UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING

School of Civil Engineering and the Environment

The Use of a Roadside Remote Sensing Device to encourage voluntary vehicle emissions related maintenance

by

Timothy James Felstead

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

TRANSPORTATION RESEARCH GROUP,
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Doctor of Philosophy

THE USE OF ROADSIDE REMOTE SENSING DEVICES TO ENCOURAGE VOLUNTARY VEHICLE EMISSIONS RELATED MAINTENANCE

by **Timothy James Felstead**

Road transport is responsible for the majority of pollutant emissions in urban areas and these emissions can have significant impacts on human health as well as the built and natural environment. The control of emissions from the road fleet is increasingly dependant on sophisticated engine management systems and after treatment components. Failure of these systems and components results in individual vehicle emissions levels far in excess of those which could be attained. As a result a small minority of cars can contribute a disproportionate and unnecessarily high percentage of the total car fleet emissions. Such cars would fail the type approval chassis dynamometer emissions standards – these vehicles are called 'gross polluters'. The mitigation of these excess emissions has the potential to assist Local Authorities in achieving the National Air Quality Strategy targets and save the individual car owner money from reduced fuel consumption.

This study has used a roadside remote sensing device (RSD) to measure the emissions of vehicles passively in the traffic stream. The RSD unit reported the measured emissions in terms of emissions efficiency by comparing the quantity of a specific pollutant (CO, HC or NO) to the quantity of fuel being burnt (using CO_2 as a proxy) in the measured vehicle's trailing exhaust plume. The RSD system also captured the measured vehicle's registration number. This record was combined with the vehicle's speed and acceleration immediately before measurement of its emissions. Using previously defined emissions efficiency thresholds relating to vehicles suspected of having an emissions related fault, the number of gross polluting vehicles in Winchester was ascertained. This was a very small proportion of all measured (0.2 to 0.4% depending on the pollutant) although the percentage of excess emissions attributed to these vehicles was higher (2-4%) it was still not particularly large.

To make use of RSD measurements and encourage owners of gross polluting vehicles to repair their vehicle, a number of emissions measurement feedback strategies were examined using a questionnaire survey. These feedback mechanisms were i) use of a roadside variable message sign (VMS), ii) use of a website database/VMS, iii) provision of a subsidised emissions check, and iv) diversion to a Park and Ride site. It was concluded the most successful strategy would be the use of a roadside VMS with support of a website plus use of email/phone SMS notification. A high percentage of respondents indicated they would submit their vehicle for a voluntary emissions check under such circumstances (~95%). The provision of a subsidised check would remove an observed reluctance of those owning older cars to have their vehicle checked although a hardcore (~4%) of respondents would not have their vehicle checked voluntarily under any of the scenarios.

In areas where the percentage of vehicles observed as gross polluters (likely to be more less affluent areas with an older vehicle population) such an approach could result in significant emissions savings from the local vehicle fleet and so have beneficial implications for the health of the local community due to improved air quality.

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DECLARATION OF AUTHORSHIP

I, ...TIMOTHY JAMES FELSTEAD..

declare that the thesis entitled:

THE USE OF A ROADSIDE REMOTE SENSING DEVICE TO ENCOURAGE VOLUNTARY VEHICLE EMISSIONS RELATED MAINTENANCE

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- none of this work has been published before submission

Signed:..

Date:..

ACKNOWLEDGEMENTS

After six years I have finally reached the end of my PhD (subject to the dreaded corrections). It has been a path which has taught me a great deal about myself, my field of work and how things are not always as obvious or straightforward as they appear on the surface! I would like to acknowledge all those who helped me along the way.

Firstly, I would like to thank Prof. Mike McDonald for his guidance throughout my studies and employment. I hope this thesis proves I wasn't always playing or watching cricket when I was out of the office.

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The fieldwork has been carried out within the EC co-sponsored CIVITAS MIRACLES project and the EPSRC sponsored FUTURES project.

ABBREVIATIONS AND UNITS

A/F	Air/Fuel ratio
AQAP	Air Quality Action Plan
AQEG	Air Quality Expert Group
AQMA	Air Quality Management Area
ASM	Acceleration Simulation Mode
BaO	Barium Oxide
BDC	Bottom Dead Centre
BET	Basic Emissions Test
BTDC	Before Bottom Dead Centre
C	Carbon
CEC	Cation Exchange Capacity
CeO_2	Cerium Oxide
CI	Compression Ignition
CO	Carbon Monoxide
Co	Cobalt
CO_2	Carbon Dioxide
CRT	Continuously Regenerating Trap
Cu	Copper
CVTF	Cleaner Vehicle Task Force
DEFRA	Department for the Environment, Farming and Rural Affairs
DETR	Department of the Environment, Transport and the Regions
DfT	Department for Transport
DIR	Dispersive Infrared
DoE	Department of the Environment
DVLA	Driver and Vehicle Licensing Agency
ECE15	Economic Commission for Europe 15 mode driving cycle
ECU	Electronic Computer Unit
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
EPAQS	Expert Panel on Air Quality Standards
ESP	Environment Sensing Products
EU	European Union
EUDC	Extra Urban Driving Cycle
FAS	Free Acceleration Smoke test

Fe	Iron
H	Hydrogen
H_2O	Water
HC	Hydrocarbons
HCC	Hampshire County Council
HCN	Hydrogen Cyanide
HGV	Heavy Goods Vehicle
HNCO	Isocyanic acid
hv	Light energy
I&M	Inspection Maintenance
IR	Infrared
JCS	Joint Commission Study
LAEI	London Atmospheric Emissions Inventory
LAs	Local Authorities
LEV	Low Emission Vehicle
LEZ	Low Emissions Zone
LDV	Light Duty Vehicle
LIDAR	Light Detection And Ranging
LightSpeed	Speed and acceleration measurement equipment
LPG	Liquid Petroleum Gas
MOT	Ministry Of Transport test
N_2	Nitrogen
N_2O	Nitrous Oxide
NAEI	National Atmospheric Emissions Inventory
NAO	National Audit Office
NAQS	National Air Quality Strategy
NAS	National Academy of Science
NDIR	Non Dispersive Infrared
NDUV	Non Dispersive Ultraviolet
NEDC	New European Driving Cycle
NEGTAP	National Expert Group on the Transport of Air Pollutants
NETCEN	National Environment Technology Centre
NH_3	Ammonia
Ni	Nickel
NO	Nitric Oxide

NO_2	Nitrogen Dioxide
NO_3	Nitrate
NOMIS	Official Labour Market Statistics
NO_x	Oxides of Nitrogen
O	Oxygen atom
O_2	Oxygen molecule
O_3	Ozone
OBD	On Board Diagnostics
OBM	On Board Measurement
OH	Hydroxyl
P&R	Park and Ride
PAH	Polycyclic Aromatic Hydrocarbons
Pb	Lead
Pd	Palladium
PM_{10}	Fine Particulate Matter (<10μm)
PM2.5	Ultrafine Particulate Matter (less than 2.5μm)
POST	Parliamentary Office of Science and Technology
PSVs	Public Service Vehicles
Pt	Platinum
RAC	Royal Automobile Club
RCEP	Royal Commission for Environmental Pollution
REVEAL	Remote measurement of Vehicle Emissions at Low Cost
Rh	Rhodium
RSD	Remote Sensing Device
Ru	Ruthenium
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SIP	State Implementation Plan
SMS	Short Message Service or Text Message
SO_2	Sulphur Dioxide
SO_3	Sulphur Trioxide
T&E	Transport and Environment
TDC	Top Dead Centre
TDLs	Tunable Diode Lasers
THC	Total Hydrocarbons

TOMPs	Toxic Organic Micro Pollutants
TRG	Transportation Research Group
TRL	Transportation Research Laboratory
TSP	Total Suspended Particulates
UK	United Kingdom
UNECE	United Nations Economic Commission for Europe
USA	United States of America
UV	Ultraviolet
V	Vanadium
VCA	Vehicle Certification Agency
VI	Vehicle Inspectorate
VIN	Vehicle Identification Number
VMS	Variable Message Sign
VOCs	Volatile Organic Compounds
VSP	Vehicle Specific Power (measured in kWtonnes)
WHO	World Health Organisation
λ	Air/Fuel Ratio

UNITS

%	percentage
%.m	percentage metres
µm	micro metres
dB	decibel
g/£	grams per pound sterling
g/kWh	grams per kilowatt hour
Hz	hertz
km	kilometres
kWtonnes^{-1}	kilowatt tonnes
m^{-1}	per metre
mS	millisecond
ms^{-1}	metres per second
ms^{-2}	metres per second per second
ppb	parts per billion
ppm	parts per million
ppm.m	parts per million metres

1 INTRODUCTION

1.1 Background

Over recent decades emissions from the road transport sector have been falling (DEFRA, 2006) despite a trend of increasing vehicle kilometres travelled (DfT, 2004). This has been brought about by improvements in engine and emissions control technology, largely driven by the use of progressively stringent vehicle emissions limits (i.e. EURO standards) and the necessary improvements in fuel quality that allow the use of such control technologies. Despite these trends Local Authorities are still failing to meet health impact based air quality targets laid out in the UK National Air Quality Strategy (NETCEN, 2006). These instances of exceedance are largely due to NO_2 or PM_{10} concentrations in urban roadside locations or areas adjacent to heavily trafficked inter-urban roads. Many options are available to Local Authorities to mitigate this problem from draconian traffic restraint strategies (e.g. closure of city centre roads) to softer travel and traffic reduction strategies (e.g. travel planning). The approach explored in this study was not a reduction in car use but instead that of ensuring a vehicle's emissions are as low as they technically can be (i.e. ensuring the vehicle's emissions related control is operating as effectively as possible). This has been specifically applied to light duty vehicles, the vast majority of which are cars.

Previous studies have shown that approximately 50% of the emissions on the road are caused by 10% of the cars (Zhang *et al.*, 1993; Stedman *et al.*, 1994; Fisher *et al.*, 2003). The studies above have been undertaken using roadside remote sensing devices which have the advantage over other emissions measurement approaches of being able to capture a high volume of cars per hour. Some of this variation in vehicle emissions from individual cars can be expected due to differences in a vehicle emissions standards and the load upon the measured vehicle but it has been shown that there is a significant maintenance factor also involved (USEPA, 2004). Currently, in the UK, the only method of identifying if a car has an emissions related fault is though the Inspection and Maintenance programme – the annual MOT. This approach has three major drawbacks (Norris, 2000 and 2001a):

i) it is undertaken annually and only for cars over three years old; although a car can develop an emissions related fault at any time.

ii) it is becoming increasing ineffective at identifying cars with an emissions related fault as the car fleet becomes increasing reliant on sophisticated technologies to control their tailpipe emissions.

iii) a driver may not be aware if their car has developed an emissions fault or if they are aware there is nothing to prevent them from avoiding its repair until it is submitted for an MOT.

To fill this gap in the current Inspection and Maintenance programme and to ensure cars with an emissions related fault are not contributing to local air quality problems, an approach to identify and encourage voluntary maintenance would be useful. Within this study a roadside remote sensing system has been used to determine the extent of this problem in the Winchester area (which has an air quality problem). A range of feedback strategies has also been examined where by drivers of vehicles suspected of having an emissions related fault are encouraged to have their car checked and, if necessary, repaired. This is the first time the effectiveness of such an approach has been assessed in a UK context. The emissions measurements collected will be set in the context of nationally enforceable standards and, in principal, allow vehicle owners to 'check' their vehicles emissions performance through time.

1.2 Objectives

i) Understand the background of vehicle emissions in the UK including issues relating to vehicle emissions, reasons for excess emissions and current approaches to minimising excess emissions (both technical and policy).

ii) Identify any shortfalls in the current UK inspection and maintenance programme and the extent to which remote sensing devices (RSDs) can mitigate these shortfalls.

iii) Determine the usefulness of supporting measurements such as vehicle speed and acceleration in interpreting RSD measurements.

iv) Understand some of the practical limitations to the use of RSDs in a UK context including the areas of site selection and variations in RSD measurements.

v) Assess the accuracy of the recently developed REVEAL RSD unit and its suitability for use in the field.

vi) Quantify the extent of the excess emissions problem in Winchester.

vii) Quantify the potential public response to various approaches to encourage voluntary vehicle emissions related maintenance and to reduce emissions from high polluters in Winchester city centre.

viii) Develop recommendations on future use of RSDs in inspection and maintenance programmes and identify areas for further research.

1.3 Approach

The approach taken to achieve the objectives of this thesis can be broken into distinct steps. These steps are illustrated and described in **Figure 1-1**.

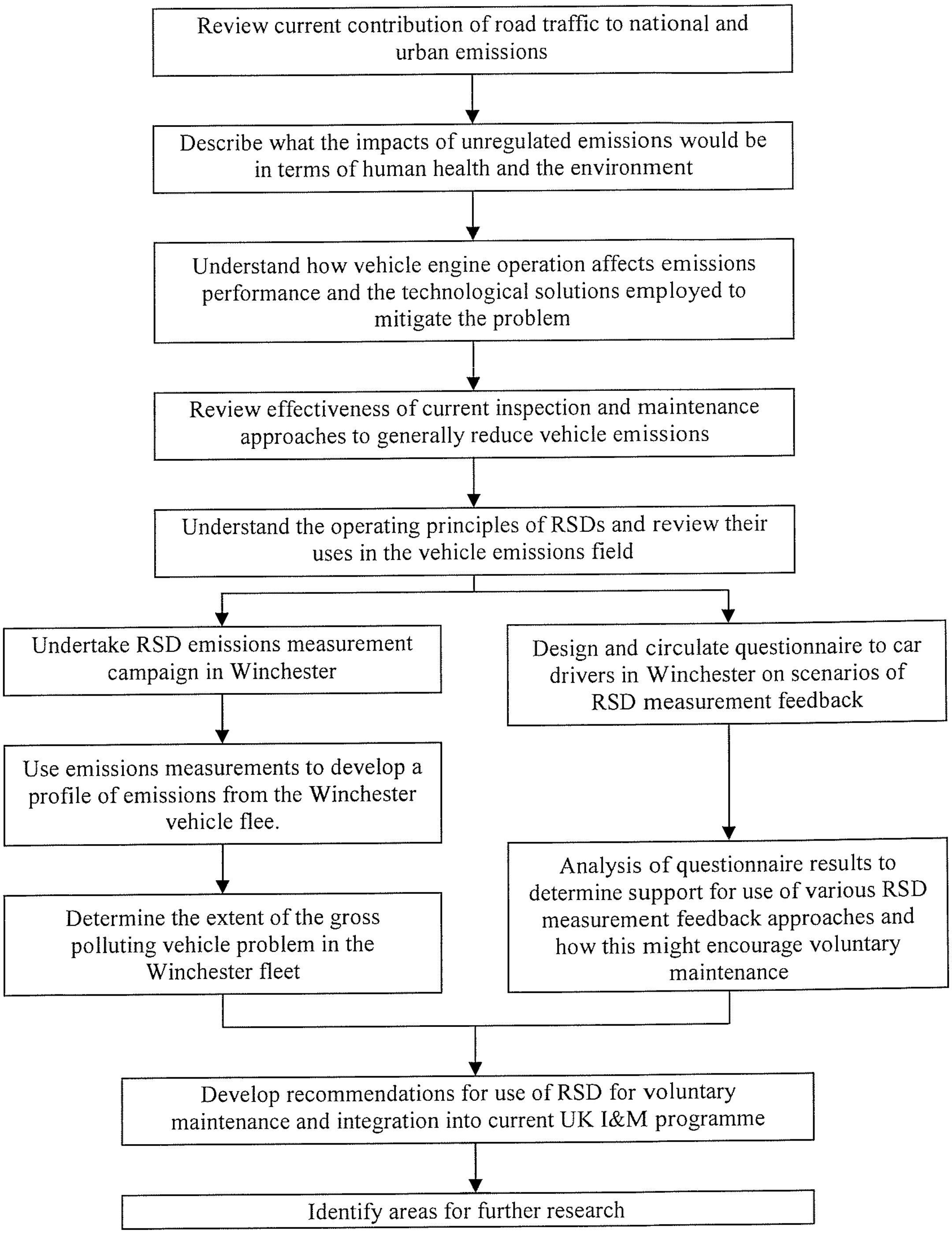


Figure 1-1: Flow chart illustrating the individual steps taken to achieve the objectives of this thesis

1.4 Structure of thesis

This document consists of seven further chapters. The intention is to tell a story of how road transport emissions are an issue that should be addressed and is one which the use of RSDs can help solve. The next chapter addresses air quality, its impacts on people's health and the environment, and the importance of road traffic as a source of emissions. Next, a review of the parameters controlling fundamental sources of traffic emissions is given (i.e. a vehicles engine) and some of the abatement strategies which are, or will be, used to reduce them is given. This third chapter is intended to give the reader the tools to understand the methods of emissions control in petrol and diesel cars. The fourth chapter examines the current method the UK uses to ensure emissions from new cars are becoming progressively lower and ensuring those from in-service vehicles remain as low as is reasonably possible. The fifth chapter gives a background to RSD's including their development history, considerations for their use in the context of vehicle emissions measurement and the range of applications for which they have been utilised. Chapter six presents results from a RSD measurement campaign in Winchester including quantifying how many vehicles exceed some proposed emissions thresholds. Results of a questionnaire to the general driving public are presented in chapter seven. The questionnaire examines how the public would react to a number of approaches to RSD measurement feedback. The final chapter presents overall conclusions, suggests ways in which RSDs could be used to identify excess emissions and some of the caveats for their use based upon the experiences of this PhD. It also identifies areas for further research.

2 TRANSPORT AND AIR QUALITY

2.1 Introduction

Transport has a significant impact upon the environment in which we live. In general, these impacts can be divided under four broad headings; climate change, local air quality, noise and watercourse pollution (RCEP, 1997). The focus of the work presented in this PhD is on reducing the contribution of high polluting vehicles to local air quality. This forms the focus of the review and background on air quality issues in the UK and Europe are presented. This includes the current standards which are in place, the contribution of road transport to the problem and the impact of local air quality pollutants on health and the environment.

2.2 National Air Quality Strategy (NAQS)

UK regulation of noxious gas emissions through parliamentary acts first began in 1863 and this was extended in 1874, 1906 and 1926. These regulations only covered emissions from industrial sources and it was not until the Clean Air Acts of 1956 (a reaction to the infamous Great London Smog of 1952) and 1968 that domestic smoke emissions were regulated. As knowledge of air pollution, its impacts and the ability to monitor its components has increased, UK policy has become more specific with particular gas species becoming regulated (Beattie *et al.*, 2001; POST, 2002). Currently, the UK government is obliged to produce a NAQS under the Environment Act 1995. The first NAQS was produced in 1997 (DoE *et al.*, 1997) and it largely laid out the policy direction and tools with which it would improve local air quality.

2.2.1 National air quality standards

Part of the suite of tools developed to achieve the objectives of NAQS were air quality standards. The standards related to maximum allowable concentrations of certain local air pollutants at outdoor ground level locations where a person could reasonably be expected to pass by. These standards were derived from World Health

Organisation (WHO) guidelines and some early directives from the EU; the standards were ratified, and in some cases modified, by the Expert Panel on Air Quality Standards (EPAQS). The standards are based on medical effect studies which use laboratory based animal and human exposure tests, epidemiological studies, cell based tests and workplace exposure studies. Following examination of the dosages at which some adverse reaction is observed in the test subjects, a suitable standard is derived with safety margins added (e.g. could be as simple as dividing the dosage by 100) (EPAQS, 1994-2002). The initial NAQS required these standards to be attained by 2005. The standards were based on scientific studies to understand thresholds below which the impact on human health and the environment was negated (or in some cases levels where the risk was 'suitably' minimised).

This first NAQS set standards for benzene, 1,3~Butadiene, carbon monoxide, lead, nitrogen dioxide, ozone, fine particulates (PM_{10}) and sulphur dioxide. A further point of note was the requirement for Local Authorities to undergo a review and assessment exercise of air quality in their area. Where the Local Authority found that the standards would not be achieved by 2005, an Air Quality Management Area (AQMA) had to be declared relating to the relevant geographical area. In such cases, an Air Quality Action Plan (AQAP) was required detailing the measures the Local Authority would implement to ensure the standards were achieved in future.

The initial NAQS was reviewed in 2000 (DETR *et al.*, 2000) with limits for benzene, 1,3~Butadiene, carbon monoxide, lead, nitrogen dioxide tightened, limits for ozone and sulphur dioxide remained the same, and limits for PM_{10} were relaxed. These revisions were partly due to new evidence on their health and environmental impacts, the awaiting of directives from the EU and practical considerations on timescales for reductions. The 2000 NAQS took into account the then recently combined legislation from the EU Air Quality Framework Directive (Directive 96/62/EC) which outlined how statutory limits were to be set for twelve air quality pollutants through the publication of a series of daughter directives. The 2000 NAQS also made it a statutory responsibility for Local Authorities (LAs) to meet the air quality standards in their area. The 2000 NAQS was subject to a 2003 addendum (DEFRA, 2003a) in light of changes to EU standards and introduced tighter limits for particulates, carbon monoxide, benzene and introduced a new limit for polycyclic aromatic hydrocarbons.

In 2006, a further review was undertaken with a consultation version of the impending revised NAQS being produced (DEFRA, 2006a). The limits adopted in the latest review are listed in **Table 2-1**. It can be seen that for some pollutants, the limits to be achieved by 2010-12 are tighter than those to which LAs' have previously worked. It should be noted that attainment of the standards is necessary for every year following the date by which it was to be achieved.

In addition to local air quality standards, the UK also has obligations as a member of the United Nations Economic Commission for Europe (UNECE) regarding transboundary pollutants that cause harm to the environment. The national limits are presented in **Table 2-2**.

2.2.2 Local Authority attainment of air quality standards

As discussed in **Section 2.2.1**, under the 1995 Environment Act, it has been the responsibility of Local Authorities to review and assess the air quality in their area. Whilst most Local Authorities have air quality monitoring stations, much of the work to determine pollutant concentrations is based upon modelling known sources of emissions and their dispersion. The third round of review and assessment is due to be completed by the end of 2007 (previous rounds ended in 2001 and 2004). Where it is indicated that the standards will not be achieved, an AQMA must be declared. In Sept 2006, 192 Local Authorities had declared AQMAs with most declared due to exceedance of nitrogen dioxide or PM_{10} standards (NETCEN, 2006). These exceedances were nearly always attributed to road traffic either because of sheer volume or because of localised canyoning effects (DEFRA, 2003b).

Pollutant	Applies to	UK objective	Measured as	Date to be achieved/ maintained by	European obligations	Date to be achieved maintained by
Benzene	UK	16.25μg.m^{-3}	Running annual mean	31 Dec 2003	5μg.m^{-3}	1 Jan 2010
	England and Wales	5μg.m^{-3}	Annual mean	31 Dec 2010		
	Scotland and Northern Ireland	3.25μg.m^{-3}	Running annual mean	31 Dec 2010		
1,3~butadiene	UK	2.25μg.m^{-3}	Running annual mean	31 Dec 2003		
Carbon monoxide	UK	10mg.m^{-3}	Max. daily running 8 hour mean/in Scotland as running 8 hour mean	31 Dec 2003	10mg.m^{-3}	1 Jan 2005
Lead	UK	0.5μg.m^{-3}	Annual mean	31 Dec 2004	0.5μg.m^{-3}	1 Jan 2005
	UK	0.25μg.m^{-3}	Annual mean	31 Dec 2008		
Nitrogen dioxide	UK	200μg.m^{-3} not to be exceeded more than 18 times a year	1 hour mean	31 Dec 2005	200μg.m^{-3} not to be exceeded more than 18 times a year	1 Jan 2010
	UK	40μg.m^{-3}	Annual mean	31 Dec 2005	40μg.m^{-3}	1 Jan 2010
Ozone	UK	100μg.m^{-3} not to be exceeded more than 10 times a year	8 hour mean	31 Dec 2005	100μg.m^{-3} not to be exceeded more than 25 times a year averaged over 3 years	1 Jan 2010
PM_{10}	UK	50μg.m^{-3} not to be exceeded more than 35 times a year	24 hour mean	31 Dec 2004	50μg.m^{-3} not to be exceeded more than 35 times a year	1 Jan 2005
	UK	40μg.m^{-3}	Annual mean	31 Dec 2004	40μg.m^{-3}	1 Jan 2005
	UK (except London)	50μg.m^{-3} not to be exceeded more than 7 times a year	24 hour mean	31 Dec 2010	Indicative Stage II limit	????
	UK (except Scotland and London)	20μg.m^{-3}	Annual mean	31 Dec 2010		
	London	50μg.m^{-3} not to be exceeded more than 10 times a year	24 hour mean	31 Dec 2010		
	London	23μg.m^{-3}	Annual mean	31 Dec 2010		
	Scotland	18μg.m^{-3}	Annual mean	31 Dec 2010		
Polycyclic aromatic hydrocarbons	UK	0.25ng.m^{-3} B[a]P	Annual mean	31 Dec 2010	1ng.m^{-3}	1 Jan 2013
Sulphur dioxide	UK	266μg.m^{-3} not to be exceeded more than 35 times a year	15 min. mean	31 Dec 2005		
	UK	350μg.m^{-3} not to be exceeded more than 24 times a year	1 hour mean	31 Dec 2005	350μg.m^{-3} not to be exceeded more than 24 times a year	1 Jan 2005
	UK	125μg.m^{-3} not to be exceeded more than 3 times a year	24 hour mean	31 Dec 2005	125μg.m^{-3} not to be exceeded more than 3 times a year	1 Jan 2005

Table 2-1: UK local air quality objectives as of June 2006 for protection of human health (*Source: DEFRA, 2006*a)

Pollutant	Applies to	UK objective	Measured as	Date to be achieved/ maintained by	European obligations	Date to be achieved maintained by
Oxides of nitrogen	UK	$30\mu g.m^{-3}$	Annual mean	31 Dec 2000	$30\mu g.m^{-3}$	19 Jul 2001
Sulphur dioxide	UK	$20\mu g.m^{-3}$	Annual mean	31 Dec 2000	$20\mu g.m^{-3}$	19 Jul 2001
	UK	$20\mu g.m^{-3}$	Winter mean	31 Dec 2000	$20\mu g.m^{-3}$	19 Jul 2001

Table 2-2: National air quality objectives for protection of vegetation and ecosystems (*Source: DEFRA, 2006a*)

2.3 Transport as a source of the NAQS pollutants

To understand the role transport plays in the emissions of the NAQS objectives, the trend and impact from both transport and more specifically road traffic will be described below. These are presented for both overall countrywide emissions and in urban areas. The increased presence of road vehicles in urban areas compared to other sources listed below leads to road transport being of particular focus in AQMA's. When this is combined with the relatively high population densities in urban areas the potential impact of road transport on human health becomes clear. The combustion chemistry associated with the formation of the pollutants discussed below is given in **Chapter 3**.

2.3.1 Volatile Organic Compounds (VOC's)

VOC's are hydrocarbons which are emitted through evaporation from solvents and fuels, or from incomplete, or as a product, of combustion of fuels. Both benzene and 1,3 ~butadiene belong to this category of NAQS pollutants.

2.3.2.1 Benzene

The dataset available for benzene emissions is shorter than for other pollutants discussed in this section. The annual UK benzene emissions since 1990 are shown in **Figure 2-1**. In 1990 road transport accounted for nearly four fifths of all benzene emissions although this has declined sharply due to the introduction of catalytic converters in petrol cars and decreasing benzene content in fuels. Total emissions in 2004 are approximately 30% of their 1990 level due in most part to reductions from the road transport sector. Benzene also evaporates from fuel and much attention has been given to the design of improved fuel tanks and vehicle fuel delivery systems in petrol road vehicles in recent years as part of the EC type approval process. In 2004, road transports share of benzene emissions was approximately a quarter of all emissions. The domestic sources include use of coal, wood and natural gas for heating (DEFRA, 2006a).

The estimated source apportionment for benzene emissions in Inner London as taken from the 2003 London Atmospheric Emissions Inventory (LAEI) is given in **Table 2-3**. These figures illustrate how road transport is producing a disproportionately high percentage of benzene emissions in urban areas compared to national proportions.

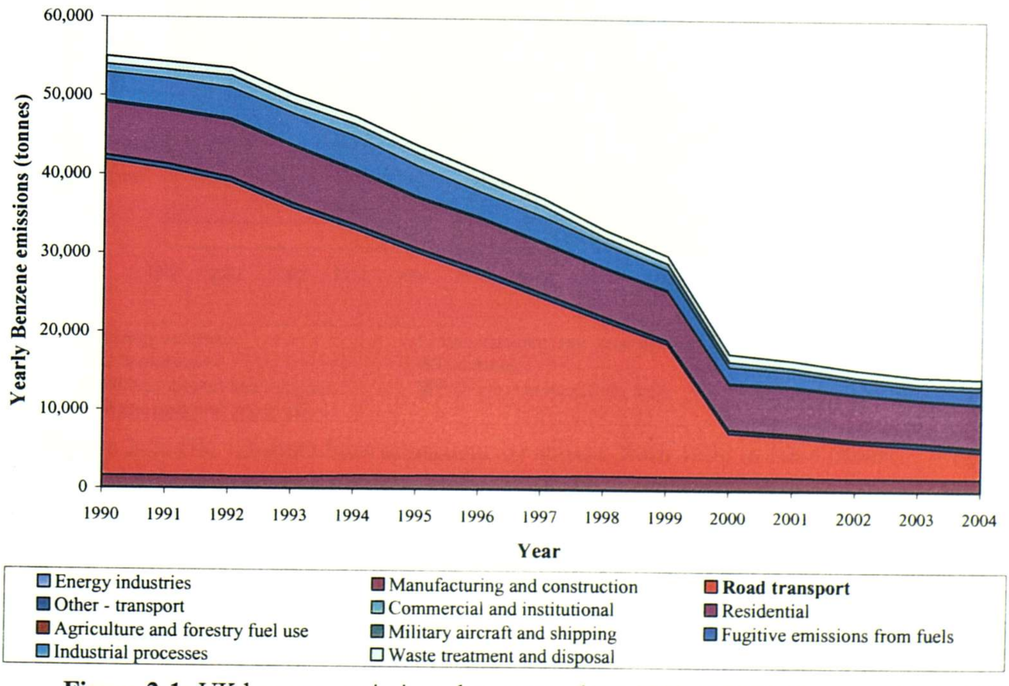


Figure 2-1: UK benzene emissions, by source, from 1990 to 2004 (*Source: NAEI, 2006*)

Source	% of total emissions
Energy (Industrial/domestic)	18.2
Industrial processes	27.3
Agriculture/nature	11.4
Road transport	43.1
Other transport	0.0

Table 2-3: Sources of benzene in Inner London *(Source: Mattai and Hutchinson, 2005)*
NB/ Rounding errors result in total of more than 100%

2.3.2.2 1,3~butadiene

The national emissions estimates for 1,3~butadiene only run from 1990. All 1,3~butadiene emissions derive from anthropogenic sources and although it is an important industrial chemical (DEFRA, 2006a) it can clearly be seen from **Figure 2-2** that road transport is responsible for nearly all emissions in 1990 (over 80%). Large decreases have been seen with 2004 emissions approximately 30% of the 1990 level. The large decreases seen from the road transport sector can be attributed to the introduction of tighter emissions standards for diesel and especially petrol vehicles. All emissions in Inner London are attributed to road transport (see **Table 2-4**).

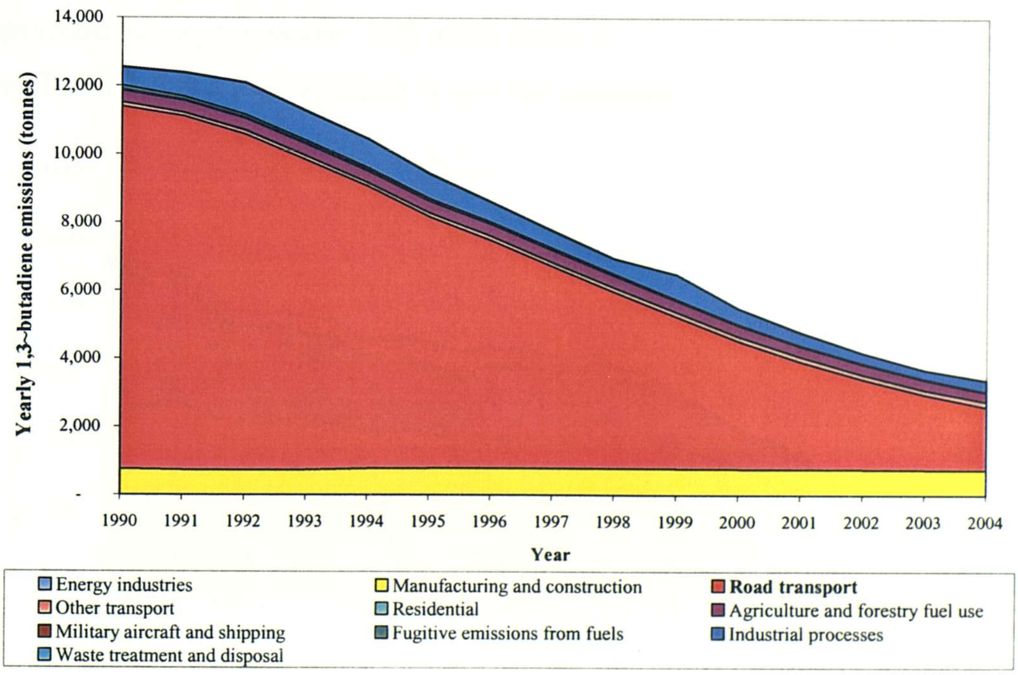


Figure 2-2: UK 1,3~butadiene emissions, by source, from 1990 to 2004 (*Source: NAEI, 2006*)

Source	% of total emissions
Energy (Industrial/domestic)	0
Industrial processes	0
Agriculture/nature	0
Road transport	100.0
Other transport	0

Table 2-4: Sources of 1,3~butadiene in Inner London *(Source: Mattai and Hutchinson, 2005)*
NB/ Rounding errors result in total of more than 100%

2.3.2 Carbon monoxide (CO)

The trend in national emissions of CO, in terms of end user, since 1970 is given in **Figure 2-3**. Overall emissions have declined to approximately 25% of their 1970 levels with emissions from road transport following this trend despite an increasing level of road kilometres being travelled. Like most of the decreases in emissions described in this section, the decrease in road transport CO is due to improved vehicle emissions standards (e.g. EURO standards) since the early 1990's. Reductions have been achieved from other users due to banning of stubble burning in agriculture and a switch from coal to gas for provision of domestic electricity (DEFRA, 2006a). The current national figures indicate that road transport is responsible for approximately 50% of the national CO emissions. It can be seen from **Table 2-5** that road transport is also the dominant source in urban areas.

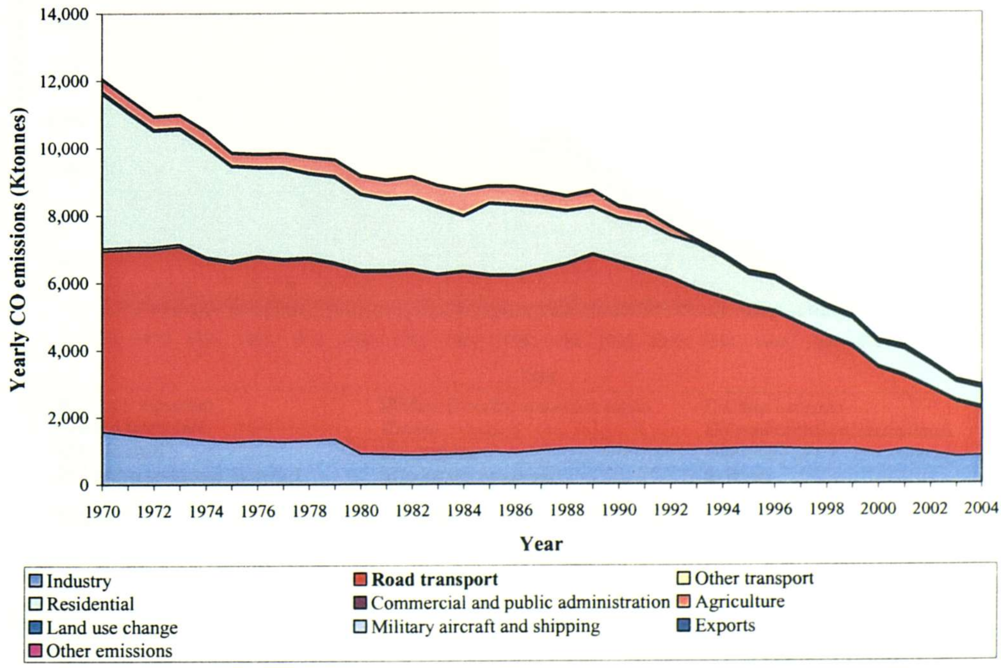


Figure 2-3: UK CO emissions, by end use, since 1970 (*Source: DEFRA, 2006b*)

Source	% of total emissions
Energy (Industrial/domestic)	1.7
Industrial processes	0.6
Agriculture/nature	12.0
Road transport	84.5
Other transport	1.4

Table 2-5: Sources of CO emissions in Inner London *(Source: Mattai and Hutchinson, 2005)*
NB/ Rounding errors result in total of more than 100%

2.3.3 Lead (Pb)

Huge reductions in emissions of Pb have been achieved since 1970 largely due to reductions in the road transport sector (see **Figure 2-4**). This has been as a result of phasing out Pb as an anti-knock additive to petrol. Other reductions have been achieved by reduced use of coal in the iron/steel industry and better control of emissions from waste incineration sites. Levels in 2004 are approximately 1% of the 1970 emissions with road transport contributing negligible amounts. With this in mind, the pollutant is not reported in the 2003 LAEI.

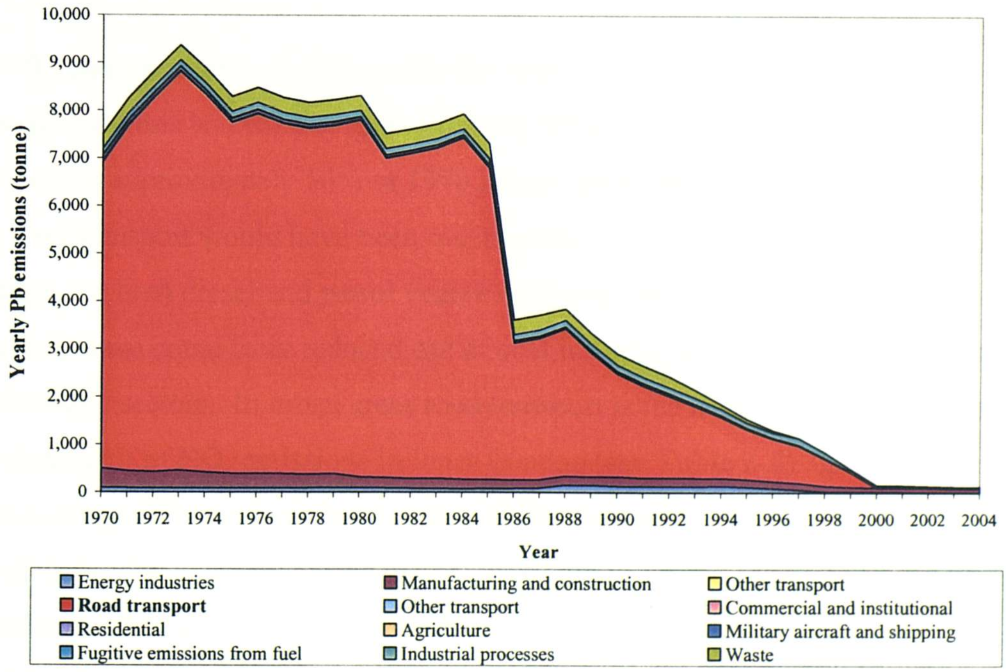


Figure 2-4: UK Pb emissions, by source, from 1970 to 2004 (*Source: NAEI, 2006*)

2.3.4 Nitrogen dioxide (NO_2)

The UK NAQS refers specifically to NO_2 but emissions are often measured in NO_x. This is because NO_2 and its closely related pollutants NO are involved in photochemical reactions when in the atmosphere. All NO has potential to take part in these reactions to form NO_2 and vice versa with light energy (*h*v) causing photodissociation. A number of other reactions with inorganic and organic third parties can also take part in the NO_x reactions (Manahan, 2000). The equations for these reactions are given in **Equation 2-1 to 2-4**. NO_x also takes part in ozone reactions (see **Section 2.3.5**). The NAQS refers to NO_2 in particular as it is in this form that NO_x damages human health.

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad \textbf{(Eq 2-1)}$$

$$2NO + O_2 \rightarrow 2NO_2 \qquad \textbf{(Eq 2-2)}$$

$$NO_2 + hv \rightarrow NO + O \qquad \textbf{(Eq 2-3)}$$

$$O + O_2 \rightarrow O_3 \qquad \textbf{(Eq 2-4)}$$

In 1970, road transport was responsible for approximately 25% of all NOx emissions whilst in 2004 this had risen to approximately 40% whilst overall emissions had decreased to approximately 50% of 1970 levels (see **Figure 2-5**). The emissions from road transport would have been much greater in 2004 had vehicle emissions standards for both diesel and petrol vehicles not been introduced. Other significant reductions have come from reduced use of coal in supplying energy to the industrial and domestic sectors. In urban areas road transport is the largest contributor of NO_x emissions; half of NO_x emissions in Inner London (see **Table 2-6**). Exceedances of the NO_2 air quality standards have increased in urban areas over recent years. This is thought to be due to the increase in primary NO_2 (as opposed to secondary NO_2 formed through chemical reactions such as those above) emitted by road vehicles, in particular diesel vehicles whose market share has been increasing and whose use of oxidation catalysts has increased to meet tighter CO and HC emissions standards (DEFRA, 2006a). Using a novel approach to examining air quality datasets, Carslaw *et al.* (2006) was able to identify points in time where changes to localised traffic composition (increased % of buses and taxis) and technology on buses (use of particulate traps) had resulted in increases in ambient NO_x. PM_{10} was also found to increase at the time of the fleet change although $PM_{2.5}$ had decreased.

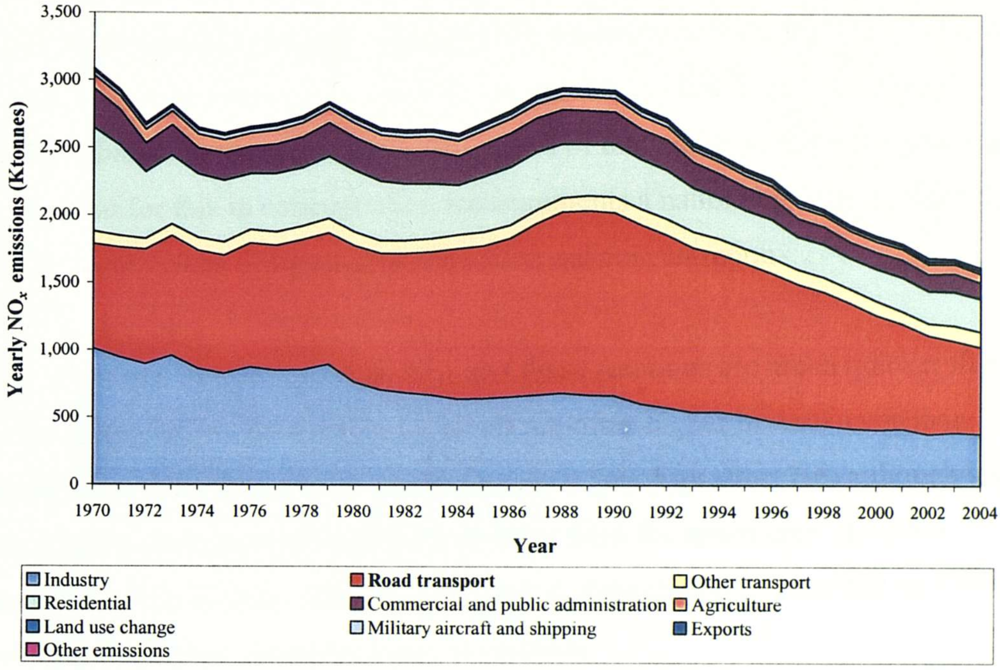


Figure 2-5: UK NO_x emissions, by end user, from 1970 to 2004 (*Source: DEFRA, 2006b*)

Source	% of total emissions
Energy (Industrial/domestic)	32.9
Industrial processes	9.9
Agriculture/nature	0.2
Road transport	49.9
Other transport	7.2

Table 2-6: Sources of NO_x in Inner London *(Source: Mattai and Hutchinson, 2005)*
NB/ Rounding errors result in total of more than 100%

2.3.5 Ozone (O_3)

O_3 is not emitted directly into the atmosphere; instead it is formed through a series of photochemical reactions featuring NO_x, CO, hydrocarbons and PM – **Equation 2-5** is a very simplified version of the reaction which occurs. More detailed equations relating to precise species can be found in Manahan (2000) or Allen (2002). Whilst stratospheric O_3 is beneficial as it reduces the energy of UV travelling to the earth, at low ground level it has an impact on human health. During the decay (or oxidation) of HC's, O_3 is formed as a by-product. Different HC's have a varying potential to take part in O_3 forming reactions (Li and Andrews, 2006). The intensity of the sunlight is also important in determining the rate of oxidation. This HC oxidation can continue for hours and days. During this period the O_3 and HC's can be carried by the weather hence, the pollutants which result in O_3 at a particular location may have travelled significant distances (of the order of 10 to 100 km) and once formed may persist for a number of days. Because the precursor pollutants that form O_3 are produced in locations beyond the jurisdiction an effected LA, high levels in a particular urban area may be beyond the control of that particular LA. To give some compensation for this in concentration measurements a national background level is used with local values designated as the additional concentration.

O_3 also takes part in reactions with NO_x and these reactions are much quicker than those involving HC's. As a result, O_3 levels are often higher in rural areas than urban areas as NO_2 often acts as a reducing agent (see **Equation 2-6**) although levels increase as the precursor pollutants travel away from the urban area (DEFRA, 2006a). This NO_3 is then broken down by photodissociation to form NO and NO_2 allowing the complex chemistry cycle to continue.

$$NO_x + HC + h\nu \longrightarrow O_3 + \text{other products} \qquad \textbf{(Eq 2-5)}$$

$$NO_2 + O_3 \longrightarrow NO_3 + O_2 \qquad \textbf{(Eq 2-6)}$$

2.3.6 Particulate matter (PM_{10})

Particulate matter is a complex pollutant. As understanding of the chemistry involved in its formation and composition has increased over recent years, so has the understanding of how road transport contributes to the problem. Rather than thinking of particulates in the sense of grains of sediment (such as those produced from quarrying or soil erosion) they should instead be thought of as complex compounds made up of many different elements. Whilst transport does produce particles in the sense of solids from wear of tyres, moving components and brake pads, particulates from combustion are far more chemically complex. Particulates from combustion are formed as primary solids, through condensation of pollutants emitted initially as a gas and secondary atmospheric reactions between other chemicals in the atmosphere (Holmén and Niemeier, 2003).

The initial concern over particulate pollution was based upon the visible smoke produced from industry and domestic coal burning. This concern can be seen in the measures of air quality in the 1950's where terms such as 'smoke' were used (essentially a measure of how much light could pass through the air). As the understanding of, and ability to, measure the composition of the smoke (i.e. it was made up of particles of different elements and compounds) increased then terms such as Total Suspended Particles (TSP) seemed to come into fashion. More recently the focus shifted to particulates below a size of 10μm as they were more easily inhaled into the body. Now, over the last few years, for the same reasons as for the refocusing on PM_{10}, the attention is being focused on $PM_{2.5}$ as they seem to have the most potentially damaging chemical composition and can travel further into the human body. As this transition of focus has recently shifted to the mass of particulates of a certain size, it is now shifting to the measurement of particle numbers (Holmén and Niemeier, 2003). This is due to concern over the higher relative surface area associated with smaller particles. The use of particle numbers may also be incorporated in the EURO IV emissions standards (EC, 2005) – this would lead to petrol vehicles being assessed on particulate emissions for the first time.

UK emissions of PM_{10} in 2004 were approximately 30% of those in 1970 (see **Figure 2-6**). Although road transport emissions had remained at the same absolute value as in 1970 it accounted for approximately 25% of all PM_{10} emissions in 2004. The major reductions in emissions have resulted from reduced use of coal and wood as a source of energy for industry and domestic use. The amount produced by road transport would be higher given increases in road mileage and penetration of diesel vehicles into the market if improved emissions standards and lower sulphur fuels had not been introduced. In Inner London, road traffic is the dominant source of PM_{10} contributing just over 50% of all emissions (see **Table 2-7**).

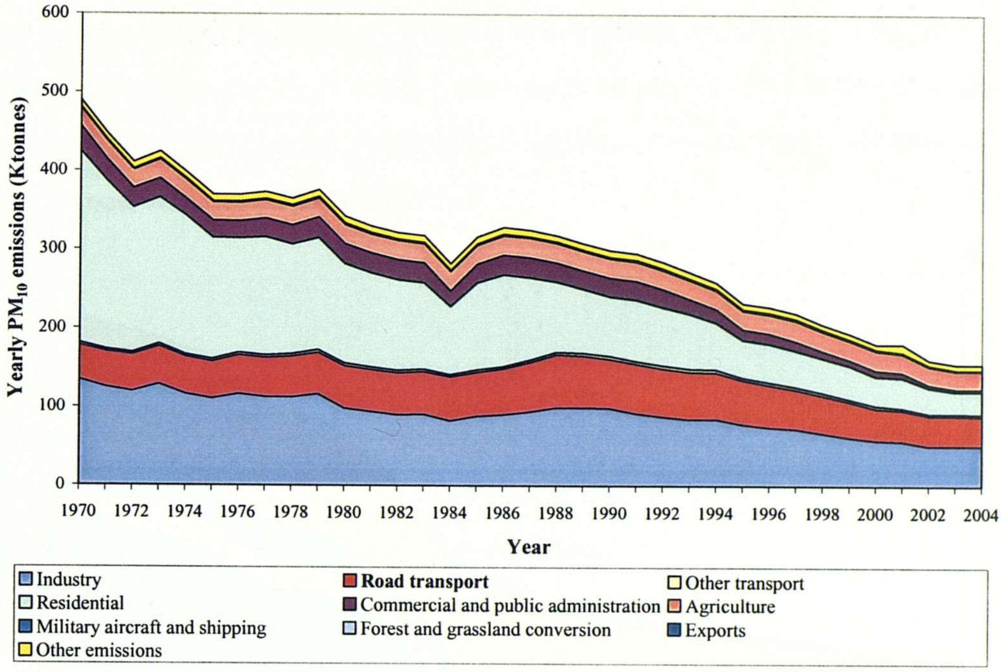


Figure 2-6: UK PM_{10} emissions, by end user, from 1970 to 2010 (*Source: DEFRA, 2006b*)

Source	% of total emissions
Energy (Industrial/domestic)	27.0
Industrial processes	13.4
Agriculture/nature	1.6
Road transport	53.8
Other transport	4.1

Table 2-7: Sources of PM_{10} in Inner London *(Source: Mattai and Hutchinson, 2005)*
NB/ Rounding errors result in total of less than 100%

2.3.7 Polycyclic aromatic hydrocarbons (PAH)

PAH is a sub group within a sub group of hydrocarbons which are broadly classed as Toxic Organic Micro Pollutants (TOMPs). Other species of TOMPS are furans, dioxins and PolyChlorinated Biphynals (PCB's). PAHs have received increased attention as a pollutant in recent years and were added to the list of NAQS pollutants in 2002. This was due to their high toxicity with even a small amount having carcinogenic properties. PAH emissions are measured using a marker species known as benzo[a]pyrene (B[a]P) which correlates well to PAH as a whole and has a relatively high potential to damage human health. PAH emissions have fallen since 1990 as shown **Figure 2-7**. In 2004, total emissions were approximately 25% of their 1990 levels although the relative share of the road transport sector has increased from approximately 25% to approximately 50%. Other sources have reduced their share (industry processes and domestic use) through more efficient processes or reduced combustion of fossil fuels. There is considerable uncertainty over the modelling of emissions of PAH and for this reason no source apportionment could be made in the 2003 LAEI (LAEI, 2005). Diesel vehicles are responsible for most of PAH from road vehicles (DEFRA, 2006a).

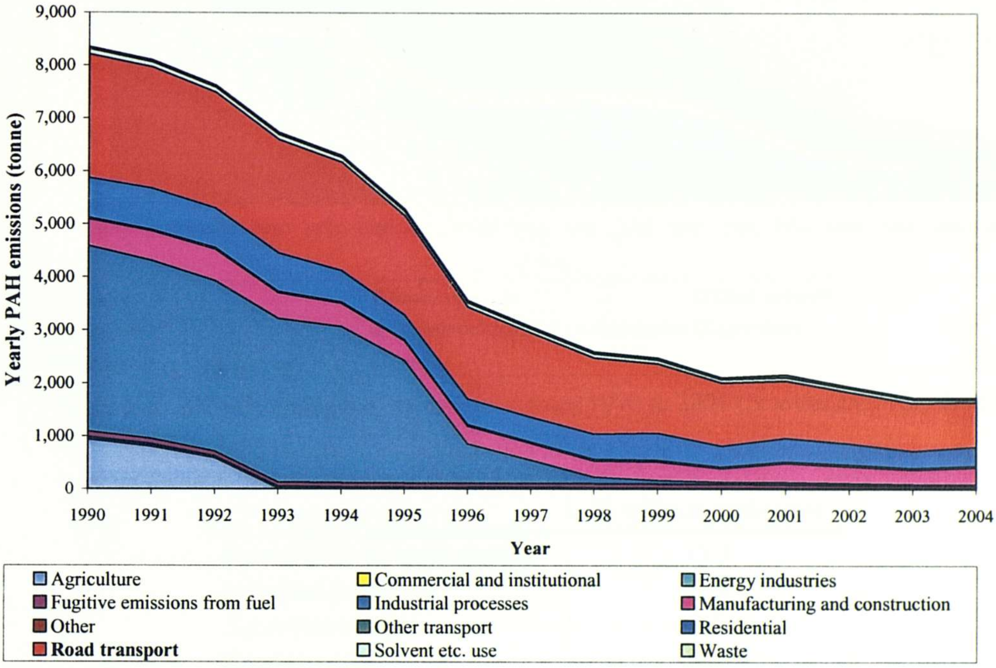


Figure 2-7:UK PAH emissions, by source, from 1990 to 2004 (*Source: NAEI, 2006*)

2.3.8 Sulphur dioxide (SO_2)

It can be seen from **Figure 2-8** that road transport contributes a negligible amount of SO_2 to total national emissions. The total amount of SO_2 emitted in 2004 was approximately 15% of its 1970 level with most of the reductions coming from decreased use of solid fuels in electricity generation and industrial processes. Road transport emissions have also decreased due to the lower sulphur content in diesel fuel. Despite its low proportion as a source within national emissions, it is still a significant contributor to emissions in urban areas (see **Table 2-8**) but this is likely to decrease as sulphur levels in petrol and diesel continue to be reduced.

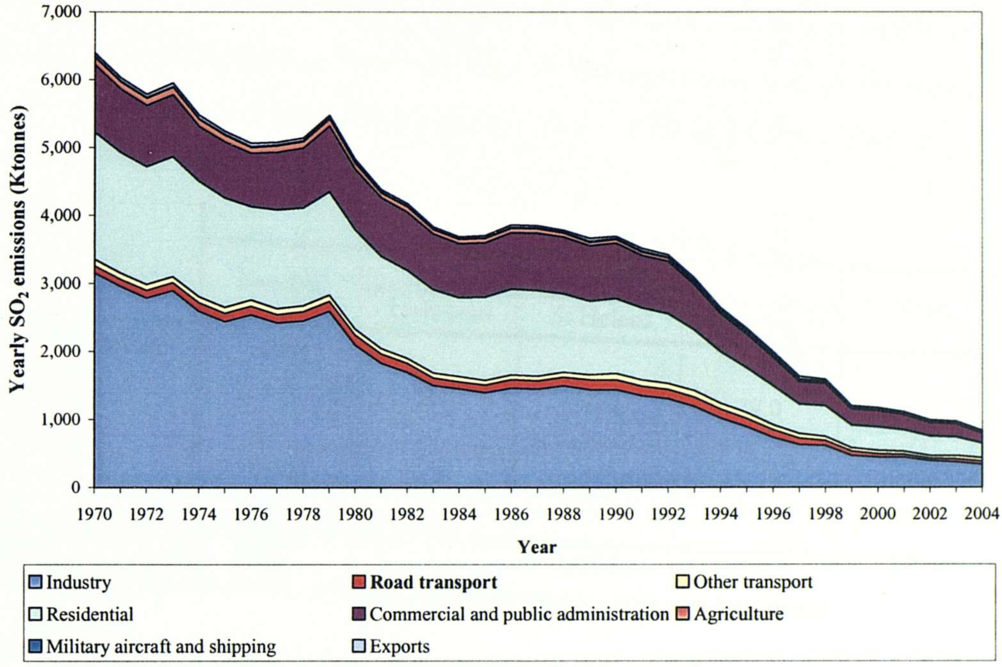


Figure 2-8: UK SO_2 emissions, by end user, from 1970 to 2004 (*Source: DEFRA, 2006b*)

Source	% of total emissions
Energy (Industrial/domestic)	25.3
Industrial processes	27.3
Agriculture/nature	1.3
Road transport	16.5
Other transport	29.3

Table 2-8: Sources of SO_2 in Inner London *(Source: Mattai and Hutchinson, 2005)*
NB/ Rounding errors result in total of less than 100%

2.3.9 How London source apportionment compares to other UK urban areas

Compared to other UK urban areas, inner city London could be expected to have a higher density of traffic per square km and as such represent the worst case scenario of the contribution of road traffic to urban emissions. **Table 2-9** shows emissions of NO_x estimated from some other UK emission inventories. It should be noted that the methodologies, groupings and year of estimation for these emissions inventories are not identical and should be considered when interpreting the data.

Emissions inventories were selected from Nottinghamshire (AQA, 2006) and Merseyside (Windel, 2006). The Merseyside emissions inventory was disaggregated into its constituent local authorities allowing three specific LA's to be selected for comparison. These LA's reflect, in general, different land uses. Liverpool is a large urbanised city, Sefton is a more rural coastal area (with some urbanised areas) whilst St Helens is a more industrial area. Nottinghamshire includes all of these land use types.

Source	% of total emissions				
	London	Merseyside LA's			Notts
		Liverpool	St Helens	Sefton	
Energy (Industrial/domestic)	32.9	19.5	76.5	29.0	88.0
Industrial processes	9.9				
Agriculture/nature	0.2				
Road transport	49.9	80.5	23.5	71.0	12.0
Other transport	7.2				
Year of inventory	2002	2004			2004

Table 2-9 : Sources of NO_x in various UK atmospheric emissions inventories

Comparing across **Table 2-9**, it is clear that, regarding the contribution of road transport to total emissions, Inner London should not be considered as the worst case scenario nationally. Clearly there is a large dependence of the relative contribution of each sector on the types of sectors located in an emissions inventory catchment area. Looking in more detail at the sources of NO_x in Inner London Emissions Inventory, this is in fact dominated by the burning of gas (likely from boilers on commercial and domestic properties). This contribution may be so high because of the high population density in London compared to the other areas considered.

2.4 Impacts of the NAQS pollutants on health and the environment

The air quality standards developed by the World Health Organisation (WHO) and the UK EPAQS are based upon mitigating harmful impacts on human health. However, there are further impacts to be had on both the natural and built environment.

2.4.1 Health impacts

The review of health effects of the NAQS pollutants has been drawn from a number of previous reviews undertaken in the area of traffic pollution and health. In nearly all instances the broad effects described for each pollutant are a consensus from these reviews (EPAQS, 1994-2002; McCubbin and Delucchi, 2003; Watkiss *et al.*, 2000a; Hienrich *et al.*, 2005; DEFRA, 2006). Most detail on individual studies can be found in Heinrich *et al.* (2005) and McCubbin and Delucchi (2003).

2.4.1.1 Benzene

Benzene is readily absorbed into the body and has a greater affinity to fatty tissue than with water although most absorbed benzene is passed from the body in urea. (EPAQS, 1994a). High industrial doses have been shown to damage bone marrow and as a consequence prevent blood formation (Duarte-Davidson *et al.*, 2001). The largest concern over benzene exposure is its association with leukaemia. This has so far only been proven in studies on industrial workers who have been exposed to far higher concentrations than would be experienced by a member of the public in an urban city centre (where concentrations are highest). (EPAQS, 1994a; Watkiss *et al.*, 2000a; Duarte-Davidson *et al.*, 2001). At current ambient levels the risk of damage to human health is considered to be low (EPAQS, 1994a; Duarte-Davidson *et al.*, 2001).

2.4.1.2 1,3~Butadiene

Animal studies of the impacts of 1,3~Butadiene have shown it to be a genotoxic substance which reacts with body proteins and causes damage to chromosomes. (EPAQS, 2002). Early exposure type studies on human subjects, undertaken before its cancerous effects were known, have shown it to irritate the eyes, nose and skin (Watkiss *et al.*, 2000a; EPAQS, 2002). Similar to benzene, many of the studies indicating its carcinogenic potential in humans have involved industrial workers who were exposed to far higher concentrations than current UK ambient levels (EPAQS, 2002).

2.4.1.3 CO

CO pollution affects the human body by reducing the oxygen carrying capacity of blood vessels. This occurs as haemoglobin binds with CO rather than oxygen forming carboxyhaemoglobin (EPAQS, 1994c; McCubbin and Delucchi, 2003). The extent of this effect is a function of the ambient concentration and exposure time as well as the depth and frequency of breathing (EPAQS, 1994c). Those most at risk from incidence of relatively high carboxyhaemoglobin are those who already have lower blood flow around the body and are susceptible to this being reduced further. With this in mind, those considered most at risk are people with heart or lung conditions relating to oxygen delivery (EPAQS, 1994c, Watkiss *et al.*, 2000a; McCubbin and Delucchi, 2003). A link between the delivery weight of children and the smoking habit of mothers has been attributed to reduction in the oxygen received by the foetus due to the carboxyhaemoglobin effect (EPAQS, 1994c). Other short term effects include loss of coordination and concentration due to lack of oxygen being transported to the brain (EPAQS, 1994c).

2.4.1.4 Pb

Once absorbed into the body, either through ingestion or inhalation, Pb accumulates throughout the body. It is the small proportion that is not stored in the body but instead circulates in the blood stream which causes harm humans (EPAQS, 1998). The main implication of lead is on the central nervous system particularly in children. The link between lead exposure and IQ levels in children has been proven (EPAQS, 1998; Watkiss *et al.*, 2000a). It has also been associated with lower productivity in later life (McCubbin and Delucchi, 2003). Since the phasing out of leaded petrol, a marked decrease in ambient concentrations have been observed with lead emissions being of little concern considering the main pathway is now through ingestion of food and water (EPAQS, 1998; Watkiss *et al.*, 2000a).

2.4.1.5 NO_2

NO_2 is thought to attack cell membranes and proteins due to its oxidising properties (EPAQS, 1996). Short term exposure is thought to induce inflammation in the lungs, airway and cause eye irritation (EPAQS, 1996; McCubbin and Delucchi, 2003). Long term exposure may cause chronic loss of lung function (EPAQS, 1996). Very high exposures such as those encountered during industrial accidents, has caused severe and, on occasions, fatal lung damage (EPAQS, 1996). At concentration levels well above those experienced in ambient healthy people show very little reaction to the inhalation of NO_2. However, those who are predisposed to asthma have shown some sensitivity (EPAQS, 1996). The inhalation of NO_2 is thought to inflame the lungs and as a consequence leave the individual more prone to reactions when in the presence of common allergens such pollen or dust mite droppings. Again, these sorts of reactions have been shown at NO_2 concentrations above the ambient norm (EPAQS, 1996). It is possible that if this effect is repeated frequently it may leave the individual more susceptible to respiratory infections (EPAQS, 1996).

Epidemiological studies have often shown negative health effects at concentration levels closer to those experienced in raised ambient pollution episodes (EPAQS, 1996; Watkiss *et al.*, 2000a; McCubbin and Delucchi, 2003) although there are some doubts over the role of other pollutants in this observed effect (Watkiss *et al.*, 2000a; McCubbin and Delucchi, 2003).

Studies examining longer term exposure to NO_2 are conflicting in their conclusions. From indoor studies considering homes with and without gas appliances (where concentrations of NO_2 tend to be lower and higher than the outdoor ambient respectively) there is some evidence to suggest that the health of children may suffer (EPAQS, 1996). Whilst there seems to be no conclusive proof that NO_2 has a long term exposure impact, it can not be discounted. NO_2 is not thought to be carcinogenic on its own but it is possible that they form known carcinogenic compounds if they react with other compounds. This risk is considered to be small (EPAQS, 1996).

2.4.1.6 O_3

Similar to NO_2, O_3 has oxidizing properties although its impact as a short term irritant at normal ambient concentrations would seem less adverse (EPAQS, 1994b). Short term exposure has been linked with irritation of the airway and lungs (whilst exposure to elevated concentration in the longer term has been associated with the development of immunity to its short term effects (EPAQS, 1994b). Some epidemiological studies have shown increased hospital admissions and mortality during episodes of elevated O_3 concentrations (EPAQS, 1994b, Watkiss *et al.*, 2000a; McCubbin and Delucchi, 2003). It is possible this lower than expected susceptibility in the long term, lies in the natural use of the body of oxygen free radicals associated with O_3 to combat infectious bacteria, with the damage caused to cells reduced by the production anti-oxidants. This action also causes localised damage to cells but only at levels above the normal ambient concentrations (EPAQS, 1994b).

2.4.1.7 Particulates

When the original NAQS standard was set it was based upon an EPAQS report. The report states that the only studies on the link between health and particulate concentration levels were based upon epidemiological studies regarding hospital admissions and death rates during episodes of high particulate concentrations (EPAQS, 1995). Strong correlations were shown during the high pollution episodes in 1950's London although the concentrations experienced today are far lower (EPAQS, 1995). On the whole, the review identified that episodes of *high* particulate levels are associated with bring forward deaths of people already suffering from heart or lung disease (EPAQS, 1995). However, later evidence suggests that *any level* of particulates has an impact in terms of bringing forward deaths, or exacerbating existing lung, heart or asthmatic conditions (EPAQS, 1995; Watkiss *et al.*, 2000a; McCubbin and Delucchi, 2003). A potential link with increased risk of development of lung cancer has also been suggested although some confounding factors such as smoking, occupational exposure or exposure to other pollutants may have a greater influence on this link (EPAQS, 1995; Watkiss *et al.*, 2000a). Studies on lab animals exposed to diesel exhaust (the main source of urban particulates) showed an increased incidence of lung cancers (Watkiss *et al.*, 2000a).

Since the EPAQS report was produced there has been a growing research effort into the effect of particulates with attention shifting to the smaller $PM_{2.5}$ (McCubbin and Delucchi, 2003). Bremner *et al.* (1999) indicated that levels of $PM_{2.5}$ did relate to increased mortality but that similar behaviour was also seen with PM_{10} and that $PM_{2.5}$ levels were closely correlated.

2.4.1.8 PAH

Some species of PAH's are known carcinogens and are associated with elevated risk of developing tumours in the lungs and skin, with some relationship with bladder cancer also indicated (EPAQS, 1999; Watkiss *et al.*, 2000a). PAHs are absorbed into the lungs either in gaseous form or adsorbed on particles (particles from diesel vehicles are of particular concern) (EPAQS, 1999; Watkiss *et al.*, 2000a). Once absorbed into the body, the PAHs can be transformed into chemicals which alter the DNA of cells although the body has some systems to mitigate this threat (EPAQS, 1999). It is thought that long term exposure is more of a threat than short term exposure since carcinogenic effects have a greater association with those with long term exposure (EPAQS, 1999).

2.4.1.9 SO_2

SO_2 is thought to have short term effects on lung capacity by causing a narrowing of the airways. It is also an irritant of the eyes, nose and airway when encountered at high concentrations (EPAQS, 1995). In healthy individuals this effect is thought to be insignificant at normal ambient concentrations and much higher concentrations are required to produce a noticeable reaction. However, asthmatics have been shown to show symptoms of this effect at much lower concentrations (EPAQS, 1995). The mechanism for this is thought to be a reduction in the airways of those who already have smaller than average airways (EPAQS, 1995). Together with NO_2, it is thought to increase the sensitivity of asthmatics to allergens (EPAQS, 1995). There is little evidence for negative health impact due to long term exposure. Most studies which have shown SO_2 as having negative health effects have had issues with it acting as an indicator for particulate pollution rather than being responsible for the observed effect (EPAQS, 1995; Watkiss *et al.*, 2000a; McCubbin and Delucchi, 2003).

2.4.2 Ecological impacts

Air pollutants also impact upon natural environment and this has wider implications than the loss of important habitats and ecosystems. Crop yields have been shown to be significantly affected by levels of ozone (formed primarily from NO_x and VOC).

As a member of the UNECE group of nations, the UK has obligations to maintain emissions of NO_x and SO_2 below an annual mean value. These limits were not set to protect human health but for the protection of the natural environment. NO_x and SO_2 are acids and when these acids are deposited on the Earth's surface, either as acid precipitation (as a solution in rain) or acid deposition (as a dry gas or salt), they can have negative impacts on soils, vegetation and freshwater (Manahan, 2000).

The impact of the influx of acid on soils (and so the wider environment) is controlled by a soil's cation exchange capacity (CEC) (Manahan, 2000). Put simply, the CEC is the ability of a soil to hold cations which neutralise the acidifying effect of pollutants such as NO_x and SO_2. This neutralising effect acts as a buffer against the effects of adding acids to the soil although this buffer will be depleted if the rate of replenishment does not match that of use. This means that some soils are more susceptible to acidification than others based on the clay and humus (organic matter) content. If the buffering effect is depleted then the increased acidity of the soil can have a direct impact on soil micro-organisms, as well as indirect effects through the release of toxic substances such as aluminium. These toxic substances can then in turn disrupt vegetation growth, or be washed into freshwater systems. Acidification of freshwater systems, from run off through acidified soils, directly leads to loss of aquatic life at all levels of the food chain due their intolerance of increasing water acidity. Vegetation can be directly affected by loss of leaf or needles coverage (NEGTAP, 2001).

As the influence of SO_2 on acidification declines to a significant reduction in its emission the impact of NO_x on both acidification and eutrophication has started to be understood. In land and sea ecosystems (and some freshwater) a lack of nitrogen is the major limiting factor in productivity. Where deposition of NO_x takes place a reduction in terrestrial vegetation diversity or freshwater eutrophication can occur (NEGTAP, 2001).

Perhaps more of an economically measurable impact is that of O_3 on crop yields. When a plant absorbs O_3 via its stomata it produces by-products which reduce the efficiency of the plant's photosynthesis (Murphy *et al.*, 1999). The impact varies amongst crop species and Watkiss *et al.* (2006) includes a list of how various crops are affected. Barley, oats, rye, and olives show no reaction to O_3 concentration, whilst wheat, pulses and cotton show the greatest yield reductions.

2.4.3 Impacts on the built environment

The built environment is also subjected to damage as a result of air pollutants. The most valuable buildings and monuments are often situated in the urban areas where pollutants levels are highest. Whilst deterioration of building materials would occur regardless of the presence of air pollutants due to precipitation, freeze/thaw and sea salt, the deterioration rates are a factor of 10 to 100 less (Watkiss *et al.*, 2000b) than those resulting from the presence of pollutants.

SO_2 and NO_x are associated with corrosion of natural stone and zinc, whilst O_3 is known to have an influence on the lifetime of rubber products and paints. (Watkiss *et al.*, 2006). The method of deposition is an important factor on the level of degradation exerted by a pollutant with dry deposition being more harmful than wet deposition.

Soiling of buildings, statues, etc. is probably the most noticeable impact of air pollutants on the built environment. This is mostly caused by primary combustion particulates with diesel derived particulates being the most damaging due to their high elemental carbon content (Watkiss *et al.*, 2006).

2.5 Relationship between local air quality and climate change

Often actions aimed at mitigating concentrations of NAQS pollutants at the local scale have been taken in isolation of the impact such a change will have on the release of greenhouse gases. However, as climate change has moved up the public and political agenda the impact of measures to reduce one can have both positive or negative impacts on the other. For example, the use of catalytic converters in petrol cars, to reduce toxic emissions, requires a certain air/fuel ratio to operate efficiently. Maintaining this air/fuel ratio results in the fuel combustion not being as efficient as it could potentially be; this results in higher CO_2 emissions per mile. The conversion reactions also result in extra CO_2, as does the extra power required from the engine to provide electricity for the converter to operate. The latest NAQS considers the synergy between policy measures to reduce emissions of toxic pollutants and reduce emissions of greenhouse gases (DEFRA, 2006a). It concludes that in the short term there will be some situations where a trade off is necessary (e.g. new EURO V standards for petrol vehicles) but others where the two objectives will compliment each other (e.g. introduction of cleaner diesel vehicles). In the long term the two objectives are envisaged to be in synergy (e.g. hybrid and fuel cell vehicles).

More detailed discussion on how the two issues interact in terms of physical and chemical reactions can be found in a draft by the DEFRA supported UK Air Quality Group (AQEG, 2005). The AQEG report also examines various sector based policies on the objective of reducing greenhouse gases and local toxic emissions. A summary of how these policy/technical measures would impact on each issue in terms of win or loss are presented in **Table 2-10**.

Measure	Local AQ	Climate change	Comments
Reducing fuel sulphur content and refinery emissions	Win	Win	If reduced sulphur enables use of more fuel efficient technologies such as lean burn petrol engines.
Control of petrol and diesel emissions	Win	Win	For petrol vehicles using lean burn technology.
	Win	Lose	For diesel vehicles with four way catalytic converters.
	Win	Win	Use of SCR on heavy duty vehicles.
	Win	Lose	Retrofitting of HGV's and buses with PM reducing technology results in 1% increase in CO_2.
Water-diesel emulsion	Win/ Lose	Win	Lower PM and NO_x but higher VOC.
Hybrid vehicles	Win	Win	Especially in urban driving.
Increased penetration of diesel over petrol	Lose	Win	The climate change benefit may be small due to increased emissions of black carbon.
Use of biofuels	Lose	Win	Emissions of certain pollutants may increase. Impact on CO_2 varies depending on methodology used in study.
Use of hydrogen	Win	Win	This may be a small climate change benefit depending on source of hydrogen. Leakage would have to be controlled as H is a greenhouse gas.
Congestion charging	Win	Win	Based on London example
Low Emissions Zones (LEZ)	Win	Win	Produce short term improvements in some AQ pollutants but little reduction in CO_2.
Urban planning	Win	Win	Based upon measures to increase urban density (prevent sprawl) and encouraging soft modes.
Modal shift	Win	Win	Encouraging shift to modes with lower emissions /passenger km
Reduced vehicle weight	Win	Win	
Reduced emissions standards	Win	Lose	Was applied to LDV's and HGV's
Car scrappage incentives	Win	Win	But would have to ensure savings over vehicle's lifetime out weighed the CO_2 emitted during its production.
Low Emission Vehicle (LEV) incentive	Win	Win	

Table 2-10: Summary of outcomes showing the potential synergy between measures to reduce emissions from road traffic considered by AQEG (*Source: AQEG, 2005*)

2.6 Summary and conclusions

The UK NAQS addresses the issue of air quality through a range of tools. Part of this suite of tools is the development of air quality standards which have been developed with the mitigation of the harmful effects of various pollutants on humans in mind. These standards, covering nine pollutants, are reviewed and monitored by LAs who have the responsibility to develop remedial action plans in the event that the standards were not achieved. In September 2006, 192 LAs had declared AQMAs mainly due to excessive levels of NO_x or PM_{10} with road transport nearly always being identified as the source of the air quality problem.

Nationally, road transport is the biggest contributor to nearly all of the nine of the NAQS pollutants with its contribution being even higher in urban areas. Whilst total emissions have continued to fall, the increase in road traffic and speciation of some of the pollutants has resulted in many urban areas still experiencing problems. Whilst the NAQS pollutants have the potential to cause harm to all humans, at the levels experienced in UK AQMAs, the main effect will be on those who have existing cardiovascular complaints, although some of the NAQS pollutants are known carcinogens of which only a small quantity could cause serious harm to the human body. In addition, there are also consequences for the built and natural environment such as building material degradation and reduced crop yields respectively.

Air quality standards are addressing a social inequality. It is apparent, from the review on the health impacts which have driven the NAQS standards, that it is the most vulnerable people in society which are most at risk. This is because they may have a predisposition to the impact of a particular pollutant. It could be argued that a substantial amount of time and money is being spent on resolving an issue which affects only a minority of people in society when road transport is for the greater good. However, on the basis of a fair and inclusive society it is right that the standards should be set to protect those who most need it.

Maintaining current road transport emissions levels and significant reductions in the future will be reliant on vehicle technology. Reductions in emissions from the road transport sector have been largely reliant on technological improvements in vehicle emissions control technology not due to decreases in total vehicle mileage. This raises a need for the on-board vehicle emissions controlled technologies to be maintained and tools to monitor the performance of such technologies to be developed. This requires an effective inspection and maintenance programme.

The potential solutions to transport derived air quality problems can have a complementary or incompatible relationship with the issue of climate change. There are a number of solutions which would appear to have a win-win result and perhaps it is these policies which should be prioritised in future policy development. This is an area which has received too little consideration in the past. It can be argued that one 'threat' (i.e. climate change or air quality) should take priority over the other, but the conflicting temporal and spatial scale of the impacts do not make policy decisions on which issue should be prioritised an easy one. What use is saving the planet for future generations to the ill person in the street who dies the next day because they have been exposed to poor air quality?

To attain specified air quality targets, emissions from road transport should be reduced as much as possible. Whilst meteorological and topographical factors can have a significant influence on air quality concentrations leading to an exceedance of the specified limits, the only control humans can have on this effect is to reduce emissions. When emissions can be minimised, they should be.

3 SOURCES OF POLLUTANT EMISSIONS FROM LIGHT DUTY VEHICLES

3.1 Introduction

In recent decades, nearly all light duty vehicles were powered by either petrol or diesel engines. Other fuel sources such as Liquid Petroleum Gas (LPG), battery power/electricity or biofuels are currently enjoying an increasing market share although their prevalence compared to petrol or diesel vehicles is still very modest. Hence, it is the emissions from petrol and diesel vehicles, and their causes and means of mitigating such emissions, which have received most attention. This chapter describes the fundamental sources of pollutant emissions in internal combustion engines and current methods to mitigate such emissions.

3.2 The basics of petrol and diesel engines

A contemporary vehicle engine has three key demands placed on it, namely performance, exhaust emissions and fuel consumption (which relates closely to CO_2 emissions). The requirement to optimise all three of these demands has increased over recent decades as consumer and legislative trends have called for improvements in all three areas. Achieving the necessary improvements in these three areas often leads to a conflict in the parameters controlling engine operation. To maintain a suitable balance between the above three demands, precise engine control through the use of computerised engine management systems has become essential. To understand the techniques employed to reduce fuel consumption and pollutant emissions of both petrol and diesel vehicles it is necessary to explain the basic operating principles used for both engine types.

An introduction to the principles covered in this chapter can be found in Bauer *et al.* (2004a and 2004b) whilst a detailed description of the processes is given by Heywood (1988) and a more detailed illustration of the thermodynamic processes involved is given in Stone (1999), additional background information was gained from the concise explanations given by Weaving (1990). Due to repetitive duplication of references to the above sources, these references are not given in the text below whilst occasionally specific references are included.

3.2.1 The four stroke cycle

Both the Spark Ignition (SI) engine and the Compression Ignition (CI) engine found in today's vehicles operate following a four stroke cycle. The nature of the fuel means that different ignition methods are used. In both SI and CI engines, combustion of a mixture of air and fuel (A/F) moves a piston within a combustion cylinder in a reciprocating manner. The piston movement is transformed into rotational movement using a 'conrod' attached at one end to the piston and the other to the crankshaft. Nearly all modern vehicle engines operate on a four stroke cycle (i.e. there are four directional movements for one complete cycle). The crankshaft goes through two complete rotations for every complete cycle.

3.2.1.1 The spark ignition engine four stroke cycle

Figure 3-1 illustrates the components and stages involved in operation of an SI engine.

a) **The induction stroke** – Here the piston is moving from the Top Dead Centre (TDC) position down to the Bottom Dead Centre (BDC) position. As it does so it draws in fresh air or an A/F mixture, depending on the fuel injection system employed, through an open intake valve. The amount of air drawn in is regulated by a throttle valve. The timing of the opening of the intake valve can be controlled by a number of mechanisms but in the example in **Figure 3-1** it is controlled by a rotating camshaft.

b) **The compression stroke** – The piston begins to move upwards compressing the fresh air or A/F mixture. If fuel has not already been added to the cylinder, as is the case in direct injection SI engines, it is added during this stage. The intake and exhaust valves both remain closed through the duration of this stroke.

c) **The power stroke** – Just as the piston reaches TDC, the spark plug ignites the A/F mixture. The time at which the ignition is applied varies depending on the requirement placed on the engine. The intake valve and exhaust valves both continue to be shut during this time. Combustion of the A/F mixture produces heat which forces the gas in the enclosed cylinder space to expand forcing the piston downward again.

d) **The exhaust stroke** – Here the exhaust valve is opened just before the piston reaches BDC of the power stroke. This allows the high pressure gases remaining after combustion to leave the cylinder. Remaining exhaust gases are pushed out as the piston moves up the cylinder

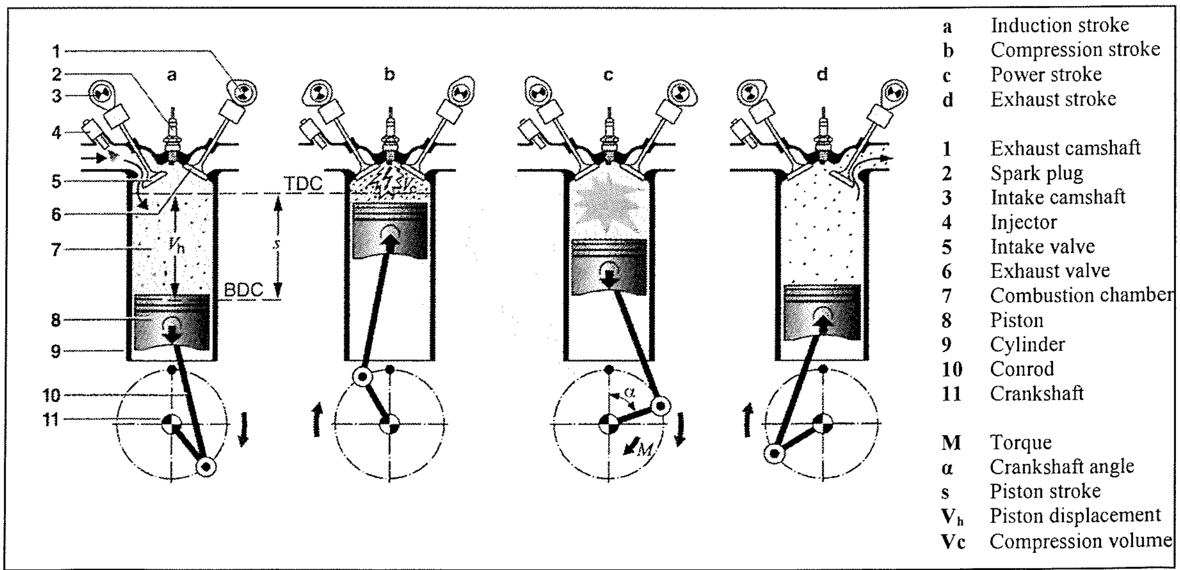


Figure 3-1: Four stroke cycle of a petrol SI engine *(Source: Bauer, 2004a)*

3.2.1.2 The compression ignition engine four stroke cycle

Figure 3-2 illustrates the components and stages involved in the operation of a CI engine.

a) **The induction stroke** – Here the piston is moving from the Top Dead Centre (TDC) position down to the Bottom Dead Centre (BDC) position. As it does so, it draws in air through the open intake valve. In comparison to the SI engine, the CI engine does not regulate the amount of air drawn but instead, regardless of the operating mode, the same volume of air is drawn for every induction stroke. The timing of the opening of the intake valve can be controlled by a number of mechanisms but in the example in **Figure 3-2** it is controlled by a rotating camshaft.

b) **The compression stroke** – The piston begins to move upwards compressing the air. The compression leads to a rise in the temperature of the air (see **Figure 3-3**). Just prior to completion of the compression stroke, fuel is injected at very high pressures (causing it to atomise producing an A/F mixture) into the now hot, compressed air. The intake and exhaust valves both remain closed through the duration of this stroke.

c) **The ignition stroke** – This stage produces the engines power. After short time lag past TDC, the fuel spontaneously ignites due to the heat in the compressed air. The intake valve and exhaust valves both continue to be shut during this time. Combustion of the A/F mixture produces even more heat which forces the gas in the enclosed cylinder space to expand forcing the piston downward again. The amount of energy produced during this stroke depends upon the amount of fuel injected.

d) **The exhaust stroke** – Here the exhaust valve is opened just before the piston reaches BDC the power stroke. This allows the high pressure gases remaining after combustion to leave the cylinder. Remaining exhaust gases are pushed out as the piston moves up the cylinder towards the second TDC position of the cycle. The cycle then begins again. As the exhaust stroke gives way to the induction stroke both the intake and exhaust valves are opened for a short time to cool any exhaust gases remaining in the cylinder.

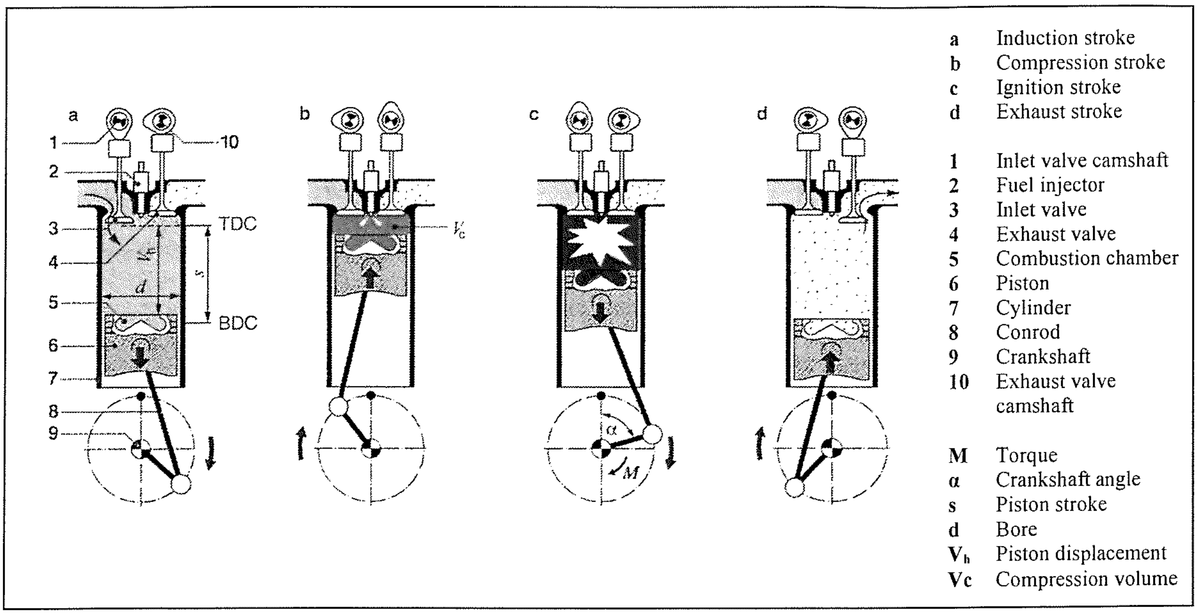


Figure 3-2: Four stroke cycle of a diesel CI engine *(Source: Bauer, 2004b)*

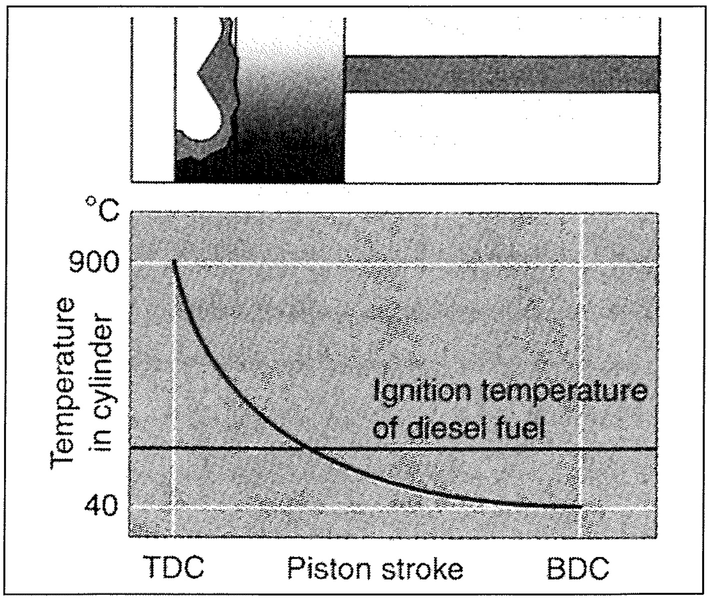


Figure 3-3: Rise in temperature with increased compression by piston during compression stroke *(Source: Bauer, 2004b)*

In general, diesel vehicles produce more useful work per unit energy in the fuel burnt (30-45%) when compared to petrol vehicles (~13%) (Bauer *et al.*, 2004a and 2004b). Indirect injection delivers precisely metered amounts of diesel into the precombustion 'swirl chamber' (a chamber where the air is agitated to encourage even mixing of the atomised fuel). Alternatively, direct injection systems which, as shown in **Figure 3-2**, deliver the fuel directly into the cylinder are used. Direct injection reduces fuel consumption by up to 20% compared to indirect injection. The precise controls required for direct injection represents an advance in diesel combustion technology and as such is expensive compared to indirect injection systems. Direct injection CI engine combustion undergoes four phases within the combustion cycle.

Delay phase – A delay is experienced in between the start of the fuel injection and the beginning of combustion as the pressure and temperature in the cylinder rise to a level great enough for auto ignition.

Premixed combustion – After the delay period, a certain amount of the injected fuel (at the outer extremes of the jet of fuel injected) has already become mixed with the air and reached sufficient conditions for rapid combustion to take place. This rapid burning results in very high temperatures, which together with presence of oxygen is important in the formation of NO_x (see **Section 3.3.2.3**). This phase sees immediate rises in both temperature and pressure within the combustion cylinder. Injection of the fuel is still occurring at this time.

Mixing controlled combustion – As fuel continues to be injected the distribution of the fuel in the cylinder is much more uniform due to thermal effects of the pre-mixed combustion. The temperatures produced by this burning phase are less than those in the pre-mixed phase although this stage lasts longer.

Late combustion – Injection of fuel has stopped at this point. However, combustion continues in the ignition stroke as any remaining fuel, some soot and fuel rich secondary HC are burnt. The temperatures and pressure in the chamber begin to fall.

In practical terms, the same phases described above are followed by indirect injection diesel CI engines. However, instead of occurring within the combustion chamber, the delay and premixed combustion phases occur within the swirl chamber next to the main combustion cylinder. The swirl chamber has heated gas forced into it in a swirling manner from the main combustion cylinder during the compression stroke. The swirling action encourages mixing of the fuel as it is injected; this is not required in direct injection CI engines since the injection pressures and shaped piston heads encourages adequate dispersion of the fuel. Additional heat is provided to the injected fuel using a glow plug (heated element). As the premixed phase is reached in the swirl chamber, the rise in heat (and pressure) forces the partially burnt A/F mixture to be ejected at high speeds back into the main combustion cylinder where the mixing controlled phase begins, etc.

A number of factors such as compression ratios, valve timing, A/F ratio and mixture type, and injection system are all important factors when considering the engine outputs such as power and torque output, fuel consumption and emission of pollutants. Altering these factors can have beneficial and negative effects on the engine outputs, however there are limits to how far each of the factors can be altered. This section will now concentrate on discussing some of the fundamental factors particularly relevant to fuel consumption and pollutant emissions.

3.2.2 Air/fuel ratio (λ)

For complete combustion of the A/F mixture, a particular mixture ratio must be maintained. This mixture is referred to as the stoichiometric ratio. The stoichiometric ratio for petrol is approximately 14.7kg air to 1kg fuel giving an A/F ratio of 14.7:1; for diesel vehicles the stoichiometric ratio is 14.5kg air to 1kg fuel leading to an A/F ratio of 14.5:1. λ is used to measure the extent to which the A/F ratio varies from stoichiometric (which has a λ value equal to 1.0). Since the stoichiometric values for both diesel and petrol vehicles are so similar it is possible to use one single version of λ to compare the A/F ratios between both types of fuels.

Rich A/F mixtures have $\lambda<1$ whilst lean A/F mixtures have $\lambda>1$. Knowledge of the λ properties of A/F mixture in the cylinder of petrol SI and diesel CI engines is crucial to the control of pollutant emissions and trade offs with fuel consumption.

How engine-out emissions and power from a petrol SI engine vary with changes in the A/F mixture from the ideal $\lambda=1$ is shown in **Figure 3-4**. Originally the formation of the A/F mixture in a SI engine was controlled by a carburettor which added the fuel to the air by vaporisation. Significant progress in controlling the A/F mixture was made with the development of manifold injection systems where precisely metered amounts of fuel are injected directly into the intake manifold. Manifold injection results in a homogenous A/F mixture (a mixture where the fuel is evenly dispersed as a vapour in the air) being drawn into the whole combustion cylinder. A more recent development is the use of direct injection which sprays the A/F mixture directly into the cylinder. The advantage of direct injection is that, when power demand on the engine is relatively low, it can form a small stoichiometric A/F mixture cloud only around the sparkplug leading to lower fuel consumption and very precise metering of the fuel used by each cylinder. However, since the rest of the chamber is filled with air and inert gas, the overall A/F mixture is lean – this has implications for the after treatment of the exhaust (See **Section 3.4.1.2**). In instances where the engines full power is required (i.e. the accelerator is fully depressed) direct injection systems can create a homogenous A/F mixture throughout the whole cylinder by injecting during the induction stroke.

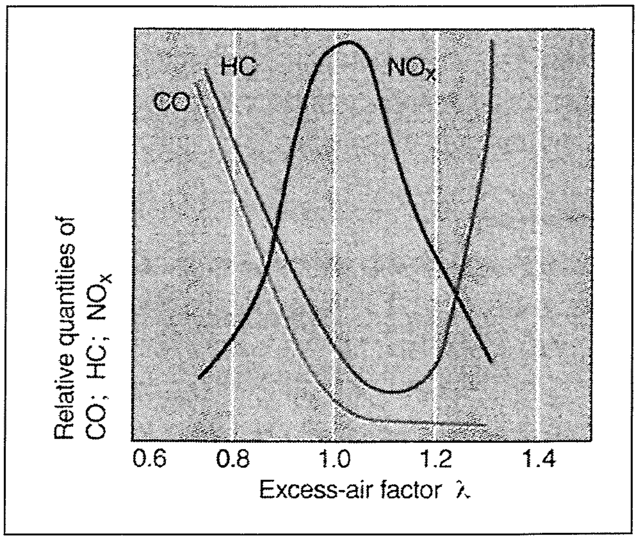


Figure 3-4: Variation of CO, HC and NO_x due to changes in the A/F ratio or λ
(Source: Bauer, 2004a)

Due to the fact diesel does not readily vaporise like petrol, the fuel is instead finely atomised, from which fuel evaporates from the droplets to create the A/F mixture. The nature of diesel fuel means that it is impossible to produce a completely homogenous A/F mixture prior to or during combustion. This means that heterogeneous (made up of different parts) A/F mixtures are combusted. This heterogeneous A/F mixture means that there are a wide range of localised λ values are observed from λ=0 (pure fuel) near the injector nozzle to λ= ∞ (pure air) at the outer extremes of spray. Rich areas of the A/F mixture cause 'sooty' emissions and so to prevent too many of these rich areas, diesel engines must always use an excess of air. There are even more localised λ variations around a single droplet. How the localised λ varies around a single diesel droplet and also how the speed of the perturbed air in the cylinder affects the flame zone is shown in **Figure 3-5.** The ideal situation, therefore, is finely atomised droplets and 'moderate' air flow thus creating many areas of lean combustion; this produces less soot and lowers NO_x. Fine atomisation is produced by injecting the fuel at very high pressures whilst the correct air flow profile is produced through a combination of shaping the top of the piston and increasing the air pressure drawn during the induction stroke (supercharging).

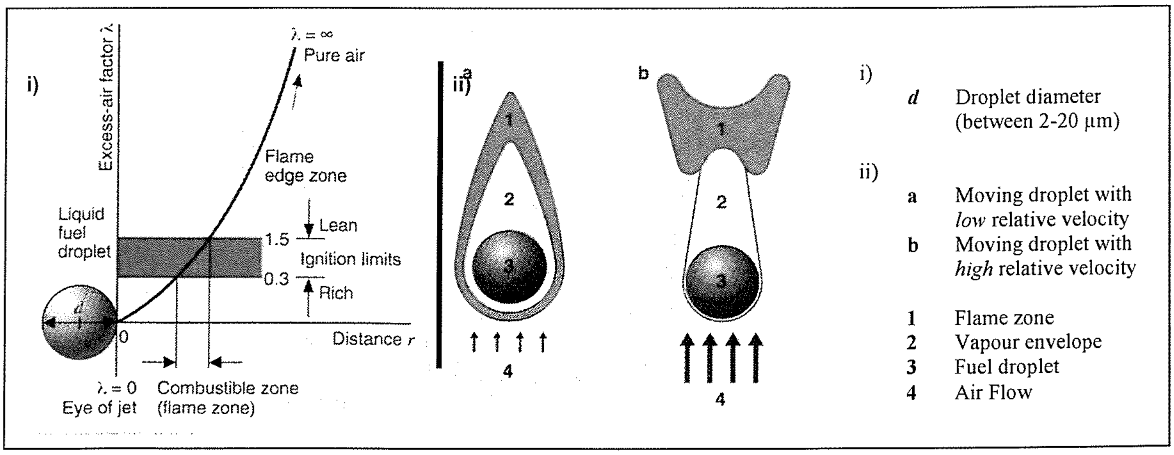


Figure 3-5: Localised variations in λ around a diesel fuel droplet, i) Variation in λ with distance from edge of fuel droplet and ii) pattern of flame and fuel vapour envelope around a droplet in moving air *(Source: adapted from Bauer, 2004b)*

Localised variations in λ occur within both SI and CI cylinders and mixtures, hence λ can be used to refer to the average A/F ratio of a mixture but also the localised variations in one 'charge' of fuel.

3.3 Combustion and exhaust gas emissions

In general, the problematic emissions from petrol SI engines differ from those related diesel CI engines. In addition, large variations in engine-out emissions occur within a single vehicle depending on the demands placed on it. To meet increasingly stringent legislative limits on pollutant emissions, vehicle designers use a variety of techniques of engine management and after engine exhaust treatment. This section deals with the formation of exhaust emissions from both petrol and diesel vehicles together allowing a comparison of the relative merits of each fuel/engine type. **Section 3.4** deal with the two fuel/engine types individually, examining how engine management and exhaust after treatment can be applied to each.

3.3.1 Emission sources

There are four sources of engine related emissions in a modern light duty vehicle. Firstly, the imperfect combustion of the A/F mixture leads to toxic components within the engines exhaust gas. As the combustion process becomes less efficient, the formation of the secondary exhaust products increases. Secondly, crankcase (the housing around the crankshaft) ventilation occurs when the exhaust gases move from the cylinder chamber down the cylinder walls, past the piston ring (a seal between the piston and cylinder) and into the crankcase. To prevent their direct release into the environment closed crankcase ventilation systems, which return the crankcase exhaust back to the intake manifold, are now mandatory for both petrol and diesel engines. Thirdly, evaporative emissions from the vehicles fuel tank which can occur regardless of whether the vehicle is in use or not. Evaporative emissions are only a real concern for petrol as diesel has only an extremely low content of highly volatile (meaning they evaporate readily) constituents when compared to petrol. New petrol vehicles have systems to capture these emissions and return them to the fuel tank. Finally, the wear on vehicle components including tyres and brakes result in particulate matter (Abu-Allaban *et al.*, 2003).

3.3.2 Exhaust gas constituents

The ideal combustion of a pure fuel with the sufficient amount of oxygen should only produce H_2O and CO_2 – this is represented by **Equation 3-1**. It should be noted that **Equation 3-1** is an extremely simplified version of the fuel oxidation (combustion) process. Even combustion of a simple HC molecule in fuel such as propane (C_3H_8) undergoes approximately 100 reactions and produces 30 separate species of secondary compounds (Stone, 1999).

$$n_1\, C_xH_y + m_1\, O_2 \rightarrow n_2\, H_2O + m_2\, CO_2 \qquad \textbf{(Eq 3-1)}$$

In reality this perfect combustion never occurs because, despite precisely metered engine management, the quantity of oxygen available varies. Together with the fuel composition, this leads to the production of toxic by-products (at least when present in sufficiently high concentrations). The composition of engine-out petrol and diesel emissions are given in **Figure 3-6**. It should be noted that direct comparisons are not possible between petrol and diesel using these charts as petrol figures are by volume and diesel figures are by weight.

As can be seen in **Figure 3-6** there are four major components of exhaust:

Water (H_2O) – The water chemically bound in the fuel is turned into water vapour during combustion. This water condenses as the exhaust gas cools. On cold days the plume which can be seen from a vehicles exhaust is the water vapour in the exhaust gas. The proportion of water present will vary significantly in diesel exhaust gases depending upon the operating mode required of the engine since stoichiometric conditions are not always maintained.

Carbon Dioxide (CO_2) – During ideal combustion, the carbon fraction of the hydrocarbon fuel bonds with the oxygen in the air creating CO_2. Fuel consumption and CO_2 are directly linked. This relationship is the cause of an increasing amount of research into producing more fuel efficient engines, both petrol and diesel, as well as exploring the possibility of 'carbon neutral' biofuels. Again, CO_2 content of diesel engine exhaust varies depending on the operating mode required of the engine.

Nitrogen (N_2) – Nitrogen is not directly involved in the combustion process but is included in the exhaust gases as it is the major constituent of the air drawn by the vehicle. Its presence does allow formation of NO_x. More detail on the formation of NO_x is given in **Section 3.3.2.3**.

Oxygen (O_2) – During stoichiometric combustion all the oxygen in the air drawn by the engine is combusted. Since this is the ideal for petrol SI engines there is very little oxygen in the exhaust, **Figure 3-6** shows that this is also true for diesel engines when $\lambda = 1$. However, since diesel engines nearly always operate with excess air there is oxygen left in the exhaust.

Of the by-products of combustion there are four which are of particular significance and more detailed discussion of their formation is given below.

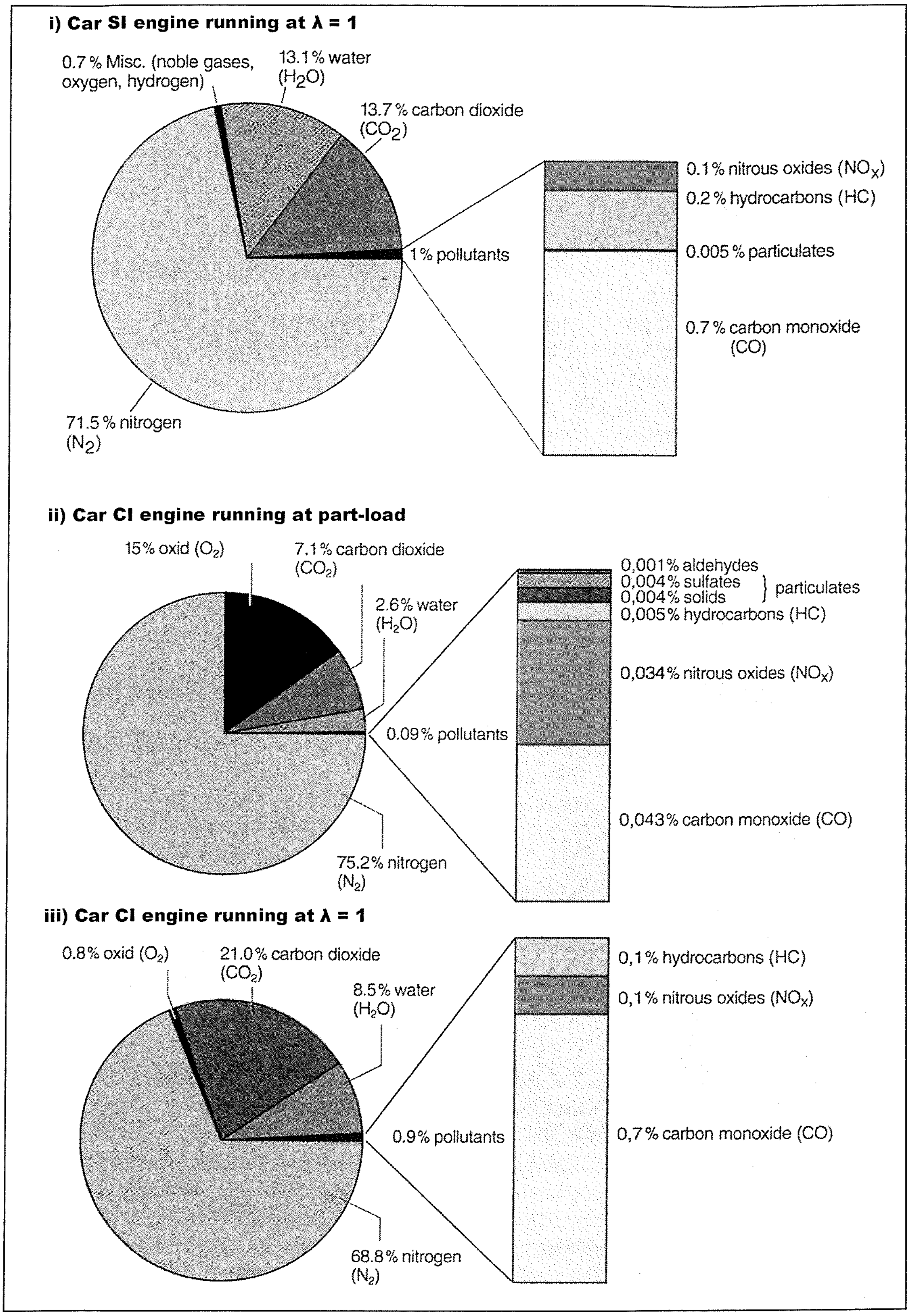


Figure 3-6: Composition of engine out emissions from i) a petrol SI engine operating at λ=1 *n.b. figures in % by volume*, ii) a diesel CI engine operating at part load with average λ>1 *n.b. figures in % by weight*, and iii) a diesel CI engine operating with average λ=1 *n.b. figures in % by weight* (*Source: i)Bauer, 2004a, ii & iii)Bauer 2004b*)

3.3.2.1 Carbon monoxide

CO is formed when there is a deficiency in oxygen ($\lambda < 1$) available to the combustion process. If sufficient oxygen were present then the carbon would instead associate itself with an oxygen molecule (O_2) and form CO_2. When there is a shortage of oxygen the carbon atoms instead 'fight' to associate with any sort of atomic oxygen, hence CO. Extremely small concentrations of CO are also formed during lean combustion conditions (i.e. even with an excess of air) due to disassociation (i.e. CO_2 separates to form CO and O), brief excursions in the A/F mixture from stoichiometric or small inconsistencies in the fuel mixture where rich conditions are present (i.e. a droplet of fuel which does not disperse correctly). It should also be remembered that virtually all vehicle engines have more than one cylinder and each cylinder is primed with the correct operating conditions for a precise moment in time. Thus inter-cylinder variations can also be important when considering levels of engine out exhaust pollutants. An example of this is given in Stone (1999) who use estimated CO values based on idealised stoichiometric combustion equations:

> *'This can be illustrated by a simple example, a two cylinder engine operating with an overall stoichiometric mixture:*
>
> *case (a)* *both cylinders stoichiometric, then exhaust will contain about 0.84% CO*
>
> *case (b)* *each cylinder operating 5% away from stoichiometric (one lean, one rich), then exhaust will contain about ([1.90 +0.22]/2) = 1.06% CO,...'*

CO emissions are also reduced when the flame temperature of the combustion is raised. Since the A/F mixture is so crucial in the level of engine-out CO, it is only of real concern for SI engines since CI engines always operate with an excess of air (e.g. CI engine CO accounts for ~ 0.1% volume of engine out exhaust gas where as in an SI engine with a rich mixture this can be up to 5% - see **Figure 3-7**).

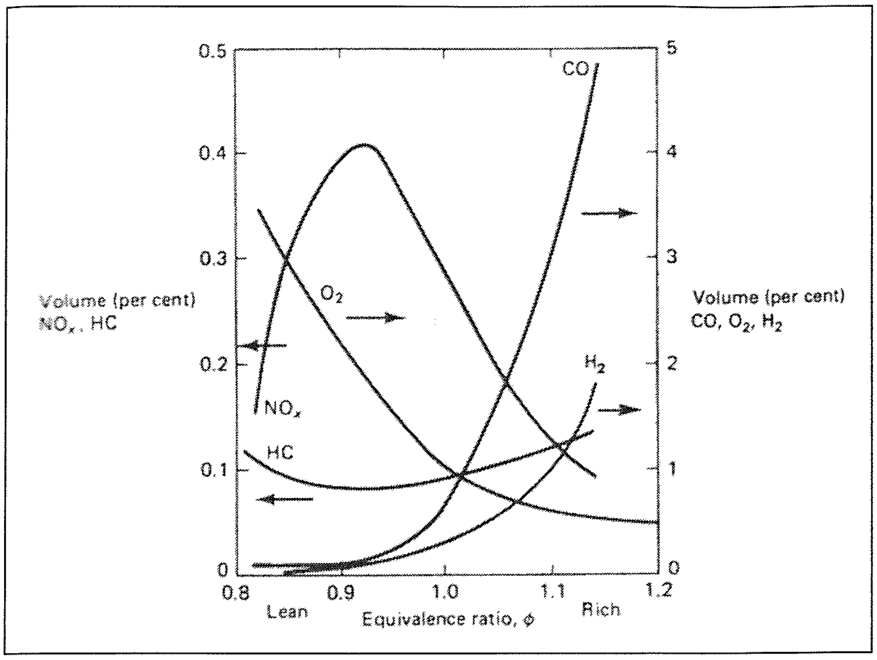


Figure 3-7: Variation in engine out emissions from a petrol SI engine with changing A/F ratio – n.b. bottom scale is based on 'equivalence ratio' which is an alternative measure of A/F ratio in which the lean and rich sides of stoichiometry are inverted. (*Source: Stone, 1999*)

3.3.2.2 Hydrocarbons

HC is a collective term for a large number of compounds in which hydrogen (H) and carbon (C) is combined. HC emissions are derived from incomplete combustion and both primary and secondary hydrocarbons are present in engine-out exhaust. Primary hydrocarbons are those which exist in the fuel in the first instance where as secondary hydrocarbons are formed by separation or joining of the primary HC molecule chains, joining of newly separated chains, etc. Hydrocarbons are caused by there being an insufficient amount of oxygen for complete combustion and their concentrations fall as the A/F mixture become leaner, although if the A/F mixture becomes too lean, the ease with which it combusts is reduced leading to an increase in HC again.

The HC is not fully combusted in specific places within the cylinder where the fuel is not exposed to the flame front of the combusting fuel. The formation locations of HC (together with CO and NO_x) within the cylinder of petrol SI engines are shown in **Figure 3-8**.

Explanation of the specific effects of the 'quench layer', oil film and crevices are given below:

Quench layer – The quench layer is caused by the flame front being extinguished close to the relatively cold cylinder walls – this distance is typically ½mm.

Crevices – Here the fuel is trapped in the small areas where the quench distance is too small for the flame to burn. The most important crevice is that between the piston, cylinder and piston ring. The A/F mixture is absorbed into the crevices as the pressure in the cylinder increases during the compression and power stroke, and desorbed back into the exhaust as the pressure begins to fall.

Oil film – The film produced by residual lubricating oil on the sides of the combustion chamber absorbs fuel vapour both before and after the combustion stroke. This effect is exhibited by the deposits which build up in the chamber.

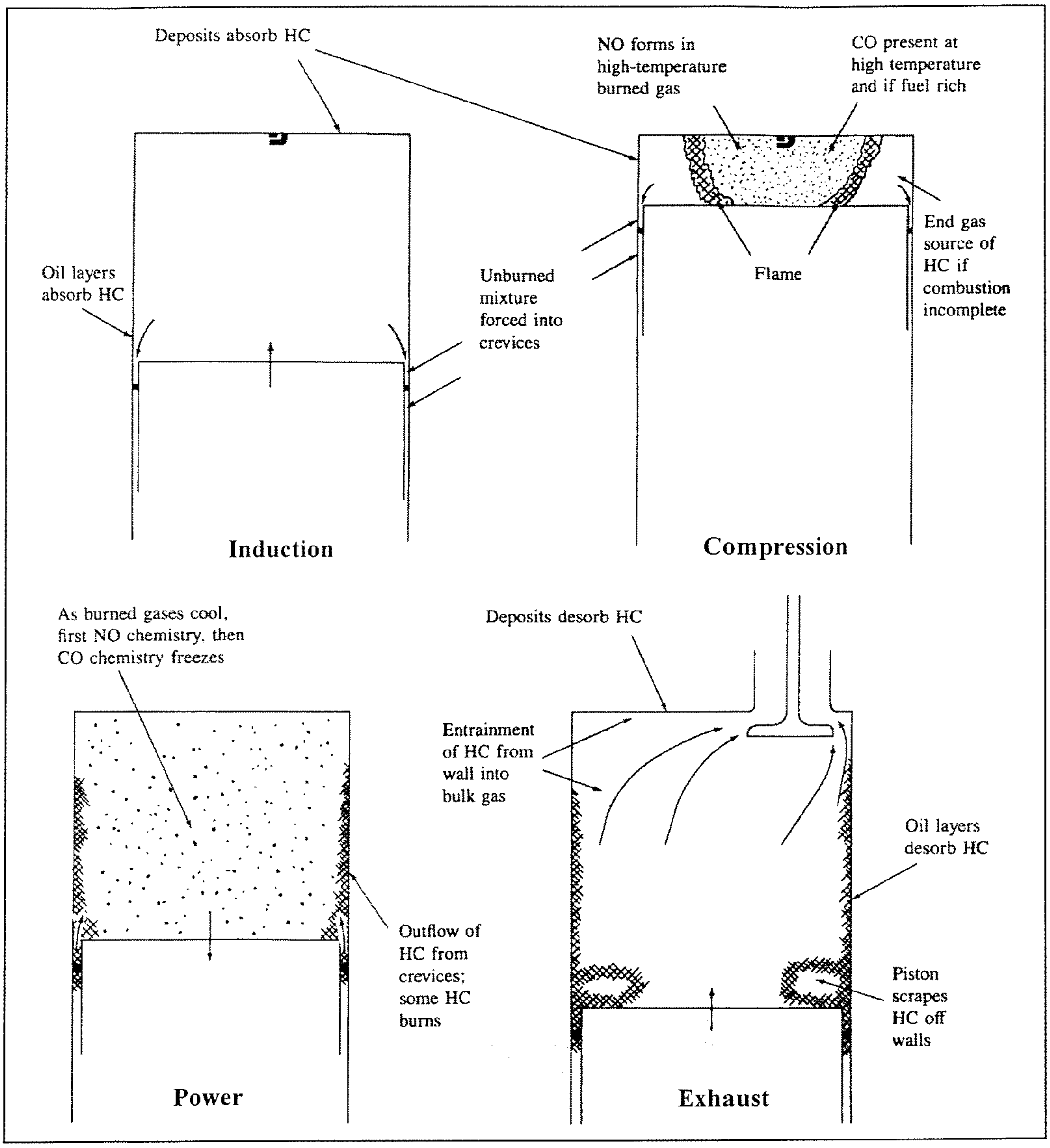


Figure 3-8: Sources of CO, HC and NO_x from a petrol SI engine (*Source: Heywood, 1988*)

A final source of engine-out HC is partial or complete misfire (i.e. very slow or no burning of the A/F mixture) or bulk quenching of the flame. This occurs when engine speeds are very low during combustion and the average cylinder λ value is lean (due to excessive use of exhaust gas recirculation or a lean A/F mixture) together with retarded ignition timing in the cycle – such conditions occur during transient operation (i.e. moving from one 'power vs engine speed' point to another - required for example when accelerating). Misfire may also occur in CI engines although to a far lesser degree because of lesser cycle to cycle variations in the combustion process.

With the exception of wall quenching, the sources of HC in diesel CI engines differ from those explained above for petrol SI engines – these sources of HC (together with CO and NO_x) within the cylinder of diesel direct injection CI engines are shown in **Figure 3-9**. In addition to wall quenching, over leaning and undermixing of the A/F mixture are important mechanisms for HC formation in diesel CI engines.

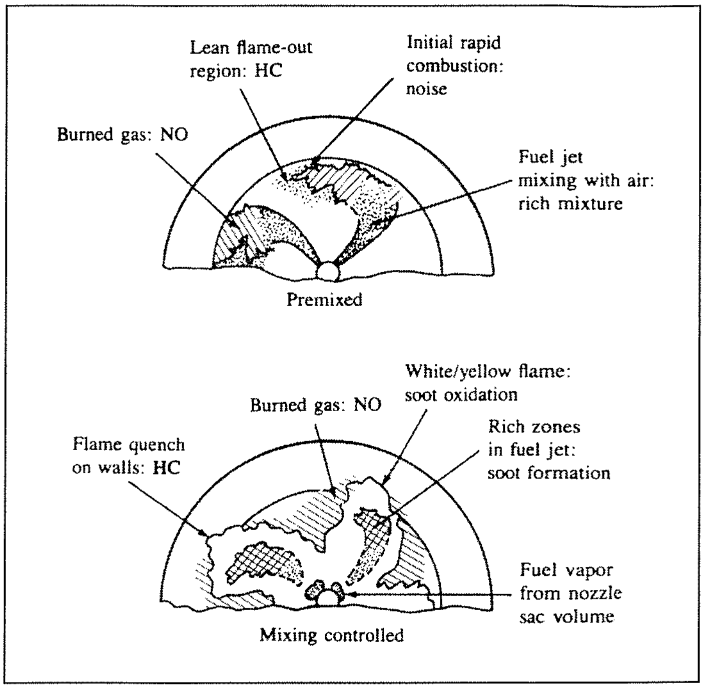


Figure 3-9: Sources of CO, HC and NO_x from a diesel CI engine (*Source: Heywood, 1988*)

> **Over leaning** – during injection of the fuel (as it is dispersing) part of the mixture becomes too lean to autoignite and can only then be oxidised by thermal effects in the cylinder – this results in unburned fuel and partially oxidised HC.
>
> **Undermixing** - A lack of mixing of the fuel with the air is caused by slow mixing of the fuel with the air (e.g. the sac of fuel remaining at the tip of the injector) or when excessive fuel is injected.

HC emissions are far greater for petrol SI engines than diesel CI engines although HC emissions from a CI engine will rise to the order of SI engines with rising engine load. Diesel CI engines generally produce hydrocarbons which are associated with a distinct odour such as aldehydes.

3.3.2.3 Oxides of nitrogen

Again this is a collective term; it refers to both nitric oxide (NO) and nitrogen dioxide (NO_2). Practically all NO_x formed during combustion is NO but as the exhaust cools some of the NO is oxidised to NO_2 leading to a ~90%/~10% split in engine out exhaust respectively (although the cooler combustion in diesel engine produces more primary NO_2. There are also miniscule amounts of nitrous oxide (N_2O) emitted. Once emitted from the vehicles tailpipe it is assumed that all NO oxidises to NO_2. NO_x is formed by the burning of nitrogen in the air drawn by the engine and as shown in **Figure 3-9** is produced in the combustion flame. The formation of NO_x can be quite complicated with three mechanisms responsible for its formation, namely 'thermal', 'prompt' and 'nitrous oxide'.

Thermal – The thermal mechanism is illustrated by the extended Zeldovich process. See **Equations 3-2 to 3-4**:

$2O_2 + 2N_2 \leftrightarrow 2NO + 2N$ **(Eq 3-2)**

$N + O_2 \leftrightarrow NO + O$ **(Eq 3-3)**

$N + OH \leftrightarrow NO + H$ **(Eq 3-4)**

The rate of these reactions is relatively slow when compared to the time taken for combustion of the A/F mixture. This mechanism only forms NO when temperatures in the flame are high and engine speed is low. Since petrol contains only very small amounts of fuel bound nitrogen the thermal mechanism is the most dominant source for SI engine NO emissions.

Prompt – This mechanism is of particular importance to NO formation when nitrogen is bound to the fuel or when the flame parameters render the thermal reaction relatively small (see **Equation 3-5**). The prompt process then makes N available for NO formation by the appropriate thermal reactions.

$CH + N_2 \rightarrow HCN + N$ **(Eq 3-5)**

Nitrous oxide – This mechanism has most influence when flame temperatures are low and there are lean conditions; it follows the reaction given in **Equation 3-6**. The nitrous oxide then decomposes to form NO.

$$N_2 + O + M \rightarrow N_2O + M \qquad \textbf{(Eq 3-6)}$$

3.3.2.4 Particulates

This type of pollutant is also referred to as smoke although it should be separated from the blue or white smoke which is characteristic of any engine burning oil or emitting unburnt fuel respectively (both of which affect SI and CI engines). Although all vehicles emit particulate pollution it is, in general, a problem associated with diesel CI engines. A comparison of particulates with other common particles is given in **Figure 3-10**. It is important to distinguish between the particulates from vehicles due to wear and tear of brakes, tyres and moving components, and those from the combustion process. The combustion derived particulate matter is made up of carbon particles (soot) which form during combustion in rich areas of the A/F mixture. The soot particles then grow by attaching themselves to each other or by adsorbing primary and secondary HC. It is also possible for primary and secondary hydrocarbons to condense resulting in separate particulate matter. When the particles move into a lean zone they are oxidised and so the amount of particulate matter in the engine-out exhaust depends on the ratio of the rate of formation to the rate of oxidation.

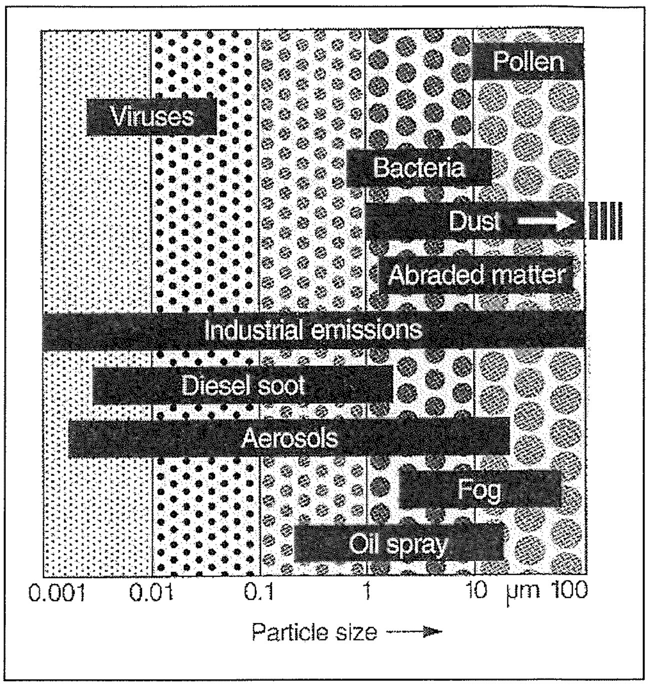


Figure 3-10: Size of particles emitted from diesel vehicles in comparison to other particles found in the environment (*Source: Bauer, 2004b*)

3.4 Emissions reduction techniques for petrol and diesel engines

To meet ever more stringent emissions limits (see **Chapter 4** for more detail) vehicle manufacturers have had to reduce tailpipe emissions using both engine management techniques and exhaust treatment systems. Since SI and CI processes, fuels, emissions etc. are quite different this section will deal with each engine technology separately.

3.4.1 Emissions control in petrol spark ignition engines

3.4.1.1 Controlling engine-out emissions

For petrol SI engines a number of key parameters can have a substantial influence on emissions of CO, HC, NO_x and even particulates. To obtain the optimum performance, low emissions and reduced fuel consumption, computerised engine management systems are used to monitor and control these parameters. However, for all situations, the ideal outcome of high performance, low fuel consumption and low emissions can not be achieved as they conflict with one and other in terms of their control parameters.

Engine load

This is expressed as the torque (rotational force) generated by the vertical piston movement and translated into the rotational movement of the crankshaft. As the torque required increases then so does the temperature of combustion. The increased temperature leads to reduced levels of HC emissions as the size of the quench layer from the cylinder walls is decreased leading to a smaller volume in the cylinder for unburned hydrocarbons to reside. The higher temperatures also result in more complete combustion of the primary and secondary HC, this effect also leads to reduced levels of CO (which is oxidised more fully into CO_2). As described above, higher combustion temperatures from increased torque have a disproportionately negative effect on NO_x emission levels.

Engine speed

Engine speed influences the amount of time available for A/F mixture formation and combustion. Higher engine speeds reduce the time for these processes leaving behind increased levels of unburned HC. CO follows the same pattern as there is less chance for complete oxidation of carbon in the A/F mixture. For NO_x the relationship is the opposite with lower engine speeds giving more time for NO_x formation. However, opposing this effect, the lower engine speed allows for more exhaust gas to remain in the cylinder following the exhaust stroke (exhaust gas has the effect of reducing the temperature of combustion thus the tendency for NO_x formation – see **Section 3.3.1.2** on EGR). Whilst, virtually no particulates are produced by petrol SI engines, the stratified charge concept used in direct injection engines can sometimes result in poor A/F mixture formation at high engine speeds causing localised fuel rich areas which result in particulates.

Increasing engine speed places more power (load or torque) demand on the engine due to increased power consumption from ancillary devices (e.g. the water pump) and also increases frictional losses hence fuel consumption increases disproportionately. When considering engine speed it is also important to consider transmission effects (i.e. chosen gear) since producing a required power at high engine speeds (e.g. low gear) consumes more fuel than if the same power were produced at a lower engine speed (e.g. higher gear); this increased fuel consumption in turn increases emissions.

Excess air

As described above, the influence of λ on the formation of pollutant emissions is great. Controlling the λ value of a petrol SI engine is crucial. Rich A/F mixtures lead to increased amounts of fuel which can not be fully oxidised thus increasing HC emissions. The lack of air also results in incomplete oxidation of the carbon in the fuel to CO_2 causing increased CO. HC emissions also rise with lean conditions due to a lack of combustible A/F mixture to allow a consistent flame front to move through the mixture. CO levels remain extremely low during lean conditions. Maximum NO_x emissions are produced with slightly lean A/F mixtures ($\lambda = 1.05$-1.1). In rich conditions there is less oxygen available to the combustion leading to it being preferentially used for other reactions instead of oxidation of nitrogen. Lean conditions lead to a reduced temperature in the cylinder (due to the increased air being drawn acting as a heat sink) thus reducing the tendency for NO_x to form. Whilst reductions in NO_x can be obtained at lean or rich conditions they are not as great the reductions obtainable using a three way catalytic converter (see **Section 3.4.1.2**) which need stoichiometric conditions to operate properly. Alternatively, a direct injection SI engine can operate lean using the stratified charge and a NO_x storage catalyst.

Ignition timing

Ignition timing is an important parameter because of its influence on the formation of the A/F mixture. Ignition timing is the point in the compression stroke that the A/F mixture is ignited. The ignition timing is measured by the angle of crankshaft with a greater angle (e.g. $\alpha_z = 50°$) indicating an earlier ignition point in the compression stroke. The time taken between ignition of the A/F mixture and formation of a full flame front moving through the A/F mixture is constant at two milliseconds. So, if engine speed increases the timing must be advanced for complete combustion within the time available between the end of the compression stroke and duration of the combustion stroke. Advancing the ignition timing (i.e. moving from $\alpha_z = 20°$ towards 50°) results in higher HC concentrations in the engine-out exhaust as the overall lower exhaust temperatures lessens the secondary oxidation of the HC. Advancing the ignition timing leads to an increase in combustion temperature since the combustion occurs in the cycle when the cylinder volume is relatively low, this in turn results in a greater and quicker formation of NO_x. Advancing the ignition timing is deliberately used in the warm-up phase of an SI engine to keep NO_x levels relatively low as the catalytic converter warms up to its optimum temperature. Retarding the ignition timing reduces the efficiency of the engine and increases specific fuel consumption. Varying ignition timing has very little effect on CO emissions.

3.4.1.2 Post exhaust treatment

As emissions limits on vehicles have become tighter, control of engine parameters alone to maintain low pollutant levels has not been enough. A number of methods to reduce engine out emissions to suitably low tailpipe emissions have been utilised since the 1970's. The methods to mitigate tailpipe emissions given below are presented in an approximate chronological order of use by the commercial automotive industry.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is a standard technique used to reduce levels of NO_x and also to reduce fuel consumption in petrol SI engines. EGR involves returning a portion of the exhaust gas back into the combustion process to dilute the A/F mixture. The inert gas acts as a sink for heat during the combustion process which has the effect of reducing the peak temperature of the combustion thus reducing NO_x. The moderate use of EGR (up to 25%) results in a small increase in HC emissions whilst higher levels of EGR increase HC emissions markedly. This occurs because as the peak combustion temperature lessens the stability of the combustion flame is compromised leading to incomplete combustion. When first implemented in US cars in the 1970's, fuel consumption increased since they used 'slow' burning engines which were susceptible to instability in the combustion flame. Today's vehicle's SI engines have higher burn rates and tolerate EGR to the extent that fuel consumption can actually be improved by 5%. As explained in **Section 3.4.1.1**, a lean A/F mixture also reduces NO_x but makes use of catalytic converters problematic since the fluctuating reduced/oxidised state required for their correct operation is not maintained.

Thermal reactors and secondary air

Once evacuated from the cylinder, HC and CO continue to be oxidised in the exhaust system. To enhance this effect an enlarged exhaust manifold unit is attached to the engine. The 'thermal reactor' causes mixing of the exhaust gases. Often a secondary source of air is required to ensure adequate oxygen is available to continue the oxidation process. For an exhaust manifold to effectively oxidise CO and HC, the temperature, time spent by the exhaust gases in the thermal reactor and ease with which it warms up all need to be high. This form of emissions reduction is not completely effective at removing HC and CO and is often used during the warm up phase of vehicle operation i.e. before the catalytic converter has warmed to an effective operating temperature. Use in this way also has the advantage of warming the exhaust gases leading to even quicker warm up of the catalytic converter and so earlier reduction of NO_x.

Oxidation, three way and NO_x accumulator catalytic converters

Catalytic converters are devices through which the exhaust gas passes for HC, CO and/or NO_x to be removed. A catalytic converter consists of a substrate or beads covered in a noble metal coating. The substrata approach uses either ceramic or metallic monoliths with a tight honeycomb-like structure which are resistant to high temperatures (up to 1000°C). The bead method uses small spherical, ceramic beads (~3mm diameter) although such designs have largely given way to the monolith approach. The advantage of the monolith approach is the relative ease with which the exhaust gases can still pass through the system and so not creating problematic back pressures in the exhaust system which can effect engine operation. On the surface of th substrate is a wash coating of extremely porous aluminium oxide impregnated with the catalyst (a noble metal). Using the washcoat increases the effective surface area of the catalytic converter by a factor of 7000. Stabilisers are added to the washcoat to enable it to maintain its porosity at high temperatures. The actual catalytic reaction is based on the adsorption of the pollutant to be oxidised

(HC or CO) or reduced (NO_x), the appropriate chemical reaction and then desorption of the new chemical species.

Catalytic converters were originally developed for industrial processes. In such processes the state and content of the exhaust gases are far more stable than those for a vehicle exhaust since the vehicle by its nature is operating in rapidly fluctuating, wide ranging conditions. Hence, the ideal characteristics of a vehicle catalytic converter are a low light-off temperature (the temperature at which it becomes 50% effective), high conversion efficiency and high resistance to thermal aging.

To minimise the period taken until light-off both passive and active systems have been used. A number of passive approaches to early light-off are available. For example, one method requires the engine to run on a rich mixture during warm up, the HC in the exhaust is then burnt in a shielded area of the converter using a glow plug (a hot element). A second approach is to place a small catalytic converter very close to the engine where the high temperature of the exhaust quickly warms it; this is often used in three way catalytic converter systems. However, the smaller converter has relatively low conversion efficiency and so a larger converter is placed downstream in the exhaust. One active warming system uses electrical heating to raise the converters temperature – this approach does have fuel consumption penalties as electrical energy is required.

Generally, catalysts are required to operate with high efficiency to beyond 50,000 miles. Other physical factors to be considered are that it should be able to withstand the high frequency oscillations from the vehicles engine and it should be sufficiently insulated to prevent it starting grass fires. The best catalysts which can be added to the washcoat are found in the transition metal group in the periodic table. Such metals include the precious metals of *platinum* (Pt), *palladium* (Pd), *rhodium* (Rh) and *ruthenium* (Ru), or the base metals *iron* (Fe), *nickel* (Ni), *cobalt* (Co), *copper* (Cu) or *vanadium* (V). A number of these metals can be discarded due to the ease with which they are attacked the acidic components in the exhaust or the possibility of toxic by products. The most commonly used catalysts in modern vehicles are Pt, Pd and Rh. Base metals can be used as catalysts but they are much more susceptible to deactivation of the surface from sulphur in the fuel.

Catalytic converter poisoning is a problem when considering the various additives present in both fuel and oils. Indeed, use of lead in petrol was phased out not only due to the increasing levels of lead in ambient air but also because they poisoned catalytic converters. Care must always be taken to prevent misfire on SI engines when fitted with a catalytic converter since when the unburnt fuel passes through the exhaust system it combusts and raises the temperature inside the converter up to 1,400°C, effectively reducing the conversion efficiency to zero.

Oxidation catalysts only remove CO and HC from the exhaust. The CO and HC are held on the catalyst surface as the exhaust passes through converters channels. Secondary air is added to the exhaust before the converter to provide sufficient oxygen for the CO and HC to be oxidised. Oxidation catalysts use a combination of Pt and Pd are used. Pd is better at oxidising CO, and olefin and methane HC's; for aromatic HC's the efficiency of Pt and Pd is equal whilst for paraffin HC's Pt is the most active.

NO_x reduction catalysts use the CO present in the exhaust to take oxygen from NO_x and oxidise. To produce sufficient CO however, the engine has to be run on a rich A/F mixture; this results in some CO and HC being present in the exhaust after it has passed through the reduction catalytic converter. The reaction used in this type of converter is given in **Equation 3-7**.

$$2CO + 2NO \rightarrow 2CO_2 + N_2 \qquad \textbf{(Eq 3-7)}$$

To oxidise the remaining CO and HC, an oxidation catalytic converter is used with secondary air being added. This approach was not entirely successful as the NO_x subsequently reappeared in the exhaust after the second converter. This is due the formation of ammonia in the first converter (NH_3) because hydrogen was present in the exhaust, the ammonia was then oxidised in the second converter to produce NO_x. Ru and Rh catalysts are far more selective when reducing NO_x, producing substantially less NH_3 than Pd and Pt catalysts when the engine is operated under slightly rich conditions. Whilst Ru would seem ideal for such converter set up, it is easily removed from the washcoat under oxidising conditions.

Three way catalytic converters are a progression in research in to vehicle catalytic converters. Three way converters use only one substrate to remove all three key pollutants (hence the name) by oxidising both CO and HC and reducing NO_x. The three way converter washcoat contains Pd and/or Pt (for CO and HC) as well as Rh (for NO_x). In addition to the usual additives, three way catalytic converters also have redox agents such as cerium oxide (CeO_2) and barium oxide (BaO) added to the washcoat. For the principle of a three way converter to work effectively, the A/F mixture must be maintained within a very small 'window' either side of stoichiometric. **Figure 3-11** shows effective margins for CO, HC and NO_x treatment either side of λ=1. As can be seen, any deviation outside this window substantially increases emissions.

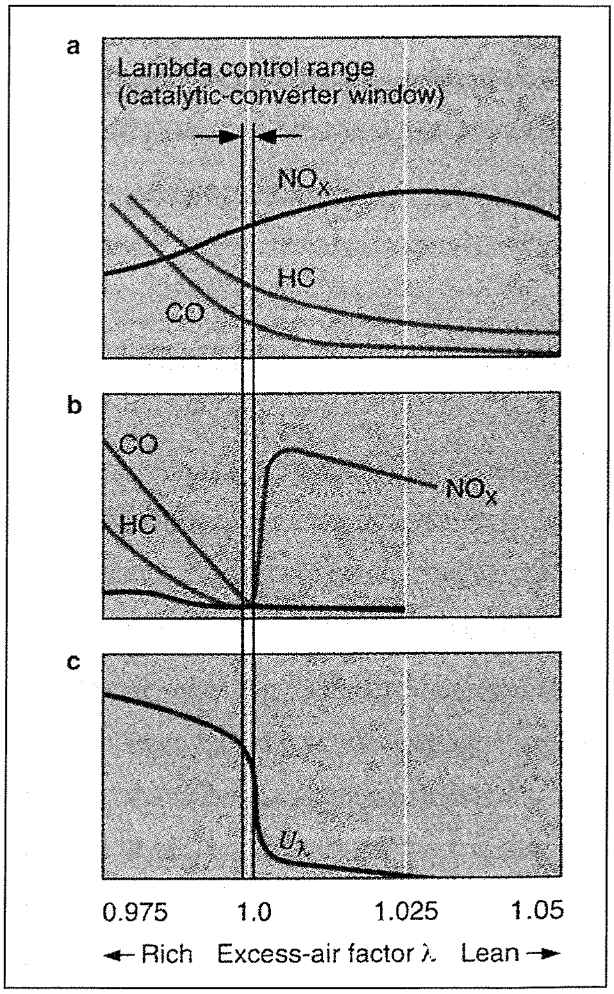


Figure 3-11: Effect of a three way catalytic converter on engine out emissions within and outside of the stoichiometric window a) engine out emissions, b) tailpipe out emissions and c) O_2 sensor voltage feedback (*Source: Bauer, 2004a*)

The operating principle of a three way converter is based on achieving a chemical balance within the exhaust gases. To broaden the window within which successful removal of CO, HC and NO_x occurs, the engine management system oscillates the λ value slightly either side of stoichiometric providing a fluctuating environment in the converter. This oscillation is in the region of 0.5 to 1 Hz. During slightly lean conditions NO_x is preferentially reacted over O_2 with any CO, H_2 and HC; some of the remaining O_2 and NO_x is stored by the redox material in the washcoat (i.e. CeO_2). During rich conditions all O_2 and NO_x in the exhaust plus the stored O_2 and NO_x is scavenged by CO, H_2 and HC which need to be oxidised. Balanced examples of the reactions which occur in a three way catalytic converter are given in **Equations 3-8 to 3-11**.

$$2CO + O2 \rightarrow 2CO_2 \quad \textbf{(Eq 3-8)}$$

$$2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_2O \quad \textbf{(Eq 3-9)}$$

$$2NO + 2CO \rightarrow N_2 + 2CO_2 \quad \textbf{(Eq 3-10)}$$

$$2NO_2 + 2CO \rightarrow N_2 + 2CO_2 + O_2 \quad \textbf{(Eq 3-11)}$$

In addition, CO is removed by water-gas shift reaction (see **Equation 3-12**) and HC by the steam reforming reaction (see **Equation 3-13**) both of which are aided by the Pt and Rh catalysts.

$$CO + H_2O \rightarrow H_2 + CO_2 \quad \textbf{(Eq 3-12)}$$

$$C_xH_y + H_2O \rightarrow CO, CO_2, H_2 \quad \textbf{(Eq 3-13)}$$

Since very close to stoichiometric combustion is always required then fuel consumption is not as economical as it should. At part load on the engine, suitable performance can be gained by running the engine on a lean A/F mixture. The fuel penalty for running the engine at stoichiometry is approximately 10% (with the associated rise in CO_2 emissions).

To maintain such close control on λ, closed loop control is required. Close loop control uses oxygen sensors which feedback to the engine management system. A schematic of the closed loop control system is given in **Figure 3-12**. Upstream of the catalytic converters, an oxygen sensor is used to monitor if there is excess oxygen in the exhaust. If excess oxygen is detected, the A/F mixture being added to the cylinders is lean, in which case, the engine management system adjusts the mixture towards the rich direction. Conversely, when the sensor detects a lack of oxygen the exhaust the A/F is too rich and the engine management adjusts to a leaner A/F mixture.

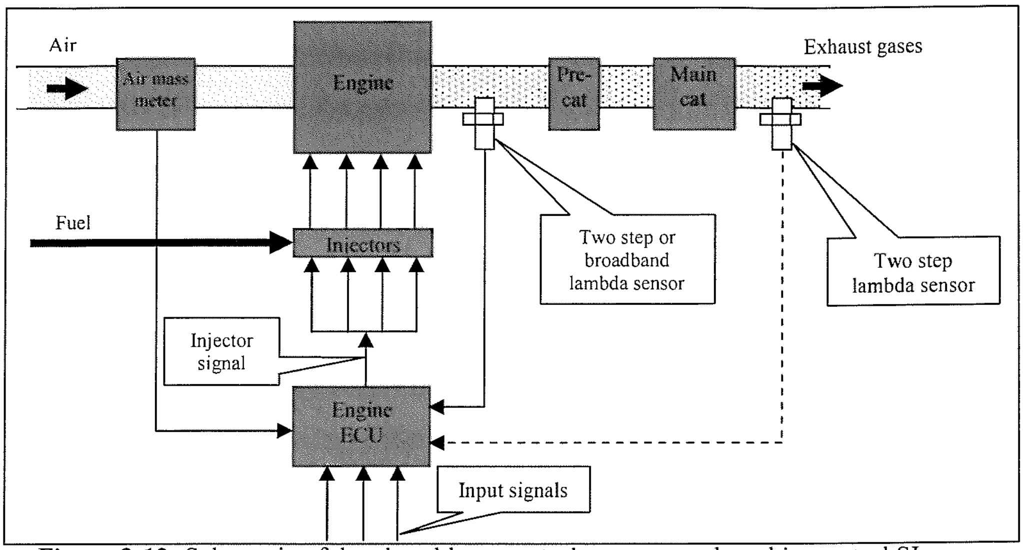


Figure 3-12: Schematic of the closed loop control system employed in a petrol SI car (*Adapted from Bauer, 2004a*)

Conventionally the detection of O_2 in this upstream position was achieved using a two step sensor which gives a higher or lower voltage feedback depending on the conditions – an example of this feedback is given in **Figure 3-11**. In this example the high voltage relates to a rich mixture and the low voltage to a lean mixture. The voltage change experienced is by no means binary but a simple algorithm in the engine management system is applied to determine the A/F mixture state because the voltage change is so distinct. The frequency at which it alters the A/F mixture is relatively high.

More recently 'continuous action' λ sensors have been used in this position. The broadband signal given by such sensors not only provide information on the λ state in the exhaust gases but also provide information on the extent of any deviation from stoichiometry. This allows much tighter control of the A/F mixture keeping it within the window for optimum operation of the three way catalytic converter for a greater proportion of driving (e.g. more of the transient operations).

Using an O_2 sensor so close to the engine leaves it vulnerable to high temperatures and untreated exhaust, limiting its accuracy. A second sensor is placed downstream of the converter but, due to its distance down the exhaust system from the engine and the influence of treated exhaust, the sensor is relatively unresponsive to changes in the engine A/F mixture. The downstream sensor, therefore, takes part in a relatively low frequency feedback allowing longer term alterations to the engine management system. The downstream sensor can also be used to monitor oxygen storage capacity of the catalytic converter by comparing its response to that of the upstream sensor. So, if the upstream sensor is detecting O_2 then a delay should occur before the downstream sensor detects excess O_2 since the catalyst should be storing the excess O_2. The extent of this delay, when considered together with other parameters, informs of the O_2 storage capacity of the catalyst – this is important for the diagnostic operation of the engine management system.

The latest development in emissions control for petrol SI vehicles is the *NO_x accumulator catalytic converter*. The use of converters which can better deal with high *NO_x* means that lean burn technology can be used by the engine (e.g. the stratified charge concept used by direct injection engines). Lean burn technology is desirable since it is a very effective way to reduce fuel consumption (and so CO_2 emissions). The problem with such operation is the excessive NO_x emissions which can not be treated. During lean burn operation the excessive O_2 levels react to oxidise the CO and HC meaning NO_x is not reduced adequately. A solution to this problem is therefore desirable.

The NO_x accumulator catalytic converter is essentially a three way catalytic converter with additional additives in the washcoat which specifically hold the excess NO_x. Additives include oxides of potassium, calcium, strontium, zirconium, lanthanum and barium. The NO_x converter undergoes a three stage process (accumulation, release and conversion) whilst the CO and HC are being constantly oxidised by the excess O_2. Typical accumulation, release and conversion reactions on the of the NO_x accumulator catalyst are given in **Equation 3-14 to 3-16** respectively.

$2BaO + 4NO_2 + O_2 \rightarrow 2Ba(NO_3)_2$ **(Eq 3-14)**

$Ba(NO_3)_2 + 3CO \rightarrow 3CO_2 + BaO + 2NO$ **(Eq 3-15)**

$2NO + 2CO \rightarrow N_2 + 2CO_2$ **(Eq 3-16)**

Accumulation – The NO is held by the Pt on the surface and oxidised to form NO_2. The NO_2 is then held by the additive oxides. Two approaches are used to determine when the converter has reached its storage limit. The first method is to take the temperature of the catalyst, the theoretical NO_x produced, etc. into account and apply a model to calculate the amount of stored NO_2. The second method requires a NO_x sensor downstream of the catalyst; when the sensor detects NO_x then the converter is full.

Removal – Once the storage threshold is reached the engine is briefly run on a rich, homogenous A/F mixture. An excess of CO, HC and H_2 is then present in the exhaust and used as reducing agents to remove the NO_x from its nitrate form. For example using CO; the excess CO is used as an oxidant to remove the NO_x from the barium nitrate ($Ba(NO_3)_2$) resulting in CO_2 and NO.

Conversion - The NO is then oxidised by more CO in the same way as on a three way converter. The oxidation reactions described can equally take place with H_2 and HC although the products are obviously different. H_2 is the most readily oxidised with HC being the slowest. Similarly to the accumulation stage, two methods are available to determine when the NO_x has been fully removed from the catalyst. The first method uses a model to calculate the level held on the catalyst. The second method uses an O_2 sensor downstream of the catalyst to detect when the λ switches from lean (significant O_2 is produced during the removal stage) to rich.

The NO_x converter's ability to accumulate is greatest in between 300 and 400°C meaning the converter has to be placed further away from the engine than a conventional three way catalytic converter. Such restrictions mean a pre-cat nearer the engine is essential. Low sulphur or sulphur free fuel is a further requirement of a NO_x accumulator catalytic converter since the oxides which accumulate the NO_x also accumulate sulphur by creating sulphates. To reduce the sulphates the converter has to be heated to between 600 and 650°C at regular intervals; if not done regularly the level of sulphates becomes so great that no amount of heating will remove them. A closed loop control system similar to the three way catalytic converter is also employed for this type of converter. However, if the model approach to storage control is not used, a two step λ sensor downstream of the converter, which also has an integrated NO_x sensor, can be utilised.

3.4.2 Emission control in diesel compression ignition engines

3.4.2.1 Controlling engine out emissions

Whilst diesel CI engines have less opportunity for cycle to cycle variations in combustion parameters when compared to a petrol SI engine, some important dynamic changes can be made by the vehicle's engine management system. The dynamic parameter with most influence on performance, emissions and fuel consumption is the fuel injection. There are many sub-variables associated with the fuel injection process namely injection timing, injection pressure, and the rate-of-discharge. Engine speed is a further important factor. Since CO is negligible from diesel CI engines they are not considered in this section. Altering dynamic parameters is a process of balancing often conflicting issues such as fuel consumption, NO_x, HC, soot and particulates and noise.

Injection timing

The point at which combustion of the A/F mixture begins can not be directly controlled by diesel CI engines (i.e. it does not require an ignition spark to be applied to begin combustion). Instead, a key method of control is varying the point within the compression stroke that the fuel injection is begins. In a similar manner to ignition timing in petrol SI engines, injection timing in CI engines is expressed in degrees of rotation in the crankshaft. The injection timing is important as it not only governs when the fuel is delivered to the cylinder but, as a consequence, it has an effect on the air flow profile, pressure and density within the cylinder (these variables change as the compression stroke progresses into the ignition stroke). All these factors combine to affect the point at which the premixed stage of ignition takes place. This in turn has an impact on the combustion by-products. Therefore, the injection timing has to be altered depending on engine speed and load (and if cold starting, temperature) on the engine.

At a given engine speed and load for a warmed up engine, the effects of retarding or advancing injection can be compared. The distribution of NO_x and HC as the injection timing changes from the top dead centre (TDC) position of the piston is shown in **Figure 3-13**. The caveat relating to how the injection varies according to load is also important. The manner in which noise, smoke (proxy for soot or particulates), NO_x and fuel consumption change with injection timing and the trade off made when optimising one over another is given in **Figure 3-14**. Advancing the timing before TDC means the premixed combustion phase is reached before the piston is ready to be forced downward and therefore actually slows down the engine. Whilst a more advanced timing is associated with improved fuel consumption, because improved thermal efficiency of the engine, there is a point where the increased work inefficiency leads to not only increased fuel consumption, but also to increased levels of noise due to higher peak pressures and NO_x due to higher combustion temperatures. HC and smoke on the other hand are both relatively low as more time is available during the mixing controlled combustion phase for complete combustion. Retarding the injection timing increases relative fuel consumption, HC and smoke emissions whilst NO_x and noise are both reduced. The increased fuel consumption in this stage can be explained by the less complete combustion (leading to the increase HC emissions). Contemporary diesel CI engines have sophisticated fuel injection systems which are capable of starting injection within $<\pm 1^\circ$ of the desired crankshaft angle.

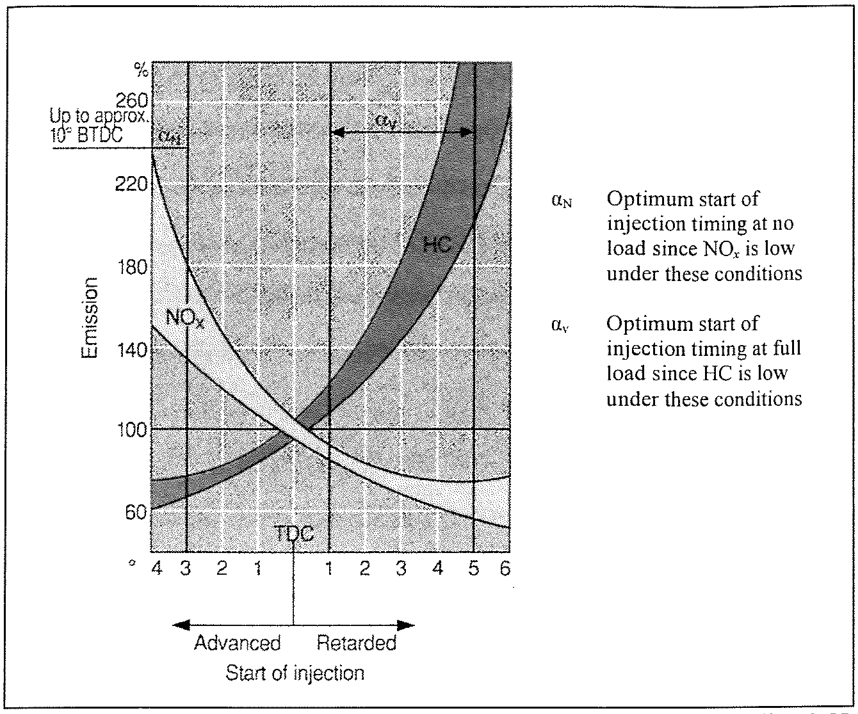


Figure 3-13: NO_x and HC distribution with variation in injection timing in a diesel CI engine (*Source: Bauer, 2004a*)

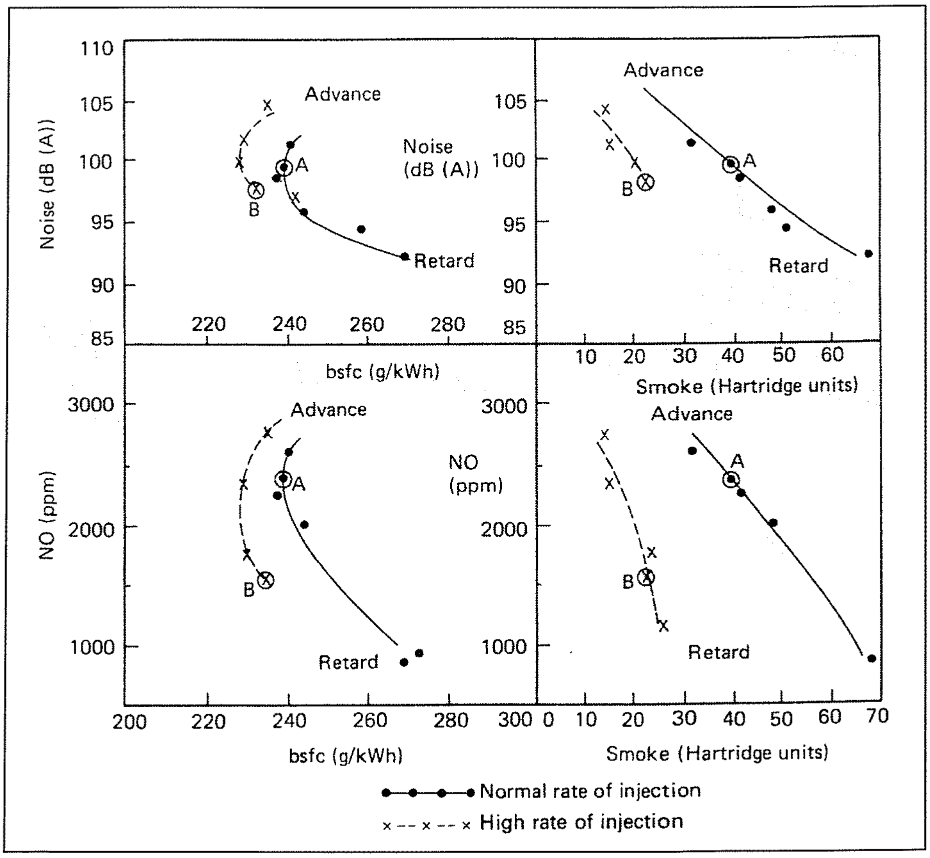


Figure 3-14: Trade off curves between noise, smoke, NO_x and fuel consumption with different injection pressure and injection timing (Source: *Stone, 1999 reprinted from Glikin, 1985 by permission of the Council of the Institution of Mechanical Engineers*)

Injection pressure

The injection pressure is a controlling factor on the manner in which the fuel is atomised with higher injection pressures leading to greater atomisation. **Figure 3-15** shows how fuel consumption, NO_x and black smoke vary with injection pressure and injection timing for a direct injection CI engine. It can be seen that both smoke and fuel consumption are sensitive to injection pressure. The greater mixing of the air and fuel leads to less of the localised rich zones which cause soot emissions. Smoke emissions are highest during the mixing controlled phase of combustion and so improved mixing of air and fuel during this stage will significantly reduce smoke. Fuel consumption is also improved by this increase in atomisation as more of the injected fuel is completely combusted.

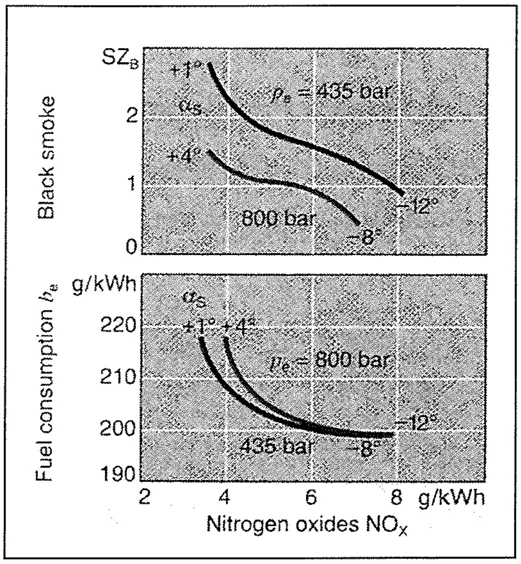


Figure 3-15: Effect of injection pressure on trade-off curves between NO_x and smoke, and NO_x and fuel consumption (*Source: Bauer, 2004b*)

The injection pressure for direct injection engines varies with engine speed (since the pressure generated by the pump is related to the engine) with peak injection pressures only possible at high engine speeds (1000bar – 2050bar). The exception to this are engines with a common rail injection system where an independent pump generates high pressures independently of engine speed and stores the fuel in a constantly, highly pressurised state. The pressure of fuel stored in the 'common rail' can be altered as a function of the engine load required by returning excess fuel to the tank. The amount of fuel injected by such systems is related to the time the injector valve is open and the known pressure in the rail. For indirect injection CI engines there is little advantage in having injection pressures above 450bar since there is a limit on how this can influence the manner in which the partially burnt A/F mixture is injected from the swirl chamber.

Injection rate-of-discharge curve

Controlling the profile of the mass of fuel injected and injection duration can lead to benefits in noise, emissions and fuel consumption. How fuel consumption, NO_x, HC and soot vary with injection duration and injection timing (at a constant engine speed and load) is shown in **Figure 3-16**. It can be seen that there is little variation in HC emissions with increased injection duration. Fuel consumption and soot both increase whilst NO_x decreases with increased injection duration.

Due to the phenomena of premixed and mixing controlled combustion phases, the profile of injection can be utilised to mitigate the negative outputs of each stage. To precondition the cylinder for the main injection event, a technique called pre-injection can be used. The pre-injection is a very small charge of fuel which has the effect of raising the temperature and pressure inside the cylinder. This rise in temperature and pressure dampens the sharp temperature and pressure rises that occur during the pre-mixed phase of the main injection event, reducing both noise, NO_x and fuel consumption. In addition, the pre-injection also reduces the delay period phase between fuel injection and ignition allowing a quicker premixed combustion phase and quicker overall combustion in the cylinder.

Post-injection can also be used to reduce emissions by injecting a delayed charge of fuel toward the end of the main combustion phases. This delayed burning event re-burns any soot particles and can reduce soot emissions by between 20 and 70%.

A useful summary of the effect of various injection related parameters on performance, emissions and fuel consumption is given in **Table 3-1**.

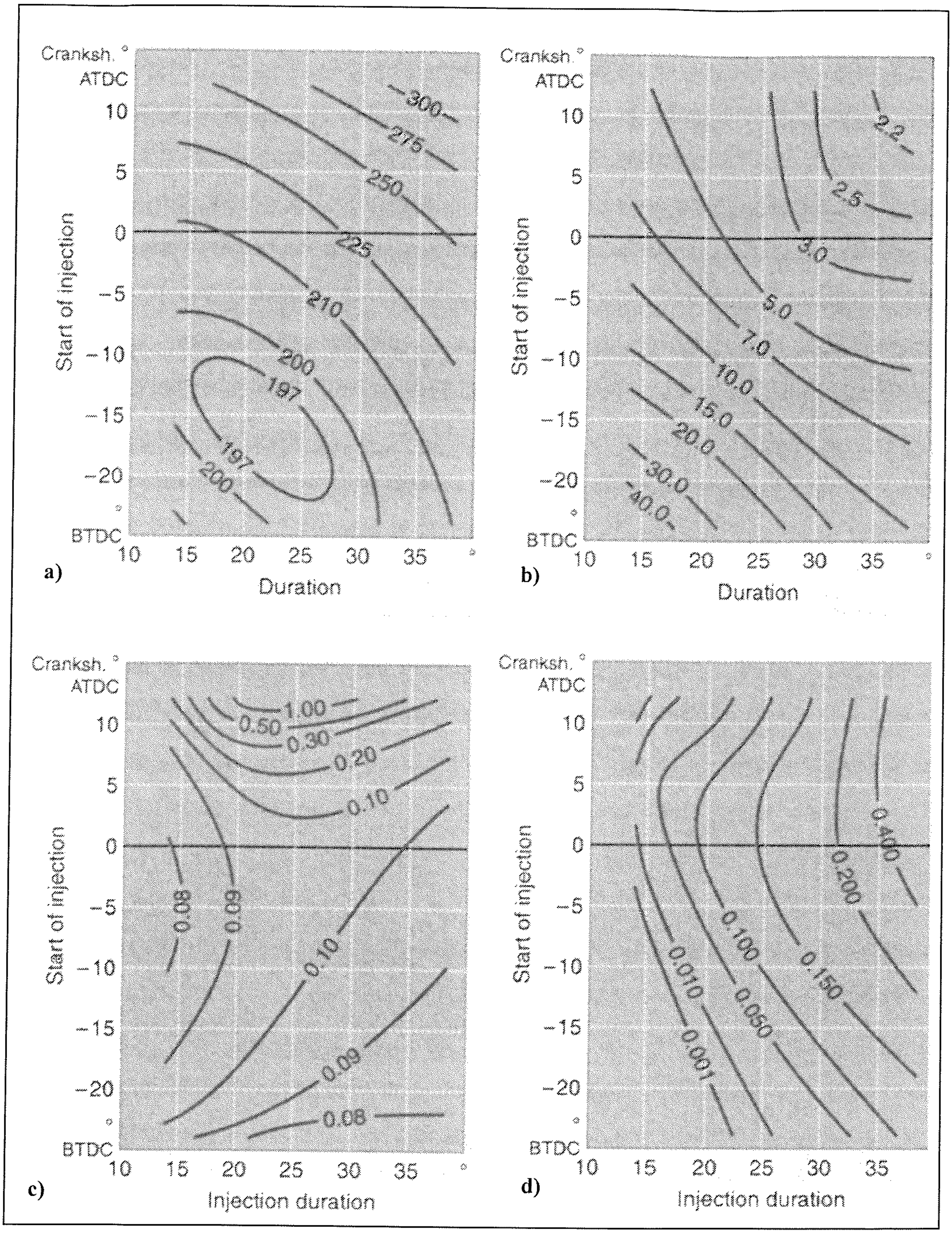


Figure 3-16: Variation in emissions, in g/kWh, of a) fuel consumption, b) NO_x, c) HC, and d) soot with injection duration and start of injection (*Source: Bauer, 2004b*)

	Effect						
	Loss of engine power	Higher fuel consumption	Increased HC and soot emissions	Increased NO_x emissions	Possible engine damage	Uneven running	Poor engine response
Injection too early	(●)	(●)	-	●	●	●	●
Injection too late	●	●	●	-	●	●	●
Injection pressure too low	●	●	●	-	-	●	●
Poor nozzle condition/positioning	●	●	●	-	-	●	●
No pre-injection	-	-	● (HC↑)	●	-	●	-
No post-injection	-	-	● (Soot↑)	-	-	-	-
Incorrect injection pattern	(●)	●	●	●	(●)	●	-

Table 3-1: Effect of various fuel injection parameters on performance, emissions and fuel consumption for a diesel CI engine (*Source: Bauer, 2004b*).

Engine speed

Variation in emissions levels at different engine speeds can be explained by the need to alter the injection timing to ensure enough time is available for complete combustion. So for higher engine speeds the injection timing has to be advanced. With this in mind the consequential changes in emissions from increased engine speed are already described above under '***injection timing***'.

Engine load

For diesel CI engines, increasing the load on the engine can be thought of as increasing both the pressure and temperature within the cylinder. Some simple relationships based on this fact can be used explain variations in NO_x, HC, and smoke. As the load increases at a given engine speed so does the level of NO_x since the higher peak temperatures are favourable for NO_x formation. Engine designers often use this relationship and advance the timing of injection at low loads as this is where best fuel consumption can be achieved (up to a limit). At full load, HC and soot levels are lower since there is less effect of wall quenching and over leaning as the higher cylinder temperatures reduces the quench layer and improves secondary burning of over leaned A/F mixtures. To capitalise on this relationship, injection is often retarded during these operations reducing noise and NO_x.

3.4.2.2 Post exhaust treatment

Similar to petrol SI engine vehicles, the emissions limits on diesel CI engine vehicles have become increasingly stringent. These limits have nearly all been achieved though improvements in the engine design and control. Of the post exhaust treatment methods EGR is currently widely used although diesel catalytic converters and particulate traps will be increasingly used in future vehicle designs although reductions of sulphur levels in diesel fuel are necessary for this. In future, to meet even tighter emissions limits combinations of the technologies described below will be required.

Exhaust gas recirculation (EGR)

EGR is used to reduce NO_x emissions and has been a standard method of emissions control on diesel cars and commercial vehicles since the early 1990s. Previously, the sensitive control systems required to meter EGR were not available. The use of EGR also has an advantageous effect in reducing combustion noise from diesel engines by causing a smoother and lower profile of pressure/temperature increases during the ignition stroke. The apparent reduction in NO_x is attributed to the influence of increasing the CO_2 included in the combustion chamber during the ignition stroke. Three effects have been identified; firstly, the increase in CO_2 in the combustion chamber displaces the amount of fresh air drawn and so reduces the amount of excess O_2 in the chamber available for NO_x formation. Secondly, the CO_2 and H_2O in the exhaust gases have a higher specific heat capacity thus reducing the temperature of combustion. Finally, the quantity of exhaust gases expelled are reduced (EGR of up to 50% is used in diesel cars). Cooled EGR increases the NO_x reducing effects (although this can cancel effects of reducing noise). The use of EGR on diesel CI engines is not as effective as observed for petrol SI engines. EGR for diesel engines requires careful control because if quantities are too high, it can have adverse effects on CO, HC and smoke emissions since too great a reduction of oxygen produces a rich A/F mixture.

Oxidation, three way and NO_x accumulator catalytic converters

These types of converters operate in the same manner as those described in **Section 3.4.1.1**. When used for diesel emissions, some reduction in more volatile particulate matter is also possible. Using catalytic converters with diesel emissions should lead to reductions in the HC compounds responsible for the distinct odour emitted by diesel engines. The three way catalytic converter method can be used when additives are added to the washcoating. The additives compensate for the high levels of excess O_2 and allow some of the NO_x (5-10%) to be reduced in the oxidation of HC and even CO emissions. One major difficulty in the use catalytic converters is the high level of sulphur present in diesel fuel. The sulphur is oxidised to form sulphur trioxide (SO_3) which leads to sulphuric acid, which in turn produces sulphates on the surface of the catalyst. This not only reduces the efficiency of the converter but also increases back pressure of the exhaust system affecting the engine. The mass introduction of ultra low sulphur diesel (<10ppm sulphur) is allowing this technology to be used more often. A further problem with the use of converters with diesel exhaust gases is that they are comparatively cool when compared to SI engines. To overcome this problem the catalysts have to be designed with very low light off temperatures and placed close to the engine.

Particulate filters

A number of types of particulate reduction techniques are available.

Regenerating particulate traps use a filter made of a porous ceramic to capture particulates in the exhaust as the pass through it. However, as the trap fills an undesirable back pressure is created. When a specified retained amount of particulates is reached, they have to be burnt at temperatures of over 600°C. A pressure sensor can be used to determine when the threshold for burning has been reached. Since these temperatures are not normally reached by the relatively cool exhaust gas the trap requires an additional source of heat. The additional heat can be produced by drastically retarding the injection timing, or the exhaust bypasses the trap and an electrical heating system is used – both lead to increased fuel consumption. To mitigate this effect additives can be used in the fuel to lower the temperature at which the particulates burn. This technique requires the trap to be cleaned manually, periodically to remove ash which remains from the additive.

The *continuously regenerating trap* (CRT) uses NO_2 produced from an oxidation catalytic converter upstream of the trap. The particulates are then burnt in the presence of the NO_2 instead of O_2 – this has the effect of reducing the temperature at which the particulates burn (>250°C). This temperature range is much more in the order observed in diesel vehicle exhausts allowing the traps to be effective even for short journeys. Sensors monitoring pressure, temperature and particulates are used to monitor the trap. It is possible to use a catalytic washcoat on the surface of the filter to oxidise and filter particulates in one unit. CRT traps can reduce particulate emissions by ~80%.

Cyclonic filters use centripetal force within a chamber to remove large particulates which are then removed through a small orifice at the bottom of the cyclone. The 'cleaned' exhaust passes out through the top of the chamber. However, this technique only work with particles >10μm and so an electrical charge must be added to the particulates encouraging them to cohere to sufficiently large agglomerations.

Selective catalytic reduction (SCR)

By using a reduction catalyst such as urea up to 90% of NO_x can be removed from the exhaust. Carefully controlled amounts of urea are, based upon the assumed (using a data map and exhaust temperature) or known (using a NO_x sensor measurements upstream of the converter) level of NO_x in the exhaust, added to a thermo/hydrolysing catalyst to produce ammonia (NH_3). The ammonia is then used in the SCR catalytic converter to reduce the NO_x to nitrogen and water. Using an oxidising catalyst upstream of the SCR converter oxidises the NO to NO_2 which improves the efficiency of the SCR method. To prevent any NH_3 not used in the reduction reaction being emitted an ammonia blocking catalytic converter is used. **Equations 3-17 to 3-20** detail the chemical reactions involved at each stage.

Oxidation: $2NO + O_2 \rightarrow 2NO_2$ **(Eq 3-17)**

Thermolysis: $(NH_3)_2CO \rightarrow NH_3 + HNCO + H_2$ **(Eq 3-18)**

Hydrolysis : $HNCO + H_2O \rightarrow NH_3 + CO_2$ **(Eq 3-19)**

Reduction: $NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$ **(Eq 3-20)**

3.5 Summary and conclusions

Engine designers have responded to increasingly stringent emissions standards and consumer desire for greater fuel economy. Based on a detailed understanding of the thermal, chemical and dilution processes inside the combustion chambers of both SI and CI engines, operating parameters of the engine have been optimised. To control the necessary parameters, sophisticated computerised engine management systems have been utilised. Control of engine parameters can only lead to partial gains in emissions reductions and fuel economy and so post-exhaust treatment techniques have been employed to gain further reductions.

Diesel CI engined vehicles will become increasingly dependent on exhaust after-treatment approaches in order to meet the required emissions standards. SI post exhaust treatment has evolved from relatively simple thermal reactors to sophisticated catalytic converters which are equipped with sensor arrays which in turn feedback to the engine management system. CI post exhaust treatment has to deal with the added burden of particulate emissions. In future, particulate traps in conjunction with NO_x reducing catalytic converters will be required to meet emissions standards. The role of cleaner petrol and diesel fuels to allow such devices to be utilised is also an important piece of the solution.

Reductions in emissions from light duty vehicles has resulted in fuel consumption trade offs. As CO_2 emissions and the associated climate change issue becomes more important in future years a more holistic approach to the combined problems of local air quality and CO_2 will be needed. This will require automotive solutions which reduce both types of emissions.

Vehicle technology approaches have their limits in their effectiveness at reducing emissions. Will there ever be a point where no more tailpipe emissions reductions can be made and air quality standards (which may also be reduced as vehicle emissions are reduced) are still being breached just because of the sheer volume of traffic?

The reliance on these sophisticated systems to maintain relatively low emissions means that monitoring their effectiveness is of increasing importance. A malfunctioning vehicle could be producing far greater emissions than if it were operating properly which makes identifying such vehicles a high priority. This leads to the question; '*how well are the current procedures, employed to detect vehicles with an emissions fault, working and how will this effectiveness change in the future*'?

Increased reliance on sophisticated emissions control technology can result in a lack of driver awareness of an emissions related problem with their vehicle and due to increased repair expense, a delay in undertaking a repair. It is also apparent the ability of vehicle owner to maintain, and more importantly being able to observe an emissions related fault, is being removed as the vehicle control systems increase in sophistication. This could result in excess emissions and the responsible fault not being rectified until the vehicle is due for its service or MOT. The cost of repairs is presumably also going to increase as the diagnosis and repair become increasingly specialised jobs and the cost of spares increases. In such circumstances if the owner is aware of the fault then they may not have it rectified due to the one-off expense, especially if a vehicle is coming the end of its useful life (e.g. as is currently the case for early generation petrol catalyst cars).

4 INSPECTION AND MAINTENANCE PROGRAMMES

4.1 Introduction

A number of approaches to reducing road traffic pollution are utilised by policy makers. One of the more successful tools is that of an Inspection and Maintenance (I&M) programme. I&M programmes are used by National or Regional governments to ensure that on-road vehicles operate somewhere near their maximum potential in terms of producing relatively low emissions compared to a malfunctioning vehicle.

4.2 The need for I&M

4.2.1 The rationale of I&M

As discussed previously the maintenance of cars is crucial if their optimum emissions performance is to be sustained. This is especially important for cars built in the last decade where the use of emissions control systems and computerised engine management has enabled large decreases in tailpipe emissions. To illustrate this point the emissions from a petrol SI engine car equipped with a three way catalytic converter are presented in **Table 4-1** (Norris, 2001b). This test involved comparing the emissions over a number of drive cycles with original, new and no catalyst fitted. This vehicle complied with EURO I limits and for petrol SI vehicles, the importance of catalyst activity (and the necessary engine management systems for its optimum performance) on meeting the stricter, later EURO standards increases (CVTF, 2000). This will become the case more and more with diesel CI vehicles as their emissions control technology matures to match that of petrol SI engines.

	Emissions (g/km)		
	CO	THC	NO_x
Vehicle with **New** catalyst	2.83	0.30	0.09
Vehicle fitted with **Original** catalyst	4.64	0.31	0.22
Vehicle fitted with **No** catalyst	8.65	0.52	1.26

Table 4-1: Emissions over the NEDC of a EURO I petrol SI vehicle which had travelled 125, 000 miles with three different catalyst states (*Source:* Norris, 2001b).

In its original state this vehicle was, when taking into account allowable degradation and the change in test cycle, within the excessive emissions limits. The impact if this vehicle's catalyst had become totally ineffective, would have been an increase in CO, THC and NO_x emissions by a factor of 2, 2 and 6 respectively – in effect increasing the number of vehicles on the road. More detailed examples of the potential effects of a malfunction in a vehicle on emissions are given in McCrae *et al.* (2001). Whilst data from a number of studies (CVTF, 2000; Norris, 2001b; McCrae *et al.* 2001) into the performance of catalysts shows, on the whole, good catalyst durability with age and use, it follows that identifying even the small percentage of cars which are not operating effectively will have a beneficial impact on overall air quality.

McCrae *et al.* (2001) review studies which show the effect of maintenance on the CO, HC, NO_x and fuel consumption. For vehicles pre-selected due to their high emissions percentage emission reductions were 84%, 80%, -107% and 20% respectively. CVTF (2000) report that for both non-catalyst and catalyst equipped petrol SI engine cars which are not high emitters, routine servicing has beneficial or at least have no negative effect on CO, HC, NO_x and fuel consumption. The effect of the regular service in terms of percentage improvements was greatest for non-catalyst cars; this effect is to be expected since the engine management system of catalyst equipped cars uses inputs from its many sensors to finely tune the vehicles operation towards its optimum. The majority of vehicle owners will under take maintenance and repairs due to annual service requirements for the vehicle (less so for older vehicles), to continue for it to be used and the need to pass the MOT test. Given the observed effect of maintenance on reducing emissions reported by the CVTF (2000), it is possible that a vehicle may be passed fit in terms of emissions at an MOT test, but not be performing in terms of reduced emissions as it could.

The cost effectiveness (the benefit as a result of improvement to air quality versus the cost of implementing the necessary tests to find an excessive polluter or vehicles where emissions improvements could be made) is the acid test of any I&M programme. The use of standards representing thresholds of emissions (or suitable proxies) is a form of deterrent to poor vehicle maintenance (although the financial case in terms of fuel use can also be a powerful incentive).

4.2.2 Common faults leading to excess emissions

Norris (2000 and 2001b) and McCrae *et al.* (2001) provide comprehensive reviews of possible faults with both petrol SI and diesel CI engine cars which could lead to increased emissions. Information for these reviews was provided by vehicle garages, roadside call outs to the RAC, leasing companies, I&M programmes elsewhere in the world and anecdotal knowledge. Petrol SI and diesel CI faults are dealt with separately below.

4.2.2.1 Petrol spark ignition engine cars

Petrol SI engine cars can be divided in to two distinct groups based on their emissions control technology (i.e. non-catalyst and catalyst). High emissions for non- catalyst cars, can largely be attributed to general wear and tear on the vehicles fuelling and ignition system. This can cause the vehicle to run rich or lean, or misfire. The effects of these faults on emissions are given in **Table 4-2**. The most common fault is a gradual shift towards a rich A/F mixture with time which is normally rectified during a regular service by replacing the air filter and adjusting the carburettor (McCrae *et al.,* 2001) – as a result it is possible that maintaining a vehicle with this sort of fault could cause a small increase in NO_x.

Fault	Possible reasons	Effect on emissions
Rich A/F mixture	Incorrectly adjusted carburettor Worn carburettor Dirty air filter	High CO, High HC
Lean A/F mixture	Incorrectly adjusted carburettor Worn carburettor Air leak at inlet manifold	Low CO, Low HC, High NO_x, *If mixture is very lean misfire occurs which may result in high HC emissions*
Engine misfire	Faulty spark plug, HT leads, etc.	Low CO, High HC

Table 4-2: Common causes of high emissions in non-catalyst petrol SI engine cars (*Source:* McCrae *et al.,* 2001)

Catalyst equipped cars can obviously have faults relating to the catalyst itself, in addition to those rich or lean mixtures or engine misfire situations experienced by non-catalyst cars. However, the causes of rich/lean mixtures more commonly relate to the engine management system whilst misfiring is more commonly due to faulty sensors or their electrical connections. The typical faults and reasons for high emissions for petrol catalyst cars are presented in **Table 4-3**. The most common faults observed relate either to failure of the catalyst due to natural aging effects or some form of sudden distress, and due to a fault with the engine management system. Faults with the engine management system will manifest itself differently between vehicle models depending on the how the system reacts. Norris (2001b) suggests, in order of frequency, the faults influencing emissions for catalyst petrol SI cars are λ sensor faults, break up of catalyst monolith, and external leaks to the catalyst (e.g. corrosion in exhaust system).

Fault	Possible reasons	Effect on emissions
Catalyst Failure	Normal thermal aging with time Thermal shock Mechanical shock	High CO, High HC and High NO_x
Rich A/F mixture	Engine management fault	High CO, High HC
Lean A/F mixture	Engine management fault	High NO_x
Engine misfire	Faulty spark plug, HT leads, λ sensor fault	Low CO, High HC

Table 4-3: Common causes of high emissions in catalyst petrol SI engine cars (*Source:* McCrae *et al.,* 2001)

4.2.2.2 Diesel compression ignition engine cars

Norris (2000) presented an extensive appendix listing the possible faults with components in CI diesel engine cars which could cause excess emissions; this can be used in conjunction with a list of technology used in different generations of diesel vehicles to produce tables similar to those for petrol SI cars above. The possible faults associated with diesel cars complying with EURO I standards are presented in **Table 4-4**. An important caveat is that diesel engines are relatively robust and the table column stating the 'probability of a fault' relates to vehicles for which an emissions related fault has been observed. Control of the engine parameters at this time was largely by mechanical means and this is reflected in the nature of faults (i.e. largely due to wear on the engine). The faults most likely in a diesel car meeting the EURO II standard are given in **Table 4-5**. The increased use of computerised engine management and exhaust after-treatment means that these components begin to appear on the faults list. It is likely that with the increased use of engine management the mechanical errors will become less of a problem as they are no longer needed (e.g. computer controlled fuel metering), or it alerts or addresses early symptoms of a fault due to wear. Based on evidence presented by McCrae *et al.* (2005) regarding vehicles using EGR (it is not specified if these vehicles are petrol or diesel) the most likely component to fail in diesel vehicles will be the EGR valves.

In a similar manner to the influence of catalysts on reducing and causing high emissions, faulty post exhaust treatment components will give the largest increases in emissions over the vehicles original design specifications. Whilst a likelihood of a particular fault causing high emissions is given there is no empirical data to support.

Fault	Component fault	Likelihood	Effect on emissions			
			CO	HC	NOx	PM
Too little air charge	Blocked air filter	Very high	Up (moderate)	Up	Down (small)	Up
Poor atomisation of fuel hence poor fuel mixing	Fuel injectors	High	Up	Up	Down (moderate)	Up (moderate)
Reduced engine compression	Worn engine rings/cylinder	Medium but worst for high mileage	Up	Up	Down (moderate)	Up (moderate)
Poor control of EGR	Faulty EGR valves	*Not stated*	-	-	Up (large)	-
Poor aspiration	Worn timing cams	Medium but high for high mileage	Up	Up	Down (small)	Up (moderate)
Over fuelling	Worn fuel meter	Medium but high for high mileage	Up	Up	Down (small)	Up (large)

Table 4-4: Faults which are likely to cause increased emissions for a EURO I diesel CI car (*Source:* Adapted from Norris, 2000)

Fault	Component fault	Likelihood	Effect on emissions			
			CO	HC	NOx	PM
Too little air charge	Blocked air filter	Very high	Up	Up	Down (small)	Up (moderate)
	Block/Leak from intercooler	Medium/High	Up	Up	Up/down (moderate)	Up (moderate)
Poor atomisation of fuel hence poor fuel mixing	Fuel injectors	High	Up	Up	Down (moderate)	Up (moderate)
Reduced engine compression	Worn engine rings/cylinder	Medium but worst for high mileage	Up	Up	Down (moderate)	Up (moderate)
No reduction of CO/HC	Faulty Oxy-cat	*Not stated*	Up (large)	Up (large)	-	-
Poor control of EGR	Faulty EGR valves	*Not stated*	-	-	Up (large)	-
Poor aspiration	Worn timing cams	Medium but high for high mileage	Up	Up	Down (small)	Up (moderate)
Wrong injection timing	ECU fault	Very low	-	-	Possible increase	Possible increase
Over fuelling	ECU fault	Very low	-	-	Possible increase	Possible increase
	Worn fuel meter	Medium but high for high mileage	Up	Up	Down (small)	Up (large)

Table 4-5: Faults which are likely to cause increased emissions for a EURO II diesel CI car (*Source:* Adapted from Norris, 2000)

4.3 UK I&M programme

In the UK, vehicle emissions standards and their enforcement are the responsibility of the Department for Transport (DfT). Whilst DfT sets policy for Britain, it must as a minimum comply with relevant EC directives on 'type approval' and 'in service testing' (i.e. I&M). A summary of the relevant EC directives and UK legislative tools is given in **Table 4-6**. DfT implements its version of EC emission standards policy through two agencies (NAO, 1999) namely the Vehicle Certification Agency (VCA) and the Vehicle Inspectorate (VI) (now covered under the VOSA umberella).

4.3.1 Type approval

The Vehicle Certification Agency (VCA) is responsible for ensuring that EC type approval legislation is satisfied. This requires that each new vehicle model to be sold in the UK meets maximum allowable limits for a number of pollutants. Over the last thirty years type approval emissions standards have become stricter and the tests used to quantify them more rigorous. Nearly all types of road vehicles are now subject to maximum allowable emission limits and, as discussed previously, this has had, and will continue to have, a large effect in reducing emissions from road vehicles. The relevant standards which have been applicable to cars (the key subject of this thesis) are listed in **Table 4-7 and 4-8** and illustrates how they have become tighter throughout the past twenty years.

Relevant EC Directives	UK legislative tools
Type approval • 91/441 (by 31/12/92) – new petrol engined passenger cars to be fitted with a catalytic converter, set strict new limits on particulate emissions for new diesel vehicles. • 94/12 (by 01/01/97) – set tighter emissions limits for both new petrol engine and new diesel cars. • 96/96 (by 01/10/98) – set tighter limits for light commercial vehicles in line with 94/12 for cars. • 91/542 - set tighter emissions limits in two stages: EURO I by 01/10/93 and EURO II by 01/10/98. • 98/69 & 98/70 – further tightening of limits in 2000 (EURO III) and again 2005 (EURO IV). **In-service testing** • 77/143 and 88/449 (by 01/01/95) – required in-service testing of emissions for goods vehicles, large passenger vehicles and taxis. • 92/55 (by 01/01/97) – sets out specific testing and limits for emissions relating to roadworthiness tests for petrol, catalyst and diesel vehicles. • 96/96, 01/09, 03/26 & 03/27 (by 01/01/04) - updates to the testing and limits for emissions of all vehicle types.	• Road Traffic Act 1988 (as amended by the Road Traffic Act 1991) provides legal basis for the Secretary of State to regulate acceptable levels of emissions, makes testing compulsory and provides Vehicle Inspectorate with powers to: - conduct statutory tests on HGVs and PSVs. - supervise the operation of the MOT scheme and enforce its standards - monitor and enforce the condition of HGVs and PSVs in-use through roadside monitoring and other checks, by prohibiting the use of polluting vehicles, and by prosecuting drivers and operators • Road Vehicles (Construction and Use) Regulations 1986 (section 61) making it an offence to drive a vehicle emitting 'smoke, visible vapour, grit, spark ashes, cinders or oily substances. • Amendments to these regulations give effect to European Community directives or in-service emissions requirements. • Road Traffic (Vehicle Emissions) (Fixed Penalty) Regulations 1997 give pilot local authorities the right to check vehicles at the roadside and to inflict a £60 penalty on excessive polluters. • Road Traffic (Vehicle Emissions) (Fixed Penalty) Regulations 2002 supersedes the 1997 regulations giving all Local Authorities which have declared an AQMA the powers to check vehicles at the roadside on roads in or leading into the AQMA. A £60 penalty can be issued to excessive polluters. Vehicles parked and idling unnecessarily in the AQMA can be issued with a £40 penalty.

Table 4-6: Legislation at both EC and UK level relating to the emissions from road vehicles
(*Source*: Update on NAO, 1999)

Emission Standard	Directive	Implementation Type approval	Limit (g/km)				
			CO	HC	NOx	HC + NOx	PM
Pre EURO	70/220	-	10.0	-	-	2.55	-
EURO I	91/441	01/01/93	2.72	-	-	0.97	-
EURO II	94/12	01/01/96	2.20	-	-	0.70	-
EURO III[1]	98/69	01/01/00	2.30	0.200	0.15	-	-
EURO IV	98/69	01/01/05	1.00	0.100	0.08	-	-
EURO V	Proposed		1.00	0.075	0.06	-	0.005[2]

Table 4-7: Emissions standards for petrol SI passenger cars sold in the EU (*Source:* Adapted from Norris, 2001b)

Emission Standard	Directive	Implementation Type approval	Limit (g/km)				
			CO	HC	NO_x	HC + NOx	PM
Pre EURO		-	3.88			1.40	0.203
EURO I	91/441	01/01/93	2.72	-	-	0.97	0.140
EURO II	94/12	01/01/96 for DI only	1.00	-	-	0.90	0.100
EURO II	94/12	01/01/97 for IDI 30/09/99 for DI	1.00	-	-	0.70	0.080
EURO III	98/69	01/01/00	0.64	-	0.50	0.56	0.050
EURO IV	98/69	01/01/05	0.50	-	0.25	0.30	0.025
EURO V	Proposed		0.50	-	0.20	0.25	0.005

Table 4-8: Emissions standards for diesel CI passenger cars sold in the EU (*Source:* Adapted from Norris, 2000)

Petrol cars are tested according to limits for CO, HC and NO_x, whilst diesel cars are tested according to CO, HC, NO_x and PM. Car produced during 2005 were required to meet EURO III standards although as far back as 2001 some manufacturers were producing cars which satisfied EURO IV standards even though this standard did not actually come into force until 2006 (VCA, 2001). The emissions standards for petrol and diesel cars for CO and HC + NO_x emissions are compared in **Figure 4-1**.

The VCA also test vehicles which have been used for real-world driving to ensure a model-type maintains its ability to adhere to the EURO standard to which it was first built to achieve. This requires vehicle manufacture to surrender a sample of vehicles which have been used on-road for representative distances to the VCA. The VCA testing procedure for these cars gives allowances are made for natural degradation of the emissions control system and general vehicle wear.

[1] New European Drive Cycle (NEDC) used. This removes the 40secs warm up period allowed under ECE15 + EUDC.
[2] Only for petrol engines using lean burn technology.

The type approval procedure for EURO I and II cars involved driving the vehicle model on a chassis dynamometer following a set drive cycle called the ECE15 + EUDC. The ECE15 + EUDC, drive cycle consists of two sub cycles, namely the urban cycle and extra urban cycle. The emissions produced over the two cycles are combined and used to calculate the average grams of each pollutant/s produced per kilometre. In addition to type emissions testing the same drive cycles are used to quantify fuel consumption and CO_2.

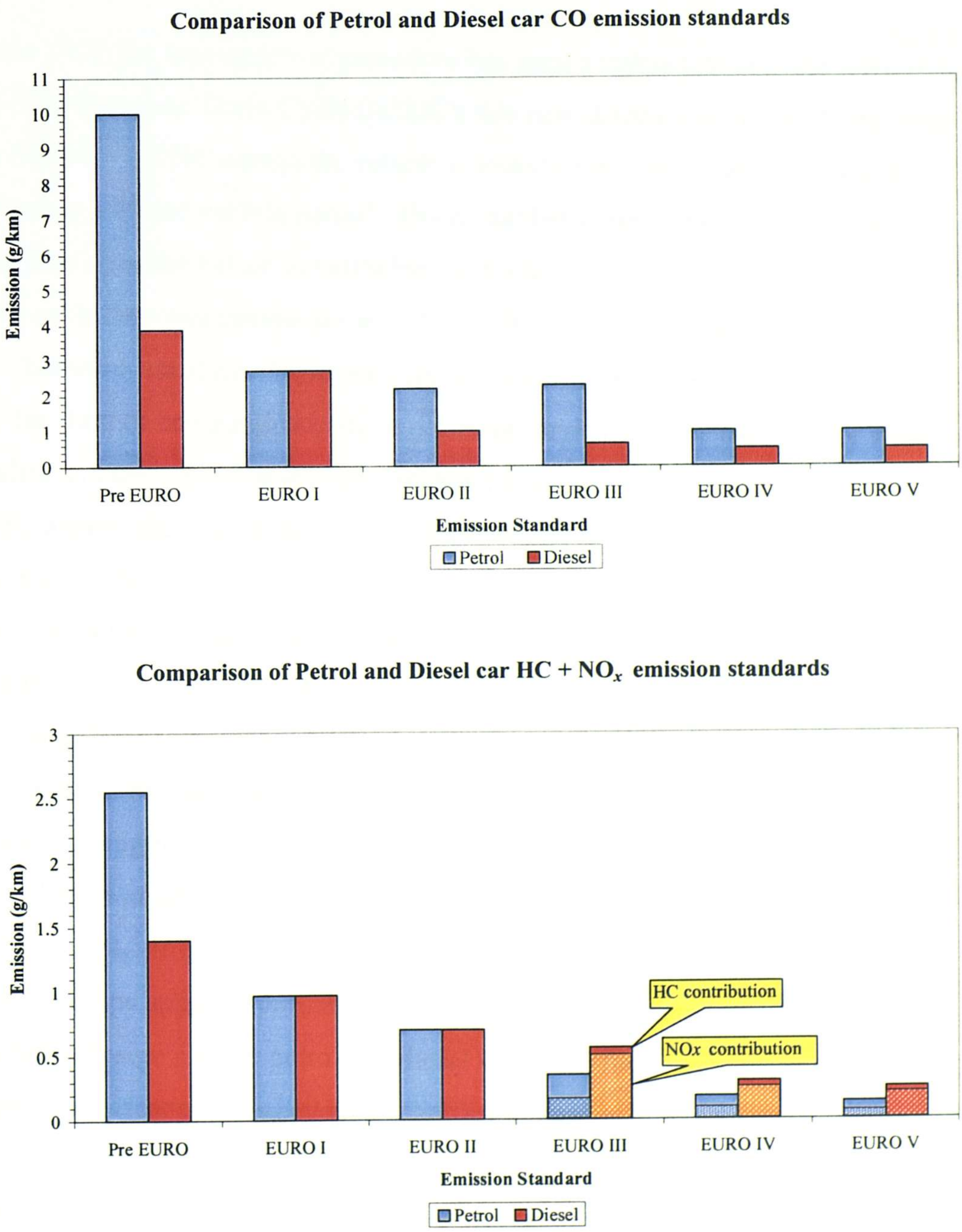


Figure 4-1: Comparison of petrol SI engine and diesel CI engine car emissions standards over the last twenty years (*Source:* Adapted from Norris, 2000 and Norris, 2001a)

The development of the emissions standards has been undertaken by the EC with the involvement of relevant stakeholders. The EURO I and II standards were developed within the AUTO OIL programme where automobile manufactures were involved; the EURO III and IV standards from the AUTO OIL II programme also involved environmental groups (AUTO OIL II, 2000). Such consultation with stakeholders enables challenging yet technically feasible standards to be agreed. However, there is evidence that the suggested EURO V standards could have been tighter (SAR, 2004; EC, 2005; T&E, 2006).

Since 1999, the type approval procedure has used a revised drive cycle referred to as the New European Drive Cycle (NEDC); this new drive cycle is exactly the same as the ECE15 + EUDC except the vehicle is tested from a cold start as opposed to following a 40 second idle period (which enabled some warming of the engines and catalytic converter before undertaking the cycle). Whilst the NEDC is a more severe drive cycle than was previously used for EURO I and II standards (reflected in the fact that some emissions limits are actually lower for EURO II than EURO III) it is still far short of being representative of driving styles, vehicle use, road or weather conditions experienced in real life (Felstead *et al.*, 2006). In addition only one car within a particular type is driven thus not accounting for any inter car variability that may exist. The subject of cycle-beating is also particularly relevant here. A number of instances have occurred in the US where the engine management system of the vehicle is able to recognise the prescribed format of a drive cycle and alter its fuelling and emissions management profile accordingly. In the EU it has been noted that a number of manufacturers do just enough to ensure low levels of emissions over the areas of engine torque and speed tested under the NEDC (Kågeson, 1998). Beyond these areas emissions are significantly higher.

The use of type approval emissions standards has forcibly encouraged the motor industry to design cleaner petrol and diesel vehicles. Improvements in engine design coupled with cleaner fuels have had significant impacts in reducing their emissions whilst catalytic converters have aided major reductions in emissions from petrol vehicles. To satisfy increasingly stringent standards (of both CO_2 and toxic emissions) new technologies such as lean burn engines, particulate traps and diesel catalytic converters will be necessary.

4.3.2 In-service emissions testing

The UK is bound by EC legislation to undertake in-service emissions inspection of all on road vehicles. Minimum requirements of the test are outlined but member states can go beyond these requirements as they see fit. The Vehicle Inspectorate (VI) is responsible for ensuring that on-road vehicles are roadworthy. The VI directly test heavy goods vehicles and public service vehicles through the 'statutory test' whilst, for private and light goods vehicles (i.e. motorcycles, cars and vans), they oversee the 'MOT test' undertaken by 19,000 certified private garages and dealerships (McCrae *et al.*, 2001). Within both tests vehicles are tested according to maximum allowable emissions. This study is concerned only with cars which are all, at sometime during their lifetime, subject to the MOT test. In addition to the off road MOT based tests, the VI also undertake roadside tests as an incentive for drivers to maintain their vehicles if they suspect their emissions are not as they should be. Failure of the roadside test can result in the owner being fined.

In 2002, following a pilot study in 1997 with seven Local Authorities, the Government granted powers to all Local Authorities which had declared AQMAs (see **Chapter 2**) allowing them to test vehicle at the roadside. A review of the Local Authority testing is given by McCrae *et al.* (2005). These schemes are intended to be funded by the Local Authority with some funding from fines generated by vehicles which fail the test; no Central Government funding is given. The issued fine can be reduced or waived if the vehicle owner can produce evidence that the:

i) vehicle passed an MOT test in the previous six months,

ii) vehicle is repaired within 14 days of the offence,

iii) vehicle has records showing all reasonable efforts have been undertaken to maintain the vehicle. Relatively rigid guidance on procedures for roadside testing by Local Authorities has been issued by Central Government (DfT, 2001).

The VI and Local Authority roadside testing procedure follows that of the MOT but uses raised emissions standards to account for some added inaccuracy of undertaking the test outdoors; the standards used compared to the MOT standards are given in **Table 4-9**.

4.3.2.1 Vehicles tested

All petrol and diesel engine private and light duty vehicles are tested once they are over three years old and thereafter annually. However, motorcycle emissions are not subject to emissions standards although the EC are currently reviewing this and it likely in the near future motorcycles will be legislated for. The lack of testing for vehicles less than three years old, and the subsequent emissions caused by malfunctioning vehicles within this age group, is not thought to significantly contribute to overall emissions from road vehicles. The logic being newer vehicles should have a better emissions performance and are less likely to suffer from faults relating to the vehicles engine management or emissions control systems.

The frequency of the UK testing regime and the age of vehicle before its initial test are stricter than those required by the relevant EC legislation. The EC requires a vehicle's emissions to be tested once it is four years of age and biannually thereafter. It has been calculated that this stricter regime cost an individual motorist £16.16 extra over a ten year period (NAO, 1999) (i.e. £1.61 per year). This is currently equivalent to approximately £2 each based on the change in the Retail Price Index since that time. This is based on a vehicle still needing an MOT each year but not foregoing the emissions element of the test every other year. The NAO report (1999) states that little has been done to assess the cost effectiveness of the UK regime, in terms of emissions saved, compared to the EC stipulated regime. However, there are other considerations regarding the higher frequency of the testing regime. Currently the emissions test sits as part of the roadworthiness test and as such is a convenient (and beneficial) opportunity for vehicle owners to implement the emissions test as well as informing them of any malfunctions regarding their vehicle.

4.3.2.2 Pollutants tested

The emissions component of the MOT test (referred to as the MOT test from here on) for petrol and diesel cars are very different procedures. The test, equipment used and the pollutants measured are completely different between the two fuel types. The pollutants tested under the petrol SI engine test are CO and HC. For catalyst equipped vehicles, λ is also calculated using values of CO_2, CO, HC and O_2 in the exhaust – this acts as a proxy to check the closed loop fuelling system. All gaseous emissions tested are measured as a percentage of total gases present in the exhaust and are either reported as % or parts per million (ppm). The testing of CO is mandatory under EC legislation whilst HC has been added at the UK's discretion. The diesel test is based on the smoke opacity of the exhaust plume by measuring how much 'light' is absorbed. The Hartridge units are m^{-1} (i.e. referenced to a measure of light penetration through a depth of 1m of smoke).

4.3.2.3 Implementing the test

Both petrol and diesel cars require preconditioning before they are tested. This normally requires the vehicle to be driven on the road or revved to high idle (approx. 3000-3500 rpm) for approximately three minutes. This is to ensure that the engine is at a normal operating temperature thus negating issues with cold starts (See Chapter 3 for more on the effect of cold starts on emissions). From this point the tests for the different fuel types differ. For both fuel types the test is unloaded (i.e. the vehicle is not required to over come any force other than its engine inertia) although the petrol test uses steady idle states (engine rpm held at a specified level) and the diesel test requires a transient (i.e. accelerating the engine rpm). A detailed description of the test procedure for both petrol and diesel cars is given in the VI's handbook on in-service emissions standards (DfT, 2001).

Petrol cars

The standards to which petrol cars are tested are dependent on the age of the vehicle. An abridged version of the standards is given in **Table 4-9**. After an initial visual test of the exhaust plume to see if there is any visible blue or black smoke, the vehicle then has a tailpipe probe inserted into the exhaust (cars first used before 1st August 1975 only undergo this visual inspection). Depending on the age of the vehicle, and hence whether it is equipped with a catalytic converter, the relevant test procedure is selected. For a vehicle used between 1st August 1975 and 31st July 1986 the vehicle only undergoes an idle test during which CO and HC is measured whilst non-catalyst cars first registered after 1st August 1986 are tested to a stricter CO standard but the same HC standard. All catalyst cars (first registered after 1992) are tested for CO at a low idle and CO, HC and λ at a specified high idle speed. In 2001, a new EC directive tightened the in-service emissions standards as a reaction to the stricter type approval emissions standards. Manufacturers of catalyst equipped petrol cars are allowed to specify limits other than the default limits given in **Table 4-9** if they can show that it adequately represents a well maintained vehicle. In reality, few vehicles differ from the default standards (although some actually set tighter standards including Lamborghini!). Where manufacturers do state their own standards, it is done so on a vehicle type 'family' basis (i.e. a specific vehicle model with the specific engine model) and included in the considerable annex to the VI's in-service emissions handbook. This requires the tester to determine the make, model, engine type and VIN of the car and determine the pass or fail to the relevant standards. This much more involved test is undertaken by the tester using a computerised, menu driven gas analyser.

In response to a review of the in-service emissions test by the NAO (1999) the procedure for testing catalyst equipped cars was simplified for testers as many reported the process to find the appropriate VIN, set up the thermocouple to measure engine temp etc., as relatively time consuming, considering how many vehicles were identified as excess emitters. In 2001 a 'fast pass' test called the Basic Emissions Test (BET) was introduced. This allowed the tester to ensure the engine is warm enough for the test in a general manner by feeling the coolant pipes or noting the activation of the cooling fan. The vehicle is then tested to the appropriate generic standards. Only if the vehicle fails is it then required to be tested under the more involved manufacturer specified conditions.

Diesel Cars

As with petrol vehicles, the standards to which diesel vehicles are tested depends on age and engine technology. For diesel cars first used before 1st August 1979, only a visual inspection of the exhaust plume is undertaken after raising the engine speed to approximately 2500rpm and then returned to the idle speed. If blue or black smoke is present then the vehicle is failed (vehicles manufactured before 1960 are allowed some tolerance if it is judged the smoke is unavoidable).

For vehicles first used after 1st August 1979, a metered Free Acceleration Smoke (FAS) test is undertaken. The standards which the vehicle must meet are given in **Table 4-9**. After an initial check to ensure the speed governor of the engine is working properly, a probe is inserted into the tailpipe and the engine is accelerated to its maximum speed and held for two seconds. The unit then reports the peak smoke emission. This process is repeated a further two times and an average of all three readings is calculated. If the value is below the appropriate standards the vehicle is passed. In the event that the first three readings do not average below the standard, the test can be repeated up to a further three times until the consecutive average is below the standard. Failure after this results in the cars being failed. A final visual check is undertaken where, regardless of the metered test, if the tester deems the vehicle to be emitting an excessive amount of smoke so as to obscure the view of other road users, the cars is failed.

Car type	Test	Pollutant	MOT limits	Local Authority limits	VI limits
Non-catalyst petrol (01/08/75-31/07/86	Idle Idle	CO HC	4.5% 1200ppm	4.95% 1320ppm	5% 1350ppm
Non-catalyst petrol (later than 01/08/86)	Idle Idle	CO HC	3.5% 1200ppm	3.85% 1320ppm	4% 1350ppm
Catalyst Petrol (before 31/12/2000)	Idle High idle High idle High idle	CO CO HC λ	0.5% 0.3% 200ppm 0.97-1.03	0.55% 0.33% 220ppm -	0.85% 0.35% 220ppm -
Catalyst petrol (later than 01/01/01)	Idle High idle High idle High idle	CO CO HC λ	0.3% 0.2% 200ppm 0.97-1.03	0.33% 0.22% 220ppm -	?
Diesel turbo	FAS	Opacity	$3m^{-1}$	$3.3m^{-1}$	$3.7m^{-1}$
Diesel non- turbo	FAS	Opacity	$2.5m^{-1}$	$2.75m^{-1}$	$3m^{-1}$
All diesel (after 01/01/05)	FAS	Opacity	$1.5m^{-1}$	$1.65m^{-1}$	?

Table 4-9: In-use emissions standards for SI and CI engine cars (*Source:* McCrae *et al.,* 2001)

4.3.2.4 *Effectiveness of test*

A number of studies have been undertaken during the last decade examining the effectiveness of the MOT test at identifying gross polluting vehicles (NAO, 1999; Norris, 2000-2005; Samaras *et al.*, 2001). A major drawback of the current MOT tests for petrol and diesel cars is its lack of parity with the type approval test procedure. Norris (2000 and 2001b) agrees with the VI's definition of an excess emitter as '*a vehicle whose emissions vary significantly away from its design parameters*'. Norris goes on to clarify this definition by addressing the meaning of *significantly*.

Account should be taken of the irreversible degradation of the vehicles' technology (e.g. catalyst aging), and the interval since it was last serviced. Given this further step, an excess emitter can be defined as '*a vehicle which fails to meet the emissions standards it first passed during the type approval process having accounted for reasonable degradation by appropriately factoring up the emissions standards*'. The factor used to raise the type approval limits will vary depending on the engine technology (i.e. EURO standard) and pollutant concerned. With this definition in mind, the real effectiveness of the MOT test should be a comparison by testing vehicles against an appropriately weighted ECE+EUDC/NEDC test (depending on the standard or pollutant) against the relevant MOT emissions test. This would result in vehicles belonging to the discrete areas shown in the schematic given in **Figure 4-2** based on how they performed in both tests. When a vehicle fails one test but not the other, this is commonly known as either an error of commission or omission respective of which test is regarded as the benchmark test. (Stephens *et al.*, 1996; and Barlow, 1998)

Benchmark is NEDC	MOT: Pass	MOT: Fail
Fail	Errors of omission	Appropriate fails
Pass	Appropriate passes	Errors of commission

Figure 4-2: Schematic showing how the effectiveness of the MOT test should be evaluated. This would need to be applied separately to the different pollutants covered under the NEDC for petrol and diesel cars manufactured to the relevant EURO standard

The nearest work that could be found which covered a direct comparison of the two tests on a vehicle by vehicle basis was a study funded by the EC referred to as the JCS study. A major deficiency in the analysis of the study is the grouping of all vehicles which have catalysts and all diesel vehicles (Samaras *et al.*, 2001). A fair study would have separated the vehicles into the relevant emissions standards. It is, however, appreciated that a study which obtained a statistically robust number of vehicles into so many facets would be costly. Despite its lack of resolution, the JCS study is a useful indicator of the effectiveness of the idle style MOT test. Norris (2000 & 2001a) includes the JCS study as part of a study of the effectiveness of the MOT. In addition relevant studies from TRL (described in McCrae, 2001) and NAO (NAO, 1997) were also considered.

Non-catalyst petrol cars

The MOT for non-catalyst petrol cars was not in the remit of the Norris study (2001b). The JCS study does examine this. It concludes that the MOT is effective at identifying excess emitters although the low idle standard for CO should be reduced to 1.5%. A recommendation was also given to add a measurement of HC to the test with threshold of 3000ppm; the UK MOT already includes the measurement of HC but has a threshold of 1200ppm. The reasoning behind the two HC thresholds is not known but there maybe errors of omission associated with the current UK test.

Catalyst petrol cars

The JCS study concluded that the current test was generally 'ineffective' in identifying failures but its ability to identify failures improved as emissions from the extent of excess emitter emissions increased. The λ element of the test did enable more NO_x excess emitters to be added but it also increased errors of commission. The use of HC did not identify any extra excess emitters.

The NAO (1997) had considered the JCS study but having taken views from other parties considered the use of 'ineffective' as too strong. There were also a high number of vehicles which recorded a zero CO reading which may indicate faulty apparatus or abuse of the testing process to enable a vehicle pass.

Conclusions from the TRL study (described in McCrae, 2001) are limited by the lack of an excess emitter definition but from the inspections made on failing vehicles it was concluded that the majority of the faults leading to failure of the MOT would also lead to excess emissions if the vehicle was tested over a loaded drive cycle.

Based on data presented in these studies, Norris addresses the common faults highlighted in **Table 4-3** and presented in a revised manner in **Table 4-10** with some additional (but less likely) faults added.

Reason for high emissions	Effectiveness of test at detecting fault
Catalyst failure:	
Loss of catalyst activity	Low (barring serious deactivation)
Loss of mechanical integrity	Low (but high in extreme cases)
Loss of exhaust integrity (prior to catalyst)	High
Closed loop fuelling system failure:	
λ sensor fault	Moderate/high
Electrical fault associated with the λ sensor	Moderate/high
ECU fault	Moderate
Injector fault	Moderate/high
Failure to move beyond 'warm up' phase	High

Table 4-10: Effectiveness of the current MOT to detect a range of emissions faults for a petrol catalyst equipped car (*Source: Norris 2001b*)

Based on the reviewed evidence, the MOT is judged to be performing 'moderately'. The current strength of the MOT test for catalyst petrol cars is its ability to identify the highest excess emitters in a low cost and quick manner. It should be noted that this strength is likely to be weakened as the catalyst and fuelling system technology matures thus reducing the number of highest excess emitters.

Diesel cars

The JCS study of the diesel MOT test observed that none of the tested vehicles failed on CO, HC or NO_x emissions from loaded chassis dynamometer tests. The only failures occurred for PM emissions. The reliability of the FAS test to identify PM excess emitters was considered suspect and there was only a very poor correlation with the PM output of the NEDC. The main reason for the lack of correlation was thought to be the comparatively extreme nature of the acceleration during the FAS. The FAS is highly dependent on the preconditioning adding further unreliability.

It should be remembered that the studies of the diesel test have examined relatively few EURO III and beyond diesel cars. For these later generation cars, the reliance on emissions control systems and computerised engine management to attain the standards may mean the FAS test becomes extremely unreliable at identifying excess emitters. These devices will reduce all pollutants suggesting pollutants other than PM will also need to be monitored.

Other considerations

Outside of the representativeness of the MOT and its ability to identify excess emitters there are also issues of timing, correct diagnosis and repair, and vehicle 'chipping' by owners (McCrae *et al.*, 2005).

A vehicle can malfunction at anytime and so from the moment a petrol or diesel car leaves the MOT garage it can become an excess emitter with no one being aware (probably not even the owner). Whilst the annual test may expose a number of excess emitters it is unknown how quickly after their last test the vehicle can become an excess emitter. Evidence for this is borne out in the NAO study (1999) which took data of vehicle emissions measurements from a number of sources to illustrate how the number of vehicles which fail the MOT increases throughout the year.

As vehicles become increasingly complicated and computerised, the ability of a small repair garage to fix items relating to emissions control are diminished.

Dealerships have access to expensive bespoke diagnosis tools which can communicate with the vehicle. For example, there is evidence that many catalysts are changed unnecessarily when the problem simply lay with the λ sensor – this would have been identified from the ECU.

Finally, as computerisation has replaced the need to manually tune an engine, so the market for devices which can alter the engine operating parameter has developed. Such devices are intended to reprogram the engine management system with the intention of giving added performance or improved fuel economy – this is at the expense of emissions. Such a simple and undemanding test as the MOT may not identify these vehicles as excess emitters when in fact their performance over the NEDC would identify them as so. Furthermore, their real world performance at higher engine load and speed ranges could be even worse.

In addition to the fitness of the test in detecting genuine excess emitters, the ease of implementation and cost effectiveness of the test should be considered. Currently, the MOT for both petrol and diesel cars is relatively inexpensive and straightforward to implement compared to other methods (e.g. using chassis dynamometers). It should not be forgotten that the motorist, whilst having a responsibility to drive a 'clean' vehicle, have a right to drive their vehicle. In the current climate of perceived high motoring costs, the additional cost of a more in depth emissions test would be an extra burden for the motorist not only under the MOT but also for use of the test for servicing (although for modern cars the use of OBD should identify most faults). An expensive servicing regime would be a deterrent and could in fact have negative impacts on air quality due to the potential development 'drive until it stops' attitude.

4.3.2.5 Emissions saved and cost effectiveness

Quantifying the emissions saved by identifying excess emitters through the MOT is not a straightforward task. Initially, it is worth examining the quantity of cars failing the MOT wholly or partly due to the emissions component. The percentage of cars failing the MOT due to the emissions component is shown in **Figure 4-3** (DfT, 2004). It can be seen that over the last ten years the figure has been falling for both petrol and diesel vehicles.

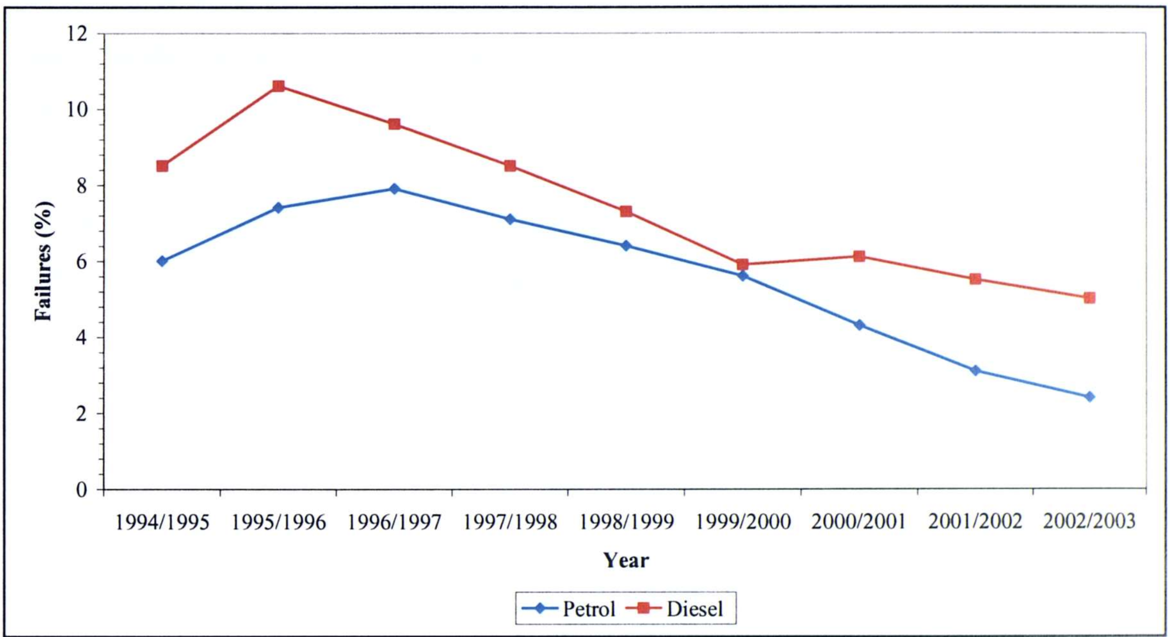


Figure 4-3: Percentage of tested petrol and diesel cars failing emissions component of annual MOT (*Source: DfT, 2004*)

A number of methodologies to quantify the emissions savings from the current MOT regime have been observed during the writing of this review. Both Norris (2000 and 2001b) and NAO (1999) have attempted to quantify the emissions saved by the current test regime whilst McCrae *et al.* (2005) go a step further and attempt to infer the reduction air pollution levels for some hypothetical roads[3].

The most comprehensive methodology is that presented by Norris (2000 and 2001b) which uses the National Atmospheric Emissions Inventory (NAEI) to scale up the estimated savings observed from the NAO report, a priori information based on component failure rates and the JCS study. As a summary, it can be observed that the current test, if continued for the next 20 years, will become less cost effective in terms of grams of pollutant saved per pound sterling spent (g/£). When put into context this trend would be expected as the vehicle fleet in twenty years time will be significantly cleaner than at present. Therefore, when the vehicles do surpass the tighter standards, the amount to which they are an excess emitter will be lower in both percentage and absolute terms than observed at present. This is also coupled with the fact that the numbers of vehicles failing the emissions component of the

[3] Strictly speaking this study examines a number of Local Authority initiatives and not the MOT but the methodology is equally applicable to quantify the MOT.

MOT is falling. A fairer method to assess the future cost effectiveness of the test would be the amount of pollutant saved as a proportion of the total emitted from all sources per pound sterling (e.g. % of total emission from all sources saved/£) – this would ultimately have to be related to impact on air quality. It is possible that whilst the MOT might be less cost effective in terms of emissions saved, the fact that road traffic is such major contributor in urban areas where the air quality issues tend to be, in terms of improving air quality it is actually a more cost effective solution.

4.3.2.6 Future changes to the MOT

In a series of reports for the DfT on the effectiveness of the current in-service procedure for SI and CI engines, Norris (2000, 2001a, 2001b, 2002a, 2002b, 2005) suggests a number of improvements and possible changes to the current test. This is largely in reaction to the changes in vehicle parc technology (i.e. moving to a fleet with a majority of catalyst/particulate trap equipped cars). The much lower emissions experienced with today' catalyst equipped cars and sophistication of the fuelling and emissions control systems requires an approach which is seen as more of a diagnostics check rather than an assessment of real life on-road emissions. Tests on emissions should be viewed as indicators of the efficiency of the systems designed to maintain low emissions.

The introduction of On-Board Diagnostics (OBD) has required vehicle manufacturers to have a dashboard indicator which informs the driver if a component in the vehicle has malfunctioned and is likely to be causing excess emissions above a defined threshold. The OBD technology is considered to be too immature to be a reliable method at identifying if the vehicle has a problem with its emissions control system. It is expected that in future OBD will shift to On-Board Measurement (OBM) as relatively low cost sensors for the relevant pollutants are developed. Indeed, NO_x sensors are already being used as the implementation of de-NO_x technology requires them.

A shift to loaded testing using chassis dynamometers and instrumentation similar to the type approval testing would improve the ability to accurately identify excess emitters as defined by the ECE+EUDC/NEDC. However, it would also be considerably more expensive and inconvenient than the current regime – the cost effectiveness may change for the worse.

As the vehicle parc becomes cleaner, the sensitivity and accuracy of the tailpipe probes will need to improve for the current style of testing to be effective.

4.4 A place for remote sensing?

Two of the reports referenced in this chapter make reference to or are written about the use of remote sensing as a tool for inspection and maintenance (NAO, 1999; & McCrae *et al.*, 2001). The use of remote sensing devices to measure the emissions of passing cars is not a new concept, indeed it has been utilised by a number of US States, with US Environment Protection Agency (EPA) approval, since 1996 (ESP, 2005a). Passive measurement of vehicle emissions using remote sensing devices has the ability to measure vehicles at any time during their use, not just on an annual basis. It also has the advantage of measuring the vehicle under some form of load which is particularly advantageous for NO_x measurement. Of course there are also drawbacks to this form of emissions measurement and these are outlined in the next chapter.

4.5 Summary and conclusions

A vehicle with an emissions related fault will produce significant excess emissions compared to what it is capable of, if operating correctly. This has the effect, in terms of emissions, of increasing the number of vehicles on the road. Natural degradation is accepted and regular servicing can minimise this degradation. To ensure improving vehicle emissions in the UK there are two strands of inspection. The first considers the type approval of a vehicle model family (i.e. the same vehicle model with the same vehicle engine). In terms of emissions, these must comply with increasingly strict emissions standards as defined by the EC (commonly known as EURO standards). Thus, the definition of a gross polluting vehicle is one which fails its type approval test when degradation is taken into account.

The second inspection checks that individual vehicles are operating as they should be in terms of emissions. Vehicles registered in the UK are required to undergo an emissions test within the annual MOT after three years of use. The tests for petrol and diesel cars are very different, both in terms of procedure and pollutants tested. The standards to which the vehicles are tested have become tighter in parallel with type approval emissions standards implemented at EU level. The effectiveness of these tests at identifying those vehicles which, under the definition above, should be classed as excess emitters has been shown to vary. The test for non-catalyst petrol cars is reasonably effective although their numbers in the UK vehicle parc is continuing to diminish. The catalyst petrol car test is considered to be performing moderately although in the future it is anticipated that this will become less effective. The diesel test does not correlate very well with identification of excess emitters. In defence of the current tests, they are relatively quick and inexpensive to implement and some changes could improve its ‘fitness for purpose’.

The declining percentage of car failures due to the emissions component of the MOT does not mean that the numbers of vehicles with an emissions related problem are falling. This can either be due to more cars actually passing the test or the test being less effective at identifying vehicles which actually have an emissions related fault. This second possibility is a result of having vehicles which rely on such technology that they are not apparent under the unrealistic conditions of the current MOT test.

Traditionally easy to identify and fix emissions related faults are becoming rarer as the car fleet increasingly depends on sophisticated emissions control technology. For both non-catalyst petrol and diesel cars the most common faults to cause increased emissions are due to mechanical wear. For vehicles that depend on computerised engine management systems and post exhaust treatment it will most often be these components causing excess emissions, although mechanical wear will inevitably still be the cause of some faults. Mechanical faults can be readily identified by an experienced mechanic through visual observation of the component alone. The use of more sophisticated means to control car emissions has, and will continue, to require equally sophisticated diagnostic tools to interrogate the vehicle. How adept the average car mechanic is with such an approach varies but fixing components of such sophistication may well be beyond them. This can lead to a full replacement of a part rather than simply fixing it. This has implications for the cost of vehicle maintenance and possible knock on effects on the avoidance of repairs. A cynic might also conclude that the use of sophisticated and expensive diagnostic tools tailored to a particular vehicle marquee, not only forces independent mechanics out of business (due to equipment costs) but also encourages vehicle owners to only take their vehicle to a marquee approved garage.

Future use of self diagnosis, using the cars ECU (using OBD), has potential but is considered to immature to be relied on at present. As real time exhaust gas sensors for the pollutants of interest become less expensive they may be suitable as a substitute to current tailpipe tests. As this develops then the need for an emissions test within the MOT will be redundant. Instead, the vehicle need only be interrogated to see if any events have occurred where emissions higher than they should be and the reason for this occurrence. Where a vehicle fails a relevant emissions limit using this approach the driver would be informed using a dashboard indicator. This approach raises two questions:

i) How *will an emissions limit be specified?* If it is from real world driving, how the emissions measurements be related back to what is considered the current definition of a gross polluter (i.e. based on the vehicles type approval standards).

ii) *Who will ensure that a vehicle is brought in for inspection and maintenance if a fault is detected?* As discussed before, the expense of the necessary repair may lead to avoidance and have a negative impact on emissions.

A further, criticism of the current testing regime is the relatively long time a car can go without being inspected and as a result it could be producing excess emissions as soon as it has left the testing garage.

A potential solution to a number of the issues identified above is the use of remote sensing as a form of driver feedback to assist them in monitoring their vehicles emissions. The use of remote sensing is discussed in the next chapter.

5 ON-ROAD REMOTE SENSING OF VEHICLE EMISSIONS

5.1 Introduction

One approach to measuring vehicle emissions, which has been used extensively in the USA, is the use of roadside remote sensing devices (RSD). The principles behind the approach and issues surrounding its use are described below. RSDs have been used for a range of vehicle emissions related applications including I&M programmes. An examination of the RSD unit used for this research was undertaken including issues regarding measurement accuracy and on-road use.

5.2 Principle of remote sensing

5.2.1 Exciting molecules

When light, regardless of wavelength (e.g. ultraviolet, infrared or visible), passes through a gas molecule some of the energy from the light is absorbed by the molecule and raises it to an excited state resulting in some loss of intensity of the light. This is the basic operating principle of remote sensing of passing vehicle emissions. Different gases react significantly to different wavelengths of light with many reacting at a number of wavelengths. A good summary of the physics behind this behaviour is given in Jimenez's excellent and detailed thesis (1999). For the purposes of this explanation it is only necessary to accept the basic principle explained above.

Using this behaviour it is possible to find wavelengths of light at which only one gas reacts. Because of this useful behaviour a number of databases mapping the different wavelengths at which gases react have been developed. **Figure 5-1** shows an example of the HITRAN database (Rothman *et al.*, 1998) which pictorially shows the wave numbers (a different expression for wavelength) and wavelengths at which a number of gases react. Some of the gas species which are of particular interest to those studying vehicle emissions are highlighted.

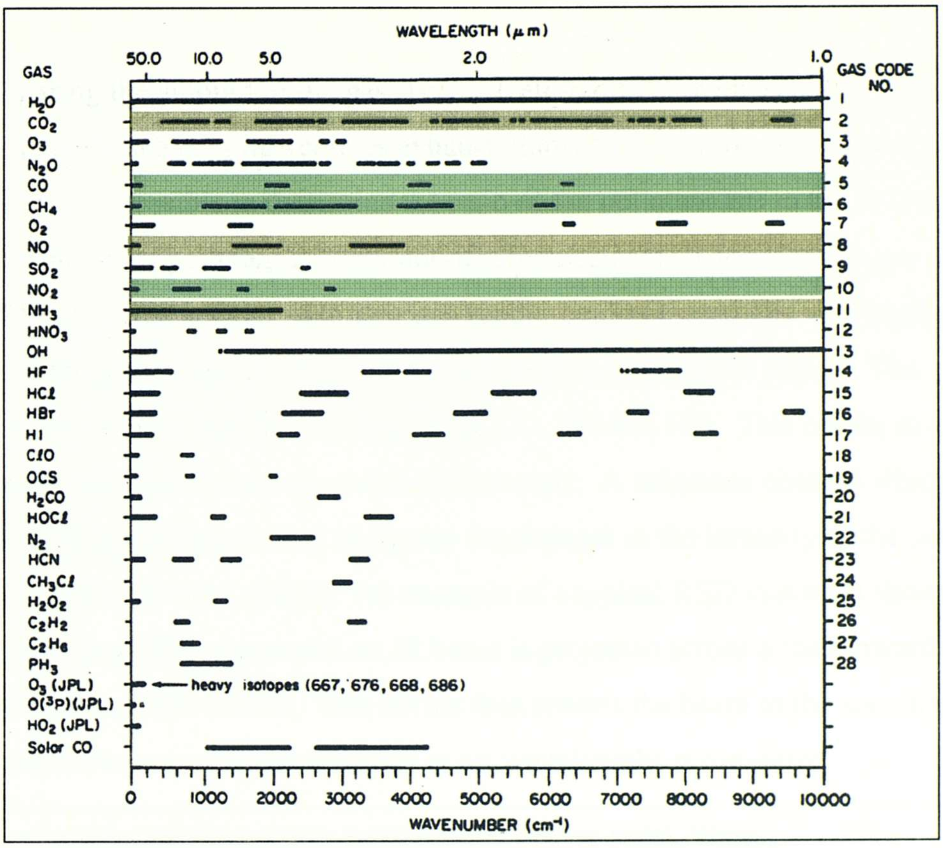


Figure 5-1: Wavelengths at which various gas species absorb IR radiation as given in the HITRAN database. Levels of absorption are not equal across the range for which absorption is indicated (Source: Rothman *et al.*, 1998)

Once the wavelengths for the gas species of interest, which have no interference from other gases, have been identified it is possible to measure the loss of energy at these wavelengths to quantify the amount of a particular gas species. A number of methods to isolate the light of a particular wavelength have been developed and whilst these could be discussed at length, the most important point is that they can be isolated. The remote sensing device (RSD) used for this research is based solely in the infrared (IR) spectrum (the same as that used by a television remote control). The intensity of the particular IR wavelength is measured by specifically designed detectors which translate this intensity to a voltage which can then be used to produce a 'meaningful' quantitative value.

5.2.2 On-road remote sensing

By comparing the amount of the gas species (referred to here on as pollutant) of interest present in a passing vehicles exhaust plume to a reference gas also emitted in the plume, it is possible to determine the ratio of the pollutant gas to the reference gas (i.e. amount of pollutant gas/amount of reference gas). The reference gas used by all RSD systems is CO_2. Whilst water vapour could be used, the very high and variable background levels make it too insensitive to the exhaust plume. The pollutant gases measured for this project are CO, HC and NO. This results in a number of 'channels' being measured concurrently. A reference channel which is not absorbed by any gas is used to correct for changes in the intensity of the output IR source (McCrae *et al.*, 2001). An example of a typical RSD system is shown in **Figure 5-2**. From the source unit an IR beam is projected across a road towards a reflective corner cube mirror. This mirror then returns the beam to the source unit where measurement of the IR intensity at set wavelengths is measured.

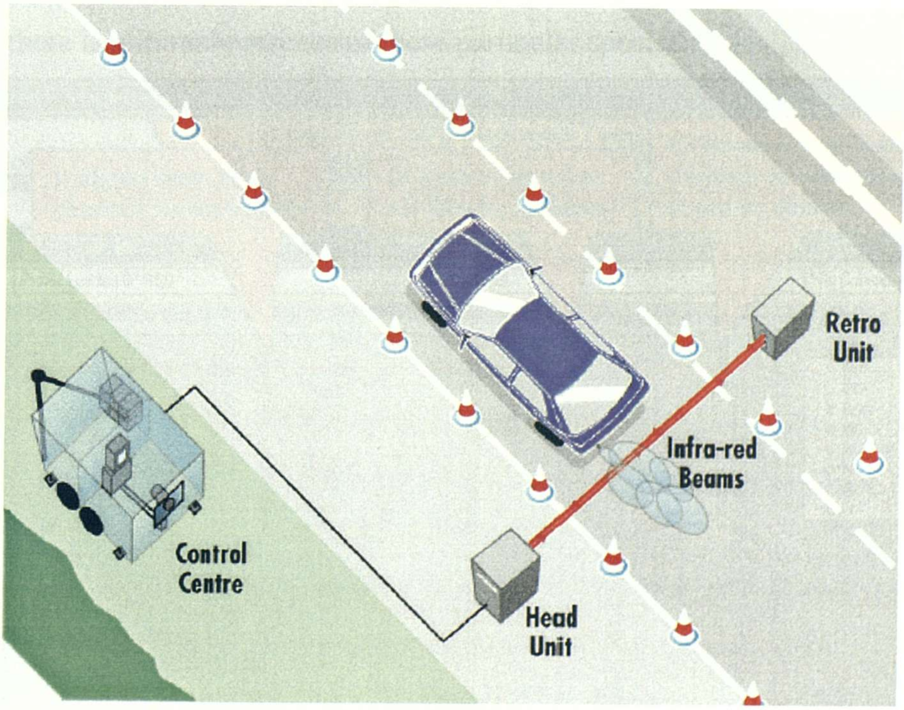


Figure 5-2: Typical RSD site setup (*Source*: Golden River Traffic, 2004)

When a vehicle passes through the beam an initial total loss of signal is experienced as the car blocks the beam. When the vehicle clears the beam, the beam then interacts with the exhaust plume as it passes through it, resulting in some loss of signal intensity. The data capture lasts for approximately 0.5 seconds which when refined to isolate the plume absorption in the measured trace, leaves 0.2 seconds of data. The instrument used for this research measured the signal with a frequency of 1750Hz. **Figure 5-3** shows a typical plume profile from a vehicle in which three distinct periods are noticeable:

i) A stable signal for each channel before a car is detected

ii) Car blocks IR beam resulting in no signal from any of the channels.

iii) Recovery of signal after car has passed and IR beam is unblocked, returning a signal.

Note how the reference channel (top, red line) stabilises to the previous background value whilst the CO (ringed second from top, green line) and the CO_2 (ringed fourth from top, yellow line) take time to recover because the channel signal is being absorbed by the presence of these gases in the decaying car plume. The variations in the other channel can be seen to match the reference channel meaning that this variation is due to obscuration of the IR beam or changes in source intensity. This means there is minimal presence of these particular species.

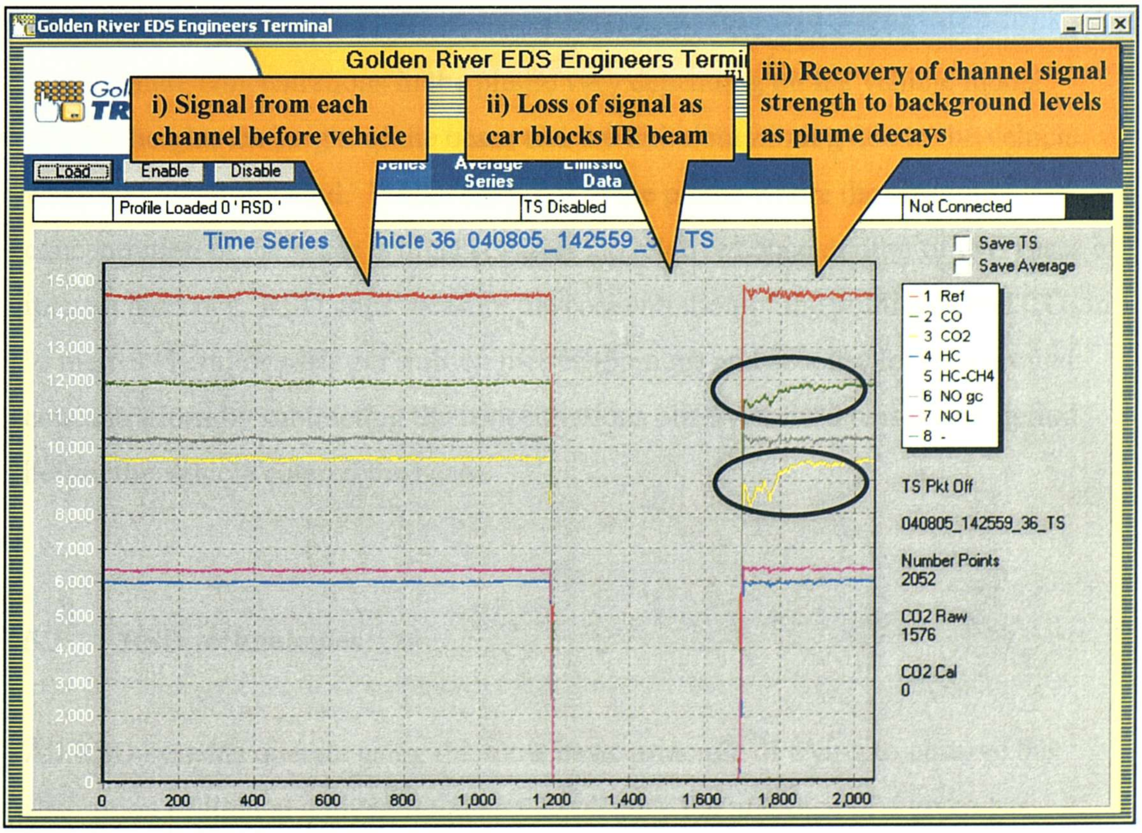


Figure 5-3: Typical vehicle trace showing a channel for each gas species of interest.

Figure 5-4 shows how the plume concentrations of CO_2 and CO (in %.m), from the above vehicle trace, follow each other.

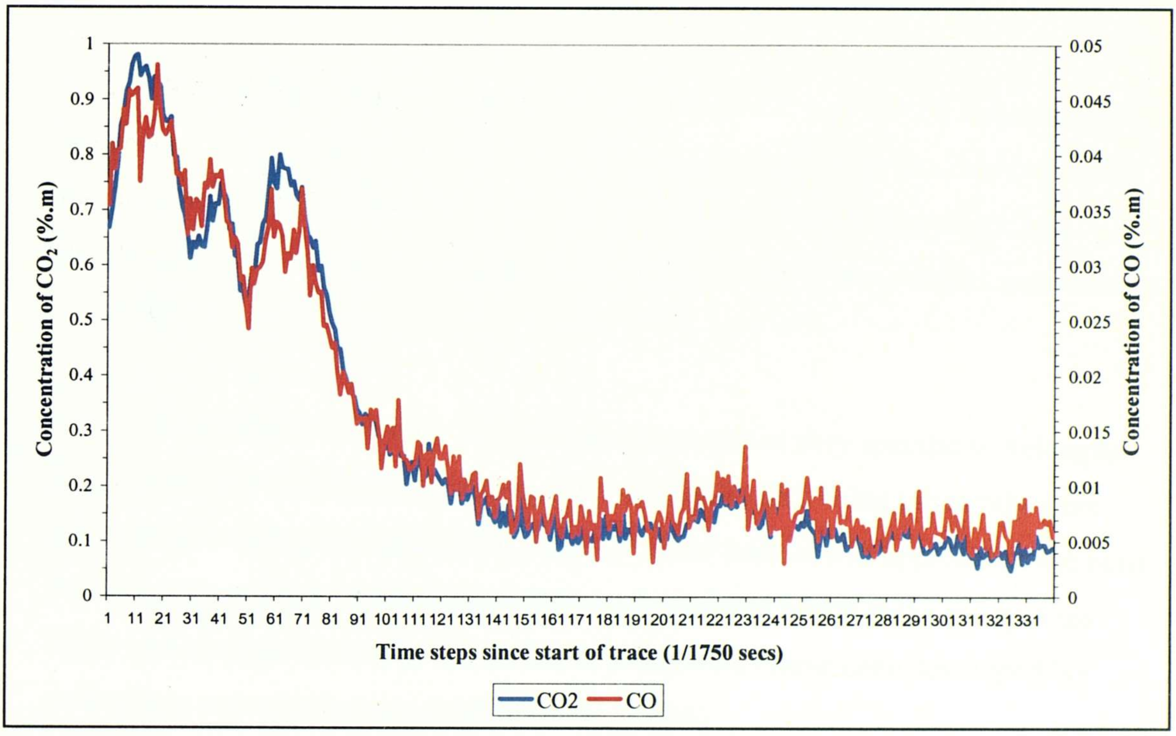


Figure 5-4: Measured concentrations of CO_2 and CO from the vehicle trace shown in **Figure 5-3**

The absolute concentrations in the plume vary depending on the vehicle model tailpipe height, the height of the beam and the turbulent mixing due to the vehicle wake and localised wind. Whilst the point in the plume where the absolute concentration of the gases is highest varies the relative concentration of two gases of interest does not. RSD units measure the concentration of the pollutants and CO_2 in % metres (%.m) or parts per million metres (ppm.m) and account for background concentrations by subtracting the concentrations observed for a reasonable period before the vehicle entered the beam.

5.3 RSD technologies

All RSD systems operate using the same basic principle of trying to observe the absorption of light at a given frequency to identify the presence of a given gas species. Over the years a number of different approaches have been applied to the problem. A history and review of these technologies have been described by McCrae *et al.* (2001) and REVEAL (2000).

Briefly three approaches have been used:

- **Non-dispersive infrared and ultraviolet** (NDIR and NDUV respectively) which samples light in the wavelengths of interest using narrow bandwidth filters in the IR region (e.g. Stedman, 1989). The main problem with this approach is interference from other exhaust constituents in the range of wavelengths measured by one filter.

- **Tuneable laser diodes** (TDLs) which transmit at very specific wavelengths in the near IR or UV regions (e.g. Nelson *et al.*, 1998) thus being inherently more accurate in isolating the species of interest. A draw back of this approach is the need for cryogenic cooling of the diode sources and receivers which make the systems bulky and comparatively expensive. Non-cooled TDLs have been developed but suffer from noise limitations (McCrae *et al..*, 2001).

- **Dispersive infrared** (DIR) which utilises rapid scanning capabilities of more recent electronic systems to capture a wide range of IR and UV wavelengths (spectra). The spectra data for each vehicle is then analysed using software to identify absorption at the frequencies of interest (Baum *et al.*, 2000 & 2001).

Most RSD studies available in the literature has used units based on the NDIR/UV approach developed by Stedman's group although the study by Jimenez utilised the TDL approach.

As interest in the impact of vehicle particulates has grown, approaches to quantifying the emissions of particulates using RSD has been explored. Early systems quantified particulates by examining the opacity of the vehicle plume (ESP, 2001) although more sophisticated Light Detecting and Ranging (LIDAR) has been demonstrated (Kuhns *et al.*, 2002). This LIDAR approach used a narrow band of UV light and observed the amount of particle reflectance, or back scattering, from within the exhaust plume. This back scattering measure was then used within an algorithm based on assumptions of particle size distribution and composition to estimate a particle mass/CO_2 ratio.

5.4 Site selection

Since the early seminal work by Don Stedman and Gary Bishop from Denver University (Stedman, 1989), a range of RSD devices have been developed but using the same operating principle of passing a beam across the road. A wealth of experience has been built up in the RSD community leading to a best practise approach to site selection (Swayne, 1999).

The use of RSD to gather meaningful data is dependent upon careful site selection. As with any fair test there should be some form of control of other variables which might influence the end result other than the aspect of interest (i.e. maintenance and vehicle emissions). There are a number of other factors which should be considered which will also have a significant affect on emissions but not offer any insight into emissions reduction capabilities of the vehicle (e.g. road gradient or vehicle power use). In addition to those factors influencing emissions, other issues such as site safety of operators, drivers and vehicle throughput need to be addressed. With these points in mind it is possible to draw up a best practice on RSD site selection. Site selection against the following criteria occurred during the Winchester study (see **Chapter 6**) in 2002/2003.

i) *Use single lanes of traffic* – the RSD would have difficulty in operating efficiently across two or more lanes of traffic. For clean capture of a passing vehicles plume there should be no interference from other vehicles. Whether over a bi-directional two lane road or two lanes in a single direction the frequency of overlap from other vehicles other than the ones of interest will be too high, and the number of correct readings will be reduced. Use of ANPR and speed measurement equipment can also be difficult when there is more than one lane of traffic, even more so when records from all three systems need to be integrated. It transpired that the road width across which the RSD could be used was 6-7 metres – fortunately the approximate width of a single lane.

ii) *Vehicles passing through the site should have reasonably consistent operating conditions* – The vehicles speed and acceleration through the measurement site can have a significant impact on the vehicles emissions. To undertake a fair comparison amongst vehicles, the range of operating conditions should be quite narrow although the development of the VSP parameter (see below) has enabled fairer inter-comparison.

iii) The s*ite should be on a slight incline, have a gentle bend and vehicles should be under moderate acceleration* – such sites enable similar speeds and acceleration rates from vehicles but more importantly they ensure the vehicle is under a load (i.e. doing reasonable work) when measured. It has been discussed in **Chapter 4** that one of the reasons why the current MOT is not particularly effective is that it is performed when there is no load on the engine. With the vehicle under load and operating in a gentle transient mode (i.e. light acceleration), the emissions control systems, be it a catalyst or EGR, will have to be working harder to control emissions to an acceptable level. This is a much more robust testing condition to identify high emitters and for comparison between vehicles.

iv) *A relatively high volume of vehicles should pass through the site* – for a low cost per measurement the site should have a high number of vehicles passing through the site. In many US studies freeway on ramps have been used. Whilst in the US this would be suitable in terms of operating conditions the higher motorway speeds of the UK would mean the vehicle would have to be accelerating quite quickly to reach a safe merging speed. Statistics from the US seem to indicate that many vehicles never actually travel on freeways, it is unsure this is the case in the UK[1]. The low proportion of gross polluting vehicles in the fleet means that the higher traffic flow, the higher the chance of observing gross polluting vehicles. It is therefore advisable to try and capture peak flow whenever possible. Care should be taken to not use data from when high levels of flow result in vehicles following each other too closely thus not allowing adequate plume dispersion from the previous vehicle.

v) *Avoid sites subject to cold-starts* - When a vehicle engine is first started the emissions and fuel consumption as higher than when fully warm. There is some fuel enrichment petrol cars as the fuel metering system compensates for condensation losses of fuel on the cold sides of the intake manifold (this is not such an issue for diesel vehicles). The engine management system will also operate the vehicle in rich fuel mode to warm the engine as quickly as possible. Beside the extra fuel used, there are direct emissions effects of cold starts due to inefficient combustion in the engine and cold catalysts. A vehicle in a cold start state may therefore appear to be a higher polluter than it really is. RSD sites away from sources of cold start vehicles, such as car parks or housing estates, is necessary. Euro II vehicles are thought to achieve a fully warm state after approximately three kilometres of driving.

vi) *Vehicles passing through the site should be under normal, freeflow driving* – the use of traffic management (e.g. signs and cones) should be kept to a minimum so as not to alter the normal driving pattern through the site. Conversely, coning can be useful in some instances to modify passing traffic

[1] Given that it is Winchester's city centre which is the AQMA it would be wise to sample traffic from vehicles travelling into the city the centre during the morning peak and not away from the city.

behaviour (e.g. by narrowing the road way with a coned 'funnel' vehicle leaving will be accelerating and so under load. Traffic devices such as give way junctions, signal junctions or pedestrian crossings should be avoided due to the possibility of vehicle backing up into the site.

vii) *Sites should be safe for operators and drivers* – safe site set-up puts restrictions on, not only what time of day the survey can take place but also what roads can be monitored. The UK Government has some fairly overbearing guidance for on-street works and their safe set up which must be adhered to for fear of prosecution in the event of an accident. This guidance is clearly designed with 'hole in the ground' type of street works rather than static cabinets which, in many instances, are not in the live roadway. For the designs have been drafted for the sites chosen for this project, it may be that the guidance has been misinterpreted. The safety of drivers passing through the site must also be a priority.

It is necessary to note that despite careful site selection, it is impossible to control for every variable. One particularly difficult factor to quantify as the vehicle passes is the load. The vehicle load can be affected by the number of persons/goods the vehicle is carrying, tyre pressure, or accessories such as air conditioning, headlights, etc.

Due to the inevitable variability discussed, more certainty can be applied to a measurement if repeat readings are taken.

5.5 Vehicle Specific Power (VSP)

Work by Jimenez (1999) identifies the useful measurement of VSP as a strong indicator of the load the vehicle in under as it passes the measuring site. VSP is calculated by assuming standard coefficients for rolling resistance, drag. etc. and determining a vehicle speed, acceleration and road gradient. VSP is useful tool for relating the emissions produced to the work undertaken by the passing vehicle. It can be used in two ways:

i) *to filter out results where the vehicle is accelerating harshly and the emissions would be expected to be high.* It has been highlighted in **Chapter 4** that vehicle manufacturers often do 'just enough' in terms of emissions abatement to pass the legislative drive cycles to which they are type approved. Beyond the operating conditions (i.e. engine speed and load) experienced on the legislative drive cycles the emissions may be much higher almost as if there were no emissions control operating. These events are referred to as off-cycle events. It would be unfair to identify a vehicle operating in an off-cycle event as a gross polluting vehicle since there would be no faulty component in the vehicle which could reduce its emissions. By calculating the maximum vehicle specific power experienced on the NEDC it is possible to use it as a threshold of vehicle operation beyond which the emissions values should be discounted for the purpose of identifying gross polluters.

ii) to *compare emissions results from different sites.* At different sites, vehicles will be operating in a different manner. For example the average work of a car at a site which is 30 mph and on a flat road will be lower than that of a site which is 40 mph and uphill. As a result the emissions from these two sites will be expected to be different and as such it will be impossible to objectively compare the emissions. By correcting the average emissions profile of Site A to that of Site B it is possible to know what the emissions distribution would have been like if the vehicles at Site A operated at the VSP of Site B.

5.6 Applications of remote sensing in the field of vehicle emissions measurement

Since its development, the roadside RSD has been applied to a number of areas of emissions research and management. The bulk of literature is from US based studies although RSD's have been used in Europe, New Zealand and Asia. Indeed, RSD devices have also been developed in New Zealand (Gong *et al.*, 1999) and Europe (REVEAL, 2004).

5.6.1 Fleet characterisation

As well as undertaking trials which proved the concept of using RSDs as vehicle emissions measurement tools, much of the early work with RSDs attempted to profile the emissions from vehicle fleets. The emissions profiles were compared to a number of parameters such as vehicle age, speed and acceleration. The characterisation of a fleet is often the first step taken when RSDs are first used by third parties in other countries (Zhang *et al.*, 1993; Guenther *et al.*, 1994; Stedman *et al.*, 1994; Sjödin and Lenner, 1995; Zhang *et al.*, 1995; Sadler *et al.*, 1996; Bishop *et al.*, 1997; Fisher *et al.*, 2003; Schifter *et al.*, 2003; ESP, 2005).

Within all of these studies some general conclusions are borne out consistently:

- **Half the emissions measured at a site are produced by a disproportionate minority of the vehicles measured.**

Within all of the fleets monitored by remote sensing it can be said that some vehicles emit more emissions than others. RSD studies often report the percentage of vehicles which produce 50% of the total emissions measured, or the contribution of the most polluting 10% towards the total measured emissions. An example of the later approach where the emissions measurements are ordered and divided into deciles is given in **Figure 5-5**; the emissions from each decile are totalled and expressed as a percentage of the total emissions measured.

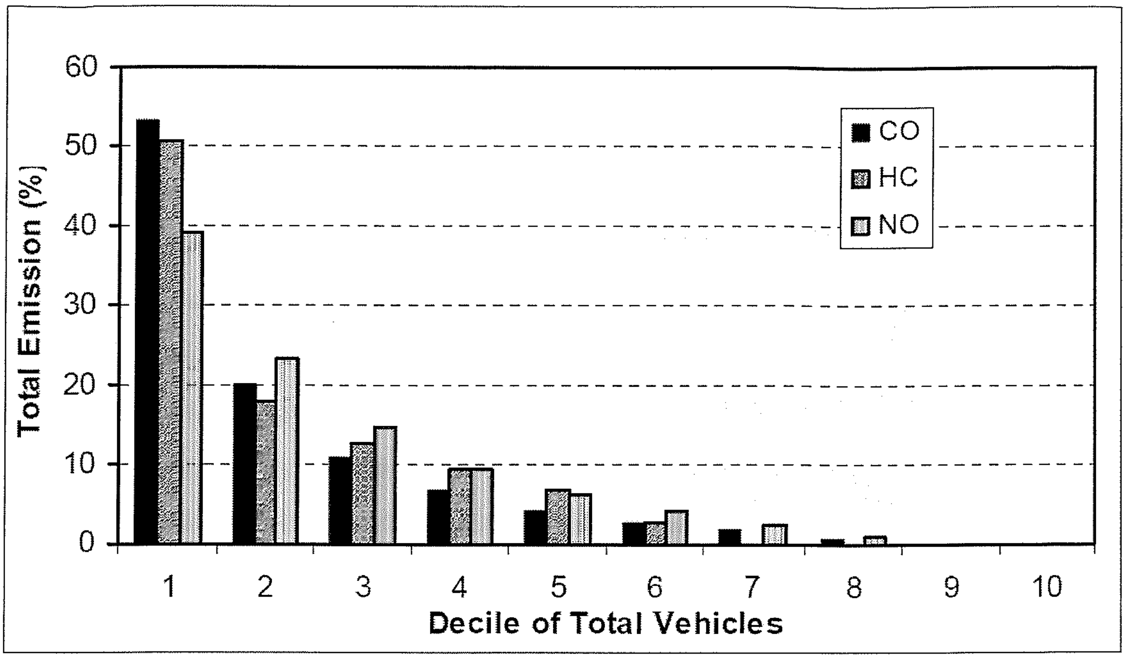


Figure 5-5: Example showing how 10% of the highest polluters contribute a disproportionate amount of emissions. (Source: *Fisher et al., 2003*)

Variations in emissions measured at a particular instant can be expected to vary in this way due to a number of factors such as engine load, emissions standards, maintenance, natural degradation with mileage, etc.. Some of the issues which confuse the statistical analysis of RSD measurements were presented by Wenzel *et al.* (2000). Early criticisms of the usefulness of RSD measurements highlighted that when looking at second by second emissions data, from a vehicle following a driving cycle on a chassis dynamometer, when the data were treated in a manner shown in **Figure 5-5**, 10% of the measurements would produce a disproportionate amount of emissions (Swayne, 1999).

However, in such circumstances the variation can be considered to be due to the variation in vehicle operating conditions, and so variation in how the emissions control system copes with these changes. Other factors are controlled for because the test is of just one vehicle. So, to ensure that the emissions profile seen in is not solely due to varying operating conditions, sites are selected where the range of vehicle operating conditions (in terms of speed and acceleration) is narrowed (Klein and Koskenoja, 1996). Furthermore, when emissions data from a chassis dynamometer tests from a large number of vehicles are considered this same effect is shown with some vehicles having significantly higher emissions than others (Zhang *et al.*, 1994). In these circumstances the operating conditions of the vehicle are controlled for (all vehicles follow the same driving profile) and so the emissions variation must be due to other factors. Jimenez (1999) shows that for fleet RSD measurements, VSP does have some influence on emissions. This highlights the benefits of VSP in restricting the data considered for use of RSD studies removing unrepresentative data

Grouping measurements as they appear in **Figure 5-5** enables a clear picture of how disproportionate the emissions distribution from a vehicle fleet is. When the distribution of a histogram showing how often a particular pollutant concentration (see **Figure 5-6**) is measured the potential of I&M programmes which target the highest polluters can be seen. This distribution has been modelled using log-normal (Stephens, 1994) or gamma (Zhang *et al.*, 1994) distributions.

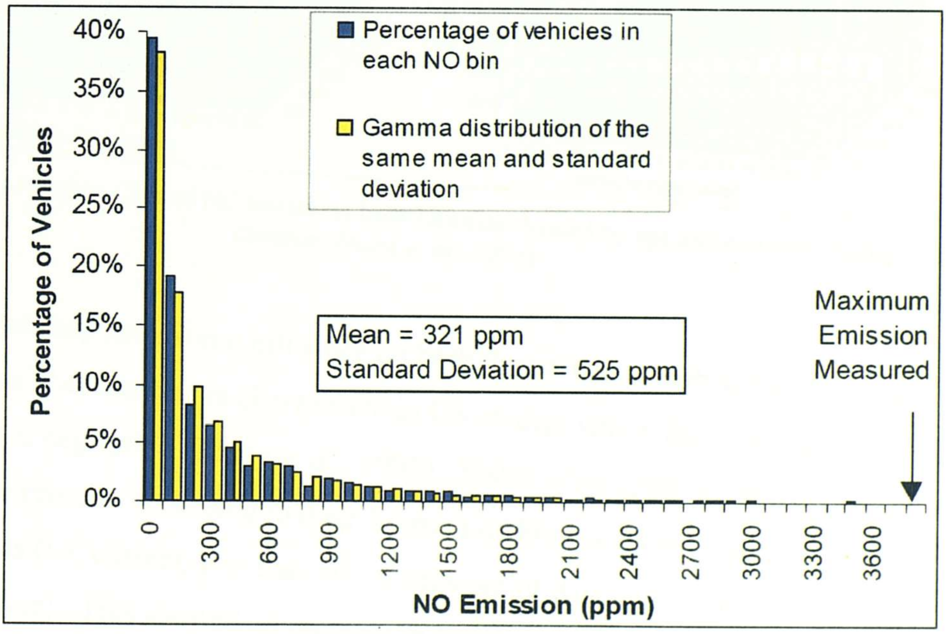


Figure 5-6: NO emissions distribution plotted against the expected value for a γ-distribution with the same mean and standard deviation (Source: *Jimenez, 1999*)

Average emissions deteriorate with vehicle age and emissions vary within individual age groups

Trends of increasing average emissions with age is attributed to a correlation between age and a combination of vehicle emissions standards, vehicle maintenance and fuel mix (diesel vs. petrol), and vehicle mileage. (Guenther, 1994; Sjodin and Lenner, 1995; Zhang *et al.*, 1995; Stephens *et al.*, 1997; McCrae *et al.*, 2001, Fisher *et al.*, 2003; Schifter *et al.*, 2003). **Figure 5-7** gives the average emissions of CO and

HC when binned by vehicle age with each age group divided into five groups according to their emissions value; these data are from Leicester in the early 1990s. It can be seen that emissions increase steadily with age (due to maintenance, vehicle design or fuel) but that emissions within age groups also vary (this maybe a maintenance, vehicle design, fuel or operating condition effect). Operating conditions can be discounted from having an influence on the increasing emissions with age as, on the whole, there is no reason why an older vehicle should be driven any differently than a new vehicle.

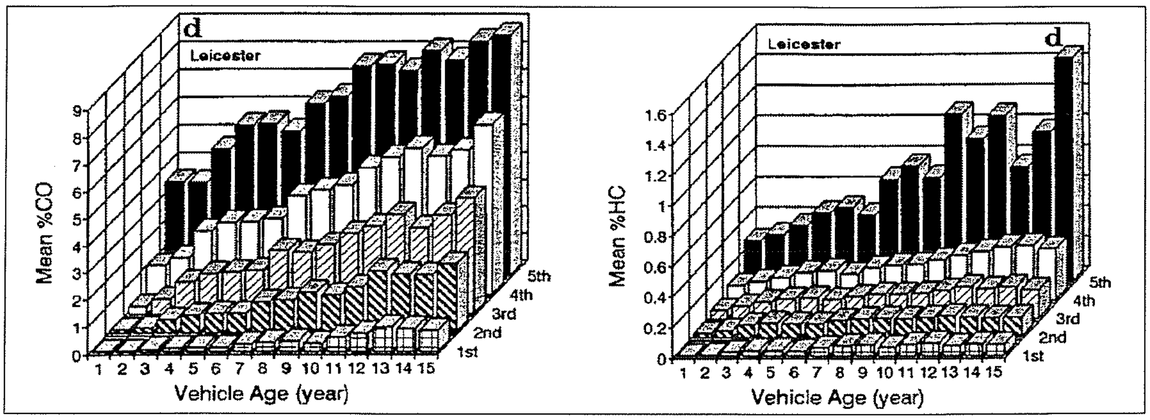


Figure 5-7: Average CO and HC emissions from Leicester binned by age and emissions value (Source: *Zhang et al., 1995*)

Whilst fuel type may have some influence on both the variation with age and within age groups, this phenomenon is also present in US studies where the influence of diesel vehicles is negligible (Zhang *et al.*, 1995). Fisher *et al.* (2003) compared emissions from vehicles according to their Warrant of Fitness (WoF; equivalent to UK MOT) status (i.e. current, less than six months out of date and more than six months out of date). This showed an increase in average emissions as the WoF became more out of date thus indicating the influence of maintenance picked up by the WoF (or would have been remedied by members of the public conscientious about having a valid WoF) does have an influence on fleet emissions.

To understand the influence of the vehicle operating conditions on the within year variation the VSP could be controlled for. If a large enough sample of vehicles were collected within a small VSP range then a similar plot as in **Figure 5-7** could be produced and if the within variation remained, with a higher degree of certainty this could be attributed to vehicle design or maintenance. Such a plot is presented in

Figure 5-8. It can be seen that for vehicles of the same year of registration, within narrow VSP bands, that the top decile of polluters have a much higher average CO emissions value.

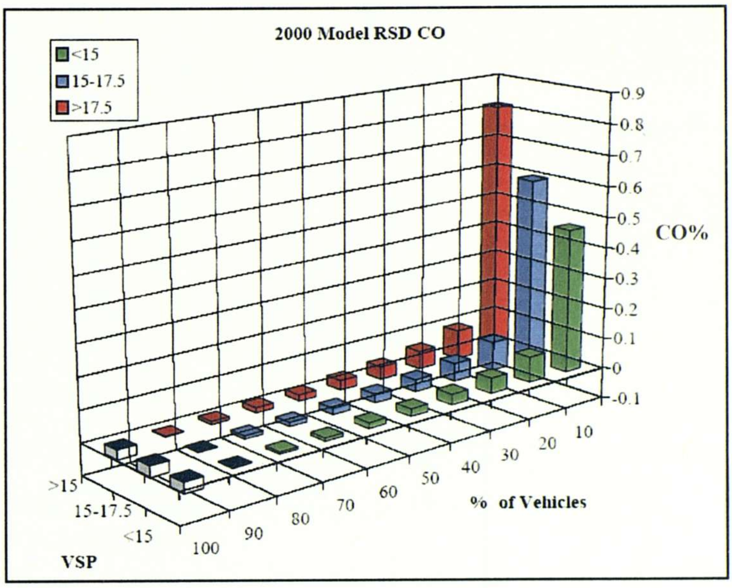


Figure 5-8: Decile plot for vehicles of same model year, and within narrow VSP bands (*Source: USEPA, 2004*)

Even better would be to separate the vehicles according to their date since last MOT as well as age. An example dataset of showing how average fleet CO emissions based upon time period leading upto and just after a vehicle had been subjected to an I&M test is presented in **Figure 5-9**. The data seem to suggest that vehicle emissions deteriorate in the few months preceding the test with some reduction in the month immediately prior to the test (perhaps as vehicle owners have repairs made to ensure their vehicle passes). A reduction due to any repairs made as a result of the inspection (or scrapping of a failure) is also apparent.

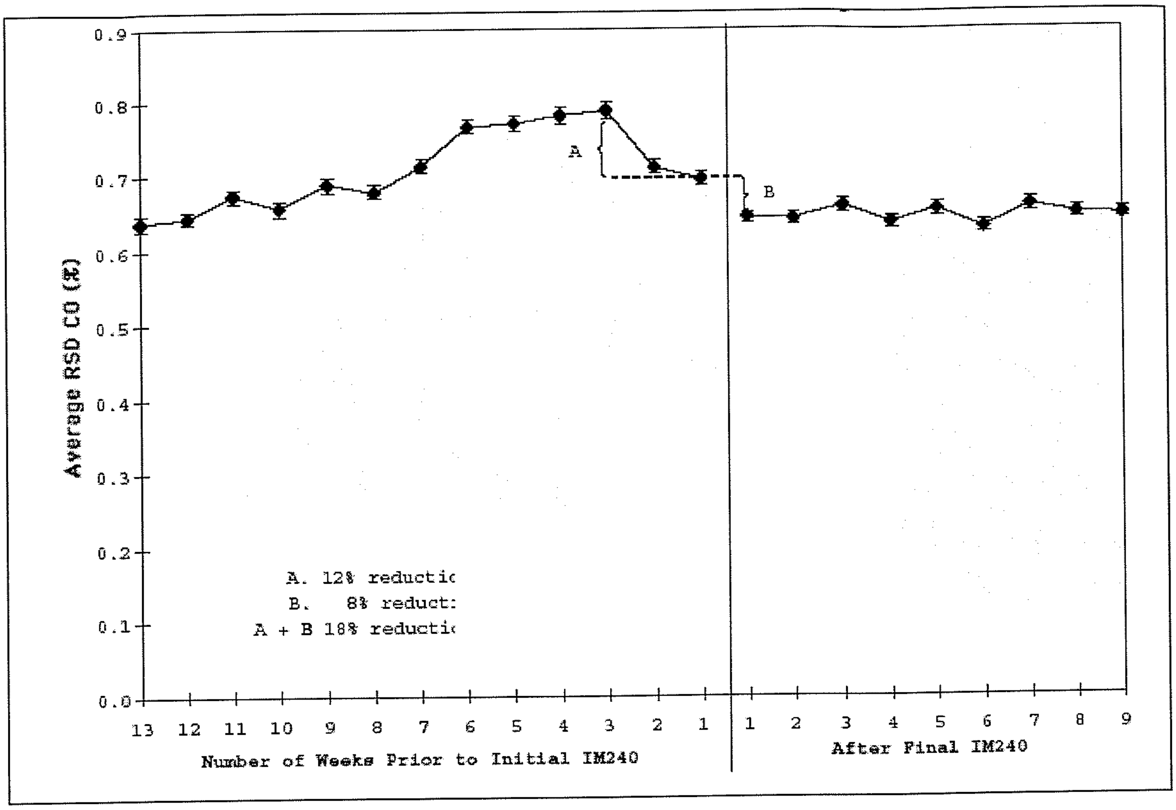


Figure 5-9: Average fleet emissions categorised by time prior to or after their last I&M inspection *(Source: USEPA, 2004)*

5.6.2 Vehicle emissions inventories

One of the key advantages of the RSD approach to measuring vehicle emissions is the high number of vehicles it can measure within any given time period (up to 4000 veh/hr). This results in large databases giving an unparalleled insight into fleet emissions. These emissions can be converted into either fuel or distance based emissions factors using idealised combustion equations and, in the distance based factors, an assumption of fuel consumption rates. Vehicle emissions factors are usually developed using chassis dynamometer measurements of a small number of vehicles and their representativeness if often questioned due to their small sample size and driving cycle design (Bluett and Fisher, 2005). RSD measurements on the other hand capture a large number of vehicle with vehicles operating over a range of operating conditions (extent of this range depends on the site chosen). RSD measurements can be used as a check on chassis dynamometer derived emissions factors in a similar manner to tunnel studies (Bishop *et al.*, 1996). Using one second chassis dynamometer data as a substitute for RSD measurements, Stephens *et al.*,

(1996) showed that the use of a large number of RSD measurements was appropriate at determining fleet representative emissions factors, although this study was limited to relatively new vehicles. Using RSD derived emissions factors a worldwide CO emissions inventory was derived by Bradley *et al.* (1999).

5.6.3 Inspection and Maintenance

Following the emergence of the RSD in the late 1980s/early 1990s, the approach was put forward as replacement for the I&M procedures in place at the time whilst others suggested the opposite. Early research confirmed the latter but did show RSDs had potential to supplement the current I&M tools by making them more efficient. (Vescio, 2002). In the USA areas in which necessary air quality standards are not achieved are subjected to State Implementation Plans (SIPs). The SIPs are analogous to the AQAPs developed by UK LAs in the event of an AQMA. SIPs which identify the reduction of vehicle emissions as a solution to the air quality problem declare enhanced areas where a more rigorous I&M campaign is introduced. This necessarily covers a much wider area than the area troubled by poor air quality due to the transient nature of motor vehicles. These areas are known as enhanced areas. Within the USA Clean Air Act Amendments (1990), a provision was made for areas with enhanced I&M programmes to monitor improvements in on-road emissions using RSD measurements of 0.5% of the fleet in the enhanced area.

Reading between the lines of the available literature it would seem that some US states were reluctant to implement the centralised chassis dynamometer tests suggested by the USEPA due to the expense, time and public accessibility to a few centralised testing stations. Indeed, California instead opted for a less expensive, decentralised testing regime simplified inertia dynamometer called the ASM due to cheaper costs etc.. Some states also resisted the implementation of the 0.5% sampling approach (Vescio, 2002).

5.6.3.1 *Gross polluter identification*

Gross polluter identification uses RSD measurements to identify those vehicles which have a high probability of failing a legislative emissions test (e.g. idle or chassis dynamometer). Since a vehicle can develop an emissions related fault at anytime regardless of when it was last subjected to I&M, the gross polluter identification approach operates as a monitoring system which supplements the current I&M programme. By identifying vehicles whose excess emissions would otherwise not have been removed from the road until they were next tested.

The cost effectiveness of such a programme requires the correct 'cut-points' or thresholds to be set for the RSD measurements (i.e. the indicator) which corresponds to a failure on the I&M test (i.e. the standard). This relationship is not perfect with the RSD identifying some vehicles as failures or passes incorrectly when compared to the I&M test (i.e. errors of omission or commission). A definition and schematic representation of these errors is given earlier with **Figure 4-2**. Barlow's study (1998) (also reported in McCrae *et al.*, 2001) is the most relevant to this current study as it considers a European fleet. A threshold for catalyst vehicles of 5% CO and 1000ppm NO was suggested as it is at this point errors of commission reach a reasonable low level whilst not incurring errors of omission which are too high (McCrae *et al.*). This strategy was chosen so as not to undermine confidence in the approach. For RSDs to be most effective a threshold would ideally be based upon comparison of RSD measurements to the I&M standard (ideally a chassis dynamometer test) based on EURO standard and fuel type. This would lead to a lower threshold for a EURO IV vehicle than that for a EURO I vehicle.

Barlow (1998) found that based on a cut point of 5% CO that 0.5% of the measured UK catalysed fleet would be classed as an RSD gross polluter. In the same study 5% of the measured fleet in Greece would have been classed as a gross polluter. Based on chassis dynamometer measurements of these gross polluters removing these excess emissions from the road would result in a 6% decrease in CO emissions. Neither estimates for reductions in HC, NO_x, CO_2 and fuel consumption and the necessary emission rates to perform this calculation were presented. The proportion of all excess emissions identified using the RSD cut-point approach can be expressed as a percentage of those excess emissions that were identified when vehicles were subjected to a chassis dynamometer test instead – this is presented in **Table 5-1**. This failure rate may be higher today as early generation catalyst vehicles begin to reach the end of their useful life this percentage of the fleet failing may increase.

Pollutant	% of actual excess emissions identified
CO	68%
HC	47%
NO_x	12%
CO_2	-2%
Fuel	16%

Table 5-1: Percentage of excess emissions identified using chassis dynamometer tests that were identified by RSD measurements using a threshold of 5% CO (*Source: Barlow, 1998*)

The USA Greely study (Klausmeier and McClintock, 1998) also examined the use of RSDs to identify gross polluters although few chassis dynamometer failures were tested. The Greeley study was undertaken over a three year period and compared RSD results with I&M chassis dynamometer results. As the RSD threshold value was decreased an increasing number of vehicles which would fail the chassis dynamometer test were identified. The use of HC in addition to CO as a threshold criteria reduced the effectiveness in terms of percentage of excess emissions identified. **Table 5-2** presents errors of omission, commission and percentage of excess CO and HC emissions saved for various CO thresholds. From the data presented it is clear that when using RSD to identify gross polluters, a balance between errors of omission/commission and percentage of excess emissions identified based on changing threshold values needs to be found. Larger datasets from Denver indicated higher errors of commission and lower percentages of excess emissions identified.

CO threshold	RSD failures (%)	Errors of omission (%)	Errors of commission (%)	Excess HC emissions identified (%)	Excess CO emissions identified (%)
1%	9.8	11	54	33	62
2%	6.4	29	44	26	50
3%	4.8	41	35	22	43
4%	2.6	58	27	15	29

Table 5-2: Percentage of vehicles above RSD CO threshold and associated errors of omission, commission and excess emissions identified (Source: Klausmeier and McClintock, 1998)

Summaries of other gross polluter enforcement studies are given in NAS (2001). Texas and Virginia operate gross emitter identification programmes (ESP, 2005a) whilst outside the US, such an approach has been used in Budapest (Asboth and Polay, 1998) and Taiwan (ESP, 2005b).

Repeat readings

It has been suggested that errors of omission/commission can be reduced using the average of two readings for the same vehicle. This seemed to be an effective strategy in the Greeley study (Klausmeier and McClintock, 1998). Other studies of the two 'hit' approach have shown three groups of vehicles – those which are consistently below the RSD threshold, those who are consistently above the RSD threshold and those which move between the two or 'flippers' (Stephens *et al.*, 1996). The presence of this flipping behaviour may indicate that the vehicle has an intermittent vehicle fault.

Whilst certainty that the vehicles identified as high polluters by RSD measurements would fail the I&M test if confirmed by two RSD measurements (rather than one) increases, the size of the fleet considered as the probability of repeat readings decreases the number of hits increase (Williams *et al.*, 2003). There is no benefit to having more than three hits for a single vehicle (Swayne, 1999).

5.6.3.2 Clean screen programmes

Whilst identification of gross polluters is possible using RSDs it is clear that it is not an appropriate substitute to an annual I&M test. If an RSD only approach is used, it is likely that most vehicles would actually avoid the RSD sites. However RSDs can still play a part in reducing burden on vehicle owners in terms of emissions testing and increase the cost effectiveness of an I&M programme. Using the RSD as a stick rather than a carrot may create antipathy with a backlash against the technology similar to that experienced by speed cameras (International Herald Tribune, 2006). Rather than trying to identify high polluters the RSD can instead be used to identify low polluters – this approach is known as clean screening.

Studies into the design of clean screening approaches (Klausmeier and McClintock, 1998; McClintock, 1998) suggest setting low thresholds of 0.5% CO, 200ppm HC and 1500ppm NO. It was found that for clean screening to be most effective, a single vehicle should have had two valid clean screening measurements to avoid unacceptable errors of omission. **Table 5-3** presents estimates of how altering the clean screen thresholds affects the percentage of excess emissions captured (compared to if all vehicles were selected) as well as the percentage of the fleet given exemptions. A significant portion of the fleet can be exempt using this approach allowing the more costly and time consuming I&M tests to be conducted on vehicles which have a higher probability of failing.

Threshold			**Vehicles exempt (%)**	**Excess emissions identified (%)**		
CO (%)	**HC** (ppm)	**NO** (ppm)		**CO**	**HC**	**NO_x**
0.5	200	-	51%	93	91	72
0.5	200	2000	40%	95	94	85
0.5	200	1500	37%	99	95	88
0.5	200	1000	29%	99	96	93

Table 5-3: Percentage of fleet exempt and excess emissions captured for various clean screening thresholds (*Source: McClintock, 1998*)

For both gross polluter identification and clean screening, the use of VSP as an additional parameter is necessary as this has been shown to influence emissions. This makes a pre-study of potential RSD sites necessary (Kuhns *et al.*, 2002).

The advantage of the clean screen approach is that it encourages vehicles to drive through the site relatively regularly and in the proper manner in order to have a valid RSD measurement. There is no reason why a clean screen approach can not be used in conjunction with gross polluter identification (i.e. exempting the cleanest on an annual basis but identifying the highest polluters as and when).

5.6.3.3 I & M evaluation

As I&M programmes are implemented, it is important to understand whether or not they are having the desired effect (i.e. a decrease in vehicle fleet emissions). In the case of USA enhanced I&M, this was initially to be assessed using chassis dynamometer data. This was revised in the late 1990s to include RSD measurements (Vescio, 2002). One of the key advantages of the use of remote sensing is the high number of measurements acquired per hour. This lends itself to collecting data on large numbers of vehicles within a fleet and so assessing changes in fleet (and sub groups within) emission rates.

The US EPA has released guidance on the use of RSDs for I&M programme evaluation (USEPA, 2004). The guidance suggests three approaches to quantifying a change in fleet emissions:

i) **Step change method** - This utilises a point in an I&M programme where half of the vehicles have been subjected to the new I&M programme and half have not. So, if applied when a new *annual* I&M regime was introduced, the comparison point would occur 6 months into the new programme (i.e. at that point half would have been subjected to the new regime and half would not). At that moment in time a large scale RSD campaign would produce a database which could be divided into two even sized sub-fleets based upon whether a vehicle has been tested or not tested under new programme. Due to the non-normal distribution of the measured vehicle emissions only relatively weak non-parametric statistics could be applied to determine a difference in the two sub fleets. To counter this the mean emissions measurement for a number of periods can be used (e.g. daily fleet averages over a week) to increase the number of values representing the two sub-fleets thus improving the statistical robustness of any comparison.

ii) **Comprehensive method** – This is the classic before and after study approach. To control for other non-I&M effects the RSD sample is divided up into time before or after the vehicles I&M test, model years and according to their I&M test outcome. This sort of analysis allows some insight into the continued effectiveness of any repairs made. Estimates of total emissions reductions based on I&M test before and after values would assume the reduction to remain constant throughout the year until tested again but RSD studies have shown increases in group average emissions as the time period since their last I&M test increases (see **Section 5.5.1**). Because of the division into numerous sub-groups, this form of appraisal can be expensive as very large datasets are required.

iii) **Reference method** – Here the I&M fleet RSD measurements are compared to RSD measurements from a fleet outside of the area subjected to the enhanced I&M programme. Additional vehicle record information such as average daily mileage or previous addresses can remove uncertainties from the comparison.

All three methods will be subject to confounding variables which have to be accounted for in any analysis including fleet age, climate, tax regimes, socio economic factors, measurement site variations etc. (Wenzel *et al.*, 2000; USEPA, 2004).

5.6.4 Other uses

5.6.4.1 Cold start quantification

Boulter (1999) used the RSD unit to measure emissions for cars as they entered three car parks which were chosen to be representative of a range of parking policies. The car parks chosen (as described by Boulter) were:

i) Supermarket – short average parking duration and high turnover
ii) Golf course – medium average parking duration and a medium turnover
iii) Railway station – long average parking duration and low turnover

As expected, due to the known emissions implications of cold starts, percentile means for CO emissions increased with increasing percentile mean parking duration. The percentile mean approach removes other variations due to the ambient temperature during measurement, variations in vehicle fleet age, site layout etc. It is suggest that this basic relationship could be used to quantify emissions from sources such as car parks for future city wide emissions models.

5.6.4.2 Traffic management schemes

Boulter (1999) also attempted to use RSD measurements to quantify changes in vehicle emissions due to the introduction of traffic calming measures (speed humps and speed cushions) on a suburban road. Whilst the average speed on the two roads under investigation had decreased as a result of the traffic calming measures, there was an increase in the variation of the speed profile as vehicles passed through the sites. It was found that emissions of CO, at locations immediately before and between the traffic calming measures, increased compared to the situation before their installation. This increase was despite expected emissions reductions due to natural fleet renewal. Prior studies had quantified this emissions effect using a small number of instrumented vehicles but the RSD enabled this to be proven for the general vehicle fleet passing the sites due to the high number of emissions measurements gathered by the RSD.

5.6.4.3 Immediate driver feedback

When a vehicle passes an RSD site the driver will often never know how their vehicle performed during the instantaneous emissions 'test' they just took. During US clean screening programmes or gross polluter identification programmes, the owner of the vehicle is normally traced by their number plate and they are called into a chassis dynamometer testing station for their emissions to be checked more thoroughly. In areas not operating clean screening gross polluter identification, there is no way of the driver knowing how their vehicle emissions compare to the required standard in between the mandatory testing intervals (in the UK this would be the yearly MOT test).

A novel solution to this problem was developed by Bishop *et al.* (1998) who developed a 'smart sign'. The smart sign was a RSD unit which measured CO and

CO_2 and was designed for unmanned operation on a freeway on ramp in Denver, USA. The RSD binned measurements of CO concentrations into three groups; GOOD, FAIR or POOR and then transmitted this measurement to an electronic roadside display. The sign's appearance for each of the three emissions bins is shown in **Figure 5-10**. By informing passing drivers of the personal financial impact of their vehicles emissions performance (i.e. POOR emitters were using more fuel than a GOOD emitter) it was hoped appropriate vehicle maintenance would be undertaken by the vehicle owner. The site topography ensured that vehicles were operating at the optimum conditions for RSD emissions measurements.

Figure 5-10: Smart Sign displaying showing three different levels of emissions and its relative financial implications (Source: *Bishop et al., 2000*)

The smart sign operated continuously for a year, after which time 3 million measurements had been made. Most vehicles were classed as GOOD although the FAIR and POOR categories contributed the majority of emissions. In a follow up questionnaire to owners of measured vehicles, 1.6% of the overall fleet (16% of those who received a POOR measurement) indicated that they had taken their vehicle for repairs following their vehicle receiving a POOR measurement – this had potential to reduce total emissions by 5% (Bishop *et al.*., 2000). More details on the response of drivers to the Smart Sign are featured in **Chapter 7**.

5.7 The REVEAL RSD unit

5.7.1 General operation

The REVEAL RSD unit was developed within an EC funded project. Documents describing the instrument in more detail were produced within the project (REVEAL, 2004a & b). In general the system operates on the same principles as all other RSD systems (described in **Section 5.2.2**).

The REVEAL instrument's beam path is illustrated in **Figure 5-11**. From the source unit an IR beam is projected across a road towards a reflective corner cube mirror. This mirror then returns the beam to the source unit where measurement of the IR intensity at set wavelengths is measured. When a vehicle passes through the beam an initial total loss of signal is experienced as the car blocks the beam. When the vehicle clears the beam, the beam then interacts with the exhaust plume as it passes through it resulting in some loss of signal intensity. The data capture lasts for approximately 1 second which when refined to isolate the plume absorption in the measured trace leaves 0.2 seconds of data. The REVEAL instrument has a sampling frequency of 1750Hz.

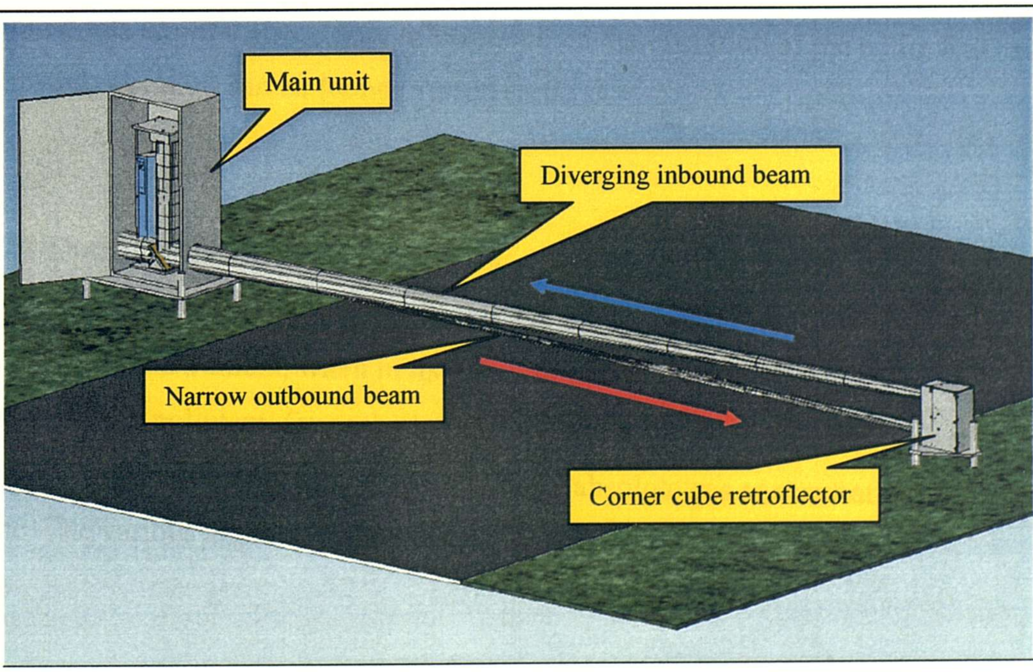


Figure 5-11: IR beam path of the REVEAL instrument (Source: REVEAL, 2004b)

In addition to the combustion and emission reduction efficiency of the vehicle, the absolute concentrations in the plume vary depending on the vehicle model tailpipe height, the height of the beam and the turbulent mixing due to the vehicle wake and localised wind. Whilst the absolute concentration of the gases varies, in theory, the relative concentration of two gases of interest does not. RSD units measure the concentration of the pollutants and CO_2 in parts per million metres (ppm.m) and account for background concentrations by subtracting the concentrations observed for a ~0.5 second period before the vehicle entered the beam.

The approach used by the REVEAL instrument is to monitor the reduction in the relevant channel signal compared to the background values. This is measured on a scale normalised to the background value and, after taking into account expected variations measured by the reference channel, this remaining normalised attenuation is converted to a gas concentration using inbuilt calibration curves. The suppliers report that part of the novel approach used by REVEAL is that on site calibration is unnecessary as a set of calibration curves are used which relate to different ranges of background CO_2 concentrations. The calibration curves are developed by introducing a known concentration of the gas of interest into a gas cell and observing the corresponding voltage drop for the respective channel. The resultant raw data has a sample of approximately 330 data points (about 0.2 seconds at the REVEAL sampling rate of 1750 Hz). More information on the operation of the entire RSD site set up and operation can be found in **Section 6.1.3**.

5.7.2 Output of the REVEAL instrument

The REVEAL instrument, when in its usual monitoring set up, outputs five ratio values for each pollutant, for each plume measured. Each ratio value is derived from a different approach to processing the measured absolute gas concentrations in the plume. The various approaches are described in **Table 5-4**.

Approach	Summary of approach
Peak emissions	Concentrations of CO_2 and pollutant at point of highest CO_2.
Total emissions	Time integrated value of emissions over the complete plume data.
Average emissions	Average of CO_2 and pollutant from a small number of the highest CO_2 values.
Average start emissions	Average of the CO_2 and pollutant during the first half of the vehicle plume data.
Average end emissions	Average of the CO_2 and pollutant during the first half of the vehicle plume data.

Table 5-4: Approaches used in producing summary values used for quantifying each passing vehicle's emissions efficiency (Source: Lloyd, 2005)

In contrast to most other RSD studies, the main results reported in this study will be based upon the ratio of the measured pollutant to CO_2. Most other RSD studies report emissions measurements in terms of ppm. This conversion from ppm.m to ppm is based upon an idealised combustion equation for petrol vehicles (this still works for diesel vehicles but is not comparable to a tailpipe probe measurement as it cannot factor-in the proportion of air not included in diesel combustion but exits via the tailpipe) (Kuhns *et al.*, 2002). Instead the basic ratios of path length pollutant concentrations give an indication of the emissions efficiency (i.e. unit of tailpipe pollutant/ unit of fuel burnt) of each passing car given that CO_2 is proportional to fuel consumption. This removes assumptions used in the idealised combustion from the vehicle emissions measurement. This does have implications for definition of emissions efficiency limits for identification of gross polluters however – this will be discussed further in **Section 6.6.3**.

The REVEAL developers recommend that the ratios resulting from the 'average emission' values be used in quantifying the emissions efficiency of each vehicle. This seems sensible since, in theory, the pollutant concentration in the plume should be highest when plume capture is greatest (i.e. CO_2 is highest). Due to an increasing influence of noise in the measurement (see below) as absolute pollutant concentrations tend to zero, the most accurate pollutant values should be gathered during this time. Due to the limited summary information produced for each vehicle measurement, it is impossible to know, with any certainty, how accurate each measurement and subsequent ratio value is. The developers recommend comparison between the peak ratio and the average ratio as a measure of accuracy. This is a crude measurement of accuracy since the peak absolute values relate to one point in the measured vehicle plume and so any measurement noise experienced at this point could significantly alter the resultant ratio values. Thinking of the signal to noise ratio (SNR) for the measurements, this will increase as the measured absolute gas concentrations tend to zero. For vehicles with low emissions values, whilst the SNR may be high, it is a relatively insignificant absolute value. This means that in terms of how the signal noise affects generalised fleet emissions efficiency profiles it is relatively insignificant (since the vehicles the noise affects most are actually very low emitters compared to those with an emissions related fault).

Using the recommended 'average' values, the stated standard deviation of a single point measurement is given in **Table 5-5**.

Gas species	Standard deviation (ppm.m)
CO_2	1200
CO	100
HC	10
NO	50

Table 5-5: Standard deviation of single point measurements as reported by REVEAL equipment suppliers

In order to understand the confidence which can be placed in measurements, the standard deviation can be compared to average decile concentration values reported in the trials reported in **Chapter 6**. The decile average values for the measured concentrations, are presented in **Figure 5-12**, together with the reported standard deviations shown as error bars. It can be seen that, for most CO_2 measurements, the standard deviation is relatively small in comparison to the measured values. This means for most CO_2 readings, the true value will be close to that reported. For the CO measurements the standard deviation is greater or equal to most of the decile average values except for the top decile. The none overlapping nature of the standard deviation in the highest decile with the ninth decile, gives greater confidence that a value of this scale has true membership of this category. The HC standard deviation is often less than the average value of decile population but because of the close nature of the decile averages the true value of a measurement could be in many of the other deciles; this is less so for the highest decile. Finally, for NO measurements a similar relationship as that seen for HC is present.

Due to the possibility of a single average value being subject to error for many vehicle measurements, relationships with the measured vehicle's VSP will not be observed. However, the instrument is still useful at identifying high emitting vehicles which are of particular interest to this study since the concentrations of interest are high and the relative potential error in the reading small. Due the nature of the error (i.e. it should follow a normal distribution) some indication of the decile distribution of all vehicle emissions efficiency can be provided from fleet data.

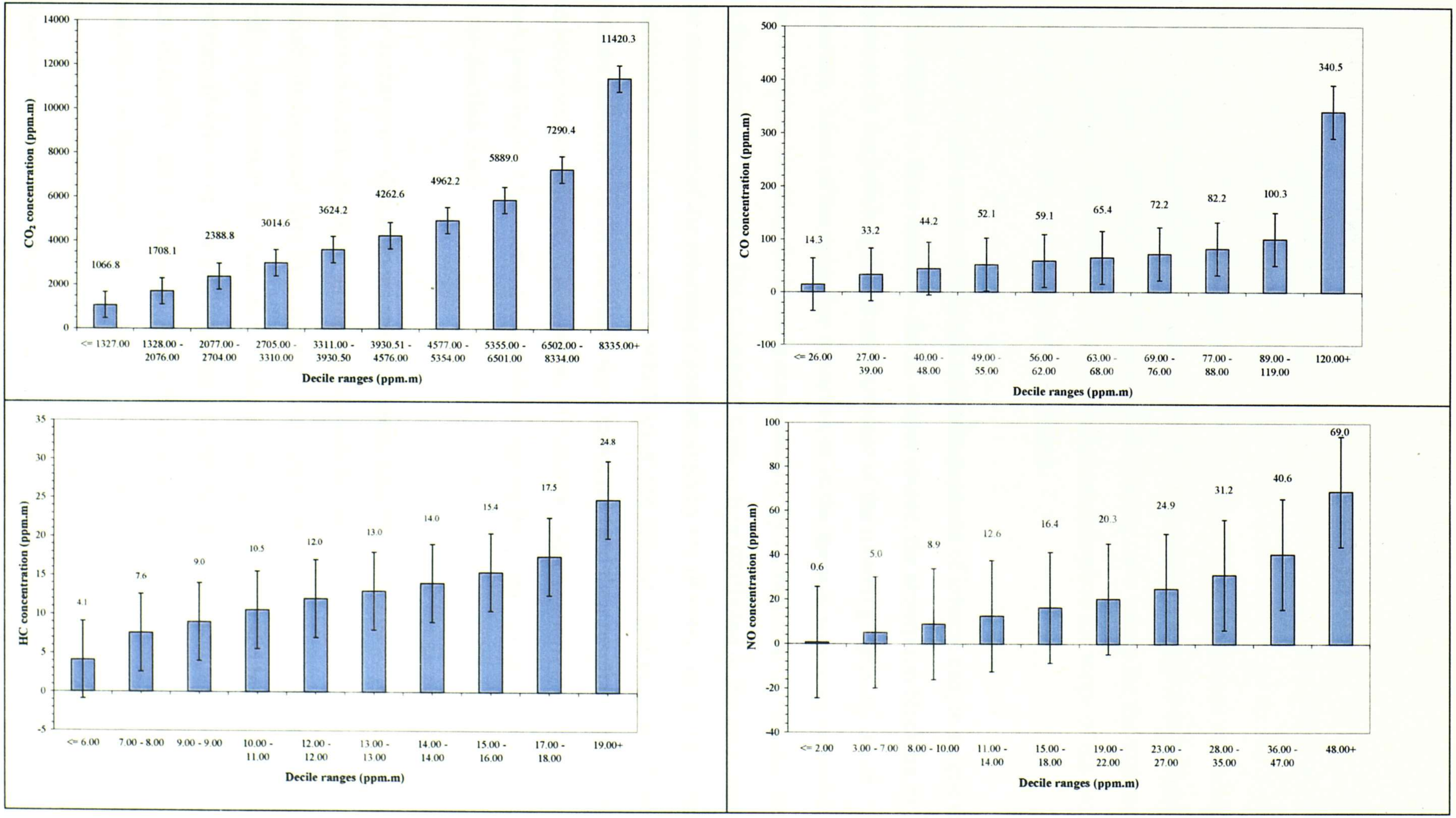


Figure 5-12: Decile average absolute concentrations from monitoring at Andover Road and Badger Farm Road, Winchester. Error bars show how the reported standard deviation when centred around the mean compares for (clockwise from top left) CO_2, CO, HC and NO.

5.7.3 Comment on the accuracy of the REVEAL instrument

Whilst it is not the objective of this study to develop or appraise the REVEAL system, some limitations in the approach used to process the data captured with each passing vehicle plume have been observed. These limitations relate mostly to the processing algorithms and approach to data capture. These limitations are thought to have greatest effect on the accuracy of the instrument results as absolute pollutant concentrations tend to zero. The result is conflicting ratio values for the various ratio approaches used. Correcting for these limitations is beyond the scope of the work presented here but some comment is provided.

Variations in the measured IR light at the frequencies of interest can, in simple terms, be attributed to three sources – the IR output source, the absorption/blocking by elements in the path length and measurement of the returning signal by the IR detectors. Most of the noise due to variations in the thermal source and obscuration due to objects blocking the beam is accounted for by normalizing the channel signals to the reference channel. The remaining noise can be attributed to the accuracy of the measurement of the returning signal strength by the IR detectors for each channel and interference from gas species which are not of interest. This noise will have greatest influence on the absolute values measured (and their resultant ratios) at low emission values. Hence, it is desirable to measure concentrations in the plume at their peak level. One method to do this is capture the plume when it is at its densest – see **Section 5.6.3**.

The signal noise should focus around a mean and standard time series noise reduction techniques, such as the use of a moving average, which smooth out variability in signal data. Because the ratios are derived from two channels the noise will not necessarily be coincident. The averaging approach used by the REVEAL instrument selects only a small number of approximately 300 samples based upon the size of the CO_2 concentration. As an example of the worst case, it is entirely possible that the highest CO_2 values are those where the noise in the CO_2 channels is at it's highest but the noise in the CO channel is at it lowest. This results in the absolute concentrations being artificially high (CO_2) or artificially low (CO), and so produces an inaccurate ratio.

Jimenez (1999) identifies the sampling rate as a further influence on the error from an RSD. A sampling rate of approximately 100 Hz is recommended and whilst the RSD instrument used in that study measures at higher frequency, the desired rate is achieved by co-averaging the signal strength from each channel over a 10mS period. Jimenez chose this period following experimental and theoretical studies of the temporal resolution of variations in plume variations. This averaging approach has the effect of smoothing out variations due to noise in the signal measurement.

It is also noted in the REVEAL documents (REVEAL, 2004a) that the response of each channel in terms of loss of signal strength is not directly proportional to absolute concentration of the gas of interest. In an ideal situation, the calibration curves (i.e. the relationship between signal loss and the concentration of a pollutant in the exhaust plume) would follow a non-linear relationship. Limitations on the accuracy of the gas cell equipment at the calibration stage seem to be the limiting factor in this calibration procedure and so linear relationships have been used instead.

Finally, rather than use the average of a small number of measurements from the sampled plume, most other RSD units use a linear least means regression method. If this approach were used then an R^2 value from the regression could be reported indicating the quality of the measurement. Examples of how such an approach would fit be applied to plume concentrations from two separate exhaust plumes (one with relatively high average pollutant emissions and one with low average CO emissions) measured by REVEAL are shown in **Figure 5-13** and **Figure 5-14**. These plumes were captured during the Winchester measurement campaign. Where the concentrations were relatively high (**Figure 5-13**), the R^2 value of the regression is much higher than when the concentrations were relatively low (**Figure 5-14**). The gradient co-efficient of the linear regression equation can also be compared to the various ratio values reported in the REVEAL summary statistics (see **Table 5-6**). Both Stedman and Jimenez report that regressions with an error greater than 20% are rejected by their systems (McCrae *et al.*, 2001; Jimenez, 1999).

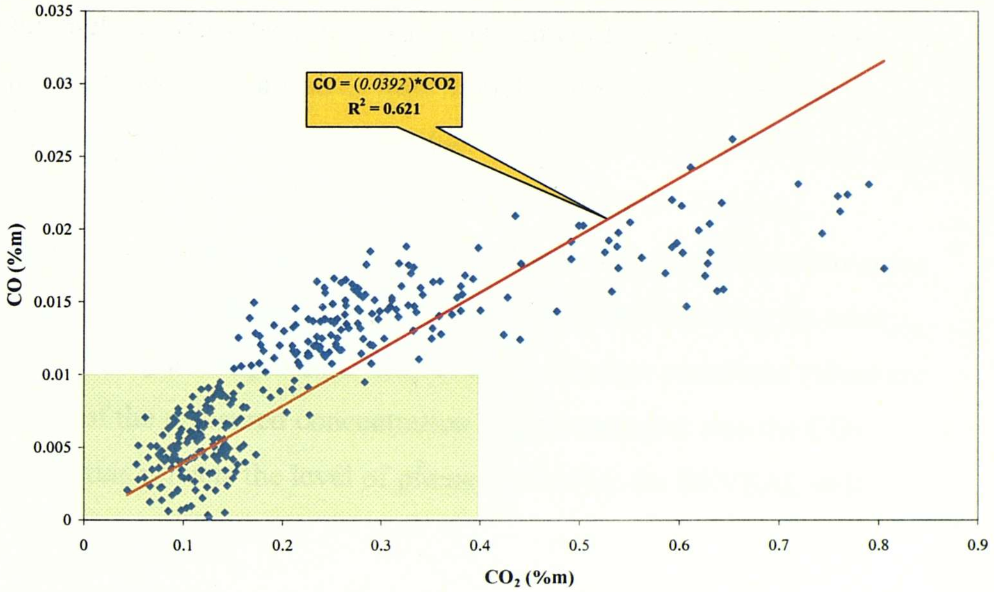


Figure 5-13: Linear least squares regression line for a plume captured during the Winchester trials which has relatively high CO concentrations and good plume capture. Area shade green indicates the range covered by values for the exhaust plume shown in **Figure 5-14**

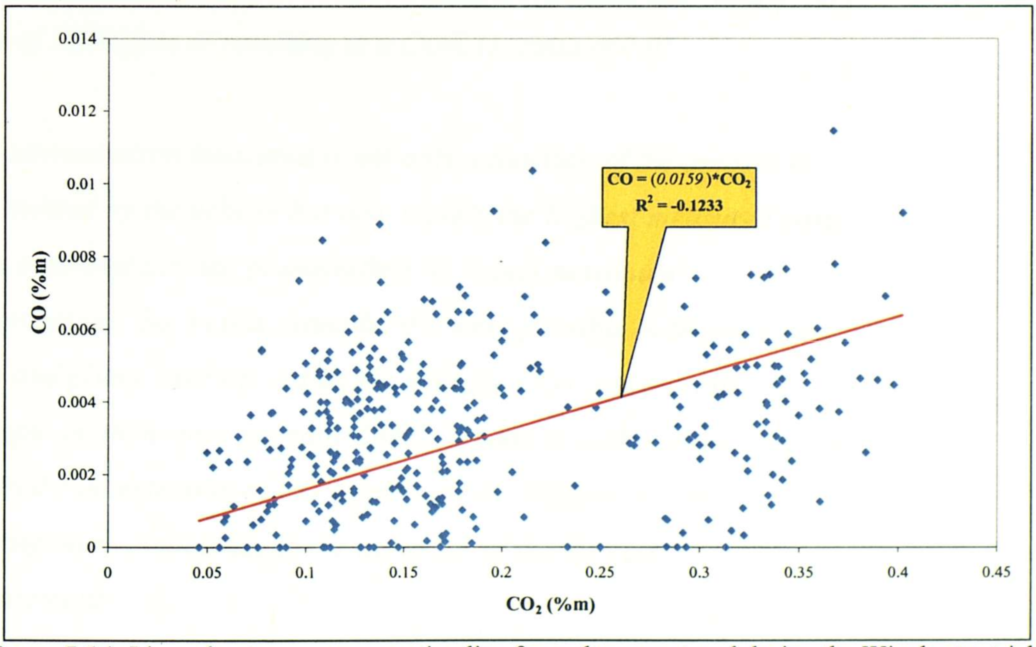


Figure 5-14: Linear least squares regression line for a plume captured during the Winchester trials which has relatively low CO concentrations and poor plume capture.

Summary approach	Ratio value	
	Figure 5-13	Figure 5-14
Peak	0.021305	0.022952
Total	0.042411	0.017045
Average	0.027013	0.013952
Average start	0.026309	0.017211
Average end	0.054292	0.023993

Table 5-6: Ratio value produced using different approaches to summarising the measurement data for **Figure 5-13** and **Figure 5-14**

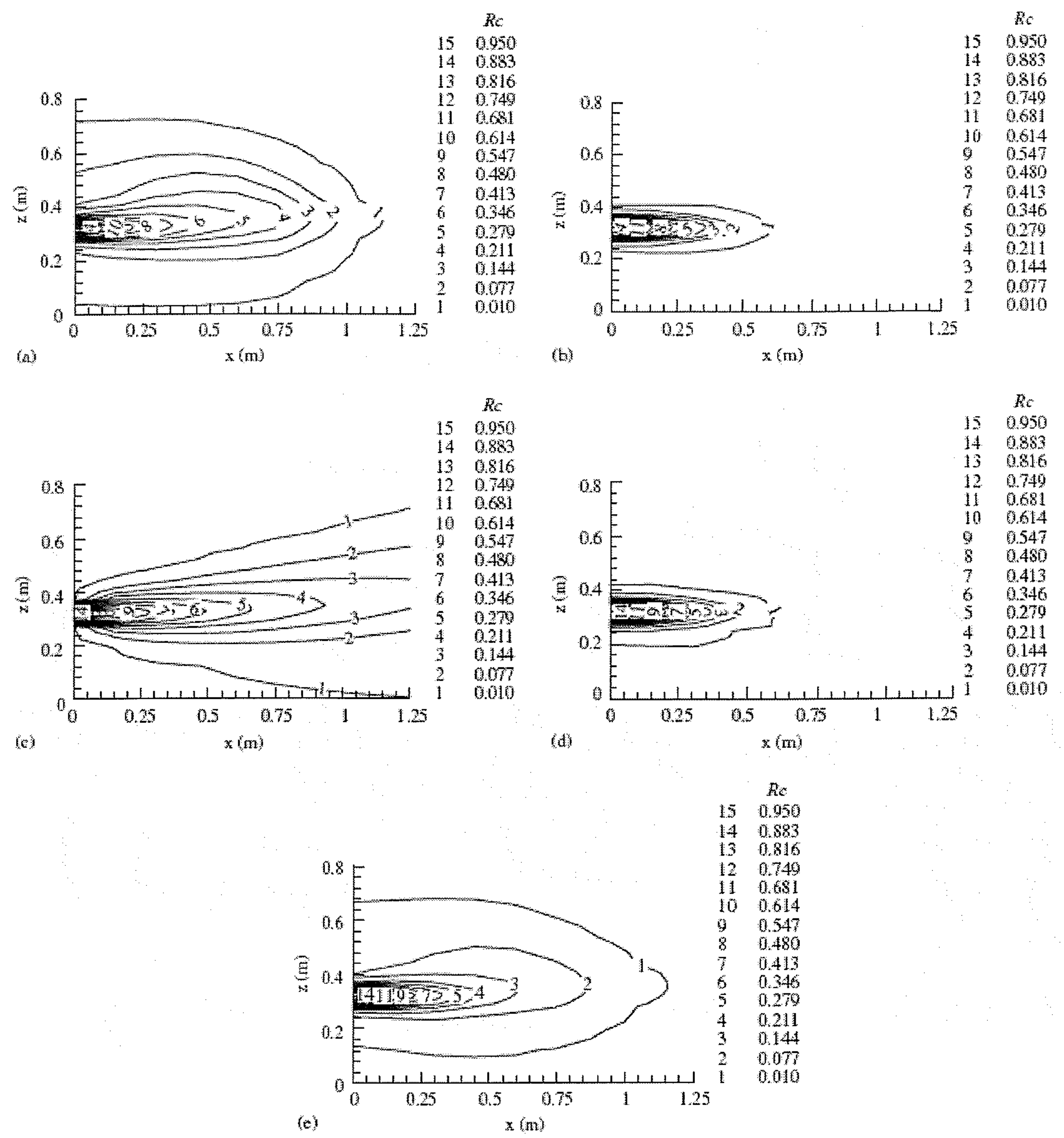
5.7.3 Plume capture

Due to relatively high errors in the emissions measurement for vehicles with low pathlength concentrations, measurements from vehicle with low pollutant/CO_2 ratios suffer from large uncertainty in their actual value. To explore any relationships between various pollutants and VSP, an increased accuracy in the REVEAL instrument measurements is necessary. Whilst the current measurements allow some estimate of the highest polluters contribution to total emissions, reducing the error would add more certainty to the profiles. However, the average emissions values are not only a function of the measured concentration of pollutants but also the CO_2 concentration since this reflects the level of plume capture by the REVEAL unit.

For example:

> *A vehicle emits a plume with an average concentration of 100ppm.m CO, if it were measured on a more sensitive REVEAL unit ,and a CO_2 value of 2000 ppm.m resulting in a CO/CO_2 ratio of 0.05.*
>
> *CO_2 concentration measured is not only a function of the amount of CO_2 emitted by the vehicle but also closely the highest measured parts of the captured exhaust plume reflect its actual maximum concentration. So, in this example, if it were possible to improve the beam and plume overlap so that the average CO_2 concentration is 4000ppm.m, then since the ratio CO/CO_2 ratio would remain 0.05, the captured concentration of CO would now be 200ppm.m – thus allowing more confidence in the accuracy of the REVEAL measurement.*

The importance of capturing the plume as soon as possible after leaving the tailpipe is supported by the REVEAL (2004b) which states that, from plume modelling evidence the concentrations in the plume are 1% of the original value when the plume is 0.5m wide. This rapid dilution process is also supported by Wang *et al.* (2006) although not at the same rate as above (these measurements were modelled for idle conditions). If the plume can be captured almost immediately as it exits the tailpipe rather than later as the plume disperses into the beam path, much higher concentrations of both CO_2 and pollutant will be detected. The relative concentration of CO as it leaves the exhaust of a stationary vehicle is shown by the contour diagrams in **Figure 5-15**. From the tightly packed contours the initial dilution and dispersion processes are relatively quick. The relative dispersion is similar to an exponential rate of decay seen in radioactive isotopes (i.e. halving with every increment). It also highlights the importance of capturing the plume in the vertical axis as close to the tailpipe as possible.



Relative concentration, R_C, of CO distributions on x–z plane along the streamwise distance of a vehicular exhaust plume at $y = 4$ m for vehicle A under a low idle and different ambient windflow conditions: (a) E direction, (b) S direction, (c) W direction, (d) N direction and (e) WDFW approach used.

Figure 5-15: Dispersion contours of CO for stationary vehicle at low idle conditions. The z-plane is the vertical plane. Each tickmark on the z-axis is approx. 4cm height from road.
(*Source:* Wang *et al.*, 2006)

A commonly used parameter from other RSD studies to measure the level of strength of plume capture is the peak CO_2 value although a better measure is the time integrated emissions measurement since the measurement noise will affect all the points rather than just one (i.e. total emissions measured) (Jimenez, 1999). Both parameters will be used in this analysis. To compare how plume capture from previous Winchester monitoring (not that presented in **Chapter 6**) varies from that observed in the Jimenez study data the Peak CO_2 emission values are used.

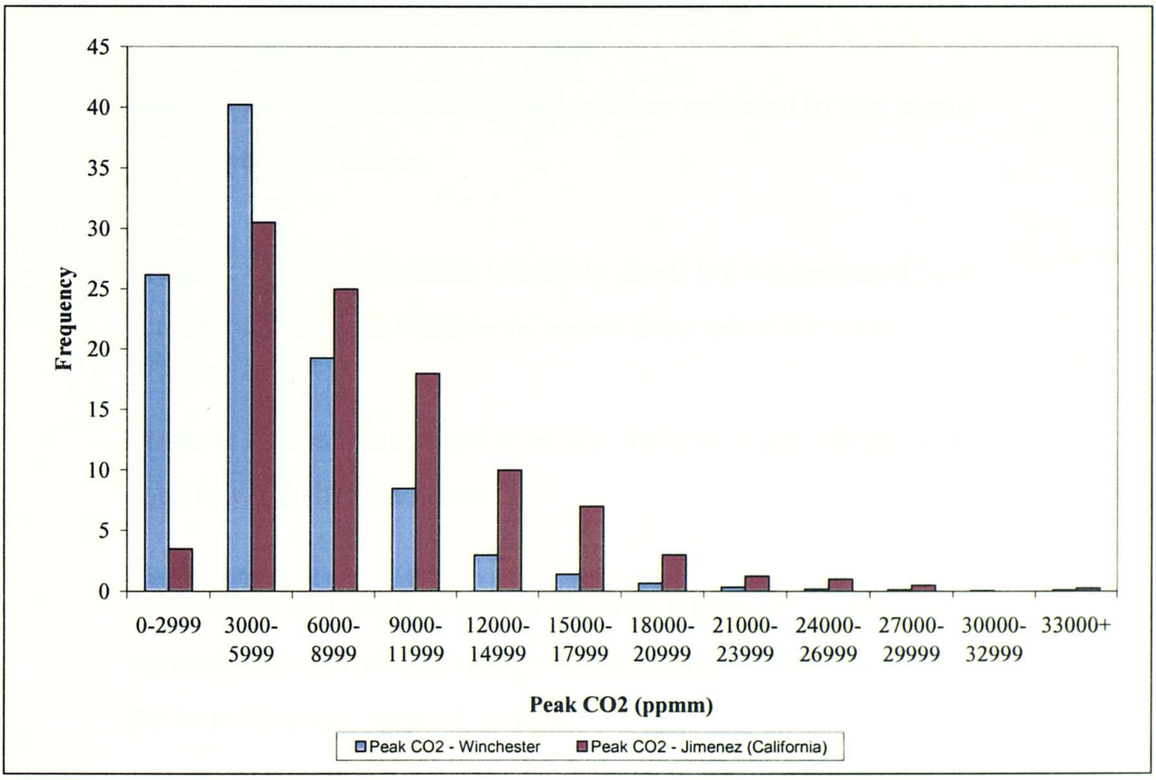


Figure 5-16: Distribution of Peak CO_2 for Winchester dataset and results presented by Jimenez (1999)

The *Peak CO_2* from this Winchester dataset compared to the distribution obtained by Jimenez (1999) in a study of cars in Santa Barbara, California is shown in **Figure 5-16**. It can be seen that the Winchester distribution has a far greater positive skew (i.e. majority of points towards the left of the distribution). Whilst some of this difference can be explained by US vehicles having higher average fuel consumption than European vehicles (proportional to tailpipe CO_2) and possible differences in vehicle operating conditions associated with the site, the difference in distributions indicate that improved plume capture may indeed be possible.

Optimising the beam height in the case of REVEAL is not just a case of altering the height of a single beam across the road but two opposing, diverging beams which result from the corner cube mirror arrangement. The beam path of the REVEAL unit is represented in **Figure 5-11** and described in stages below; one particular point of note is the fact that the beam is diverging throughout its path. This means the intensity of the beam per m^2 is decreasing as it diverges.

Stage 1: $3mm^2$ IR source emits IR beam.

Stage 2: IR Beam from outbound aperture reflected by top mirror onto lower gold mirror.

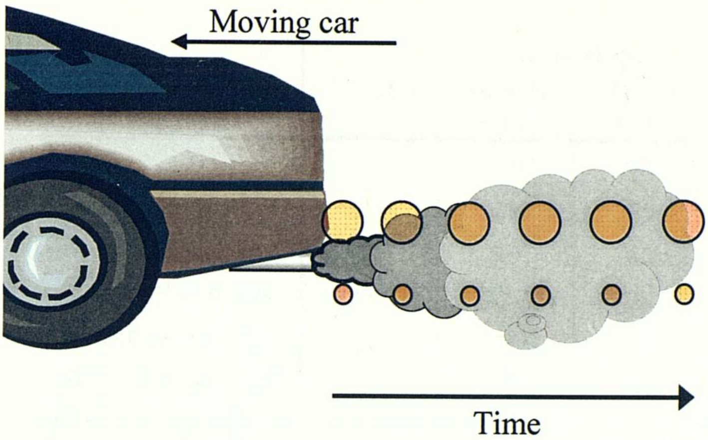
Stage 3: Gold mirror sends relatively small but concentrated beam across road to lower window of corner cube retroflector unit.

Stage 4: IR beam is emitted from top window of retroflector unit back towards the main unit.

Stage 5: Beam hits large area of the gold mirror and is reflected upward onto concave top mirror which focuses a large proportion of the beam into the inbound aperture.

Stage 6: The focused beam is sent to the detectors.

Looking at the beam path it is clear that there is opportunity for the point at which exhaust leaves the tailpipe not to be in the path of either beam although the beam will detect the plume eventually as it disperses. This effect is represented schematically in **Figure 5-17**.



This example shows how the two beams can miss much of the exhaust when at the early stages of the plume's 'life'. This period is when species concentrations are highest. Whilst the detected concentrations will still show the diminishing concentrations with time in the plume profile the initial concentrations will not be as high as possible.

Figure 5-17: Schematic diagram illustrating how the area of the vehicle plume where concentrations are highest can be missed.

So, the ability to capture the vehicle plume is dependent on i) the vehicle exhaust height, ii) the heights of the main unit and the retroflector unit, iii) position of the vehicle in the road, and iv) position of the exhaust along the rear of the vehicle

The optimised beam height

Instructions on the unit's set up (Golden River Traffic, 2004) require the outgoing, lower beam to be 20 -25cm above the road surface. Given the need to optimise the beam heights, in order to capture the highest possible plume concentrations, and a lack of empirical evidence to support the suggested set up, a small survey of 174 vehicles parked in the vicinity of the University of Southampton was undertaken. Tailpipe heights, position (nearside or offside) and shape (straight or down turned) were recorded. The results of this survey are presented in **Table 5-7**. It can be seen that regardless of which side the exhaust is positioned or the shape, the optimum height for direct plume capture should be approximately 29cm and 50% of all exhaust heights lie within a 4cm range around this point. So the 20-25cm window for the narrow, lower beam would rarely directly hit the tailpipe. From the idle state modelling presented by Wang (2006) missing the tailpipe by only a small distance could reduce the concentration measured by 100th of its original value.

Height statistics	All (cm)	Exhaust shape*		Exhaust position	
		Straight (cm)	Down (cm)	Passenger (cm)	Driver (cm)
Mean	29.03	29.00	29.06	28.86	29.2
Median	29	28	29	29	28
Std Deviation	4.0	3.9	4.2	3.8	4.5
Inter Quartile Range	4 (27-31)	4 (27-31)	4 (27-31)	4 (27-31)	4 (27-31)
10th percentile	25	25	25	25	25
90th percentile	33	33	34	33	33

* 'Straight exhausts' were measured from centre point of exhaust and 'downward' exhausts were measured from the lowest point

Table 5-7: Results of exhaust tailpipe height survey for 174 cars

The questions now remaining are; which beam should be optimised to the height of 29cm and should vehicles be encouraged to drive closer to the main unit than the retroflector unit since most exhausts are on the side nearest the unit (approximately a 70/30 split for passenger/driver side position). There seem to be trade offs between the intensity of the beam and the chances of the beam achieving a 'direct hit' on the exhaust. To understand the best set up the height of the retroflector unit was altered systematically at the same site and the time integrated CO_2 distribution compared to see which gave the best plume capture distribution.

Figure 5-18 shows how the distribution changes with variations in the height above the road surface of the bottom window on the retroflector. Statistics relating to each distribution are presented in **Table 5-8**. The centre of the bottom mirror on the main unit was set at the optimal 29cm above the road height. It can be seen the best distribution (i.e. most skewed from zero) is when the retroflector is placed as low to the ground as possible.

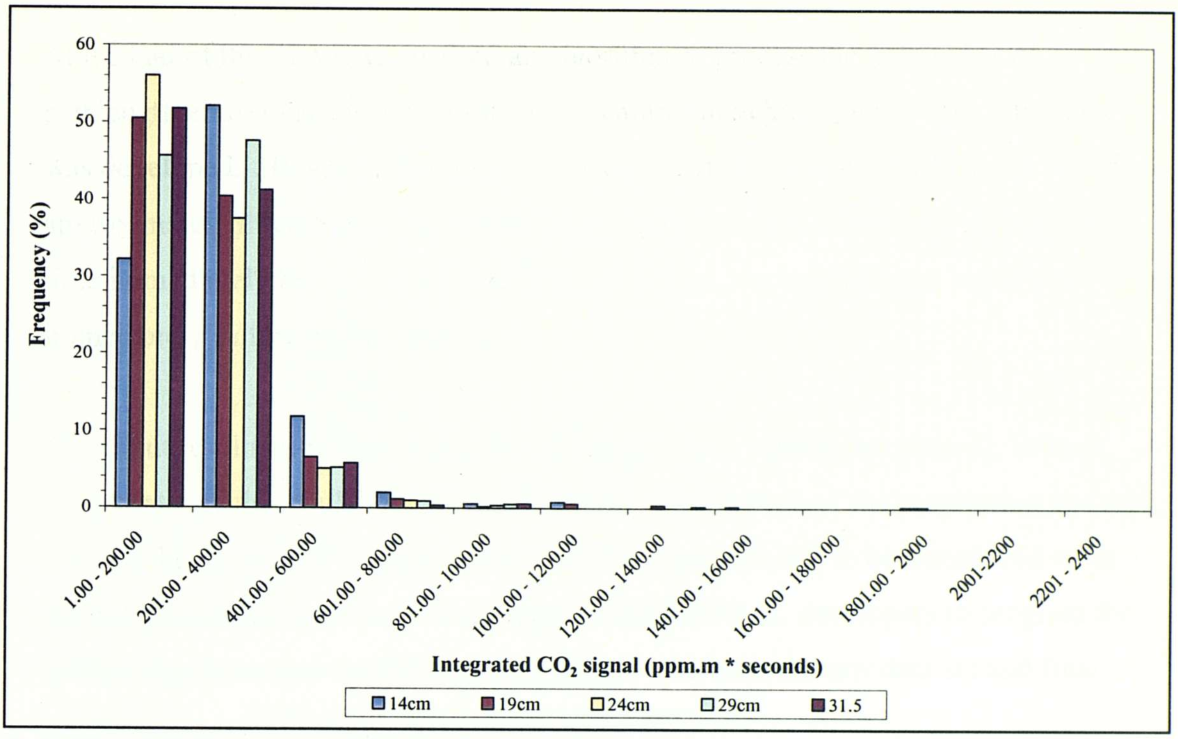


Figure 5-18: Distribution of plume capture parameter 'time integrated CO_2' for a range of heights of the bottom window of the retroflector unit above the road surface.

		Height of bottom window above road surface				
		14cm	19cm	24cm	29cm	31.5cm
Valid		497	515	507	550	514
Mean		281.8	229.6	203.4	224.9	212.1
Median		250.0	199.0	181.0	210.0	197.0000
Std. Deviation		176.9	174.2	121.7	121.8	127.8
Minimum		62.0	42.0	35.0	51.0	44.0
Maximum		1995.0	1958.0	926.0	921.0	1262.0
Percentiles	25	178.5	121.0	116.0	137.0	122.7
	50	250.0	199.0	181.0	210.0	197.0
	75	334.0	283.0	267.0	274.2	268.0

Table 5-8: Statistics relating the distribution of the timer integrated CO_2 measurement at different retroflector heights above the road surface

This new approach to the instrument set up can be explained by the wider returning beam from the retroflector having a greater chance of overlapping the most concentrated parts of the dispersing plume.

5.8 Moving REVEAL from an offline to real time processing algorithm

At the end of the REVEAL project, an algorithm to process the time series of pathlength emissions concentrations into meaningful vehicle plume concentrations was developed. However, this algorithm was an off-line approach which processed approximately three seconds of data containing pathlength concentrations from the time immediately before the vehicle broke the beam, during the beam break and immediately following the beam break.

To output results in real-time (i.e. immediately after a vehicle has passed), to have immediate results available to post on a VMS down stream of the monitoring site and remove the burden of off-line processing, the algorithm had to be transferred to an on-line processing approach. This required the REVEAL developers to program the offline algorithm into the REVEAL unit itself with both the raw data set and final output being recorded onto an external laptop PC.

Upon delivery of the REVEAL unit in Sept 2004, some initial on-road trials were performed in Southampton to investigate the accuracy of the real-time output. This process highlighted some peculiarities in the results being delivered from the unit.

5.8.1 Comparing a trial dataset to high polluter thresholds

By comparing a dataset of measured vehicles to the gross polluter thresholds suggested in the REVEAL project (REVEAL, 2004a) it was apparent that there were too many gross polluting vehicles being returned by the unit.

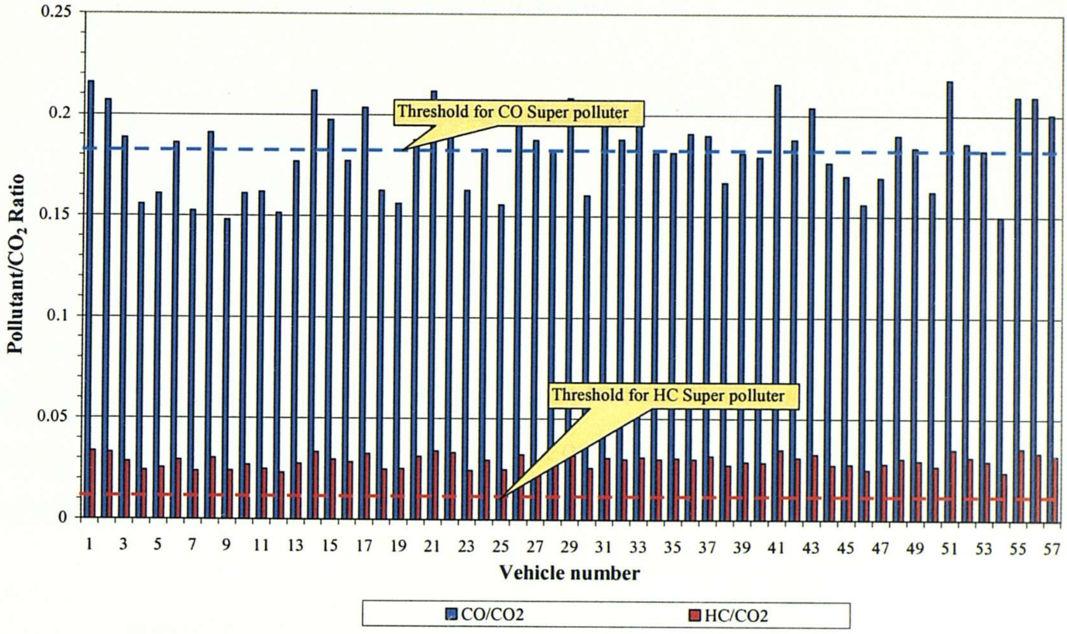


Figure 5-19 shows how the results compare to suggested polluter thresholds for CO and HC (at this time the NO channel had not been added to the unit). It can be seen that a considerable percentage of CO readings and all HC readings were above the thresholds and so indicated an unusually high number of gross polluters in the small fleet of cars measured in this trial.

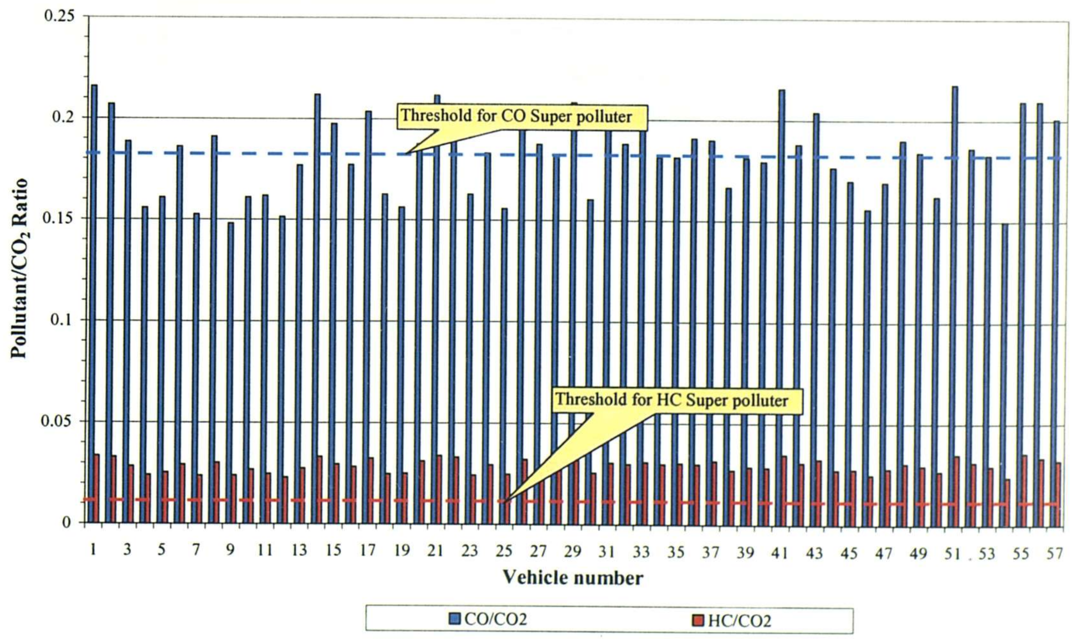


Figure 5-19: Comparison of reported REVEAL CO/CO_2 and HC/CO_2 ratio from initial Southampton trial (Sept. 2004) to suggested gross polluter thresholds

5.8.2 Comparing to original REVEAL trial data

Following the presentation of the above dataset to the REVEAL developers, it was agreed that there was a fault in deriving the summary results being reported by the unit. The dataset was then compared to the results which had been collected during the development of the unit. At this point the online data produced by the REVEAL unit was compared to the data produced from offline processing of raw data collected from a site in London. A comparison of these two datasets is given in **Figure 5-20**. For these figures the data was sorted in rank order and then normalised according to the vehicle population size to illustrate the emissions profile.

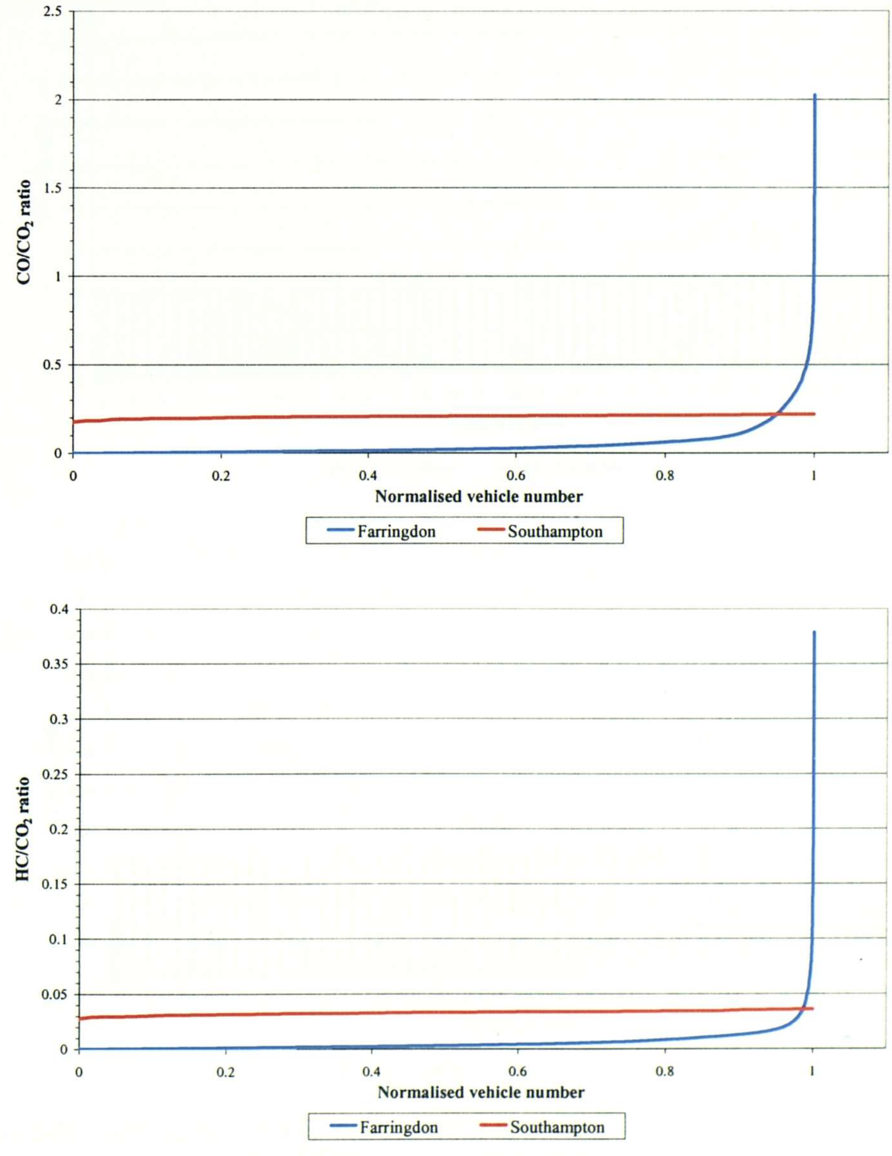
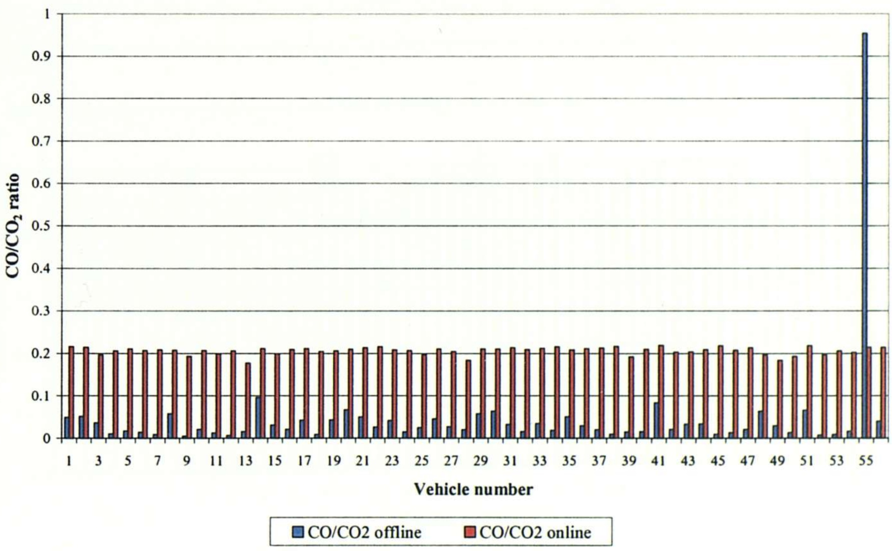


Figure 5-20: Rank ordered fleet CO/CO_2 (top) and HC/CO_2 (bottom) emissions ratio profiles from the initial Southampton trials and REVEAL project Farringdon Road, London trials

At this point it was clear that there was some sort of error in emissions values being produced. The raw data from the Southampton trial was then processed using the offline algorithm used to process the London dataset. Comparisons of the offline and online ratios of CO/CO_2 and HC/CO_2 as well as the pathlength concentrations for each measured gas are given in **Figure 5-21** and **Figure 5-22**. It is clear from these comparisons that the error lay in deriving the raw pathlength concentrations and this was in turn resulting in erroneous ratio values. Having diagnosed the problem with the online results, the developers spent two days on site assessing the unit in operation and reprogramming of the REVEAL online algorithm until the offline and online results matched.



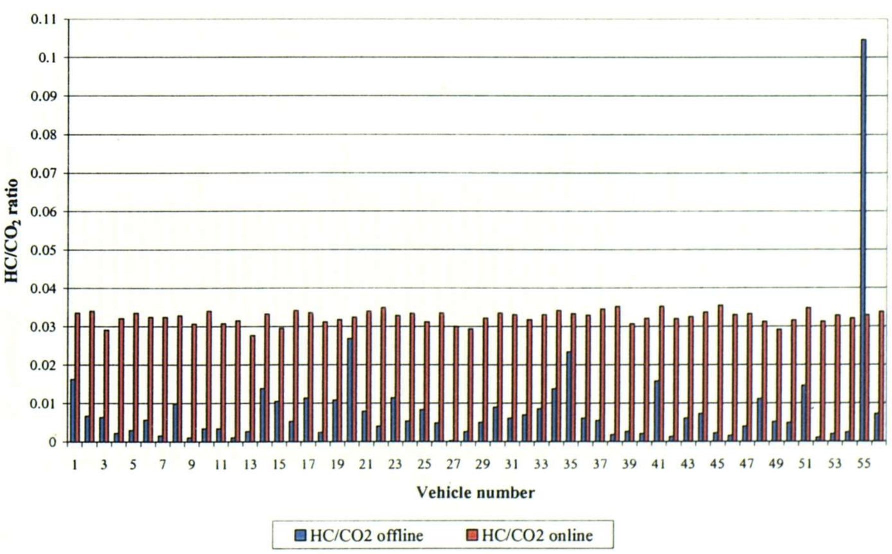


Figure 5-21: CO/CO_2 (top) and HC/CO_2 (bottom) ratios from initial Southampton trial using online and offline REVEAL processing algorithms

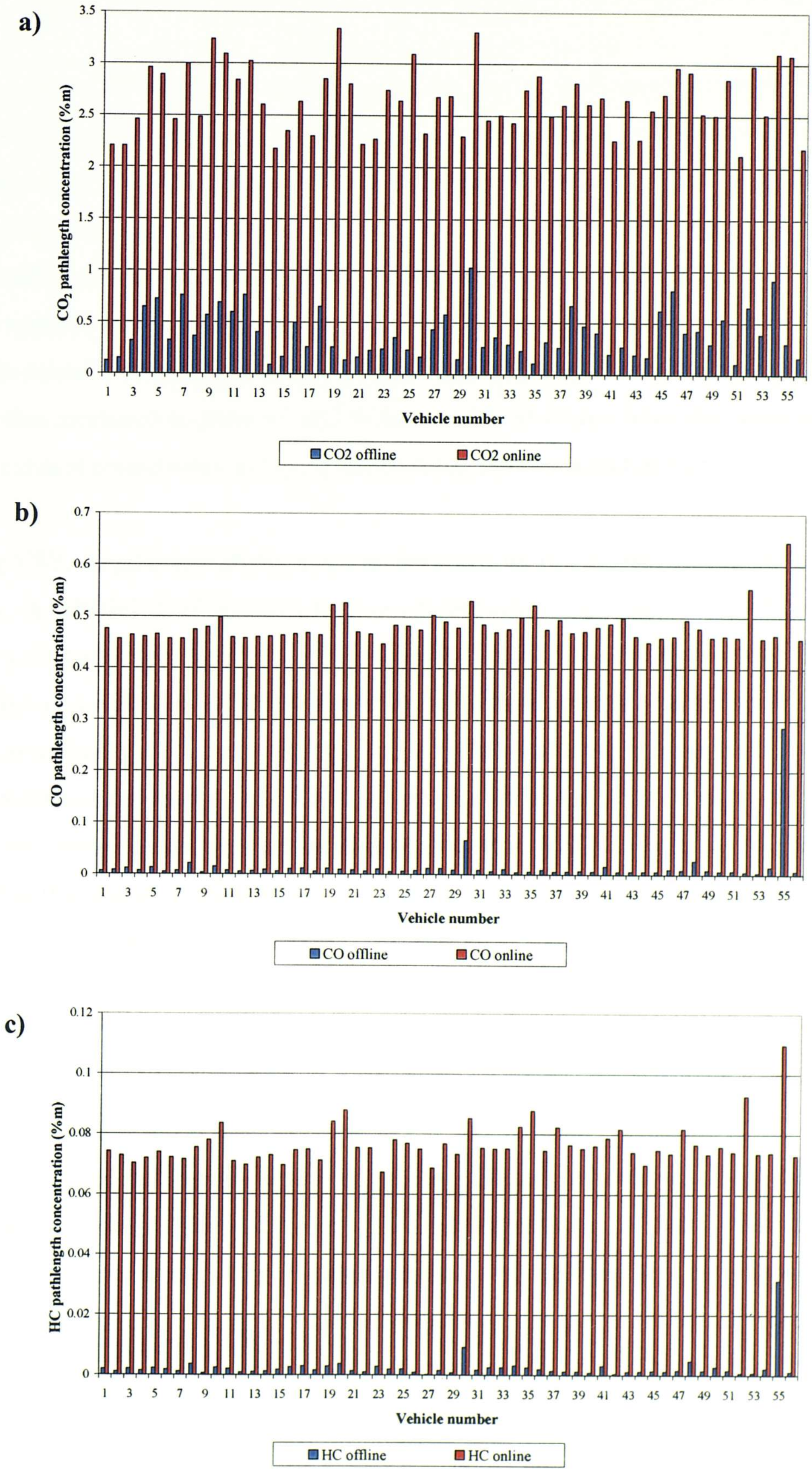


Figure 5-22: Comparison of a) CO_2, b) CO and c) HC pathlength concentrations from initial Southampton trial using online and offline REVEAL processing algorithms

5.9 Summary and conclusions

The principle of absorption spectroscopy can be used to measure emissions from vehicle as they pass and it has the advantage over some forms of legislative emissions tests in that the measured vehicle is under some load. Whilst a number of different technologies have been used for roadside RSDs, the basic approach is the same with losses in signal strength for particular light wavelengths being converted into a concentration pathlength (ppm.m). Most RSDs used for measurement of vehicle emissions measure CO_2 as a reference gas (a proxy for fuel burnt) and CO, HC (often measured as propane) and NO; a number of studies have also measured other exhaust constituents including particulates, ammonia and primary NO_2.

Using VSP, an estimate of the work undertaken by the measured vehicle can be made. A vehicle's RSD measurement can be influenced by a number of different factors although some level of control of these factors can be achieved by the selection of a suitable site and measurement of vehicle operating parameters. Using VSP, an estimate of the work undertaken by the measured vehicle can be made. This VSP measurement can help filter out vehicles for which high emissions would be expected either because they are producing a negative VSP or a positive VSP which is higher than the legislative cycle to which they are tested (an off-cycle event). VSP is also a useful parameter to determine the suitability of a site for use in an RSD study. Other variables such as fuel type can only be known by linking to vehicle databases making ANPR essential to the system.

Due to imperfect agreement between the vehicles which exceed the RSD thresholds and the legislative test thresholds, RSDs are not able to *replace* legislative testing. Using emissions cut points or thresholds to identify vehicles which are suspected of failing or passing the appropriate legislative emissions tests, RSDs can be used as a screening tool. Instances of disagreement between the two test approaches are called errors of commission and omission. These errors vary depending on the RSD threshold used and so selection of the appropriate threshold is important when striking a balance between ensuring public confidence in the system and capturing sufficient real polluters so as to remove excess emissions from the road. Use of RSD reading to identify gross polluters or likely non-failures often requires two readings to be sure of their status. Use of two measurements for the same vehicle reduces errors of commission and omission although it does reduce the sample size measured. Using a gross polluter threshold approach based upon thresholds (5% CO and 1000ppm NO) from a UK fleet study (Barlow, 1998) 0.5% of the fleet would fail. This appears to be a small amount but it is feasible that there are variations in this figure around the country due to variations in vehicle maintenance. Indeed, a similar study in Greece found that 5% of the fleet would have exceeded the thresholds. A previous use of RSD measurements to encourage voluntary vehicle repair using a roadside VMS was estimated to have reduced total emissions by 5% (Bishop *et al.*, 2000).

The REVEAL RSD unit used within this project has a susceptibility to errors at low pollutant concentrations although it is useful for producing estimates of fleet profiles or identifying gross polluting vehicles. Some improvements in the accuracy of the system have been suggested and relate to the processing algorithms, the calibration curves used and the physical build. The summary statistic used for the analysis of the much of the RSD results in **Chapter 6** should minimise any measurement error. Most of the recommended improvements are beyond the scope of this study although one adjustment to the unit alignment was found to be beneficial.

6 MEASUREMENT CAMPAIGN IN WINCHESTER

6.1 Introduction

During April and July 2006, a measurement campaign was undertaken using the REVEAL RSD instrument in conjunction with a speed and acceleration measurement instrument over a total of seven days. This campaign was undertaken at the Badger Farm Road and Andover Road in Winchester.

6.2 Site setup, selection and valid readings

6.2.1 Site selection

Five sites on the outskirts of Winchester were identified as having potential to be suitable for use of the RSD at the roadside. These sites satisfied most if not all of the criteria for an 'ideal site' as described in **Section 5.4**. Of the five selected sites two (Badger Farm Road and Andover Road) were chosen to be the basis of the RSD emissions measurement campaign in Winchester – a map showing the location of these sites in relation to Winchester is given in **Figure 6-1**. A brief description of the sites and how they satisfied the 'ideal site' criteria is given below:

> **Andover Road** – This site had a gentle up hill gradient (2%) and speed limit of 40mph. It was a single direction carriageway with space either side for the safe location of the RSD at the correct width. Under normal conditions most vehicles were estimated to be travelling at a steady speed if not under going moderate acceleration. The site had a small slip road adjacent to the road where the equipment trailer and van could park and act a base for the associated computers. Due to the location of the RSD close to the road way some traffic management (i.e. traffic cones, signs etc.) were necessary. The site was relatively remote from housing. Regarding the potential for cold start vehicles, the nearby army barracks is estimated to be a five minute drive from

the site and few vehicles were observed to be passing through the site from there. The adjacent sewage works was approximately a three minute drive from the site and contributed very few travelling through the site. Given the small number of vehicles from these potential cold start sources and their distance from the site their effect on the overall emissions profiles is considered negligible. The site is also on one of the main radial routes into Winchester city centre and as such had a relatively high hourly traffic flow.

Badger Farm Road – This site was located on a roundabout exit arm near the M3 motorway. The site was again on a gentle gradient (2.5%) and had a speed limit of 60mph. Due to the location of the site so close to the roundabout, this speed limit was rarely achieved by passing vehicles although they were estimated to be undergoing modest acceleration. The site had sufficient verge area for the trailer and van to be safely located. Again, because the limitations on the separation of the two RSD components meant they needed to be located close on the live carriageway, therefore there was a need for traffic management. The site was located on a single direction carriageway and was on one of the main radial routes leading into Winchester. The only sources of potential cold start vehicles identified were a small number of residences a three minute drive from the site. The number of vehicles which would chose to travel through the site from their location was considered to be negligible in terms of the results presented.

Detailed traffic management setup for each site is given in **Appendix 1**.

Figure 6-1: Map showing location of RSD sites in Winchester. Only results from Andover Road and Badger Farm Road were used in this analysis.

6.2.2 Equipment

The general equipment layout for both sites is shown in **Figure 6-2**. As the vehicle travelled through the site the LightSpeed equipment measured two speeds and an acceleration value. As the vehicle was in the same approximate location as the LightSpeed equipment the ANPR system captured its number plate. The vehicle then passed through the RSD unit beam. This whole process took place within one second. Each component is described in more detail below.

LightSpeed instrument – Two infra red (IR) sources and receivers were used as light gates. The beam on which the sources and receivers were mounted were aligned parallel to the road and each source was aligned to its opposite receiver. This produced two IR beams across the road perpendicular to the road's edge. The receivers were connected to a high resolution data logger which stored the voltages from each receiver. The data logger then passed a buffer containing 500ms of voltage values from each receiver to a laptop computer. When a vehicle broke the beams the voltage would increase. The laptop ran a program continuously which examined the buffer information and where it identified a vehicle blocking the beams, used the time stamp of the blocking and unblocking of each receiver (and the known distance between the receivers) to calculate the speed and acceleration. The sources and receivers were made by Banner Industries, Inc. and were kindly donated by Prof Don Stedman at the University of Denver.

Each vehicle pass resulted in two speed values and one acceleration value. Each 'event' was logged to a text file on the laptop computer together with the laptop time stamp. Each event was later combined, offline, with the appropriate emissions reading using a macro (which matched the emissions and speed/acceleration readings using both the time stamp and vehicle sequence number). This instrument was located 15m upstream of the RSD unit. This distance was chosen based on results presented by Jimenez (1999) who estimated the residence time of the exhaust gases in the vehicle's exhaust system for vehicle speed versus its VSP. This distance was based upon a vehicle speed and VSP in the range of 35-40mph and 5-10kWtonne^{-1} respectively. This gave more relevance of the measured VSP to the captured emissions reading. In an ideal situation the speed and acceleration would be measured using a 25m long array of sensors with the data used final speed and acceleration values used being based on the average over the whole array.

ANPR system – This operated using separate computer equipment fitted with a Jetgrab graphics card and ANPR platform. The system was a bespoke design developed by Goldenriver Traffic Ltd. The camera was a standard black and white surveillance camera. As each vehicle approached the RSD unit, the number plate was recorded by the system. This was then combined with the RSD emissions file online using a serial connection between the ANPR computer and the laptop computer connected to the RSD unit. The number plate was combined with the appropriate emissions reading based on both the vehicle sequence and an estimated delay time between ANPR capture and RSD measurement.

In optimum light conditions the capture rate for all passing vehicles (including HGV's, buses, which often have irregular number plates were not recognised by the software) was estimated at 90-95%. On some occasions low sun behind approaching vehicles prevented the necessary contrast between the number plate and the vehicle bumper colour and so no number plate was associated with the RSD reading. This problem was often associated with white and silver cars.

RSD system – A detailed description of the RSD unit in terms of the operating algorithms, specific height setup of the main unit and retroflector, and the potential sources of error is given in **Section 5.7**. The physical set up routine was as follows. The main unit was located on the side of the road where the van was parked with the front lined up approximately parallel to the road edge. The retroflector unit was placed on the opposite side of the road approximately opposite the main unit, again, with its front approximately parallel to the road edge.

The mid point of the bottom mirror on the main unit was set to 29cm above the road level and front of the unit horizontally levelled using the precision spirit level on top of the unit's cabinet. The retroflector unit was set as low to the roadway as was possible meaning the bottom window of the unit was approximately 14cm above the roadway. The front of the retroflector unit was then levelled horizontally using the unit's spirit level. The units were then roughly aligned to face each other at the correct angle using the sighting scopes on top of the cabinets with a final precision alignment using the inbuilt gun sights. The optimum beam alignment was then made by altering the pitch and yaw of the bottom mirror based upon the signal levels reported on the laptop computer.

Upon measurement of a passing vehicle's plume the data is processed by the inbuilt PC and the resultant summary emissions values transmitted to the laptop computer via a high speed ethernet connection. Each vehicle reading is stored as a separate text file and combined with the appropriate number plate being transmitted from the ANPR computer. To extract the data in these individual files into one spreadsheet containing a complete day of data, a macro was written.

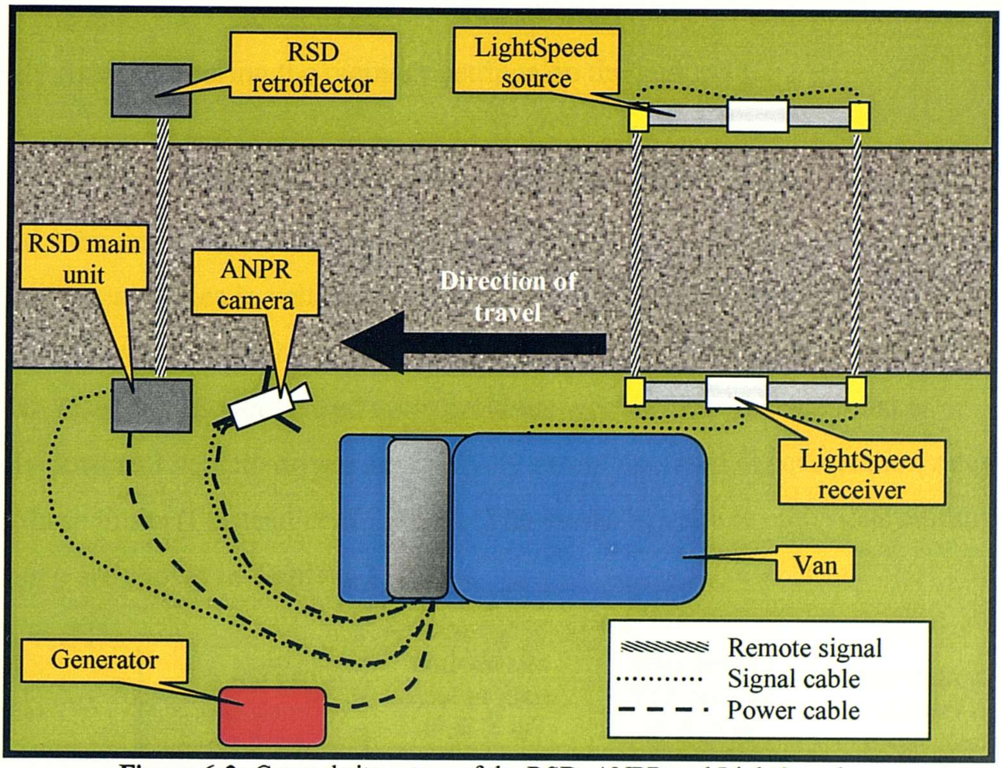


Figure 6-2: General site set up of the RSD, ANPR and LightSpeed instruments.

6.2.3 Selection of valid readings

A total of 13221 readings were gathered from the REVEAL instrument (11029 from Andover Road and 2192 from Badger Farm Road). The total dataset was processed to remove invalid readings. Readings for which there was no associated number plate were removed as it was impossible to be sure if these readings related to motor vehicles or had been triggered by non-motorised objects such as bicycles, dogs or site operators. This could also be due to the ANPR subsystem not being connected during emissions measurement.

The next stage of processing matched the acquired VSP readings with the emissions data using the timestamps of each vehicle in the datasets. Emissions readings without a matched VSP reading were removed – for the Andover Road data the losses in emissions readings due to a lack of VSP reading were substantial on some days due to problems with the laptop computer. This was thought to be caused by the laptop computer having difficulty in saving both the emissions readings and speed/acceleration readings simultaneously; this was fixed in the last few days of testing. The fault was thought to be due to a lack available PC memory and was seemingly fixed by altering the memory settings on the laptop PC.

Finally, some further readings for which a sensible acceleration value was not measured were removed. Some measurements from the LightSpeed instrument were affected by peculiarities in vehicle shape or difficulties with triggering the light detectors; only readings with acceleration between -2.5ms^{-2} and 2.5ms^{-2} were included. These limits were based upon previous work which indicated that a relatively powerful vehicle driven aggressively rarely operated at acceleration rates beyond these limits (Felstead *et al.*, 2006). The losses of vehicle emissions readings at each step are shown in **Table 6-1**.

Site	**Total of emissions readings**	**With invalid number plate (# & % of *original total*)**	**With invalid VSP reading (# & % of *original total*)**	**Final database size plate (# & % *of original total*)**
Andover Road	11029	899 (*8.1*)	6308 (*57.2*)	**3822 (*34.6*)**
Badger Farm Road	2192	297 (*13.5*)	424 (*19.3*)	**1471 (*67.1*)**
Combined	**13221**	**1196 (*9.0*)**	**5293 (*50.9*)**	**5293 (*40.0*)**

Table 6-1: Losses due to removal of invalid emissions readings

6.3 Non-emissions measurements

6.3.1 Speed, acceleration and VSP

The distribution of speed, acceleration and VSP at each site is presented in **Figure 6-3** to **Figure 6-5**, and **Table 6-2**.

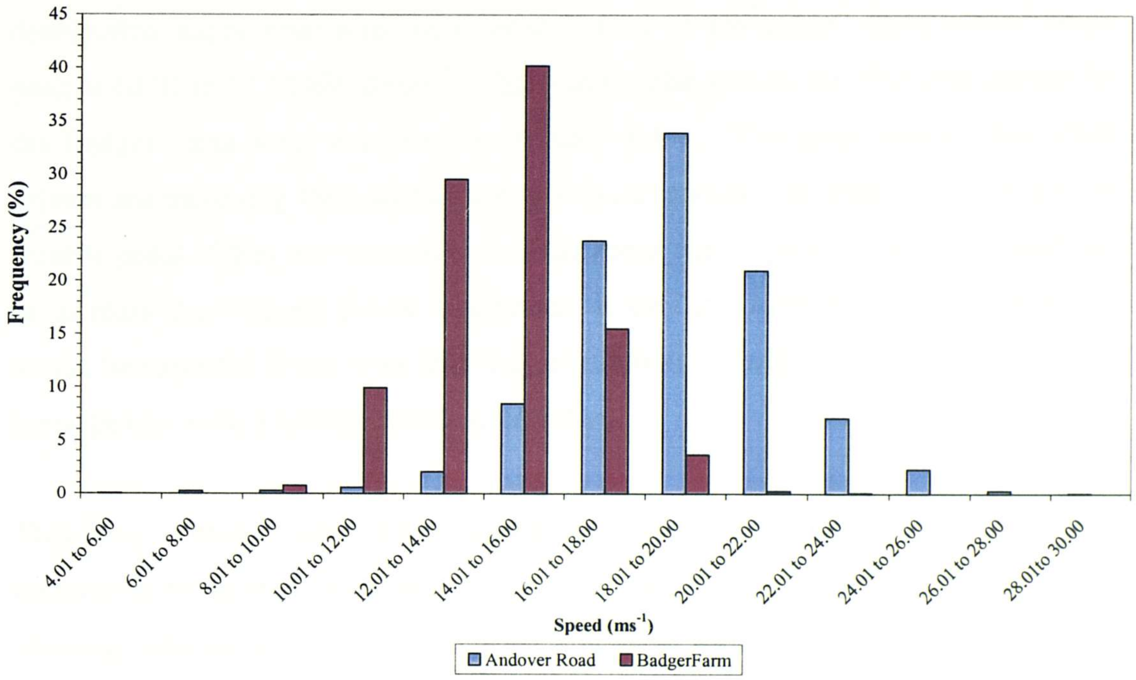


Figure 6-3: Distribution of speed measurements at Andover Road and Badger Farm Road

Badger Farm Road has a tendency to have vehicles travelling through the measurement site at a lower speed when compared to the speeds observed at the Andover Road site. This result is not unexpected considering the nature of the two sites (i.e. Badger Farm Road site is just after a roundabout exit whilst Andover Road is at brow of a long straight road). The influence of the site on the speed profiles of the passing vehicles can also be seen in the distribution of accelerations from the two sites. Given that most vehicles passing the Andover Road site were at or close to the sites speed limit of 50mph (~23ms^{-1}) it can be assumed that the vehicle driver is close to their target speed and so only require relatively small acceleration rates or indeed feel they should slow down as they drive through the measurement site. At the Badger Farm Road site however, the vehicles are passing through the site at a relatively low speed compared to the 60mph (~27ms^{-1}) speed limit and so require relatively large accelerations in order to reach their target speed.

It is also likely that the driver passing through the site will be less worried about the nature of the site (i.e. is it a speed trap) if they know they are not close to the speed limit and so continue accelerating through the site. This site influence is also seen in the distribution of VSP. For the Andover Road measurements a bi-modal distribution can be seen with one peak at -7.49 to -5 kW tonne^{-1} and a second larger peak at 10.01 to 12.50 kW tonne^{-1}. This trend is also seen in the VSP distribution for the Badger Farm Road site albeit to a lesser extent. This may indicate that when drivers are travelling through the site there is a tendency to either brake or lift the throttle pedal if they are worried or curious about the purpose of site, or to continue or increase their current power requirement if they are unconcerned by the site. As would be expected if this were true, the distribution at Badger Farm Road is far more homogenous with a smaller standard deviation.

This is an important result when considering future site layouts and selection. This could even be used to the improve the number and homogeneity of valid readings by slowing vehicles before they reach the site (e.g. a 100m stretch of 30 mph) and allowing them to speed up to the higher speed limit as they travel through the RSD equipment.

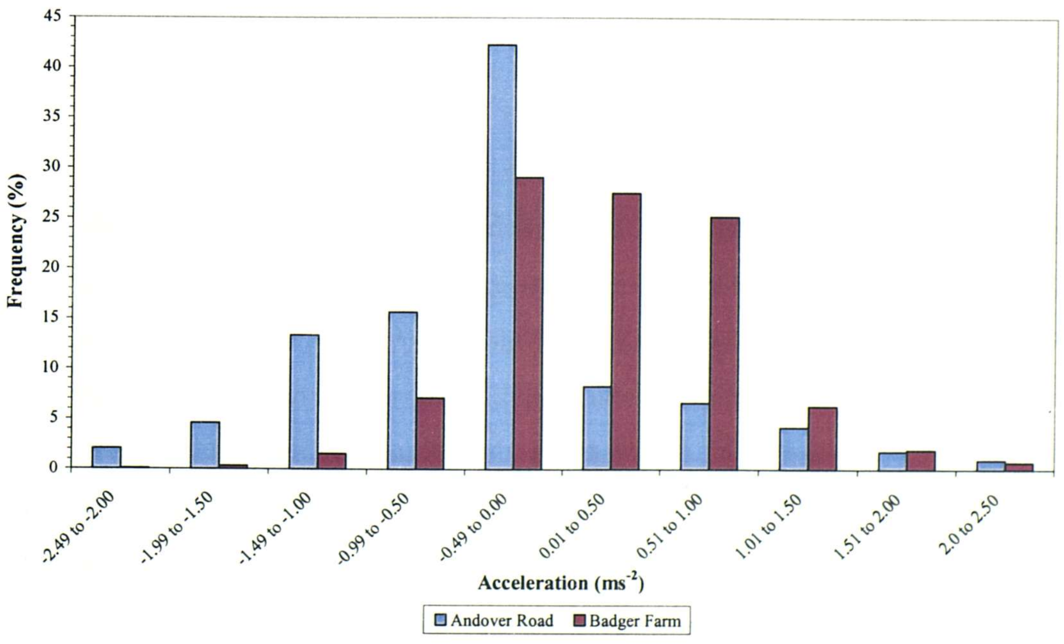


Figure 6-4: Distribution of acceleration measurements at Andover Road and Badger Farm Road

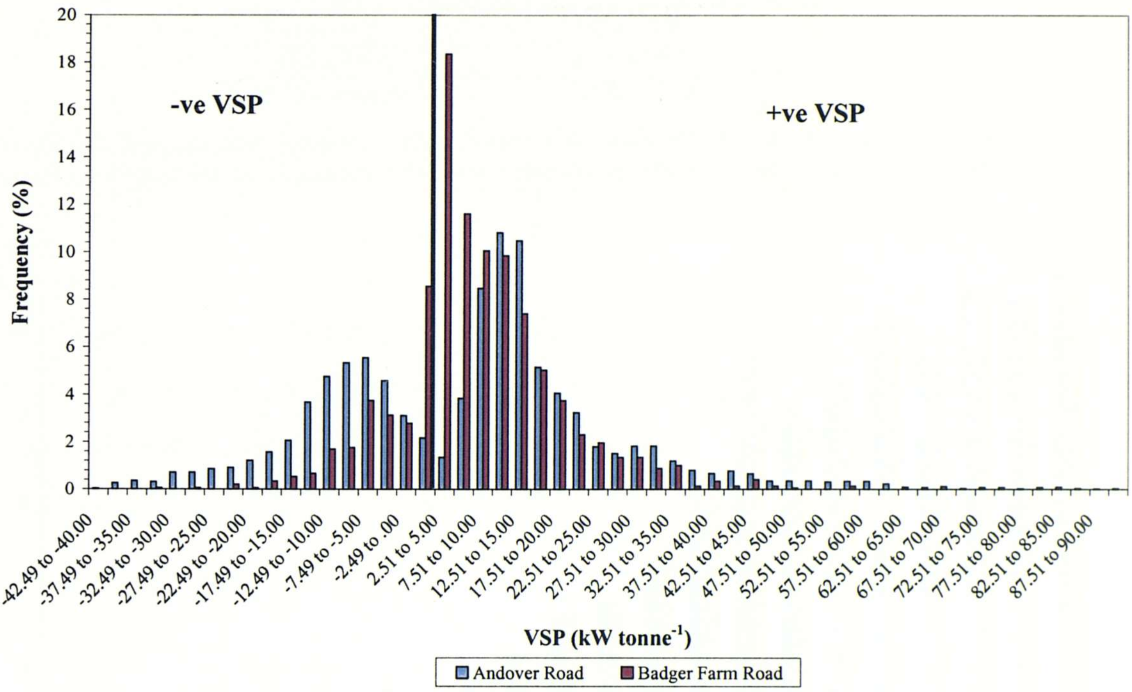


Figure 6-5: Distribution of VSP at Andover Road and Badger Farm Road

Site	Speed (ms^{-1}) Andover Road	Speed (ms^{-1}) Badger Farm Road	Acceleration (ms^{-2}) Andover Road	Acceleration (ms^{-2}) Badger Farm Road	VSP (kW tonne^{-1}) Andover Road	VSP (kW tonne^{-1}) Badger Farm Road
Mean	18.86	14.46	-0.25	0.29	7.25	7.8682
St. Dev.	2.59	1.98	0.83	0.58	18.30	10.26204

Table 6-2: Mean and standard deviation of speed, acceleration and VSP at Andover Road and Badger Farm

6.3.2 Age profile of vehicles

The age of each vehicle captured was estimated based on the relevant character/s within the number plate. The determining character was different for the three most common number plate types as shown in **Table 6-3**. A macro was written which firstly determined the format of the number plate and then used a look-up table to determine the year the number plate was issued. This was not always a perfect approximation of the vehicle age due to the release of private number plates which are associated with the owner and not the vehicle. However, given the small percentage of such number plates in the measured fleet their effect on the overall distributions presented are considered negligible.

Period	Example number plate format
1963 -1983	PNA 61**W**
1984 - 2001	**E**51 WWT
2002 - present	HN**03** UGS

Table 6-3: Number plate formats as an indication of the year the vehicle was first registered. The character/s in bold for each format can be used with look up tables to determine the appropriate year.

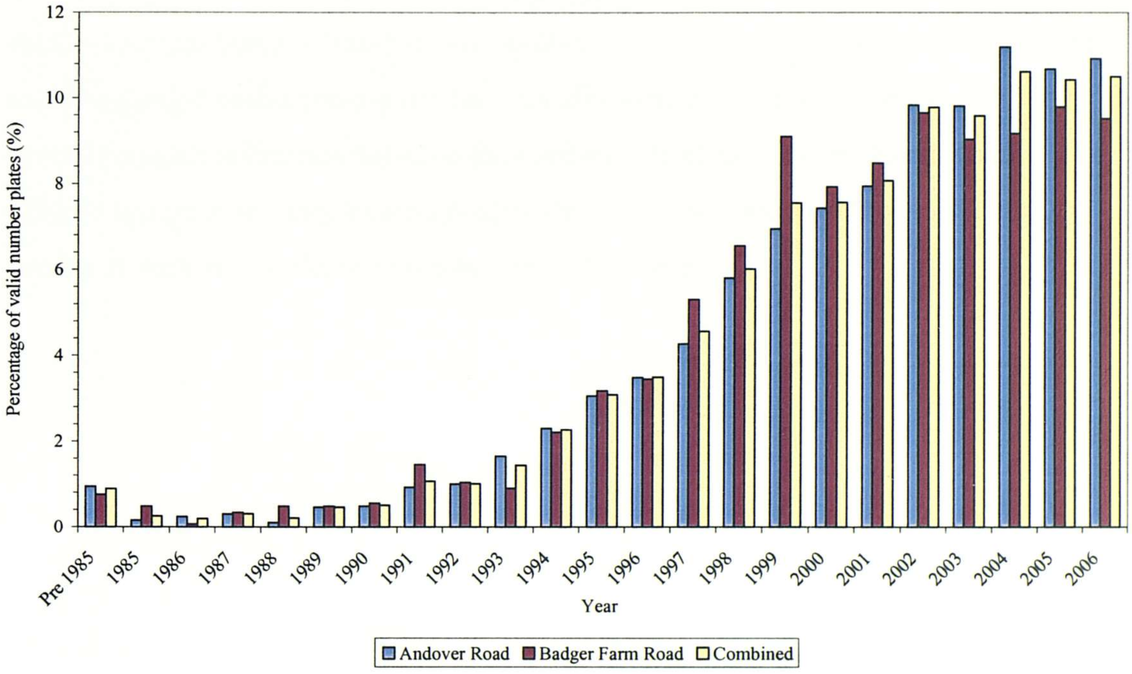


Figure 6-6: Age distribution of the measured vehicle fleets at Andover Road and Badger Farm Road

The age distribution of the vehicles passing through both sites is similar although the Andover Road site appears to have a greater proportion of newer vehicles travelling through the site. The reason for this apparently newer fleet is unknown but could be due socio-economic differences in the areas the vehicle were travelling into to Winchester from thus having an influence on their vehicle choice. A χ^2 test shows (see **Table 6-4**) that the relationship between site and year of registration distribution maybe significant (i.e. the difference in the distributions based upon which site the vehicle was observed at is significant) although the Cramers V statistic indicates that this possible relationship is very weak (Field, 2006). So whilst the distributions are different and this is more than would be expected than if just due to chance the difference is small.

Statistical test	Value	Degrees freedom	Significance
Pearsons χ^2	38.195	22	0.017
Cramers V	0.086	-	0.017

Table 6-4: Results of χ^2 test on vehicle age distributions at Andover Road and Badger Farm Road sites. A significance of < 0.05 indicates that the site and age distribution variable are related but the low Cramers V value (shows strength of relationship on scale of 0 to 1) indicates this relationship is very weak.

As shown from previous studies (see **Section 5.6.1**) vehicle age (a proxy for vehicle technology and maintenance) can have an affect on fleet emissions profiles. But given the small difference between the Andover Road and Badger Farm Road vehicle age profiles, only a small proportion of any difference in the emissions profile at each site could be explained by vehicle age.

6.4 Plume capture

Using the time integrated CO_2 value, the distribution of plume capture between both sites can be compared. This gives an indication of the overlap of the RSD beam with the passing vehicle plume. These distributions are shown in **Figure 6-7**.

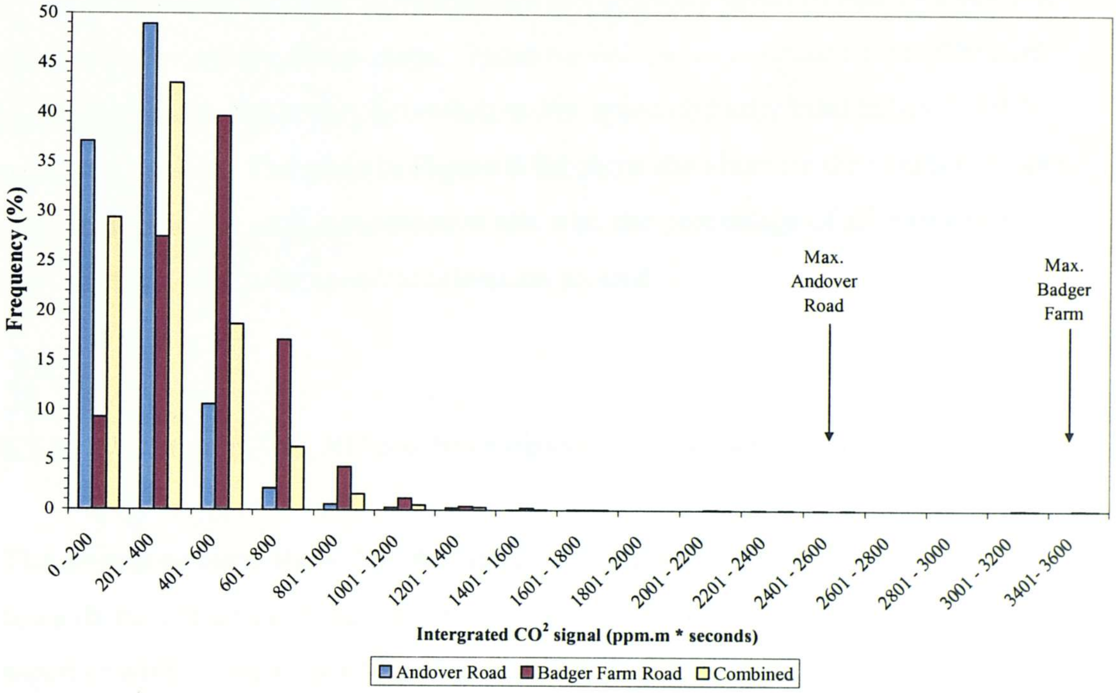


Figure 6-7: Time integrated CO_2 distribution for Andover Road and Badger Farm Road

It is clear that better plume capture was experienced at the Badger Farm Road site. However, since the RSD equipment set up was exactly the same at each site this improved plume capture cannot be explained by better overlap of the beam and the exhaust plume and the nature of the fleets should be similar in terms of relative exhaust pipe position. The difference is more likely to be due to high exhaust output experienced due to the higher VSP distribution shown in **Figure 6-5**.

6.5 Emission variation with combined speed and acceleration

To examine how the emissions efficiency of the measured Badger Farm Road and Andover Road vehicle fleets compare, a series of contour plots showing average emission ratios for bivariate speed/acceleration bins are given in **Figure 6-8**; these are also known as emissions maps. These emissions maps illustrate how the fleet average emission ratios vary according to the speed and acceleration bin of the measured vehicle. The plots in **Figure 6-8d** show the bivariate distribution of speed and acceleration at each measurement site with the percentage of all measured vehicles for a particular speed/acceleration plotted.

6.5.1 Variation in CO, HC and NO emission maps at same sites

The emissions maps show that the highest average areas (or peaks) are located towards the extremes of the measured operating conditions. When considered together with the joint speed/acceleration distribution, it can be seen that the speed and acceleration of most vehicles measured also forms the centre where emissions are lowest. The very low values on the periphery of the emissions maps are due to no measurement being made in that bin rather than the average emissions being particularly low.

The CO and HC emissions maps closely follow each other with areas of high emissions being coincident. This is to be expected given that high emissions of CO and HC are formed in the same combustion circumstances (i.e. a rich A/F ratio) and the same after-treatment approach (i.e. oxidation). The NO peaks are in areas where some elevation in the CO and HC readings are observed but are on the whole in areas distinct from CO and HC peaks.

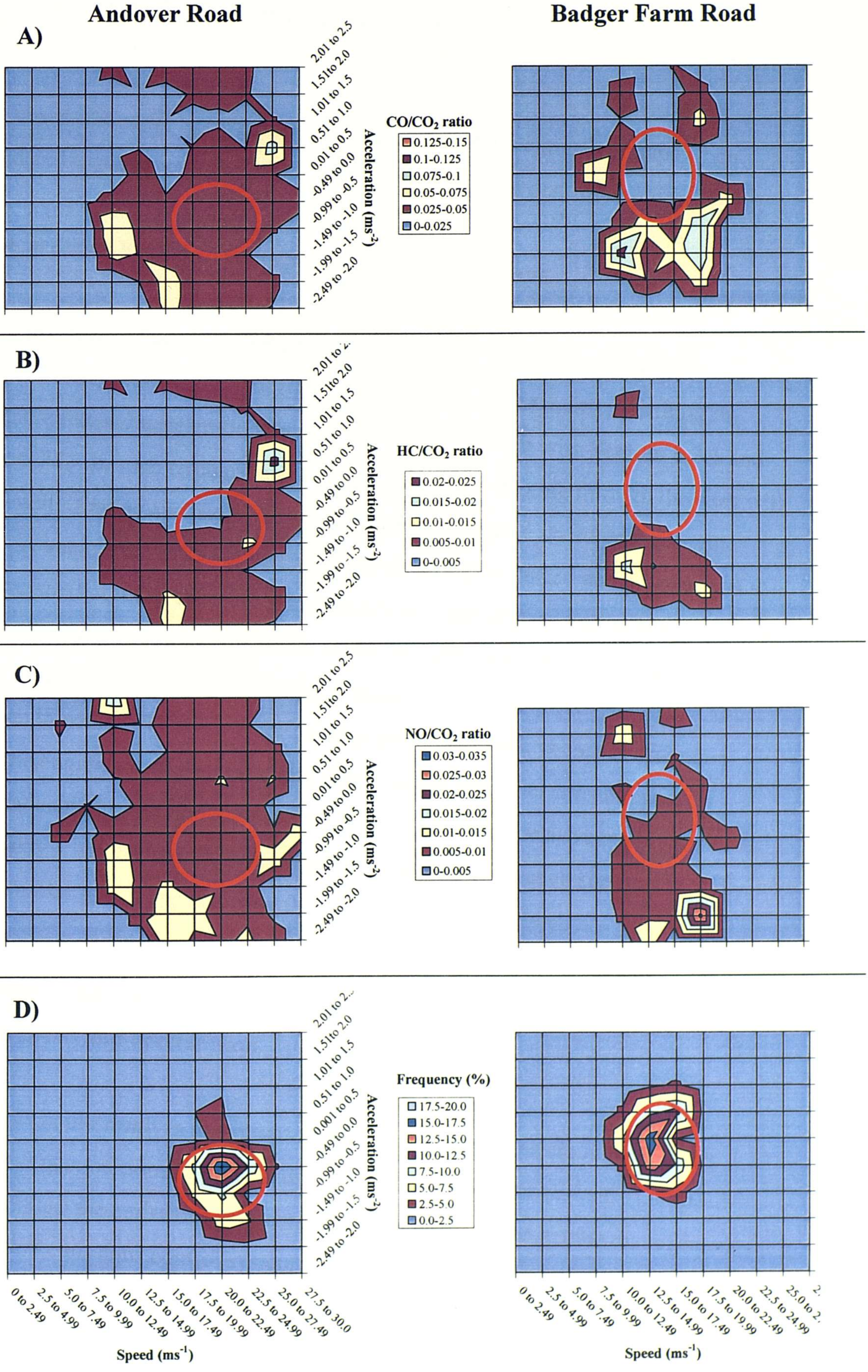


Figure 6-8: Speed vs Acceleration maps for CO, HC and NO to CO_2 ratios at Andover Road and Badger Farm Road (**Rows A-C**) and a joint distribution of Speed vs Acceleration readings (**Row D**)

6.5.2 Explaining the speed and acceleration map

Two observations are apparent in the speed/acceleration emissions maps when considered together with the joint speed and acceleration distribution.

i) The two sites have different speed and emissions maps.

Firstly, it is not useful to use the speed and acceleration maps to compare emissions across different sites because the two sites have different capacities resulting in different speed and acceleration profiles. This is consistent with **Section 6.3.1** and **Figure 6-8d**. In such circumstances the choice of gear driving through the sites will be different. *Engine* emissions maps are based upon engine speed versus engine torque. A vehicle measured travelling at exactly the same speed and acceleration at a particular site but using different gears would, on a speed/acceleration emissions map be located at the same point, but on an engine speed/torque emissions map would be in different areas with one having a higher emission efficiency (i.e. *pollutant*/CO_2 ratio) than the other. The reason for using gears is to move a vehicle's drivetrain back to the engine's optimum (whether it be performance, fuel consumption or emissions) engine speed and torque. Beyond this optimum, relative emissions concentrations will be higher. So the emission profiles from each site may actually be more similar than it appears from the speed/acceleration maps.

ii) The areas of high average emissions are located to the extremes of the measured speed and acceleration.

Three factors could result in this observation. Firstly, emissions are highest under extreme driving conditions. For most driving performance requirements (i.e. speed and acceleration) the emissions are controlled adequately by the engine management and associated emissions control systems and thus emissions are relatively low. However, more extreme demands on the engine can result in the loss of this emissions control thus resulting in lower emissions efficiencies (Felstead *et al*, 2006).

The second factor relates to the apparent insensitivity of the REVEAL equipment at low emission concentrations. As described previously in **Sections 5.7.2 and 5.7.3**, if a measurement is taken where the plume capture is relatively poor, the measurement noise can create artificially high emissions measurements. As shown in **Section 5.7.2**, for most measurements the relative error for each measurement channel on the REVEAL instrument is high. Therefore, when considering average emissions, the average value is far more susceptible to the influence of high or low noise values when the frequency of measurement is low as there is less chance of the *observed* mean value centring on the *true* mean value. Due to the manner in which a measurement was reported by the REVEAL system, the quality of the measurement (i.e. for a single plume, how closely the variation in a pollutant concentration matched that for CO_2) was unknown and so this can not be explored further.

Also, it is possible that different emissions standards/fuel types are apparent at the more extreme speed/acceleration bins due to the lower frequency of vehicles measured at those points (i.e. a Pre-EURO diesel vehicle would be expected to have a high NO emissions reading compared to a EURO IV petrol vehicle).

Each of these three factors is likely to be influencing the observed speed/acceleration maps though it is impossible to know the extent of each. Also, it should be noted that because the relative concentrations are higher, it does not mean the absolute concentrations are also higher. The influence of relative fuel consumption on absolute emissions is important. Considering two vehicles, one with a low pollutant/CO_2 ratio the other with a high pollutant/CO_2 ratio, if the former has a particularly high fuel consumption compared to the latter then the absolute emissions from the former could be greater than the latter. So, in instances where relative emissions are high during deceleration, the actual fuel consumption is likely to be low, especially in modern vehicles which have a fuel shut off in such driving modes.

6.6 Relationship of emissions to VSP

Emission measurements can be binned according the estimated VSP of the measured vehicle and these measurements then averaged for each VSP bin. This was undertaken separately for the Andover Road and Badger Farm Road datasets for CO/CO_2, HC/CO_2 and NO/CO_2 emission ratios (see **Figure 6-9**).

Two observations can be made regarding these data. Firstly, the average emission ratios appear to fall with increasing VSP and, secondly, in general Andover Road and Badger Farm Road appear to follow the same trend but are offset from each other.

Due to the influence of noise on the majority of measurements contributing to the average emission ratio value for each VSP bin, the uncertainty in the average values is high. This means that any apparent relationship is highly unlikely to be due to the emissions performance of the fleet rather due to another confounding variable.

The apparent decrease in emissions with VSP and the offset between the two sites can be explained by the quality of plume capture. It has already been shown in **Section 6.4** that the quality of plume capture is best at the Badger Farm Road site. If the quality of plume capture is better then the measured CO_2 pathlength concentration will be higher thus have a higher SNR. This does not mean however that the CO, HC or NO measurement is high enough for the SNR to be as insignificant. Remember, of the four channels, the CO_2 channel is already the least susceptible to noise and so the relative error is much bigger for CO, HC and NO channels than for CO_2. This means that the average CO_2 denominator in the emission ratio will be higher for the site with best plume capture (i.e. Badger Farm Road). This will result in a consistently lower *pollutant*/CO_2 ratio for the same VSP for the Badger Farm Road dataset compared to the Andover Road dataset. This 'offset' effect is seen less with the CO/CO_2 data because the CO concentrations are often higher than that of HC and NO, so will be less affected by noise.

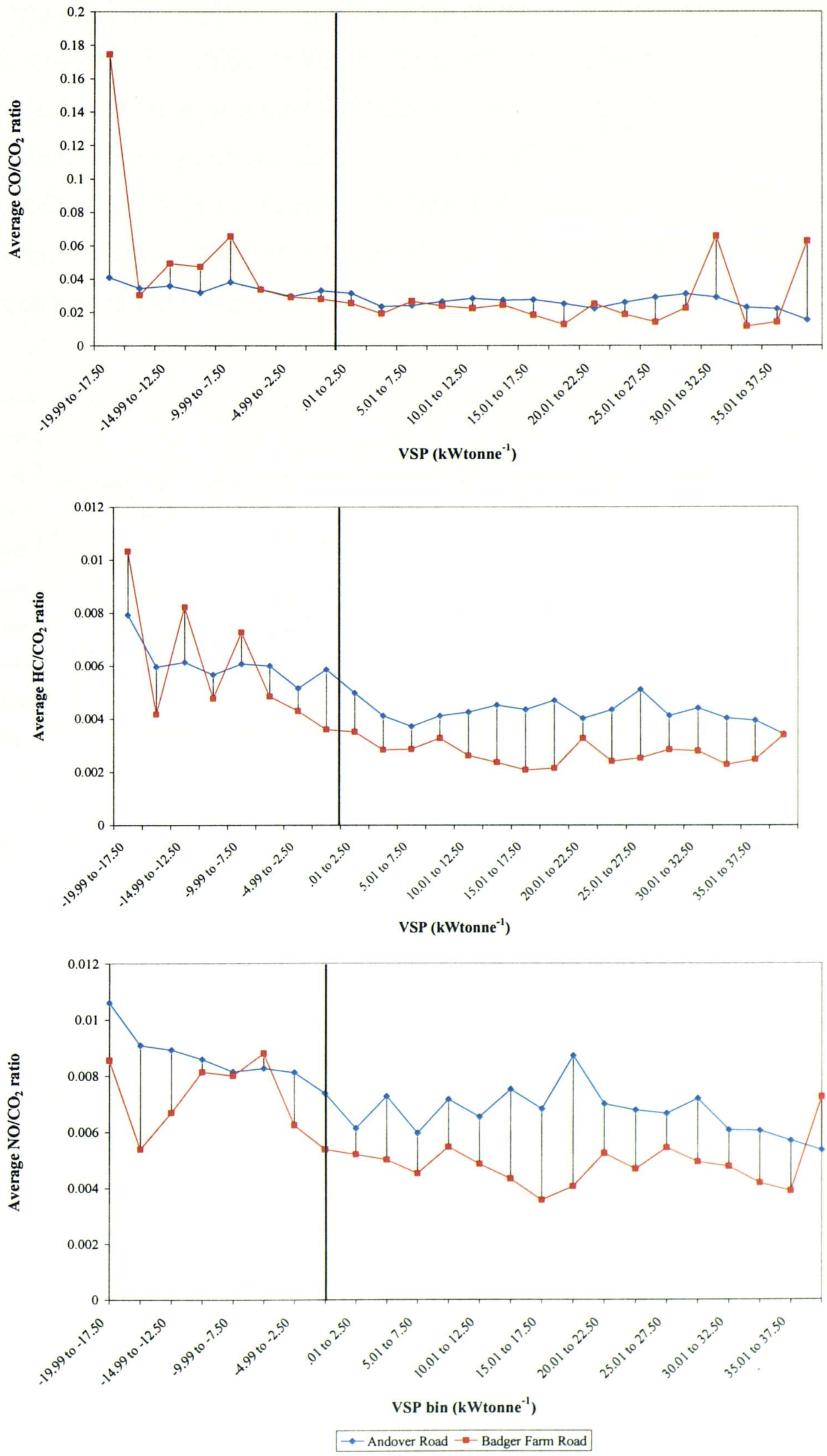


Figure 6-9: Average a) CO/CO_2, b) HC/CO_2 and c) NO/CO_2 ratios, binned according to VSP, for Andover Road and Badger Farm Road

This explanation also explains why the average *pollutant*/CO_2 ratio values decrease as VSP increases. The CO_2 output is will be greater as the power required by the engine increases (due to increased fuel consumption) thus the fact that the CO_2 error diminishes at a quicker rate than the CO error means that the denominator in the *pollutant*/CO_2 ratio begins to dominate the ratio and so a decreasing trend is seen. To confirm this explanation, the average CO_2, CO and HC pathlength concentrations have been binned according to VSP (see **Figure 6-10**).

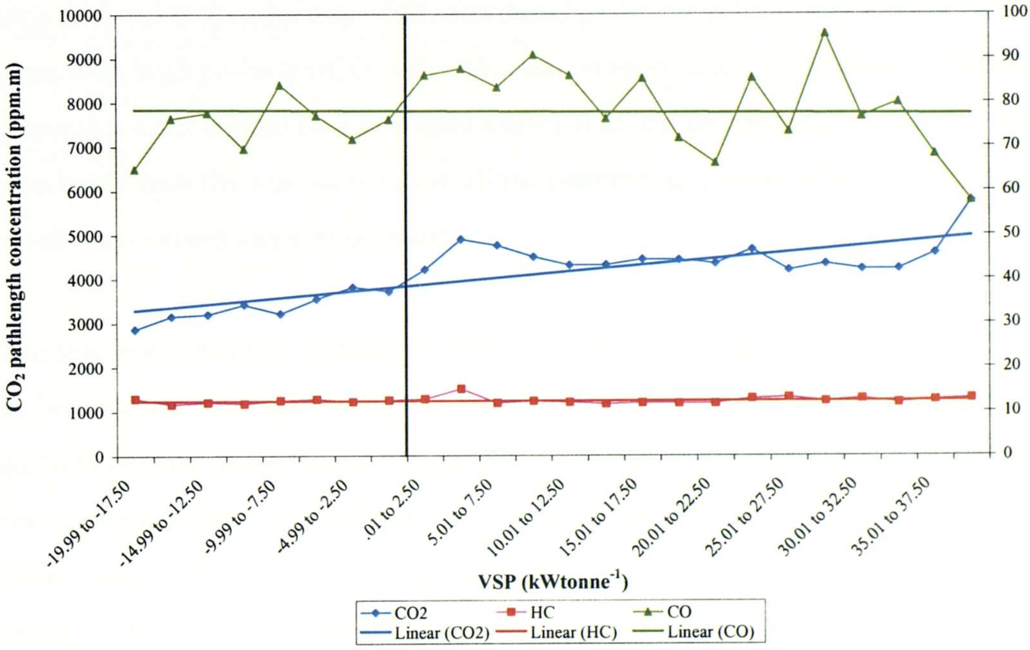


Figure 6-10: Average pathlength concentrations of CO_2, HC and CO from Andover Road site, binned by VSP

So, for data collected using the REVEAL instrument, plotting emission ratio values according to VSP will not offer any insight into how fleet vehicle emissions vary according to VSP.

6.7 Decile emissions distribution

The REVEAL instrument has been observed to be fairly insensitive at low pollutant concentrations (ppm.m). So, for most emissions measurements, a particular vehicle can not confidently be attributed to the reported emissions value – instead it can be said that the vehicle's true emissions value will be within a range of values (i.e. a confidence interval). This range becomes smaller as a percentage of the true value as the measured emissions concentration increases. Since more certainty can be placed in the CO_2 value than for any of the measured pollutant values (see **Section 5.7.2**) for values with high *pollutant*/CO_2 ratios the ratio is more likely to be correct. Thinking of how this error should be distributed amongst all measurements (e.g. some higher, some lower than the true value) over all measurements a reasonable estimation of overall fleet values can still be made.

With this in mind some estimation of the fleet decile average emissions efficiency can be undertaken. This is useful at showing how the upper most decile for CO, HC and NO compare to the lower nine deciles. The top decile is the least affected by the measurement noise discussed previously, whilst the effect of noise in the lowest nine deciles even itself out over (i.e. the distribution over the lowest 9 deciles should be similar to that that would have been produced if the true values were known and used in this analysis). This is a standard way to analyse RSD study data although it is normally undertaken using data converted to ppm. This conversion is undertaken using idealised combustion equations under the assumption that combustion is under stoichiometric metric conditions (see **Appendix 2**). Other conversions to units such as *g* pollutant/*l* fuel or *g* pollutant/*kg* fuel can also be undertaken and are used in some RSD studies. The combustion equations are used to convert the RSD ratio measurement to a measurement which would be equivalent to that of a tailpipe probe (such as those used in the MOT idle test) (Kuhns *et al.,* 2002). The equations use generalised values regarding fuel density, fuel Carbon/Hydrogen ratios and fuel molar mass (Ning *et al.,* 2004). These three parameters are different for petrol and diesel fuels, so using generalised values would distort any results; the use of ratios negates the problem of the analysis including vehicles of unknown fuel type. In addition, the use of ratios is arguably more relevant as it reports the emissions per unit CO_2 (i.e. proxy for fuel consumption). A comparison of the use of just ratios shows good correlation with the combustion equation approach used in most RSD studies (REVEAL, 2004a).

Figure 6-11 presents the percentage contribution to the total of all measured *pollutant*/CO_2 ratios when grouped into deciles rank ordered by the ratio value. **Table 6-5** presents the total emissions ratios when grouped into deciles rank ordered by the ratio value. It can be seen that the often quoted figures of 10% of the measured vehicles are responsible for 50% of the pollution, is not true in this study. It would appear that Winchester has a cleaner fleet than has been reported in previous RSD studies. Despite this, the frequently reported trend of a minority of vehicles producing a disproportionately high amount of emissions seems to hold true for CO, HC and NO.

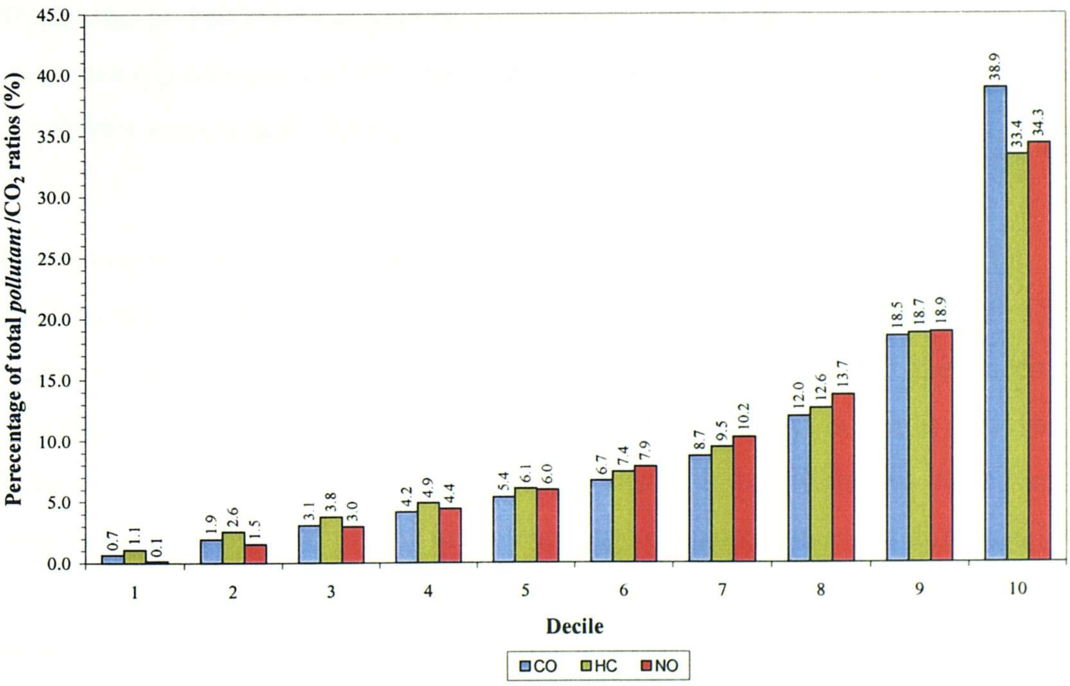


Figure 6-11: Percentage of total *pollutant*/CO_2 ratios for each decile of the vehicle fleet rank ordered by ascending *pollutant*/CO_2 ratios. Results are for CO, HC and NO.

Pollutant	Decile									
	1	2	3	4	5	6	7	8	9	10
CO	1.0	2.9	4.6	6.3	8.0	10.1	13.1	18.0	27.9	58.4
HC	0.3	0.6	0.9	1.2	1.4	1.8	2.2	3.0	4.4	7.9
NO	0.1	1.5	3.0	4.4	6.0	7.9	10.2	13.7	18.9	34.3

Table 6-5: Total *pollutant*/CO_2 ratios for each decile of the vehicle fleet rank ordered by ascending ratio values.

There are a number of possibilities to explain this departure from previously reported trends:

- The Winchester fleet is better maintained than previously measured fleets,
- As the fleet is renewed with vehicles which adhere to tighter emissions standards, the impact of relative high polluters is less, and there maybe fewer of them,
- The REVEAL instrument is underestimating emissions, or
- The inclusion of diesel vehicles in the analysis has affected the emissions data.
- The Winchester fleet has a greater proportion of new vehicles compared to previously measured fleets

The results in **Table 6-5** can also be used to derive the decile average pollutant emissions (ppm.m) per unit CO_2 for each of the pollutants by dividing by the number of vehicles in each decile (529).

Examining the top decile for each site (see **Table 6-6**) it can be seen that the top decile at Badger Farm Road has a higher contribution to the total CO/CO_2 ratios and higher average CO/CO_2 ratio than at Andover Road. For HC and NO, the percentage contribution to the total ratios is similar although the average is higher at Andover Road than at Badger Farm Road. Reasons for this could be differences in the fleet make up at each site (differences in fuel type, age or maintenance), or differences in the VSP distribution. Without supporting data to control for these effects it is impossible to determine a precise cause for this.

Pollutant	Average ratio		% of total ratios	
	Andover Road	Badger Farm Road	Andover Road	Badger Farm Road
CO	0.106	0.122	35.6	48.7
HC	0.016	0.011	31.7	34.8
NO	0.025	0.018	33.4	35.0

Table 6-6: Average ratio value and contribution to total ratios of top decile at each site for CO, HC and NO

6.8 Influence of vehicle age on emissions

Many RSD studies have shown a link between vehicle age and emissions. This relationship was attributed to vehicle maintenance but has more recently been associated with tighter emissions standards. To see if this was true for the Winchester fleet, the emissions ratios were separated into groups which broadly related to the periods for each EURO standard. For each emissions species, sub divided by the age groups, the quintile values and averages have been plotted (see **Figure 6-12**).

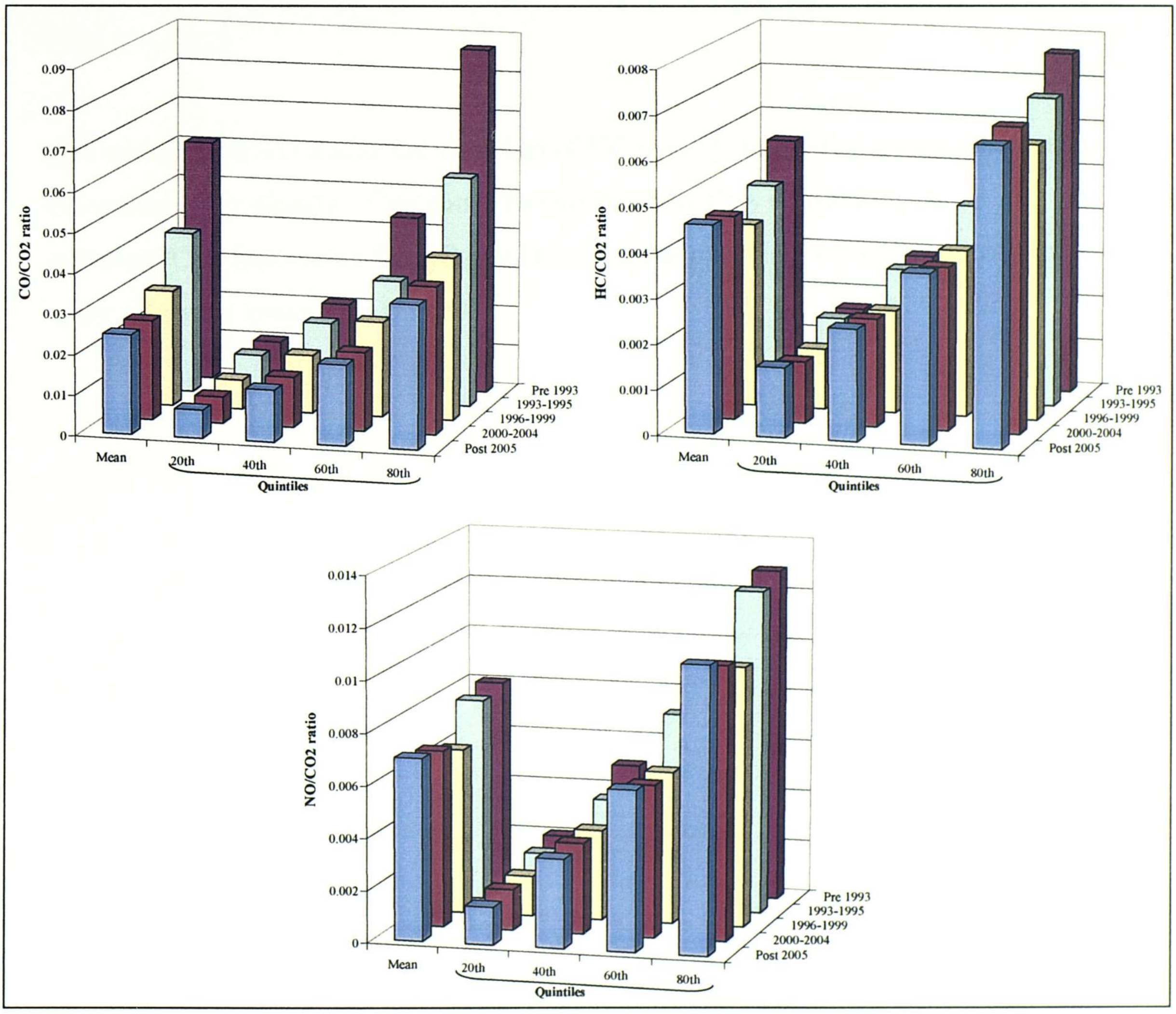


Figure 6-12: Mean and quintile values for vehicle emissions grouped by vehicle age. (broadly relate to emissions standards to which vehicles were designed) Clockwise from top left for CO, HC and NO.

The relationship of increasing emissions with age band can clearly be seen in the CO data with the effect becoming more apparent with age. The relationship is less clear when considering HC and NO emissions. This does not mean that it does not exist but it is more likely that the poor sensitivity of the REVEAL instrument at the normal concentrations experienced in the measured vehicle plume results in more of the measurements being an artefact of measurement noise rather than a detected concentration. If this analysis could separate petrol vehicles from diesel vehicles the difference may be come clearer (e.g. diesel vehicles inherently have low CO and would fall into the lowest quintile for CO emissions regardless of age). This analysis could not be undertaken as verifying the fuel type of all the measured vehicles would have taken too much time. This would have involved cross checking the vehicle registration with the vehicle image captured at time of measurement to determine the manufacturer, and then using this data to search for each individual vehicle on the DVLA website.

The variation in NO tracks the variation of HC closely but neither tracks changes in CO particularly closely. This could be explained by CO_2 dominating the *pollutant*/CO_2 ratio value for NO and HC since the measured concentrations were an order of power lower than for CO.

6.9 Identifying gross polluters

6.9.1 Definition of gross polluters

Gross polluters are commonly defined as vehicles being over a specific emissions limit. Each I&M campaign (whether RSD based or not) which seeks to identify vehicles over a certain limit has its own objectives and so a range of thresholds are available from the literature. A number of possible cut points or thresholds to compare the data against. These various thresholds are presented in **Table 6-7**.

Study/legislation	Test type	Vehicle type	Pollutant	Threshold
UK MOT (2001)	Tailpipe probe	Petrol – catalyst post 2001	CO – low idle CO – high idle HC	0.3% 0.2% 200ppm
		Petrol – catalyst pre 2001	CO – low idle CO – high idle HC	0.5% 0.3% 200ppm
		Petrol – non catalyst	CO – low idle HC	3.5% 1200ppm
McCrae *et al.*, 2001	RSD	Petrol - catalyst	CO NO	5% 1%
		Petrol – non catalyst	CO	7%
Stedman, (2002)	RSD	All vehicles	All Selection based on ratio of CO:HC:NO	Top 1% vehicles 4:1:2 until 1% of total vehicle population is selected
Dept of Environmental Quality, Oregon (2003)	RSD	All vehicles	*Clean* CO HC NO *Fair* CO HC NO *Dirty* CO HC NO	 0-0.49% 0-110ppm 0-499ppm 0.5-1.0% 111-220ppm 500-1000ppm >1.0% >220ppm >1000ppm
	Tailpipe probe	All vehicles	CO HC	1% 220ppm
REVEAL (2004) – Gross polluter	RSD	All vehicles	CO HC NO	5% 1500ppm 1%
REVEAL (2004) – Super polluter	RSD	All vehicles	CO HC NO	2.8% 1500ppm 0.6%

Table 6-7: Various thresholds used to identify gross polluting vehicles

It can be seen that a range of values for each of the pollutants measured are used in the small selection of studies presented above. The study by McCrae *et al* (2001) has been chosen to represent the thresholds used here to identify gross polluting vehicles. This study was based on UK and European fleets and the thresholds identified were based upon comparisons of RSD measurements with MOT style idle test measurements. The thresholds were set to avoid unacceptable errors of commission (i.e. RSD gross polluters not failing the MOT emissions test) associated with lower threshold values. The concern is that having false failures would undermine public confidence in the use of RSD measurements.

A flaw in this approach is that the comparison of RSD measurements to a standard value is only as good as the standard being worked to. It has already been discussed in **Chapter 4** how the current MOT test is not a particularly good indicator that the vehicle has an emissions related error. Switching the relationship between the two types of emissions measurement (i.e the RSD measurement is the standard and the MOT test is ad hoc test) then the MOT test could be considered to undermine public confidence in the RSD test. Many areas of the US use centralised chassis dynamometer tests as the method of testing a vehicle's emissions compliance. If this approach were used in the UK then the relevant EURO standard chassis dynamometer emissions limit (with an allowance for vehicle degradation with age) would be the standard to be attained.

The data presented by McCrae (2001) shows how chassis dynamometer data for legislative cycles compares to the vehicles RSD measurement. Decreasing the CO RSD threshold increases the percentage of true failures (according to the chassis dynamometer). With this in mind, the Winchester dataset will also be compared to tighter RSD CO threshold of 3% simulating how RSD use could supplement a more centralised chassis dynamometer testing approach. This lower threshold will only be applied to vehicles of an age where they could be expected to adhere to EURO I or higher standards (i.e. first registered 1992). If RSD were to be used as part of an I&M programme then ideally thresholds would be derived considering the fuel type and the EURO standard the vehicle was designed to meet. For the on-road RSD measurements this could be derived from DVLA database.

A further important outcome of the McCrae (2001) study was that RSD CO is a better indicator than RSD HC of whether a vehicle will be a HC chassis dynamometer failure. With this in mind, only CO and NO will be used as RSD gross polluter criteria.

6.9.2 Translation of % or ppm limits into ratios

Rather than transform all the Winchester data into ppm or % values using the idealised combustion equations (see **Appendix 2**), the thresholds will be transformed into an appropriate ratio value (this has the advantage of making the limits applicable to diesel vehicles as well as petrol vehicles).

To do this, firstly, an assumed CO_2 concentration value needs to be derived. Using the idealised combustion equations on the Winchester dataset, the average % concentration from all vehicle measurements is 14.7. So the denominator for the ratio of CO %/CO_2 % used will be 14.7. However, because there is only a limited amount of carbon in the fuel being burnt, when CO is relatively high the amount of CO2 will be lower. To account for this carbon balance effect the denominator has to be %CO_2 minus %CO (REVEAL, 2004a).

So the 5% and 3% *CO thresholds*, when expressed as a ratio of CO/CO_2 are **0.51** (i.e. 5/(14.7-5)) and **0.26** (i.e. 3/(14.7-3)) respectively.

Calculation of the *NO threshold* as a ratio does not need to consider a carbon balance and so equals **0.06** (i.e. 1/14.7).

6.9.3 Numbers of gross polluters

Based on the thresholds identified above, the numbers of vehicles which would be defined as gross polluters are presented in **Table 6-8**. Few vehicles measured in Winchester would appear to be gross polluters.

	Pollutant and threshold		
	CO		NO
Threshold (% of exhaust)	5%	3%*	1%
Pollutant/CO2 threshold	0.51	0.26	0.071
# of measurements	**5294**	**4947**	**5294**
# of vehicles exceeding	**4**	**22**	**3**
% of measurements	**0.1**	**0.4**	**0.1**

Table 6-8: Numbers of vehicles above gross polluter thresholds

*only considers vehicles first registered in 1992 or later

If vehicles over the 5% and 3% CO emissions threshold were removed from the road, total emissions, from the total measured fleet, of CO per unit CO_2 emitted would be reduced by 2% and 5% respectively. If vehicles over 1% NO threshold were removed from the road, total emissions of NO per unit CO_2 emitted would be reduced by 2%.

The DVLA website allows for some data (including year of manufacture, fuel type, engine size and CO_2/km where measured) for individual vehicles to be checked if the registration and make of a vehicle are known. By checking the still images of the gross polluting vehicles, their make could be determined. The three NO gross polluters were diesel vehicles. This is not entirely surprising as diesels have inherently high NO emissions compared to an equivalent model year petrol engines (see **Chapters 3 and 4**). It could well be that these vehicles were in fact not gross polluters as when tested on a chassis dynamometer they would be well under the relevant limits although it is also possible that the EGR mechanism (which reduces NO_x) for these vehicles had failed. All but one of the CO gross polluters were petrol vehicles. This result is to be expected since diesel vehicle produce negligible CO as they operate fuel lean and CO is produced in fuel rich conditions. The one diesel vehicle which failed the CO threshold is likely to have had a far higher fuel consumption than it should.

6.9.4 Use of REVEAL unit to clean screen vehicles

The REVEAL instrument was not sensitive enough to be used as a 'clean screen' tool with any certainty that the vehicle was in fact below the low threshold required for such an approach.

6.10 Conclusions

Site selection is important in gathering results from vehicles travelling through the site in a more homogenous operating conditions. The use of VSP is important in filtering out results from vehicles passing through the site using extreme power requirements thus ensuring non-representative results are not included in the analysis for gross polluters.

A link to other vehicle information would be beneficial to gain more understanding of how various parameters such as fuel type affect RSD readings and to control for these variations. This data could also be used to set various gross polluter thresholds based upon the EURO standard with which the vehicle was designed to comply.

The visual impact of the site appears to be important with both sites showing a bimodal distribution. This would indicate that there are two types of reaction by drivers to the site. Some drivers allow their vehicle to slow down as they travel through the site either out of curiosity or fear of a speed trap, whilst others are unperturbed by the site and so drive through normally.

The average vehicle emissions deteriorate with vehicle age, this is most likely due to a combination of the varying emissions standards, the level of maintenance and some factor relating to degradation of the emissions related controls of the vehicle. Some difference in the estimated age of the vehicle fleets seems to be apparent but this difference is small and is unlikely to result in the differences in emissions from the highest polluters which has been seen.

The contribution of the highest decile to total emissions can be estimated to be between 35 to 40% for each of CO, HC and NO. This is a lower figure than is often quoted in the literature although no comparable data for the UK could be found. It is unknown how typical these results are of the rest of the current Hampshire or UK fleet.

There are seemingly very few gross polluting vehicles (0.4% of measured fleet) being measured at the test sites indicating that Winchester does not have a problem with excess emissions from passenger cars. Removal of these few gross polluters would only improve emissions by a small amount. It is unknown if this is typical of Hampshire or UK car fleets. All but one of the CO gross polluters were petrol vehicles and the three NO gross polluters were diesel vehicles – these are results were expected given the nature of the emissions produced by each fuel type.

This number of gross polluters can be compared to the 0.5% of the fleet which were identified in a previous UK RSD study (Barlow, 1998). The current MOT test fails approximately 1.5% of tested vehicles due to emissions (DfT, 2004) and recent in-use compliance testing by the VCA on vehicles built since 2001 has found 6% of both diesel and petrol vehicles to fail to meet their natural aging adjusted emissions limits. The VCA sample is subject to wide confidence limits due to only a relatively small number of vehicles being tested. It can be expected that the RSD percentage would be less than that of the MOT. Due to the tendency for older vehicle to have lower annual mileage, their likelihood of being observed by the RSD is less than that of a newer vehicle. The MOT also exempts vehicles under three years old exacerbating this effect – if vehicle under three years old were exempted from this analysis then the gross polluter percentage is estimated to be 0.6%. This still below the MOT failure rate suggesting that the relevant thresholds, when using the REVEAL equipment, should be reassessed.

Future work should use a more sensitive instrument. This will allow a more accurate understanding of the contribution of the highest polluters to the whole fleet, as well as allowing confident use of VSP as a parameter to control for variations in the vehicle operating conditions between sites. Other sites should be used to understand how the results from Winchester compare to other areas of Hampshire and the UK.

7 QUESTIONNAIRE ON RSD MEASUREMENT FOR PUBLIC FEEDBACK

7.1 Introduction

To understand how the general driving public would react to various mechanisms of delivering feedback of their vehicles RSD measurement a questionnaire survey was undertaken. This chapter describes the survey methodology, the various feedback mechanisms explored within the questionnaire and presents and discusses the outcomes. A review of issues surrounding questionnaire survey design is also included.

7.2 The survey process

The purpose of the survey was to understand how various approaches to feeding back emissions information from RSD's would be accepted by the public and to explore the potential for using the voluntary emissions test approach. There were time and cost implications for the design of the survey which restricted its scale and running period. A review of literature on survey sampling design is given in **Section 7.3** to illustrate that the issues surrounding survey design have been appreciated, particularly how a sampling frame would be derived for a larger, more comprehensive survey.

7.2.1 The sample

In March 2006, a total of 2120 questionnaires were distributed to drivers who travel within or into Winchester. The sample was derived from a number of sources. A panel *list* of ~1800 names and addresses of people known to travel in Winchester was available from a previous survey undertaken for the MIRACLES project (MIRACLES, 2007) which was used to gauge opinions on transport related issues in Winchester. Those approached in the earlier survey comprised of a simple probability sample of all addresses in the electoral role (which in theory should be 100% of occupied addresses in Winchester) and of an on-street handout of similar questionnaires to members of the public who lived outside Winchester. The questionnaire offered two £50 shopping vouchers as an incentive to complete and return the questionnaire. Respondents who filled out the initial questionnaire were invited to become members of a questionnaire panel to help formulate Hampshire County Council transport policy in Winchester and to have the chance of winning extra prizes.

For the RSD survey, the panel list was filtered to include only people who had previously indicated that their household had at least one car which was available for continuous use. If the name on the *list* was not a car driver, they were instructed to pass the questionnaire to a member of the household who did have access to a car for private use. The postal sample size was 1320. To supplement this postal sample, 800 questionnaires were also circulated to drivers using car parks in the city centre. Half of the questionnaires were handed to people parking in the morning peak period at Tower Street car park (typically commuters working in Winchester city centre) and the rest were handed to people parking in The Brooks Shopping centre or Middlebrook Street car park (typically city centre shoppers).

As an incentive to raise the response rate to the questionnaire a prize of an in-car satellite navigation system was offered (or the equivalent value in shopping vouchers, ~ £250). An overall response rate of 38% was achieved. This was a pleasing result considering the large amount of text presented in the questionnaire, which was considered necessary to fully explain the scenarios being examined including the potential costs and benefits.

The sample technique used in this survey was that of convenience sampling (i.e. take all willing volunteers). Data input errors when transferring from the questionnaire to computer were minimised by use of 100% verification (i.e. the questionnaires were entered twice and discrepancies between the response to a particular variable flagged with the correct response being entered)

7.2.2 The questionnaire

The aim of the questionnaire was to understand how the general public would react to various scenarios where RSD readings of their vehicle's emissions would be fedback to them. The scenarios were aimed at encouraging owners/drivers of those vehicles suspected of having an emissions problem to have their car inspected and repaired.

The area of emissions testing using RSD's is one in which very few of the general public would have any knowledge. Any questionnaire approach to understanding their reactions to various scenarios would have to allow the respondent to have adequate information on the motivation, technology and design behind the scenarios being tested. To qualify the respondent in predicting how they would react in the scenarios presented, a sufficient amount of background information on the emissions monitoring scheme would need to be provided.

With these requirements in mind it was felt that a postal questionnaire approach would be the most appropriate option. All content of the questionnaire and accompanying leaflet was drafted within this study. Useful guidance on the design of questionnaires was taken from Weiers (1984), Luck and Rubin (1987) and Malhotra and Birks (2006) as well as previous experience. This approach allowed sufficient written material to be included within the questionnaire pack and allowed the respondent to take the questionnaire away to complete it in their own time. Completing the questionnaire at the respondents convenience allowed them to take their time to understand the scenarios being presented and also decreased the number of people refusing to initially take the questionnaire. Copies of the contents of the questionnaire pack are given in **Appendix 3**. The questionnaire pack included:

- Envelope which gave details of the content of the pack, who it was from (HCC) and advertised the incentive of the prize draw.

- Covering letter from the MIRACLES project manager at HCC. The letter introduced the project, the idea of vehicle emissions monitoring, gave brief instructions on how to complete the questionnaire and how long it would take. It also stressed that confidentiality in the results would be maintained.

- A leaflet which described the emissions monitoring program in more detail including why it was being done, how it was being done and the potential benefits from the scheme. It also introduced the various scenarios which were being tested in the questionnaire. The rear of the leaflet gave a list of tips on how drivers could reduce their emissions and fuel consumption, as well as information on the MIRACLES project.

- Questionnaire which explained each of the scenarios being presented including the time required for the actions suggested by each scenario, the cost of having their vehicle checked and the potential benefits from having an emissions fault corrected. Other information about the respondent which may have an influence on their reaction to the scenarios was also collected. The front of the questionnaire again introduced the subject being examined and how to complete the questionnaire. In addition to the prize draw being offered, respondents were also given the opportunity to enter their vehicles registration to receive feedback on their vehicles emissions.

- Reply paid envelope to make posting the questionnaire back less of a burden.

The questionnaires which were to be sent by post and those handed out on street were requested to be different colours. This would have allowed the responses from each group to be compared in the analysis – unfortunately the printers did not follow these instructions.

The questionnaire used a number of question types but mainly used likert scale questions for the respondent to rate various attributes, yes/no questions to understand how their experience of or reaction to given situations, and category questions to understand frequency reaction and demographic information. In addition, open ended questions were used to allow the respondent to further explain their thoughts on the various scenarios presented.

7.2.3 The scenarios

Using RSDs to quantify the numbers of gross polluters has been done in numerous contexts in the US and other studies worldwide although only to a small extent in the UK (see **Chapter 5**). The second aspect of this study is to understand how the general public might react to a number of approaches to providing them with feedback on their RSD emissions measurement and so encouraging voluntary maintenance of their vehicle as well as reducing the number of gross polluting vehicles in Winchester city centre. These approaches were presented as scenarios within the questionnaire. The scenarios examined were:

- Following a similar approach to that presented in **Section 5.6.4.3**, a drivers emissions reading would be displayed to them at the roadside using a VMS. Their vehicle emissions would be placed into three bands (GOOD, FAIR or POOR). Supported by an appropriate dissemination exercise, the vehicle drivers would know that a change in their vehicle emissions reading would indicate their vehicle had an emissions related problem and would be costing them extra in fuel costs. By linking the measurement with the registration number using the ANPR associated with the RSD, the driver would know that a particular reading was associated with their vehicle – i.e. the US approach.

- The location of the RSD sites on the edge of Winchester limits the number of vehicles which would pass through the site. In addition to the RSD check it is likely that a greater incentive would be needed to encourage a driver to drive out of their way to pass the site. By integrating the RSD emissions reading with the current MOT test, it is possible that a 'clean screen' approach (see **Section 5.6.3.2**) be used where an emissions test would be foregone if the vehicle had recently had two valid RSD readings which were below a certain threshold for each pollutant considered. The incentive in the questionnaire is a reduced priced MOT although for this to be effective the vehicle would have to be normally subject to a more rigorous, more expensive and more time consuming emissions test (i.e. a separate chassis dynamometer test).

- Using a website database or telephone hotline as an alternative or complementary approach to the roadside VMS would allow the public to check their vehicles last emissions reading at their own convenience.

- To further encourage repair of high polluting vehicles a subsidised inspection and repair service could be offered to those vehicles which had been identified by the RSD as a gross polluter. This may encourage more people to actually have their vehicle inspected and repaired if a fault is found than those who would have it repaired voluntarily.

- The final scenario would be for a vehicle whose emissions were measured as being FAIR or POOR to be diverted to a Park and Ride site instead of being allowed to continue their journey into a city centre. Winchester has one Park and Ride site. This could not be enforced as the driver might actually be driving through the city centre en route to another location. It would therefore have to be a voluntary diversion.

7.3 A review of survey sampling

One of the most neglected stages of a survey design is the composition of the sample. This questionnaire for various reasons used a convenience sample. A discussion of survey sampling follows.

7.3.1 Define the target population

The first stage in the sample design determines exactly the population to which the researcher wants to generalise the result to. The definition of the target population, particularly the size as a whole, and within different stratified sub-classes can be a difficult task. If it is done within an institution (e.g. a University or workplace) where details of the whole population are already held on record the task is relatively straight forward. On the other hand, knowing population sizes and characteristics of the general population living in a city is problematic but can be helped by the wider release of census data and government population size estimates.

7.3.2 Define the sampling frame

It is nearly always impractical on financial grounds alone to collect data from the whole population of interest unless it is very small. Even the UK census which attempts to capture data from the whole population living in the UK will never achieve a 100% success rate due to people not responding. Conveniently, by using a fraction of the whole population, information relating to the population can be gathered – this is sampling. Each individual within the population or sample is called a unit.

A number of approaches to sampling can be taken, and creating a good sample is no trivial task. Sampling approaches can be divided into probability and non-probability approaches:

7.3.2.1 *Probability sampling strategies*

Probability samples result in a particular unit within the sampling frame having a known probability of selection within the sample. A number of probability sampling approaches exist.

Simple random sample

This approach requires no prior knowledge of the population which is being sampled and is based upon each unit within the population having an equal chance of selection. This type of sample is often drawn by having a full list of the population of interest and assigning to each an unique identification number. A random number generating program can then be used to produce a list of unique numbers of a specific size. The list of random numbers can then be matched to the unique numbers in the population list. Those units which have a match are selected to be included in the sample. For small populations, issues of sampling with or without replacement need to be considered as this affects the probability of selection and so some of the accuracy of inference of the result to the general population.

Systematic sampling

Here a unit is chosen because they are a particular number within a sequence. By dividing the known population size by the required sample, size the interval between unit selections can be determined. A random number which is less than the interval number is then chosen as the start point. So for a population of 10000, for which a sample of 1000 is required, the sampling interval would be 10. If the random number chosen was 2, then the first unit selected would be the 2^{nd} on the list then the next would be the 12th, next 22nd, next 32nd etc.. Every unit at each interval has an equal chance of selection but those units which do not lie on the interval have no chance of selection. The list from which the units are chosen can either be ordered according to an attribute which is unrelated or related to the characteristics being studied. Depending on the nature of the list ordering, can either increase or decrease the accuracy of the result inferred to the general population.

Stratified random sampling

This approach follows two or more stages. The population is divided according to non-overlapping characteristics (e.g. number of cars in the household) – this is called a stratum. A number of units within the stratum is then sampled using a simple random sample. The stratification variable should be related to the characteristics of interest. Stratified sampling can increase the accuracy of the results without increasing the cost. The increased accuracy comes from each stratum having units of similar characteristics and so the variation between units in the stratum is less. The numbers of units chosen can either be proportional to the relative size of the stratum membership to the population (e.g. the sample within each stratum contains 5% of the units contained within that stratum) or disproportionate to counter issues relating to wider variation in behaviour of particular stratum such as response rates.

Cluster sampling

Similarly to stratified sampling, the population is divided according a non-overlapping characteristic except this time it is unrelated to the characteristics of interest. Each cluster is assumed to have the same variation in behaviour as is shown in the population of interest. The clusters used for the sample are then chosen using some form of probability sampling. The clusters can be chosen either according to the number of units within the cluster so that those with more units have more chance of being selected or by a simple probability approach. Either all the units within the selected clusters can be chosen to be in the sample or they can also be subjected to a probability sampling approach. A common form of cluster sampling is based upon geographical area in which the unit lives (e.g. voting wards). Cluster sampling increases the efficiency of the sampling procedure (i.e. covers a wider area but with more variation in behaviour within clusters) where as stratified sampling increases the sampling precision (i.e. covers a smaller area but with greater precision).

7.3.2.2 Non-probability sampling

Non-probability sampling is useful where the units of interest are difficult to reach or costs for the survey need to be minimized. The probability of selecting a particular unit is not known.

Convenience sampling

As the name suggests this approach relies on the unit being available at the convenience of the person doing the sampling. The units are selected because they were willing to be selected. This approach is considered to be the cheapest and least time consuming form of sampling but has the potential to have considerable limitations in terms of accuracy and inference to the population of interest due to potential biases involved in the selection process. The biggest bias with convenience sampling is that of self-selection.

Judgmental sampling

The choice of which units are included in the sample is left to the judgment of the researcher. The units are chosen to represent what the researcher considers is representative of the population of interest. Similarly to convenience samples, judgment samples are often quick and inexpensive but are subject to bias introduced by the researcher in selection of the units. Inferences to the general population are prone to bias with this sampling approach.

Quota sampling

This method is a hybrid approach between probability sampling and, either convenience or judgmental sampling. Initially, some prior information relating to the population is used to select the proportion of units within a particular group which should be selected (e.g. within a certain age and sex category). Based on a given sample number the numbers of units within each of the categories is calculated. The researcher can then chose units either by convenience (to achieve a quota as quickly as possible) or judgment (to represent what the researcher considers to be the population of interest)

Snowball sampling

This approach is useful for reaching units within the population which have rare characteristics and associate with other units with those particular characteristics. If only a very small minority of units have a particular characteristic, a probability sample would not prove a cost effective approach. Once a small number of units with the characteristic of interest have been contacted it is possible for them to suggest which other units would be of interest to the researcher.

7.3.2.3 Probability vs non-probability samples

Smith (1976) presented a review of the history of the development of probability sampling with much of the theory used today being attributed to Neyman (1936). Doherty (1994) summarised the development of probability versus non-probability samples. Non-probability approaches to sampling are often given scant discussion in more academically orientated texts on sampling theory and procedures (Foreman, 1991; Maisel and Hodges-Persell, 1996; Lohr, 1999). However, texts related to market research give the approach more consideration but still stress its limitations (Weiers, 1984, Luck and Rubin, 1987; Malhotra and Birks, 1999). This is perhaps a reflection on the number of circumstances in real-world situations where cost and time limitations are the determining factors in a survey design.

It is widely accepted in the references in the above paragraph, that samples which include some form of randomness in their selection produce results which can be inferred to be true for the target population with more certainty than those which do not. This is because the errors associated with the sample selection, and its upscaling to represent the general population, can be quantified and so a value of prediction accuracy determined.

Whilst there are a number of tools which can transform a non-probability sample to look more representative of the target population there is no way of knowing how these transformation reduce (or introduce) error or bias in the final predictions. Smith (1983) discusses the validity of making inferences from non-probability samples. Other techniques are available which apparently allow non-random samples to be used for inferences to the general population with an estimation of the accuracy of any inference. Such techniques include propensity scoring or matching (Rubin, 1997; Larsen, 1999; Schonlau *et al.*, 2004; Cobben and Bethlehem, 2005) or through a combination of random and non-random samples (Schonlau *et al.*, 2001; Rivers *et al.*, 2003). These techniques are still in their infancy and there is some debate as to the effectiveness at addressing the inference issue; with this in mind combined with limited information on how to implement these methodologies they were not pursued further.

7.3.3 Errors in surveys

Errors or bias relating to how accurate and representative responses derived from surveys are in terms of the general population can come from two sources (Luck and Rubin, 1987; Lohr, 1999, Malhotra and Birks, 1999, Ortuzar and Willumsen, 2002):

7.3.3.1 Sampling error

This error occurs because the sample selected is not representative of the target population due to random variations. This uncertainty does not affect the values for the variables of interest but it does affect the level of confidence or uncertainty which can be placed in inferring the values to the target population (i.e. a measure of the variation between the value acquired from the sample and the value which exists in the target population). With random samples this error can be estimated using central limits theory and the use of the normal distribution as a 'model' to which data gathered from random samples apply. The fact that a non-probability sample has been used does not mean that the frequencies acquired would not be reflected in the general population, just that there is no way of measuring the level of confidence or uncertainty for the derived values. This is because assumptions of what 'model' the sample should fit can not be made. With this rationale in mind, for self-completion postal questionnaire surveys, this error may actually be relatively small for both probability and non-probability samples when compared with other errors or biases which can affect the final values.

7.3.3.2 Sampling bias

This is also referred to as non-sampling errors in some texts and relates to all errors which are not related to variations of a probability sample. Malhotra and Birks (2006) divided these biases as response and non-response.

Non-response bias

Non-response bias occurs when some of the units with the chosen sample do not reply either because they choose not to or are not contactable. Non-response should always be factored into required sample size approximation as the achieved sample size will always be smaller than that used in the first instance. Such is the potential importance of non-response entire chapters of sampling and market research texts are dedicated to the issue – a short discussion is presented here. For a good target population list (e.g. address of the electoral role), the not-contactable proportion of this bias should be relatively small although it is possible that for postal surveys, a significant portion of the sample receive the survey but do not even open it (e.g. may be mistaken for junk mail) (Brennan and Hoek, 1992). However, some population lists will miss elements of the target population (e.g. the typical example quoted in older literature is of telephone surveys where not everyone in the population had telephones). It is thought that the behaviour of this group of non-respondents does not vary from those who respond (Armstrong and Overton, 1977).

The other form of non-response bias is introduced by those who are contacted but refuse to complete survey – this is often just quoted as non-response in the text. For postal questionnaires this can be particularly high. Refusals have the potential to add significant bias as the opinions or reported data from those who did not respond may be very different to those who did respond. If this portion of the sample were ignored then the generalisations to the rest of the population could be very different from the reality. On the other hand it is possible that those non-respondents would, in general, report exactly the same behaviours or responses as the respondents – their only reason for non-response is a lack of motivation or time to complete the survey in question (reply by Ehrenberg in Copas and Li, 1997). To protect against and understand bias from non-response researchers can use a number of approaches

i) **Improving the response rate -** By minimising the proportion of the original sample which does not respond, the bias is also reduced. Prior notification informs the sample that they should expect to be included in a survey in the near future, what the survey pertains to and what the benefits there are to them personally. This prior notification can take the form of a telephone call, postcard/letter or a short doorstep visit.

   Incentives can be used to encourage a response. With falling response rates to the UK National Travel Survey (NTS), an incentive trial was implemented. This found that a small incentive of £5 per completed questionnaire not only reduced the number of partially completed questionnaires returned but also reduced the total non-response rate (Stratford *et al.*, 2003). In general, incentives do increase response rates but the means and type of incentives have varying effects (Church, 1993). Incentives can be non-monetary (e.g. a pen or feedback on the results) or monetary (some form of payment). It is thought that incentives given on first contact rather than as a condition of a completed survey are more effective. Regarding monetary incentives a direct payments (i.e. to each person unit completing the survey) are thought to be more successful than lotteries (completed questionnaires are entered into a prize draw) (Roberts *et al.*, 2000). The key balance of offering incentives is whether the increase in responses (and so decrease in non-response bias) is worth the cost and effort spent on providing the incentives.

The design of the survey and the manner in which it is administered has an impact on the number of respondents completing the survey. The language, structure of the questions, appearance etc. of a survey are important. The manner in which the survey is disseminated (e.g. personalised address rather than just 'the occupier' or a friendly persuasive person handing out the questionnaires) can also encourage completion of a survey.

Common in questionnaire surveys are follow-up procedures. Postal surveys are often undertaken in a series of 'waves' where those who have not replied after a short time after the initial questionnaire was posted are sent a reminder letter with another questionnaire included. Up to four waves can still improve the overall response rate and information from those late responders can be used in later analysis to mitigate any non-response issues.

ii) **Assessing and correcting for non-response** - A wealth of information is available on various techniques which can be used for identifying when non-response bias may exist and methods of correcting for this non-response. (Filion, 1975; Armstrong and Overton, 1977; Pearl and Fairley, 1985; Holt and Elliot, 1991;

Lynn, 1996; Malhotra and Birks, 2006; Lindner *et al.*, 2001; Pickering *et al.*, 2005).

Methods to identify non-response bias include comparing responses for different waves of surveys returns or comparing characteristics of respondents to those who do not respond by performing a limited follow-up of non-respondents asking them to complete socio-demographic information.

If non-response bias is detected then a number of approaches are available such as trend analysis (based upon the wave or time taken to respond to the survey), imputation (using logistic regression models where the characteristic of interest is dependent on the socio demographic data collected by the respondents and then applied to same socio-demographic details of the non-respondents to suggest what their response might have been), or weighting (where the answers given by particular respondents are given more or less importance in terms of the overall value for the achieved sample).

Response bias

Response bias occurs when the answers given by individuals in the sample either do not reflect their true behaviour or are incorrectly recorded. These errors can be mitigated by careful design of the distribution method, the design of the survey medium or quality control at the data imputation stage. Luck and Rubin (1987) list the most common sources of response bias whilst a more indepth discussion on response bias is given in Malhotra and Birks (2006).

7.4 Sampling for this study

The difficultly with transport related surveys is that they attempt to study transient populations and as such the characteristics and even size of the whole population is difficult to define or contact. This makes the selection of probability samples extremely problematic and decreases the accuracy of inference from surveys to the population of interest. Ortuzar and Willumsen (2001) describe some of the problems faced when sampling for transport surveys. These include knowing the whole population characteristics, getting the people to fill in/respond to the survey, accessing the target sample and turnover of respondents.

In the particular case of this survey there are two populations of interest; firstly, car driving residents of Winchester and secondly, car driving non-residents of Winchester who visit the city for a variety of reasons.

Regarding Winchester residents, an ideal approach to make contact would have been to send out questionnaires to a simple random sample of addresses held on the electoral role for Winchester. Within the questionnaire pack, the covering letter would instruct whoever opened the letter (expected to be a head of household when addressed to the occupier) to give the questionnaire to the person, out of all those in the household who owned a car and had a birthday next. These two sampling stages would ensure that random individuals were chosen to complete the questionnaire. However, due to the extensive text required to fully explain the various scenarios under examination in the questionnaire it is likely that the response rate to the questionnaire would have been extremely low thus introducing potentially high level of non-response, requiring a very large sample to achieve a sufficient number of responses, and/or undertaking a lengthy and costly process of sending repeated waves and reminders for completion of the questionnaires.

There is no clear method to probabilistically sample the population of non-residents driving into Winchester. A postal approach would have contacted too few households with a car driver who travelled to Winchester and would have been both costly and time consuming. Those travelling into or through Winchester varied by time, day, purpose, and parking location (if they parked).

For both samples, it would have been problematic to implement in a probabilistic manner. Given cost, time and sampling considerations the decision was taken to follow a convenience sample approach hence the nature of the sampling procedure followed.

In addition to their relatively low cost per questionnaire ratio, convenience samples are useful to understand the issues surrounding the survey topic as well as being useful to understand between group differences (Schonlau, 2004). The purpose of this questionnaire was to understand what the most effective design of a feedback mechanism would be as well as to determine if there were particular cohorts which did not respond favourably to the feedback mechanisms being suggested. Based on the results from this study it is possible to present a more generic final design of a single feedback approach to understand how a wider population would behave in response.

By examining isolated respondents with characteristics typically prone to the above biases in terms of those who answered positively to those who answered negatively it is possible to monitor the current sample for bias.

7.5 Questionnaire results

7.5.1 Screening the data for non-response bias

Both the Winchester residents and non-residents samples were screened for non-response bias. This followed a procedure recommended by Miller and Smith (1983) and Lindner *et al.* (2001) which divided those who did respond into two equal groups based upon how soon after the questionnaire was distributed the respondent replied. This approach is based upon the assumption that respondents who reply later are more similar in their behaviour to non-respondents than those who reply earlier. The two groups are then compared for each variable of interest to determine if there is a relationship between the period in which the questionnaire was returned and the frequencies of response to the various options for a given variable. This relationship is tested statistically using the χ^2 test. The significance level of the χ^2 test for the key variables in the questionnaire for both the Winchester residents and non-residents samples is reported in **Table 7-1**.

Quest. No.	Variable description	χ^2 sig.	Possible non-resp. bias
Winchester residents			
A3	Rating of air quality in Winchester	0.628	✗
B1a	Arrange voluntary check if change from GOOD to FAIR	0.689	✗
B1b	Arrange voluntary check if change from GOOD to POOR	0.081	✗
B1c	Arrange voluntary check if change from FAIR to POOR	0.037	✓*
B2	Drive out of way to drive through site	0.771	✗
B3	Drive out of way to drive through site if potential to reduce cost of MOT	0.796	✗
C2	Use a website to check emissions readings	0.200	✗
C4	Use a telephone hotline to check emissions readings	0.995	✗
D1	Use a free emissions check service if readings POOR	0.156	✗
D2	Use a free emissions check with £50 repair subsidy if readings POOR.	0.834	✗
F9	Aware Winchester city centre was an AQMA	0.544	✗
Winchester non-residents			
A3	Rating of air quality in Winchester	0.307	✗
B1a	Arrange voluntary check if change from GOOD to FAIR	0.524	✗
B1b	Arrange voluntary check if change from GOOD to POOR	0.250	✗
B1c	Arrange voluntary check if change from FAIR to POOR	0.236	✗
B2	Drive out of way to drive through site	0.420	✗
B3	Drive out of way to drive through site if potential to reduce cost of MOT	0.203	✗
C2	Use a website to check emissions readings	0.094	✗
C4	Use a telephone hotline to check emissions readings	0.405	✗
D1	Use a free emissions check service if readings POOR	0.048	✗
D2	Use a free emissions check with £50 repair subsidy if readings POOR	0.998	✗
E3	Divert to P&R if requested to	0.307	✗
E4a	Divert to P&R if requested to but had free parking in city centre	0.313	✗
E4b	Divert to P&R if requested to but had to pay for parking in city centre	0.070	✗
F9	Aware Winchester city centre was an AQMA	0.138	✗

** Given that all other variables indicate there to be no non-response bias and that the Cramer's V statistic indicates only a very weak relationship (0.115) this result will be ignored.*

Table 7-1: Analysis for non-response for a number of questions based on comparison of groups delimited by reply date. A χ^2 test was used to determine whether there was any relationship between the frequency of response to particular questions and whether the respondent was in the 1st or 2nd half of respondents when sorted by reply date. A significance value of $p<0.05$ indicated a relationship existed (i.e. non-response bias may exist).

7.5.2 Approach to analysis

The approach taken in analysing the questionnaire was to first divide the respondents into two distinct groups based on where they live. Each sample has been weighted to match an estimated age/sex structure relating to drivers who are Winchester residents and those who are non-residents. These estimated age/sex structures can be thought of as hypothetical population models which have been developed to reflect the target populations of interest. This form of weighting is known as poststratification weighting (Smith, 1983; Holt and Elliot, 1991; Lynn, 1996). It is used here to reduce bias when inferring results to a population model although, it can also be used to reduce any non-response error. The samples are weighted to match the population models to better allow the results to be inferred to the general population although caution should be taken when doing this as explained below.

The assumed target age/sex structure of these population models was derived from 2001 census data for the selected areas using the NOMIS service. The non-resident population was assumed to follow that of those living in adjoining district or unitary authorities such as Southampton, New Forest, East Hampshire etc.. The NOMIS population estimates were then altered to account for the percentage of the various age groups, delimited by sex, which held driving licences – these percentages were derived from the 2004 UK National Travel Survey. Respondents aged 17-24 have been removed from the weighted samples as their numbers were too few for which to create reasonable weights.

When inferring these results to the general populations of Winchester residents and non-residents a number of assumptions have to be taken:

- The proportions, by age and sex, of the Winchester resident and non-resident driving licence holding populations are the same as the national proportions
- There is no correction necessary for non-response
- Those answering the questionnaire are representative in their opinions of their respective general populations.
- The age and sex structure, from the 2001 census, of both Winchester, and the areas surrounding Winchester, are true for the 2006 Winchester residents and non-residents age/sex structures respectively.

- Non-residents of Winchester who travel there by car for whatever purpose have the same age/sex attributes as the non-resident population model.

As can be seen from the age/sex structures in **Figure 7-1** both Winchester resident and non-resident questionnaire respondents differ from the population models they are supposed to represent. This difference is an artefact of the method of sampling and differing response rates by age and sex. The weighting adjusts the contribution of an individual's response to a particular question to account for this difference.

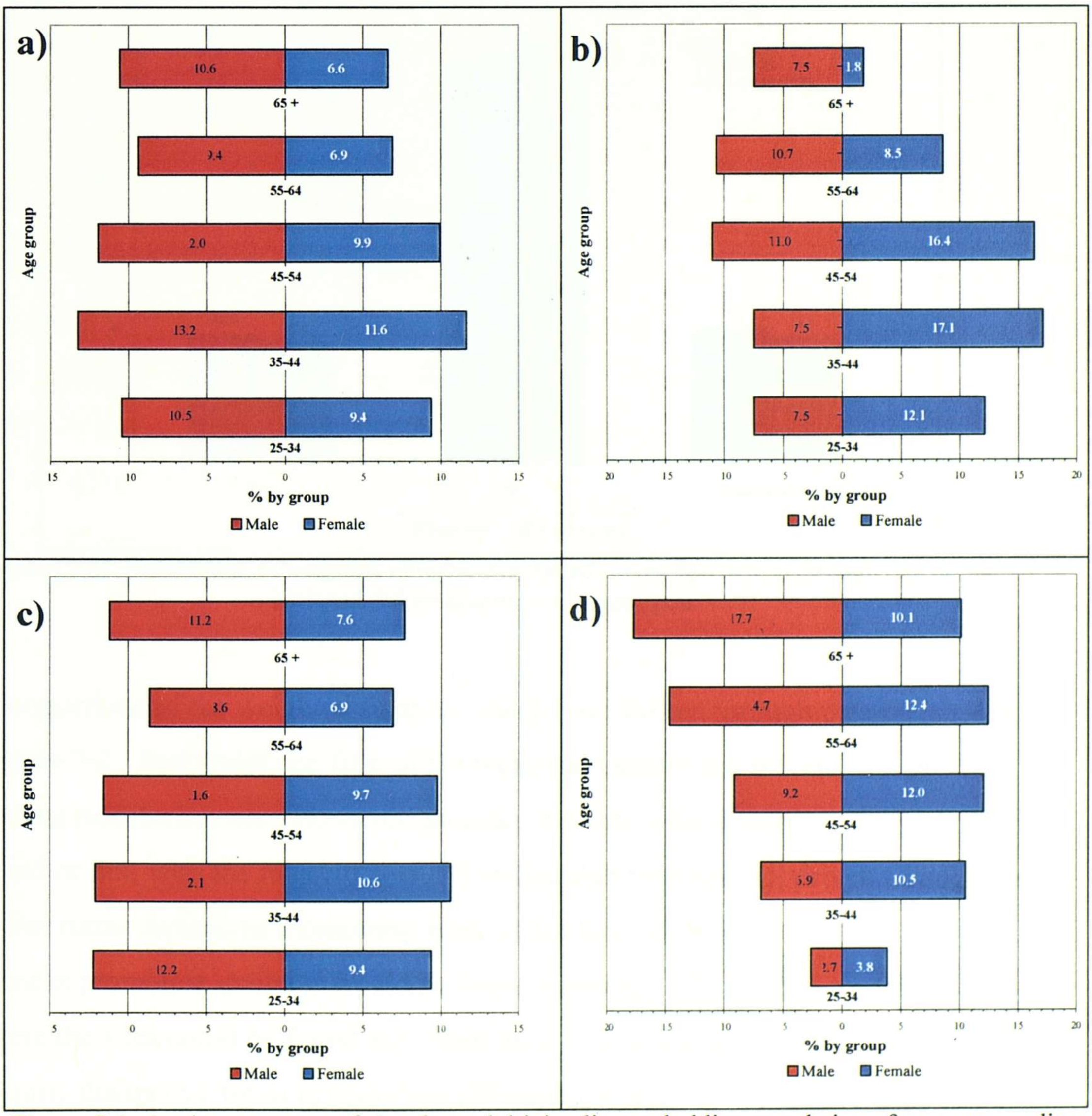


Figure 7-1: Age/sex structure of a) estimated driving license holding population of area surrounding Winchester, b) questionnaire respondents – City of Winchester non-residents c) estimated driving license holding population of City of Winchester residents d) questionnaire respondents – City of Winchester non-residents questionnaire

7.5.3 Have you ever driven through one of the emissions monitoring sites?

Roadside emissions monitoring was carried out at two sites in Winchester intermittently over a 22 month period from Sept 2004 to August 2006. Resources were focused on measurements from these two sites as they provided good testing conditions and had a high throughput of traffic. Three other possible sites on the outskirts of Winchester were identified in the early stages of the work.

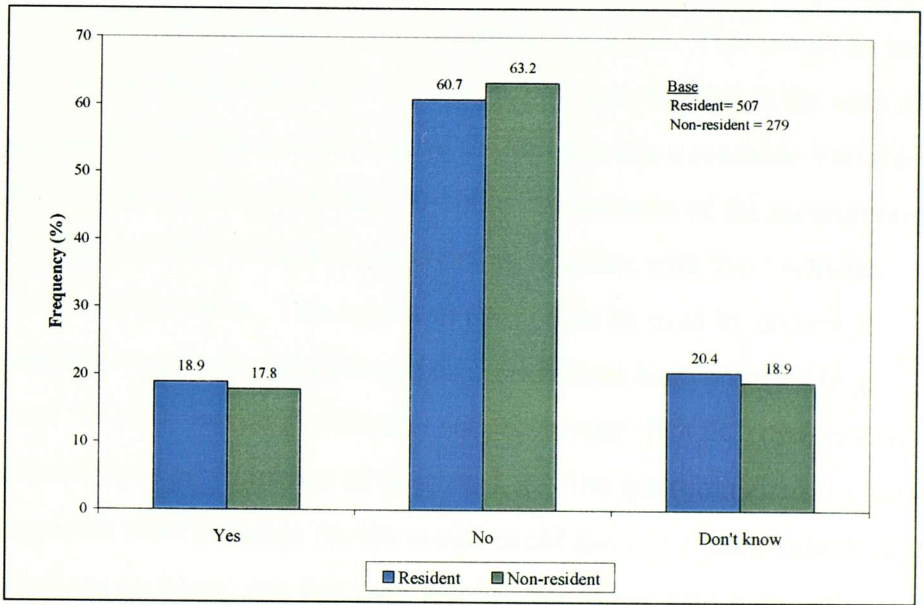


Figure 7-2: Proportions of weighted samples who stated if they had driven through one of the MIRACLES emissions monitoring sites.

The proportions of the weighted samples which have driven through the site is shown in **Figure 7-2**. Just under one fifth of the weighted sample had driven through the emissions monitoring site. However, an equal number were unsure as to whether they had or not, with the majority (~60%) stating that they had not driven through the site. For future emissions monitoring work some form of public awareness/promotion exercise would be recommended, with particular reference as to where the sites could be found and when they were going to be active. The sites were quite distinctive when in operation although the signing could have been more obvious as the amount of traffic cones and traffic management signs would have been taken the attention away from the single roadside sign which read 'WINCHESTER VEHILCE EMISSIONS MONITORING'. The trailer which transported some of the equipment to the site was also given livery which advertised what the activity was. However, drivers were unlikely to see this as the livery was on the sides of the unit which was always parallel to the road way and not facing the approaching driver.

7.5.4 Reaction to changing emissions band

The questionnaire explained how the scheme could provide drivers with information on their vehicles emissions when they drove through the site. This would be based upon a banding scale of GOOD, FAIR or POOR based on thresholds for each of the measured pollutants. When a vehicle drove through the site a roadside Variable Message Sign (VMS) situated between 30-100m downstream of the measurement site would then relay their vehicles measurement, together with their vehicles registration number, to them. This approach could then be used by drivers to monitor emissions regularly. By noting if their emissions band changed (e.g. normally read 'GOOD' but on the last few occasions read 'POOR') drivers could monitor the emissions performance of their vehicle. The questionnaire also informed of the respondents what a change for the worse could mean (i.e. their vehicle may have an emissions problem) and that they would have to pay for a garage to confirm this. The estimated costs, time requirement and organisation of the check by the driver was explained as well as the potential benefits of remedying any problem.

The responses to each scenario are given in **Figure 7-3**.

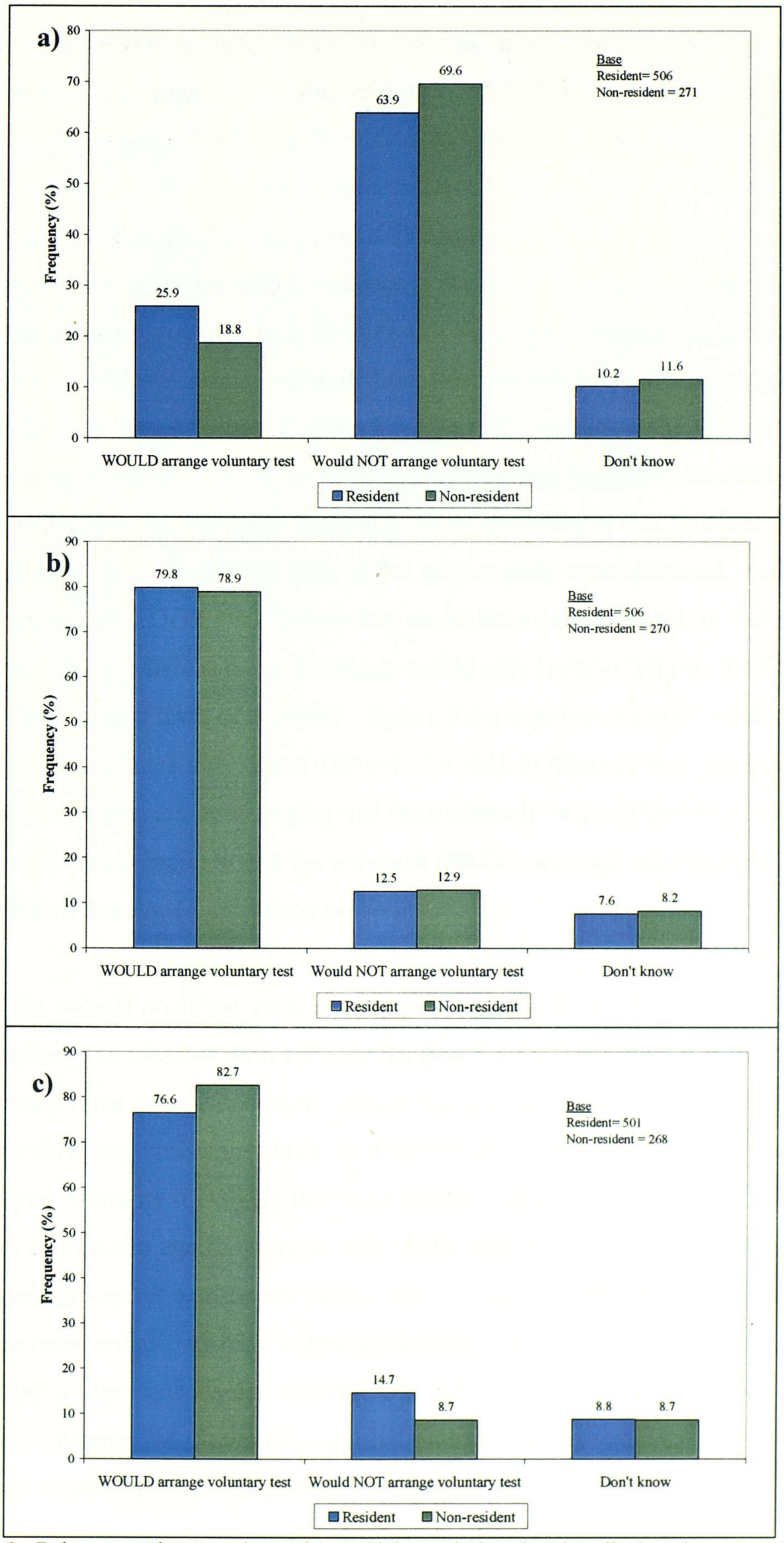


Figure 7-3: Drivers reaction to a change in a vehicles emissions band as displayed on a VMS sign; a) change from GOOD to FAIR, b) change from GOOD to POOR and c) change from FAIR to POOR.

The results indicate that a change to the POOR band from either the GOOD or FAIR category would encourage most of the weighted sample to have their vehicle checked. It would seem that the FAIR emissions band is a useful step to ensure that people do not have their car checked unnecessarily although it would encourage some people to organise a check. The POOR band thresholds have to be set sufficiently high to allow enough confidence in the acquired emissions measurement due to uncertainties associated with the measurement. The rationale for the FAIR banding is that it allows a staggered shift from what would be considered a 'good' emissions level to a 'poor' one. Without this intermediate stage some vehicles which have no problem could be falsely identified as having one; it also allows drivers of vehicles with different emissions technology to act accordingly (i.e. an older vehicle which has inherently higher emissions to one only recently manufactured, would have to fall into the POOR band before they could have enough certainty that their vehicle has a fault, whereas the new vehicle would only have to fall into the FAIR category for a similar level of certainty. Again, dissemination material would have to make this sort of message clear to drivers. Overall, in terms of how drivers would react, the results are very encouraging and the extremely large difference observed in the responses would indicate that the approach would encourage maintenance of vehicles which developed emissions problems.

Many of the vehicle profiling studies have found that the numbers of gross polluters have a tendency to increase with age (see **Section 5.6.1**). Therefore, it is important to understand if the age of an owners vehicle has any influence on their propensity to undergo a voluntary emissions check on their vehicle. Since new vehicles tend to have a 3 year warranty it is likely that these vehicle owners would behave in the same way so vehicles aged 3 years or under have been grouped together to ensure each vehicle group has a sufficient sample size. Vehicles over the age of 15years have been removed as they have only a small sample size. The results of the analysis for a change in the signs display from GOOD to POOR (the worst scenario) are presented in **Figure 7-4**. It would seem that owners of older vehicles are less likely to undergo a voluntary test under these circumstances.

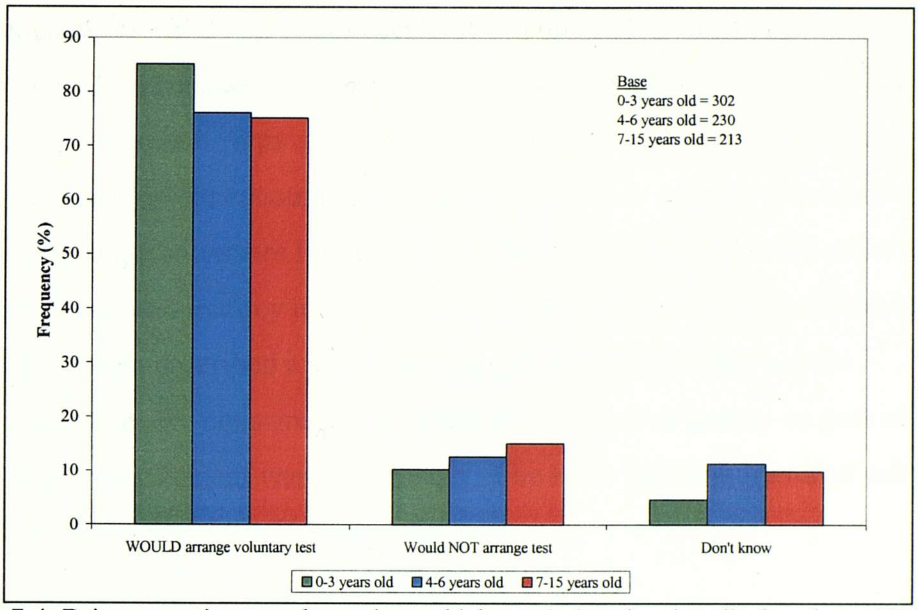


Figure 7-4: Drivers reaction to a change in a vehicles emissions band as displayed on a VMS sign from GOOD to POOR, grouped according to the drivers' vehicle age.

A χ^2 test indicates that there is a relationship between vehicle age and the respondents' likelihood of reaction to the sign (see **Table 7-2**) although the Cramer's V statistic indicates this is a relatively weak relationship.

Test	Statistic	Degrees of freedom	Significance
Pearsons χ^2	12.461	4	0.015
Cramer's V	0.091	-	0.014

Table 7-2: χ^2 statistics for relationship between age of vehicle and Drivers reaction to a change in a vehicles emissions band as displayed on a VMS sign from GOOD to POOR A χ^2 significance value <0.05 indicates a relationship exists. Cramer's V statistic indicates the strength of any relationship on a scale 0 to 1 with 1 being a very strong relationship.

7.5.5 How a link with the MOT might encourage people to check regularly

As described in **Section 5.5.6.3**, in the USA, RSD measurements of vehicle emissions are used in some places which have air quality problems as a filter for the mandatory emissions test. In such areas the emissions test is more demanding and representative than that used in the UK's MOT test because it involves chassis dynamometer replication of a drive cycle. The RSD filtering approach enables vehicles which will almost certainly pass the chassis dynamometer test to receive an annual exemption from having to take the test. Not only does this approach encourage people to drive past the RSD sites in the correct way in order for their measurement to be valid (i.e. slight acceleration) but it also allows the resources directed towards the chassis dynamometer centres to be spent on those vehicles which need to be tested. This question was designed to understand if a similar link to the UK MOT test would encourage people to change their driving routes and behaviour. The questionnaire first of all asked if the respondent would make a detour from a normal journey into or around the city to determine their vehicle emissions. It then described a scenario where vehicles which had a valid measurement from the emissions monitoring site could save money on part of the MOT if their measurement was low enough. The same question was then asked again. The results are given in **Figure 7-5**.

The initial results are not particularly favourable with few of the weighted samples being prepared to change their route into or within Winchester to check their emissions. This in part could be because the respondents were training their thoughts on the Andover Road and Badger Farm Road sites only and that these sites were inconvenient to their usual routes. However, it can be seen that the incentive of a reduced cost MOT scheme encouraged more of both weighted samples to divert from their normal journey to visit the site including persuading those who previously said 'no'. A potential problem of any future emissions testing approach such as this, is that the cost of the RSD units and associated staff costs could be too high to allow extensive networks to be installed. By having the incentive of reduced cost vehicle checks, the cost per measurement of the scheme would be improved by encouraging more drivers to find and go through the sites. Whilst it is feasible for such a scheme to be implemented for MOT test stations in or around Winchester, there is also an issue with the portion of vehicles driving through Winchester originating from outside the city. It is unknown how many of the measured vehicles so far are based in Winchester.

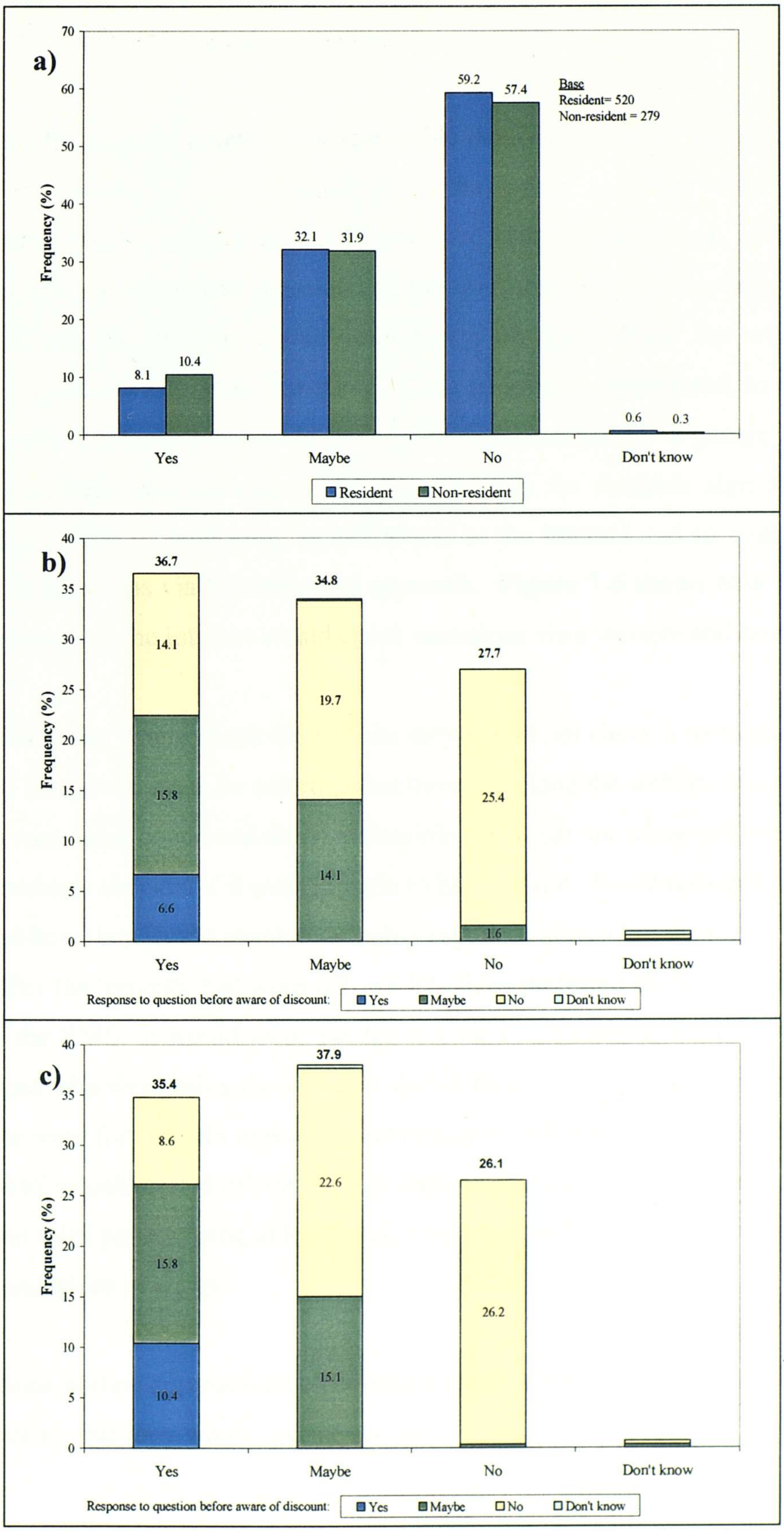


Figure 7-5: Would divert from normal trip into or around Winchester to check emissions at monitoring site a) with no MOT test incentive, b) with an MOT test incentive – Winchester resident sample, and c) with an MOT incentive – Winchester non-resident sample.

7.5.6 Use of a website or telephone hotline

It would also be possible to develop a searchable database based upon the collected emissions measurements. This could allow the public to check their vehicle emissions and observe if their measurements were changing with time. The same banding scheme as above was presented in the questionnaire and respondents told they would only be able to obtain information on the vehicle for which the registration number was given. For those whose emissions deteriorated, to confirm their vehicle had a fault they would have to have it checked by a garage of their choice and at their own expense in the same way as the roadside sign scenario. Approximately 90% of both samples had access to the internet and so could check their vehicle emissions via the described approach. **Figure 7-6** shows how many of those with access to the internet would check emissions via a website and how often.

Whilst the majority would check the website they would not check it particularly frequently. However, it can be assumed that those checking the website would be those who were most concerned about maintaining their car and so would organise to have their vehicle checked if it were thought to have a fault. Some respondents commented how they would check reasonably regularly at first but then desist from doing so after the 'novelty had worn off' whilst others preferred the instant feedback offered by the VMS. It would seem that the website could serve as a useful reference tool for those who were using the sign and alerted by a 'POOR' measurement. Other suggestions were for an SMS messaging service, to which the public could be subscribed to, which alerted drivers of their emissions reading. There were concerns raised about third parties being able to track a vehicle's movements or acquire a vehicle's emissions readings.

The telephone hotline approach received little support with only 10% of the weighted samples stating that they would use the service.

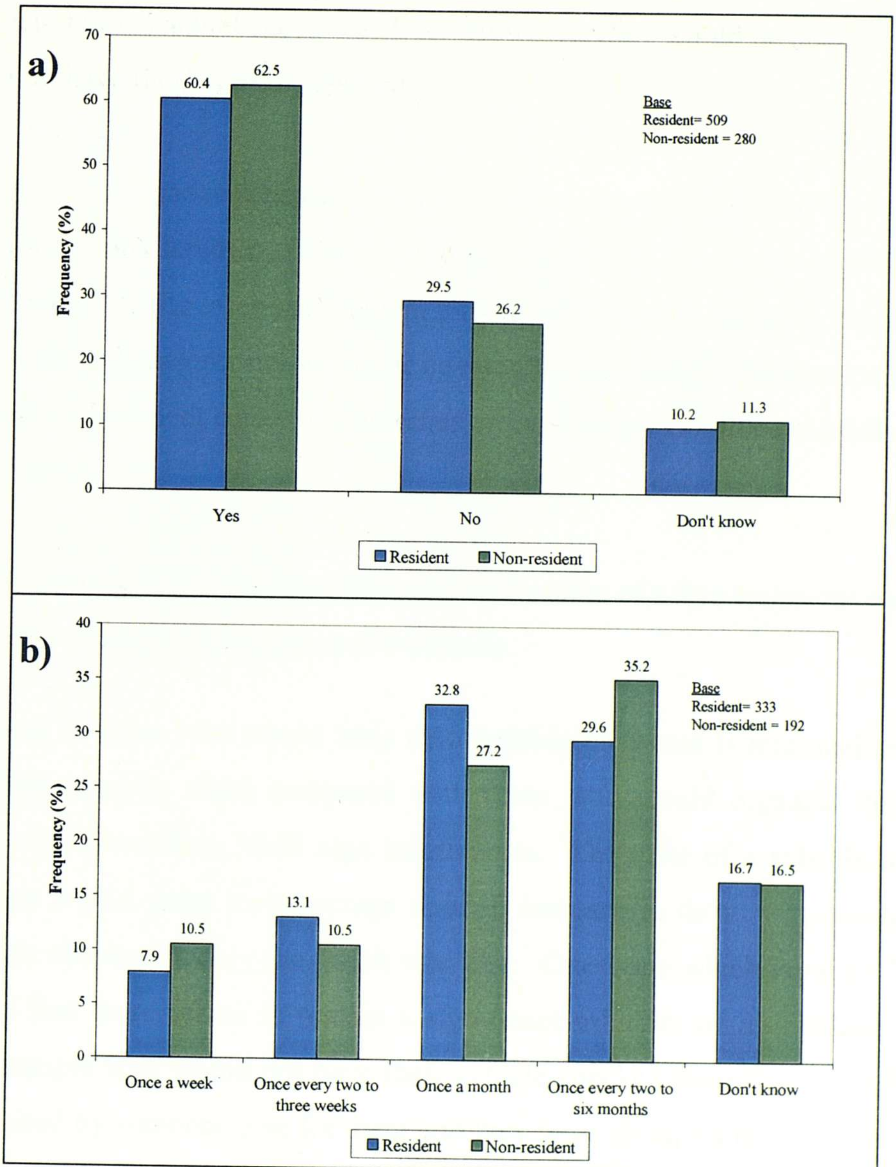


Figure 7-6: Use of website to check emissions from database a) what percentage of the samples, and b) of those that would, how often they would do so.

7.5.7 The incentive of a free emissions check

For those drivers whose vehicles are detected as having high emissions, by taking away some of the effort of organising an emissions check it was hoped that more drivers would have their vehicle checked than would be the case if they had to organise and pay for it themselves. The questionnaire described how, by registering to be alerted if their vehicle had produced a POOR reading, the vehicle owner would be eligible for a free emissions check of their car. This check would be organised by Hampshire County Council at an approved garage in Winchester at a time convenient to the vehicle owner. If any repairs were necessary the vehicle owner would have to pay for them but the actual check was free. However, they would be under no obligation to have their vehicle repaired.

An extension of the above scenario was also described in which a small (£50) subsidy towards any repair was also offered as a further incentive to have their vehicle checked. Quite often the problem may just lie with the tuning or replacement of spark plugs and such repairs would be covered by the subsidy. More expensive repairs (e.g. replacement catalytic converters or O_2 sensors) would be subsidised up to the £50 limit.

Figure 7-7 show how people would respond to the offer of a free emissions check and to a free emissions check plus a £50 subsidy.

The increase in those who would have their vehicle inspected is marginal amongst the weighted samples when compared with those who would organise their own emissions check based on VMS sign information. The offer of a subsidy towards maintenance would seem to encourage a small increase in those who would have their vehicle checked if only the check was free. One issue which is raised by this question is that there seems to remain a significant minority of respondents in the weighted sample who would not have their vehicle checked even if this check were free, organised by someone else for them and they were given a subsidy towards any repair; this is in addition to potential fuel cost benefits which may be gained and potential improvements in their vehicle contribution to air quality.

To understand if the same relationship between vehicle age and the respondents decision to have their vehicle checked (as described in Section 7.5.4) still existed in light of the subsidy offer, an identical analysis was carried out for this question. These results are presented in **Figure 7-8** whilst the χ^2 statistics are presented in **Table 7-3**. The difference between the responses according to vehicle age is much smaller than that shown in **Section 7.5.4** whilst the χ^2 results indicate that there is no relationship between the respondent's vehicle age and their likelihood of taking up the free emissions check and subsidy. This would indicate that the subsidised check would be a more effective approach in terms of reducing excess vehicle emissions as previous studies indicate that older vehicles are more likely to fail an emissions check than new ones.

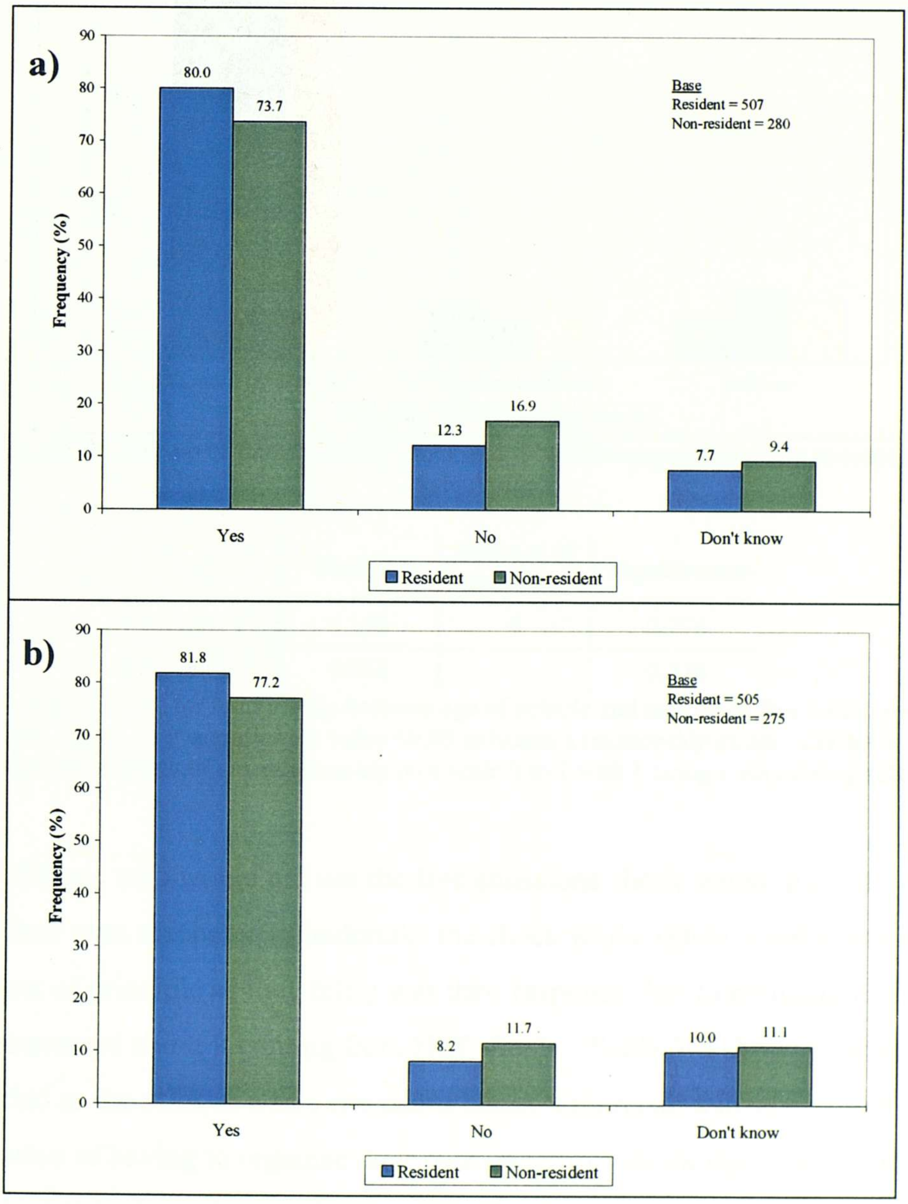


Figure 7-7: The weighted samples take up of a) a free emissions check if their vehicle was measured as having poor emissions, and b) a free emissions check and £50 subsidy towards repair.

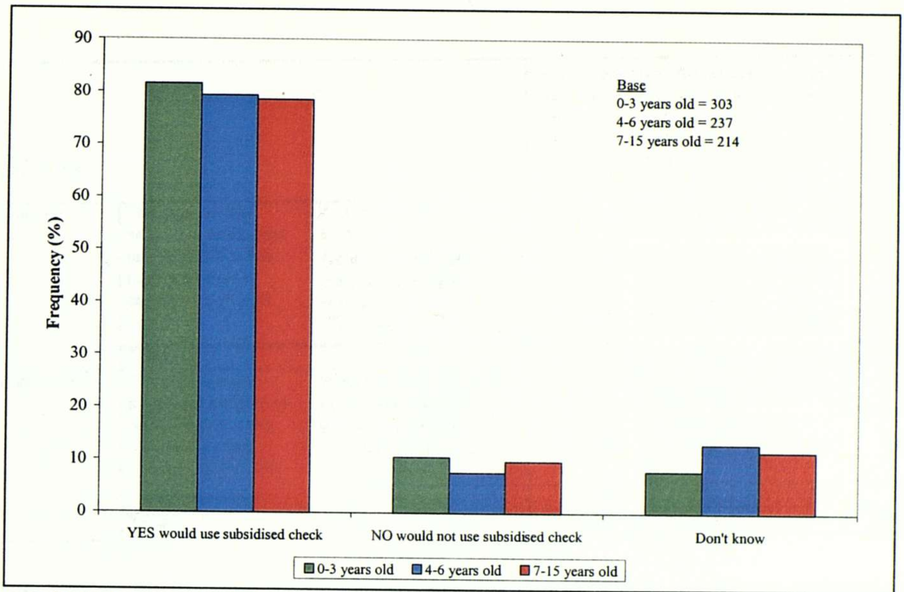


Figure 7-8: Take up of free emissions check and subsidised repair according to respondent's vehicle age

Test	Statistic	Degrees of freedom	Significance
Pearsons χ^2	5.113	4	0.276
Cramer's V	0.058	-	0.276

Table 7-3: χ^2 statistics for relationship between age of vehicle and take up of free emissions check and subsidised repair. A χ^2 significance value <0.05 indicates a relationship exists. Cramer's V statistic indicates the strength of any relationship on a scale 0 to 1 with 1 being a very strong relationship.

Some of those who would not use the free emissions check stated that they would prefer their own mechanic to undertake the check whilst others would not have a check out of principle as they felt it was their responsibility to maintain their car or were concerned about it coming from HCC funds. **Table 7-4** shows how those who responded to the offer of a free emissions check with repair subsidy replied to the proposition of having to organise their own emissions check voluntarily. Those that stated 'no' to both can be considered as the 'hard core' of drivers who would not react to the scheme at all – this group of respondents is present in both weighted population samples.

% of Total

Please indicate where you live			If you were also offered £50 towards the cost of any repairs done at the HCC appointed garage, would you use the emissions check service described? Yes	No	Don't know	Total
I live in Winchester	The sign usually says your emissions are GOOD but the next few times it changes to POOR	Would arrange voluntary emissions test	68.7%	4.0%	8.9%	81.6%
		Would not arrange voluntary emissions emissions test	6.9%	2.8%	1.3%	11.0%
		Don't know	5.3%	1.1%	.9%	7.3%
	Total		80.9%	8.0%	11.1%	100.0%
I live outside Winchester	The sign usually says your emissions are GOOD but the next few times it changes to POOR	Would arrange voluntary emissions test	63.5%	6.5%	8.5%	78.5%
		Would not arrange voluntary emissions emissions test	9.1%	3.5%	1.2%	13.8%
		Don't know	5.8%	.6%	1.2%	7.6%
	Total		78.5%	10.6%	10.9%	100.0%

Table 7-4: Cross tabulation showing proportion of respondents who would not undergo either a voluntary or subsidised emissions check. Proportions in red boxes indicate the respondents who would not undergo either emissions check.

By comparing the characteristics of those who would not have their vehicle checked, either voluntarily or with the incentive of a subsidy, to those who would in one, or both scenarios, some potential differences can be identified.

7.5.8 Diversion to Park and Ride

The final scenario presented in the questionnaire examined how people would behave if they were presented with a sign which told them their emissions were POOR and asked to redirect to the adjacent Park and Ride. A number of Winchester residents stated that this question was not appropriate for them as they would actually be travelling home when they would pass the sign. For this reason only those living outside Winchester were analysed for this question. The results are divided depending on the respondent's previous use of the Park and Ride service. **Figure 7-9** shows how respondents who live outside Winchester would react to the sign.

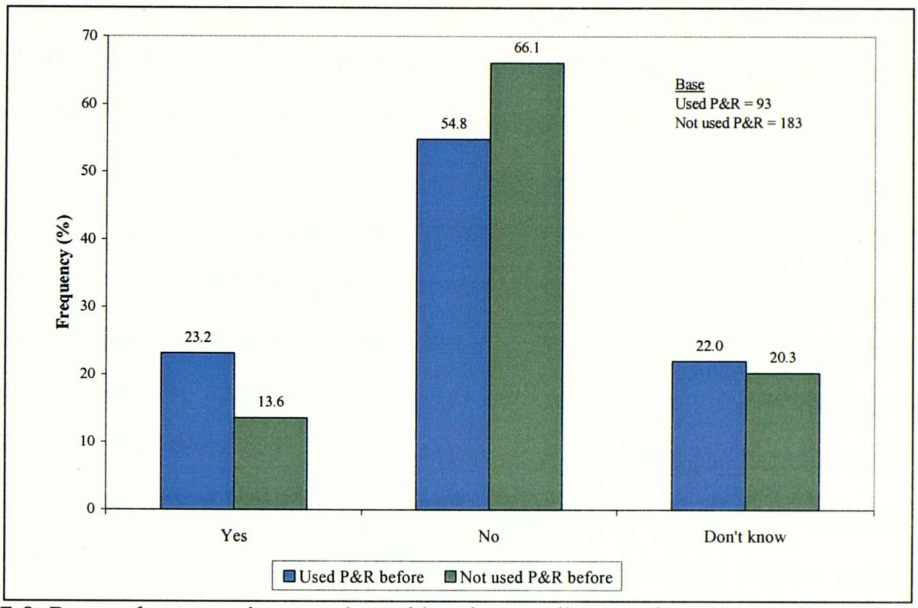


Figure 7-9: Respondents reaction to a sign asking them to divert to the P&R site due to their vehicle having POOR emissions.

It can be seen that regardless of whether the respondent had used the Park and Ride service previously most respondents would not divert to the Park and Ride site although respondents were more likely to divert if they had used the service before.

7.6 Previous RSD feedback studies

Two studies in the US have explored the possibilities of RSD measurement feedback and driver/owner reactions to such methods. One study examined the use of a subsidised emissions check following a vehicle being assessed as having a high emissions reading (Jasper, 1998) whilst the second study examined the impact of immediate feedback using a VMS (Jasper, 1998; Bohren and Williams, 1997; Bishop *et al.,* 1998; Bishop *et al.,* 2000).

Due to non-attainment of air quality standards in Ada County, Idaho, a new vehicle emissions test design was investigated. This was based on a clean screening approach to exempt vehicles from undergoing a basic idle emissions test. To encourage drivers of vehicles observed as high polluters to have their vehicle checked voluntarily, the group of vehicles observed as high polluters were divided into three sub-groups. These sub-groups were offered either a free or discounted ($20 off) emissions check, or were informed by letter their vehicle was observed as having high emissions. Vehicle owners were contacted via post following their vehicles high reading. Of those given a free emissions check voucher, 8% redeemed it, whilst none of those who received the discounted check voucher redeemed it. Those who only received a letter informing them their vehicle may have an emissions problem were later contacted by telephone; 30% stated that they had taken some remedial action. This last result was considered to be suspect given that a lower proportion of those who had the maximum incentive had under gone remedial work compared to those who had no added incentive (Jasper, 1997). However, the report states that those who were only sent a letter were informed of the benefits (emissions, fuel consumption etc.) of having their vehicle checked; it does not say the same for those offered a discount. It is possible that if those who received a letter only, were exposed to a more persuasive argument for having their vehicle examined they may have been more likely to act.

The second study related to the Denver SMART sign (described in **Section 5.6.4.3**). Owners of vehicles which had been detected by the sign were contacted for a follow up interview by telephone (Bohren and Williams, 1997). As a vehicle drove past, the sign reported the emissions band of the vehicle based on the measured CO emissions value. The following percentages of emissions readings were observed; GOOD (86%), FAIR (10%) and POOR (4%). The follow-up questionnaire asked respondents whether they would take any action as a result of the signs reading. 8% stated that they planned to do something with those who had received a POOR reading being more likely to take some action compared to those who received a FAIR reading (31% and 16% of group respectively). This would be just over half of all those who had received a POOR or FAIR reading. As well as examining planned action, the survey also asked if respondents had taken some remedial action already with just 1.6% stating they had already taken some action. This is about one tenth of those who had received either a POOR or FAIR reading. Again, more of those who received a POOR reading showed a higher likelihood of actually undertaking some form of remedial action than those who had received a FAIR reading (16% and 2%). Based upon the number of unique vehicles measured by the SMART SIGN it was estimated that 4,400 voluntary vehicle repairs had taken place (from 232,000 unique vehicles).

In the above studies the incentive approach to encouraging a vehicle check seems to have had only a small impact when compared to the percentage of those who would take up the offer of a free emissions check or react to a VMS sign in the Winchester questionnaire. This can be explained by:

i) cultural/attitudinal differences towards maintaining a properly working vehicle especially towards reducing its environmental impact or towards financial burden of extra fuel consumption,
ii) presentation of benefits/scenario in the two studies,
iii) respondents having a false perception of how they would really react.

7.7 Motivation for emissions related vehicle repairs

The two USA studies described in **Section 7.6** and UK government guidance on roadside emissions testing by LAs underlines the importance of a successful dissemination exercise. This dissemination should not only raise awareness of the campaign in question but also the rationale behind it and the benefits to the driver.

Whilst the objective for vehicle emissions testing and encouraging voluntary emissions related vehicle maintenance, from the LA perspective is to lower emissions and improve air quality, the motivation for the car driver may be very different. In a study of consumer attitudes to low carbon/fuel efficient cars, Lane (2005) reviewed a number of sources to understand what the motivations for car choice are. Whilst, emissions from road traffic are generally of concern to the general driving population, when considered against other environmental issues in life (Lane, 2005), the environmental performance of a vehicle is not a particularly high priority. **Table 7-5** lists the relative importance of various factors in the car buying decisions according to the responses to a questionnaire survey for the DfT (Lehman *et al.,* 2004) on the CO_2 graduated vehicle excise duty system. However, it is interesting to note that some factors which are associated with a car with an emissions problem do rank highly, namely fuel consumption, service/running costs and reliability.

Most important (10-30%)	5-10%	Least important (<5%)
Price	Performance/power	Depreciation
MPG/fuel consumption	Image/style	Personal experience
Size/practicality	Brand name	Sales package
Reliability	Insurance costs	Dealership
Comfort	Engine size	Environment
Safety	Equipment levels	Vehicle emissions
Service costs		Road tax
Style/appearance		Recommendation
		Alternative fuel

Table 7-5: Percentage of respondents who indicated a particular factor was important to their car purchase decision. (Source: DfT, 2004)

This general attitude can still be considered to be the case for car owners after their purchase. So whilst dissemination materials should discuss the environmental benefits of properly functioning vehicle (for the general public rather than the individual driving) it should also stress the associated benefits in terms fuel savings, the possibility of more repairs expensive repairs in future and continued reliability of their car. It can be seen from the explanation of the various scenarios in the RSD questionnaire, and from the accompanying leaflet, that this full range of benefits were explained. This may result in the higher likelihood of undergoing an emissions check indicated in the RSD questionnaire results compared to the US studies. Other factors discussed in **Section 7.6** could also contribute to this observed difference.

7.8 Conclusions

Responses were similar for those living inside or outside Winchester. Little variation in the responses provided by the resident and non-resident groups were observed. There was potential for significant differences between the two groups with the residents being more concerned about 'their' local air quality and so being more receptive to the scenarios presented.

A high percentage of respondents would have their vehicle checked if they were told it was suspected of having an emissions related fault. The majority of respondent would arrange for their car to have an emissions check voluntarily if their emissions readings, which were feed back to them at the roadside via a VMS, indicated their vehicles emissions had deteriorated to the POOR band. Those with older vehicles (more likely to be a high polluter) would be less likely to react to the sign if their emissions reading changed from GOOD to POOR. An exemption from the emissions element of the MOT test for vehicles which had been measured to have low emissions would seem to be a potentially successful incentive at increasing the numbers of drivers who would deliberately drive out of their way to drive through the site.

The web service would seem to be more useful as a support tool for vehicle owners rather than a stand alone service operated instead of the use of the roadside sign. This approach had the appeal of allowing vehicle owners to check their vehicle emissions if their reading on the sign had changed recently. Some respondents suggested it would be convenient if they could go to the website only once and subscribe to an SMS messaging service which informed the driver of their latest emissions reading.

The offer of a subsidy removed the effect of owners of older vehicles not having their vehicle checked. The offer of a free emissions check only slightly increased the proportion of respondents who would have their vehicle checked compared to them having to organise their own check voluntarily and the additional offer of a repair subsidy again only slightly increased the proportion taking up the offer. The offer of a subsidy removed the effect of owners of older vehicles not having their vehicle checked. This could be due to socio-economic issues (i.e. those who own an older car can not afford a voluntary check if they had to pay for it). There appears to be a proportion of the respondents who would not be willing to have their vehicle checked under any circumstance based on the measurement of the RSD.

Diverting people to Park and Ride would seem to have chance for limited success at preventing drivers of POOR vehicles entering the city. However, those who had used the Park and Ride previously were more likely to divert if asked to do so.

A higher rate of remedial action is reported when the Winchester stated preference results are compared with those from revealed preference surveys of similar initiatives undertaken in the USA. The reason for this difference is not known although differences in how the benefits are presented, cultural/attitudinal differences and/or false perception of their behaviour in real life could offer some explanation. The relative cost of fuel in the total cost of an individuals driving (and lifestyle) is also higher in the UK and so the reduced fuel consumption benefits of identifying a malfunction will be more influential.

Motorists are more concerned about the cost implications of motoring than their environmental impact. Dissemination campaigns which support emissions feedback campaigns should discuss the environmental benefits to society but also stress the cost benefit and reliability benefits from having their vehicle checked should their vehicle receive a high reading. Successful strategies to reduce emissions from private cars should therefore be strongly linked to polluter pays principle.

8 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

8.1 Introduction

Air quality is an issue which can have serious health and environment related consequences if left unabated. The UK government has developed a National Air Quality Strategy (NAQS) as a policy tool to address the issue of air quality for nine pollutants. Part of this policy is the setting of threshold concentration standards for the NAQS pollutants with the responsibility for monitoring and achievement of these standards being devolved to LAs. Road traffic is a significant contributor to national emissions of air quality and in urban areas can often be the largest (or only) contributor. Some vehicles produce a disproportionate amount of emissions which can not be controlled for as it is inherent in their design but there is also a portion of vehicles which are not operating to their potential in terms of minimising emissions. This thesis has examined how vehicle emissions are currently controlled and how successful the current I&M strategy is at identifying vehicles which have an emissions related fault. It is apparent that identifying and removing (either by scrapping or repair) these excess emissions from the road would be beneficial. One such approach examined in this thesis is the use of RSDs to inform vehicle owners/drivers that their vehicle has an emissions problem sooner than they would normally have been aware. The potential effectiveness of various feedback strategies has been examined using a questionnaire.

8.2 Controlling and maintaining vehicle emissions

A new or modified emissions test will be needed in the future to successfully identify gross polluting vehicles. The true definition of a gross polluting vehicle is *'a vehicle which fails to meet the emissions standards it first passed during the type approval process having accounted for reasonable degradation by appropriately factoring up the emissions standards'* (Norris, 2000 and 2001b). Similar to many countries around the world, in the UK, to ensure the vehicle continues to comply with the emissions standards it was designed to meet, part of the vehicles roadworthiness test includes an emissions test (for both petrol and diesel vehicles). For cost and convenience these are relatively simple tests which have variable success at identifying vehicles that have an emissions related fault. The MOT emissions test is really being used as an indicator as to how a vehicle would fare if it were tested against the type approval emissions standard (and the associated test procedure) it was designed to meet. However, an indicator is only useful if it can successfully represent the state it is supposed to show. The current tests have been assessed as being effective for non-catalyst petrol cars but have limited effectiveness for diesel and catalyst petrol cars. This has been attributed to the design of the tests not reflecting on-road driving conditions, to the insensitivity of the equipment and possible abuse of the system. As the vehicle fleet becomes more technologically advanced, the ability of the current MOT tests to identify vehicles with excess emissions is predicted to become less effective.

The future in-service emissions tests will require external monitoring to ensure gross polluters are removed from the road as soon as possible. It is envisaged that in the long term, vehicles will become self-policing in that they will use on-board diagnostics (evaluating the performance of components) or monitoring (the real time emissions) to determine whether emissions are being controlled as they should be. The problem with such an approach is how the OBD/M (On-Board Diagnostics/Monitoring) approach would be applied. In the case of OBD, if a component began to show signs that it was not operating with a required efficiency then the vehicle would know it had a potential problem. In the case of OBM, this approach taken could be a system where the OBD samples the instantaneous emissions measurements and selects measurements from those power ranges covered by the type approval test. If the average emission rate exceeds the type approval test limits (within a certain tolerance) then the vehicle would know it had a potential problem. In either of these instances it would be down to the driver to arrange an immediate inspection when such an 'alarm' is activated although it is possible they could just ignore or reset it. In the medium term likely the UK I&M programme will based upon a refinements of the current approach. Some gaps exist in the current and future I&M programme in the UK:

- Emissions checked once a year but can develop a problem anytime without owners knowledge
- Test is unrepresentative of on-road driving conditions
- If the owner is alerted to an emissions problem with their vehicle no-one can make them fix it.

8.3 Use of roadside Remote Sensing Devices (RSDs) for vehicle emissions measurements

The use of Vehicle Specific Power (VSP) will increase the usefulness of RSD measurements as an indicator that a vehicle would be a gross polluter according to the type approval definition. The current literature, comparing emissions results for RSDs and type approval chassis dynamometer tests show that there are errors of omission and commission. However, this work did not consider using VSP as a filter to use RSD measurements that were take from vehicles in the appropriate power range. Using VSP as and RSD measurement filter, USA clean screen and gross polluter programmes have been able to increase the probability that a vehicle which has an RSD measurement above a set threshold should be subject to a more detailed inspection. By using RSD measurements from when the vehicle is under load should make the measurement more representative of real world driving than the current MOT emissions tests. The use of VSP with RSD measurements was only just becoming common place in the USA when the European comparison was undertaken by Barlow (1998).

RSDs have the ability to fill some of the current and future gaps in an in-service emissions programme. Since RSDs can be used to measure vehicles throughout the year they are not subject to only seeing a vehicle once a year and so can be used to detect vehicles which have a fault which is either being ignored or is unknown to the owner. This is limited by the manner in which the vehicle drives through the RSD site. For those vehicle owners who genuinely want to check their vehicle's emissions status, with the correct education on how to drive through the site to obtain a valid VSP reading, RSD measurements are a solution. Those people who still want to avoid being measured could simply drive through the site in a manner which would produce a VSP that rendered the RSD measurement unrepresentative. There would need to be an incentive for the vehicle to drive through the site properly. The key issue with their use, is the number of units needed to cover a road network or whether they could be targeted for use in areas with air quality problems. Could all vehicles registered within a certain radius of an AQMA be subject to a more indepth, time consuming and costly I&M inspection with a network of RSDs offering the opportunity to be exempt from such a test?

If a clean screen programme were to be implemented in the UK using RSDs it is likely that people would drive out of their way to an RSD site to ensure they had a chance of forgoing the expense of a check. This is shown in RSD questionnaire results with a higher percentage of respondents (~36%) stating they would drive out of their way if they would not have to pay for an emissions test at their next MOT than if there were no MOT implications (~8%) . The extra inconvenience if the emissions test were a separate chassis dynamometer test can be expected to enhance this public reaction. Providing they had been educated beforehand, a clean screen approach would also encourage drivers to pass through the site in the correct manner to ensure their vehicle measurement was valid. The gross emitter identification approach could also be used in conjunction informing suspect vehicles to come for a check sooner than they were scheduled to. Using two readings gives more confidence to the emissions state of a passing vehicle so such an approach would also be more successful at getting two reading for a single vehicle.

Roundabout exit arms provide excellent sites for RSD units meaning the UK should have a large number of sites suitable for RSDs. There are issues with the selection of appropriate RSD measurement sites which limits its use. Perhaps the greatest challenge in identifying suitable sites is satisfying the topographical requirements (gentle upward gradient), the need to remove the effect of cold starting vehicles which have inherently high emissions and ensuring the site is suitable and safe for operators and drivers. However, selecting a suitable site will not guarantee the drivers pass through the site with a similar VSP profile. Regardless of site topography and road characteristics if the site is conspicuous then they is always a percentage of drivers who will slow down for fear of speed enforcement or just out of curiosity. There is evidence from this study to indicate that people react to the site differently depending upon how quickly they were travelling in relation to the speed limit. If the RSD site has tendency for relatively low travelling speeds compared to speed limit, the more homogenous the VSP at the site will be. Roundabout exit arms were found to be ideal as vehicles circulate the roundabout at a relatively low speed compared to the speed limit to prevent the vehicle losing grip on the road and sliding wide of the carriageway. As drivers leave the roundabout onto a relatively straight road, a higher speed can be safely achieved and so the drivers accelerate to this speed. RSDs located close to the roundabout exit (less than 100m) therefore measure vehicles operating under ideal conditions. With an RSD instrument that can operate over a wider range of road widths than the REVEAL instrument, the key is then identifying sites where cold starts are accounted for. This can be done by using sites away from significant sources of cold start vehicles.

RSDs emissions measurements can not be used to prevent access to an area with any practical certainty. Using an RSD measurement as a criteria for preventing access to an area (e.g. a city centre) on air quality grounds would not be an effective way of isolating the highest polluting vehicles. Whilst the REVEAL instrument was not sensitive enough to analyse repeat readings, data within the reviewed literature indicated that there can be considerable variation in RSDs measurements for the same vehicle. To be certain (or at least be certain enough that there is a right to restrict someone's movements) that a vehicle exceeded a predefined threshold at least two measurements are necessary. It would require a gross polluting vehicle to have already been allowed to pass through before they could be restricted on their second observation. A possible solution could be the use of RSDs in tandem although there would be nothing to stop someone driving through the site in such a way that the measurement is unrepresentative.

8.4 The REVEAL instrument

The current REVEAL RSD instrument is sufficiently accurate to detect gross polluting vehicles but could not be used for a clean screening application. The influence of the errors increased as the measured emissions decreased and so for high emitters a higher degree of confidence could be placed in the measurement. Future RSD studies should always ensure the instrument is capable of measuring the emissions of low emitting vehicles with reasonable accuracy. This adds value to any use of RSDs as it can be used to develop an understanding of the fleet emissions characteristics. The limitations of the current REVEAL RSD unit meant that only the contribution of the top decile of vehicle emissions measurements could be compared to the rest of the fleet and that relationships with vehicle VSP could not be explored. The current REVEAL instrument could not be used in a clean screening application although it is apparent there are some methods to improve the current REVEAL instrument. The scale of this improvement is unknown.

8.5 High polluting vehicles in Winchester

The use of RSDs to identify gross polluters in Winchester would result in negligible emissions savings. Using the REVEAL instrument and based on the RSD thresholds selected very few vehicles in Winchester could be classed as gross polluters. The excess emissions saved by identifying and remedying these vehicles can be estimated to be small (in the range of 2-5% for CO gross polluters and 2% for NO gross polluters). Approximately 0.1-0.4% of the car fleet were estimated as gross polluters depending on the pollutant and threshold used. This can be compared with the 0.5% of gross polluters observed with the same thresholds in a 1998 study in Leicester (Barlow, 1998), so the Winchester result is not unreasonable. A study in Greece undertaken at the same time as the Leicester trials reported 5% of vehicles being classed as gross polluters. How the gross polluter percentage varies around Hampshire and the UK is unknown.

8.6 Response to RSD questionnaire

In the UK, using a roadside VMS is would be a successful feedback mechanism to encourage voluntary repair of a gross polluting vehicle. The most successful method of feedback, in terms of how the respondents would react, was the use of a VMS sign at the roadside with approximately 80% of respondents stating they would organise a voluntary emissions check if their reading changed from GOOD to POOR. The web based database was viewed as a good supporting tool for the VMS approach rather than just being a stand alone approach. Some respondents suggested using an SMS service or email to inform owners of their vehicles emissions.

A subsidised or free check should be offered with any scheme aiming to remove gross polluting emissions from the road. There was some variation in how drivers would react if their vehicle's emissions were displayed as POOR according to the respondent's vehicle age with those with older vehicles being less likely to organise a repair. Since older vehicles are more likely to develop an emissions fault this observation is not ideal. Providing a free emissions check and a subsidised repair removed this age effect. Offering such a subsidy is important in order to overcome a probable socio-economic effect on the likelihood of undergoing an emissions check. There was some concern about HCC paying for such subsidies with some respondents indicating they would not take up such an offer on principle.

Some people would never have their vehicle repaired on the basis of feedback from an RSD. There was a 4% hardcore of respondents who would not have their vehicle checked regardless of whether a subsidy was offered or not. As a solution, a follow-up letter could be sent to the registered vehicle owner highlighting the problem. Such an approach would require a partnership with the DVLA in order to link the measured vehicle to the owners address. Upon repeated measurement of gross polluting vehicles and several notifications via post, it could be demanded that the vehicle be brought to the nearest VOSA test station for inspection by a set date. If the owner did not comply, the vehicle could be confiscated.

A public awareness campaign that highlights the financial benefits to the individual, as well as the community benefits of cleaner air resulting from the repair of a gross polluting vehicle is essential. The results from the questionnaire were compared to previous studies in the USA which examined subsidised maintenance and use of a roadside VMS for RSD emissions measurement feedback. It would seem that the respondents to the Winchester questionnaire were far more likely to arrange an emissions check if their vehicle has a POOR reading that either approach in the USA. Whilst some over estimation is common in stated preference surveys compared to revealed preference, the scale of the difference seems too large. One key reason for this may have been the associated dissemination material distributed with the Winchester questionnaire. This information highlighted both the environmental benefits to the community and the financial benefits to the vehicle owner of having a vehicle with an emissions fault repaired.

8.7 Recommendations

If RSDs were to be used in future to encourage voluntary emissions checks and repairs the following key recommendations from this thesis should be considered:

- Select a range of RSD sites which are on gentle inclines, where sources of cold starts are accounted for and where the vehicles are accelerating to the speed limit.
- Choose an RSD unit flexible enough to operate over varying carriageway widths to minimise the scale of traffic management (e.g. signs and cones).
- Set the RSD beam height to be 29cm above the roadway.
- Characterise the fleet to understand the extent of the problem before embarking on a campaign as there may be few gross polluting vehicles present.
- Use an RSD unit which is sensitive enough measure emissions from those vehicles whose plume capture is weak or whose actual emissions are low.

- If a sufficient number of gross polluters are observed, use a roadside VMS to provide feedback with website, SMS and/or email as supporting tools.
- Offer a subsidised emissions check and repair to remove any financial risk for those with less disposable income.
- Develop a supporting marketing campaign which stresses the financial benefits to the vehicle owner of having a gross polluting vehicle repaired as well as the environmental benefits to the community.

8.8 Future research

During the course of the work presented in this thesis, a number of areas have been identified where a gap in the current knowledge exists.

i) **Improved accuracy of the REVEAL instrument** – some aspects of the work presented in this thesis were limited by the accuracy of REVEAL instrument. Some suggestions of how the instruments accuracy could be improved are given in **Chapter 5**. This may involve some re-engineering of the physical design of the unit but also some software changes to the processing algorithm and the internal calibration curves.

ii) **Fleet characterisation at a range of sites in UK** – the number of gross polluting vehicles identified in Winchester was smaller than expected. Whilst the result was comparable to that of an RSD survey in Leicester the variation in fleet emissions around Hampshire and the UK is unknown. Since fleet emissions have been shown to reflect the degree of vehicle maintenance and vehicle age, it could be expected that less affluent areas may have fleets with higher emissions in general and more gross polluters.

iii) **Definition of EURO standard and fuel specific gross polluter thresholds** – a general set of thresholds has been used within the work presented here. However, it is reasonable to expect the appropriate thresholds to vary not only according to the emissions standard to which the vehicle was designed but also by fuel type. Suitable thresholds would have to be derived by comparing a sample of vehicle RSD reading to the appropriate standard (be it the MOT idle test or the NEDC type approval test). These may lead to variations in the CO and NO RSD thresholds used. By then linking to the DVLA using the vehicles registration number, some extra information (e.g. year, fuel type and type approval emissions) could be added to help determine the EURO standard of the vehicle and what threshold profile should be applied to the vehicle.

iv) **Understand RSD measurement differences in diesel and petrol vehicles** – Use of RSDs in the US normally ignores the possibility that the measure car could be a diesel vehicle meaning the conversion of pathlength concentrations (ppm.m) to relative concentration (ppm) is not appropriate. The UK has a far higher market share of diesel vehicles and so the influence of diesel vehicle emissions on the general fleet profile can not be ignored. The Auckland study was able to link vehicle registrations to the New Zealand vehicle database and divide the fleet according to petrol and diesel (*Fisher et al.*, 2001). A similar approach should be taken in future UK studies although current access to data of this type from the DVLA is expensive.

v) **Understanding of catalyst failure numbers** – catalytic converters are required to have a lifetime of 100,000km or five years (Directive 98/69/EC). This means that many of the early catalyst equipped vehicles could now be coming to the end of their useful life and so catalyst failures in between MOT tests could conceivably increasing as more of the early catalyst equipped vehicles pass the minimum design standard. This issue will also become relevant for future diesel vehicles as they rely on catalytic converters to maintain their emissions. Due to the mechanisms of failure, it may also be that some vehicles are more susceptible to failure (e.g. those which undergo a high frequency of cold starts).

iv) **Cost effectiveness of MOT at reducing urban pollution** – some reports on the current MOT which have been reviewed attempted to calculate the cost effectiveness of the MOT. This is done in terms of emissions saved per £ spent. It could be argued that a better test of the cost effectiveness would be to calculate the % of all emissions saved per £ spent. Some weighting for the higher share of emissions from road traffic in urban areas would also have to be accounted for. This also links with the point below.

v) **Desk study of cost effectiveness of integrating RSDs into an I&M regime** – within the above work some estimate could also be made of alternative I&M programmes in the UK. One such approach could be the use of clean screening and a move to centralised chassis dynamometer test. Would it reduce the burden on owners of vehicles which are maintained, would it enable RSDs to identify gross polluters sooner, would the emissions savings be greater, would it cost more money?

9 REFERENCES

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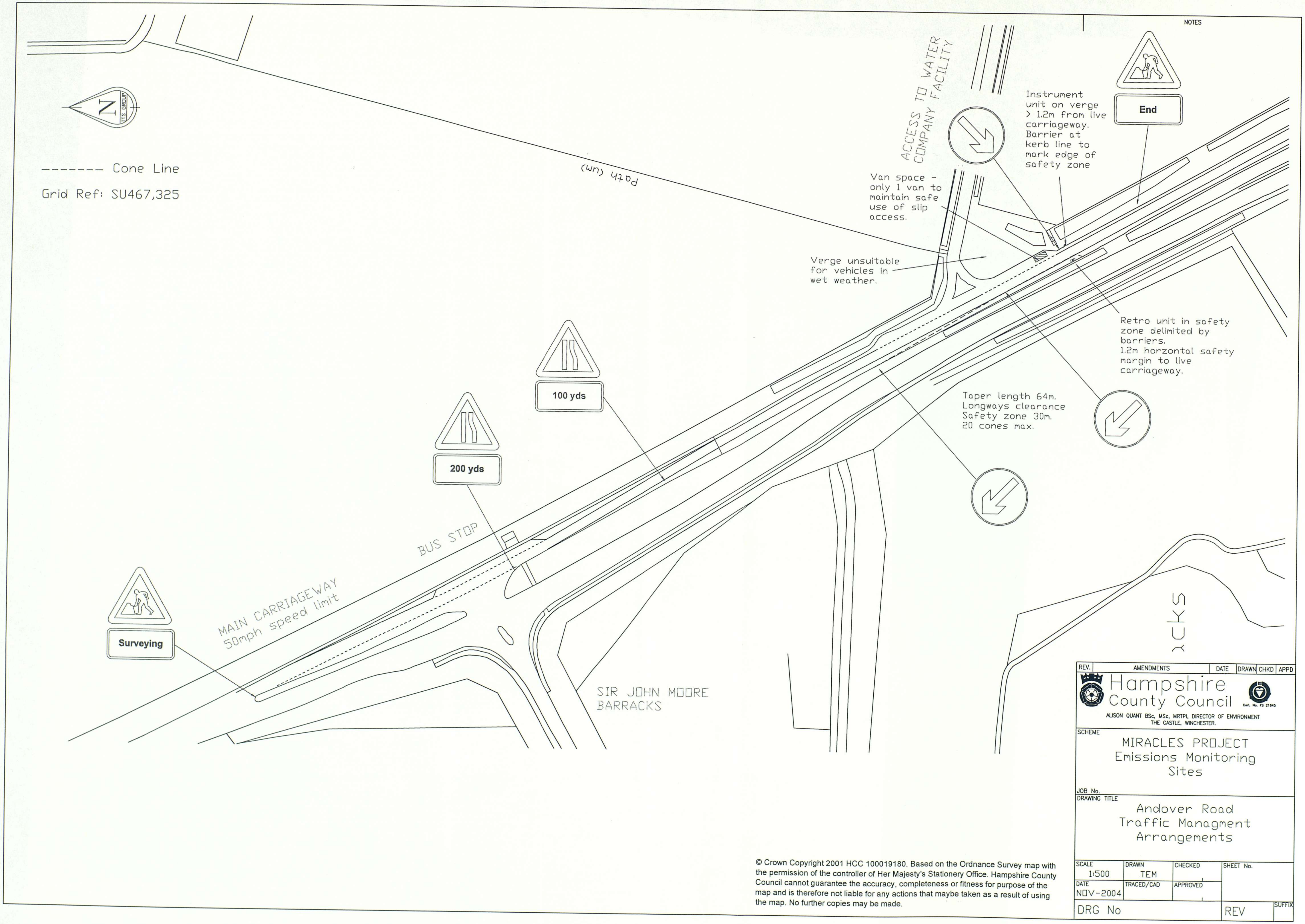
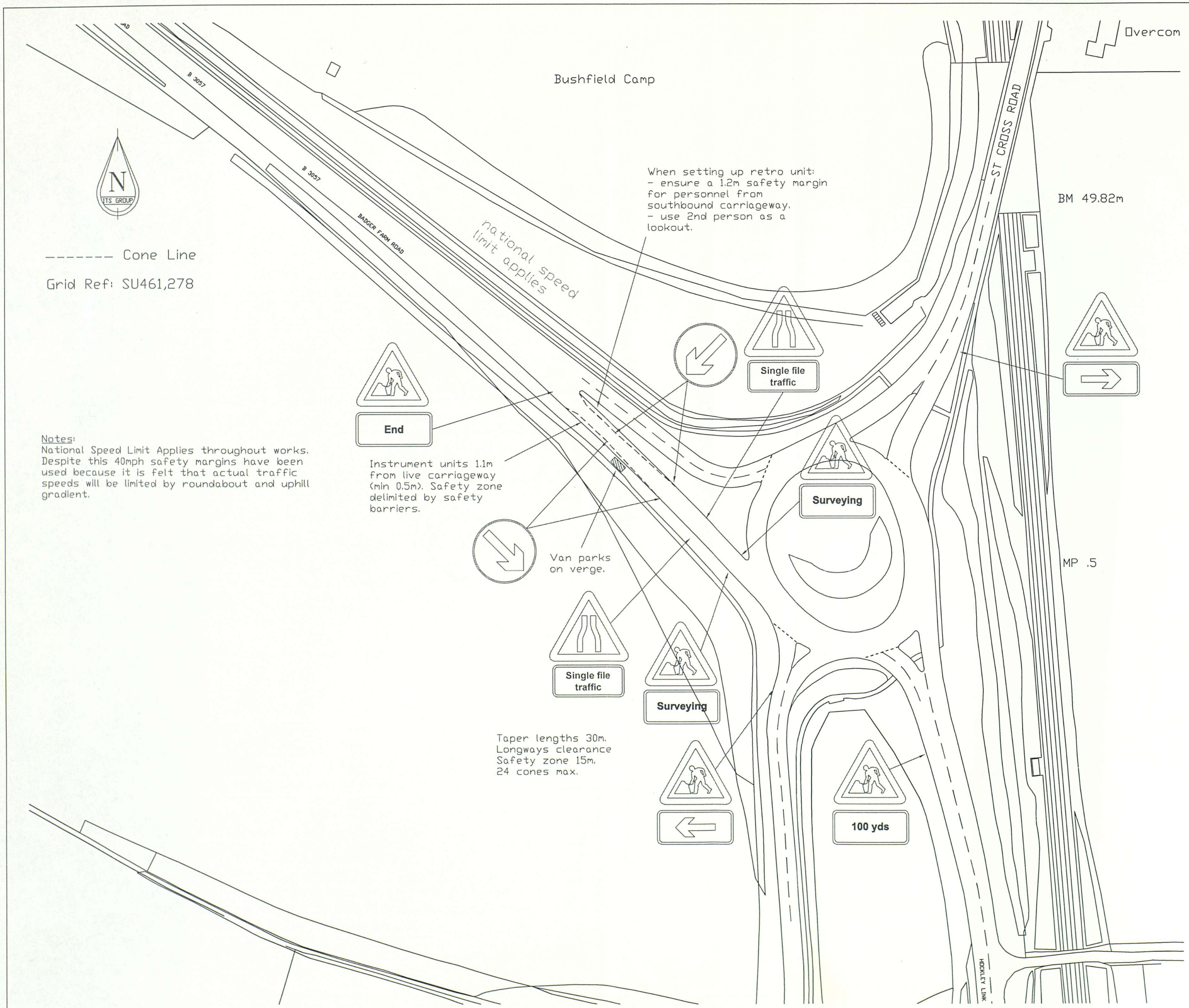
Appendix 1

Traffic management layout at Andover Road and Badger Farm Road sites



NOTES
Cone Line
Grid Ref: SU467,325
Path (um)
ACCESS TO WATER COMPANY FACILITY
Instrument unit on verge > 1.2m from live carriageway. Barrier at kerb line to mark edge of safety zone
End
Van space - only 1 van to maintain safe use of slip access.
Verge unsuitable for vehicles in wet weather.
Retro unit in safety zone delimited by barriers.
1.2m horzontal safety margin to live carriageway.
Taper length 64m.
Longways clearance Safety zone 30m.
20 cones max.
100 yds
200 yds
BUS STOP
MAIN CARRIAGEWAY
50mph speed limit
Surveying
SIR JOHN MOORE BARRACKS
REV. AMENDMENTS DATE DRAWN CHKD APPD
Hampshire County Council
ALISON QUANT BSc, MSc, MRTPI, DIRECTOR OF ENVIRONMENT
THE CASTLE, WINCHESTER.
SCHEME
MIRACLES PROJECT
Emissions Monitoring Sites
JOB No.
DRAWING TITLE
Andover Road
Traffic Managment Arrangements
SCALE 1:500
DRAWN TEM
CHECKED
SHEET No.
DATE NOV-2004
TRACED/CAD
APPROVED
DRG No
REV
SUFFIX



NOTES

REV.	AMENDMENTS	DATE	DRAWN	CHKD	APPD

Hampshire County Council

ALISON QUANT BSc, MSc, MRTPI, DIRECTOR OF ENVIRONMENT
THE CASTLE, WINCHESTER.

SCHEME
MIRACLES PROJECT
Emissions Monitoring Sites

JOB No. none

DRAWING TITLE
Badger Farm Road
Traffic Managment
Arrangements

SCALE	DRAWN	CHECKED	SHEET No.
1:1,000	TEM		
DATE NOV-2004	TRACED/CAD	APPROVED	

DRG No | REV | SUFFIX

Appendix 2

Idealised combustion equations used to convert
pollutant/CO_2 ratios to ppm

(*Source:* Dr Gary Bishop at University of Denver)

FEAT Equations for CO, HC and NO.

ASSUMPTIONS:

Fuel C:H ratio is 2 and non-oxygenated.

Fuel density is 0.726 g/ml and is approximated with a mix of Octane and Benzene that averages the molecular formula of CH_2.

Fuel out tailpipe is similar (to make the math simpler we have chosen for the exhaust HC to be a multiple of the input HC) to calibration gas which is propane.

Concentrations are calculated on a dry basis and corrected for any excess air not involved in combustion (these equations are correct for diesel vehicles, and the ratios are correct for diesel vehicles. However, if remote sensing data are to be compared to a direct tailpipe measurement, that measurement comparison either must consider only the ratios, or must be corrected for the considerable excess oxygen not involved in typical diesel combustion).

Equal amount of seen HC's and unseen HC's in the exhaust (Singer & Harley et al, Environ. Sci Technol. 1998, 32, 3241-3248)

$$CH_2 + m(0.21O_2 + 0.79N_2) \rightarrow$$
$$aCO + bH_2O + c(C_3H_6 + inv\ C_3H_6) + dCO_2 + eNO + (0.79m - \frac{e}{2})N_2$$

$$Q = \frac{CO}{CO_2} = \frac{a}{d} \qquad Q' = \frac{HC}{CO_2} = \frac{c}{d} \qquad Q'' = \frac{NO}{CO_2} = \frac{e}{d}$$

by Carbon balance : a + 6c + d = 1

by Hydrogen balance: 2b + 12c = 2

by Oxygen balance: a + b + 2d + e= 0.42m

Eliminate a: a = dQ and c = dQ'

a + 6c + d = 1; dQ + 6dQ' + d = 1

$$d = \frac{1}{Q + 6Q' + 1}$$

Eliminate b: 2b + 12dQ' = 2 ; b = 1 - 6dQ'

dQ + b + 2d + e= 0.42m; dQ + 1 - 6dQ' +2d + e= 0.42m substituting d from above:

$$0.42\frac{m}{d} = Q+\frac{1}{d}-6Q'+2+Q'' = Q+Q+6Q'+1-6Q'+2+Q'' = 2Q+3+Q''$$

From the combustion equation the mole fraction of CO_2 is:

$$fCO_2 = \frac{d}{a + 2c + d + e + 0.79m - \frac{e}{2}}$$

divide numerator and denominator by d:

$$fCO_2 = \frac{1}{\frac{a}{d} + 2\frac{c}{d} + 1 + 0.5\frac{e}{d} + 0.79\frac{m}{d}}$$

substituting from above for a/d, c/d and e/d to get:

$$fCO_2 = \frac{1}{Q + 2Q' + 1 + 0.5Q'' + 0.79\frac{m}{d}}$$

multiply numerator and denominator by 0.42:

$$fCO_2 = \frac{0.42}{0.42Q + 0.84Q' + 0.42 + 0.21Q'' + (0.79)(0.42\frac{m}{d})}$$

substituting from above (0.42 m/d = 2Q + 3 + Q”) leads to:

$$fCO_2 = \frac{0.42}{2.79 + 2Q + 0.84Q' + Q''}$$

from which follows:

$$\%CO_2 = \frac{42}{2.79 + 2Q + 0.84Q' + Q''} = \frac{100}{6.64 + 4.76Q + 2Q' + 2.38Q''}$$

$$\%CO = Q*\%CO_2 \qquad \%HC = Q'*\%CO_2 \qquad \%NO = Q''*\%CO_2$$

Some useful conversions are:

For grams/gallon assume fuel density of 726 g/l, a fuel carbon fraction of 86%, 3.79 l/gallon and for CO 28g/mole; for HC (propane, C_3H_8) 44g/mole for NO 30g/mole; for C 12g/mole:

$$\frac{gmCO}{gal} = \frac{28*Q*0.86*726*3.79}{(1+Q+6Q')*12}$$

$$\frac{gmHC}{gal} = \frac{2*44*Q'*0.86*726*3.79}{(1+Q+6Q')*12}$$

$$\frac{gmNO}{gal} = \frac{30*Q''*0.86*726*3.79}{(1+Q+6Q')*12}$$

We now prefer to use grams of pollutant/kg of fuel because it requires no assumption about the fuel density:

$$\frac{gmCO}{kg} = \frac{28*Q*860}{(1+Q+6Q')*12}$$

$$\frac{gmHC}{kg} = \frac{2*44*Q'*860}{(1+Q+6Q')*12}$$

$$\frac{gmNO}{kg} = \frac{30*Q''*860}{(1+Q+6Q')*12}$$

If you want to express the measured ratios in the units of other molecules, for example $gmNO_2/kg$ since all emitted NO will eventually oxidize in the atmosphere to NO_2, you only have to change the molecular weight of the species in the appropriate equation.

Appendix 3

Questionnaire pack

drafted by Tim Felstead

Hampshire
County Council

Environment Department
Intelligent Transport Systems Group
5 Upper High Street, Winchester
Hampshire SO23 8UT
Telephone 01962 841841
Fax 01962 845154

www.hants.gov.uk/environment

1003 29681

Enquiries to	Andy Wren	*My reference*	ACW/2420/DH
Direct Line	01962 847500	*Your reference*	
Date	28 March 2006	*E-mail*	andy.wren@hants.gov.uk
		Project website	www.winchestermiracles.org

Dear Sir/Madam

MIRACLES Project emissions monitoring

In 2003 you agreed to become a member of a 1,600 strong panel of Winchester residents, workers and visitors who were sent a series of questionnaires regarding transport related issues in Winchester. This information has been used for the County Council's MIRACLES project which aims to achieve better and cleaner transport for Winchester. I would like to take this opportunity to thank you for your participation, the feedback we have received from panel members has been invaluable in understanding some of the impacts of the project.

The project is now coming to an end but some final tasks on the impact of our work need to be completed. To help with this final phase of the project, I would be grateful if you could find time to complete the enclosed questionnaire. Only panel members who previously indicated that their household has access to a car for private use are being asked to complete this questionnaire. If you do not drive this car please pass the questionnaire to a member of the household who does.

The questionnaire asks you about a number of possible ways in which the County Council can use vehicle emissions measurements that are collected when a vehicle passes through a monitoring site. Further details on how your emissions are measured are given in the enclosed leaflet.

The questionnaire should take around 15 minutes to complete. **Read the instructions on the front of the questionnaire carefully before answering the questions** and refer to the leaflet which gives you further background on the potential scheme. Completed questionnaires will be entered into a prize draw for an IN-CAR SATELLITE NAVIGATION SYSTEM. In order to get this questionnaire to the right audience you

Director of Environment
Alison Quant BSc MSc MRTPI

may be handed one in some of the Winchester Car Parks, if you recognise the envelope please just inform the person distributing them you have received one in the post; only one entry into the prize draw per household will be accepted.

All information will be treated as strictly confidential. No individuals will be identified in the analysis of the questionnaire. Your address will only be processed if you wish to enter the prize draw or would like us to check if your car is in our database.

Please return the completed questionnaire by 26 May 2006 using, the REPLY PAID envelope provided If you have any queries, please contact Tim Felstead on 023 8059 2834, or email T.J.Felstead@soton.ac.uk, at the Transportation Research Group, University of Southampton, who are carrying out this research on our behalf.

Yours faithfully

A C Wren

A C Wren
MIRACLES Project Manager

Hampshire County Council

CIVITAS
Cleaner and better transport in cities

MIRACLES
MULTI INITIATIVE FOR RATIONALISED ACCESSIBILITY AND CLEAN LIVEABLE ENVIRONMENTS

The CIVITAS Project is Co-Financed by the European Union

CHECK YOUR CAR'S EMISSIONS AND FUEL CONSUMPTION

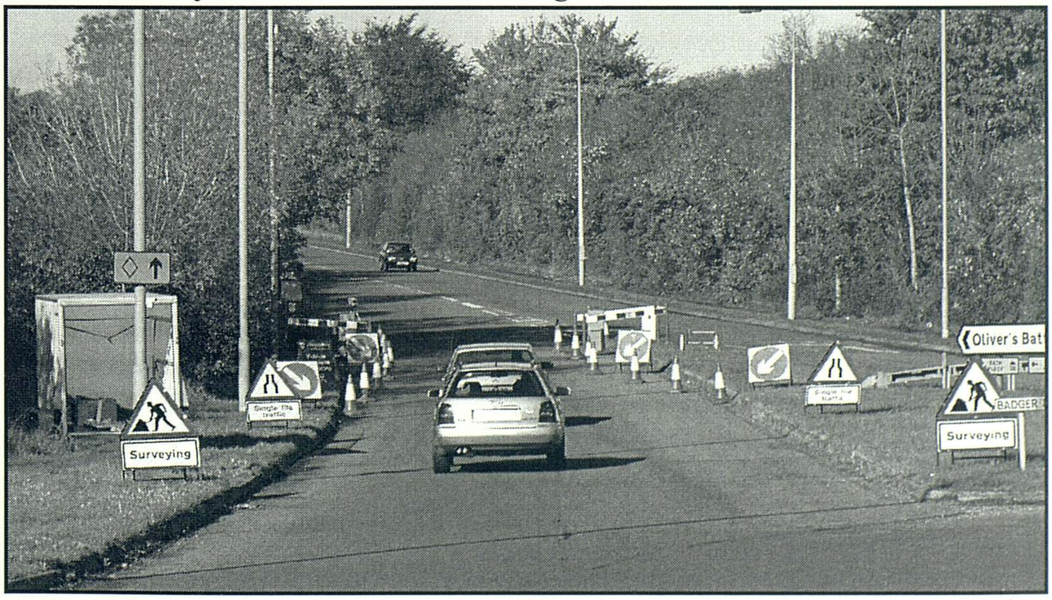
Hampshire County Council is considering a scheme to help motorists check their vehicles' emissions between the annual MOT tests. Your car can develop an emissions-related fault at any time; this is not only bad for air people breathe in the places you drive, but could also cost you money in repairs and poor fuel consumption if not corrected quickly. Measurements of vehicle emissions are taken as the car drives through an emissions monitoring site. Further details on how your emissions are measured are given in the leaflet enclosed in this pack.

The questionnaire asks you to imagine how you would react to four different scenarios describing possible ways the emissions measurements could be used. **Please answer the questions as you think you would really behave in the situations described. There is no right or wrong answer.** The questionnaire should **take around 15 minutes** to complete. This research is being carried out on behalf of Hampshire County Council by the University of Southampton and no other organisation will have access to your personal data. Please contact Tim Felstead on 02380 592834 if you have any queries.

When you return a completed questionnaire, you will automatically be entered into a free prize draw for an **IN-CAR SATELITTE NAVIGATION SYSTEM** if you fill in your name and address at the end of the questionnaire. Please return the questionnaire in the REPLY PAID envelope provided by *DATE IN HERE.*

General questions

A1) A photo of an emissions monitoring site (as mentioned above and described in the enclosed leaflet) is shown below. So far they have been located on Badger Farm Road and Andover Road.



Have you ever driven through one of the emissions monitoring sites on Badger Farm Road or Andover Road? (Please tick one box only)

Yes	No	Don't know
☐	☐	☐

A2) How often do you drive a car into or through Winchester city centre? (Please tick one box only)

Most days	2 to 3 days a week	Once a week	Once a fortnight	Less than once a fortnight	I never travel through Winchester city centre
☐	☐	☐	☐	☐	☐

A3) In general, how would you rate the air quality in Winchester city centre? (Please tick one box only)

Very good	Quite good	Neither good nor poor	Quite poor	Very poor	Don't know
☐	☐	☐	☐	☐	☐

Scenario 1 Sign at the roadside informing you of your emissions

Please read the following carefully and then answer the questions:

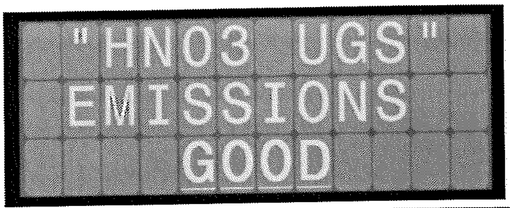
Imagine when driving into Winchester you pass one of the emissions monitoring sites described in the leaflet included in this pack. **The site is located just on the outskirts of the city.** At the roadside is an electronic sign which displays your registration plate and your car's most recent emissions measurement as you drive towards it. Your emissions measurement is put into three categories **– GOOD, FAIR or POOR.** From our measurements to date, approx. **1% of vehicles fall into the POOR category** and they would be **extremely likely** to fail the emissions part of the MOT test if done on the same day.

If your emissions were POOR, to fix your cars likely emissions fault, you would have to take it to your normal, trusted garage. You would ask them to check the emissions and emission controls of your car. This routine check is already done once a year as part of the annual MOT test but the fault may not be detected until your next MOT in a year's time -your emissions can go wrong at any time during the year! The test would take approximately 20 mins. and cost approx. £20. If your car was found to have a fault which required repairing, this could cost you extra.

In addition to lower emissions in future, by having your car checked sooner than your MOT date, you could prevent a more expensive repair bill later. You could also save up to 10% on your normal fuel costs (for a normal weekly fuel bill of £50, you could save £5).

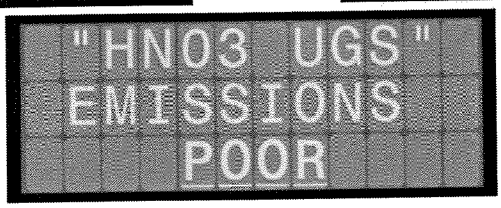
Taking your car for a check is entirely voluntary and would be organised by you.

THE SIGN WOULD LOOK LIKE:



OR

OR



B1) Imagine you drive past the sign regularly. With the above information in mind, please think how you would react in the following situations? (Please tick one box only)

The sign usually says…	WOULD arrange voluntary emissions test	WOULD NOT arrange voluntary emissions test	Don't know
…your emissions are GOOD but the next few times it changes to FAIR	☐	☐	☐
…your emissions are GOOD but the next few times it changes to POOR	☐	☐	☐
…your emissions are FAIR but the next few times it changes to POOR	☐	☐	☐

B2) If you were on a normal car journey into/around Winchester, would you drive out of your way to check your car's emissions using the sign? (Please tick one box only)

Yes ☐ Maybe ☐ No ☐ Don't know ☐

Imagine that the measurements taken when you drive through the site are stored on a list linked to the new, electronic MOT database. If your last two emissions measurements from the site were GOOD and were **within two months** of your *next* MOT date, your emissions would not need to be checked at your next MOT.

This would give you a £10 discount on the cost of the MOT, which normally costs £45.

B3) With this new information in mind, if you were on a normal car journey into/around Winchester, would you drive out of your way to check your car's emissions using the sign? (Please tick one box only)

Yes ☐ Maybe ☐ No ☐ Don't know ☐

B4) Do you have any comments on the above type of scheme, including why you would or would not arrange a voluntary test? (Please write in the space below)

....

....

....

Scenario 2 A website and hotline you can check

Please read the following carefully and then answer the questions:

Imagine that instead of using a sign at the roadside, Hampshire County Council create a list of the registration plates and emissions measurements of the vehicles passing the monitoring sites. You could see if your car was on the list through a website or telephone hotline (local call rate). *The list would be updated every week.* The monitoring sites are well signed so it would be obvious if you had passed through one.

To check your vehicles emissions, you would have to type in or give the telephone operator the registration number of your car. You would **only** be able to **see or hear** information **on the vehicle registration number you gave**. Hampshire County Council would not have any of your personal details.

The list would show all of your vehicles emissions measurements sorted by date. If your emissions measurement became worse over time (for example, from GOOD to POOR), to fix your cars likely emissions fault you would need an emissions test on your vehicle and pay for any repairs needed. Remember as well as lowering your vehicles emissions, fixing any problem sooner than your next MOT could save you from more expensive repairs later and save on fuel costs. This is explained in more detail in **Scenario 1** on the second page of this questionnaire

Taking your car for a check is entirely voluntary and would be organised by you.

C1) Do you have access to the internet for personal use at home or work (Please tick one box only)

Yes ☐ No ☐ Don't know ☐

C2) Would you check your emissions readings using a website? (Please tick one box only)

Yes ☐ **(Go to C3)** No ☐ **(Go to C4)** Don't know ☐ **(Go to C4)**

C3) How often would you check your emissions readings using the website? (Please tick one box only)

Once a week	Once every two to three weeks	Once a month	Once every two to six months	Don't know
☐	☐	☐	☐	☐

C4) Would you check your emissions readings using a telephone hotline? (Please tick one box only)

Yes ☐ **(Go to C5)** No ☐ **(Go to C6)** Don't know ☐ **(Go to C6)**

C5) How often would you check your emissions readings using the telephone hotline? (Please tick one box only)

Once a week	Once every two to three weeks	Once a month	Once every two to six months	Don't know
☐	☐	☐	☐	☐

C6) Do you have any comments on the above type of scheme, including why you would or would not use the website or telephone hotline? (Please write in the space below)

....

....

....

Scenario 3 A Free emissions check

Please read the following carefully and then answer the questions:

Imagine that you check the website or telephone hotline and find that your car's emissions are listed as POOR, and all cars listed as POOR can apply for a *free* emissions check organised and paid for by Hampshire County Council (HCC).

To take up the offer you would need to apply for the check either through the website or by phone. HCC would contact you to arrange the emissions check at a time and date that suited you. The emissions check would be carried out by a garage in Winchester, chosen by HCC, which had been approved by the local 'Trading Standards' office.

The check would take about 30mins. and a report giving details of your emissions levels and any recommended repairs would be given to you afterwards. You would be under **no obligation to have your car repaired**.

D1) Would you use the emissions check service described? (Please tick one box only)

Yes ☐ No ☐ Don't know ☐

D2) If you were also offered £50 towards the cost of any repairs done at the HCC appointed garage, would you use the emissions check service described? (Please tick one box only)

Yes ☐ No ☐ Don't know ☐

D3) Do you have any comments on the above type of scheme, including why you would or would not use the free emissions check service? (Please write in the space below)

....

....

....

Scenario 4 A sign asking you to redirect to Park and Ride

E1) Have you ever used the Winchester Park and Ride service? (Please tick one box only)

Yes ☐ **(Go to E2)** No ☐ **(Read on after E2)** Don't know ☐ **(Read on after E2)**

E2) Overall, how satisfied were you/are you with the service? (Please tick one box only)

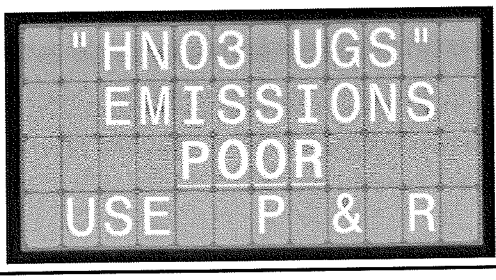
Very satisfied	Fairly satisfied	Neither satisfied nor dissatisfied	Fairly dissatisfied	Very dissatisfied
☐	☐	☐	☐	☐

Please read the following carefully and then answer the question:

Imagine you are entering Winchester near the Park and Ride site (near M3). Just like in **Scenario 1**, an electronic sign displays your registration plate and your latest emissions reading as you are driving towards it.

The sign tells you your emissions are POOR and asks you to use the Park and Ride site *just around the corner*. Following the request on the sign is entirely voluntary; you could still drive into the city centre if you wanted.

THE SIGN WOULD LOOK LIKE:



E3) If you saw the sign and it asked you to use the Park and Ride service, would you ...

...follow the request on the sign and use the Park and Ride service instead of driving into the city centre?	... *ignore the request on the sign* and drive into the city centre?	Don't know what I would do
☐	☐	☐

Please read the following carefully and then answer the questions:

The Park and Ride service costs £1.50 for all day parking and includes the cost of the bus trip into and out from the city centre. The bus service runs approx. every 10 mins.

From the Park and Ride site, the bus takes approx. 10 mins. to reach the bottom end of the city centre (outside the Guildhall) and 15 mins. to reach the top of the city centre (outside the Railway Station). The service stops about 1 min. walk from most city centre destinations.

If you continued to drive to the city centre, it would take you 13 mins. to drive and find a parking space, and a further 2 mins. to walk from your car park to your destination.

E4) Still thinking of the Park and Ride sign, and with the above information in mind, if your parking in the city centre...(Please tick one box only for each line)

	...follow the request on the sign and use the Park and Ride service instead of driving into the city centre?	... *ignore the request on the sign* and drive into the city centre?	Don't know what I would do
...was ***free or paid for by your employer***, would you...	☐	☐	☐
...cost ***you 60p for every hour***, would you...	☐	☐	☐

E5) Do you have any comments on the above type of scheme, including why you would or would not use the Park and Ride service if you were asked to? (Please write in the space below)

....

....

....

About you

To ensure that the results of the questionnaire are representative of people living and working in Winchester we need some information about you. This information is strictly confidential and no information from this questionnaire will be published which will allow an individual to be identified.

F1) Are you...? (Please tick one box only)

Male ☐ Female ☐

F2) Please indicate your age (Please tick one box only)

17-19 ☐
20 - 24 ☐
25 - 34 ☐
35 - 44 ☐
45 - 54 ☐
54 - 65 ☐
65+ ☐

F3) Please indicate where you live (Winchester means the City of Winchester and not surrounding villages such as Littleton or Easton). (Please tick one box only)

I live in Winchester ☐ I live outside Winchester ☐

F4) Are you...?(Please tick one box only which <u>best</u> describes your situation)

Employed full time (30 hours a week or more) ☐
Employed part time (less than 30 hours a week) ☐
Self employed ☐
On training scheme ☐
Unemployed ☐
Full time student ☐
Retired from paid work ☐
Full time house husband/wife ☐
Not in work (permanently sick/disabled) ☐
In receipt of state benefits ☐

F5) What is your most common reason for driving into or through Winchester city centre? (Please tick one box only)

- Never drive into Winchester city centre ☐
- Returning home from trip elsewhere ☐
- Travel to work ☐
- Travel during work ☐
- Shopping ☐
- Education as a student ☐
- Social/leisure/visiting/recreation ☐
- Other (please specify) ☐ ....
- Personal - medical ☐
- Taking/collecting children from school ☐
- Taking/collecting someone ☐

F6) How many cars does your household own or have continuously available for private use? (Please tick one box only)

None ☐ One car ☐ Two cars ☐ Three or more cars ☐

F7) Roughly, how old is the car you have driven into Winchester today/most recently? (Please tick one box only)

Less than 1 year old ☐ 2 to 3 years old ☐ 4 to 6 year old ☐ 6 to 15 years old ☐ More than 15 years old ☐

F8) What fuel does your car use? (Please tick all that apply)

Petrol ☐ Diesel ☐ LPG ☐ Hybrid electric ☐ Other ☐

F9) Were you aware Winchester City Centre has been declared an Air Quality Management Area which means that levels of some pollutants in the air are higher than they ideally should be? (Please tick one box only)

Yes ☐ No ☐ Don't know ☐

F10) We can check to see if we have your vehicle's emissions in our database and give you feedback. If you would like us to check please write in your registration number below and fill in your address overleaf. You will not be penalised whatever your vehicle emissions measurement. (Please write in the space below)

CAR REG. NUMBER: |_|_|_|_|_|_|_|_|

F11) What is your home postcode? ((Please write in the space below)

|_|_|_|_| |_|_|_|

F12) Please write in your name and address if you wish to be entered into the free prize draw to win a £50 shopping voucher of your choice or would like us to check if your vehicle's emissions are in our database. ***This information will not be used for anything other than informing winners of the prize draw or contacting those who would like us the check for their vehicle in the emissions database.*** (Please write in the space below)

Name: ....

Address: ....

....

....

....

Thank you for your time and cooperation

Data Protection Act 1998. The information you provide will only be used for the purposes of helping to improve the environment and access to Winchester. Your address will only be processed if you wish to enter the prize draw or would like us to check if your car is in our database. The winner of the prize draw will be contacted before publication of the results. This research is being carried out on behalf of Hampshire County Council by the University of Southampton and no other organisation will have access to your personal data.

What can I do to help keep my vehicle emissions down?

There are a number of ways you can keep your fuel consumption and emissions down. Here are 10 tips you can try and follow:

1. **Drive defensively** - avoiding harsh acceleration and heavy braking wherever possible. Remember that pulling away too fast uses up to 60% more fuel
2. **Concentrate** - look ahead, anticipate the road conditions and the actions of others. You'll be less likely to have an accident and will reduce fuel consumption
3. **Use the gearbox efficiently** - changing gear between 1500 and 2000 rpm can reduce fuel consumption by 15%
4. **Drive off straight away when starting from cold** - idling to heat up the engine wastes fuel and causes rapid engine wear
5. **Service your car regularly** – ensuring your car is properly tuned and maintained can save 10% off your normal fuel use.
6. **Avoid short journeys** - a cold engine uses almost twice as much fuel while catalytic converters can take five miles to become effective
7. **Stick to speed limits and make your fuel go further** - driving at 70mph uses up to 30% more fuel than at 50mph
8. **Plan your journeys** - to avoid congestion, roadworks and getting lost, plan your route before setting off
9. **Check your tyre pressure regularly** - under-inflated tyres wear out more quickly and can increase fuel consumption by up to 3%
10. **If you're stuck in a jam, switch off** - turning off the engine after two minutes will save fuel and cut all emissions

Thinking of buying a new car?

If you are thinking of buying a new car, visit the Vehicle Certification Agency (VCA) website which has lots of helpful tips and information on what you should look for in a car to ensure it has low fuel consumption and emissions. You will also find a database which lets you compare different vehicle models against each other.

www.vcacarfueldata.org.uk

What is CIVITAS MIRACLES?

CIVITAS is an initiative that is co-funded by the European Union. The initiative is concerned with innovation and originality in environmentally friendly travel schemes.

The European Union is providing financial support for those cities that wish to demonstrate and test the effectiveness of integrated action.

MIRACLES (Multi-Initiatives for Rationalised Accessibility and Clean Liveable Environments) is one of four projects that form the **CIVITAS** initiative. There are in total 19 cities, including Winchester, that are taking part in the CIVITAS program.

Why do we need MIRACLES in Winchester?

Winchester's many attractions, combined with the high level of car use, means that large volumes of traffic enter and leave the city each day. An ancient street pattern still exists in many areas and this is ill-equipped to deal with today's heavy traffic. As a result congestion is commonplace, and air pollution is becoming a serious issue, with Winchester recently being declared an Air Quality Management Area (AQMA).

MIRACLES hopes to tackle and resolve these issues of congestion and pollution, through an integrated package of 13 transport-related schemes.

For more information about the MIRACLES project please telephone

01962 847474

or visit:

www.winchestermiracles.org

Winchester Vehicle Emissions Monitoring

Helping car drivers and the environment

CIVITAS
Cleaner and better transport in cities

MIRACLES
Multi initiative for rationalised accessibility and clean liveable environments

The CIVITAS Project is Co-Financed by the European Union

Hampshire County Council

University of Southampton

What is vehicle emissions testing?

As part of the CIVITAS MIRACLES project, Hampshire County Council has been looking at ways to reduce traffic pollution in Winchester city centre. One way is to make sure that vehicles driving around Winchester are working properly. Lots of things can go wrong with your vehicle which cause it to produce higher concentrations of pollutant gasses than it should – when a vehicle is in this state it is called a 'high-polluting vehicle'.

One way to help to identify high-polluting vehicles within the City is via the development and use of high-tech. emissions monitoring equipment. The equipment is used to identify vehicles entering the city that are producing high levels of pollution.

Equipment at the roadside on Badger Farm Road

This equipment is portable, and can be set up at the roadside. It can identify the levels of each pollutant coming from the exhaust of every passing vehicle. The levels of pollutants measured are compared with MOT standards, so that only those vehicles producing more than the legal limit can be targeted.

Trials of the equipment are currently being carried out, which will identify the number of high-polluting vehicles entering the city. Once these trials are complete, and the number of high-polluting vehicles are known, the most appropriate solutions will be developed.

Why identify high-polluting vehicles?

Like many UK city centres, the level of some pollutants in the air in Winchester city centre does not meet the objectives set out in the Air Quality (England) Regulations 2000. Identifying and fixing high-polluting vehicles is not only good for the environment and people's health, it is also good for the motorist's pocket.

Environment and health - Conventional petrol and diesel engine exhausts emit a number of chemicals which are harmful to both human health and the environment – high-polluting vehicles produce more of these harmful chemicals than they should.

Chemicals emitted	Impact on health and the environment
Carbon Monoxide (CO)	Poisonous gas. At low concentrations it makes heart problems worse, while at high concentrations it can be fatal.
Carbon Dioxide (CO_2)	Major contributor to the greenhouse effect and climate change.
Nitrogen Oxides (NO_x)	Cause respiratory diseases. Contribute to acid rain production.
Hydrocarbons (HC)	React with NOx in sunlight to form ozone and smog, which can irritate the eyes and throat.
Particulate Matter (PM)	Cause respiratory diseases and are linked to premature deaths.
Benzene	Toxic and carcinogenic, linked to leukemia.

Reducing motoring costs - Drivers also benefit from a properly tuned engine. If your vehicle is being used when it has an emissions-related fault, it could not only be using more fuel than it needs to (about an extra 10%), but it could also be damaging parts of your engine or exhaust which are expensive to repair.

Apart from the annual MOT test it is difficult for a motorist to know if their vehicle has an emissions problem. Hampshire County Council are looking at ways of using the roadside emissions measurements to help advise drivers that their vehicle has developed a fault.

How we can help drivers?

Based on the measurements collected, we are considering a number of ways to help drivers be aware of their emissions and reduce the number of high-polluting vehicles in Winchester city centre. Some of the possible ways are :

- using a roadside sign providing advice on their vehicle emissions;
- directing high-polluting vehicles to use a Park and Ride car park as an alternative to entering the city centre;
- creating a website which details your emissions measurements when you enter your vehicle registration number.
- offering a discount on servicing for identified high-polluting vehicles, in order to improve their emissions.

A roadside sign informing drivers of their vehicles' emissions as they drive past a monitoring site