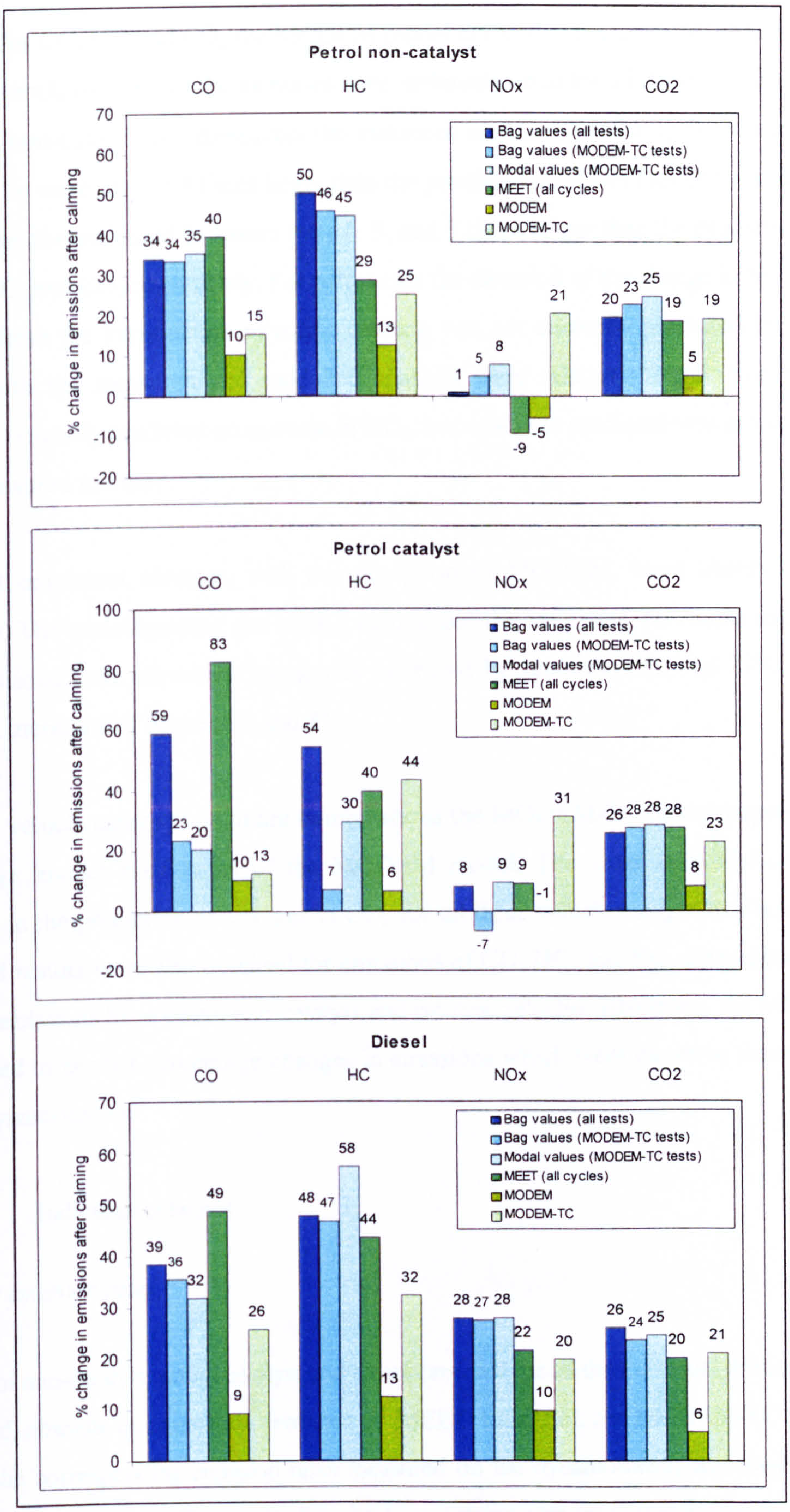

Figure 11.3 Percentage change in mean emissions measured in dynamometer tests vs. percentage changes predicted by MEET and MODEM for petrol non-catalyst, petrol catalyst, and diesel cars.

Although for CO, HC and CO_2 the MODEM model correctly predicted that emissions would increase overall, the sizes of the increases were underestimated for all three vehicle categories. For petrol non-catalyst and diesel cars the measured increases (series 1) in emissions of CO, HC and CO_2 were around 4 times larger than the predicted increases (series 5), and for petrol catalyst cars the measured increases were 6, 9, and 3 times larger than the predicted increases for CO, HC, and CO_2 respectively. For petrol cars the direction of the change in NO_x emissions resulting from the introduction of traffic calming was not correctly predicted by MODEM, though both the measured and modelled changes were relatively small. For diesel cars MODEM correctly predicted an increase in NO_x, but again the predicted was around one third of the measured increase.

The most consistent changes, with the exception of MODEM, were observed for CO_2 emissions. The measurements, the MEET model, and the MODEM-TC model indicated that CO_2 emissions from all vehicle categories increased by between 19% and 29%. MODEM predicted increases of between 5 and 8%.

For most vehicle category-pollutant combinations the MODEM-TC model improved on the percentage impact predictions of the MODEM model. The most marked improvements occurred in the prediction of changes in CO_2 for all three vehicle categories, though greatly improved results were also obtained for emissions of CO, HC, and NO_x from diesel vehicles, and HC emissions from petrol non-catalyst and catalyst vehicles. However, the MEET model still tended to predict percentage changes in emissions which were closer to those measured on the dynamometer.

11.3.2 Individual schemes

Absolute emission rates

For petrol non-catalyst, petrol catalyst and diesel cars, and for all the individual driving cycles, the (weighted) absolute emission rates predicted by MEET, MODEM, and MODEM-TC were plotted against the corresponding emission rates measured on the dynamometer, and linear regression analyses were conducted. The results for petrol non-catalyst cars are shown in Figure 11.4, and the results of the regression analyses for the three vehicle categories are given in Table 11.4.

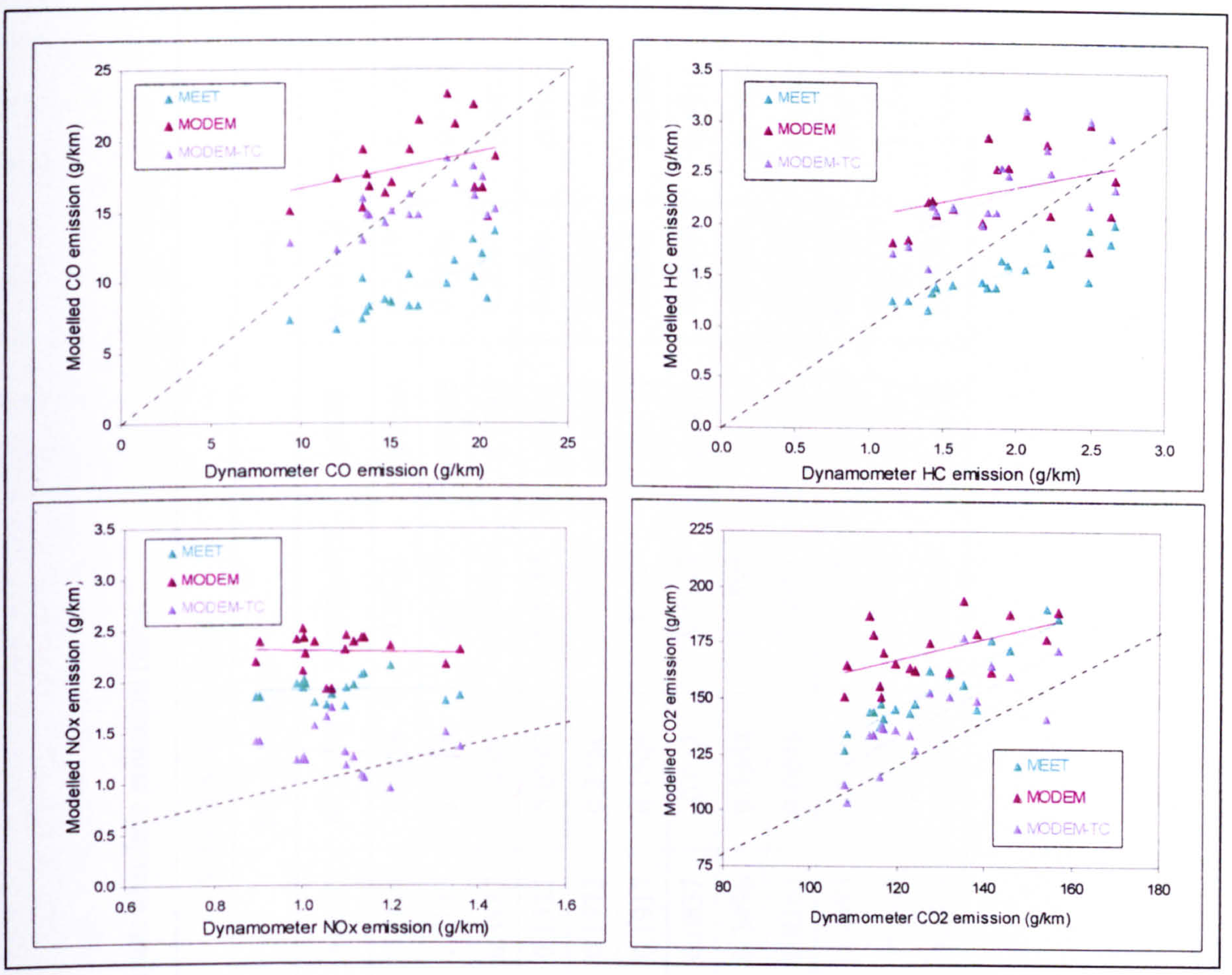

Figure 11.4 Emission rate of petrol non-catalyst cars predicted by MEET, MODEM, and MODEM-TC vs. emission rate measured in chassis dynamometer tests for all driving cycles (the dotted line represents a ratio of 1:1).

It is clear that none of the models produced very good results at this level. With the MODEM model in its original format, there was a poor level agreement between the absolute measured and modelled emission rates over both the 'before calming' and 'after calming' cycles. This lack of agreement is reflected in the low correlation coefficients observed in most cases. The MODEM-TC model improved on MODEM, but could hardly be considered much better than MEET, even though it was based on the very data it was being used to predict.

Table 11.4 Regression output: absolute emission rates.

Pollutant	Regression Output	Vehicle type and cycle								
		Petrol non-catalyst			Petrol catalyst			Diesel		
		MEET	MODEM	MODEM-TC	MEET	MODEM	MODEM-TC	MEET	MODEM	MODEM-TC
CO	Gradient	0.4716	0.264	0.3677	0.2519	0.0838	0.0872	0.7166	0.2419	0.9383
	Constant	1.9741	14.051	9.4178	1.7137	3.5198	4.1512	0.0095	0.3956	0.2557
	R^2	0.6003	0.1157	0.4763	0.3987	0.2000	0.2314	0.7385	0.2572	0.6431
HC	Gradient	0.4491	0.2824	0.6638	0.1522	0.0587	0.5288	0.076	0.0436	0.5137
	Constant	0.6834	1.8175	1.0618	0.1972	0.2356	0.3283	0.0838	0.0835	0.29
	R^2	0.7541	0.1089	0.5156	0.1917	0.1509	0.212	0.1573	0.0837	0.3436
NO_x	Gradient	0.0561	-0.04	-0.1957	0.0837	-0.017	0.5163	0.6782	0.1809	0.5515
	Constant	1.8762	2.3511	1.5363	0.3496	0.3364	0.1808	0.3342	0.6839	0.4806
	R^2	0.0038	0.0008	0.0138	0.0165	0.0043	0.0701	0.6344	0.0354	0.2428
CO_2	Gradient	1.0846	0.4602	1.0339	1.2095	0.5113	0.9556	1.0152	0.3329	0.9778
	Constant	15.768	112.71	9.8159	15.634	106.07	15.508	38.333	114.19	11.559
	R^2	0.8505	0.2775	0.6046	0.8719	0.2949	0.6523	0.9433	0.2613	0.6944

For the petrol non-catalyst, petrol catalyst and diesel cars, the percentage changes in emissions predicted by MEET, MODEM , and MODEM-TC for each appropriate layer in the model were plotted against the corresponding percentage changes measured on the dynamometer, and once again linear regression analyses were conducted (though it is accepted that the absolute emission rates varied substantially). The results for petrol non-catalyst cars are shown in Figure 11.5. The results of the regression analyses are given in Table 11.5. Again, all three models performed badly, and the ability of MODEM to predict the relative impact of traffic calming on emissions of a given pollutant was again found to be particularly poor.

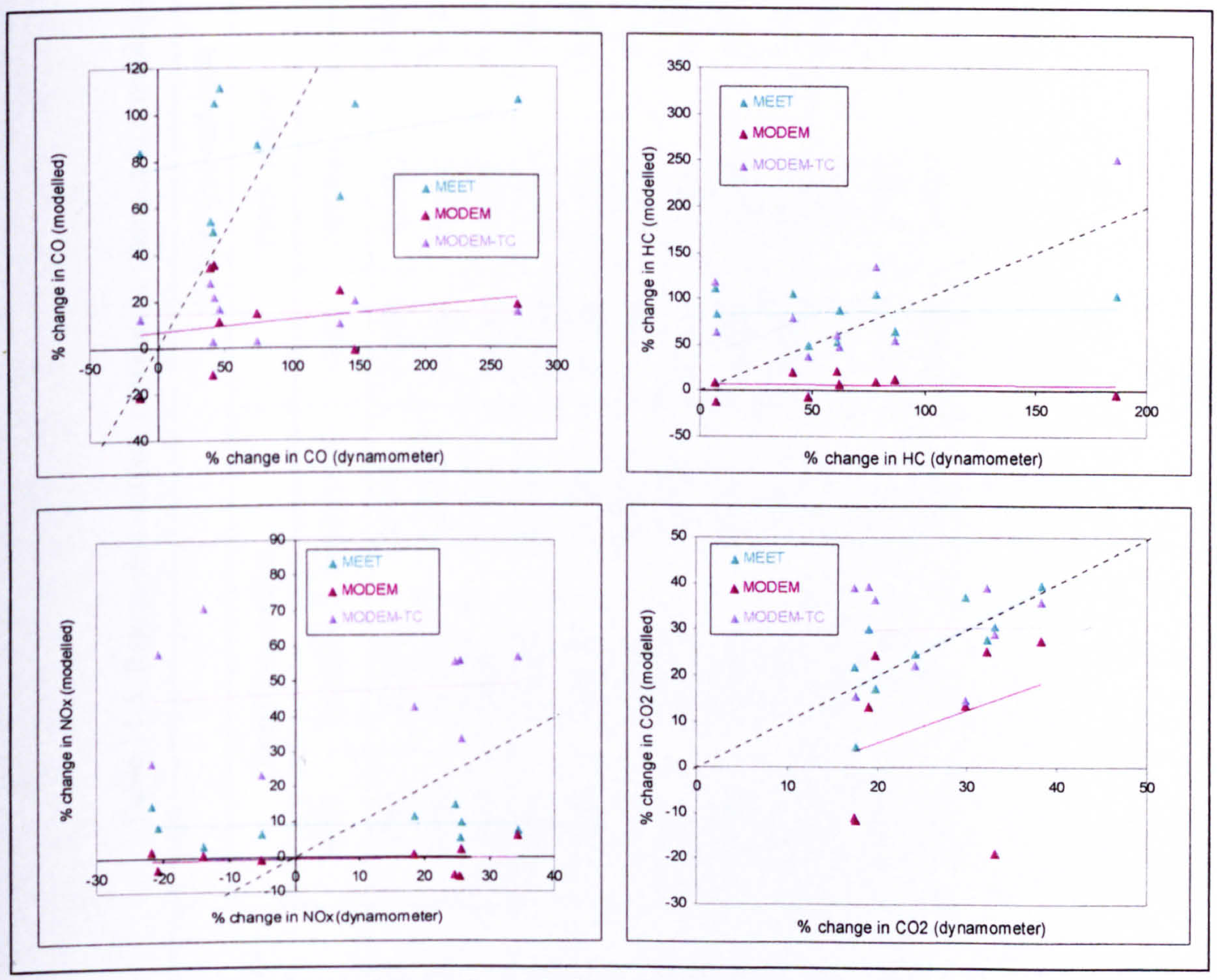

Figure 11.5 Percentage changes in emissions from petrol non-catalyst cars predicted by MEET, MODEM, and MODEM-TC vs. percentage changes in emissions measured in chassis dynamometer tests for all driving cycles (the dotted line represents a ratio of 1:1).

Table 11.5 Regression output: percentage changes in emission rates.

Pollutant	Regression Output	Vehicle type and cycle								
		Petrol non-catalyst			Petrol catalyst			Diesel		
		MEET	MODEM	MODEM-TC	MEET	MODEM	MODEM-TC	MEET	MODEM	MODEM-TC
CO	Gradient	0.0702	0.1177	0.0501	0.0899	0.0562	0.0017	0.4716	0.264	0.3677
	Constant	36.939	16.351	16.683	77.542	6.6683	14.277	1.9741	14.051	9.4178
	R^2	0.0097	0.0073	0.0143	0.1043	0.059	0.0003	0.6003	0.1157	0.4763
HC	Gradient	0.2095	0.3666	0.3925	0.0413	-0.0081	0.903	0.4491	0.2824	0.6638
	Constant	17.825	3.3199	14.04	82.701	7.2892	36.653	0.6834	1.8175	1.0618
	R^2	0.2034	0.0509	0.4239	0.0088	0.0013	0.5177	0.7541	0.1089	0.5156
NO_x	Gradient	0.0173	-0.2675	-0.0053	0.0101	0.0165	0.0808	0.0561	-0.04	-0.1957
	Constant	-8.9726	-4.7823	26.013	9.0999	-0.583	46.548	1.8762	2.3511	4.5363
	R^2	0.0213	0.1085	7E-05	0.0032	0.0097	0.0126	0.0038	0.0008	0.0138
CO_2	Gradient	0.5934	0.5819	-0.2303	1.0211	0.7005	0.0343	1.0846	0.4602	1.0339
	Constant	6.7092	-5.6726	29.016	-0.3446	-8.6234	29.255	15.768	112.71	9.8159
	R^2	0.384	0.1299	0.0411	0.5568	0.0905	0.0007	0.0585	0.2775	0.6046

11.4 Improving the modal modelling approach

There are clearly deficiencies in the modal modelling approach which cannot be entirely resolved by changing the emission factors or the way in which the models operate. It may be that any attempt at a comparison between emission models predictions and measurements is confounded by the general variability in the emission rates of the vehicle samples used in the models and the vehicle samples used in the measurements. Because the vehicle fleet is so large, and only a tiny proportion of it can be sampled, this will always lead to problems, to a greater or lesser extent, where emission model predictions (based on one sample of vehicles) are being compared with emission measurements (based on a second sample). Other than dramatically increasing the sample sizes in both cases, these two sources of uncertainty cannot be resolved, and this problem could not be addressed in this Thesis.

A number of further suggestions for improving modal models have been proposed. Firstly, 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. Under particular operating conditions the catalyst may be working 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 11.6). 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. Joumard *et al.* have argued that efforts should concentrate on extreme engine operating conditions, particularly for catalyst-equipped vehicles, and this approach is being followed in France (Lacour *et al.*, 2000). Unfortunately, the work conducted so far indicates that a modal model which treats extreme events separately provides no improvement in accuracy over existing instantaneous models, or even over average speed models. In addition, research in Switzerland (INFRAS, 1998) has indicated that the introduction into models of a parameter relating to gear activity could help to reduce the variability of the emission values in matrix cells.

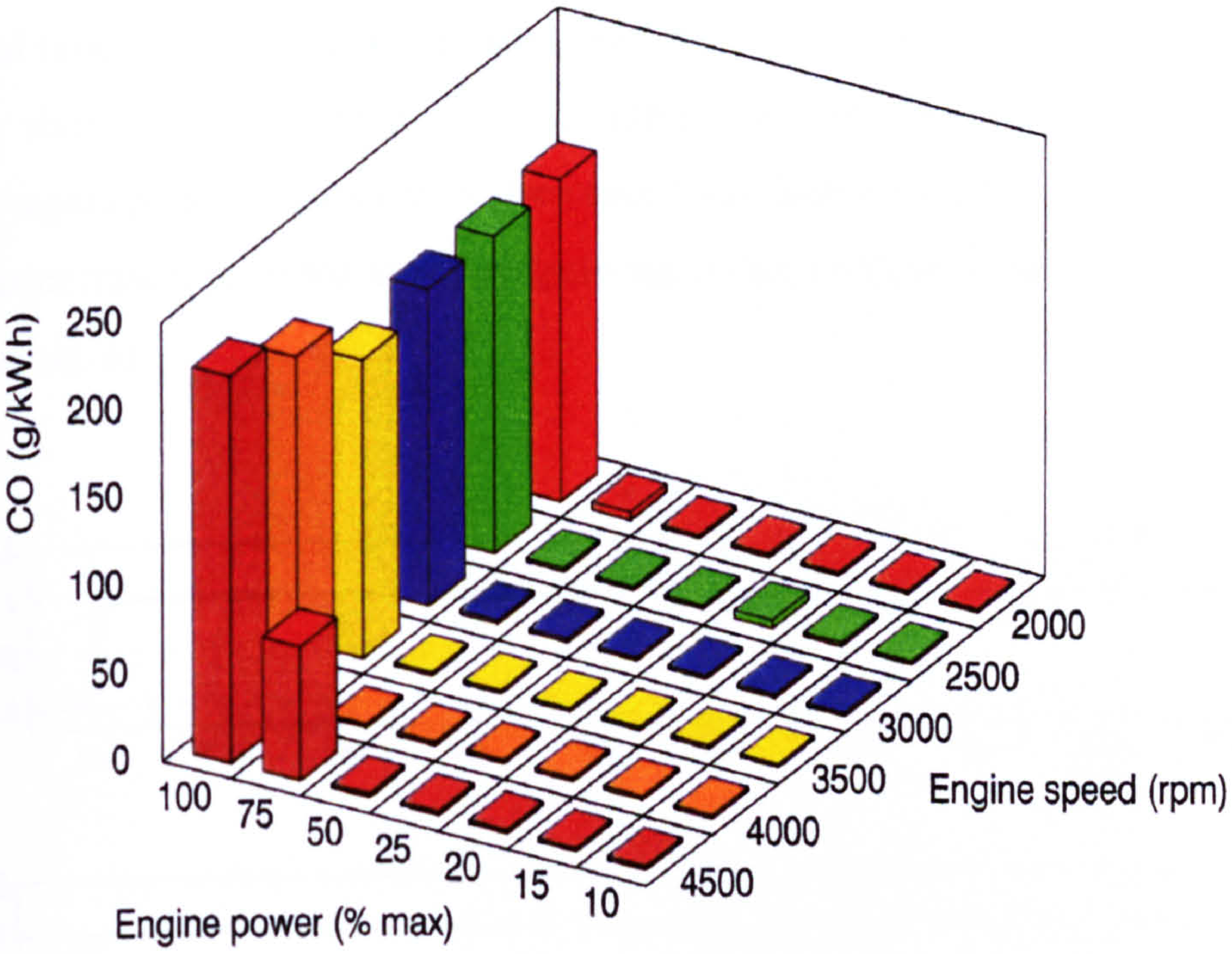

Figure 11.6 Instantaneous CO emissions from a catalyst car versus engine speed and load over a motorway cycle (Joumard *et al.*, 1998).

However, the approaches investigated in this Thesis, as well as the alternatives highlighted, do not address the most fundamental problem relating to modal emission modelling: it is extremely difficult to measure emissions on a continuous basis with a high degree of precision, and the emissions and fuel consumption values recorded in the one-second steps might not be successfully allocated to the associated operating conditions. For example, because of the time required to transport the exhaust gas to the analysers, and the actual response time of the analysers themselves, the emission signals are delayed relative to the driving cycle. Furthermore, the exhaust gas is mixed in the exhaust system. This results in a general flattening of instantaneous emission peaks over a period of more than one second. The dynamics of mixing also depend on the gas flow rate, and the situation is even worse when dilute exhaust gas is being sampled using a CVS.

The phenomena of time lag and damping have been illustrated by Weilenmann *et al.* (2000). In the experiment shown in Figure 11.7 a non-catalyst petrol car was mounted on a chassis dynamometer and a gas injection inlet was installed directly after the exhaust manifold. The engine was operated in three steady-state modes at loads associated with idling (test 1), urban driving (test 2), and inter-urban driving (test 3). The exhaust volume flow ranged from 0.005 m^3/s during idling to 0.130 m^3/s during operation at the highest load. During the driving the gas (oxygen) valve was opened and closed several times (resulting in a step input) and the gas analyser response was recorded. The figure clearly shows that the analyser signal is delayed, and that the delay between the emission peak and the signal peak is dependent on the exhaust gas flow rate (which is varying constantly). Also, the concentration recorded at the analyser takes much longer to reach its maximum value than the input signal.

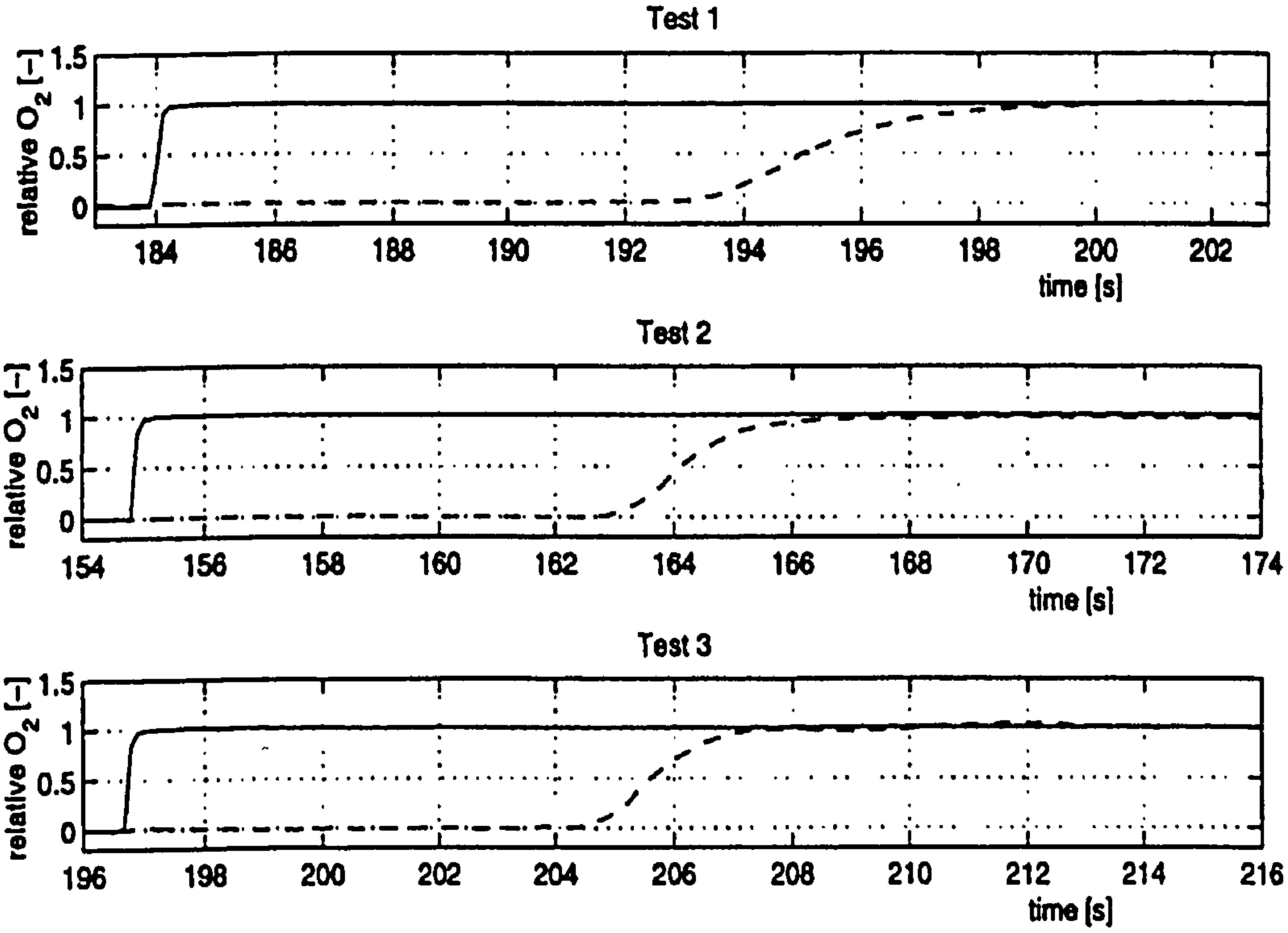

Figure 11.7 Results of gas injection tests; the valve signal is represented by the solid line, the analyser oxygen signal is represented by the dashed line (adapted from Weilenmann *et al.*, 2000).

In modern cars equipped with a three-way catalyst, oxygen peaks occur in fuel cut-off situations. Figure 11.8 shows a two-second fuel cut-off (~418s) at 60 km/h in such a car. The fuel cut-off creates an oxygen peak of 1.2 seconds at the lambda sensor downstream of the catalyst. The raw gas analyser response follows at time 425s, and is much smaller. This shows that the dynamics of the raw exhaust gas line and the analyser are too slow for a peak of this duration to be measured accurately. In the dilute gas measurement the peak occurs at 437 seconds, and is even wider and flatter than the raw exhaust peak.

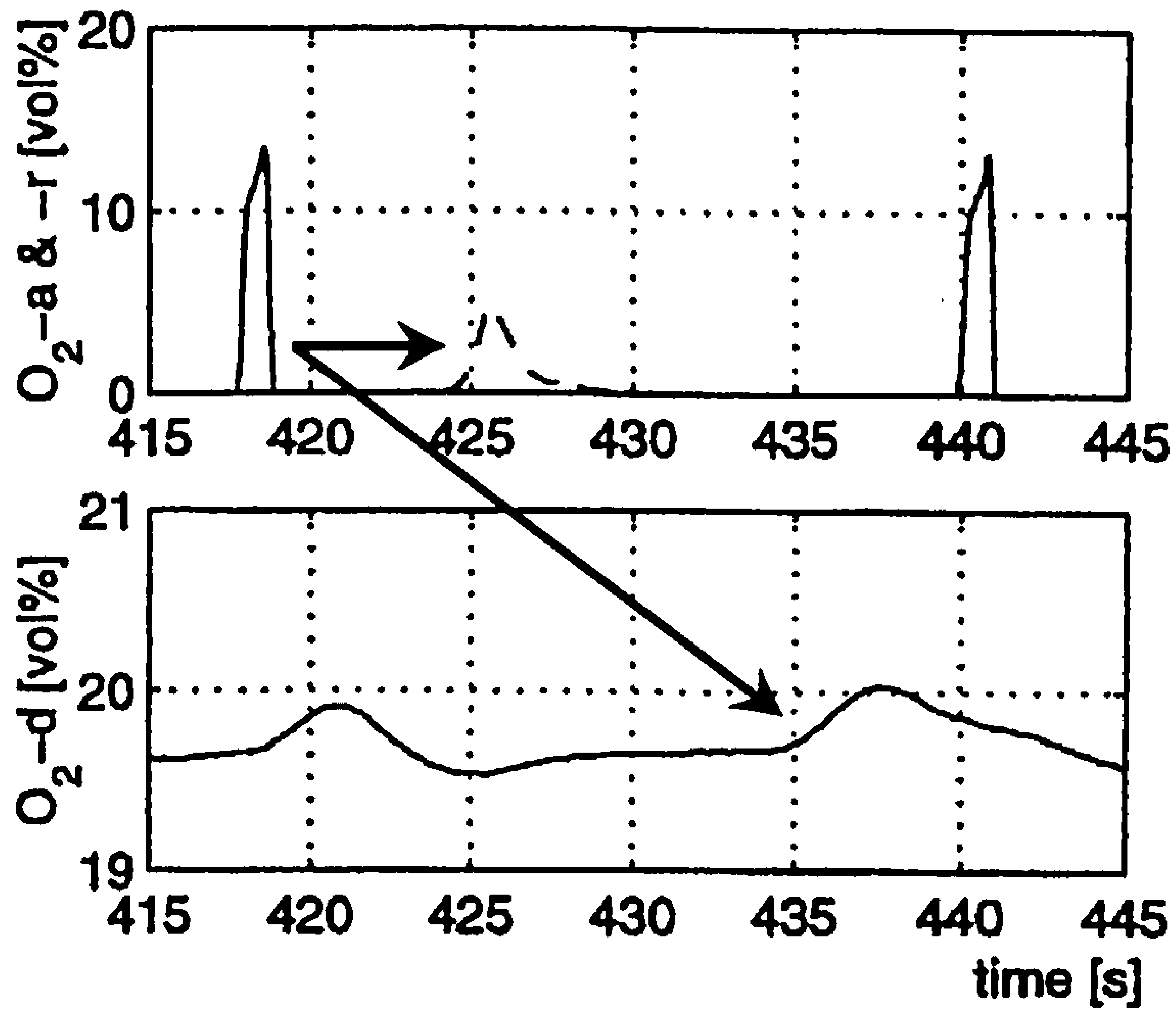

Figure 11.8 Oxygen concentrations after a two-second fuel cut off. In the top graph the raw exhaust valve signal is represented by the solid line, and the raw exhaust analyser oxygen signal is represented by the dashed line. The bottom graph shows the signal recorded by the anlayser in the dilute exhaust (adapted from Weilenmann *et al.*, 2000).

These results have obvious implications for the development of modal emission models based on instantaneous vehicle operation. The time delay is usually taken into account by shifting the data backwards by a fixed number of seconds. However, Weilenmann *et al.* (2000) have shown that, when raw exhaust gas is being sampled, the delay is not constant, and varies by more than one second depending on the gas flow rate in the exhaust. Correcting the time lag by shifting the entire emission signal be a fixed number of seconds is clearly going to mean that emission events are temporally misaligned with the speed data, resulting in model inaccuracy. Over a transient driving cycle engine load varies every second, and hence there will inevitably be moments when the emission signal preceded the generation of the emission itself. The damping of the raw exhaust signal means that, in general, the 'real' emission peaks will be underestimated, and the emission troughs overestimated. Even if no original emission has occurred in a given instant, a model can produce a value because of the temporal spreading of the emission peaks.

Therefore, even if modal emission models were constructed using raw exhaust measurements, such results indicate that there would clearly be problems matching an emission signal in any given second to the appropriate speed or acceleration measurement. MODEM is based upon measurements on *dilute* exhaust, even though Figure 11.8 indicates that the signal obtained from measurements in a dilution tunnel bears little relation to the real signal. Because the cells in each MODEM emission matrix contain average values for a particular mode of operation, the net result is that the second-by-second prediction by MODEM during a given driving cycle is damped even further. This is illustrated for a single petrol non-catalyst vehicle driven over one of the traffic calming cycles developed in the study in Figure 11.9. In Figure 11.9, the measured CO emission profile was obtained using the diluted exhaust gas, and the modelled CO emission profile was obtained using a MODEM emission matrix based on the measured profile alone. Although points A and B have similar speed and acceleration values, point A corresponds to a CO emission rate of almost 3000 g/h, whereas point B corresponds to an emission rate of less than 1000 g/h. It is likely that this variability in the emission rate associated with given operational parameters will occur throughout the emission profile, and therefore the model will tend not to pick up the peaks and troughs of the (already highly damped) emission trace. This would still probably occur, though hopefully to a much lesser extent, even if a 'true' emission profile could be obtained.

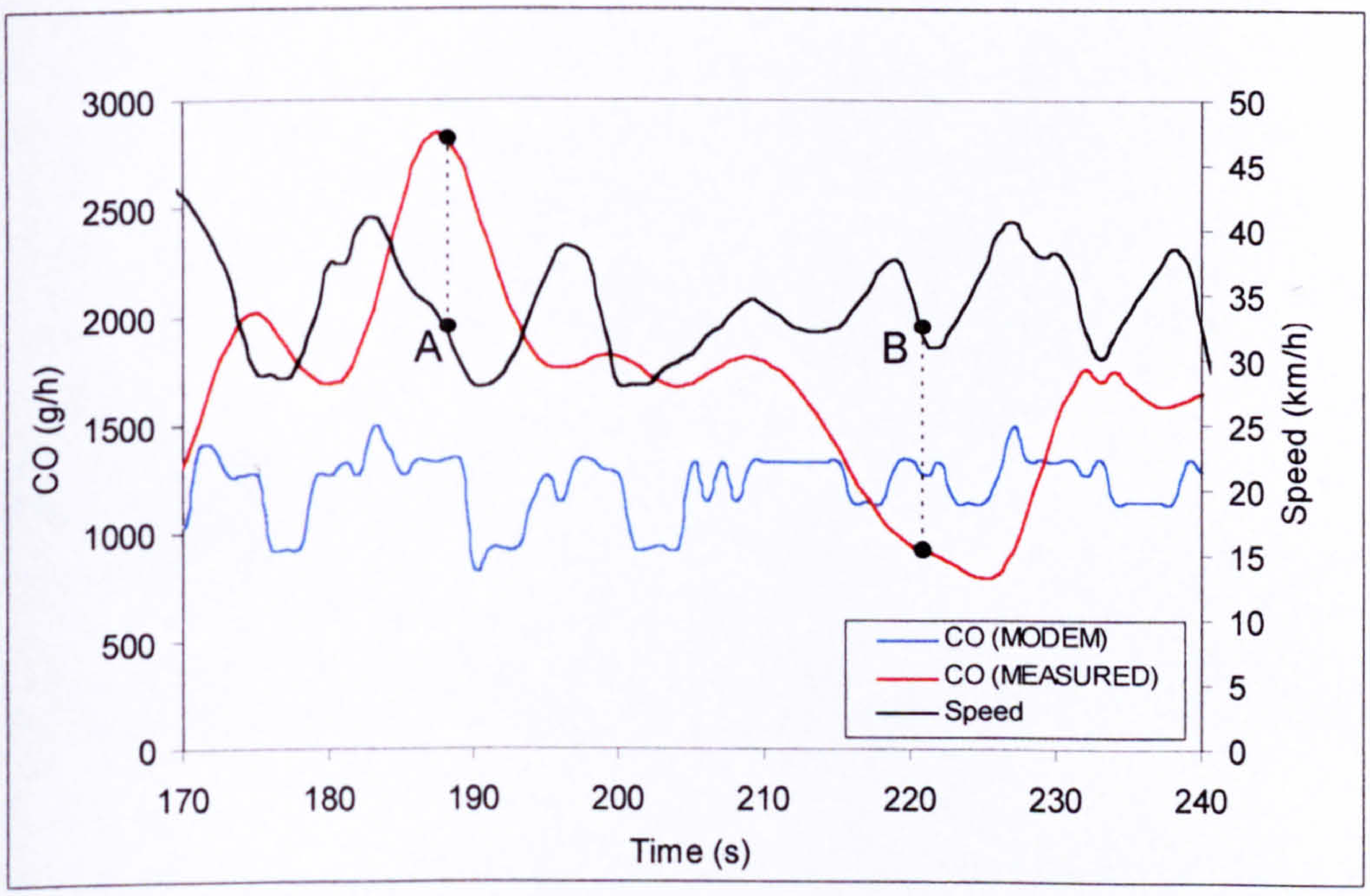

Figure 11.9 CO emission profile measured for a single vehicle in the traffic calming study compared with the emission profile predicted by MODEM using an emission matrix based on the measured profile (Vehicle 6, Scheme C after calming).

Clearly, advances in the field of modal emission modelling will not be forthcoming until realistic continuous emission data are available. Efforts are now underway to reduce the dynamic distortion of the emission data. Weilenmann *et al.* (2000) have developed a mathematical model of the measurement system which can then be 'inverted' or solved in order to reconstruct the original emission signal in the exhaust pipe from the one measured at the analyser. This process increases in complexity with the level of exhaust dilution used. It is least complex when emissions are recorded at the exhaust manifold, more complex when emissions are recorded in the exhaust pipe, and the most complex when a dilution tunnel is used. However, the implication is that a number of parameters relating to the sampling equipment and the vehicle need to be recorded for each test.

The raw exhaust model is represented schematically in Figure 11.10. It contains three sub-models to represent gas transport, mixing, and the analyser response.

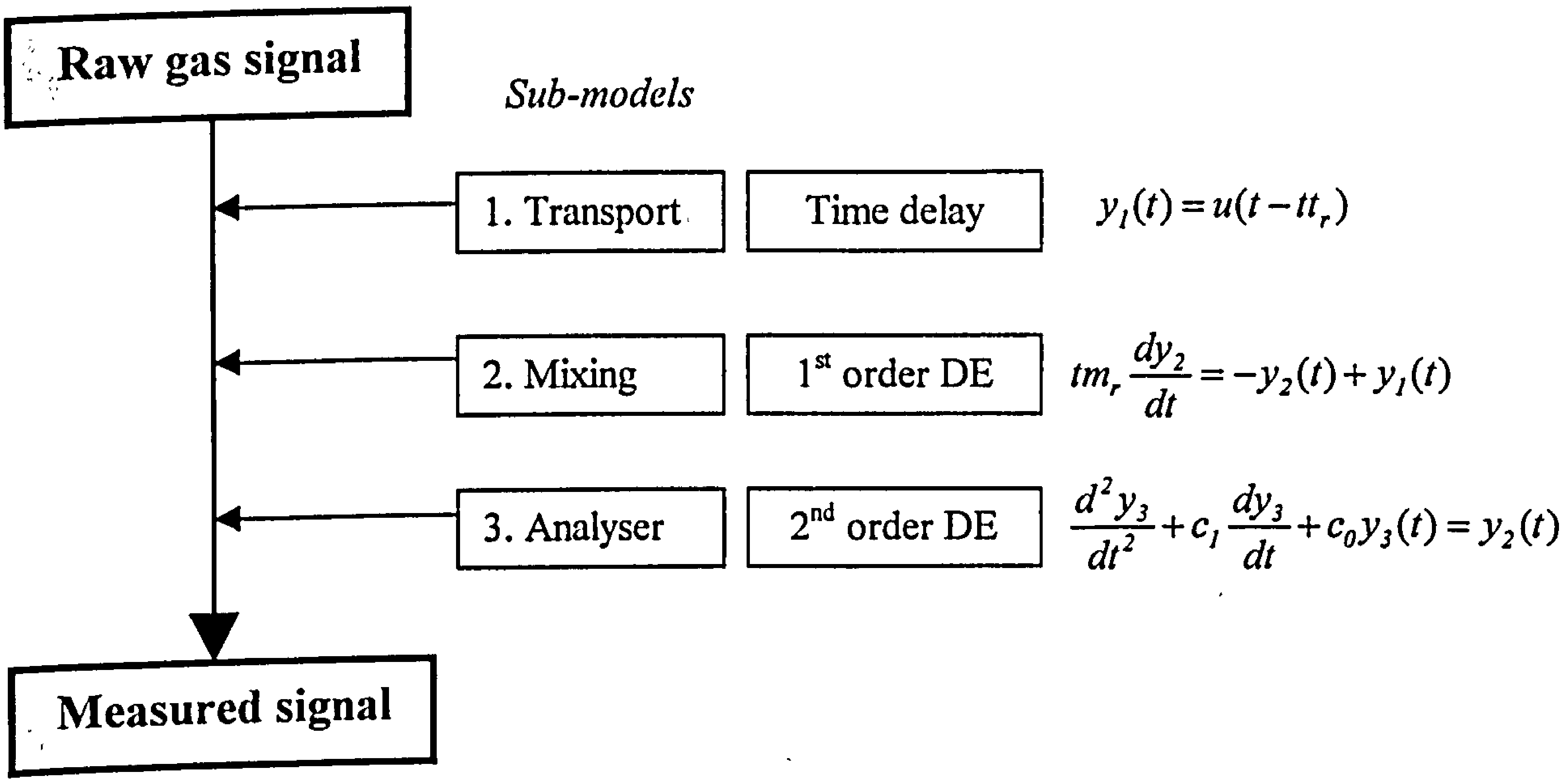

Figure 11.10 Schematic diagram of the raw gas system model (adapted from Weilenmann *et al.* (2000)). The variable *yn(t)* represents the output of sub-model *n*.

The first sub model describes the time delay between the input signal $u(t)$ (the gas concentration at the end of the exhaust pipe) and the output signal at the analyser $y_n(t)$. The value tt_r represents the time delay in the raw exhaust gas line. Mixing is modelled using a first order differential equation, with tm_r at the mixing time constant. The analyser behaviour can be described by a second-order differential equation. If the equations describing the three sub-models are combined, the overall system can be described by the equation:

$$\frac{d^3y}{dt^3}+a_2\frac{d^2y}{dt^2}+a_1\frac{dy}{dt}+a_o y(t)=u(t-tt_r)$$

(a_2 and a_o replace c_1, c_0, and tm_r)

Because measurements are obtained at discrete time intervals, this overall equation can be converted to a much simpler difference equation, and a simple experiment with zero gas and span gas must be carried out with each analyser to obtain the parameters required for the simplified equation (Weilenmann *et al.*, 2000).

Weilenmann *et al.* (2000) stated that their model could be used in conjunction with a dilute sampling system, but the calculation are complex and the results are less reliable than those obtained when the emission signal is being reconstructed using raw exhaust gas measurements.

It was not possible to attempt any modification of this type to the existing MODEM model; the reconstruction of the 'true' emission signal at the analysers could also not be achieved because the relevant sampling parameters were not available.

CHAPTER 12 SUMMARY AND DISCUSSION

12.1 Background

The Environment Act 1995 confirmed that traffic management schemes could be used for air quality management purposes. Plans drawn up by local authorities under Section 84(2) of the Act could include alterations to existing schemes, or the development of new schemes, on air quality grounds. Where local authorities considered that traffic management could make an appropriate contribution to improving air quality, they were advised to consider and carefully evaluate all the opportunities available to them, and set out a balanced and integrated approach tailor-made to their specific local circumstances (Department of the Environment *et al.*, 1996b). The introduction of the UK National Air Quality Strategy meant that local authorities had to be aware of any air quality impacts resulting from their traffic management operations. However, at the time the Strategy was drawn up there was little information relating to the effects of different schemes on vehicle exhaust emissions and air quality. In order to provide more robust information and guidance for local authorities, the Government commissioned an extensive programme of work aimed at improving the level of understanding. A large proportion of the programme was, and is still being, conducted at the Transport Research Laboratory (TRL). The environmental appraisals undertaken at TRL have been spread over number of projects, and have covered a range of subject areas. These subject areas have included noise, vibration, vehicle emissions, air pollution, and perceived impacts. This Thesis has incorporated a large proportion of the TRL research relating to the impacts of a particular type of traffic management - traffic calming - on vehicle emissions.

The main objectives of the research undertaken for the PhD programme were:

(i) To review the existing level of understanding regarding traffic calming and vehicle emissions.

(ii) To determine the effects of different types of traffic calming measure on exhaust emissions, primarily from passenger cars but also from goods vehicles and buses. Subordinate objectives here included:

- To assess the impact of traffic calming on vehicle speed profiles.
- The development of driving cycles using external speed measurement techniques.
- Determination of the impact of traffic calming on emissions from passenger cars based on the driving cycles.
- The measurement of emissions from large numbers of vehicles on the road using remote sensing in the vicinity of traffic calming measures.

(iii) To develop a system of comparative performance indicators and guidance for local authorities which would enable them to predict the effects of their proposed traffic calming schemes on area-wide emissions.

(iv) To assess the performance of an existing micro-scale emission model in traffic calming applications, and to explore the ways in which its performance could be enhanced.

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

A 75mm-high round-top road humps
B 80mm-high flat-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

12.2 Review of traffic calming methods and effects

The literature review described the main stages in the assessment of how traffic calming schemes affect vehicle emissions. The topics covered included specific traffic calming measures, the changes in driver behaviour imposed by traffic calming schemes, and the factors affecting emissions from road vehicles in the context of traffic calming. A summary was also been presented of case studies in which the effects of traffic calming on emissions have been determined, either by direct measurement or by the use of emission models and databases. The review provided information on the most common traffic calming measures in the UK, and this information was used as the basis for the selection of schemes to be investigated in the research.

It was noted in the review that descriptions of driver behaviour include both detailed data on parameters relating to vehicle operation, such as speed and gear selection, and information on trips such as journey purpose, duration, mode, time of day, and time of year. The factors influencing vehicle operation are numerous, and the relative importance of these factors is unclear at present. There are also few quantitative data relating to how emissions might be influenced by traffic calming. Work relating to driver behaviour has usually been concerned with its relationship to accident causation, rather than to vehicle emissions. Consequently, existing studies invariably relate to speed selection, and rarely to other parameters known to affect emission rates (*e.g.* acceleration rates, gear selection). Vehicle speed at specific locations on a road is one of the most frequently measured parameters in the assessment of traffic calming schemes, but it is knowledge of continuous vehicle operation that is a fundamental requirements for accurately determining changes in vehicle emissions on the scale of an individual road, and this kind of continuous information is not widely available. Also, changes in traffic flow and composition are required to determine the overall impact of a traffic calming scheme, especially where a diversion of traffic is likely to occur.

A review of previous case studies indicated that fuel consumption and emissions of CO, HC, and CO_2 per vehicle-km increase after the introduction of traffic calming, although the range of results for each pollutant was rather wide. For NO_x, both increases and decreases in emissions have been observed, and the variability in impacts is the most pronounced of any pollutant. One study showed a decrease in NO_x emissions of 60%, whilst another showed an increase of 900%. It is likely that the variability of the impacts is related to a number of factors, including the method of assessment, the types of vehicle considered, the configuration of the road, and the arrangement of the traffic calming scheme. Most of the information on emissions that has been presented in these case studies has been obtained through the use of emission models or databases. The results of a few studies in which measurements have actually been taken have often been used to make general predictions about the effects of traffic calming on emissions. However, there was clearly a need for more detailed empirical information relating to a wider variety of schemes. The research presented in this Thesis was designed to address this issue.

12.3 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. The speed data used to develop the driving cycles for the traffic calming measures were obtained using both an external method of measurement, which should not have affected the behaviour of drivers as they negotiated the schemes, and an internal method. The speed-time profiles of vehicles passing through each scheme were measured using the external technique. Initially, a separate set of internal speed profile measurements, obtained using instrumented cars driven through the same schemes by selected subjects, were 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 were 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, were 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 were 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 simplified after some early analysis.

12.4 Speed measurement techniques

The proposed methodology relied in part on a statistical method for matching the speed profiles obtained by external 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 methods of external 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 external 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 external measurements. 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, but it was considered that the possibility of covering the entire speed range observed in the external measurements at all sites could be increased by including a third ('small') instrumented car.

12.5 Traffic surveys

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 external 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, changes to the timetable for scheme implementation dictated that for the 1.9m-wide speed-cushions external speed measurements had to be conducted on one road before calming, but on a different road after calming.

Traffic flow

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 were 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 of 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 external speed measurements were obtained before calming, the mean speed of passenger cars varied between 38 km/h and 53 km/h. 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 and 42 km/h, with the actual speed reduction, excluding the three sites for which no measurements were obtained before calming, ranging from 10 km/h to 19 km/h. 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 and 50 km/h before calming to between 20 and 42 km/h after calming, with a speed reduction of between 10 and 17 km/h. 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 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. Also, the speeds recorded in the vicinity of the build-out and mini-roundabout may have been affected by the installation of round-top road humps nearby on the same road.

Implications for emission test programme

Only small differences were observed between the means and standard deviations of the speeds of 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.

12.6 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 external 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 driveable, 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. For schemes F, G and H, external 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.

12.7 Laboratory emission tests

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, Züger 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), 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 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 Züger 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.

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. 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.

One 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.

12.8 Remote sensing of vehicle emissions

In the first reported study of its kind, vehicle speed, vehicle acceleration, and carbon monoxide and hydrocarbon emissions were recorded using a remote sensing system near and between two types of traffic calming measure (flat-top road humps and speed cushions).

The observed speeds, speed reductions, accelerations and decelerations were normal for traffic calming schemes. The mean percentages of carbon monoxide in the exhaust gas recorded near the hump and between humps were found to be higher than the level recorded before calming by 30% and 38% respectively, and the corresponding median %CO values increased by 56% and 38%. The increases in the mean %CO near and between speed cushions were 32% and 20%, with corresponding increases in the median CO levels of 47% and 2%. Based on the disaggregated data for a single lane of traffic near a road hump, the largest proportional increase in the mean %CO (73%) was observed for vehicles other than passenger cars. The mean CO level for non-catalyst cars increased by 44%, and that for catalyst-equipped cars by 60%. These values for passenger cars are close to the changes in CO mass emissions measured in the laboratory tests. The level of instrument noise on the hydrocarbon emission measurements was considered too great for firm conclusions to be drawn for this pollutant, and TRL will be reassessing the hydrocarbon channel in further experiments.

In order to provide a reasonable estimate of the change in the total mass of CO emitted per vehicle-km by on each of the roads investigated, the 25% change in fuel consumption (and hence exhaust gas volume) measured in the laboratory emission tests was applied systematically to the remote sensing results for all vehicles. It was found that traffic calming would cause the average mass of CO emitted per vehicle-km to increase by 50-73%. This estimate did not account for effects on traffic flows which, on the two roads investigated, were reduced by 8% after calming. This would have slightly reduced the impact of the changes in operation on these roads, though the diverted traffic would have contributed to the emission levels on other roads unless it had been suppressed completely. As the before and after surveys were conducted at different ambient temperatures, it was also possible that the contribution of cold start emissions to total emissions would have been different in each survey. It was calculated that changes in cold start emissions of CO probably accounted for no more than around one third of the 50-73% change in mass emissions per vehicle-km.

Given the uncertainties in the remote sensing estimate, the 50-73% increase in mass emissions of CO per kilometre (for all vehicles) determined by remote sensing agrees reasonably well with the range of impacts measured in the laboratory emission tests. However, the relatively high CO emission rate of petrol non-catalyst cars means that the effect on these vehicles would probably dominate the change in emissions of a stream of traffic at the present time. Also, the percentage increase in the mass of CO emitted, as determined from the FEAT results, also show a reasonable level of agreement with the results from the previous studies, even though the methods of assessment, the traffic calming scenarios, and the vehicle types were different. These findings provide encouragement for further investigation using the remote sensing approach. However, although remote sensing is a useful tool there are still areas of doubt concerning the wider use of the technique in this type of application. The experimental technique is still being developed and the level of understanding and interpretation of the data will benefit from future refinement.

It is reasonable to assume that because the mass emission rate of CO is dependent upon vehicle speed and acceleration, then these variables might be used to explain differences between the FEAT results and those of the modelling and on-road measurement studies. However, whereas the large increase in CO emissions recorded by Züger and Blessing (1995) - albeit for one vehicle -coincided with low mean speeds and rapid accelerations and decelerations, Webster observed increases in CO emissions that were larger than those in the FEAT study even though he used a similar speed and less severe accelerations and decelerations. This suggests that the situation is more complex than a simple speed/acceleration-based approach would suggest, and it appears that other factors - such as the spacing of humps, cushions, and other measures - are also important in determining any overall effects on emissions.

12.9 Performance indicators and guidance

The main findings of the research, as well as any relevant information drawn from other sources, were used to generate develop a system of performance indicators for the different traffic calming measures. The indicators were speed reduction, accident reduction, vehicle emissions, and traffic emissions.

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 demonstrated 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.

12.10 Emission model assessment and development

In order to examine whether the modal (or instantaneous) emission modelling approach was able to offer any improvements over the average-speed approach in the assessment of traffic calming, the results from the experimental work presented in the Thesis were used to compare the performance of the MEET (average speed) and MODEM (modal) models. Also, an attempt was made to improve the accuracy of MODEM model in such applications by developing a variant model (MODEM-TC) for use in traffic calming applications, and a re-appraisal of the variant model was undertaken.

The choice of driving cycles used to develop emission matrices is an important determinant of a model's accuracy, but neither the parameters used to describe operation, the grid size, nor the use of an interpolation scheme have previously been shown to result in any improvements in accuracy. Consequently, in the development of the MODEM-TC model, a decision was taken to concentrate on the driving cycle element. This was considered to be particularly appropriate for traffic calming, as it tends to impose a particular regime of low-speed operation for which a specific emissions database might be more appropriate.

It was found that there was generally only a fair level of agreement between the overall absolute emission rates in the traffic calming study (both before and after calming) and those predicted by the MEET model. However, there tended to be a fairly good agreement between the overall percentage impacts recorded in the traffic calming study and those calculated using the MEET equations, though the ability of MEET to predict these changes in emissions depended very much on the vehicle type and pollutant being considered. These comparisons suggest that the average-speed modelling approach used in MEET does, to a first approximation, give a good overall indication of the percentage impacts of traffic calming in general on emissions per vehicle, though the assessment of the reliability of the comparison between the different vehicle samples was somewhat hindered by the differences in absolute emission rates. MODEM exhibited a mixture of underestimation and overestimation compared with the laboratory measurements, though in some cases there was a good level of agreement between the measured and modelled values. MODEM-TC, on the other hand, overestimated bag emissions in almost all cases. The percentage changes predicted by the MEET and MODEM models showed an unexpected pattern. For almost all combinations of vehicle type and pollutant, the MEET model provided a more reliable indication of the likely impact of traffic calming than the MODEM model, in spite of the fact that the latter employs a more detailed mechanism for representing vehicle operation. Although for CO, HC and CO_2 the MODEM model correctly predicted that emissions would increase overall, the sizes of the increases were underestimated for all three vehicle categories by a factor of between 3 and 9. For petrol cars the direction of the change in NO_x emissions resulting from the introduction of traffic calming was not correctly predicted by MODEM, though both the measured and modelled changes were relatively small. For diesel cars MODEM correctly predicted an increase in NO_x, but again the predicted was around one third of the measured increase. The most consistent changes, with the exception of MODEM, were observed for CO_2 emissions. The measurements, the MEET model, and the MODEM-TC model indicated that CO_2 emissions from all vehicle categories increased by between 19% and 29%. MODEM predicted increases of between 5 and 8%.

For most vehicle category-pollutant combinations the MODEM-TC model improved on the percentage impact predictions of the MODEM model. The most marked improvements occurred in the prediction of changes in CO_2 for all three vehicle categories, though greatly improved results were also obtained for emissions of CO, HC, and NO_x from diesel vehicles, and HC emissions from petrol non-catalyst and catalyst vehicles. However, the MEET model still tended to predict percentage changes in emissions which were closer to those measured on the dynamometer.

For petrol non-catalyst, petrol catalyst and diesel cars, and for all the individual driving cycles, the (weighted) absolute emission rates and percentage changes predicted by MEET, MODEM, and MODEM-TC were plotted against the corresponding emission rates measured on the dynamometer. None of the models consistently produced very good results at this level of disaggregation.

There are clearly deficiencies in the modal modelling approach which cannot be entirely resolved by changing the emission factors or the way in which the models operate. A number of further suggestions for improving instantaneous models have been advanced. These include concentrating on the engine operating conditions which account for a large proportion of the emissions from catalyst-equipped vehicles, and introduction into models of a parameter relating to gear activity could help to reduce the variability of the emission values in matrix cells. Unfortunately, the work conducted so far indicates that an instantaneous model which treats extreme events separately provides no improvement in accuracy over existing instantaneous models, or even over average speed models.

However, existing approaches described here do not address the most fundamental problem relating to instantaneous emission modelling: it is extremely difficult to measure emissions on a continuous basis with a high degree of precision, and the emissions and fuel consumption values recorded in the one-second steps might not be successfully allocated to the associated operating conditions. For example, because of the time required to transport the exhaust gas to the analysers, and the actual response time of the analysers themselves, the emission signals are delayed relative to the driving cycle. Furthermore, the exhaust gas is mixed in the exhaust system. This results in a general flattening of instantaneous emission peaks over a period of more than one second. The dynamics of mixing also depend on the gas flow rate, and the situation is even worse when dilute exhaust gas is being sampled.

These phenomena have obvious implications for the development of emission models based on instantaneous vehicle operation Firstly, emission events can be temporally misaligned with the speed data. Secondly, the damping of the raw exhaust signal means that, in general, the 'real' emission peaks will be underestimated, and the emission troughs overestimated. Even if no original emission has occurred in a given instant, a model can produce a value because of the temporal spreading of the emission peaks. MODEM is based upon measurements on *dilute* exhaust gas. Because the cells in each MODEM emission matrix contain average values for a particular mode of operation, the net result is that the second-by-second prediction by MODEM during a given driving cycle is damped even further, and the model will tend not to pick up the peaks and troughs of the (already highly damped) emission trace. This would still probably occur, though hopefully to a much lesser extent, even if a 'true' emission profile could be obtained.

Clearly, advances in the field of modal emission modelling will not be forthcoming until realistic continuous emission data are available. Efforts are now underway to reduce the dynamic distortion of the emission data, and researchers have developed a mathematical model of the measurement system which can then be 'inverted' or solved in order to reconstruct the original emission signal in the exhaust pipe from the one measured at the analyser. However, it was not possible to attempt any modification of this type to the existing MODEM model here; the reconstruction of the 'true' emission signal at the analysers could also not be achieved because the relevant sampling parameters were not available.

13 CONCLUSIONS AND RECOMMENDATIONS

13.1 Conclusions

This Thesis has described a 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 below.

(i) 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.

(ii) 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.

(iii) 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. In areas where air pollution is a particular concern, 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. However, it is also important to note that a range of other factors will influence the acceptability of a given traffic calming scheme to drivers, residents, pedestrians and the emergency services. Such factors include physical levels of noise and vibration, perceptions relating to the visual appearance of the road environment, perceptions of safety, perceptions of 'smoke', 'dirt', 'fumes', 'noise', 'odour', *etc.*, perceived damage to vehicles, and ride comfort.

(iv) In spite of the variability in the results 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), with those found in previous TRL traffic calming studies using MODEM. 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 MODEM in other studies than to the results of on-board measurements. For CO_2, there is a good level of agreement between different studies.

(v) The 50-73% increase in mass emissions of CO per kilometre (for all vehicles) determined by remote sensing agrees reasonably well with the range of impacts measured in the laboratory emission tests. In the laboratory tests, the mean CO emission of petrol non-catalyst, petrol catalyst, and diesel cars increased by 34%, 59%, and 39% respectively. However, the relatively high CO emission rate of petrol non-catalyst cars means that the effect on these vehicles would probably currently dominate the change in emissions of a stream of traffic. Although remote sensing is a useful tool there are still areas of doubt concerning the wider use of the technique in this type of application. The experimental technique is still being developed and the level of understanding and interpretation of the data will benefit from future refinement.

(vi) The average-speed modelling approach used in MEET does, to a first approximation, give a good overall indication of the percentage impacts of traffic calming in general on emissions per vehicle. For almost all combinations of vehicle type and pollutant, the MEET model provided a more reliable indication of the likely impact of traffic calming than the MODEM model, in spite of the fact that the latter employs a more detailed mechanism for representing vehicle operation. When the emission matrices used in MODEM were replaced with ones derived using the laboratory emission data from the traffic calming tests, the resulting MODEM-TC model improved on the percentage impact predictions of the MODEM model. However, the MEET model still tended to predict percentage changes in emissions which were closer to those measured on the dynamometer.

(vii) 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 , MODEM, and MODEM-TC have suggested that the model cannot be used with confidence to rank different types of traffic calming measures according to their impact on emissions.

(viii) The time lag and damping associated with a continuous raw exhaust signal means that, in general, the 'real' emission peaks will be underestimated, and the emission troughs overestimated. This has serious implications for modal emission modelling. MODEM is based upon measurements on *dilute* exhaust gas, which makes the situation even worse. In effect, MODEM cannot be considered to be more effective in micro-scale modelling than a conventional average-speed model.

13.2 Recommendations for future work

The most modern petrol cars tested in the study conformed to the Euro I legislation, but these are now several years old. It has been shown that newer-technology vehicles can be (relatively speaking) particularly susceptible to traffic calming. It would be of interest to examine how more modern vehicles behave under the real-world driving conditions simulated in the traffic calming cycles, and whether the emission levels of such vehicles are elevated.

The general level of agreement between the remote sensing study and the results of previous traffic calming studies provides encouragement for further investigation using the remote sensing approach. However, at present there are still areas of doubt concerning the wider use of the technique in this type of application. For example, a more consistent approach would have to be agreed on how to treat negative emission values, and remote sensing cannot be simply used as an independent means of determining changes in mass emissions per kilometre resulting from changes in operation since this requires information on fuel consumption. In addition, a method for remotely measuring exhaust gas temperature would help to identify vehicles in cold start mode, and this should remove some of the uncertainty in the results. Research into the technical feasibility of measuring temperature remotely is currently underway in the United States. The remote sensing experimental technique is still being developed and the level of understanding and interpretation of the data will benefit from future refinement. It would be particularly useful if the problems with the HC channel observed in this experiment could be resolved, and more information on NO levels could be obtained. The latter is particularly important as existing results show that the effects of traffic calming on NO_x emissions are unclear.

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 unlikely that that it would result in breaches of air quality 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, and further empirical air quality information would be valuable. The guidance provided here would be enhanced if information relating to the other factors which are thought to influence the acceptability of traffic calming (noise, vibration, perceived impacts, *etc.*) were to be included.

It is extremely difficult to measure emissions on a continuous basis with a high degree of precision, and time lags and damping effects are particular problems. Advances in the field of modal emission modelling will not be forthcoming until realistic continuous emission data are available, and efforts are now underway to reduce the dynamic distortion of the emission data. Researchers are developing mathematical models of the measurement system which can then be solved in order to reconstruct the original emission signal in the exhaust pipe from the one measured at the analyser. Unfortunately, it was not possible to attempt any modification of this type to the existing MODEM model; the reconstruction of the 'true' emission signal at the analysers could also not be achieved because the relevant sampling parameters were not available.

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APPENDIX A

A BRIEF CHRONOLOGY OF RECENT TRAFFIC CALMING LEGISLATION

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

Highways (Road Humps) Regulations 1990

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

Road Traffic Act 1991

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

Traffic Calming Act 1992

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

Highways (Traffic Calming) Regulations 1993

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

Highways (Road Humps) Regulations 1996

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

Highways (Road Humps) Regulations 1999

These provide local highway authorities outside London with considerable flexibility in the design and placement of road humps. However, the regulations make local highway authorities responsible for the design and placement, so authorities will need to ensure that an adequate duty of care is exercised. The Greater London Authority Act 1999 allows local authorities in London to construct humps of any dimension on roads subject to any speed limit (without the need for special authorisation but with a requirement for consultation with the Secretary of State). This greater freedom of action places greater responsibility on the London Boroughs to ensure that an adequate duty of care is exercised. Humps where the height could be varied mechanically need particular consideration regarding the safety of road users. Local authorities wishing to install such devices on the public highway are advised to consult with Road Safety Division, DETR on the need for special authorisation even if the humps conform to 1999 regulations.

Highways (Traffic calming) Regulations 1999

The Highways (Traffic Calming) Regulations further clarified the powers available to local highway authorities to construct particular measures for traffic calming purposes. The measures include gateways, pinch points, islands, overrun areas, rumble devices, build-outs, and chicanes. In 20 mph zones, warning signs for traffic calming features may be omitted, but this does not apply to non-traffic calming features. For these features, warning signs, as appropriate, should be provided. Give way markings to assign priority at a chicane would also still be required in a 20 mph zone.

APPENDIX B

EMISSION TEST RESULTS

NB: In this Appendix, 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 B1 Carbon monoxide (g/km): Petrol non-catalyst cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number							
				Small				Medium		Large	
				1	2	3	4	5	6	7	8
A	Flat-top road humps	Before calming	Test results	4.944 4.728	-	6.968 5.820	-	7.179 6.025	16.154 21.475	6.751 6.348	10.967 14.351
			Mean	4.836	-	6.394	-	6.602	18.815	6.550	12.659
		After calming	Test results	6.727 6.721	-	10.213 9.050	-	9.751 7.774	25.044 26.950	9.208 8.358	19.461 21.327
			Mean	6.724	-	9.632	-	8.763	25.997	8.783	20.394
		% change in mean		*+39*	-	*+51*	-	*+33*	*+38*	*+34*	*+61*
B	Round-top humps	Before calming	Test results	8.615 9.140	-	15.301 9.582	-	9.562 9.083	25.729 26.656	9.914 9.326	16.302 15.678
			Mean	8.878	-	12.442	-	9.323	26.193	9.620	15.990
		After calming	Test results	13.038 13.884	-	23.531 14.798	-	13.431 9.895	35.789 31.319	12.981 13.144	27.547 26.009
			Mean	13.461	-	19.165	-	11.663	33.554	13.063	26.778
		% change in mean		*+52*	-	*+54*	-	*+25*	*+28*	*+36*	*+67*
C	1.7m-wide speed cushions	Before calming	Test results	10.755 9.733	-	11.710 7.402	20.351 15.270	9.885 9.327	29.803 27.851	9.127 8.545	16.256 24.273
			Mean	10.244	-	9.556	17.811	9.606	28.827	8.836	20.265
		After calming	Test results	13.361 13.600	-	11.543 11.618	23.123 21.625	11.341 10.261	27.056 35.550	11.938 12.723	25.755 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*
D	Pinch point/speed cushion	Before calming	Test results	6.450 7.190	-	10.345 13.071	-	9.618 8.499	21.360 22.201	11.683 12.648	18.440 21.390
			Mean	6.820	-	11.708	-	9.059	21.781	12.166	19.915
		After calming	Test results	11.455 11.969	-	13.082 15.988	-	14.220 13.673	29.288 29.330	13.309 14.021	25.559 25.905
			Mean	11.712	-	14.535	-	13.947	29.309	13.665	25.732
		% change in mean		*+72*	-	*+24*	-	*+54*	*+35*	*+12*	*+29*
E	Raised Junction	Before calming	Test results	-	17.380 17.318	13.879 10.020	-	6.784 4.756	23.794 22.257	11.707 11.580	21.430 18.185
			Mean	-	17.349	11.950	-	5.770	23.026	11.644	19.808
		After calming	Test results	-	24.369 22.276	18.162 16.879	-	8.507 8.678	29.866 28.964	15.264 14.476	33.945 28.083
			Mean	-	23.323	17.521	-	8.593	29.415	14.870	31.014
		% change in mean		-	*+34*	*+47*	-	*+49*	*+28*	*+28*	*+57*
F	Chicane	Before calming	Test results	-	17.885 16.866	10.370 9.793	-	5.267 4.164	17.105 16.546	12.097 10.944	11.024 11.854
			Mean	-	17.375	10.081	-	4.176	16.826	11.520	11.439
		After calming	Test results	-	21.866 24.078	17.847 17.475	-	14.740 13.854	30.039 30.621	15.212 14.477	19.795 23.570
			Mean	-	22.972	18.161	-	14.297	30.330	14.844	21.683
		% change in mean		-	*+32*	*+80*	-	*+203*	*+80*	*+29*	*+90*
G	Build-out	Before calming	Test results	-	18.285 17.580	13.304 11.929	-	7.340 8.113	26.953 24.104	13.122 14.785	19.901 -
			Mean	-	17.932	12.616	-	7.727	25.529	13.954	19.901
		After calming	Test results	-	17.143 22.875	16.578 15.258	-	12.809 14.376	29.166 27.546	12.321 15.586	26.787 -
			Mean	-	20.009	15.918	-	13.593	28.356	13.954	26.787
		% change in mean		-	*+12*	*+26*	-	*+76*	*+11*	*0*	*+35*
H	Mini-roundabout	Before calming	Test results	-	18.285 17.580	12.570 12.890	-	10.780 8.010	26.953 24.104	13.122 14.785	21.500 17.400
			Mean	-	17.932	12.730	-	9.395	25.529	13.954	19.450
		After calming	Test results	-	21.565 22.144	16.420 16.820	-	9.110 11.610	32.233 28.823	14.711 14.855	23.690 29.330
			Mean	-	21.584	16.620	-	10.360	30.528	14.783	26.510
		% change in mean		-	*+22*	*+31*	-	*+10*	*+20*	*+6*	*+36*
I	1.9m-wide speed cushions	Before calming	Test results	-	15.534 16.406	9.361 9.857	-	6.590 5.192	21.407 19.678	13.710 10.028	16.210 16.619
			Mean	-	15.970	9.609	-	5.891	20.543	11.869	16.414
		After calming	Test results	-	20.098 18.371	14.269 14.328	-	5.899 5.496	21.366 20.880	14.647 14.342	22.041 20.099
			Mean	-	19.235	14.299	-	5.698	21.123	14.494	21.070
		% change in mean		-	*+20*	*+49*	-	*-3*	*+3*	*+22*	*+28*

Table B2 Carbon monoxide (g/km): Petrol catalyst cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number										
				Small				Medium					Large	
				9	10	11	12	13	14	15	16	17	18	19
A	Flat-top road humps	Before calming	Test results	2.268 2.100	-	-	0.363 0.424	-	0.563 0.554	-	-	1.368 1.784	2.075 3.467	0.152 0.282
			Mean	2.184	-	-	0.394	-	0.559	-	-	1.576	2.771	0.217
		After calming	Test results	2.014 1.965	-	-	1.483 0.893	-	1.202 2.254	-	-	2.147 2.774	15.996 24.969	0.881 0.473
			Mean	1.990	-	-	1.188	-	1.728	-	-	2.461	20.483	0.677
		% change in mean		*-9*	-	-	*+202*	-	*+209*	-	-	*+56*	*+639*	*+212*
B	Round-top humps	Before calming	Test results	-	21.706 19.668	-	2.478 4.794	-	-	3.399 7.270	-	1.629 1.514	17.212 22.632	0.851 1.442
			Mean	-	20.687	-	3.636	-	-	5.335	-	1.572	19.922	1.147
		After calming	Test results	-	28.816 25.439	-	9.039 5.700	-	-	7.413 7.583	-	3.312 5.144	25.282 27.171	1.461 2.092
			Mean	-	27.128	-	7.370	-	-	7.798	-	4.228	26.227	1.777
		% change in mean		-	*+31*	-	*+103*	-	-	*+41*	-	*+169*	*+32*	*+55*
C	1.7m-wide speed cushions	Before calming	Test results	-	-	-	0.909 0.754	-	-	-	3.535 3.896	0.353 0.491	2.448 3.070	0.701 0.764
			Mean	-	-	-	0.832	-	-	-	3.715	0.422	2.759	0.733
		After calming	Test results	-	-	-	0.810 0.828	-	-	-	5.957 7.265	1.519 1.798	7.424 11.633	1.126 1.471
			Mean	-	-	-	0.819	-	-	-	6.611	1.658	9.529	1.298
		% change in mean		-	-	-	*-2*	-	-	-	*+78*	*+293*	*+245*	*+77*
D	Pinch point/speed cushion	Before calming	Test results	-	-	1.490 4.184	1.043 1.256	3.972 10.568	-	-	-	0.783 0.831	3.937 13.264	0.276 0.562
			Mean	-	-	2.837	1.150	7.270	-	-	-	0.807	8.600	0.419
		After calming	Test results	-	-	3.423 3.899	1.411 1.427	8.374 11.866	-	-	-	1.076 1.025	8.425 16.374	0.507 0.802
			Mean	-	-	3.661	1.419	10.120	-	-	-	1.051	12.400	0.655
		% change in mean		-	-	*+29*	*+23*	*+39*	-	-	-	*+30*	*+44*	*+56*
E	Raised Junction	Before calming	Test results	-	-	4.708 18.173	0.825 6.190	3.737 4.568	-	-	-	1.202 2.516	4.205 9.680	0.554 0.539
			Mean	-	-	11.441	3.508	4.153	-	-	-	1.859	6.943	0.547
		After calming	Test results	-	-	13.829 23.794	3.886 13.163	5.056 12.595	-	-	-	1.709 2.623	8.467 18.430	0.445 0.910
			Mean	-	-	18.812	8.525	8.826	-	-	-	2.166	13.453	0.678
		% change in mean		-	-	*+64*	*+143*	*+113*	-	-	-	*+17*	*+94*	*+24*
F	Chicane	Before calming	Test results	-	-	1.362 5.180	0.974 0.750	1.973 7.008	-	-	-	0.469 0.792	3.693 2.230	0.428 0.899
			Mean	-	-	3.271	0.862	4.490	-	-	-	0.631	2.962	0.664
		After calming	Test results	-	-	3.859 7.218	2.902 2.651	9.953 17.501	-	-	-	0.981 0.335	6.358 9.891	0.923 1.158
			Mean	-	-	5.539	2.776	13.727	-	-	-	0.658	8.125	1.041
		% change in mean		-	-	*+69*	*+222*	*+206*	-	-	-	*+4*	*+174*	*+57*
G	Build-out	Before calming	Test results	-	-	3.767 16.074	0.763 2.208	7.277 8.776	-	-	-	1.798 4.512	1.565 8.726	0.568 2.080
			Mean	-	-	9.921	1.486	8.027	-	-	-	3.155	5.146	1.324
		After calming	Test results	-	-	6.587 15.082	1.763 4.301	12.71 12.374	-	-	-	3.197 3.400	6.951 11.349	2.372 2.433
			Mean	-	-	10.835	3.032	12.542	-	-	-	2.999	9.150	2.403
		% change in mean		-	-	*+9*	*+104*	*+56*	-	-	-	*+5*	*+78*	*+81*
H	Mini-roundabout	Before calming	Test results	-	-	3.767 16.074	0.763 2.208	7.277 8.776	-	-	-	1.798 4.512	1.565 8.726	0.568 2.080
			Mean	-	-	9.921	1.486	8.027	-	-	-	3.155	5.146	1.324
		After calming	Test results	-	-	4.410 9.518	2.093 1.375	8.422 3.427	-	-	-	2.733 2.305	3.663 6.301	3.258 3.113
			Mean	-	-	6.964	1.734	5.925	-	-	-	2.519	4.982	3.186
		% change in mean		-	-	*-30*	*+17*	*-26*	-	-	-	*-20*	*-3*	*+41*
I	1.9m-wide speed cushions	Before calming	Test results	-	-	2.625 2.165	0.407 1.186	4.510 13.223	-	-	-	1.355 7.957	3.521 1.921	0.442 1.142
			Mean	-	-	2.395	0.797	8.867	-	-	-	4.656	2.721	0.792
		After calming	Test results	-	-	2.773 2.806	1.676 3.083	6.030 13.969	-	-	-	2.679 4.952	6.946 11.573	0.636 1.734
			Mean	-	-	2.790	2.380	9.999	-	-	-	3.816	9.260	1.185
		% change in mean		-	-	*+16*	*+198*	*+13*	-	-	-	*-18*	*+240*	*+50*

Table B3 Carbon monoxide (g/km): Diesel cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number		
				No size discrimination		
				20	21	22
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*
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*
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*
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*
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*
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*
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*
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*
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*

Table B4 Total hydrocarbons (g/km): Petrol non-catalyst cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number							
				Small				Medium		Large	
				1	2	3	4	5	6	7	8
A	Flat-top road humps	Before calming	Test results	0.863 0.915	-	1.417 1.352	-	0.862 0.780	1.730 1.738	0.914 0.845	1.192 1.186
			Mean	0.889	-	1.385	-	0.821	1.734	0.880	1.189
		After calming	Test results	1.567 1.714	-	2.283 2.277	-	1.360 1.351	3.110 2.890	1.128 1.091	2.224 2.261
			Mean	1.641	-	2.280	-	1.356	3.000	1.110	2.243
		% change in mean		*+85*	-	*+65*	-	*+ 65*	*+73*	*+26*	*+89*
B	Round-top humps	Before calming	Test results	1.244 1.270	-	1.926 1.649	-	1.221 1.307	1.932 1.851	0.861 0.898	1.701 1.548
			Mean	1.257	-	1.788	-	1.246	1.892	0.880	1.625
		After calming	Test results	2.134 2.453	-	3.564 2.911	-	1.941 1.966	3.392 3.300	1.087 1.152	3.025 2.853
			Mean	2.294	-	3.238	-	1.954	3.346	1.120	2.939
		% change in mean		*+82*	-	*+81*	-	*+55*	*+77*	*+27*	*+81*
C	1.7m-wide speed cushions	Before calming	Test results	1.174 1.144	-	1.878 1.606	2.423 2.144	1.345 1.340	1.859 1.785	0.906 0.769	1.606 1.868
			Mean	1.159	-	1.742	2.284	1.342	1.822	0.838	1.737
		After calming	Test results	1.748 1.651	-	2.271 2.345	3.262 3.052	1.964 1.762	2.391 2.646	1.021 1.250	2.449 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*
D	Pinch point/speed cushion	Before calming	Test results	1.091 1.164	-	1.566 1.848	-	1.331 1.026	1.693 1.774	1.177 1.016	1.559 1.681
			Mean	1.128	-	1.708	-	1.179	1.784	1.097	1.620
		After calming	Test results	1.737 1.784	-	2.124 2.578	-	1.954 1.783	2.606 2.711	1.291 1.344	2.585 2.156
			Mean	1.761	-	2.351	-	1.869	2.659	1.317	2.371
		% change in mean		*+56*	-	*+38*	-	*+59*	*+49*	*+20*	*+46*
E	Raised Junction	Before calming	Test results	-	2.660 2.640	2.159 1.883	-	1.043 0.995	2.108 2.023	0.937 0.858	1.978 1.787
			Mean	-	2.650	2.021	-	1.019	2.066	0.898	1.883
		After calming	Test results	-	3.703 3.420	3.510 3.428	-	1.672 1.838	3.097 3.045	1.202 1.129	2.947 2.873
			Mean	-	3.562	3.469	-	1.755	3.071	1.166	2.910
		% change in mean		-	*+34*	*+72*	-	*+72*	*+49*	*+30*	*+55*
F	Chicane	Before calming	Test results	-	2.070 2.130	1.520 1.423	-	0.765 0.745	1.518 1.505	0.993 0.830	1.636 1.664
			Mean	-	2.086	1.472	-	0.755	1.152	0.911	1.650
		After calming	Test results	-	3.361 3.660	2.586 2.596	-	3.057 1.925	2.683 2.721	1.130 1.024	2.351 2.573
			Mean	-	3.510	2.591	-	2.491	2.072	1.077	2.462
		% change in mean		-	*+68*	*+76*	-	*+230*	*+79*	*+18*	*+49*
G	Build-out	Before calming	Test results	-	2.308 2.683	2.093 2.067	-	1.190 1.730	2.187 2.031	1.008 1.097	2.025 1.880
			Mean	-	2.496	2.080	-	1.460	2.109	1.053	1.953
		After calming	Test results	-	2.786 2.949	2.395 2.433	-	1.787 2.587	2.452 2.481	1.332 1.163	2.108 2.157
			Mean	-	2.868	2.414	-	2.187	2.467	1.248	2.133
		% change in mean		-	*+15*	*+16*	-	*+50*	*+17*	*+19*	*+9*
H	Mini-roundabout	Before calming	Test results	-	2.308 2.683	1.960 1.730	-	1.410 1.090	2.187 2.031	1.008 1.097	2.090 1.960
			Mean	-	2.496	1.845	-	1.250	2.109	1.053	2.025
		After calming	Test results	-	3.473 3.830	2.810 2.960	-	1.970 1.960	3.364 2.967	1.251 1.269	2.570 3.110
			Mean	-	3.651	2.885	-	1.965	3.166	1.260	2.840
		% change in mean		-	*+46*	*+56*	-	*+57*	*+50*	*+19*	*+40*
I	1.9m-wide speed cushions	Before calming	Test results	-	1.952 1.810	1.262 1.194	-	0.897 0.875	1.542 1.365	1.046 0.893	1.165 1.105
			Mean	-	1.881	1.228	-	0.886	1.454	0.970	1.135
		After calming	Test results	-	2.682 2.550	2.110 2.115	-	1.251 1.121	2.549 2.383	1.185 1.096	1.974 1.620
			Mean	-	2.616	2.113	-	1.186	2.466	1.140	1.797
		% change in mean		-	*+39*	*+72*	-	*+34*	*+70*	*+18*	*+58*

Table B5 Total hydrocarbons (g/km): Petrol catalyst cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number										
				Small				Medium					Large	
				9	10	11	12	13	14	15	16	17	18	19
A	Flat-top road humps	Before calming	Test results	0.291 0.359	-	-	0.019 0.007	-	0.027 0.038	-	-	0.028 0.041	0.143 0.133	0.015 0.023
			Mean	0.325	-	-	0.013	-	0.033	-	-	0.035	0.138	0.019
		After calming	Test results	0.454 0.367	-	-	0.032 0.028	-	0.062 0.085	-	-	0.032 0.043	0.350 0.483	0.046 0.024
			Mean	0.411	-	-	0.030	-	0.074	-	-	0.038	0.417	0.035
		% change in mean		*+26*	-	-	*+131*	-	*+126*	-	-	*+9*	*+250*	*+84*
B	Round-top humps	Before calming	Test results	-	2.091 2.033	-	0.043 0.078	-	-	0.062 0.273	-	0.023 0.016	0.145 0.403	0.027 0.042
			Mean	-	2.062	-	0.061	-	-	0.168	-	0.020	0.274	0.035
		After calming	Test results	-	2.955 2.609	-	0.135 0.088	-	-	0.169 0.280	-	0.043 0.068	0.465 0.470	0.041 0.056
			Mean	-	2.782	-	0.112	-	-	0.225	-	0.056	0.468	0.049
		% change in mean		-	*+35*	-	*+84*	-	-	*+34*	-	*+185*	*+71*	*+41*
C	1.7m-wide speed cushions	Before calming	Test results	-	-	-	0.054 0.023	-	-	-	0.100 0.102	0.013 0.018	0.094 0.118	0.013 0.021
			Mean	-	-	-	0.038	-	-	-	0.101	0.016	0.106	0.017
		After calming	Test results	-	-	-	0.021 0.013	-	-	-	0.175 0.243	0.025 0.031	0.227 0.262	0.017 0.022
			Mean	-	-	-	0.017	-	-	-	0.209	0.028	0.245	0.020
		% change in mean		-	-	-	*-55*	-	-	-	*+107*	*+79*	*+130*	*+13*
D	Pinch point/speed cushion	Before calming	Test results	-	-	0.064 0.143	0.019 0.020	0.361 0.589	-	-	-	0.031 0.014	0.132 0.292	0.022 0.016
			Mean	-	-	0.103	0.020	0.475	-	-	-	0.023	0.212	0.019
		After calming	Test results	-	-	0.226 0.251	0.026 0.019	0.643 0.910	-	-	-	0.010 0.017	0.230 0.381	0.011 0.011
			Mean	-	-	0.239	0.023	0.777	-	-	-	0.014	0.305	0.011
		% change in mean		-	-	*+131*	*+15*	*+63*	-	-	-	*-40*	*+44*	*-42*
E	Raised Junction	Before calming	Test results	-	-	0.213 0.449	0.040 0.141	0.078 0.098	-	-	-	0.034 0.044	0.158 0.312	0.043 0.003
			Mean	-	-	0.331	0.091	0.088	-	-	-	0.039	0.235	0.023
		After calming	Test results	-	-	0.323 0.528	0.141 0.313	0.109 0.364	-	-	-	0.021 0.053	0.283 0.476	0.000 0.004
			Mean	-	-	0.425	0.227	0.237	-	-	-	0.037	0.380	0.002
		% change in mean		-	-	*+29*	*+151*	*+169*	-	-	-	*-5*	*+61*	*-91*
F	Chicane	Before calming	Test results	-	-	0.099 0.146	0.050 0.026	0.090 0.209	-	-	-	0.038 0.022	0.154 0.105	0.003 0.007
			Mean	-	-	0.123	0.038	0.150	-	-	-	0.030	0.130	0.005
		After calming	Test results	-	-	0.301 0.468	0.070 0.066	0.464 0.690	-	-	-	0.041 0.038	0.223 0.350	0.003 0.007
			Mean	-	-	0.385	0.068	0.577	-	-	-	0.040	0.287	0.005
		% change in mean		-	-	*+214*	*+79*	*+286*	-	-	-	*+32*	*+121*	*0*
G	Build-out	Before calming	Test results	-	-	0.203 0.557	0.028 0.058	0.422 0.404	-	-	-	0.029 0.101	0.077 0.231	0.044 0.110
			Mean	-	-	0.380	0.043	0.413	-	-	-	0.065	0.154	0.077
		After calming	Test results	-	-	0.183 0.481	0.040 0.102	0.977 0.673	-	-	-	0.056 0.049	0.188 0.285	0.218 0.100
			Mean	-	-	0.332	0.071	0.825	-	-	-	0.053	0.236	0.159
		% change in mean		-	-	*-13*	*+64*	*+100*	-	-	-	*-19*	*+54*	*+106*
H	Mini-roundabout	Before calming	Test results	-	-	0.203 0.557	0.028 0.058	0.422 0.404	-	-	-	0.029 0.101	0.077 0.231	0.044 0.110
			Mean	-	-	0.380	0.043	0.413	-	-	-	0.065	0.154	0.077
		After calming	Test results	-	-	0.143 0.343	0.048 0.040	0.513 0.578	-	-	-	0.088 0.030	0.133 0.188	0.163 0.153
			Mean	-	-	0.243	0.044	0.546	-	-	-	0.059	0.160	0.158
		% change in mean		-	-	*-36*	*+1*	*+32*	-	-	-	*-9*	*+4*	*+105*
I	1.9m-wide speed cushions	Before calming	Test results	-	-	0.163 0.232	0.018 0.033	0.336 0.567	-	-	-	0.015 0.130	0.107 0.055	0.053 0.068
			Mean	-	-	0.197	0.025	0.451	-	-	-	0.072	0.081	0.061
		After calming	Test results	-	-	0.223 0.219	0.050 0.088	0.243 0.410	-	-	-	0.026 0.068	0.183 0.220	0.033 0.123
			Mean	-	-	0.221	0.069	0.327	-	-	-	0.047	0.202	0.078
		% change in mean		-	-	*+12*	*+172*	*-28*	-	-	-	*-35*	*+148*	*+29*

Table B6 Total hydrocarbons (g/km): Diesel cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number		
				No size discrimination		
				20	21	22
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*
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*
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*
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*
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*
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*
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*
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*
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*

Table B7 Total NO$_x$ (g/km): Petrol non-catalyst cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number							
				Small				Medium		Large	
				1	2	3	4	5	6	7	8
A	Flat-top road humps	Before calming	Test results	1.191 1.170	-	0.878 0.843	-	1.182 1.033	0.641 0.642	1.939 1.924	1.161 1.068
			Mean	1.181	-	0.861	-	1.108	0.642	1.932	1.115
		After calming	Test results	1.557 1.448	-	0.911 0.931	-	1.368 1.329	0.879 0.958	2.205 2.163	1.287 1.242
			Mean	1.503	-	0.921	-	1.349	0.919	2.184	1.265
		% change in mean		*+27*	-	*+7*	-	*+22*	*+43*	*+13*	*+13*
B	Round-top humps	Before calming	Test results	1.186 1.123	-	0.623 0.621	-	0.901 0.865	0.602 0.635	1.950 1.729	0.795 0.781
			Mean	1.155	-	0.622	-	0.883	0.619	1.840	0.788
		After calming	Test results	1.270 1.277	-	0.615 0.653	-	1.031 1.024	0.722 0.792	1.936 1.978	0.670 0.678
			Mean	1.274	-	0.634	-	1.028	0.757	1.957	0.674
		% change in mean		*+10*	-	*+2*	-	*+16*	*+22*	*+6*	*-14*
C	1.7m-wide speed cushions	Before calming	Test results	1.276 1.259	-	1.134 0.970	0.622 0.768	1.237 1.136	0.745 0.771	1.911 1.851	1.072 0.853
			Mean	1.267	-	1.052	0.695	1.187	0.758	1.881	0.962
		After calming	Test results	1.553 1.475	-	1.207 1.288	0.814 0.858	1.480 1.416	1.011 0.861	2.154 2.165	1.175 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*
D	Pinch point/speed cushion	Before calming	Test results	1.008 1.072	-	0.706 0.655	-	0.906 0.898	0.578 0.543	2.137 2.034	0.807 0.685
			Mean	1.040	-	0.681	-	0.902	0.561	2.086	0.746
		After calming	Test results	1.093 1.046	-	0.709 0.668	-	0.903 0.923	0.607 0.585	2.348 2.300	0.828 0.776
			Mean	1.070	-	0.689	-	0.913	0.596	2.324	0.802
		% change in mean		*+3*	-	*+1*	-	*+1*	*+6*	*+11*	*+8*
E	Raised Junction	Before calming	Test results	-	0.579 0.588	0.820 0.911	-	1.281 1.338	0.676 0.725	2.149 2.028	1.036 1.020
			Mean	-	0.584	0.866	-	1.310	0.701	2.089	1.028
		After calming	Test results	-	0.639 0.708	0.789 0.875	-	1.383 1.410	0.698 0.733	2.053 2.089	0.880 0.874
			Mean	-	0.674	0.832	-	1.397	0.716	2.076	0.877
		% change in mean		-	*+15*	*-4*	-	*+7*	*+2*	*-1*	*-15*
F	Chicane	Before calming	Test results	-	0.491 0.508	0.966 0.980	-	1.449 1.526	0.778 0.754	2.299 2.188	1.261 1.181
			Mean	-	0.500	0.973	-	1.488	0.766	2.243	1.221
		After calming	Test results	-	0.435 0.408	0.696 0.666	-	1.148 1.192	0.613 0.574	2.153 2.068	1.080 0.971
			Mean	-	0.422	0.681	-	1.170	0.594	2.110	1.026
		% change in mean		-	*-16*	*-30*	-	*-21*	*-22*	*-6*	*-16*
G	Build-out	Before calming	Test results	-	0.603 0.489	0.788 0.776	-	1.160 1.257	0.568 0.575	1.992 2.056	0.943 0.852
			Mean	-	0.546	0.782	-	1.209	0.572	2.024	0.898
		After calming	Test results	-	0.660 0.546	0.641 0.658	-	0.992 0.938	0.558 0.570	1.835 1.893	0.782 0.733
			Mean	-	0.603	0.649	-	0.965	0.564	1.864	0.758
		% change in mean		-	*+10*	*-17*	-	*-20*	*-1*	*-8*	*-16*
H	Mini-roundabout	Before calming	Test results	-	0.603 0.489	0.780 0.690	-	1.130 1.220	0.568 0.575	1.992 2.056	0.910 0.990
			Mean	-	0.546	0.735	-	1.175	0.572	2.024	0.950
		After calming	Test results	-	0.657 0.546	0.680 0.740	-	1.360 1.300	0.668 0.662	1.929 1.938	1.020 0.820
			Mean	-	0.602	0.710	-	1.330	0.665	1.934	0.920
		% change in mean		-	*+10*	*-3*	-	*+13*	*+16*	*-4*	*-3*
I	1.9m-wide speed cushions	Before calming	Test results	-	0.636 0.617	1.023 0.950	-	1.328 1.275	0.662 0.667	2.296 2.229	0.985 0.963
			Mean	-	0.626	0.986	-	1.301	0.644	2.262	0.974
		After calming	Test results	-	0.491 0.489	0.674 0.678	-	1.041 1.023	0.592 0.652	1.807 1.721	0.771 0.778
			Mean	-	0.490	0.676	-	1.032	0.622	1.764	0.775
		% change in mean		-	*-22*	*-31*	-	*-21*	*-3*	*-22*	*-20*

Table B8 Total NO_x (g/km): Petrol catalyst cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number										
				Small				Medium					Large	
				9	10	11	12	13	14	15	16	17	18	19
A	Flat-top road humps	Before calming	Test results	0.377 0.551	-	-	0.014 0.021	-	0.206 0.260	-	-	0.112 0.104	0.158 0.158	0.029 0.044
			Mean	0.464	-	-	0.018	-	0.233	-	-	0.108	0.158	0.037
		After calming	Test results	0.476 0.450	-	-	0.035 0.034	-	0.425 0.413	-	-	0.149 0.214	0.152 0.192	0.088 0.104
			Mean	0.463	-	-	0.035	-	0.419	-	-	0.182	0.172	0.096
		% change in mean		*0*	-	-	*+94*	-	*+80*	-	-	*+69*	*+9*	*+159*
B	Round-top humps	Before calming	Test results	-	0.209 0.191	-	0.039 0.046	-	-	0.263 0.371	-	0.125 0.134	0.003 0.171	0.034 0.087
			Mean	-	0.200	-	0.043	-	-	0.317	-	0.130	0.087	0.061
		After calming	Test results	-	0.248 0.186	-	0.041 0.032	-	-	0.415 0.454	-	0.189 0.194	0.107 0.097	0.055 0.067
			Mean	-	0.217	-	0.037	-	-	0.435	-	0.192	0.102	0.061
		% change in mean		-	*+8*	-	*-14*	-	-	*+37*	-	*+48*	*+17*	*0*
C	1.7m-wide speed cushions	Before calming	Test results	-	-	-	0.028 0.005	-	-	-	0.370 0.351	0.233 0.209	0.131 0.128	0.026 0.042
			Mean	-	-	-	0.016	-	-	-	0.361	0.221	0.130	0.034
		After calming	Test results	-	-	-	0.041 0.011	-	-	-	0.454 0.468	0.218 0.237	0.143 0.180	0.058 0.104
			Mean	-	-	-	0.026	-	-	-	0.460	0.228	0.162	0.081
		% change in mean		-	-	-	*+63*	-	-	-	*+27*	*+3*	*+25*	*+138*
D	Pinch point/speed cushion	Before calming	Test results	-	-	0.246 0.220	0.028 0.032	0.173 0.144	-	-	-	0.079 0.128	0.099 0.168	0.035 0.069
			Mean	-	-	0.233	0.030	0.159	-	-	-	0.104	0.133	0.052
		After calming	Test results	-	-	0.263 0.307	0.010 0.024	0.153 0.225	-	-	-	0.145 0.204	0.160 0.128	0.116 0.048
			Mean	-	-	0.285	0.017	0.189	-	-	-	0.175	0.144	0.082
		% change in mean		-	-	*+22*	*-43*	*+19*	-	-	-	*+68*	*+8*	*+58*
E	Raised Junction	Before calming	Test results	-	-	0.208 0.160	0.049 0.047	0.158 0.151	-	-	-	0.116 0.144	0.092 0.137	0.029 0.093
			Mean	-	-	0.184	0.048	0.155	-	-	-	0.130	0.115	0.061
		After calming	Test results	-	-	0.160 0.121	0.029 0.031	0.126 0.069	-	-	-	0.195 0.156	0.063 0.036	0.043 0.052
			Mean	-	-	0.141	0.030	0.098	-	-	-	0.176	0.050	0.048
		% change in mean		-	-	*-23*	*-38*	*-37*	-	-	-	*+35*	*-57*	*-21*
F	Chicane	Before calming	Test results	-	-	0.251 0.208	0.033 0.047	0.246 0.171	-	-	-	0.138 0.129	0.092 0.072	0.116 0.159
			Mean	-	-	0.230	0.040	0.208	-	-	-	0.134	0.082	0.138
		After calming	Test results	-	-	0.256 0.223	0.028 0.033	0.093 0.031	-	-	-	0.152 0.267	0.071 0.077	0.133 0.069
			Mean	-	-	0.240	0.030	0.062	-	-	-	0.210	0.074	0.101
		% change in mean		-	-	*+4*	*-25*	*-70*	-	-	-	*+57*	*-10*	*-27*
G	Build-out	Before calming	Test results	-	-	0.224 0.157	0.055 0.073	0.085 0.113	-	-	-	0.096 0.185	0.071 0.117	0.259 0.223
			Mean	-	-	0.191	0.064	0.099	-	-	-	0.141	0.094	0.241
		After calming	Test results	-	-	0.173 0.181	0.035 0.050	0.083 0.125	-	-	-	0.125 0.132	0.107 0.119	0.200 0.247
			Mean	-	-	0.177	0.042	0.104	-	-	-	0.129	0.113	0.224
		% change in mean		-	-	*-7*	*-34*	*+5*	-	-	-	*-9*	*+20*	*-7*
H	Mini-roundabout	Before calming	Test results	-	-	0.224 0.157	0.055 0.073	0.085 0.113	-	-	-	0.096 0.185	0.071 0.117	0.259 0.223
			Mean	-	-	0.191	0.064	0.099	-	-	-	0.141	0.094	0.241
		After calming	Test results	-	-	0.197 0.208	0.042 0.067	0.144 0.221	-	-	-	0.137 0.100	0.063 0.102	0.254 0.430
			Mean	-	-	0.203	0.054	0.183	-	-	-	0.119	0.083	0.342
		% change in mean		-	-	*+6*	*-16*	*+84*	-	-	-	*-16*	*-12*	*+42*
I	1.9m-wide speed cushions	Before calming	Test results	-	-	0.236 0.255	0.046 0.038	0.244 0.146	-	-	-	0.132 0.122	0.164 0.124	0.069 0.186
			Mean	-	-	0.245	0.042	0.195	-	-	-	0.127	0.144	0.128
		After calming	Test results	-	-	0.151 0.155	0.039 0.043	0.119 0.066	-	-	-	0.149 0.219	0.093 0.090	0.115 0.157
			Mean	-	-	0.153	0.041	0.093	-	-	-	0.184	0.092	0.136
		% change in mean		-	-	*-38*	*-2*	*-52*	-	-	-	*+44*	*-36*	*+7*

Table B9 Total NO_x (g/km): Diesel cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number		
				No size discrimination		
				20	21	22
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*
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*
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*
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*
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*
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*
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	0.609
			Mean	0.849	0.602	0.612
		% change in mean		*+13*	*+26*	*+21*
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*
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*

Table B10 Total CO_2 (g/km): Petrol non-catalyst cars.

Scheme	Traffic calming *measure*	Stage		Vehicle size and reference number							
				Small				Medium		Large	
				1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
A	Flat-top road humps	Before calming	Test results	75.900 73.400	-	70.500 67.200	-	*108.000* 105.100	*91.600* 89.700	*188.000* 174.700	*126.800* 121.300
			Mean	74.650	-	68.850	-	106.550	90.650	181.350	124.050
		After calming	Test results	99.900 98.800	-	93.000 92.300	-	135.300 138.700	121.000 124.200	221.300 209.600	165.100 157.400
			Mean	99.350	-	92.650	-	137.000	122.600	215.450	161.250
		% change in mean		*+33*	-	*+35*	-	*+29*	*+35*	*+19*	*+30*
B	Round-top humps	Before calming	Test results	92.270 90.370	-	81.720 78.950	-	118.870 113.950	110.290 112.920	209.470 197.780	130.360 134.580
			Mean	91.320	-	80.335	-	116.410	111.605	203.625	132.470
		After calming	Test results	120.890 121.520	-	107.330 107.480	-	153.660 153.070	144.520 146.610	249.340 251.010	160.510 165.330
			Mean	121.205	-	107.405	-	153.365	145.565	250.175	162.920
		% change in mean		*+33*	-	*+34*	-	*+32*	*+30*	*+23*	*+23*
C	1.7m-wide speed cushions	Before calming	Test results	88.782 87.826	-	88.308 83.045	89.317 90.908	123.543 120.755	108.156 107.563	212.420 201.930	140.342 131.325
			Mean	88.304	-	85.676	90.113	122.149	107.859	207.175	135.834
		After calming	Test results	109.705 106.565	-	105.487 108.226	107.992 108.713	151.849 150.175	133.914 133.801	245.660 250.770	163.091 161.676
			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*
D	Pinch point/speed cushion	Before calming	Test results	90.510 87.130	-	84.22 80.13	-	113.150 113.400	100.640 99.690	195.991 187.982	127.190 121.800
			Mean	88.82	-	82.175	-	113.275	100.165	191.986	124.495
		After calming	Test results	103.450 102.030	-	99.000 94.620	-	129.830 134.030	118.050 118.890	217.877 213.945	144.720 146.180
			Mean	102.74	-	96.810	-	131.930	118.470	215.911	145.450
		% change in mean		*+16*	-	*+18*	-	*+16*	*+18*	*+12*	*+17*
E	Raised Junction	Before calming	Test results	-	90.560 92.020	90.12 89.69	-	125.880 127.700	101.490 103.860	203.380 193.410	134.200 134.230
			Mean	-	91.290	89.905	-	126.790	102.675	198.395	134.215
		After calming	Test results	-	115.060 118.000	113.380 113.340	-	160.890 161.550	127.830 127.910	239.220 235.930	164.990 171.100
			Mean	-	116.530	113.360	-	161.220	127.870	237.575	168.045
		% change in mean		-	*+28*	*+26*	-	*+27*	*+25*	*+20*	*+25*
F	Chicane	Before calming	Test results	-	78.703 78.404	72.429 71.677	-	113.750 114.500	83.770 84.740	188.964 182.671	117.230 112.460
			Mean	-	78.554	72.053	-	114.125	84.255	185.818	114.845
		After calming	Test results	-	86.583 84.814	77.565 77.275	-	121.020 120.010	93.310 93.280	189.688 188.228	132.920 129.570
			Mean	-	85.698	77.420	-	120.515	93.295	188.958	131.245
		% change in mean		-	*+9*	*+7*	-	*+6*	*+11*	*+2*	*+14*
G	Build-out	Before calming	Test results	-	84.851 81.562	79.893 78.658	-	115.650 120.660	90.080 85.090	195.020 188.710	126.630 125.820
			Mean	-	83.207	79.276	-	118.155	87.585	191.865	126.225
		After calming	Test results	-	101.420 100.800	92.973 97.946	-	136.520 132.010	108.220 106.540	199.270 204.780	148.340 153.420
			Mean	-	101.110	95.459	-	134.265	107.380	202.025	150.880
		% change in mean		-	*+22*	*+20*	-	*+14*	*+23*	*+5*	*+20*
H	Mini-roundabout	Before calming	Test results	-	84.851 81.562	79.250 76.950	-	110.160 113.740	90.080 85.090	195.020 188.710	124.890 131.090
			Mean	-	83.207	78.100	-	111.950	87.585	191.865	127.990
		After calming	Test results	-	109.420 109.009	103.880 102.960	-	114.350 144.310	117.240 115.660	210.950 216.600	161.550 160.180
			Mean	-	109.214	103.420	-	144.330	116.450	213.775	160.865
		% change in mean		-	*+31*	*+32*	-	*+29*	*+33*	*+11*	*+26*
I	1.9m-wide speed cushions	Before calming	Test results	-	82.270 83.236	81.287 78.281	-	119.067 119.034	90.193 91.263	206.791 193.850	123.060 120.088
			Mean	-	82.753	79.784	-	119.050	90.728	200.321	121.574
		After calming	Test results	-	91.735 92.128	94.253 91.773	-	129.753 134.354	106.300 110.070	199.868 194.367	142.173 140.466
			Mean	-	91.932	93.013	-	132.054	108.185	197.118	141.320
		% change in mean		-	*+11*	*+17*	-	*+11*	*+19*	*-2*	*+16*

Table B11 Total CO_2 (g/km): Petrol catalyst cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number										
				Small				Medium					Large	
				9	10	11	12	13	14	15	16	17	18	19
A	Flat-top road humps	Before calming	Test results	93.000 101.800	-	-	89.300 86.900	-	134.6 133.0	-	-	112.600 108.500	147.400 147.300	148.300 144.900
			Mean	97.400	-	-	88.100	-	133.8	-	-	110.550	147.350	146.600
		After calming	Test results	120.700 121.400	-	-	116.400 112.500	-	197.9 191.0	-	-	141.600 140.900	177.600 196.100	196.500 202.500
			Mean	121.050	-	-	114.450	-	194.45	-	-	141.250	186.850	199.500
		% change in mean		*+24*	-	-	*+30*	-	*+45*	-	-	*+28*	*+27*	*+36*
B	Round-top humps	Before calming	Test results	-	103.650 88.530	-	102.000 98.640	-	-	153.99 149.69	-	135.000 132.720	152.060 149.690	148.260 172.270
			Mean	-	96.090	-	100.320	-	-	151.84	-	133.860	150.875	160.265
		After calming	Test results	-	137.810 123.250	-	128.680 128.370	-	-	217.34 215.83	-	172.400 169.190	209.090 204.150	244.460 242.780
			Mean	-	130.530	-	128.525	-	-	216.58	-	170.795	206.620	243.620
		% change in mean		-	*+36*	-	*+28*	-	-	*+43*	-	*+28*	*+37*	*+52*
C	1.7m-wide speed cushions	Before calming	Test results	-	-	-	108.582 105.894	-	-	-	169.042 166.662	136.034 134.337	181.814 174.314	177.923 175.786
			Mean	-	-	-	107.238	-	-	-	167.832	135.185	178.064	176.854
		After calming	Test results	-	-	-	124.966 126.339	-	-	-	208.529 208.505	165.135 163.389	224.017 210.693	234.083 235.885
			Mean	-	-	-	125.653	-	-	-	208.517	164.262	217.355	234.984
		% change in mean		-	-	-	*+17*	-	-	-	*+24*	*+22*	*+22*	*+33*
D	Pinch point/speed cushion	Before calming	Test results	-	-	114.310 108.480	99.790 100.820	129.910 127.420	-	-	-	132.030 130.850	166.668 150.736	165.790 163.300
			Mean	-	-	111.395	100.305	128.665	-	-	-	131.440	158.702	164.545
		After calming	Test results	-	-	134.570 132.620	117.450 117.580	152.040 152.050	-	-	-	154.210 153.950	195.356 188.053	205.720 200.680
			Mean	-	-	133.595	117.515	152.045	-	-	-	154.080	191.705	203.200
		% change in mean		-	-	*+20*	*+17*	*+18*	-	-	-	*+17*	*+21*	*+23*
E	Raised Junction	Before calming	Test results	-	-	119.590 105.050	104.960 110.380	141.870 145.590	-	-	-	140.670 135.930	178.900 170.600	179.900 174.670
			Mean	-	-	112.320	107.670	143.730	-	-	-	138.300	174.750	177.285
		After calming	Test results	-	-	143.870 134.380	146.060 139.970	177.230 169.410	-	-	-	178.990 175.960	232.420 227.830	247.620 243.980
			Mean	-	-	139.125	143.015	173.320	-	-	-	177.475	230.125	245.800
		% change in mean		-	-	*+24*	*+33*	*+21*	-	-	-	*+28*	*+32*	*+39*
F	Chicane	Before calming	Test results	-	-	95.910 92.400	87.390 91.203	124.811 118.445	-	-	-	115.110 117.700	140.016 139.992	125.620 153.740
			Mean	-	-	94.155	89.297	121.628	-	-	-	116.405	140.004	139.68
		After calming	Test results	-	-	112.670 110.200	103.389 102.672	137.219 130.530	-	-	-	134.620 134.320	167.998 162.433	168.980 182.840
			Mean	-	-	111.435	103.030	133.875	-	-	-	134.470	165.216	175.910
		% change in mean		-	-	*+18*	*+15*	*+10*	-	-	-	*+16*	*+18*	*+26*
G	Build-out	Before calming	Test results	-	-	110.800 94.720	106.920 99.624	133.200 128.963	-	-	-	133.790 131.170	163.623 151.041	173.110 183.250
			Mean	-	-	102.760	103.272	131.082	-	-	-	132.480	157.332	178.180
		After calming	Test results	-	-	127.230 121.570	112.189 118.401	149.698 157.783	-	-	-	152.510 153.740	191.665 188.403	197.840 223.980
			Mean	-	-	124.400	115.295	153.741	-	-	-	153.125	190.034	210.910
		% change in mean		-	-	*+21*	*+12*	*+17*	-	-	-	*+16*	*+21*	*+18*
H	Mini-roundabout	Before calming	Test results	-	-	110.800 94.720	106.920 99.624	133.200 128.963	-	-	-	133.790 131.170	163.623 151.041	173.110 183.250
			Mean	-	-	102.760	103.272	131.082	-	-	-	132.480	157.332	178.180
		After calming	Test results	-	-	142.670 137.430	133.207 128.871	166.894 168.403	-	-	-	169.790 169.280	217.916 221.283	223.780 264.540
			Mean	-	-	140.050	131.039	167.649	-	-	-	169.535	219.600	244.160
		% change in mean		-	-	*+36*	*+27*	*+28*	-	-	-	*+28*	*+40*	*+37*
I	1.9m-wide speed cushions	Before calming	Test results	-	-	110.737 105.581	99.663 98.822	132.216 122.628	-	-	-	122.798 119.504	158.677 161.842	166.598 145.868
			Mean	-	-	108.159	99.243	127.422	-	-	-	121.151	160.260	156.233
		After calming	Test results	-	-	129.855 126.325	112.859 110.322	150.901 145.353	-	-	-	141.604 142.862	188.651 185.808	193.355 211.692
			Mean	-	-	128.090	111.590	148.127	-	-	-	142.233	187.230	202.524
		% change in mean		-	-	*+18*	*+12*	*+16*	-	-	-	*+17*	*+17*	*+30*

Table B12 Total CO_2 (g/km): Diesel cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number		
				No size discrimination		
				20	21	22
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*
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*
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*
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*
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*
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*
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*
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*
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*

Table B13 Total particulate matter (g/km): Diesel cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number		
				No size discrimination		
				20	21	22
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*
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*
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*
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*
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
		After 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*
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*
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*
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*
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*

Table B14 Total FC (l/100km): Petrol non-catalyst cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number							
				Small				Medium		Large	
				1	2	3	4	5	6	7	8
A	Flat-top road humps	Before calming	Test results	3.729 3.615	-	3.708 3.481	-	5.266 5.051	5.284 5.563	8.694 8.063	6.378 6.369
			Mean	3.672	-	3.595	-	5.159	5.424	8.389	6.374
		After calming	Test results	4.980 4.955	-	5.018 4.909	-	6.686 6.696	7.347 7.581	10.328 9.762	8.748 8.546
			Mean	4.968	-	4.964	-	6.691	7.464	10.045	8.647
		% change in mean		*+35*	-	*+38*	-	*+30*	*+38*	*+20*	*+36*
B	Round-top humps	Before calming	Test results	4.740 4.690	-	4.830 4.280	-	5.940 5.710	6.770 6.930	9.830 9.290	6.960 7.080
			Mean	4.715	-	4.555	-	5.825	6.850	9.560	7.020
		After calming	Test results	6.390 6.520	-	6.720 6.040	-	7.810 7.550	9.130 8.900	11.790 11.880	9.210 9.290
			Mean	6.455	-	6.380	-	7.680	9.015	11.835	9.250
		% change in mean		*+37*	-	*+40*	-	*+32*	*+32*	*+24*	*+32*
C	1.7m-wide speed cushions	Before calming	Test results	4.721 4.606	-	4.862 4.305	5.566 5.252	6.185 6.026	6.942 6.774	9.910 9.400	7.378 7.568
			Mean	4.664	-	4.584	5.409	6.106	6.858	9.655	7.473
		After calming	Test results	5.879 5.747	-	5.646 5.779	6.675 6.575	7.590 7.417	7.940 8.546	11.550 11.850	9.119 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*
D	Pinch point/speed cushion	Before calming	Test results	4.490 4.410	-	4.550 4.600	-	5.720 5.610	6.040 6.050	9.410 9.108	6.950 6.940
			Mean	4.450	-	4.575	-	5.665	6.045	9.259	6.945
		After calming	Test results	5.480 5.460	-	5.450 5.520	-	6.830 6.950	7.440 7.490	10.480 10.366	8.330 8.360
			Mean	5.470	-	5.485	-	6.890	7.465	10.423	8.345
		% change in mean		*+23*	-	*+20*	-	*+22*	*+23*	*+13*	*+20*
E	Raised Junction	Before calming	Test results	-	5.450 5.510	5.130 4.810	-	6.030 5.970	6.280 6.270	9.700 9.250	7.500 7.270
			Mean	-	5.480	4.970	-	6.000	6.275	9.475	7.385
		After calming	Test results	-	7.210 7.070	6.610 6.510	-	7.220 7.810	7.970 7.900	11520 11.320	9.820 9.680
			Mean	-	7.095	6.560	-	7.515	9.935	11.420	9.750
		% change in mean		-	*+29*	*+32*	-	*+25*	*+58*	*+21*	*+32*
F	Chicane	Before calming	Test results	-	4.892 4.815	4.037 3.952	-	5.370 5.320	4.980 4.980	9.110 8.738	6.030 5.880
			Mean	-	4.854	3.994	-	5.345	4.980	8.924	5.955
		After calming	Test results	-	5.679 5.794	4.911 4.943	-	6.640 6.380	6.430 6.470	9.371 9.244	7.400 7.540
			Mean	-	5.737	4.927	-	6.510	6.450	9.307	7.470
		% change in mean		-	*+29*	*+22*	-	*+25*	*+58*	*+21*	*+32*
G	Build-out	Before calming	Test results	-	5.219 5.079	4.636 4.486	-	5.650 5.990	6.101 5.580	9.440 9.300	7.090 5.690
			Mean	-	5.149	4.561	-	5.820	5.795	9.370	6.390
		After calming	Test results	-	5.941 6.305	5.464 5.594	-	7.000 7.030	6.980 6.800	9.620 10.050	8.510 6.910
			Mean	-	6.123	5.529	-	7.015	6.890	9.835	7.710
		% change in mean		-	*+19*	*+21*	-	*+21*	*+19*	*+5*	*+21*
H	Mini-roundabout	Before calming	Test results	-	5.219 5.079	4.540 4.430	-	5.010 5.600	6.010 5.580	9.440 9.300	7.130 7.100
			Mean	-	5.149	4.485	-	5.305	5.795	9.370	7.115
		After calming	Test results	-	6.660 6.730	5.980 5.990	-	7.120 7.280	7.710 7.350	10.270 10.530	8.930 9.330
			Mean	-	6.695	5.985	-	1.200	7.530	10.400	9.130
		% change in mean		-	*+30*	*+33*	-	*+36*	*+30*	*+11*	*+28*
I	1.9m-wide speed cushions	Before calming	Test results	-	3.815 4.952	4.315 4.210	-	5.707 5.608	5.554 5.459	9.995 9.166	6.568 6.460
			Mean	-	4.384	4.262	-	5.658	5.507	9.581	6.514
		After calming	Test results	-	5.689 5.570	5.324 5.221	-	6.170 6.323	6.385 6.492	9.779 9.509	7.899 7.646
			Mean	-	5.630	5.727	-	6.247	6.438	9.644	7.773
		% change in mean		-	*+28*	*+24*	-	*+10*	*+17*	*+1*	*+19*

Table B15 Total FC (l/100km): Petrol catalyst cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number										
				Small				Medium					Large	
				9	10	11	12	13	14	15	16	17	18	19
A	Flat-top road humps	Before calming	Test results	4.207 4.584	-	-	3.882 3.779	-	5.848 5.783	-	-	4.953 4.809	6.518 6.61	6.409 6.274
			Mean	4.396	-	-	3.831	-	5.816	-	-	4.881	6.556	6.342
		After calming	Test results	5.408 5.421	-	-	5.127 4.920	-	8.631 8.405	-	-	6.259 6.273	8.796 10.219	8.546 8.773
			Mean	5.415	-	-	5.024	-	8.518	-	-	6.266	9.508	8.660
		% change in mean		*+23*	-	-	*+31*	-	*+46*	-	-	*+28*	*+45*	*+37*
B	Round-top humps	Before calming	Test results	-	6.230 5.430	-	4.570 4.590	-	-	6.880 6.990	-	5.940 5.830	77.500 8.050	6.460 7.540
			Mean	-	5.830	-	4.580	-	-	6.935	-	5.885	7.900	7.000
		After calming	Test results	-	8.310 7.400	-	6.180 5.940	-	-	9.900 9.860	-	7.670 7.660	10.800 10.720	10.650 10.620
			Mean	-	7.855	-	6.060	-	-	9.880	-	7.665	10.760	10.635
		% change in mean		-	*+35*	-	*+32*	-	-	*+42*	-	*+30*	*+36*	*+52*
C	1.7m-wide speed cushions	Before calming	Test results	-	-	-	4.754 4.623	-	-	-	7.547 7.467	5.895 5.832	8.024 7.746	7.726 7.639
			Mean	-	-	-	4.689	-	-	-	7.507	5.864	7.885	7.683
		After calming	Test results	-	-	-	5.450 5.509	-	-	-	9.425 9.522	7.231 7.176	10.200 9.916	10.179 10.280
			Mean	-	-	-	5.479	-	-	-	9.474	7.204	10.058	10.230
		% change in mean		-	-	-	*+17*	-	-	-	*+26*	*+23*	*+28*	*+33*
D	Pinch point/speed cushion	Before calming	Test results	-	-	5.040 5.350	4.380 4.440	5.920 6.300	-	-	-	5.750 5.700	7.476 7.443	7.180 7.090
			Mean	-	-	5.195	4.410	6.110	-	-	-	5.725	7.460	7.135
		After calming	Test results	-	-	6.070 6.020	5.170 5.170	7.220 7.490	-	-	-	6.730 6.710	9.032 9.276	8.910 8.710
			Mean	-	-	6.045	5.170	7.355	-	-	-	6.720	9.154	8.810
		% change in mean		-	-	*+16*	*+17*	*+20*	-	-	-	*+17*	*+23*	*+23*
E	Raised Junction	Before calming	Test results	-	-	5.510 5.830	4.590 5.200	6.390 6.610	-	-	-	6.160 6.040	8.030 8.060	7.810 7.570
			Mean	-	-	5.670	4.895	6.500	-	-	-	6.100	8.045	7.690
		After calming	Test results	-	-	7.190 6.280	6.580 6.970	8.003 8.210	-	-	-	7.840 7.780	10.640 11.150	10.710 10.590
			Mean	-	-	6.735	6.775	8.107	-	-	-	7.810	10.895	10.650
		% change in mean		-	-	*+19*	*+38*	*+25*	-	-	-	*+28*	*+35*	*+38*
F	Chicane	Before calming	Test results	-	-	4.240 4.360	3.844 3.990	5.531 5.614	-	-	-	5.000 5.140	6.313 6.206	5.450 6.700
			Mean	-	-	4.300	3.917	5.573	-	-	-	5.070	6.259	6.075
		After calming	Test results	-	-	5.160 5.310	4.667 4.619	6.659 6.913	-	-	-	5.880 5.820	7.710 7.727	7.350 7.970
			Mean	-	-	5.235	4.643	6.786	-	-	-	5.850	7.719	7.660
		% change in mean		-	-	*+22*	*+19*	*+22*	-	-	-	*+15*	*+23*	*+26*
G	Build-out	Before calming	Test results	-	-	5.060 5.250	4.669 4.456	6.300 6.215	-	-	-	5.900 5.980	7.177 7.140	7.510 8.060
			Mean	-	-	5.155	4.563	6.258	-	-	-	5.940	7.158	7.785
		After calming	Test results	-	-	5.960 6.330	4.966 5.414	7.455 7.739	-	-	-	6.800 6.870	8.767 8.938	8.730 9.840
			Mean	-	-	6.145	5.190	7.597	-	-	-	6.835	8.852	9.285
		% change in mean		-	-	*+19*	*+14*	*+21*	-	-	-	*+15*	*+24*	*+19*
H	Mini-roundabout	Before calming	Test results	-	-	5.060 5.250	4.669 4.456	6.300 6.215	-	-	-	5.900 5.980	7.177 7.140	7.510 8.060
			Mean	-	-	5.155	4.563	6.258	-	-	-	5.940	7.158	7.785
		After calming	Test results	-	-	6.470 6.620	5.896 5.659	7.842 7.578	-	-	-	7.520 7.460	9.669 10.001	9.900 11.650
			Mean	-	-	6.545	5.778	7.710	-	-	-	7.490	9.835	10.775
		% change in mean		-	-	*+27*	*+27*	*+23*	-	-	-	*+26*	*+37*	*+38*
I	1.9m-wide speed cushions	Before calming	Test results	-	-	4.978 4.734	4.330 4.349	6.057 6.265	-	-	-	5.392 5.714	7.100 7.121	7.226 6.381
			Mean	-	-	4.856	4.340	6.161	-	-	-	5.553	7.110	6.803
		After calming	Test results	-	-	5.821 5.671	4.990 4.981	6.953 7.275	-	-	-	6.295 6.509	8.636 8.832	8.390 9.268
			Mean	-	-	5.746	4.986	7.114	-	-	-	6.402	8.734	8.829
		% change in mean		-	-	*+18*	*+15*	*+15*	-	-	-	*+15*	*+23*	*+30*

Table B16 Total FC (l/100km): Diesel cars.

Scheme	Traffic calming measure	Stage		Vehicle size and reference number		
				No size discrimination		
				20	21	22
A	Flat-top road humps	Before calming	Test results	3.690 3.550	4.090 3.970	4.530 4.320
			Mean	3.620	4.030	4.420
		After calming	Test results	5.020 4.820	5.800 5.850	6.300 6.140
			Mean	4.920	5.820	6.220
		% change in mean		*+36*	*+44*	*+41*
B	Round-top humps	Before calming	Test results	4.080 4.030	5.190 5.250	5.140 5.170
			Mean	4.055	5.220	5.155
		After calming	Test results	5.20 5.060	7.130 6.920	6.796 6.396
			Mean	5.130	7.025	6.596
		% change in mean		*+27*	*+35*	*+28*
C	1.7m-wide speed cushions	Before calming	Test results	4.217 4.157	5.105 5.134	5.157 5.096
			Mean	4.187	5.120	5.127
		After calming	Test results	5.076 5.019	6.479 6.586	6.456 6.315
			Mean	5.047	6.533	6.385
		% change in mean		*+21*	*+28*	*+25*
D	Pinch point/speed cushion	Before calming	Test results	4.110 4.110	4.821 4.888	4.943 5.001
			Mean	4.110	4.855	4.972
		After calming	Test results	4.790 4.800	5.977 6.331	6.116 6.210
			Mean	4.795	6.154	6.163
		% change in mean		*+17*	*+27*	*+24*
E	Raised Junction	Before calming	Test results	3.015 4.118	5.468 5.600	5.474 5.645
			Mean	3.566	5.534	5.559
		After calming	Test results	5.034 4.941	5.468 7.310	7.062 7.151
			Mean	4.987	6.389	7.107
		% change in mean		*+40*	*+15*	*+28*
F	Chicane	Before calming	Test results	3.340 3.560	4.330 4.450	4.447 4.386
			Mean	3.450	4.390	4.417
		After calming	Test results	4.100 4.180	5.350 5.520	5.264 5.150
			Mean	4.140	5.435	5.207
		% change in mean		*+20*	*+24*	*+18*
G	Build-out	Before calming	Test results	3.983 3.937	4.863 4.698	5.066 4.995
			Mean	3.960	4.781	5.030
		After calming	Test results	4.697 4.656	5.917 5.742	6.093 5.881
			Mean	4.677	5.829	5.987
		% change in mean		*+18*	*+22*	*+19*
H	Mini-roundabout	Before calming	Test results	3.983 3.937	4.863 4.698	5.066 4.995
			Mean	7.490	9.835	10.775
		After calming	Test results	4.962 4.930	6.080 6.209	6.878 6.702
			Mean	3.960	4.781	5.030
		% change in mean		*+25*	*+29*	*+35*
I	1.9m-wide speed cushions	Before calming	Test results	3.969 3.899	4.694 4.664	4.957 4.940
			Mean	3.934	4.679	4.948
		After calming	Test results	4.372 4.289	5.551 -	5.685 5.867
			Mean	4.331	5.551	5.776
		% change in mean		*+10*	*+19*	*+17*

APPENDIX C

EMISSIONS BY VEHICLE TYPE

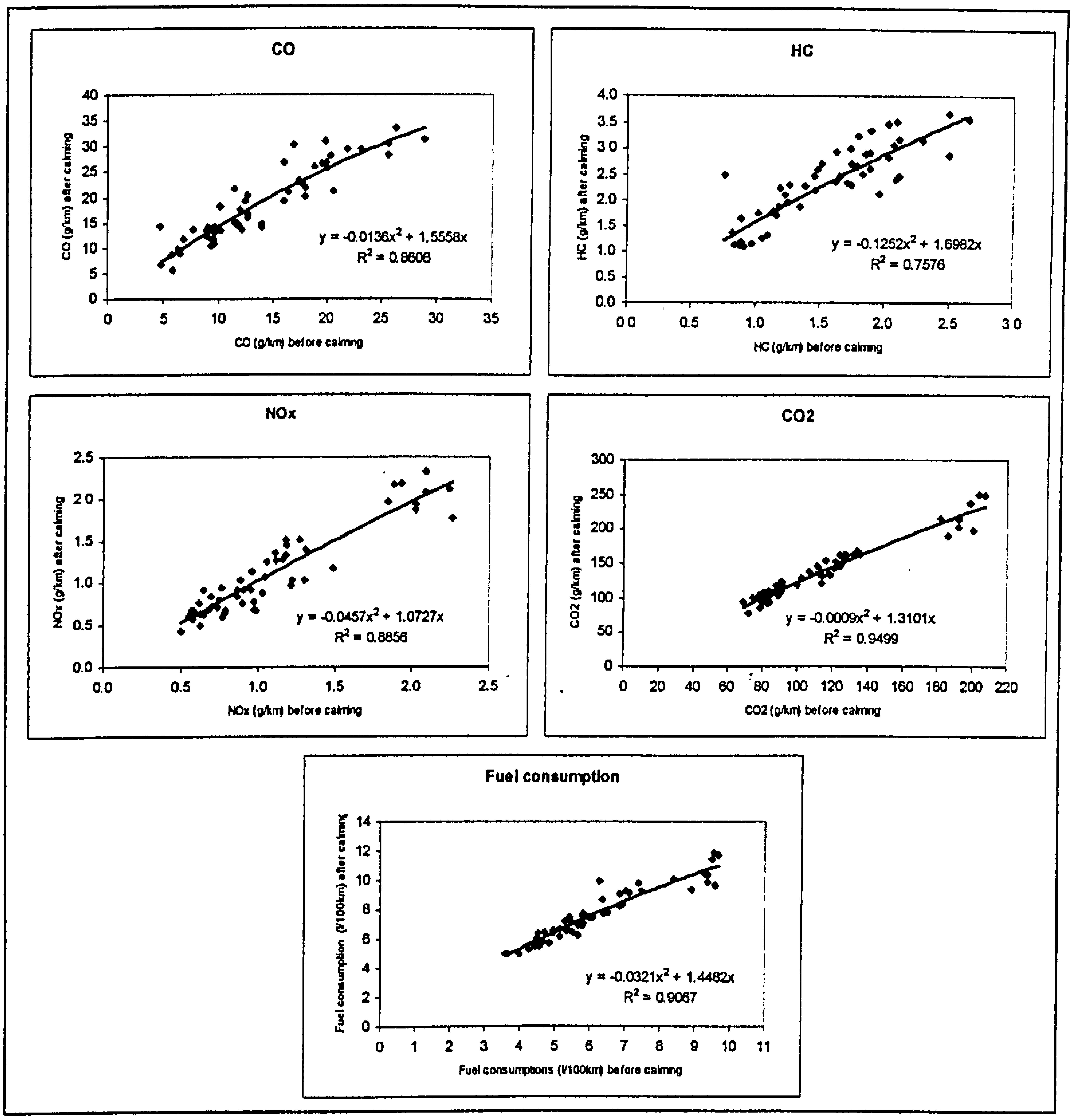

Figure C1 Emissions and fuel consumption after calming plotted against emissions before calming for petrol non-catalyst cars (results for all nine schemes).

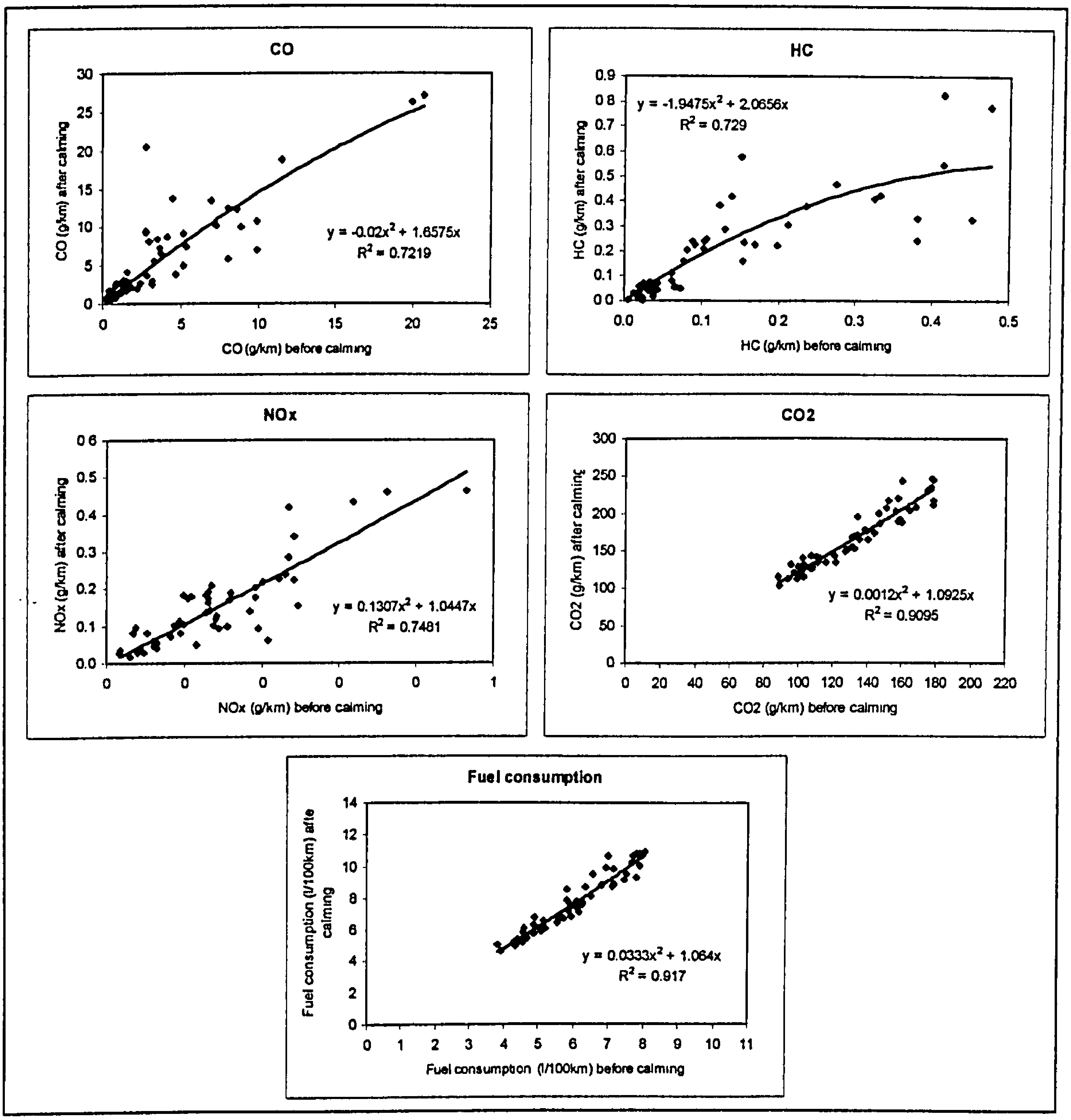

Figure C2 Emissions and fuel consumption after calming plotted against emissions and fuel consumption before calming for petrol catalyst cars (results for all nine schemes).

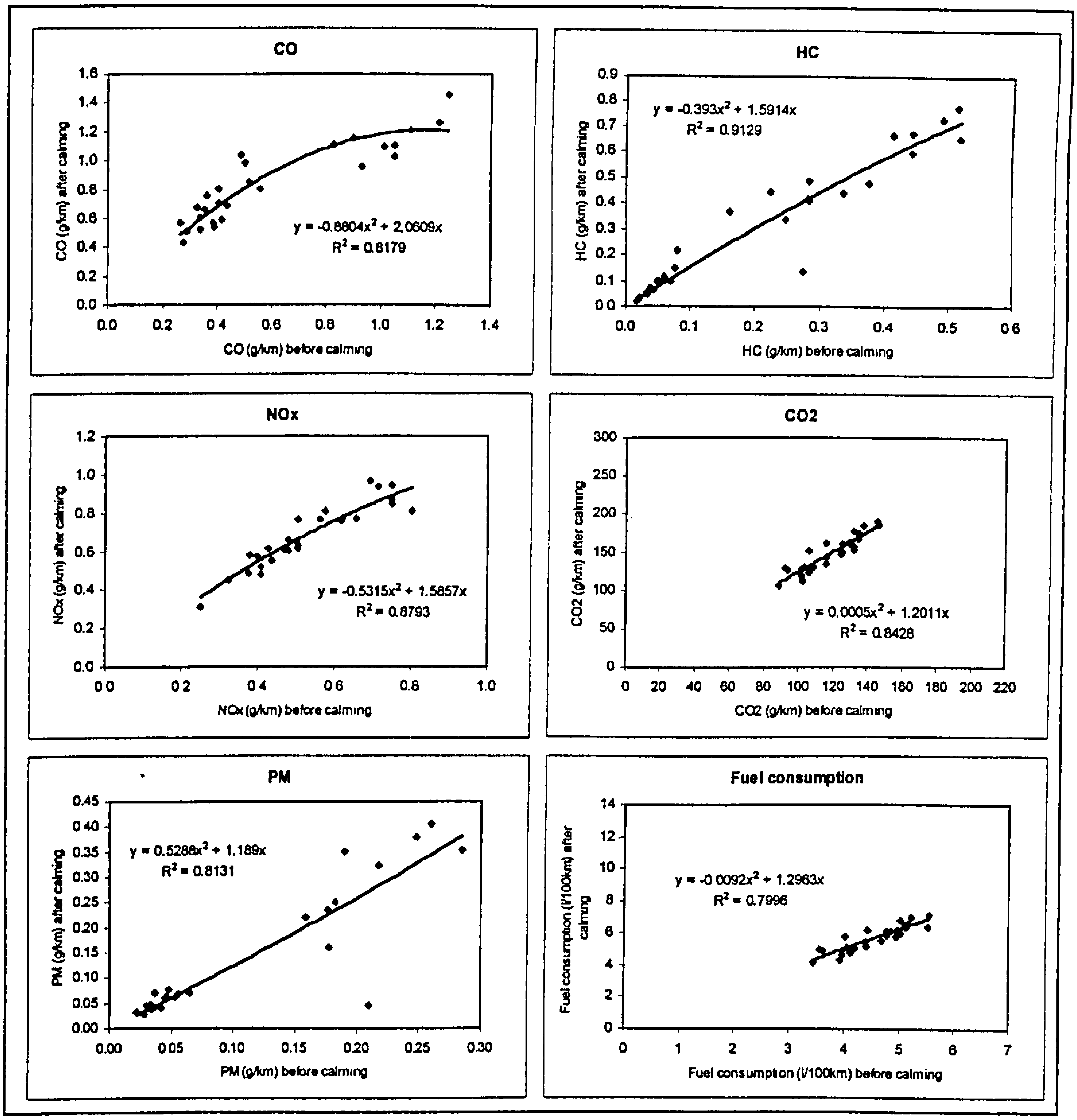

Figure C3 Emissions and fuel consumption after calming plotted against emissions and fuel consumption before calming for diesel cars (results for all nine schemes).

APPENDIX D

EMISSIONS BY VEHICLE

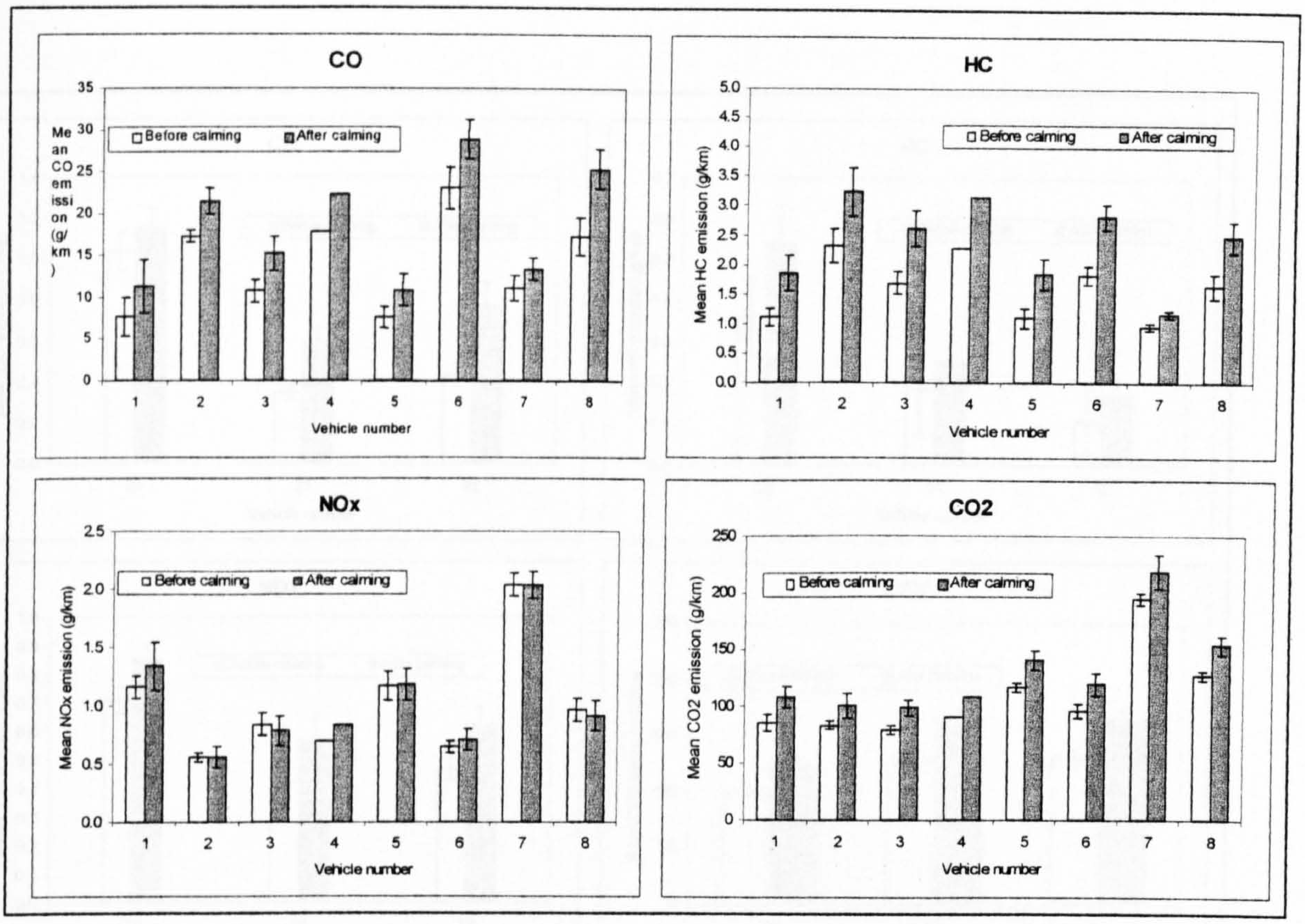

Figure D1 Emissions before calming and after calming for individual petrol non-catalyst cars. The emission levels have been averaged over all the schemes for which a vehicle was tested. The I-beams represent the 95% confidence intervals on the means. Where there are no confidence intervals, the vehicle was only tested on one scheme.

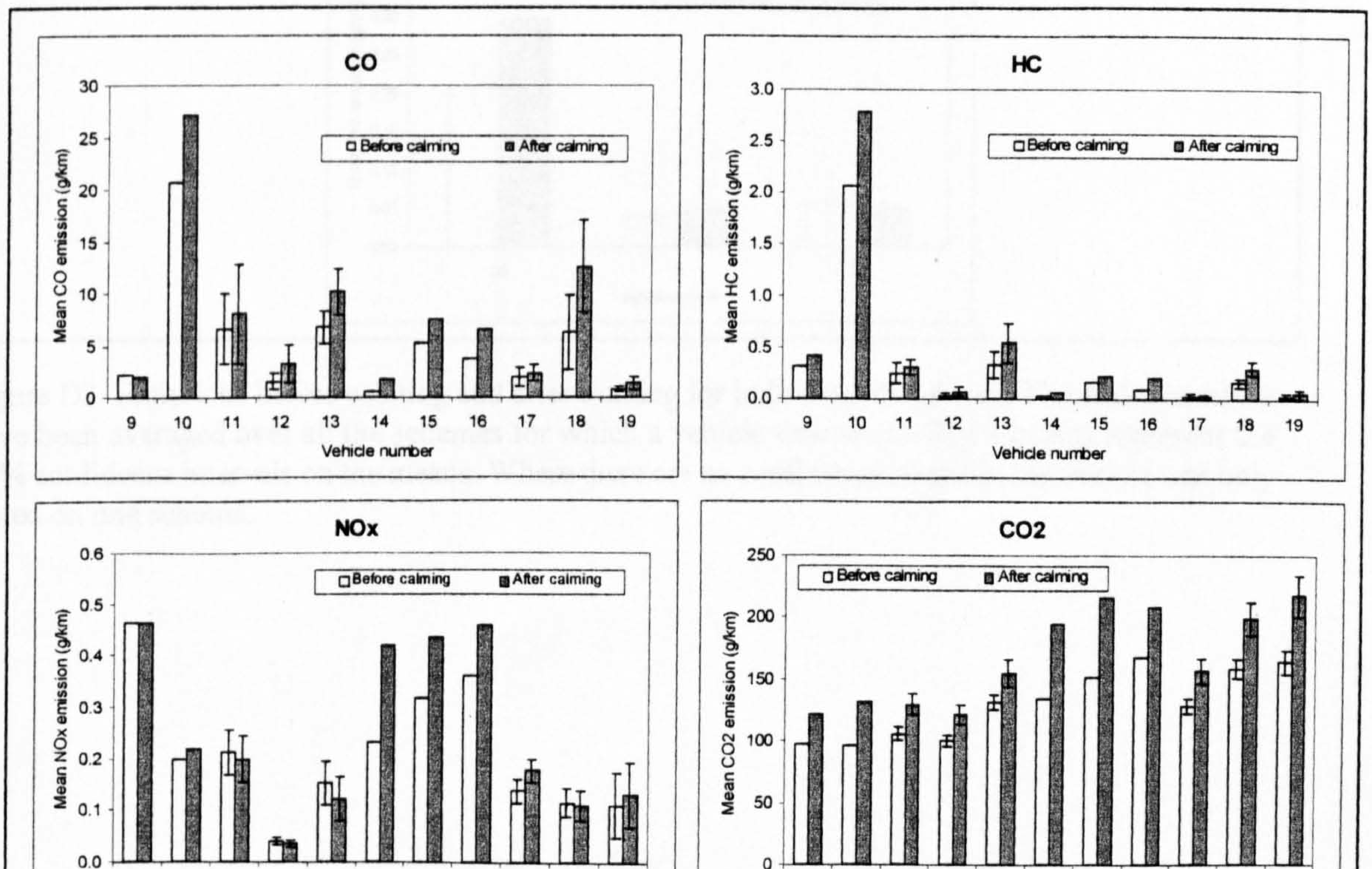

Figure D2 Emissions before calming and after calming for individual petrol catalyst cars. The emission levels have been averaged over all the schemes for which a vehicle was tested. The I-beams represent the 95% confidence intervals on the means. Where there are no confidence intervals, the vehicle was only tested on one scheme.

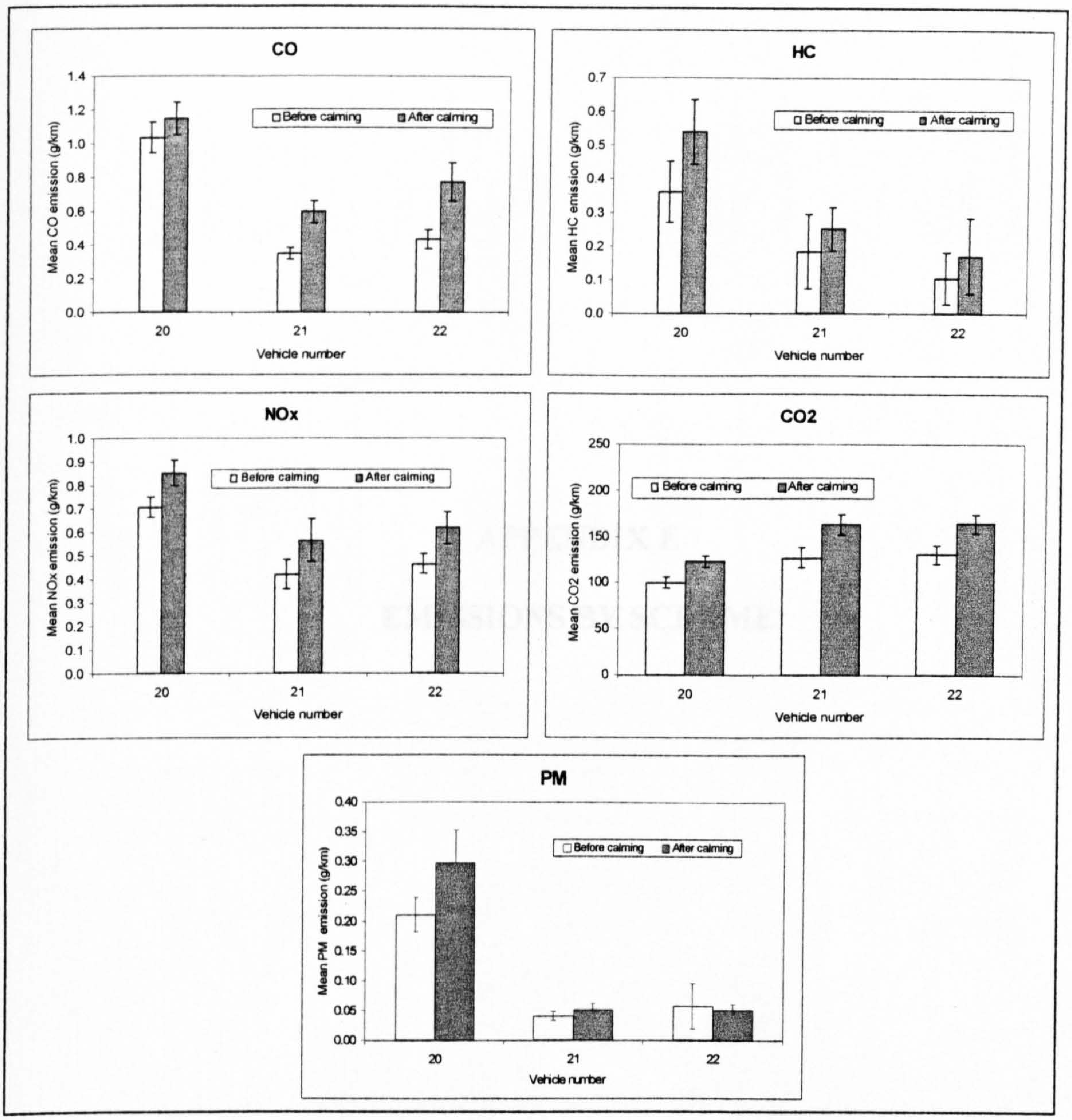

Figure D3 Emissions before calming and after calming for individual diesel cars. The emission levels have been averaged over all the schemes for which a vehicle was tested. The I-beams represent the 95% confidence intervals on the means. Where there are no confidence intervals, the vehicle was only tested on one scheme.

APPENDIX E

EMISSIONS BY SCHEME

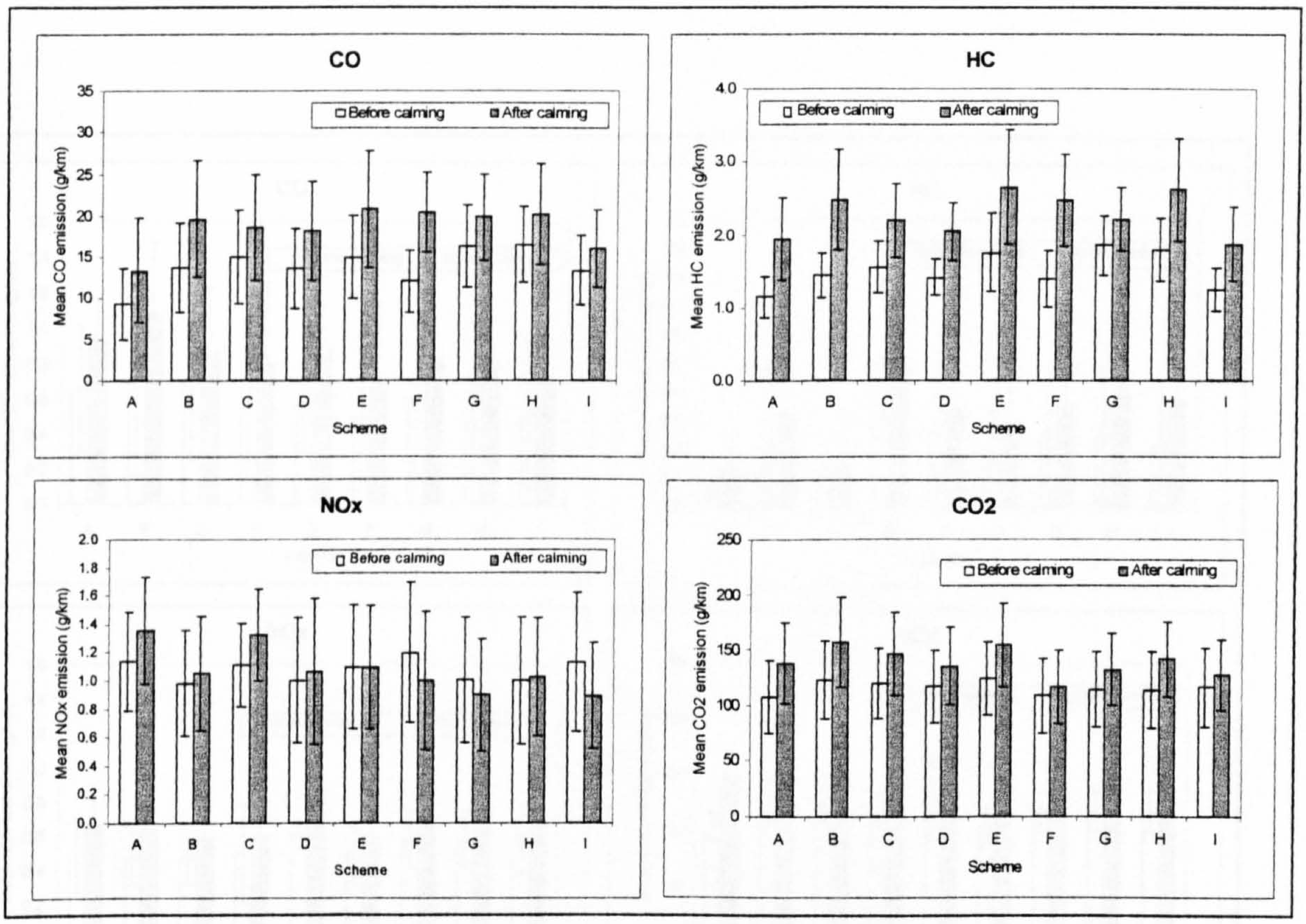

Figure E1 Emissions from petrol non-catalyst cars before calming and after calming for individual schemes. The emission levels have been averaged over all the vehicle tested for a particular scheme. The I-beams represent the 95% confidence intervals on the means.

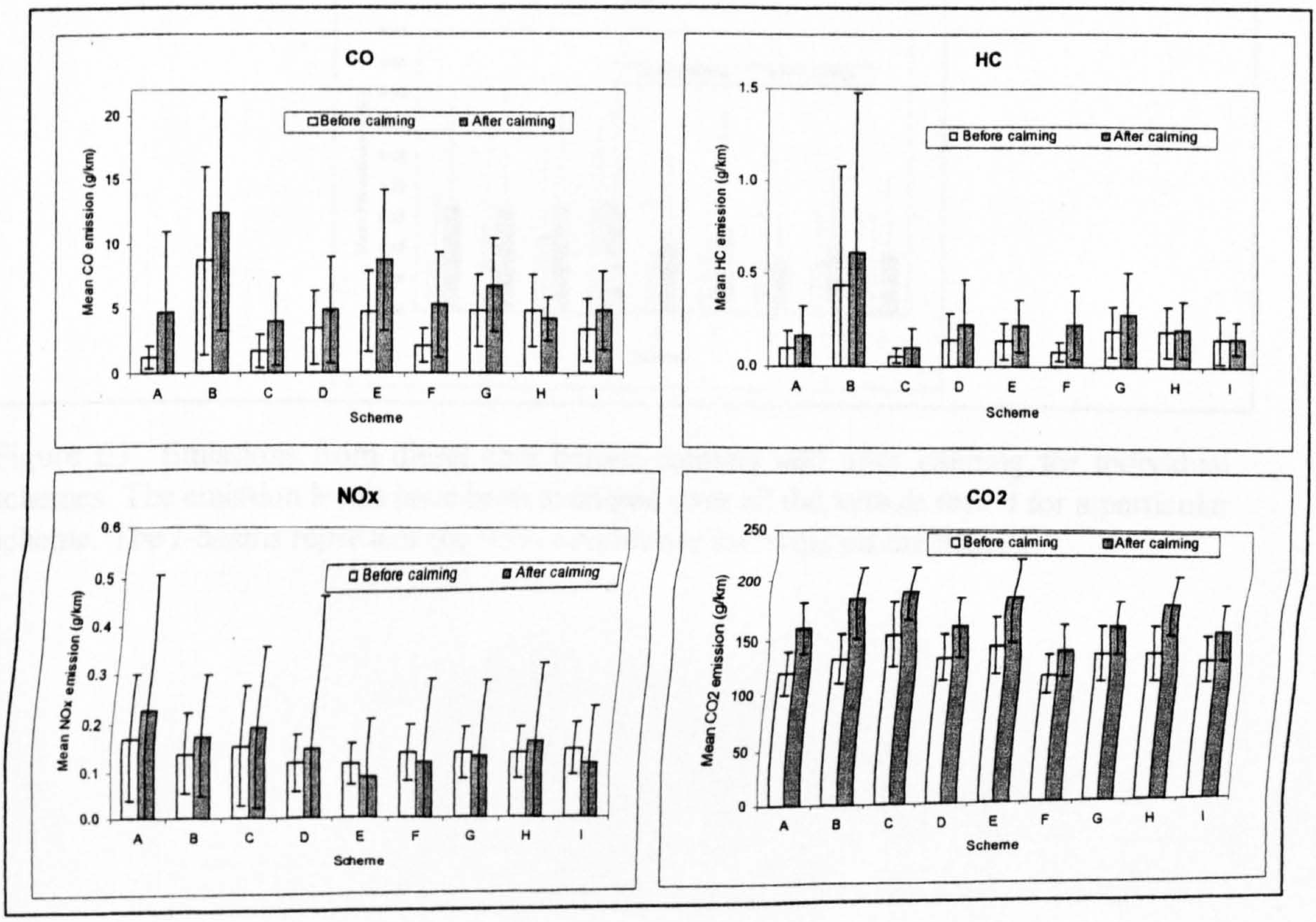

Figure E2 Emissions from petrol catalyst cars before calming and after calming for individual schemes. The emission levels have been averaged over all the vehicle tested for a particular scheme. The I-beams represent the 95% confidence intervals on the means.

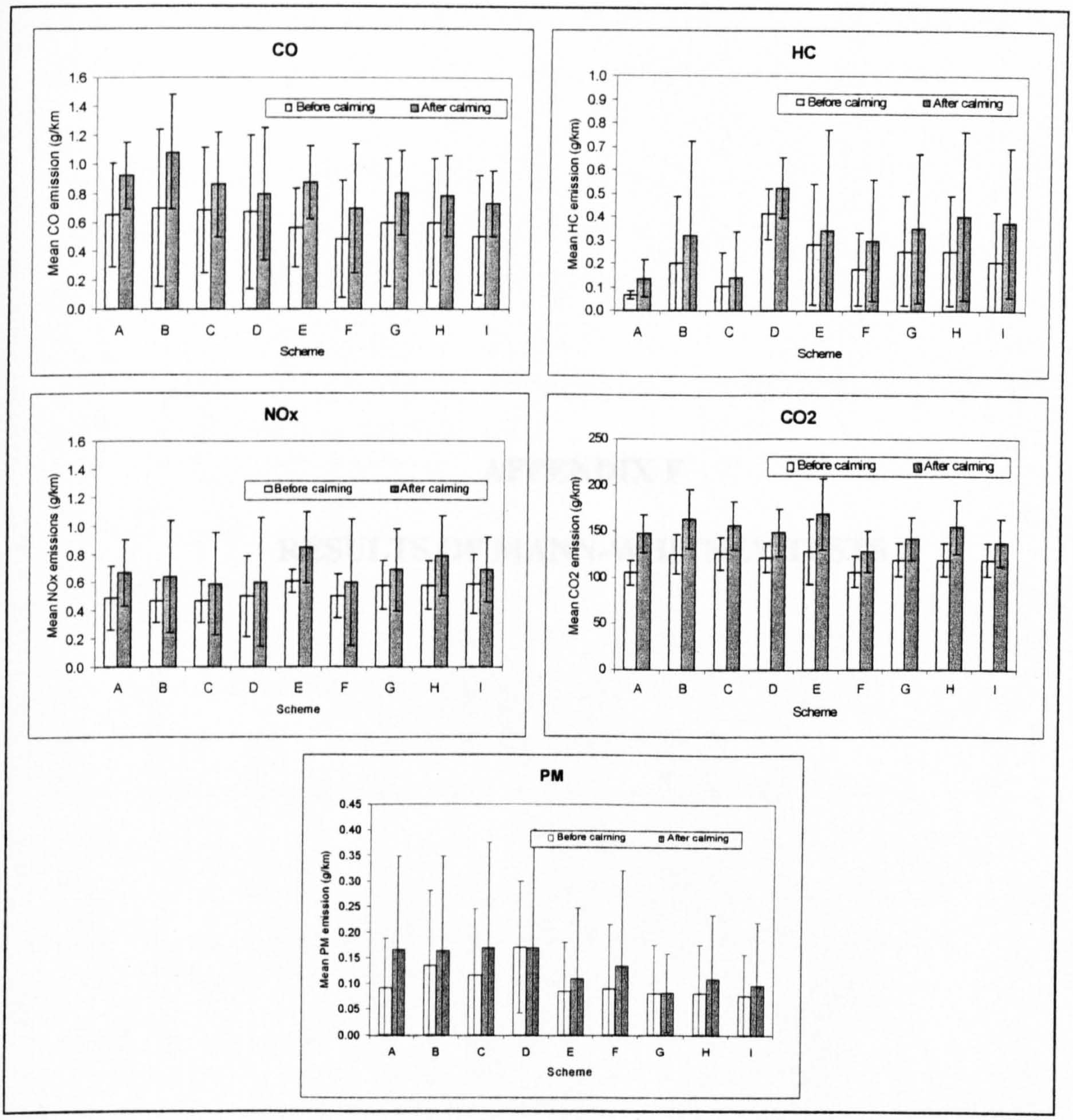

Figure E3 Emissions from diesel cars before calming and after calming for individual schemes. The emission levels have been averaged over all the vehicle tested for a particular scheme. The I-beams represent the 95% confidence intervals on the means.

APPENDIX F

RESULTS OF MANN-WHITNEY TESTS

The Mann Whitney test is a non-parametric test for comparing the median values of two samples (A and B) that are not normally distributed. The null hypothesis in assumes that the medians of two samples are equal. The alternative hypotheses tested here were:

1. Median of variable A ... median of variable B
2. Median of variable A > median of variable B
3. Median of variable A < median of variable B

If the probability value (P) for any of the hypotheses is less than 0.05 (for a 95% confidence level), the null hypothesis should be rejected.

These hypothesis were tested for the distributions that were recorded at each site. Three comparisons were undertaken:

A Before calming vs. after calming at the measure
B Before calming vs. after calming between measures
C After calming near the measure vs. after calming between measures

The results for each traffic calming measure and each pollutant are presented on the following pages. The cases for which the null hypothesis has been rejected are highlighted.

F1 Flat-top humps

The results in Table F1 show that the median CO level after calming both near the hump and between humps was significantly greater than that before calming. After calming the median CO level near the hump was significantly greater than that between humps.

The results in Table F2 show that the median HC level after calming was significantly greater near and between humps than that before calming, and after calming the median level near the hump was significantly greater than the median level between humps.

Table F1 Results of Mann-Whitney tests for CO (road humps).

Variable A	Variable B	P value for alternative hypotheses		
		Median A <> Median B	Median A > Median B	Median A < Median B
Before calming	After calming near hump	0.00	1.00	0.00
Before calming	After calming between humps	0.00	1.00	0.00
After calming near hump	After calming between humps	0.01	0.00	0.99

Table F2 Results of Mann-Whitney tests for HC (road humps).

Variable A	Variable B	P value for alternative hypotheses		
		Median A <> Median B	Median A > Median B	Median A < Median B
Before calming	After calming near hump	0.00	1.00	0.00
Before calming	After calming between humps	0.00	1.00	0.00
After calming near hump	After calming between humps	0.00	0.00	0.99

F2 Speed cushions

The median CO level (Table F3) was found to be significantly higher near and between the cushions than before calming The median CO level at the 'near cushion' site was significantly higher than that at the 'between cushion' site. For hydrocarbons (Table F4) it was found that the median level near the cushion after calming was significantly greater than that before calming, but the median between cushions was not significantly greater than the median level before calming.

Table F3 Results of Mann-Whitney tests for CO (speed cushions).

Variable A	Variable B	P value for alternative hypotheses		
		Median A <> Median B	Median A > Median B	Median A < Median B
Before calming	After calming near cushions	0.00	1.00	0.00
Before calming	After calming between cushions	0.05	0.98	0.02
After calming near cushions	After calming between cushions	0.00	0.00	1.00

Table F4 Results of Mann-Whitney tests for HC (speed cushions).

Variable A	Variable B	P value for alternative hypotheses		
		Median A <> Median B	Median A > Median B	Median A < Median B
Before calming	After calming near cushions	0.00	1.00	0.00
Before calming	After calming between cushions	0.31	0.15	0.85
After calming near cushions	After calming between cushions	0.00	0.00	1.00