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An In-Service Emissions Test for Spark Ignition (SI) Petrol Engines – PPAD 9/107/09

Phase 1 Report

Definition of an excess emitter and effectiveness of current annual test

A report produced for the DTLR VSE Division

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Executive Summary

The UK Department for Transport (DfT) has commissioned this phased project. Its focus is the in-service testing of petrol engined cars fitted with three-way catalytic converters. The objectives of this first phase are to establish the significance of vehicles with deteriorated emissions performance, to define which are the excess emitter vehicles and to assess the effectiveness of the current annual test at identifying the excess emitters. The key output from this study is an argued case as to whether there may be a significant air quality benefit, when weighed against likely costs, from the introduction of a more effective test. If such a case exists, devising an improved test would form the focus of the Phase 2 study.

In summary, the project has concluded that poorly maintained excess emitter vehicles on the road are adversely affecting the UK's air quality. A definition of what constitutes an excess emitter has been derived that is in harmony with other European emissions directives. This is that a vehicle is an excess emitter if its CO, HC or NO_X emissions are outside those of the Euro standard that applied when it was new, when measured over the Euro III type approval drive cycle (the NEDC) after due allowance has been made for degradation at the rate of an additional 20% for each 50,000 miles (80,000 km) that the vehicle has been driven.

A reanalysis of a study by TRL of over 2,000 in-service emissions (MOT) tests concluded that the current test is moderately effective in identifying the excess emitters, most notably the vehicles that are severely over-fuelling. However, there is scope for improvement with the failure of the current test to adequately assess catalyst activity identified as one focus for an improved test.

Two species of most concern to the nation meeting its air quality standards are NO_X and PM. Petrol fuelled vehicles currently contribute 24% and 3.7% to the total inventories of these pollutants. They also make major (greater than 60%) contributions to the UK National Atmospheric Emissions Inventory (NAEI) for benzene, 1,3 butadiene, carbon monoxide and lead. Further, the contributions are geographically localised in urban areas where air quality is generally poorer.

The significance of vehicles with deteriorated emissions performance on the meeting of air quality standards has been examined by developing a mathematical model that described the distribution of emissions over the chosen drive cycle. Principal conclusions from this analysis are that:

- the number of vehicles whose emissions are above the NO_X type approval standard is surprisingly high (25%),
- the fraction of excess NO_X emitters appears to be independent of the vehicle sample and the state of maintenance,
- there is a high degree of variability of CO emissions dependent on vehicle sample selection, with maintained vehicles having a very different emissions distribution relative to the same vehicles before maintenance.

An assessment of the likely degradation mechanisms and their impact on emissions performance was undertaken. Critical evaluation of data from a number of sources showed that there are

serious difficulties in gathering unbiased, objective, statistically meaningful data. Notwithstanding, the general consensus for the frequency of faults influencing emission is in descending order:

- λ sensor faults
- catalyst internal integrity
- catalyst external integrity (corrosion or other leaks)

A major part of the study has been an assessment of the effectiveness of the current annual test at identifying excess emitters. The success criteria were that the test should:

- maximise the likelihood of detecting the worst offenders and
- minimise the number of vehicles erroneously identified as requiring maintenance.

The analysis of UK in-service test data undertaken here concluded:

- for the statistically large sample used (>2000 vehicles) the detection of a few high emitters is having a very clear impact on reducing emissions and improving air quality,
- there are a large (>30%) number of vehicles requiring a high idle retest because of insufficient preconditioning and
- there are greater than 2% of vehicles failing on high λ, with it being unclear what maintenance, and air quality benefit, accrues from identifying these failures.

The data from a more recent study gave some evidence that overall average levels of emissions from TWC vehicles may be reducing.

On the key question of how the current test might be improved, this study makes some recommendations that would improve the current procedure, and details issues to be considered in the devising of an improved procedure.

On balance this study:

- advocates caution when interpreting data from vehicles close to the 0.3% CO level because of the influence of preconditioning,
- does not recommend a relaxation of the high idle CO limit, to a value greater than the current 0.3% limit because the majority of air quality improvements arise from vehicles whose CO concentration is >0.3%,
- does not recommend a tightening of the limit to a value less than 0.3% because it is adjudged that this would lead to little net air quality benefit, whilst at the same time it would increase the number of errors of commission, thereby undermining confidence in the test.

The report identifies the current meter specification as one area where improvements could be made. It makes some recommendations that it is believed would increase the ease with which testers can test vehicles and increase confidence in the answers indicated by instruments.

In the longer term an improved test would be needed to overcome some key deficiencies of the current test. This study recommends that consideration be given to devise an improved test – the primary focus of Phase 2 of this project. Areas that the proposed Phase 2 study should address are recommended to include:

1. an evaluation on the likely impact of E-OBD on changing the distribution of emissions from vehicles when in-use,

2. consideration of alternative test procedures to improve on the current in-service test, and
3. an evaluation of the cost effectiveness of PM measurement.

It is recommended that aspects to be specifically addressed in the consideration of an alternative test procedure include:

- improving the correlation of the test to the emissions from vehicles over transient loaded cycles (i.e. real driving),
- introducing an improved assessment of catalytic activity,
- improving (i.e. reducing) the currently high number of vehicles which fail the first high idle emissions test but after further preconditioning pass a second high idle emissions test,
- reducing what may be an unreasonably high number of inappropriate failures because of the high idle upper λ limit.

A preliminary analysis of the cost effectiveness of in-service testing was also undertaken in this study. Within the assumptions given the cost effectiveness (in g/£) were calculated to be:

	Cost effectiveness achieved	Maximum cost effectiveness that might be achieved		
	1997/8	2005	2010	2015
NO_X	31.8	581.2	405.9	323.1
Non-methane volatile organic compounds	273.7	242.7	204.5	182.6
Benzene	14.5	11.98	9.61	8.41
1,3 butadiene	4.0	2.53	1.84	1.54
CO "Total"	7,503	14,313	10,995	8,792
CO "Random"		1,175	902	722

The two estimates for CO are based on JCS data representing extremes of a well-maintained fleet (Random) and a fleet with an unlikely high proportion of very high emitters (Total).

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1 Introduction

Key issues addressed in Chapter 1

The chapter opens by reviewing the DTLR's need to critically assess the current in-service emissions test for petrol fuelled vehicles. Issues included are:

- the objectives of the in-service emissions test
- the driver of the nation's Air Quality Strategy,

and the findings of

- the Cleaner Vehicle Task Force initiative and
- the National Audit Office report on vehicle emissions.

The scope of the project as a whole and this first phase specifically are then summarised, together with the approach adopted to address the issues involved.

Vehicles emit a cocktail of chemicals whose exact composition depends on the vehicle's fuel, the driving conditions (speed, load, rate of acceleration etc) and on the vehicle's condition (e.g. age and its state of maintenance). It is widely recognised that these emissions have a detrimental effect both on human health and the environment. The extent of this is species and their concentration specific. This recognition has led to the specification of maximum emission levels of key species from vehicles both prior to use and in-service.

Before a new vehicle can be approved for sale in the EU it must meet certain standards for exhaust emissions as specified by EU directives. These standards are vehicle type specific and have evolved over time with improvements in engine design allowing lower limits to be achievable. Once in service a vehicle's condition degrades and emissions generally increase above the original levels. The "type approval" regulations now include limits on rates of in-use degradation. Timely maintenance is also required to reduce the extent of this degradation.

In parallel with the vehicle emissions regulations, the UK has in place a national Air Quality Strategy. This was reviewed in the past few years, and the revised strategy was published in January 2000. In the foreword to the revised Air Quality Strategy for England, Scotland, Wales and Northern Ireland John Prescott declares that new objectives have been set as a consequence of a commitment to reducing risks to health and the environment. Pollution from road transport was singled out, with a reduction in the effect of traffic pollution on local air quality by more than half being a specified target.

An initiative to promote the acceptance of environmentally friendly vehicles is the "Cleaner Vehicle Task Force" which was launched by the Prime Minister in November 1997. The main work of the Task Force is undertaken through specialist sub-groups, of which the Technology and Testing working-group is the one most pertinent to this study. One of the objectives of the Technology and Testing working-group is to *consider tighter standards based on model specific information for MOT and annual testing for a wider range of vehicles*. The conclusions and recommendations of this sub-group, as reported in "Technical solutions for reducing the emissions from in-use vehicles", are incorporated as an input into this report.

In-service emissions testing is one of several measures designed to reduce pollution from vehicle emissions. The Vehicle Inspectorate, VI, (an agency of the Department of Transport Local Government and the Regions, DTLR), oversees the testing of light-duty vehicles which is carried out by 18,600 private garages around Britain. The VI are also directly responsible for the roadside testing of all vehicles.

In May 1999 the National Audit Office, NAO, published a report entitled Vehicle Emissions Testing. This was a study of the effectiveness of the regime for in-service testing of vehicle emissions in Britain. Its main findings and recommendations, specifically those concerning the testing of petrol-engined vehicles, are incorporated into this report. The report concluded, amongst other things, "that there are some limitations with the current test techniques" and "that the DTLR will need to continue to update its research into the emissions characteristics of catalyst petrol vehicles as these vehicles get older".

This project has been commissioned by the UK Governments' Department of Transport Local Government and the Regions (DTLR). Its primary objective is to examine the case for improving the annual roadworthiness gaseous emissions test applicable to petrol engined cars fitted with three-way catalytic converters. Drivers for the project include the concerns and recommendations expressed in the NAO report, concerns raised by a study for the European Commission regarding the effectiveness of the current in-service test, and recommendations made by the Cleaner Vehicle Task Force. Together these lead to the requirement to investigate whether for cleaner vehicles the current test may not adequately identify vehicles whose emissions performance has deteriorated significantly. If this is the case there may be a significant air quality benefit to be obtained from introducing a more effective test. The study is to be undertaken in the context of the introduction from August 2001 of a fast pass test (more formally known as the Basic Emissions Test, or BET) in response to the NAO report, for vehicles registered on or after 1/8/92. The basic philosophy of this test is to check a vehicle against generic levels. If the vehicle is within these limits then the vehicle has passed, and no further testing is required. If the vehicle does not meet these limits it is not failed but tested using the existing, standard test.

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The programme of work designed to address these issues is phased. The first phase of the project is to establish:

- the significance of vehicles with deteriorated emissions performance and the definition of an excess emitter, and
- the effectiveness of the current annual test at identifying the excess emitters
- recommendations of minor modifications to improve the current test.

The final part of this phase of the project is to undertake a preliminary cost effectiveness analysis estimating the reduction in emissions (in units of mass/year) and the cost of identifying, and then rectifying, the faults to effect this reduction.

It is emphasised that this is the first phase of a multi-phase project, and as such it formulates, and prioritises, issues that require further consideration in subsequent phases. It is not intended to provide all the answers to the issues involved at this stage.

2 Review of vehicle exhaust emissions

Key issues addressed in Chapter 2

This chapter reviews the exhaust emissions from petrol fuelled vehicles in the context of the UK's air quality. This is achieved by considering:

- the emissions from new vehicles, i.e. the type approval emissions limits, (Appendix 1)
- the species included in, and the standards set by, the UK's Air Quality Strategy,
- the methodology of estimating annually the national atmospheric emissions inventory and
- the contribution of petrol fuelled vehicles to this inventory.

Both the existing regulations and likely changes in the current decade are considered.

2.1 AN OVERVIEW OF THE AIR QUALITY STRATEGY

2.1.1 Introduction

Air quality in the UK is generally very good, but there are still sometimes unacceptably high levels of pollution that can harm human health and the environment. The Air Quality Strategy for England, Scotland, Wales and Northern Ireland describes the plans drawn up by the Government and the devolved administrations to improve and protect ambient air quality in the UK in the medium-term. The proposals are intended to protect people's health and the environment without imposing unacceptable economic or social costs. They form an essential part of the government's strategy for sustainable development and will be subject to regular review so that policy can be refined in the light of experience and advances in technology.

The Air Quality Strategy (AQS) sets objectives for eight main air pollutants to protect health. Performance against the objectives will be monitored where people are regularly present and might be exposed to air pollution. The latest revision of the strategy was published in January 2000 and includes two new objectives to protect vegetation and ecosystems. These will be monitored away from urban and industrial areas and motorways. The pollutants covered are: benzene, 1,3-butadiene, carbon monoxide, lead, nitrogen dioxide, ozone, particles (PM_{10}) and sulphur dioxide. The objectives for these species are given in Table 1 of Appendix 2.

2.1.2 Assessment of principal contribution of road transport to air quality.

A summary is given in Appendix 2 for each of the eight pollutants. This provides background information about the pollutant and lists its most important sources. It considers the current and future inventory levels and reviews ambient concentrations relative to the AQS objectives . For all pollutants except ozone (which as explained in Appendix 2 occupies a unique position) tables are also included of the recent UK annual emissions and those predicted up to 2015. The latter table subdivides the road transport emissions into those arising from different vehicle types, both by fuel and by vehicle type (cars, LGVs, HGVs buses etc).

The tables in Appendix 2 contain a wealth of information regarding the contribution of the different components of road transport to the overall emissions inventory. This can be expressed as a bar graph giving the contribution (as depicted in the 1999 NAEI) of petrol and diesel fuelled vehicles to the whole, see Figure 1. In the case of PM_{10} there is also an additionally identified component from the brakes and tyres (of all vehicles). The contribution from road transport as a whole agrees well with that of Figure 8 (on page 25) of the NAO report[1] after making some adjustments for the age of the data. The important additional information contained in Figure 1 is the subdivision of the road transport contribution so that the petrol vehicle contribution is clearly identified. The figure indicates that petrol fuelled vehicles contribute more than half of the total inventory for 1,3 butadiene, carbon monoxide, benzene and lead, and a significant proportion of nitrogen dioxide. The largest change relative to the earlier NAO data is the reduction in the road transport proportion of the lead inventory, down from around 73% to just under 60%.

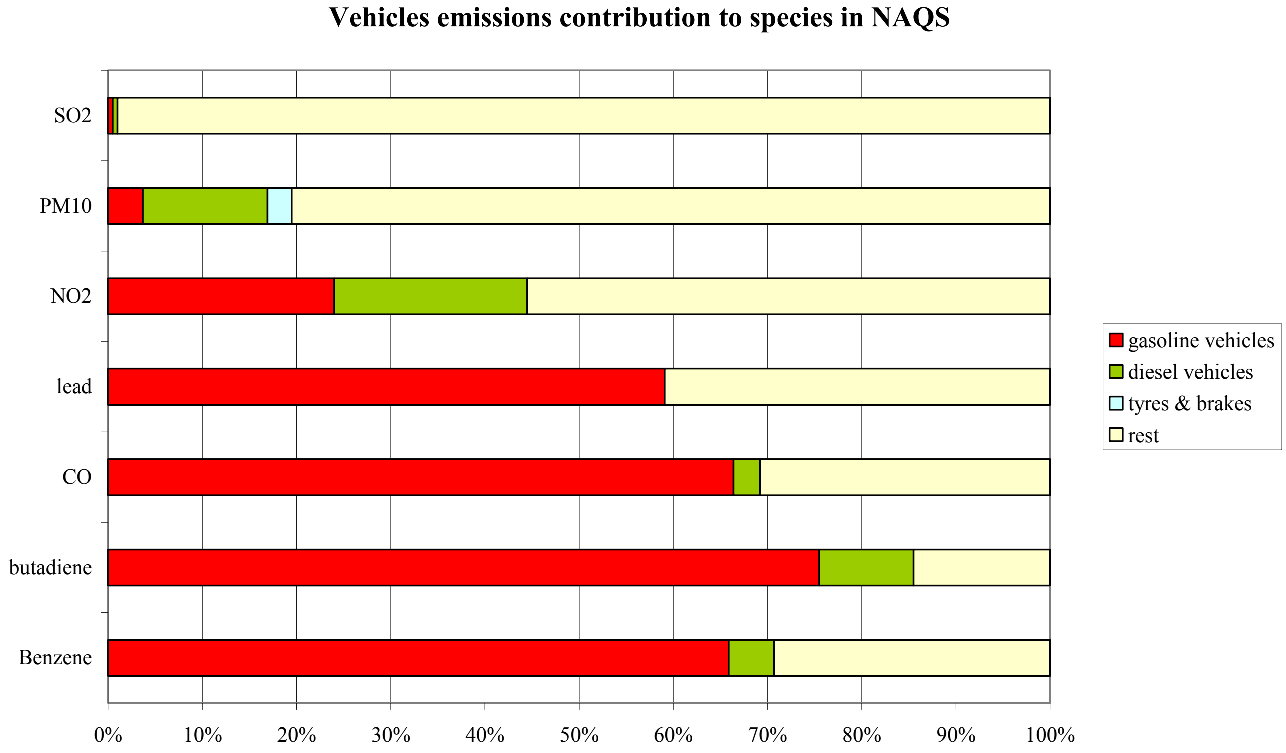

Figure 1 Contributions to mobile sources of the 7 pollutants listed in the NAQS

However, the presentation in Figure 1 omits any weighting of air concentrations against the NAQ standard. A qualitative assessment was made of the concentrations reported by the national network of sites when compared against the AQS standard (data taken from the Air Quality Standard for England, Scotland and Northern Ireland). For example, mean butadiene

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[1] NAO Report HC 402 on Vehicle Emissions Testing, May 99

concentrations are around 40% of the 2.25 μg/m^3 standard, with one of the thirteen monitoring sites being just above the standard (at 2.34 μg/m^3) in the context of a decreasing inventory. In contrast, nearly half of the 83 national monitoring sites exceeded the target annual mean NO_2 concentration of 40 μg/m^3, with concentrations generally being highest at roadside and kerbside sites. A "mean" concentration of 120% of the AQS was taken for this pollutant. However, the situation is more complex than this because for NO_2 there are both hourly, and annual means. Further, with the latest revision the standard for the hourly mean has been reduced from 150 ppb to 105 ppb (the standards for the annual mean has remained unaltered).

Figure 2 shows the previous data modified to include this weighting. All but two of the pollutants have an inventory less than 100, i.e. less than that required to meet the AQS Standards. The two pollutants that need further reducing are NO_2 and PM_{10}. Further, the contribution of petrol vehicles to the overall NO_2 inventory is significant.

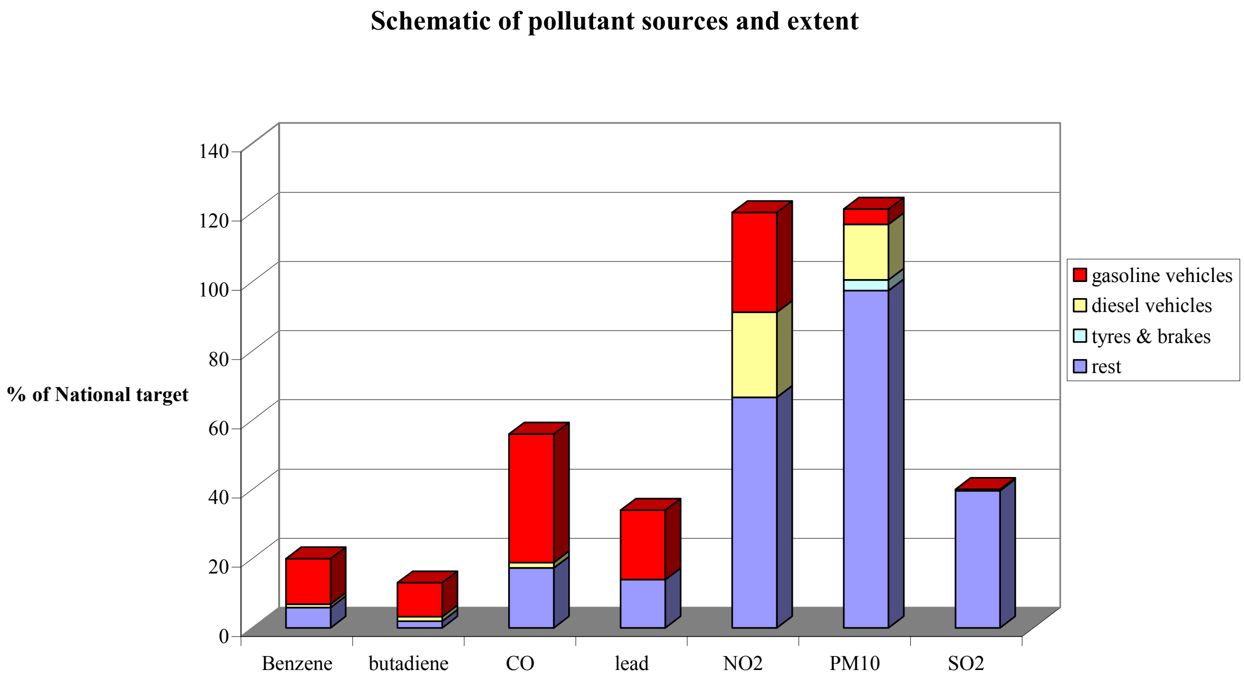

Figure 2 Contributions to mobile sources of 7 pollutants listed in the AQS weighted by air concentrations relative to the AQS

2.1.3 Future trends

NO_2 concentrations currently exceed the AQS standard, as discussed above. There are a number of steps being taken to reduce these, not least in terms of the lowering of emission levels from vehicles, and the effective policing of these changes to type approval standards. **No change** is expected in terms of the species specified in the AQS over the next decade, i.e. it is expected to remain as NO_2.

The situation is not as simple for particulate matter. This is currently the subject of intensive research, and the complexity of the generic term is becoming apparent. The Air Quality

Strategy does not complicate the issue of particulate matter by giving any data for size ranges other than PM_{10}. Such data can be obtained from the National Atmospheric Emissions Inventory directly[2]. Table 1 lists the UK emissions of various PM fractions in each sector in the PM_{10} inventory. The data is from the 1998 inventory, and for each size range is expressed in terms of % of the whole, with the total mass in the size range, in k tonnes also being included.

Table 1 UK emissions for various PM size ranges

	PM_{10}	$PM_{2.5}$	$PM_{1.0}$	$PM_{0.1}$
Combustion in energy production	19%	17%	14%	16%
Combustion in comm/inst/residential	19%	16%	18%	7%
Combustion in industry	10%	10%	7%	9%
Production processes	22%	16%	12%	3%
Road transport				
Diesel combustion	17%	26%	33%	49%
Petrol combustion	4%	7%	9%	12%
Tyre & brake wear	3%	2%	1%	1%
Other transport	2%	3%	4%	2%
Waste treatment & disposal	1%	1%	1%	1%
TOTAL (k tonnes/year)	163	100	74	30

The message from this table is that whilst combustion processes in road transport are an important contribution to the PM_{10} inventory, they become increasingly more important for smaller size fractions. Consequently, any move to regulate or set standards for smaller size fractions will lead to further pressure on road transport. It is noted that the principal contributor is the diesel fuelled fraction of the fleet which provides around 80% of the PM generated by road transport combustion for all size ranges.

It is concluded that in anticipation of future trends in terms of the pollutants specified and likely standards, an in-service test for petrol vehicles should aim to confirm that the emissions of CO, hydrocarbons (thence 1,3 butadiene and benzene) and NO_X remain acceptable. Recent changes in fuel specification mean that lead is no longer an issue. In contrast, because of its importance to air quality and possible changes in the metrics used, it is appropriate that this project consider the options for particulate measurement, specifically related to petrol vehicles that may be burning lubricating oil.

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[2] National Atmospheric Emissions Inventory: UK Emissions of Air Pollutants 1970 – 1998, Taken for the web site: http://www.aeat.co.uk/netcen/airqual/naei/annreport/annrep98/chap4_2.html.

2.2 AN OVERVIEW OF THE NATIONAL ATMOSPHERIC EMISSIONS INVENTORY AND THE CONTRIBUTION OF MOBILE SOURCES.

2.2.1 Introduction

This section of the report considers the National Atmospheric Emissions Inventory (NAEI) from road transport emissions, and the assumptions that are used to forecast future emissions. It is important to this project because it is the standard reference air emissions inventory for the UK and includes emission estimates for a wide range of important pollutants. This includes seven of the eight pollutants listed in the AQS, and for all the species specified in the type approval regulations (assuming road vehicle PM is equivalent to PM_{10}, and “hydrocarbons” are equivalent to non-methane volatile organic compounds). The NAEI was used to generate the inventory data discussed in the previous section. It also is the basis upon which the effectiveness of various in-service testing scenarios are quantified, to give the reduction in emissions in units of mass/year, and their context in terms of the overall emissions inventory.

The objective of the NAEI with regard to road transport is to quantify:

$$\sum_{\text{all vehicles}} \sum_{\text{all journeys}} \text{mass of pollutant emitted, } \textit{in a year.}$$

In practice this has to be achieved using a model. The fundamental methodology involves the combining of vehicle emission factors with traffic activity and fleet composition data. The fleet composition is subdivided into six broad classifications: cars, LGVs, rigid HGVs, articulated HGVs, buses and motor cycles. The first two of these are then further subdivided according to the type of fuel its engine runs on; petrol or diesel. Each of the eight resulting classifications is then further subdivided into different emissions standards as defined by successive EC directives, except the motor cycles, for which different regulations apply (Directives 97/24/EC and 2000/51/EC).

A single average emissions factor (expressed in grams of pollutant per kilometre driven) can be produced for each vehicle type and emissions class at each average speed for vehicles operating at their normal operating temperature. The total emissions for the pollutants NO_X, CO, benzene, 1,3-butadiene, methane, N_2O, PM_{10} and non-methane volatile hydrocarbons (NMVOCs) are then, to a first approximation, calculated by multiplying the emissions factors by the number of vehicle kilometres for each vehicle type and road type and summing.

The basic assumptions and methodology that are pertinent to this study on petrol fuelled vehicles and were used for the 1998 NAEI road transport emission projections are summarised in Appendix 3.

The model incorporates assumptions, often as sub-models, to take account of

- the degradation in emissions as vehicles age,
- the additional emissions that arise from vehicles when they start from cold and
- evaporative emissions from vehicles.

One aspect of particular significance to this project is that of “cold start emissions”. These when expressed as a fraction of the urban inventory from petrol fuelled vehicles, were calculated to be:

- NO_X	15.8 %
- PM_{10}	12.8%
- CO	54.1 %
- NMVOCs	26.9 %

i.e. contribute a significant proportion of the inventory.

2.2.2 The use of this model in this project

It can be assumed when assessing the effectiveness of various in-service emissions testing regimes that these will only affect the emissions factors (the mass of pollutants emitted per km driven). Therefore it is assumed that different in-service testing scenarios will have no impact on the fleet composition, or the traffic activity. Consequently, when quantifying the effectiveness of various in-service emissions testing regimes, the parameter that will be varied is the emission factors, to give a revised inventory, and therefore by subtraction from the base cases tabulated in Appendix 3B net changes in pollutant mass emitted per year can be computed.

It is also noted that the NAEI model used in this study is the same model that was used by the Cleaner Vehicle Task Force in its analysis.

3 Modelling the distribution of exhaust emissions

Key issues addressed in Chapter 3

The primary objective of this chapter is to develop a relevant mathematical model. This is achieved by:

- considering models that may be appropriate
- assessing the suitability of the available data sources
- developing a mathematical model of the distribution of exhaust emissions in the fleet,
- fitting it to pre-existing emissions data

3.1 INTRODUCTION

The purpose of this section of the study is to:

1. establish the emissions performance of the fleet
2. *estimate the number of catalyst equipped vehicles which are above the new vehicle emissions values (accounting for scatter on new vehicle emissions figures)*
3. *estimate the distribution of the excess emissions from these vehicles, e.g. what percentage of them are more than 25%, 50%, 100%, 200% etc above the new vehicle emissions level*

(Italics are used to identify phrases taken verbatim from the Customer's ITT.)

This information is a precursor to

- quantifying the effect of different levels of degradation on the AQS targets,
- identifying the reasons for excessive emissions
- evaluating the effectiveness of the current in-service test at identifying the excess emitters
- quantifying the "savings potential", and hence the cost effectiveness that a revised test might deliver
- providing some indications as to the proportion of the savings potential that revised tests might achieve.

It is appreciated that reality is not so simple.

3.2 APPROACH FOR QUANTIFYING WHAT VEHICLES ARE EMITTING – DEVELOPMENT OF A MATHEMATICAL MODEL

The ITT states: *It is envisaged that this task will require the development of a mathematical model which will need to take account of:*

- *the amount and proportion of the vehicle fleet whose emission performance has degraded,*
- *the impact of failing vehicles on National Air Quality Strategy objectives.*

Therefore, the approach adopted in this project is to use existing data to check/construct a mathematical model and then to use the model as the principal predictive tool. Further data, or data collection exercises would then be used initially to confirm the validity of the model and then to refine key parameters.

Despite extensive searching the author has been unable to find a validated model, or accepted methodology, in the literature. Therefore such a model is developed here.

Some desirable characteristics of the model are:

- it is statistically validated,
- the number of variables subsumed within it is as small as possible, i.e. it is a simple as practicable, and
- the variables can be related to physical observables, rather than abstract constants.

The following distributions were compared with the data available:

1. binomial distribution
2. multinomial and χ^2 distributions
3. normal distribution
4. Poisson distribution.

None of these common distribution functions provides a good representation of the real distributions. The principal mismatch occurs because of the asymmetric shape of the real data.

3.2.1 Log normal distributions

A distribution profile that is much closer, providing a good fit for many data, is the log normal distribution. This can be described as the normal distribution plotted on a logarithmic abscissa.

In a normal distribution the fraction of the whole population (δN/N) with values of property x between x and x+δx is given by:

$$\frac{\delta N}{N} = \frac{1}{\sqrt{2\pi}\sigma} \exp - \left(\frac{(x-\mu)^2}{2\sigma^2} \right) \delta x$$

where μ = the arithmetic mean value of x in the whole population, and
σ is a constant, the standard deviation of the population from the mean.

This distribution is often seen in a simplified form where the mean value, μ, is zero to give the formula for a gaussian error curve which is symmetric about the y-axis.

$$\phi(x) = \frac{1}{\sqrt{2\pi}} \exp - \left(\frac{x^2}{2} \right)$$

In the log normal distribution x is replaced by log(x), to give

$$\phi(\log x) = \frac{1}{\sqrt{2\pi}\sigma} \exp - \left(\frac{(\log(x) - \mu)^2}{2\sigma^2} \right)$$

Figures 3 and 4 show illustrative graphs of this function, with μ = 1.0 and σ = 1.5. In Figure 3 the value of x is plotted on a linear axis, whilst in Figure 4 it is plotted on a logarithmic axis, demonstrating the function's relationship with a gaussian. The axes of both graphs are labelled emissions in g/km, and fraction of the population because these units are relevant to this study.

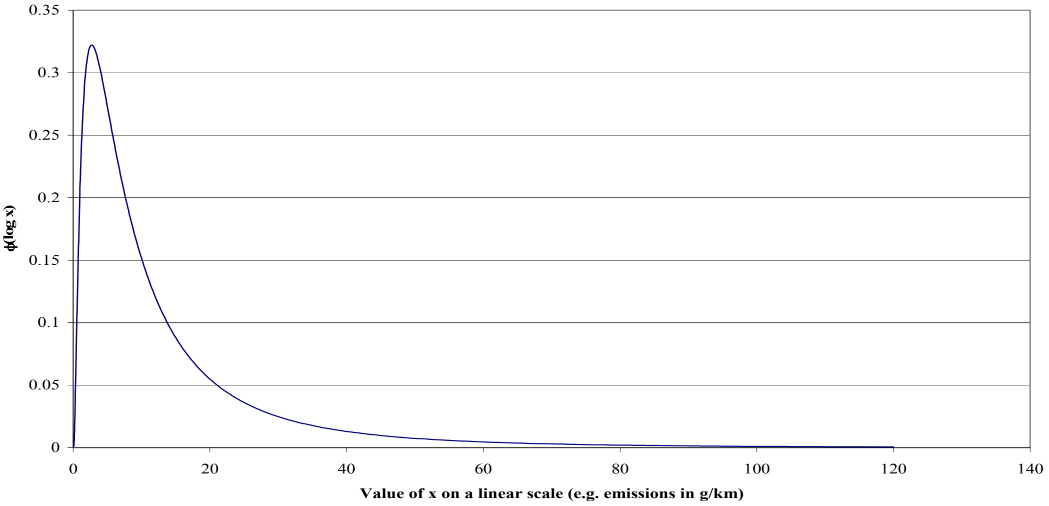

Figure 3 Graph of log normal function, with μ = 1.0 and σ = 1.5 plotted on a linear axis

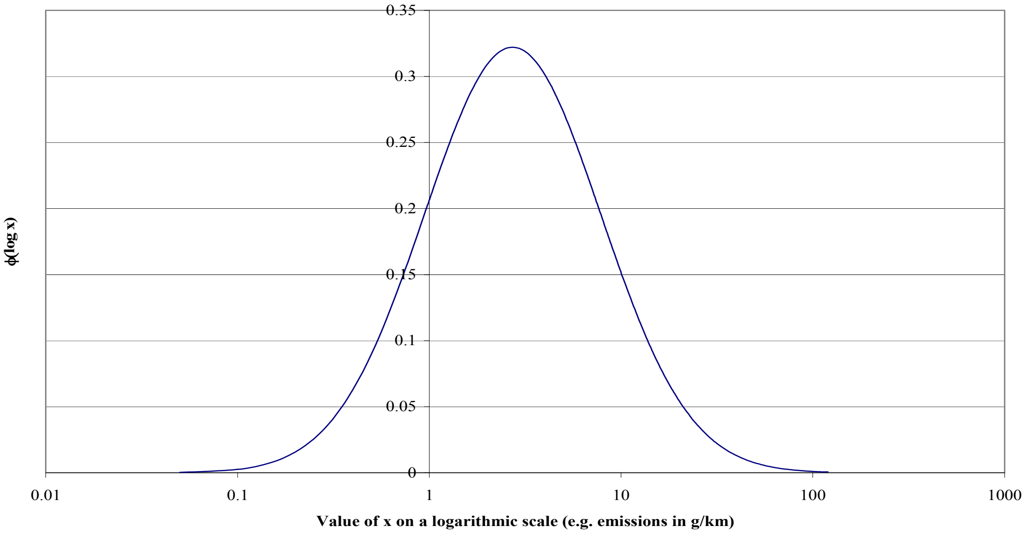

Figure 4 Graph of log normal function, with μ = 1.0 and σ = 1.5 plotted on a logarithmic axis

Having defined a distribution function using the log-normal model, the data can be further manipulated. For each emissions level (g/km) given the fraction of the population emitting at this level, the emissions from this fraction of the population is the product of the two. These products can be summed to give an accumulating value of emissions, which can be expressed as a percentage of the whole. When this parameter is plotted against the emissions level (in g/km), a graph as illustrated in Figure 5 is formed. The EU Joint Commission study (JCS) presented some of its data in this form, see for example Figure 7 reproduced from the JCS Main Report.

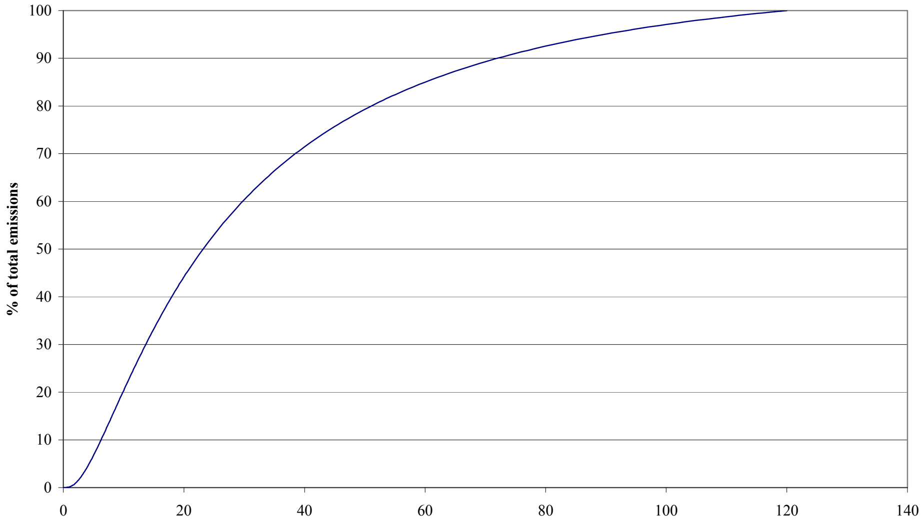

Figure 5 Accumulating value of emissions plotted against emission levels

The fraction of the population emitting at a particular level can also be summed and expressed as a percentage of the whole population. When the cumulative emissions (as a %) is plotted against this parameter a graph as illustrated in Figure 6 results. The JCS study presented some of its data in this form also, see also Figure 7 reproduced from the JCS Main Report.

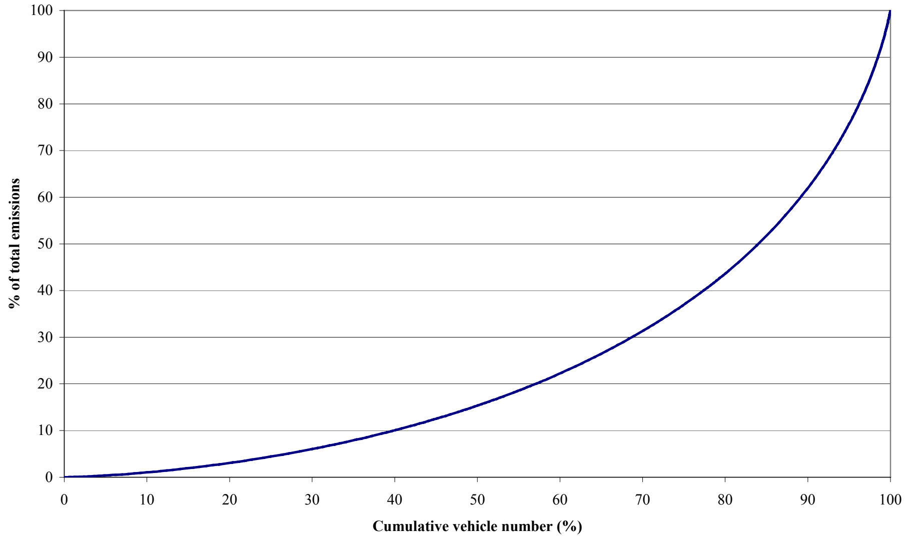

Figure 6 Cumulative emissions plotted against the fraction of the population emitting at a particular level

Fitting the model to experimentally determined data is the reverse of the process described. It requires the experimental data to be digitised, e.g. data in the format of either Figures 5 or 6, and then superimposing calculated data. The values of the model's two parameters (the mean and standard deviation) are then varied such that a best fit is obtained. This fitting can be achieved using a least squares fitting algorithm or by eye. The latter is useful if it is found that no ideal fit can be obtained and one wishes to use one's judgement to define the "best fit". In this work both approaches were used.

3.3 REVIEW OF DATA SOURCES AVAILABLE

This section reviews the available datasets against which to fit the model.

In general there are three types of source data that are available, and a fourth that might be available, that might be appropriate for this study. These are:

- the JCS study on in-use car I&M,
- the DTLR's rolling programme of emissions factor generation for the NAEI,
- the German in-use compliance programme
- various other in-use compliance programmes both within Europe and in the US.

The two principal criteria on which the potential quality of data can be judged are the drive cycles over which it was collected and the size and method of selection of the vehicles sampled.

3.3.1 The JCS study on in-use car I&M

This study was funded by three of the European Commission's Directorate Generals (DG VII, XI and XVII). It title, *the inspection of in-use cars in order to attain minimum emissions of pollutants and optimum energy efficiency* describes its principal objectives. A range of cars were tested, which included 192 cars fitted with TWCs. Testing was undertaken principally during 1995 – 1997.

Two distinct sample populations were tested. The first was known as the **Random** (JCS nomenclature) sample and comprised 135 vehicles that were offered for testing by owners. (The owners would have been aware of why the testing organisations wished to borrow their vehicles.) The JCS study comments "despite the fact that the sample is considered as random, it has to be stressed that there is a certain bias, due to the voluntary participation in the test programme; in general, owners of well maintained cars are suspected to have a higher willingness to participate in such tests.

The second sample population is referred to as the **Total** sample and comprised the 135 vehicle from the random sample **plus** a further 57 vehicles selected from vehicle groups where high emitters can be expected, e.g. high mileage vehicles and high emitters as detected by remote sensing (of CO, HC and NO). These additional 57 vehicles were acknowledged to have unrepresentatively poor emissions performance.

Therefore the emissions distribution of a truly representative sample probably lies somewhere in between the emission distribution of the two sample groups.

All vehicles were tested over a number of long cycles, including the NEDC, and a range of short cycles, including the current two speed idle test. The results from the latter tests are discussed in the next chapter. The data is attractive for this study because:

- it contains emissions over the NEDC
- it is reasonably contemporary
- the sample size is moderately large, and
- the method of sample selection has been carefully considered such that two data sets exist, most probably bracketing the emissions performance of the fleet as a whole.

3.3.2 The DTLR's rolling programme of emissions factor generation

The latest batch of data from this programme has kindly been supplied by DTLR's VSE2 Division.

The latest set of data was obtained from 5 vehicles, 2 diesel and 3 petrol (with TWCs) fuelled vehicles. Not only is this sample small, but it is believed to be unrepresentative because the very purpose of testing these vehicles (to obtain emission factors for the NAEI model) means that a poorly maintained excess emitter would be rejected as inappropriate for testing.

The data collected was for steady state driving, i.e. hot start, driving at 90 and 113 km/hr, evaluating the effects of:

- ambient temperature – vehicles were tested at –7°C, 7°C and 25°C;
- running on standard and low sulphur fuel; and
- turning the air conditioning on at 25°C ambient temperature.

Whilst these data are valuable for developing the model for which they were collected, they are not relevant to defining the distribution of emissions performance of the fleet as a whole over the type approval regulatory cold start cycle.

3.3.3 The German in-use compliance programme

The objective of this programme is to establish whether or not the emissions performance of "new" vehicles remains within EU defined limits of the revised type approval standard as they accumulate miles; the in-service compliance aspect of the directive. Importantly, it is the emissions of vehicles maintained according to the manufacturers specifications that are assessed as part of the enlarged type approval specification, as detailed in directive 98/69/EC (an amendment to directive 70/220/EEC).

AEA Technology has been provided with a report on in-use compliance testing by the UBA[3]. This report, which is in German, contains information on 34 vehicles, taken from 10 specific models. The vehicles were tested over both the relevant type approval drive cycle (ECE+EUDC) and the in-service two speed idle test. Emissions data is presented for each vehicle. None of the vehicles had high (more than twice) the type approval emissions standard, although several were outside the in-use compliance standards. The author is not aware of the

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[3] Report kindly supplied by W Niederle, UBA, report issued by RWTÜV, author Helge Smidt, 14 February 2001, in German.

details of the vehicle selection procedure, however, as noted earlier what should be tested are appropriately maintained vehicles.

The above German in-use compliance data can be compared with the data from the JCS study. For the latter 60% of the cumulative CO emissions from the “Total” sample were generated by the worst 10% of the sample, and it is recognised that the emissions from the “Total” sample are poorer than would be expected from the fleet as a whole. The former studied only 34 appropriately maintained vehicles. Given that it would probably be inaccurate to describe the worst 10% of vehicles in the fleet as appropriately maintained and the size of the sample, it is not too surprising that no high excess emitters were found in the German study. However, another plausible hypothesis that is not eliminated by these data is that generally levels of emissions degradation have reduced between the two studies.

Overall, it is felt that the data in the UBA report is generally consistent with the JCS findings. It is acknowledged that the sample size is significantly smaller, and that the degree of maintenance is above average. Consequently, this data was not used as the basis for fitting the model.

3.3.4 Other in-use compliance programmes

Summary information from the Swedish in-use compliance assessment programme has been forwarded by DTLR’s VSE2 Division. This is much more extensive than the German data, containing emissions results for around 100 different models, which involved testing around 450 vehicles.

The data available to date, however, is of **average** emissions for each model. This smoothes out individual very high emitters, reducing the extreme value by around a factor of 3 to 6 (dependent on the number of vehicles of that model that were tested). The comments made in the previous section regarding the selection of vehicles for the German in-use compliance programme apply equally here – it is very likely that the vehicles tested were “above average” with regards to their level of maintenance, and below average with regards to their emissions.

These data were not fitted to the distributions.

3.4 MODELLING OF THE JCS DATA

In this section the log normal distribution model, as described in Section 3.2 will be fitted to the JCS data. The key data in the JCS Main Report are contained in Figures 13 to 15 of the JCS report, where data from both the “Total” and “Random” groups are given before and after maintenance. These figures are reproduced as Figure 7 of this report to aid the reader. The data are presented as percentage cumulative emissions against cumulative vehicle number (expressed as a percentage) and percentage of total emissions against emissions in g/km. The predictions from the model can be manipulated to generate data in this form.

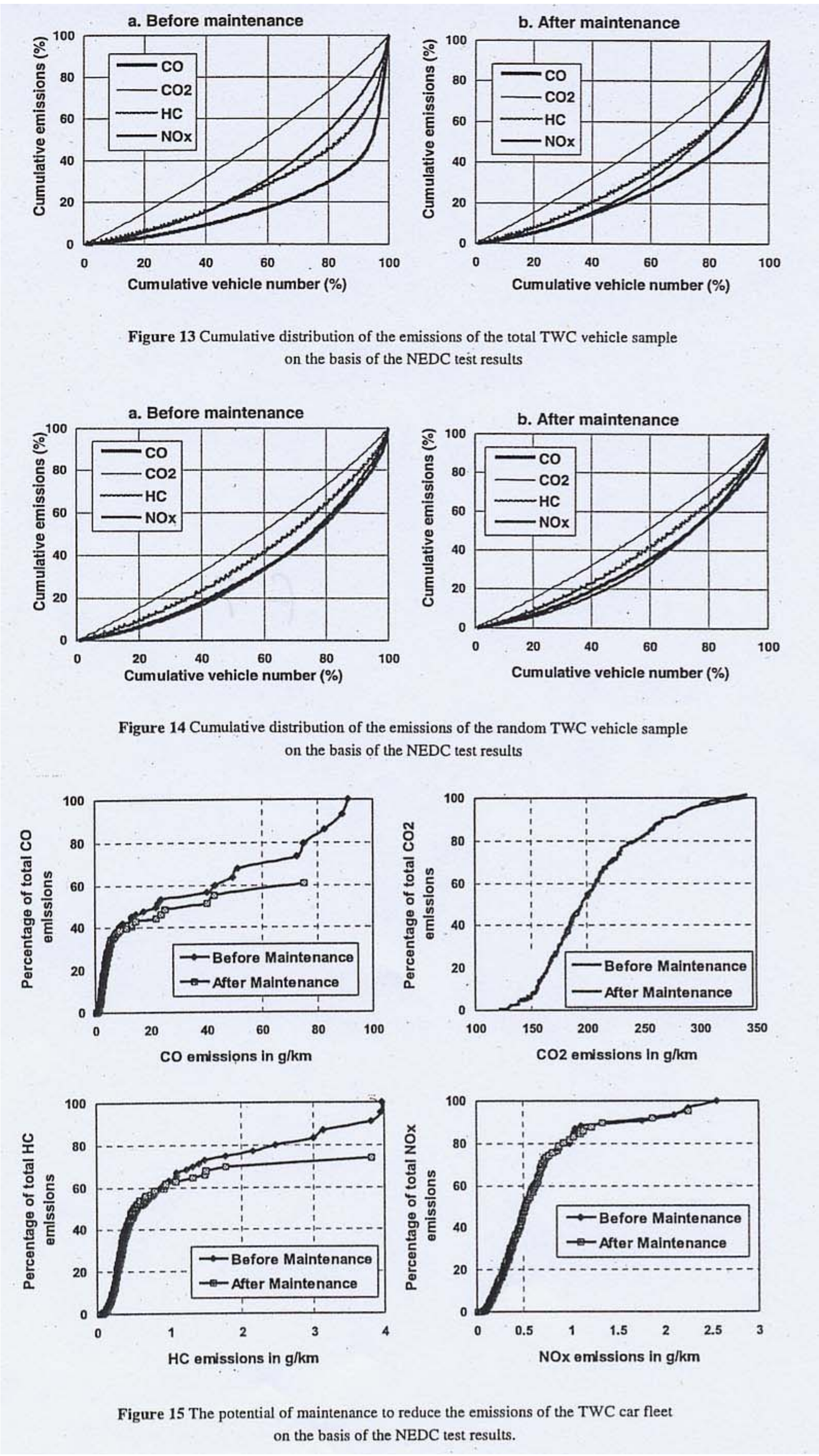

Figure 13 Cumulative distribution of the emissions of the total TWC vehicle sample on the basis of the NEDC test results

Figure 14 Cumulative distribution of the emissions of the random TWC vehicle sample on the basis of the NEDC test results

Figure 15 The potential of maintenance to reduce the emissions of the TWC car fleet on the basis of the NEDC test results.

Figure 7 Figures 13, 14 and 15 of the JCS Study main report

3.4.1 Oxides of nitrogen

Figure 8 shows a fit of the model to the JCS experimental data for the “Total” sample. The values of the mean and standard deviation parameters within the model are given in Table 2. Also included in the table is an indication of the error for the parameters. This was obtained semi-quantitatively by noting the range of values for the parameters before the fit deteriorated from good to moderate (as judged by eye).

Figure 8a, Percentage of total NO_X emissions for cumulative vehicle number

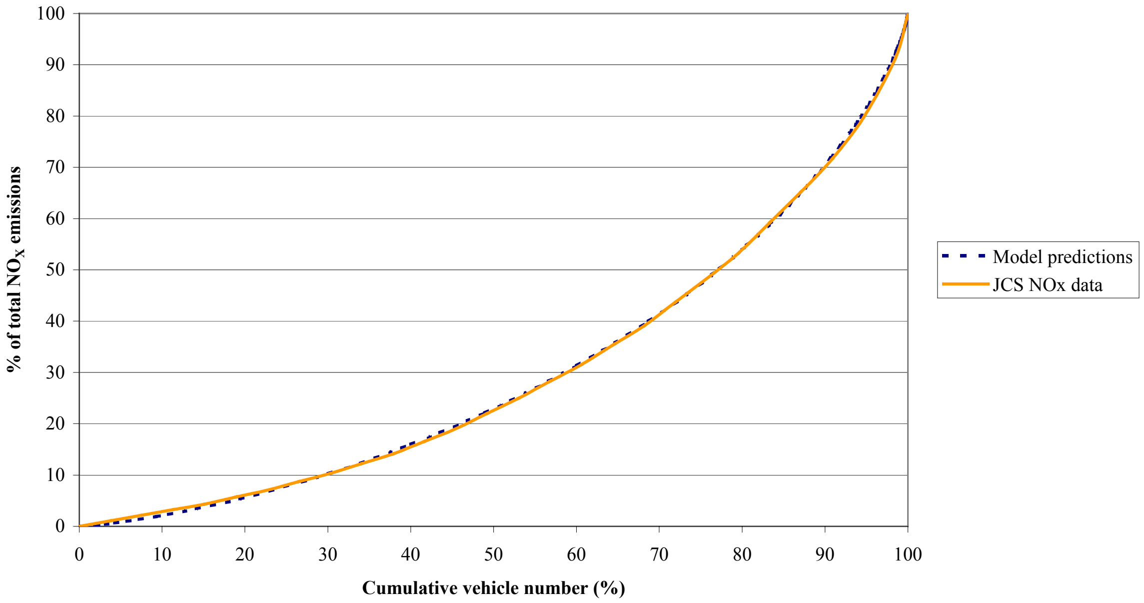

Figure 8b, Percentage of total NO_X emissions against vehicular emission rate

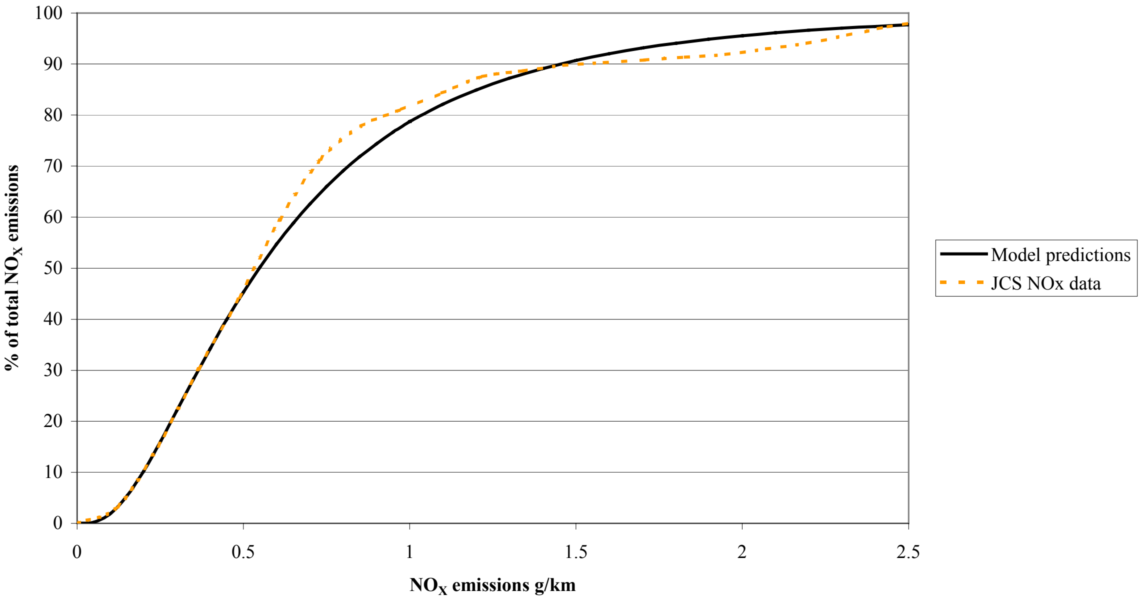

Figure 8 Fitting of the model to the JCS NO_X data

Table 2 Parameters used in the log normal model to reproduce the JCS data

	mean	standard deviation
Oxides of nitrogen	0.192 ± 0.01 g/km	1.05 ± 0.05
Hydrocarbons	0.22 ± 0.03 g/km	1.0 ± 0.1
Carbon monoxide – "Total" sample	2.7 ± 0.2 g/km	1.5 ± 0.2
Carbon monoxide – "Random" sample	2.7 ± 0.2 g/km	0.95 ± 0.05
Carbon dioxide	183 ± 5 g/km	0.30 ± 0.03

From Figures 13 and 14 of the JCS report it is seen that for NO_X there was little difference between the emissions distributions from the "Total" and "Random" samples and therefore a single set of parameters for the model reproduced the emissions from both samples. Similarly, from JCS Figure 15 it is apparent that maintenance of the "gross polluters" led to little change in NO_X emissions (around 5% and selectively for only the very worst emitters. Both these observations imply that NO_X emissions, like CO_2 emissions, are affected only very little by the state of maintenance of the vehicle.

3.4.2 Hydrocarbons

The experimentally determined emissions from both the "Total" and "Random" samples are plotted in Figure 9 together with a fit using the model. Parameters were selected for the model that gave a distribution profile intermediate between the two sample groups, and these are given in Table 2.

Figure 9a, Percentage of total hydrocarbons emissions for cumulative vehicle number

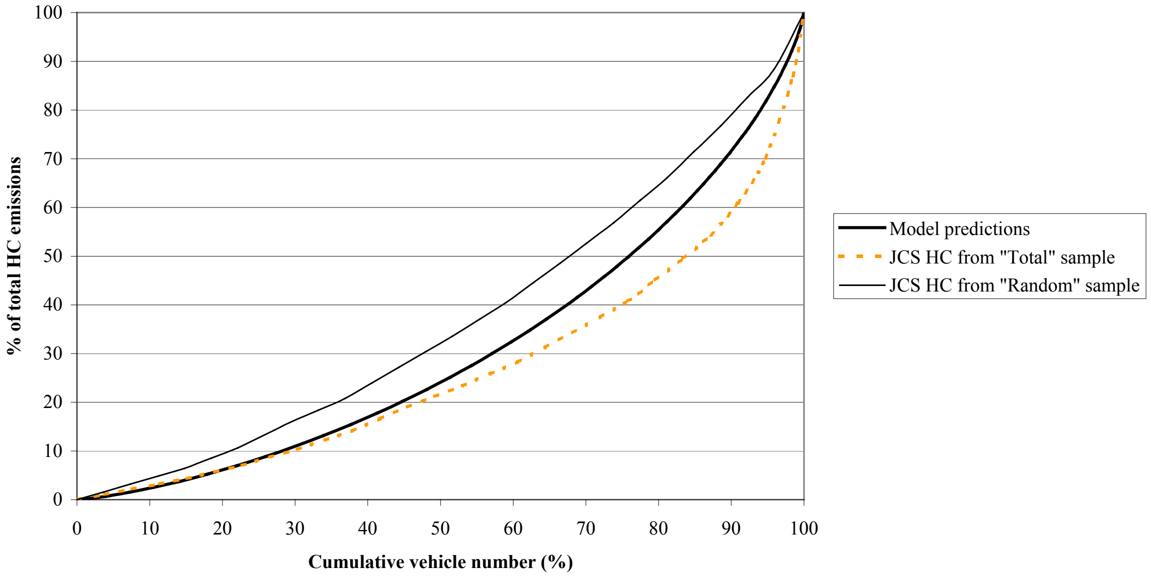

Figure 9b, Percentage of total HC emissions against vehicular emission rate

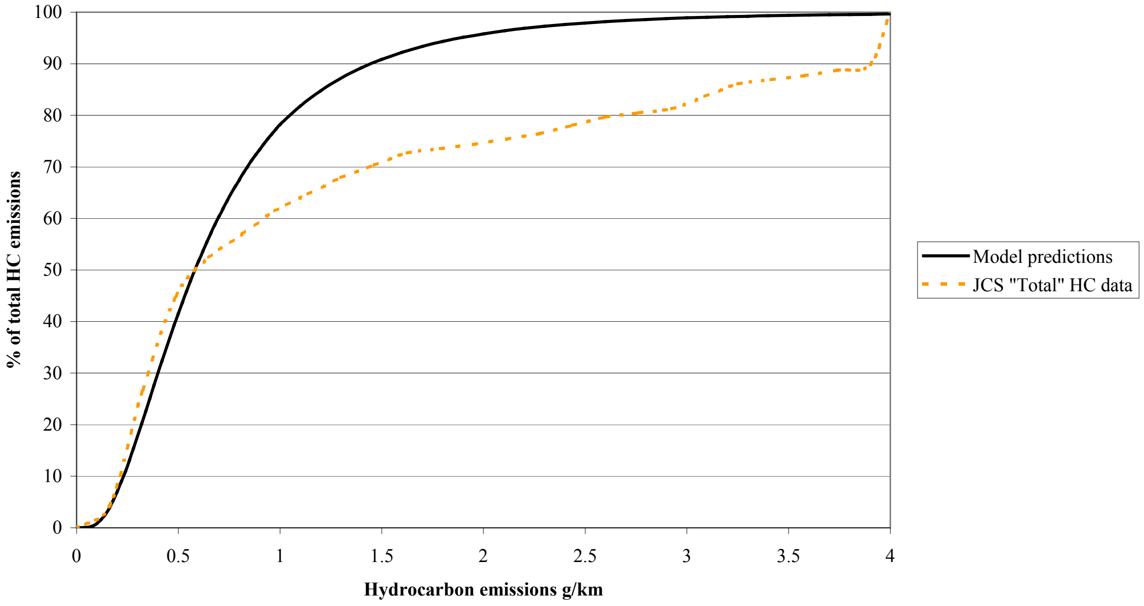

Figure 9 Fitting of the model to the JCS HC data

It was possible to select parameters for the model that accurately reproduced the emissions from the JCS study's "Random" sample, and moderately reproduces the emissions from the "Total" sample. However, because the model is used later in this report to compute the number of excess emitter vehicles and the accompanying emissions savings potential, a single distribution was selected to give a reasonable representation of the likely hydrocarbon emissions from the UK catalyst car fleet as a whole.

In Figure 9b the model's predictions are compared with what was reported by the JCS, in their Figure 15, for the "Total" sample only. Given the relationship between the model and the two experimental data sets the model is somewhat underestimating the number of highest emitters relative to that observed for the "Total" sample. This will have the effect of reducing the total emissions inventory predicted by the model relative to the observed data. When the vehicle emission rate (g/km) is then plotted against the percentage of total emissions a systematic error occurs with the model data lying to the right of the experimental data, as plotted, for the lowest emissions levels and then to the left when the emissions from the larger number of experimentally observed higher emitters are included. This is exactly what is observed.

On balance it is felt that the model is reproducing the experimental data moderately well.

3.4.3 Carbon monoxide

The largest difference between the "Total" and "Random" sample distributions occur for CO. This in itself implies that this pollutant is the most sensitive to the state of maintenance of vehicles. For this reason it is difficult to confidently state how far between the two the distribution of the UK catalyst car fleet lies, as a whole.

Figure 10 shows the two experimentally determined distributions together with a model for the data that lies some where between the two. The values for the model's parameters are given in Table 2. Generally the fit can be at best described as moderate.

A fit to just the "Random" sample's data is also shown in Figure 10a. This was obtained by merely varying the standard deviation parameter, i.e. keeping the mean emissions rate constant. In this case the fit can be described as good. The model's predictions compared with the emission distribution when plotted against % of total emissions, Figure 10b, is moderate to poor. The same systematic variations that applied to the modelling of the hydrocarbons data also apply to, and are observed with, this data.

These two distributions should be regarded as a lower limit for the number of excess emitters (the "Random" sample) and a more likely, but possibly high, limit of the number of excess emitters. When evaluating the cost effectiveness of an in-service scheme, see Chapter 7, both these distributions are used to provide a measure of the uncertainty involved when computing the CO emissions savings potential.

The good agreement between the model's predictions and the "Random" sample indicates that this sample can be accurately described by a log normal distribution function. However, the generally only moderate agreement between the model's predictions and the "Total" sample's CO emissions indicates this is not the case for the "Total" sample. This most probably arises because the selection methodology for the "Total" sample leads to a high fraction of very high emitters, more than is in the fleet as a whole, and more than the simple log normal distribution predicts. Further, because the data in the JCS study reports are always presented using cumulative emissions, or percent of total emissions, this high fraction of very high emitters distorts the scaling of the y-axis. This distortion, in turn, further emphasises the difference.

Figure 10a, Percentage of total CO emissions for cumulative vehicle number

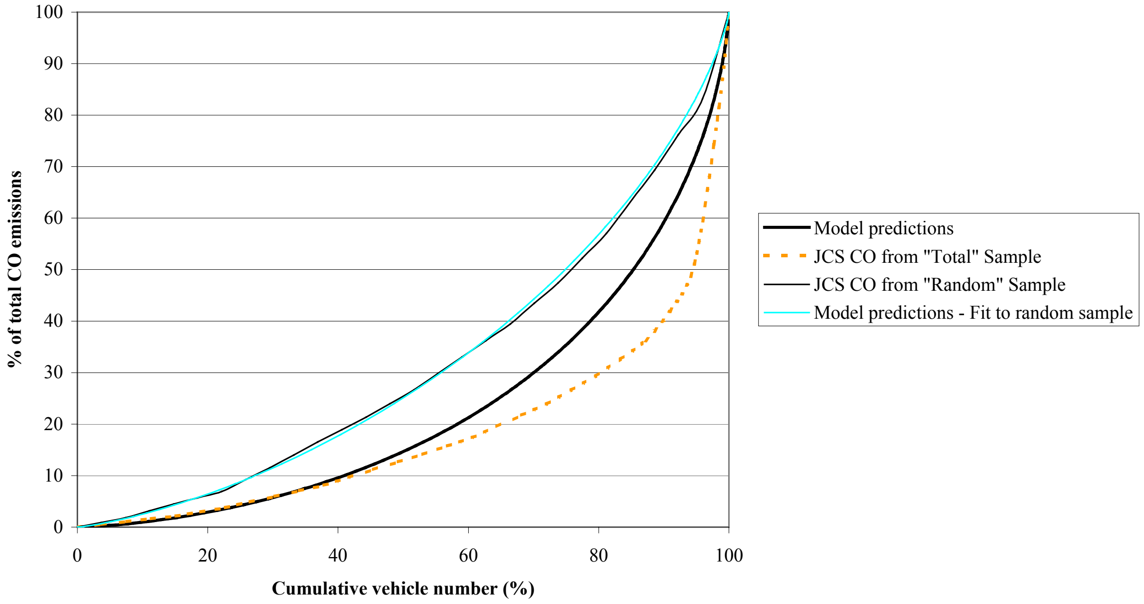

Figure 10b, Percentage of total CO emissions against vehicular emission rate

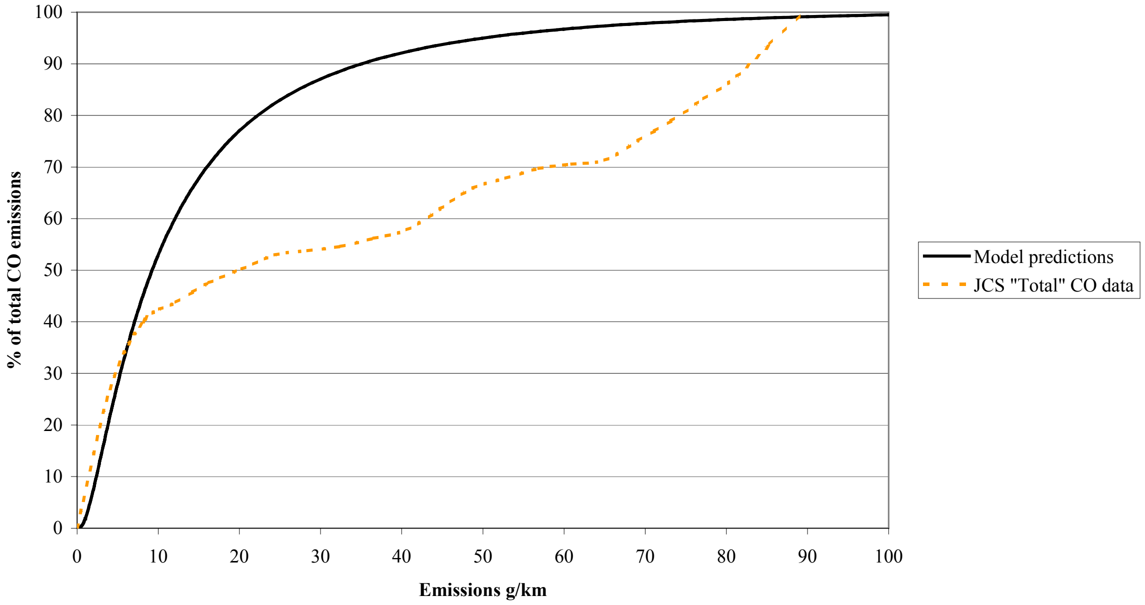

Figure 10 Fitting of the model to the JCS CO data

Overall, it is felt that the model is providing a useful descriptive tool for the data reported in the JCS study. Consequently, it is a potentially useful predictive tool, with the quality of fit to experimental data providing an estimate of the robustness of quantitative predictions.

3.4.4 Carbon dioxide

The JCS CO_2 data was also fitted to the model, although this parameter is not directly relevant to this study. The details are given in Appendix 4. It is interesting to note that for this atypical component of the exhaust emissions good agreement between the model and experimental data was obtained.

3.4.5 Summary of modelling

A log normal model has been applied and was found to be a moderate to good fit to the data obtained from the JCS study depending on the pollutant. For carbon monoxide the JCS data showed a large difference between the "Total" and "Random" samples. It is believed that the distribution of emissions from the whole fleet lies somewhere between the two JCS distributions.

4 Definition of an “excess emitter vehicle and significance of vehicles with deteriorated emission performance

Key issues addressed in Chapter 4

This chapter builds on the mathematical model developed in the previous one. Its primary focus is to derive a definition for the excess emitter vehicles and to assess the importance of these to the emissions inventory by using the model to calculate the emissions from the excess emitters. This augmented by considering the degradation mechanisms that lead to a vehicle becoming an excess emitter.

4.1 DEFINITION OF AN EXCESS EMITTER

The principal parameter when quantifying the degradation of emissions performance is the change in what vehicles actually emit into the environment and its impact on human health and the environment.

Regulatory emissions measurements, made on an elderly vehicle fitted with closed loop fuelling control and a TWC, illustrate some of the complexities involved. The vehicle had travelled around 125,000 miles (200,000 km), and was approved to 91/441/EEC. Emissions were measured with the vehicle in three configurations:
1. with a new replacement catalyst fitted
2. with the vehicle fitted with its original catalyst, and
3. with an empty catalyst casing replacing the catalyst.

The vehicle was tested over three different drive cycles:
a. a directive 98/69/EC defined type approval cycle (the NEDC),
b. the NEDC cycle but with the vehicle started when its oil temperature was already at its operating temperature, i.e. around 85°C, instead of soaked for at least 12 hours at ambient temperature as in test a), and
c. at a steady 120 kph, when all temperatures were stable.

The CO, HC and NO_X emissions are given in Table 3.

Table 3 Emissions of vehicle with variable catalytic activity over various drive cycles

Cold start NEDC			
all emissions expressed as g/km	CO	THC	NO_X
Vehicle fitted with **New** catalyst	2.827	0.303	0.089
Vehicle fitted with **Original** catalyst	4.638	0.315	0.224
Vehicle fitted with **No** catalyst	8.646	0.519	1.261
Hot start NEDC			
all emissions expressed as g/km	CO	THC	NO_X
Vehicle fitted with **New** catalyst	0.206	0.013	0.075
Vehicle fitted with **Original** catalyst	2.038	0.086	0.195
Vehicle fitted with **No** catalyst	7.115	0.534	1.192
Hot steady 120 kph			
all emissions expressed as g/km	CO	THC	NO_X
Vehicle fitted with **New** catalyst	0.018	0.01	0.063
Vehicle fitted with **Original** catalyst	0.062	0.01	0.104
Vehicle fitted with **No** catalyst	6.107	0.332	3.213

MOT emission measurements					
	Normal idle speed		Fast idle speed		
	CO (%)	THC (ppm)	CO (%)	THC (ppm)	Lambda
Vehicle fitted with **New** catalyst	0.002	7	0.001	6	1.005
Vehicle fitted with **Original** catalyst	0.005	16	0.174	15	1.010
Vehicle fitted with **No** catalyst	0.534	63	0.495	24	1.000

An in depth analysis of these data is not appropriate but some comments pertinent to the current project illustrate some important issues. The data are of interest because they are a series of controlled experiments where two parameters are varied: catalyst activity and the test cycles. In terms of the vehicle catalysts the brand new and no catalyst are two extremes with the original catalyst intermediate between these.

For the new catalyst the cold start NEDC gives significant CO and hydrocarbon emissions because of the over-fuelling required for cold starting, see Section 2.2.1 and the catalyst not up to its operating temperature. In contrast, the hot start NEDC give much lower emissions of both because no over-fuelling occurs, and because the catalyst operates effectively from the start of the cycle. Similarly, 120 kph steady state driving leads to very low emissions.

For the original (an aged) catalyst, the CO and hydrocarbon emissions caused by over-fuelling are expected to be the same as when the new catalyst was fitted (it being the same vehicle). The additional emissions arise from the longer time it takes the original catalyst to reach a temperature at which it converts virtually all CO to CO_2. This phenomenon is seen again over the hot start NEDC cycle, where the emissions for the vehicle fitted with the original catalyst arise principally from the time it takes for the catalyst to reach a temperature where it oxidises the CO, the new catalyst doing this virtually from the start of the cycle.

In contrast, at a steady 120 kph, both catalysts give negligible CO, hydrocarbons or NO_X emissions, especially with respect to when no catalyst was fitted. This is because under these conditions both the new and original catalyst are at a sufficiently high temperature (known colloquially as the "light-off temperature" or "being lit") to efficiently destroy the pollutants present. Therefore despite the large volumes of exhaust gas being produced, emission values are low. Whilst the data presented here are for 120 kph steady state driving, data at idle, 30 kph, 70 kph and 90 kph follows this trend also.

The data for the MOT test, the unloaded engine at normal or fast idle, also follows the pattern of both catalysts giving similar emissions, especially with respect to when no catalyst was fitted.

To summarise, the reduction in catalyst efficiency is only apparent at intermediate "conditions": When the catalyst is either cold or very hot its activity is very similar to that of a new catalyst.

The findings that low idle, high idle and 120 kph measurements do not show large changes between the new and old catalysts, but the cold, or hot, start NEDC does demonstrate an important shortcoming of the current in-service test, and provide guidance on how it might be improved:

- steady state testing under no load is not effective at monitoring catalyst activity, and
- making the catalyst work harder by testing under load at a steady state is also ineffective at evaluating catalyst activity.

It must be emphasised that what is being stated here is that **the current test is very poor at assessing catalytic activity**. However, loss of catalytic activity is only one of several faults that cause changes in emissions, see Section 4.2.2. Further, the current in-service test is found to be better at identifying the majority of other faults, see the table at the end of Section 5.3.6. It is this ability to detect other faults that leads to the assessment that the current test is performing moderately, and is providing a positive contribution to improving air quality.

From Table 3 the type approval test cycle when the vehicle was fitted with a new catalyst gave emissions that met the limit values specified in directive 94/12/EC (after making due allowance for the change in test cycle, which the Vehicle Certification Agency give as being 30%), see below:

Table 4 Limit values for emissions from passenger cars as specified in directives 94/12/EC and 98/69/EC Stage A

	CO	HC	NO_X	$HC+NO_X$
94/12/EC standard for ECE+EUDC	2.2 g/km			0.5 g/km
Inferred 94/12/EC standard over NEDC	3.28 g/km			0.5 g/km
98/69/EC Stage A standard for NEDC	2.3 g/km	0.2 g/km	0.15 g/km	0.35 g/km

From this we can conclude that in terms of emissions the vehicle was well maintained and running close to its specification. When compared to the emissions measured when no catalyst was fitted, it is also apparent that for all pollutants the catalyst is having an advantageous effect.

The performance of a catalyst can be expressed in a number of ways: e.g. as a change in the emissions, in absolute terms, relative to some standard, or as a percentage of its effect relative to their being no catalyst present.

If E_1, E_2 and E_3 denote the emissions of a pollutant from the vehicle for the configurations 1 to 3 listed above, then two measures of performance are:

- performance of old catalyst relative to a new catalyst = E_2/E_1
- performance of old catalyst relative to a no catalyst = E_2/E_3.

The first definition is usually adopted with E_1 being an emissions standard.

Over the 98/69/EC defined type approval cycle (NEDC) the CO emissions of the vehicle when fitted with the original catalyst are 1.64 times the CO emissions from when the vehicle is fitted with a new catalyst, i.e. the aged catalyst has caused emissions to increase by 64%. However, for the hot start NEDC test the original catalyst leads to 9.9 times the CO emissions from the new catalyst, an 890% increase. As explained earlier this is attributed to the original catalyst requiring some time to reach its operating temperature, whereas the new catalyst converted efficiently from the start of the test. At the steady speed of 120 kph CO emissions show a 245% increase.

If the effect of the original catalyst is expressed as a percentage of the total emissions (measured when no catalyst was fitted), then it consumes:

for the type approval test 46.4% of CO emissions
for the hot start NEDC test 71.4% of CO emissions, and
at a steady 120 kph 99.0% of CO emissions.

On the basis of this information is this vehicle, when fitted with its original catalyst an excess emitter?

Whilst the answer should be a simple yes or no, one would be forgiven for saying yes in response to some data and no in response to other data. **The variable rates of emissions degradation for different drive cycles** are an important, fundamental finding. This impacts on both the definition of an excess emitter, and the efficacy of different testing procedures at identifying them.

The definition of an excess emitter adopted by this project is to use that embodied in the "in-service compliance" portion of the amending EC directive 98/69/EC to directive 70/220/EEC. Some reasons/justification for this adoption include:

- it is building on the collective wisdom of many interested parties
- it is the "accepted" degradation rate used within the EU
- it is based on absolute emissions, measured in g/km, contributing directly to the nation's atmospheric emissions inventory, and
- it is measured over a cold start loaded cycle, simulating some urban driving where the impact of emissions on air quality to human health is most sensitive.

Therefore, **a vehicle is an excess emitter if its CO, HC or NO_X emissions are outside those of the European standard that applies when measured over the 98/69/EC specified type approval drive cycle (the NEDC) after due allowance has been made for degradation at the rate of an additional 20% for each 50,000 miles (80,000 km) that the vehicle has been driven.**

This is exactly equivalent to the 1.20 degradation factor for all three regulated pollutants that is written into directive 98/69/EC.

On this basis, for the vehicle tested because it had travelled 200,000 km, the degradation factor to apply is an additional 50% (20% x 200/80) to the revised 94/12/EC limit values standards given in Table II of the directive. This gives:

	CO	HC	NO_X	$HC+NO_X$
Inferred 94/12/EC limit values for NEDC	3.28 g/km			0.5 g/km
Inferred 94/12/EC limit values + 50% degradation	4.875 g/km			0.75 g/km
Actual emissions	4.64 g/km	0.32 g/km	0.22 g/km	0.54 g/km

On this basis the vehicle when fitted with its original catalyst and tested over the NEDC, **this vehicle is not an excess emitter!** However, if the vehicle were assessed over a hot start NEDC relative to the performance of a new catalyst it would be viewed as an excess emitter. The explanation for this being that on a hot start test a new catalyst very rapidly reaches a temperature at which it efficiently oxidises CO, whereas the old catalyst is slower to do so.

There is a further issue involved in deciding whether or not an individual vehicle is an excess emitter. This arises because the EC directives consider a vehicle type as a whole. (Initially a single "representative" vehicle of each type is tested before an approval is issued. The CoP and in-service compliance testing use statistical sampling, once vehicles are in production, to demonstrate compliance. This testing is conducted by the manufacturer and the results are audited by the approval authority.) Consequently, only a small fraction of the vehicles produced are tested and not all the vehicles tested have to meet the limits, merely a sufficiently high proportion have to be sufficiently below the limit. In contrast, in-service testing considers each vehicle individually. Consequently, it is possible for a brand new vehicle of a make that is type approved, to never meet the type approval limit values. If the in-service test exactly matched these limit values this vehicle would, therefore, fail in its "showroom" condition. Exactly the same dilemma occurs when defining an excess emitter because, like the in-service test, individual vehicles, rather than the ensemble, are measured against limit values.

4.1.1 Calculation of the number of excess emitters in the fleet

In the previous chapter we have defined the basis for a mathematical model of the fleet's emissions distribution (Section 3.2), and fitted the model to the JCS study's data (Section 3.4). In the first section of this chapter we have derived a definition for an excess emitter. These are now to be combined such that the model is used to calculate the number of excess emitters. However, whilst it is the model that is used for these calculations, the model's parameters are those chosen that gave a good fit to the JCS data. Consequently, the data from the JSC study, though not being used directly, is intimately linked to the results obtained.

It is noted that the majority of vehicles tested in the JCS study complied with directive 91/441/EEC, rather than the more recent 94/12/EC directive. This is not too surprising given the dates the two standards were introduced and the date of the study. Therefore the "standard that applies" in the definition will be taken as that specified by directive 91/441/EEC.

The limit values given in the directive 91/441/EEC for the ECE + EUDC test are (see in Appendix 1):

CO 2.72 g/km HC + NO_X 0.97 g/km.

What is required in order to relate these data to JCS study data is the equivalent limit values for directive 91/441/EEC over the NEDC.

Considering CO first: it is generally accepted that 98/69/EC CO limit value over the NEDC represents a 30% reduction over the 94/12/EC limit.
Given the former is 2.3 g/km CO, then the latter is simply:

$$94/12/\text{EC limit values over NEDC} = 2.3 \times \frac{100}{100-30} \text{ i.e. } 3.28 \text{ g CO/km.}$$

The 91/441/EEC and 94/12/EC CO limit values are 2.72 and 2.2 g CO/km, respectively.

$$\text{Therefore the } 91/441/\text{EEC CO limit value over the NEDC} = \frac{2.72}{2.20} \times 3.28 \text{ g CO/km, i.e. } 4.06 \text{ g/km.}$$

Moving on to consider hydrocarbons and NO_X:
for 98/69/EC Stage A and B the ratio of HC:NO_X is 56.5%:43.5%.

Using this same proportion the 0.97 g/km HC + NO_X 91/441/EEC limit values are sub-divided into 0.55 g/km HC and 0.42 g/km NO_X.

The reduction in HC and NO_X limit values between directives 94/12/EC and 98/69/EC Stage A appear more severe, since there is a reduction of 30% (from 0.50 to 0.35 g/km for the sum of the two) **before** any difference in the effect of changing the drive cycle is included. It was seen that the 30% reduction for the CO standard is predominantly due to the change in drive cycle and the sensitivity of CO emissions to cold start conditions. In section 2.2.1 the contributions of cold emissions, expressed as a fraction of the urban inventory were calculated to be:

NO_X 15.8% CO 54.1% and NMVOCs 26.9%.

A pro rata scaling of the 30% cold start contribution for CO on going from the ECE+EUDC to the NEDC gives the following cold start contributions:

NO_X +9% CO +30% and NMVOCs +15%.

These figures are taken as the reduction in emissions caused by changing the drive cycle, and are compounded with the change given in g/km. Thus the 91/441/EC limit value for the ECE+EUDC standard need to be increased by these amounts, i.e.

$$91/441/\text{EC NMVOC limit values over NEDC} = 0.55 \times \frac{100}{100-15} \text{ i.e. } 0.65 \text{ g/km, and}$$

$$91/441/\text{EC } NO_X \text{ limit values over NEDC} = 0.42 \times \frac{100}{100-9} \text{ i.e. } 0.46 \text{ g/km.}$$

Finally, the definition of an excess emitter requires that allowance be made for degradation in emissions performance caused by the distance the vehicle has travelled. From Table 5 within the JCS Detailed Report 3, it is found that for the “Total” sample the average distance travelled was 58,000 km, and for the "Random" sample it was 49,000 km. (For both samples the range of mileages spanned <20,000 km to > 150,000 km.) The rate of degradation specified in directive 98/69/EC is 20% over 80,000 km. A degradation rate of 14.5% (that applicable to 58,000km on a pro-rata basis) is applied.

The factors discussed and derived above lead to emission values for the NEDC beyond which vehicles can be considered excess emitters. These values are tabulated below:

Table 5 Emission levels complying with directive 91/441/EEC beyond which they can be considered excess emitters

	CO	HC	NO$_X$
91/441/EEC limit values over ECE+EUDC	2.72 g/km	0.55 g/km	0.42 g/km
Increase caused by change in drive cycle	30%	15%	9%
Derived 91/441/EEC limit values over NEDC	4.05 g/km	0.65 g/km	0.46 g/km
Degradation factor for 58,000 km	1.145	1.145	1.145
Emission level beyond which vehicle can be viewed as an excess emitter	4.64 g/km	0.74 g/km	0.53 g/km

Using the parameters presented earlier, given in Table 2, to define the modelled distributions for the various pollutants, the number of vehicles, expressed as a percentage of the total, for vehicles emitting greater than X% of the standard can be found. This data is contained in Table 6. (Graphs of the distributions from which the values in Tables 6 and 7 are derived are shown in Section 3.4.)

Table 6 Percentage of vehicles emitting beyond various threshold levels

	Excess emitter	Excess emitter +25%	Excess emitter +50%	Excess emitter +100%	Excess emitter +200%	Excess emitter +400%	Excess emitter +900%
NO$_X$ Excess emitter threshold = 0.53 g/km, mean = 0.192 g/km, σ = 1.05							
	25.3%	16.3%	10.7%	5.3%	1.6%	0.24%	0.00%
HC Excess emitter threshold = 0.75 g/km, mean = 0.22 g/km, σ = 1.00							
	12.3%	8.1%	4.9%	2.0%	0.46%	0.05%	0.00%
CO "Total" sample Excess emitter threshold = 4.66 g/km, mean = 2.7 g/km, σ = 1.50							
	34.4%	27.0%	21.6%	14.5%	7.4%	2.6%	0.80%
CO "Random" sample Excess emitter threshold = 4.66 g/km, mean = 2.7 g/km, σ = 0.95							
	5.2%	2.5%	1.3%	0.39%	0.05%	0.00%	0.00%

The data in Table 6 only contains half of the tale. What is important in terms of air quality is not how many vehicles are emitting above various levels, but what fraction of the total petrol road transport emissions are being emitted by these vehicles. This data is given in Table 7.

Table 7 Percentage of total emissions generated by vehicles emitting beyond various threshold levels

	Excess emitter	Excess emitter +25%	Excess emitter +50%	Excess emitter +100%	Excess emitter +200%	Excess emitter +400%	Excess emitter +900%
NO$_X$ Excess emitter threshold = 0.53 g/km, mean = 0.192 g/km, σ = 1.05							
	52.9%	40.4%	30.9%	19.2%	8.1%	1.9%	0.1%
HC Excess emitter threshold = 0.75 g/km, mean = 0.22 g/km, σ = 1.00							
	35.9%	24.6%	17.4%	9.1%	2.9%	0.5%	0.0%
CO "Total" sample Excess emitter threshold = 4.66 g/km, mean = 2.7 g/km, σ = 1.50							
	74.2%	67.0%	60.4%	50.7%	34.6%	18.8%	5.8%
CO "Random" sample Excess emitter threshold = 4.66 g/km, mean = 2.7 g/km, σ = 0.95							
	16.8%	9.8%	5.9%	2.3%	0.5%	0.04%	0.00%

Some observations on these data are:

- for NO$_X$ a somewhat surprisingly high number of vehicles generate emissions above the standard, and this gives rise to a high associated fraction of total emissions;
- for NO$_X$, where the model fits the JCS data well, the figures are very close to those seen in Figure 15 of the JCS Main Report; i.e. around 50% of total emissions coming from vehicles emitting >0.5 g/km and around 20% from vehicles emitting >1.0 g/km;
- for HC the percentages are smaller than for NO$_X$; i.e. around 40% of total emissions coming from vehicles emitting >0.75 g/km, the standard for HC;
- for CO there are large differences between the data for the "Random" and "Total" samples;
- for the "Random" sample only 5.2% of vehicles emitted more than the 4.66 g/km standard, contributing 16.8% of the emissions;
- the point above agrees with the JCS data, see Figure 14 of the JCS Main Report, i.e. Figure 7 of this report;
- for the "Total" sample, the model indicates 34.4% of vehicles emit more than 4.66 g/km CO, and now contribute around 75% of the emissions;
- the point above agrees with the JCS data, see Figure 13 of the JCS Main Report, i.e. Figure 7 of this report;
- from Figure 15 of the JCS Main Report, around 30% of the cumulative emissions come from vehicles emitting >50 g/km CO, whereas the model predicts only 5.8% with emissions more than 47 g/km, i.e. the model underestimates the number of the very highest emitters.

4.1.1.1 NO$_X$ performance:

The data for NO$_X$ emissions are something of an enigma. The model reproduces the JCS data well, i.e. the model's predictions and the JCS data are in good agreement. Both find (surprisingly?) high numbers of vehicles emitting above the NO$_X$ standard. Even if the standard was incorrect, and the figure used was the same as for HCs, the percentage of vehicles emitting beyond the standard, and their contribution to the total emissions, would have been similar to those for HCs, i.e. around 12% of vehicles contributing around 35% of the total emissions. What is more notable is that the fraction of excess emitters appear independent of the sample (with the distributions of the "Random" and "Total" samples being virtually identical). In addition the emissions performance is very resistant to maintenance, with the maintained vehicles performing in a nearly identical manner to samples pre-maintenance.

Given the importance of vehicular NO_X emissions to the meeting of Air Quality standards, the reasons for the above observations require further study, with appropriate remedial strategies to be identified. This should be undertaken in Phase 2 of the project.

4.1.1.2 CO performance:

The second notable aspect of this analysis is how the range of excess emissions predicted for CO is very dependent on sample selection/vehicle maintenance. The two sets of model parameters chosen might be taken as bracketing the real situation. However, it is noted that the model predictions for the "Total" sample, is still a significant **underestimation** of the emissions from vehicles emitting greater than ten times the standard. The percentages of total emissions generated by vehicles beyond the standards are 74.2% and 16.8% for the "Total" and "Random" groups modelled, respectively. However this presentation of data somewhat hides the nature of the excess emissions because there is an inverse proportionality involved. This is because:

$$\text{Excess emissions} = \frac{\text{Emissions from fleet before maintenance - Emissions from fleet after maintaince}}{\text{Emissions from fleet after maintentance}}.$$

It will be seen in Chapter 7, where savings potentials are calculated, that the savings potential for these two scenarios are approximately 300% and 23% respectively.

For this pollutant we have the opposite effect noted for NO_X, namely that the emissions potential is very dependent on vehicle sample or state of maintenance. Therefore, the introduction of a perturbation to current practice, e.g. E-OBD, could change the emissions distribution, and consequently the savings potential. This too will be considered further in Phase 2 of the project.

4.2 ASSESSMENT OF LIKELY DEGRADATION MECHANISMS

4.2.1 Overview of TWC vehicle technology

Modern petrol fuelled vehicles are very far removed from vehicles of two decades ago. Consequently, there has been a major change in the degradation mechanisms that lead to changes in the vehicles' emissions. It is therefore useful to briefly review the technology involved.

Internal combustion engines consume air and fuel to generate useful mechanical work, heat and emissions. An extremely valuable parameter characterising the combustion mixture is the ratio of the quantity of air supplied relative to the theoretical requirement to obtain **total** oxidation of the fuel supplied. This parameter is known as lambda (λ). When the quantity of air supplied is **equal to** the theoretical requirement **λ=1.00**, a lean mixture ($\lambda>1$) contains excess air, and a rich mixture (λ<1) contains less air[4]. λ can be expressed mathematically by complex expressions, which vary according to the assumptions used. (In this report calculations involving λ have used the "simplified Lambda calculation" given in the VI MOT exhaust gas analyser specification[5]). SI engines attain maximum power with an air deficiency of between 0 and 10% (i.e. 1.0 < λ < 0.9) and minimum fuel consumption with approximately 10% excess air (i.e. λ = 1.1).

In terms of emissions, if λ<1.00 then complete combustion of the fuel is not possible and unburned fuel (hydrocarbons) and carbon monoxide are emitted from the engine, higher concentrations being emitted for smaller values of λ. Emissions of NO_X are more complex, peaking at around λ=1.1, falling as λ either increases or decreases. Figure 11, below, shows the typical dependence of the concentration of CO, NO_X, HC and O_2 as a function of λ in the engine" exhaust gases, i.e. the effects of any catalyst are not included.

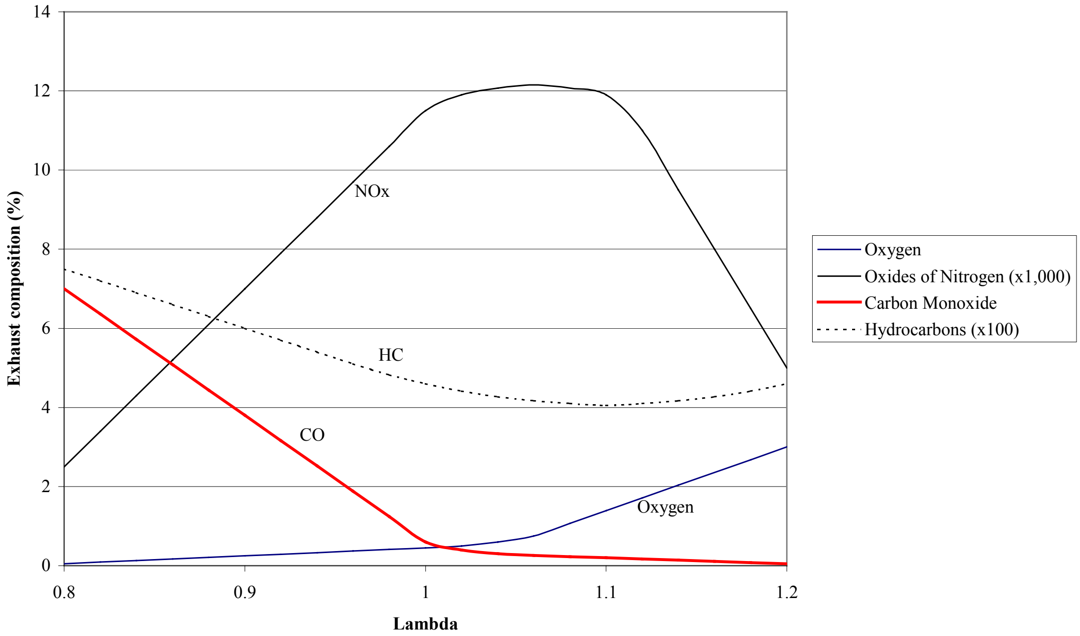

Figure 11 Concentrations of emissions in the raw exhaust as a function of λ

For older petrol engines where the fuel is supplied via a carburettor, the fuelling was tuned to give around 1 – 2% CO at low idle. This corresponds to 0.98>λ>0.95, and is consistent with the in-service test pass/fail limits of CO < 3.5%.

Modern petrol vehicles use three way catalysts to oxidise CO and HC and to reduce NO_X. These require the air fuel ratio at all times to be within a narrow window of about ± 0.05 around stoichiometric (λ = 1.00). The ability of the catalyst to operate efficiently is dependent

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[4] λ=1.00 equates to an air/fuel mass ratio of 14.6 for dry air for a fuel of composition $CH_{1.85}$. In practice this ratio varies with atmospheric conditions and fuel composition.

[5] See Appendix 3 – Calculation of Lambda value according to Brettschneider, in 4th revision of the VI's 1996 MOT exhaust gas analyser specification, 20/7/1999.

on it maintaining a sufficient oxygen storage capacity (often known as the OSC) and the engine's control system providing both the correct range of lambda and at the right frequency.

Most modern vehicles are fitted with an array of sensors. These include, for example, engine temperature sensors, an inlet air mass flow meter and a manifold depression sensor. There is also the accelerator pedal, whose position is sensed. The outputs of these, and other sensors, are fed into the electronic control unit (ECU) and are used to define which map, and which point on it, should be used to define the quantity of fuel injected and its timing. However, the ECU is programmed to learn, and to update the map with "modified" values that ensure λ is kept in the correct range. Further, if a sensor were to fail, the ECU would detect this and use a conservatively pre-set default value, or default engine control maps. The ECU would also illuminate a warning lamp on the dash-board. This might be an engine management warning light, or for a car with emissions on-board diagnostics (E-OBD) the malfunction indicator light (MIL).

4.2.2 Faults that cause changes in emissions

For a correctly operating vehicle with closed loop fuelling control and a three way catalyst there are far fewer faults that lead to excess emissions than on older petrol cars. The following "single" faults, however, do lead to excess emissions:

failure of the closed loop fuelling system

- lambda-sensor fault
- electrical fault associated with the lambda-sensor (e.g. earthing, connector separating or a wiring fault)
- ECU fault
- injector failure
- engine temperature sensor
- failure to move beyond the "warm up" phase into closed loop control (e.g. caused by a faulty engine temperature sensor)
- air fuel meter

failure of the catalyst

- loss of catalytic activity
- loss of mechanical integrity such that some of the exhaust gas can bypass the active element

leakage in the exhaust system between the engine and the catalyst.

In addition to the primary faults above, there are a number of other faults which could affect emissions performance in a less serious manner by causing the engine's management system to revert to "default" values or engine maps rather than fine tuning the fuelling quantity and timing to the actual conditions. For a vehicle operating in closed loop fuelling mode, these faults are, to a large extent, self-rectifying. These faults include failure of the:

- fuel trim value sensor
- misfire sensor
- knock sensor
- air intake temperature sensor

- intake manifold air pressure sensor
- throttle position sensor
- idle speed actuator
- air mass flow sensor
- coolant temperature sensor
- oil temperature sensor
- engine speed sensor
- camshaft position sensor
- EGR valve sensor
- secondary air injection pump
- E-OBD MIL light bulb.

4.2.3 Detection of faults and rates of failure

The question: "what are the rates of failure for the different faults listed in the previous section" is actually profound! Unless something is deliberately measured or checked, or unless it causes an undesirable effect (e.g. the vehicle can not be driven, or it uses large additional quantities of fuel) changes will pass unnoticed.

For the vast majority of vehicle owners the inspection and maintenance and self policing they undertake is:

- the statutory annual roadworthiness test (for vehicles > 3 years old)
- sufficient repair to enable continued use of the vehicle, and
- an annual service.

The faults listed above can be analysed in terms of their visibility to, or impact on, these three checks:

Fault	**MOT**	**Vehicle stopper**	**Annual service**
Failure of closed loop control			
λ-sensor fault	50% probability	rarely	possible if check engine light on
electrical fault from λ or other critical sensors	50% probability	possible	possible if check engine light on
ECU fault	possible – rarely gets to this stage	probable	possible – rarely gets to this stage
Failure of catalyst			
loss of catalytic activity	not unless extremely severe	no	no
loss of mechanical integrity	yes if >20% leakage	no	no
corrosion etc	yes – c.f. exhaust leakage	rarely	yes – c.f. exhaust leakage
leakage in exhaust system	yes – checked	rarely	

An interesting aspect of the above analysis is that catalytic activity is not really assessed in any test. (Catalytic activity can be described as the ability of the catalyst to convert gaseous pollutants into acceptable gaseous emissions.) The fast idle emissions component of the MOT test is undertaken on a hot engine, with a hot catalyst using relatively low gas flows and CO levels. Therefore, apart from virtually a catastrophic loss of activity, high conversion rates would be seen provided that the exhaust gas's stoichiometry was correct, i.e. the close loop fuelling system was operating correctly.

In terms of quantifying the rates of degradation, the most thorough data is provided in a TRL report entitled "An analysis of data from the MOT test"[6]. In this report data on how vehicles fail was found from three sources:

- garages
- road-side callout data from the RAC, and
- leasing companies.

Information was also provided by a company that manufactures replacement exhaust and catalyst systems.

Data from garages

Three garages were selected, two were main dealers (Audi/VW and Ford) and the other "specialised" in MOT testing. Over around a four month period 523 MOT tests were reported, of these there were 11 failures (2.1%).

Three of the failures occurred at the main dealers. Two failed on high λ for the fast idle test. Rectification comprised mending an electrical connection between the λ sensor and the ECU for one vehicle and replacing the exhaust system for the other vehicle. The third failure was due to high CO at fast idle, where the heated exhaust gas oxygen (i.e. λ) sensor was found to be faulty.

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[6] "An analysis of data from the MOT test", TJ Barlow, RS Bartlett and ICP Simmons, TRL Project report PR/SE/474/98, September 1998.

The other eight MOT failures were at the non-main dealer garage, and faultfinding and repair was not undertaken at that garage. Hence no further information was forthcoming about these vehicles.

Statistically this sample is very small, and care should be exercised when trying to project these findings to the parc as a whole.

Roadside callout data

The RAC provided TRL with data on breakdowns for the years 1995, 1996 and 1997. Around three million incidents were recorded for each year. Faults are categorised by a three digit code, and TRL extracted those they felt were related to emissions as:

- ECU engine management
- wiring loom – engine management
- catalytic converter
- air flow sensors
- throttle sensors
- manifold pressure sensors
- oxygen/λ sensors.

Based on this assumption, the following data were extracted:

	1995		1996		1997	
Fault	No of incidences	% of all faults	No of incidences	% of all faults	No of incidences	% of all faults
ECU engine management	6,349	0.21	6,564	0.20	8,404	0.27
Wiring loom – engine management	3,001	0.10	3,157	0.10	2,971	0.10
Catalytic converter	764	0.03	1,124	0.03	1,284	0.04
Air flow sensors	1,204	0.04	1,403	0.04	1,252	0.04
Throttle sensors	1,007	0.03	1,241	0.04	1,001	0.03
Manifold pressure sensors	271	0.01	285	0.01	320	0.01
Oxygen/λ sensors	226	0.01	310	0.01	300	0.01
Total emission faults	12,822	0.43	14,084	0.44	15,533	0.50

The majority of callouts are for faults which prevent the vehicle from either starting or continuing a journey, vis:

flat battery	6.0% of all incidences
defective battery	4.9% of all incidences
wheel change	3.54% of all incidences, etc.

Most emissions based faults are not actually vehicle stoppers – they may cause an "engine fault" light to become illuminated, and the driver requests help to check whether it is sensible to continue the journey or start the car. The author also questions TRL's inclusion of all engine management and wiring faults, and throttle sensor faults. The majority of faults classified in either of the first two are most likely to be for sub-systems other than those related to emissions. Similarly, if the throttle sensor stops working the vehicle will probably stop, having lost a crucial control signal, but the emissions will probably be unaffected. Consequently, the author believes the 0.43 – 0.50% total of all callouts is an overestimate by a factor of 2 to 4, i.e. only 0.12 – 0.25 of all callouts are emissions related.

It is again emphasised that these figures are not the totality of the frequency of failures of the emissions system because many failures neither prevent the vehicle from starting nor cause a running vehicle to stop.

<u>Data from lease companies</u>

TRL obtained data from a major leasing company that owns around 71,000 vehicles. They provided data on vehicles that had their catalysts replaced in 1997. There were 105 replacement catalysts fitted, with the average distance driven per failure as 69,300 miles (111,500 km).

A summary of the catalyst failure modes was given, classified into:

Damaged	Noisy	Leaks	Worn	Contaminated	Corroded	Defective
5	1	2	5	2	12	78

These findings have been discussed, in general terms, among a number of automotive engineers. Broadly they were sceptical regarding what "defective" covered, particularly in the context of it being 75% of the catalyst failures, and the necessity of replacing all the catalysts that were replaced. For example, if a repairer experiences difficulty in removing a failed λ sensor from the can he might "opt" for a total catalyst replacement even though the catalyst was still sufficiently active.

TRL comment that the average failure rate of a catalyst per 69,300 miles is significantly above the 150,000 mile lifetime "claimed" (although there is no further explanation of the origins of the 150,000 miles expected life). However, it is likely that closer scrutiny might reveal that this is a pessimistically biased figure.

A second major leasing company also supplied data covering its passenger car fleet of about 60,000 vehicles. Table 8 shows the failure rates for emissions related components that they recorded.

Table 8 Failure rates for emissions related components

Component	Number of failures	Failure rate (per million km)
Catalyst	286	0.15
λ sensor	153	0.08
Idle valve	135	0.07
Exhaust manifold	132	0.07
Ignition coil	103	0.05
Ignition ECU	95	0.05
Crankshaft sensor	79	0.04
Distributor	68	0.04
Map sensor	33	0.02
Throttle switch	33	0.02
Fuel system ECU	17	0.01
Cambelt	7,855	4.09

The sum of the faults tabulated above, ignoring the cambelt, is 0.60 faults per million km. The cambelt is included because it is also present in the RAC data, where it accounted for 1.64% of all callouts. Using the factor 0.4 to "convert" the lease hire data (failure rate / million km) with the RAC data (fraction of total callouts), this lease hire data would predict a callout proportion of 0.24% (0.60 × 0.4). Therefore, whilst it is accepted that this data is quite old, it is for 1994, it is consistent with the RAC data.

Data from catalyst and replacement exhaust manufacturer

TRL also approached catalyst and replacement exhaust manufacturers. Information was received from one exhaust manufacturer, who gave the following approximate breakdown of the reasons for catalyst failure:

- 90% of replacements are due to the ceramic monolith breaking up;
- a further 5% are due to the failure of supporting pipe-work or brackets, necessitating a replacement part, and
- the remaining 5% are due to a fault in the closed loop management system damaging the monolith, again resulting in a new replacement being fitted after rectification of the fault.

Poisoning through the use of leaded fuel, unusual drive cycle or crash impact damage are also reasons for failure, but these were not thought to be significant.

Some likely causes for ceramic monolith break-up are:

- mechanical shock sustained because of rough terrain, poor driving style or human intervention,
- thermal shock sustained by cold water dowsing/enveloping the catalyst,
- poor catalyst design or manufacture resulting in the thermal blanket/monolith support system yielding and allowing monolith movement and subsequent self destruction,
- incorrect tuning of the engine or malfunction of an engine management component resulting in continued high temperature operation beyond the monoliths normal range,
- poor engine design leading to poor combustion efficiency or over-fuelling producing continued high temperature operation beyond the monoliths normal range.

The implementation from October 1999 of the EC Directive which prohibits the sale of non-type approved catalysts should cause the frequency of the third item on the list to become negligible.

4.2.4 Concluding summary

Overall, the major faults that cause deterioration in emissions performance have been listed. In terms of the real frequency of failure there are serious difficulties in gathering unbiased, objective, statistically meaningful data.

For some faults like catalyst activity, none of the three routes whereby faults are usually identified will detect other than a major failure. Specifically, the current in-service test is not effective at detecting low catalyst activity and consequently catalyst failure is not being detected and rectified as frequently as might be required.

The general consensus for the frequency of faults influencing emissions is, in descending order:

- λ sensor faults
- catalyst internal integrity
- catalyst external integrity (corrosion or other leaks)
- others.

5 Effectiveness of current annual test at identifying “excess emitters”

Key issues addressed in Chapter 5

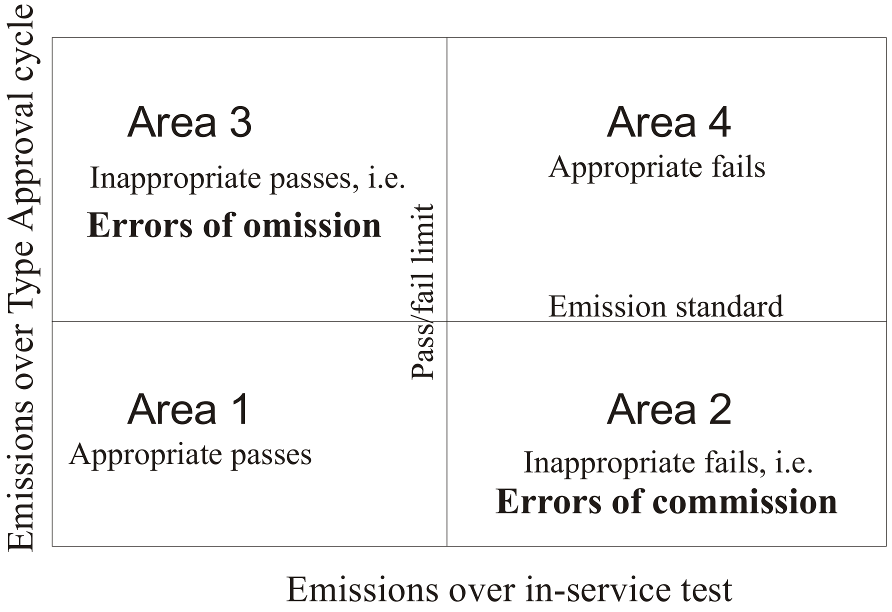
Given that Chapter 4 concludes that the UK’s vehicle fleet does contain excess emitting vehicles whose emissions contributions are adversely affecting air quality, the study moves on to consider the effectiveness of the current annual emissions test. This is accomplished by answering the following questions.

- What are the criteria for the success of an in-service test?
- What is the current in-service test procedure?
- What is the effectiveness of the current test from an assessment or reanalysis of data from previous studies?

5.1 SUCCESS CRITERIA

The criteria for the success of an in-service test are not simply the percentage of target vehicles detected; they are more complex. In this report they are assumed to be:

- to maximise the likelihood of detecting the worst offenders, i.e. to maximise the reduction in emissions, and
- to minimise the number of vehicles erroneously labelled as requiring maintenance.



This can be explained pictorially in the manner used, for example, in the JCS study. In the illustration above, the emissions of a vehicle over the type approval cycle are plotted against the emissions measured by an in-service short test. A horizontal line is drawn perpendicular to the "real" emissions axis at the standard. A vertical line denotes the pass/fail limit for the short test. The resulting four areas are:

area 1	vehicles whose "real" emissions are below the standard and are correctly identified as passes by the in-service test.
area 2	vehicles whose "real" emissions are below the standard but are identified as fails by the in-service test. These are known as the errors of commission
area 3	vehicles whose "real" emissions are above the standard but are identified as passes by the in-service test. These are known as errors of omission
area 4	vehicles whose "real" emissions are above the standard and are correctly identified as fails by the in-service test.

The objective of the in-service test is to maximise the proportion of vehicles in area 4 and to minimise the proportion of vehicles in area 2. Further, given a non-ideal test, and given there will be some vehicles in area 3, the pass/fail threshold should be optimised in such a way so as to maximise the emissions savings made, i.e. if the in-service test fails to detect some vehicles emitting above the emissions standard, these vehicles should be those that are only just over the standard.

5.2 CURRENT TEST PROCEDURE FOR VEHICLES WITH SI ENGINES AND A TWC

Information on the current test procedure to be applied to vehicles was taken from the VI publication "In-service exhaust emission standards for road vehicles, 7th Edition.

5.2.1 Visual inspection

Once the preliminary checks have been completed, the tester will raise the engine speed to typically 2,500 rev/min, or half the maximum engine speed if this is lower. The engine speed will be held steady for about 20 seconds then the engine will be allowed to return to its natural idle speed. Once the emissions have stabilised the tester will assess the smoke emitted from the tailpipe. If the vehicle is emitting dense blue or clearly visible black smoke then the vehicle will fail the test.

5.2.2 Catalyst test procedure

For vehicles subject to this procedure the emissions are assessed during two separate tests. The first test consists of checking the emissions at "high-idle" which involves running the engine at the speed specified in the Annex to the VI's in-service exhaust emission standards for road vehicles publication, typically 2,500 – 3,000 rev/min over a 30 second period. During this high idle the analyser automatically checks the emissions of CO and HC and a check is made on the λ value (limits also listed in the VI standards publication). Provided that the results are equal to or below the specified limits, the vehicle will have passed this section of the test and the analyser automatically proceeds to the standard idle test.

Whilst there is some variability in the emissions limits for the high idle test, as discussed in depth in Section 6.4, standard/default values are:

$CO \leq 0.3\%$

$HC \leq 200$ ppm (as calibrated with propane, i.e. C_3 equivalent)

$0.97 \leq \lambda \leq 1.03$.

The standard idle test is carried out with the engine at its normal idling speed and the analyser displays the results continuously. Once a stabilised figure is achieved, the analyser records the CO value only and compares it with the value from the VI standards publication. There is some variability in this emissions limits. The standard/default value is:

$CO \leq 0.5\%$.

Because the extended emissions test (used for vehicle fitted with catalysts) is more complicated than a single engine speed test (used for pre-catalyst vehicles) the emissions analysers are designed to a more stringent standard and include menu driven computer software designed to guide the tester through the test sequence. The analyser requires the tester to complete each stage of the test before proceeding to the next. In addition, where a failure is recorded during the high idle test then the analyser automatically schedules a repeat test. This is to ensure, as far as practical, that the catalytic converter has reached its normal operating temperature.

Before starting the emissions test the tester will check the engine oil temperature to ensure that the engine is at the manufacturer's stated operating temperature. This requires a temperature probe to be inserted into the dipstick tube.

In the event of a vehicle failing the high idle test but passing the low idle test, the analyser automatically sequences a period of "preconditioning" followed by a further high idle test. The vehicle must pass both the high idle test and the standard idle test to secure a pass result.

5.2.3 Basic emissions test (BET)

In order to reduce testing time, improve convenience and answer some of the criticisms made in the NAO report, the VI have introduced a voluntary fast track test for vehicles registered on or after 1/8/92. This came into effect from 1/9/01. Its basic philosophy is to check a vehicle against generic levels. If the vehicle is within these limits then the vehicle has passed, and no further testing is required. If the vehicle does not meet these limits it is not failed but tested using the longer test, described in Section 5.2.2. The use of generic limits obviates the need to find, and enter into the test equipment, the vehicles engine number thereby circumventing one of the principal difficulties encountered by testers.

The test involves ensuring the engine is hot enough to test, e.g. by inspecting the vehicle's coolant temperature sensor, checking it has hot coolant hoses or noting that the coolant fan has cut in. (This removes the need to insert a thermocouple into the engine's sump, via the dipstick port to measure engine temperature.) The fast idle test is then conducted with the engine running at between 2500 and 3000 rev/min. The criteria for a pass are that for the raw exhaust

CO and HC concentrations should be below, and λ should be between, the standard/default values listed in the previous section.

The engine is then tested at normal idle, which is required to meet the relatively generous limits of being between 450 and 1500 rev/min. The criteria for a pass are that for the raw exhaust:

- CO concentration <= 0.5% (rather than testing to manufacturer defined limits as is currently done).

If the vehicle's emissions comply with these generic limits then it passes the emissions test for this roadworthiness inspection.

5.3 EFFECTIVENESS OF THE CURRENT TEST PROCEDURE

5.3.1 Assessment methodology

The success criteria given at the start of this section were concerned with correctly identifying the "excess emitter" vehicles and, at the same time, not failing vehicles whose emissions performance is satisfactory.

Section 4.1 defined the target vehicles, the excess emitters, as those outside the appropriate European standard, after making allowances for degradation, when assessed over the standard type approval cycles, the NEDC. Herein lies a challenge because most information on the current in-service test does not have data on the type approval emissions. Therefore such data can not be used to assess how effectively the excess emitters are being detected, or the extent to which vehicles with satisfactory emissions are being incorrectly failed. However, such data does contain some relevant information regarding the current pass/fail rates, the principal reasons for failure and other insights into the current test which give indications regarding how it could be improved.

The data assessed here are:

- the Joint Commission Study (JCS),
- the Transport Research Laboratory's (TRL's) study,
- the National Audit Office (NAO) report and
- some recent studies undertaken by the VI.

5.3.2 Analysis of the findings from the JCS study

The Joint Commission Study (JCS) was entitled "The inspection of in-use cars in order to attain minimum emissions of pollutants and optimum energy efficiency". As part of this study vehicles were tested over the type approval cycle specified in directive 98/69/EC (NEDC), a number of other loaded cycles and the in-service two speed idle test according to directive 92/55/EEC. (This has now been subsumed into, and superseded by, more recent roadworthiness directives, i.e. directive 96/96/EC and its amending directives 1999/52/EC and 2001/9/EC.) Therefore, although the number of vehicles tested in the JCS study is less than in the TRL study, the JCS data is crucial because it also contains emission information from these different test cycles.

In Chapter 3 of this report, the JCS data was used as the foundation for developing a model of current vehicle emissions for on-the-road driving. In this part of the study the vehicles are viewed as individual test platforms. They can be categorised as either excess or acceptable emitters, using the criteria established in the previous chapter, and the results from an in-service test can be correlated with this categorisation.

The researchers responsible for generating the JCS reports did this, and their comments and conclusions are relevant to this study. It must be remembered that the in-service test according to the directive differs slightly from that used in Britain in a few respects, namely:

- HC emissions were not measured, merely CO and λ, and
- the same pass/fail points were used for all vehicles (CO $\leq$ 0.5% for normal idle and at high idle CO $\leq$ 0.3%, $0.97 \leq \lambda \leq 1.03$) as opposed to the UK where vehicle specific limits are used except for high idle CO.

The JCS study evaluated 192 cars fitted with closed loop fuelling and TWC systems. 135 were in the "Random" group and a further 57 were selected as "likely high emitters".

The JCS defined "high emitters" as vehicles emitting more than 50% above the type approval standard. This JCS definition of "high emitters" is more lax than the proposed "excess emitter" definition developed in this report. For the average 58,000 km travelled by the vehicles tested in the JCS study, those emitting 14.5% above the their type approval standard would be viewed as "excess emitters" by the definition given in Section 4.1. This is in contrast to the 50% excess required before the JCS study labelled a vehicle as being a "high emitter".

Following testing the vehicles the JCS defined as "high emitters" were maintained and then retested. The emissions before and after maintenance can be used to calculate an "Emission Reduction Rate Potential" (ERRP). ERRP is defined in the JCS study as[7]:

$$\text{ERRP for pollutant} = \frac{100 \times \textbf{excess emissions} \text{ of vehicles identified as needing maintenance}}{\text{cumulative emissions of pollutant from whole sample}}$$

where **excess emissions** = emissions before maintenance – emissions following maintenance.

This is exactly the parameter required to assess the effectiveness of an I&M regime.

The ERRPs for the "Total" (Random + High Emitters) and the "Random" samples were calculated for each pollutant, and are shown in Figure 12. The number of vehicles correctly identified as requiring maintenance (labelled P6) and incorrectly identified as requiring maintenance (labelled P2) are shown in Figure 13.

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[7] See Section 4.2 of JCS Detailed Report 5, by LAT/AUTh, published April 1998.

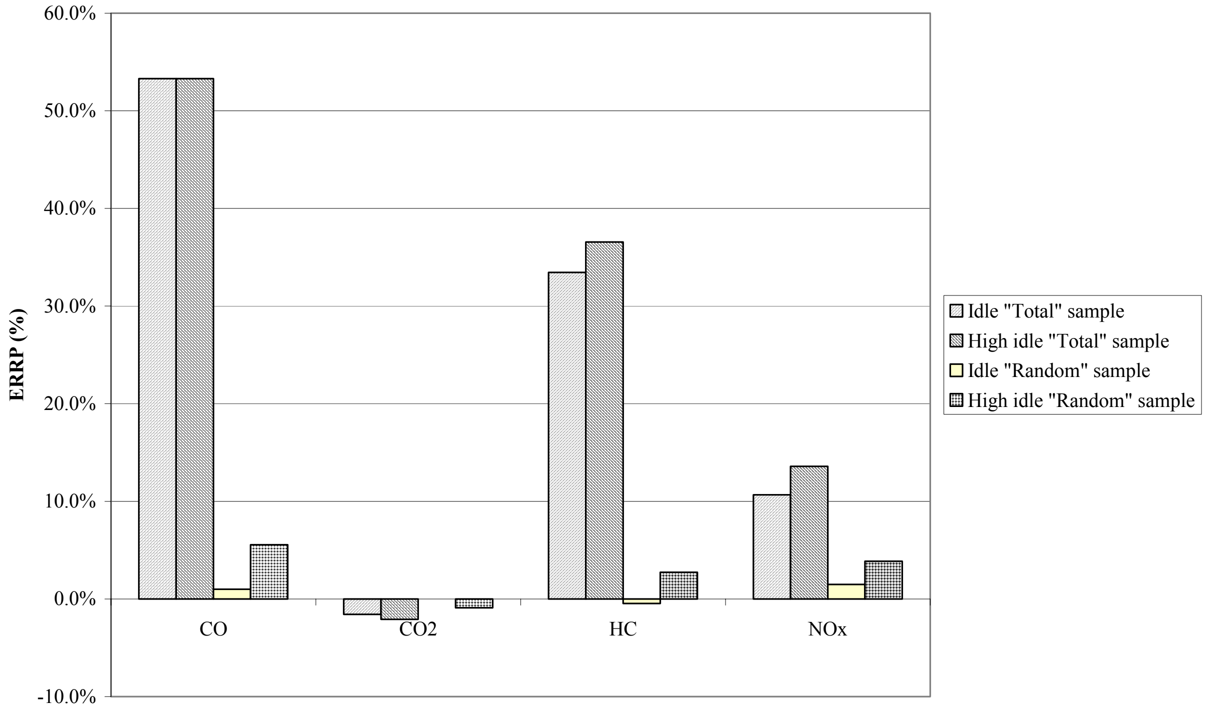

Figure 12 The ERRPs for the "Total" and the "Random" samples

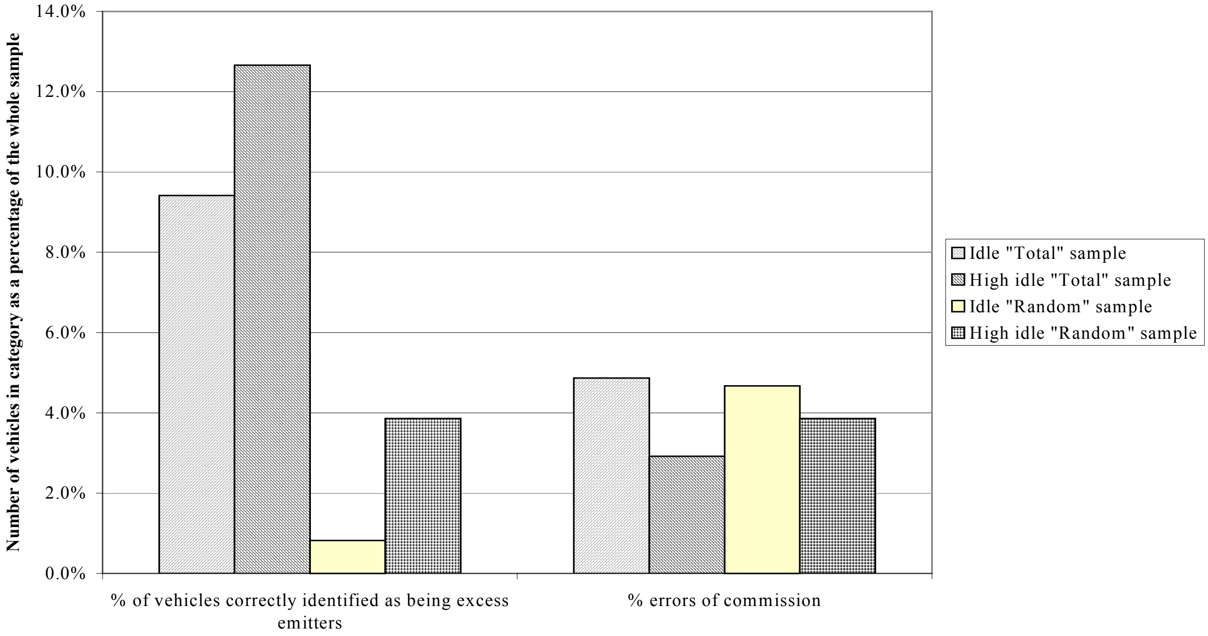

Figure 13 The number of vehicles correctly and incorrectly identified as requiring maintenance

From the NEDC emissions the number of vehicles identified as requiring maintenance (i.e. that were more than 50% above the vehicles' type approval standard) were 24 (18%) and 55 (29%) for the random and total samples, respectively. Given the number of vehicles correctly identified as requiring maintenance from the high idle test, see Figure 13, (3.9% and 12.7%, or 5 and 24, respectively), the number of errors of omission (the difference between the number of vehicles identified by the two speed idle test and the number that should have been identified relative to the total sample size) are 19 and 31 vehicles for the random and total samples, respectively. For these samples the 2-speed idle test only successfully detected 21% and 44% of the "high emitters" in the random and total samples, respectively.

From these data the JCS researchers made the following remarks[8]: (It should be remembered that the JCS study assessed a range of short tests, i.e. less than the full type approval test, some of which were loaded. The aspects of the study reviewed here concerns the results from the unloaded test as per directive 92/55/EEC.)

- *The short test in question seems to be efficient enough when the vehicle sample comprises of many high polluters (total sample). However, this environmental benefit is accompanied by a relatively large number of errors of commission especially when only vehicles emitting 50% above the standard is the objective.*
- *When only the random vehicle sample is taken into account the environmental benefit becomes extremely small. This remark along with the fact that there are many errors of commission leads to the conclusion that this short test is completely ineffective when applied to TWC equipped vehicles, which is representative to the vehicle fleet.*
- *The first partial test measuring CO at idle seems to have no effect on the short test when only the randomly chosen vehicles are selected. It detects very few vehicles and as a result the environmental benefit is extremely small.*
- *λ measurement is, as expected, capable of detecting vehicles emitting very high levels of NO_X. However, it is the parameter principally responsible for the errors of commission. This is particularly obvious when targeting only to polluters 50% above the standard. When targeting to all vehicles emitting above the standard it can be stated that even though λ measurement adds approximately 3% errors of commission, it also contributes to environmental benefit (1% CO, 0.5% HC and 4.5% NO_X) by detecting almost 3% of these excess emitters.*

The validity of the above results and the fact that the randomly chosen vehicles are indeed representative of the vehicle fleet has been proved by comparing these results to those coming from RWTÜV[9]. According to them 3.47% of vehicles have been detected as having emissions above the type approval standard, while in the sample of this report the corresponding percentage is 8.73%. The difference is attributed to the fact that the RWTÜV data is from an official inspection programme and as a result the owners have their vehicles maintained before being tested, whilst this study is a laboratory study.

In their conclusions to the report[10] the JCS researchers reach the following conclusions regarding TWC cars and the current 2 speed idle test:

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[8] Quoted verbatim from section 9.4, Discussion, of the Detailed Report 5, Short Test Evaluation, by LAT, AUTh, April 1998.

[9] AU Pruefergebnisse von RWTUEV and TUEV Rheinland, 2. Jahreshaelfte, 1996

[10] Quoted verbatim from section 10, Conclusions, of the Detailed Report 5, Short Test Evaluation, by LAT, AUTh, April 1998.

- *On the basis of the test results of the random vehicle sample, the short test legislated by the 92/55/EEC was found to be completely ineffective. It can identify only 15% of the excess emitters, while the environmental benefit (ERRPs) from it does not exceed 4% reduction in any of the pollutants involved. Especially as regards the λ test, it was found to add in the identification of NO_X emitters, but had the drawback of increasing the errors of commission. It is of importance to note that there is virtually no improvement at all if to the current CO measurement at idle and high idle, HC measurement is added.*
- *However, the efficiency of this test clearly increases with increasing share of excess emitters (>50% above the standard) in the fleet. This is demonstrated in the case of the total sample, where the 92/55/EEC test was found to identify about 50% of the high polluters.*

5.3.3 Analysis of the findings from the TRL study

In 1998 TRL reported on a programme of work whose objective was to investigate the performance of the current MOT emissions test. This programme collected data from a large number (>4,600) of tests. No data was available for the type approval cycles, and consequently only somewhat limited conclusions can be drawn regarding the effectiveness of the test at identifying excess emitters.

2,174 vehicles fitted with TWCs were tested. Overall 121 (5.6%) failed the test. The last paragraph of the VI's test procedure, given in Section 5.2.2, is that vehicles that fail the high idle test but pass the low idle test should under go a further period of preconditioning followed by a further high idle test. In the TRL study 679 (31.2%) of vehicles were in this category, with the vast majority, 576 (26.4%) failing because of high CO emissions! With further preconditioning 565 of these vehicles were able to pass the second test. This observation raises serious questions regarding the values obtained for CO concentration during the high idle tests. If the number failing first time but passing second is so high the following questions are raised:

- Would the remaining vehicles that failed the CO standard have passed with yet more preconditioning?
- Given this poor reproducibility, what measurement accuracy is required?

Of the 121 vehicles that failed the "complete" test, 31 failed the CO at normal idle test, and 114 failed part of the high idle test, i.e. 24 vehicles failed at both idle speeds. An analysis of the 114 vehicles that failed the high idle tests showed:

51 failed high λ only,
40 failed high CO only,
10 failed on high CO and low λ,
9 failed on high CO, high HC and low λ,
3 failed on high CO and high HC and
1 vehicle failed on high HC and high λ.

No vehicle failed on high CO and high λ.

These findings do not contradict the findings from the JCS study. However, they do not appear to give the whole picture.

The TRL raw data was reanalysed, after removing duplicate entries, taking the first test (earliest time label) for vehicles which were submitted for testing more than once. This gave:

- number of vehicles in the sample = 2172
- average values: normal idle CO = 0.246%; fast idle CO = 0.175%, HC = 34.2 ppm; λ = 1.009.
- for normal idle 383 vehicles (17.6%) gave 0.00% CO
- for high idle 601 vehicles (27.7%) gave 0.00% CO
- 225 vehicles (10.4%) gave 0.00% CO for both idle tests.

The data for the normal idle CO and the high idle CO and HC were then further analysed. The data were sorted and then plotted to show the distribution of values obtained, see Figure 14. Note that the ordinates are expanded to show the pass/fail limit a significant distance from the origin; a number of vehicles had emissions that lay outside the values shown, vis:

- normal idle 16 vehicles had CO concentrations greater than 5.0%
- high idle 20 vehicles had CO concentrations greater than 5.0%
- high idle 1 vehicle had is HC concentration greater than 1000 ppm.

In addition, the data can be summed to give the cumulative distribution of the emissions against cumulative vehicle number. This is done in Figure 15 for the two CO and the HC measurements. An ERRP was then computed, similar to that used in the JCS study. The basis of the calculation was that maintentance caused all pollutant concentrations greater than the pass/fail limit to be reduced to the pass/fail limit. The ERRPs calculated were:

normal idle CO	34.1%
high idle CO	53.8%, and
high idle HC	7.2%.

As noted earlier, the lack of any data over a regulatory cycle meant that these data can not be directly related to whether or not the vehicle was an excess emitter using the criteria set in the previous chapter.

Indeed, there remains the question of preconditioning. Is a significant quantity of the ERRP calculated above caused by vehicles which with further preconditioning would give a much smaller CO concentration? This issue can be assessed using the TRL raw data because generally it is found that a vehicle with an unlit catalyst has a CO concentration greater than 0.3% at high idle BUT λ is within the expected range, i.e. the oxygen to remove the CO is present, but the catalyst is unable to effect the oxidation. A filter was applied to the data such that only tests with a high idle CO concentration above 2.0%, and a $\lambda<0.95$ were projected out. This gave 27 vehicles, 1.24%, and the ERRP recalculated for this sub-set was 35.1% (c.f. 53.8% for all high idle CO failures).

It was also noted from the TRL data that these worst emitters were spread over a wide variety of makes, had an average mileage very similar to that of the whole sample and contained at least three vehicles which, as 3 year olds, were most probably being tested for the first time.

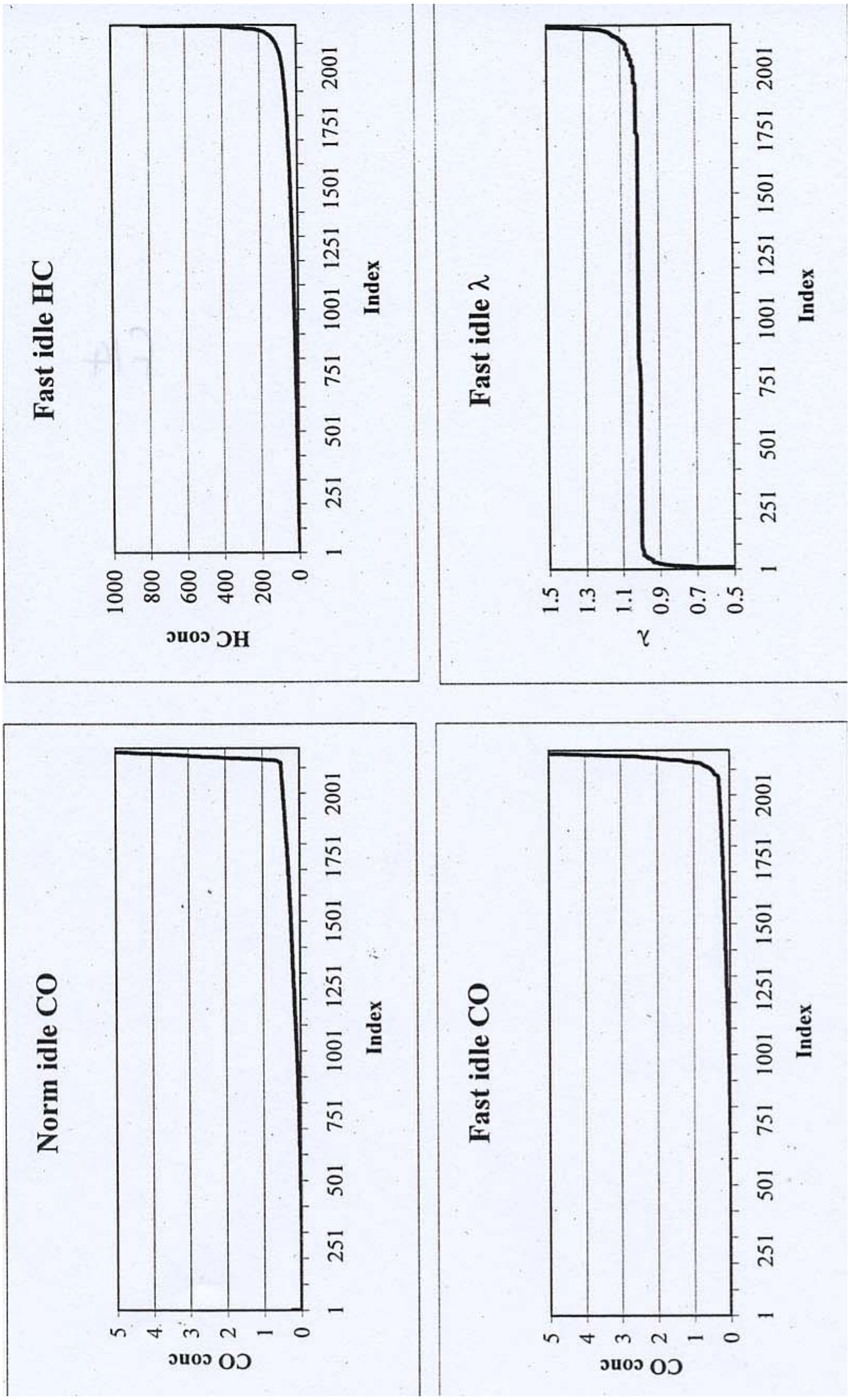
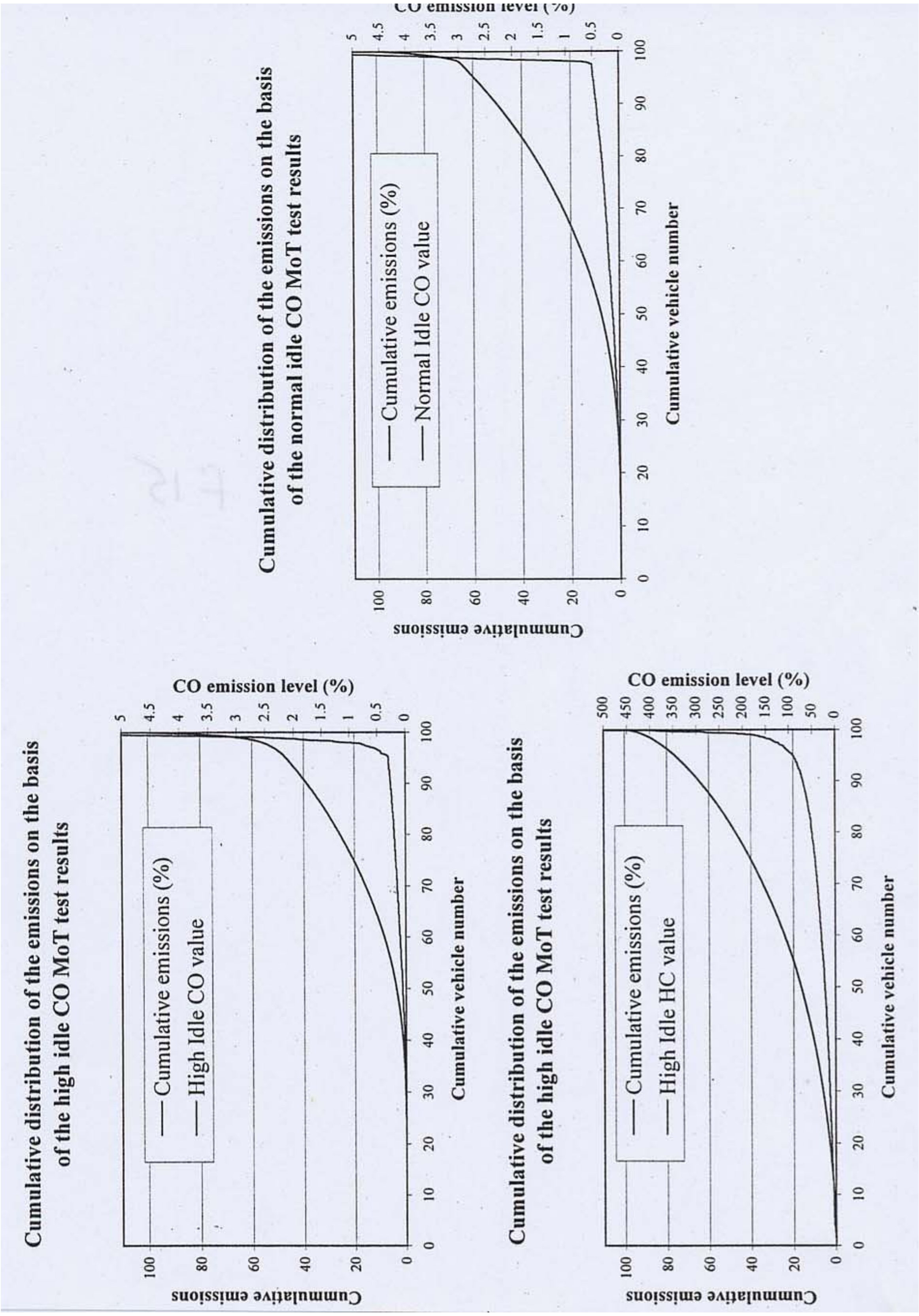


Figure 14 Distribution of normal idle CO and the high idle CO and HC data from the TRL study



Cumulative distribution of the emissions on the basis of the normal idle CO MoT test results

Cumulative distribution of the emissions on the basis of the high idle CO MoT test results

Cumulative distribution of the emissions on the basis of the high idle CO MoT test results

Figure 15 Cumulative distribution of the emissions against cumulative vehicle number for the two CO and the HC measurements from the TRL study

5.3.4 Analysis of the findings from the NAO report

The NAO report on "Vehicle emission testing" was on the effectiveness of the regime for the in-service testing of vehicle emissions in Britain.

In part 3 of their report, the practical application of the testing regime, the NAO focuses on CO emissions. Given the discussion in the previous two sections this is unfortunate because of the poor reproducibility of this measurement (believed to be caused by variable catalyst temperature). The NAO report notes this – in section 2.32 (on page 36) it comments that 28% of passes for SI engines fitted with TWCs were achieved *simply by rerunning the test*. There is a nuance in this wording that the fault may lie with the testing equipment. If the cause is variable catalyst temperature then the procedure itself would need to be revised.

Section 3.3 of the NAO report shows graphically the normal idle CO emissions, and notes that the average CO reading was around 0.2%. The data indicates the cumulative number of vehicles with CO>0.5% as around 1.5%, consistent with the findings of other studies, e.g. the TRL study which found 1.43% of vehicles failed the normal idle CO test. The figure also shows a small but non-zero number of vehicles that had a CO concentration > 3.0%, again consistent with the TRL data. However, these data alone do not provide a good assessment of the effectiveness of the current regime at successfully identifying the excess emitters. This is because an excess emitter is defined in terms of emissions over a standard loaded road cycle, the NEDC, and these were not measured. Consequently no assessment of the correlation between the test and on-road emissions is possible.

Amongst the other interesting data contained in the NAO report are the comments regarding problems with the practical application of the test. The majority of complaints from the testers concerned the need to identify and enter details about the make, engine size, and model of car – information required because of the variable pass/fail limits that apply to different vehicle types.

The issue that the NAO highlighted, Section 3.4 on page 43 of their report, was that >25% of SI cars fitted with TWCs recorded **zero emissions**. It is believed that this meant 0.00% CO. The NAO note that *whilst a zero is technically possible since vehicles with very low emissions may record this result due to the imprecision of the test equipment* they conclude *the high proportion of zero results and their concentration in some garages suggests that test equipment was not working or was not being used properly*.

This issue is commented on further in the concluding portion of this section, 5.3.6.

5.3.5 Analysis of the findings from VI study

In the first quarter of 2001 the VI collected data on some MoT tests as part of a programme considering possible improvements to the test[11]. 228 vehicles were tested using the current in-service test. No data on the emissions performance of the vehicles for the type approval cycles was obtained, and consequently no comments can be made about the effectiveness of the test at identifying "excess emitters". Also, the data provided for this study were insufficient to enable

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[11] Data supplied by L Emmett, VI, Croydon Road, Bristol

the manufacturer declared limits to be found for each of the vehicles tested. Consequently, assessments of pass/fail ratios are made against generic values.

However, useful information relevant to this study was obtained. In summary:

- number of vehicles tested = 228
- number of vehicles that failed the test was 3 (1.3%)
- average values were: normal idle CO = 0.102%; fast idle CO = 0.090%, HC = 39.4 ppm; $\lambda = 1.006$.
- for normal idle 70 vehicles (30.7%) gave 0.00% CO
- for high idle 51 vehicles (22.4%) gave 0.00% CO
- 29 vehicles (12.7%) gave 0.00% CO for both idle tests.

The last three points echo the concerns raised by the NAO.

The three failures were all for different aspects of the test: one for CO at normal idle (2.1% instead of 0.5%), one for CO at high idle (0.48% instead of 0.3%) and the third for HC at high idle (220ppm instead of 200ppm).

The average CO concentrations measured, given in the third dot point above, are smaller than the values measured in the TRL study. This may be a quirk of the statistics, the VI study being around a tenth of the size of the TRL study, or it may reflect a general improvement in emission levels in the parc as the closed loop fuelling + TWCs technology matures.

Figure 16 plots the data collected, after sorting into ascending order, to give a visual representation of the actual values obtained.

5.3.6 Conclusions

At first reading it may appear that the evidence regarding the effectiveness, or otherwise, of the current in-service idle test is contradictory. However, the author believes there are some consistent themes, and important conclusions that can be drawn.

The JCS study draws three principal conclusions:

- the current test is “ineffective” for the current parc,
- the current test is more effective for the significant polluters, and
- <u>the number of error of commission, assessed against the type approval standard, is worryingly high</u>.

The NAO, drawing together and objectively assessing comments from a number of sources felt:

- “ineffective” was probably too strong a condemnation, and
- the number of 0.00% CO concentration recorded appeared to be a problem.

The TRL study had by far the largest sample, close to a factor of ten larger than the JCS or the VI studies. However, it contained no methodology for categorising vehicles as “excess emitters” over real drive cycles. It found that there was a small (around 1%) sample of very high emitters. The author believes that the vehicle faults that caused these high readings during the in-service test are such that these vehicles would also give grossly excessive emissions over

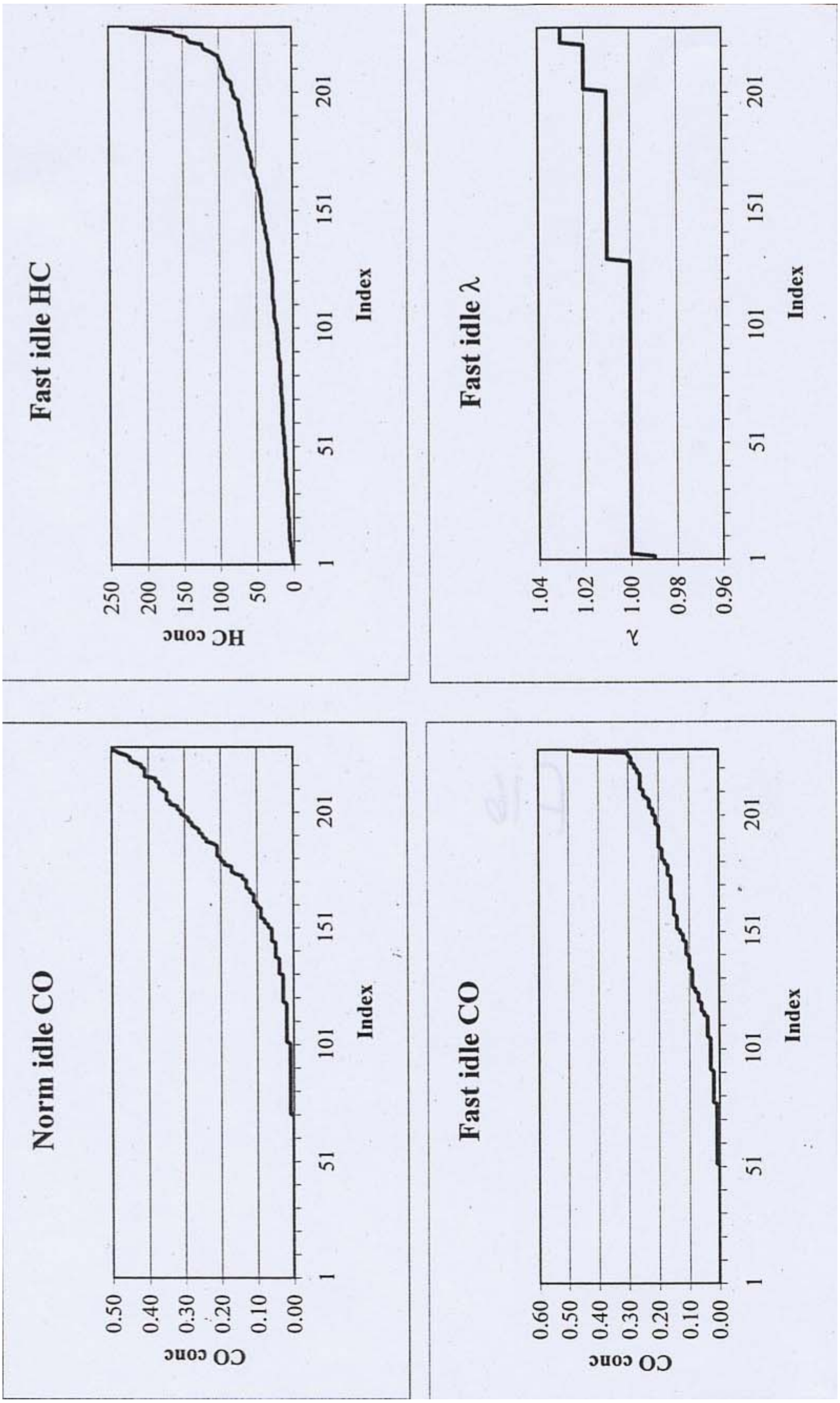

Figure 16 VI study data collected, after sorting into ascending order, to give a visual representation of the actual values obtained

loaded drive cycles. **On this basis the in-service test is achieving a significant positive improvement in air quality.** Estimates of the ERRP were between 35 and 53%; the former being the ERRP for the worst 1.3% of the vehicles tested. Hence, the significant positive improvement in air quality being achieved is from the identification of a small proportion of the fleet which are the worst emitters.

The basis on which the NAEI is calculated should be remembered: the emission factors used are found from a sub-set of vehicles that would exclude such high emitters. Consequently, if the true value for the ERRP were 33.3%, then the NAEI computed corresponds to the 66.7% emissions remainder, i.e. the in-service test would be saving 50% of the NAEI figure.

Remaining issues include the following:

- Is the TRL data truly representative?
- What are the trends in the distribution of emissions with time?

The author believes that the TRL data is representative of the parc at the time of the study. However, the TRL data is pass/fail data assessed against vehicle specific, rather than generic, limits. There are concerns that manufacturers are using vehicle specific limits to accommodate high emissions at idle which are a result of cycle beating strategies. This implies data recorded at idle when compared with vehicle specific limits might be failing to detect vehicles which are excess emitters over the European drive cycle. Despite this caveat, analysis of both the vehicle specific idle limits, see Section 6.4, and of which vehicles are most significantly adversely affecting air quality, suggests that changing the pass/fail limits for the data collected by TRL from vehicle specific to generic cause on minor changes to the conclusions reached.

The reason why relatively few of the highest excess emitters appeared in the JCS "random" sample is, it is believed, a combination of statistical effects, and a systematic bias. Statistically, if an event has a 1 in 100 chance of occurring, then in a sample of 100 there is a 36% probability that NO such events are present. The systematic bias was introduced by the method of vehicle selection: the random sample comprising vehicles "offered" for testing by members of the public. It is very likely that the highest excess emitters will not have been volunteered.

The argument is weaker regarding the VI sample. What might be happening in the parc is that the durability of vehicle emissions technology is improving. The sample in the TRL study was of some of the earlier examples of TWC vehicles (vehicles 3 – 6 years old when the technology had been adopted for 3 – 0 years). In the VI study, three years later, the 3 – 6 year old vehicles were employing technology that was 6 – 3 years mature.

In terms of the list of single faults that lead to excessive emissions discussed in section 4.2.2, the effectiveness of the current in-service test at identifying these is found to be:

failure of the closed loop fuelling system	
lambda-sensor fault	moderate to high[12]
electrical fault associated with the lambda-sensor	moderate to high
ECU fault	moderate
injector failure	moderate to high
failure to move beyond the "warm up" phase into closed loop control	high

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[12] tolerant manufacturer declared limits can reduce the effectiveness of the test at detecting these faults.

failure of the catalyst	
loss of catalytic activity	low barring very serious deactivation
loss of mechanical integrity	high for extreme cases otherwise low
leakage in the exhaust system between the engine and the catalyst	high

Overall, this review concludes that the current test is performing **moderately**. Key weaknesses include:

- a high number of errors of commission – vehicles incorrectly flagged up as faulty, and
- a high number of errors of omission – excess emitters not identified as faulty.

Its key strength is:

- successfully identifying the worst of the excess emitters and thereby effecting a significant reduction in pollutant emissions at a low cost and little inconvenience.

If vehicle technology were to evolve such that the number of very high excess emitters were to fall to a small fraction of those identified in the TRL study, then the key strength would diminish, and the performance of the current in-service test would fall to **poor** – the assessment made by the JCS study.

6 Possible improvements to the current test

Key issues addressed in Chapter 6

The preceding chapter concluded that the current annual emissions test whilst achieving a significant improvement in air quality has some serious short comings. In this chapter the following issues are considered.

- Are there any simple modifications to the current procedure, meters or their use that might improve the current test?
- Are the manufacturer declared limits detrimentally affecting the number of excess emitters identified by the current test?

It is evident from the preceding sections that the current in-service test is not optimal. The author firmly believes that "better" tests can be devised. However, whether these are:

- technically valid,
- practicable for the testers and
- cost effective

remains to be evaluated.

Notwithstanding, from the preceding conclusions it is believed that the current test has some merit in detecting excess emitters from the current TWC parc, and could be improved upon. In this section it is assumed that:

- the test procedure remains broadly unaltered, comprising a normal and high idle test
- the species measured remain the same: CO, CO_2 HC and O_2 (from which λ is calculated), and
- the basic specification of the meters remains unaltered.

6.1 MODIFICATIONS IN TESTERS ROUTINE

The test would be easier for the testers if the test equipment allowed testing outside the "normal" operating conditions and applied pass-not pass filtering.

Oil temperature: If the engine's oil temperature is not sufficiently high then emissions MAY be anomalously high. Hence testing could be allowed at oil temperatures below those specified, and if the vehicle passes the test is successfully completed. If it does not pass the test continues until either the vehicle does pass, or the oil temperature reaches the required temperature and the vehicle fails. This approach would speed up testing by circumventing the time required to fully warm the engine in many cases.

Vehicle identification: A complaint from the testers, noted by the NAO, was that "much the greatest complaint ……..was the need to identify details about the make, engine size and model of car because this entails locating the engine code which is not in a standardised position." This information is required to determine the manufacturer declared values that are appropriate to the vehicle being tested. The introduction of the new "basic emissions test", (BET) described in Section 5.2.3 does not have this requirement. Therefore for vehicles which pass the BET test this activity is not required. However, for vehicles that fail the BET test and are then tested against according to the procedure described in Section 5.2.2, the vehicle identification number is required because the pass/fail limits for this test are those declared by manufacturers on a model by model basis. For this test it is recommended that consideration is given to having the controlling computer "help" the tester by indicating when it has sufficient information to unambiguously identify the appropriate limits. For example, if all the models and their variants of an OEM have the same limit, the manufacturer's identity is all the information required. Otherwise the model might further narrow down the selection sufficiently. It is expected from a somewhat cursory glance at the spread of data for manufacturers within the VI's "In-service exhaust emission standards for road vehicles" publication, that finding the engine code would not then be required for the majority of tests, relieving the testers of an unnecessary burden.

6.2 PASS/FAIL LIMITS

The JCS study considered the pass/fail threshold. Indeed for high idle CO concentrations they advocated a 0.2% threshold. However, the author is cautious about the real advantage this would bring. The benefit of the current test derives principally from identifying and rectifying the worst excess emitters, not those on the borderline. Further, given the current meter specification, see next section, and the number of errors of commission, it is believed that on the basis of the TRL MOT test data 0.50 and 0.30% CO for normal and fast idle remain appropriate.

The JCS expressed reservations about the purpose of measuring HC. The author's view is that although only a small number of vehicles fail on HC emissions alone, its value does need to be measured to compute λ, and a 200 ppm upper limit is not unreasonable. Further, it does prohibit one known way of "beating" the test by disconnecting an HT lead. Therefore it is recommended that this limit too remains unchanged.

6.3 MODIFICATIONS TO THE USE/READOUTS OF METERS

The basic assumption made here is that a major drafting of instrument specification is not appropriate. (The meter specification is given in the next section.) However, it appears that minor modifications could increase confidence in meter readings.

The three recommendations are addressed at:

- improving the accuracy of CO readings (currently the maximum permissible error is ± 20% of 0.3% vol (the high idle limit)
- improving the confidence that the current 0.00% CO readings are from vehicles with low emissions and not faulty, or poorly zeroed meters.

When meters are set up there are normally three aspects that are checked:

• zero	i.e. the meter reads zero when the concentration of the measurement species is zero
• full scale, or span	i.e. the meter correctly reads the maximum of its range when the concentration of the measurement species is this upper limit.
• calibration	i.e. the meter correctly reads some selected intermediate values using know intermediate concentrations of the measurement species.

Currently meter calibration occurs a maximum of 12 times a year (i.e. monthly) and for most instruments 2 – 4 times a year. The calibration requirements (including the frequency) are given in Appendix 7 of the VI Specification VPB/07/24/20, 4th Revision July 1999. The procedure includes a zero check and a calibration check using a mixture comprising 3.5% CO, 2,000 ppm propane, 14% CO_2 balance nitrogen. Zero checks are only performed as part of this calibration process.

It is recommended that meter displays are actually in the range - 0.1% to 5.0% CO with 0.001% (i.e. 10 ppm) resolution. The objective of this is not to increase the precision of the readings but to provide a "live" reading such that 0.00% is covered by 0.004% to - 0.005%, i.e. 90% of this range becomes non-zero. Further, by enabling meters to display to – 0.100% the occurrence of a zero reading because the meter is off the bottom of its range is eliminated.

Secondly, it is recommended that the zero check of meters is undertaken weekly (or daily) not just during calibration. The threshold limit value (TLV) and time weighted average (TWA) concentration for CO in a workplace are 25 ppm (0.0025%). Therefore, ambient air has a sufficiently low CO concentration to provide a zero check for the current raw exhaust gas analysers. The adjustment to zero could be made electronically, and recorded, as it is for baseline drift in smoke meters.

Thirdly, it is recommended that an additional calibration gas containing 200 ppm propane and 0.4% CO be used when the meter is calibrated to check the calibration around the pass/fail limits rather than assume a linear response from the span concentration which is around 10 times the pass/fail standard.

6.4 ANALYSIS OF IDLE LIMITS

The ITT states the requirement that this phase of work *includes an assessment of how using vehicle specific high idle limits, derived from the type approval high idle test results (plus some allowance for reasonable deterioration and scatter) would increase the proportion of excess emitters identified.* (Italics are used to identify phrases taken verbatim from the Customer's ITT.) The concern behind this is that the "manufacturer declared values" provided to the DTLR/VI are decoupled from the values measured at type approval. It is possible that manufacturers could/do take advantage of this. In particular consideration should be given to the width of the declared λ window.

The approach adopted here is:

1. an audit of the current values from surveying the VI's in-service exhaust emissions standards for road vehicles,
2. a critical assessment of the influence of extreme values on the prospects of excess emitters being passed.
3. the making of recommendations.

6.4.1 Audit of current limit values

An audit of the current values from surveying the VI's "in-service exhaust emissions standards for road vehicles" (6th edition published in August 2000) was undertaken.

This standard comprises two sections. The first is the largest and is for passenger cars as defined by regulation 61 of the road vehicles (construction and use) regulations 1986 (as amended). Section II is for other petrol fuelled vehicles which are not "passenger cars" that fall under the regulation 61 definition either because:

1. they have >6 seats, i.e. Section II includes all the MPVs,
2. they have a gross weight >2500 kg, i.e. the Rolls Royce, Bentley etc. or
3. they are light goods vehicles.

For this analysis such a sub-division is unnecessary, and the audit presented is for the two sections combined.

For each of the 10 parameters (either engine speed, oil temperature or emissions), the minimum and maximum values, the mean, and the most commonly occurring are tabulated. A graph of the profile of the values is also given in Figure 17, so that the reader can rapidly gain a visual impression of the values declared. For pairs of engine speeds that bracket either normal or fast

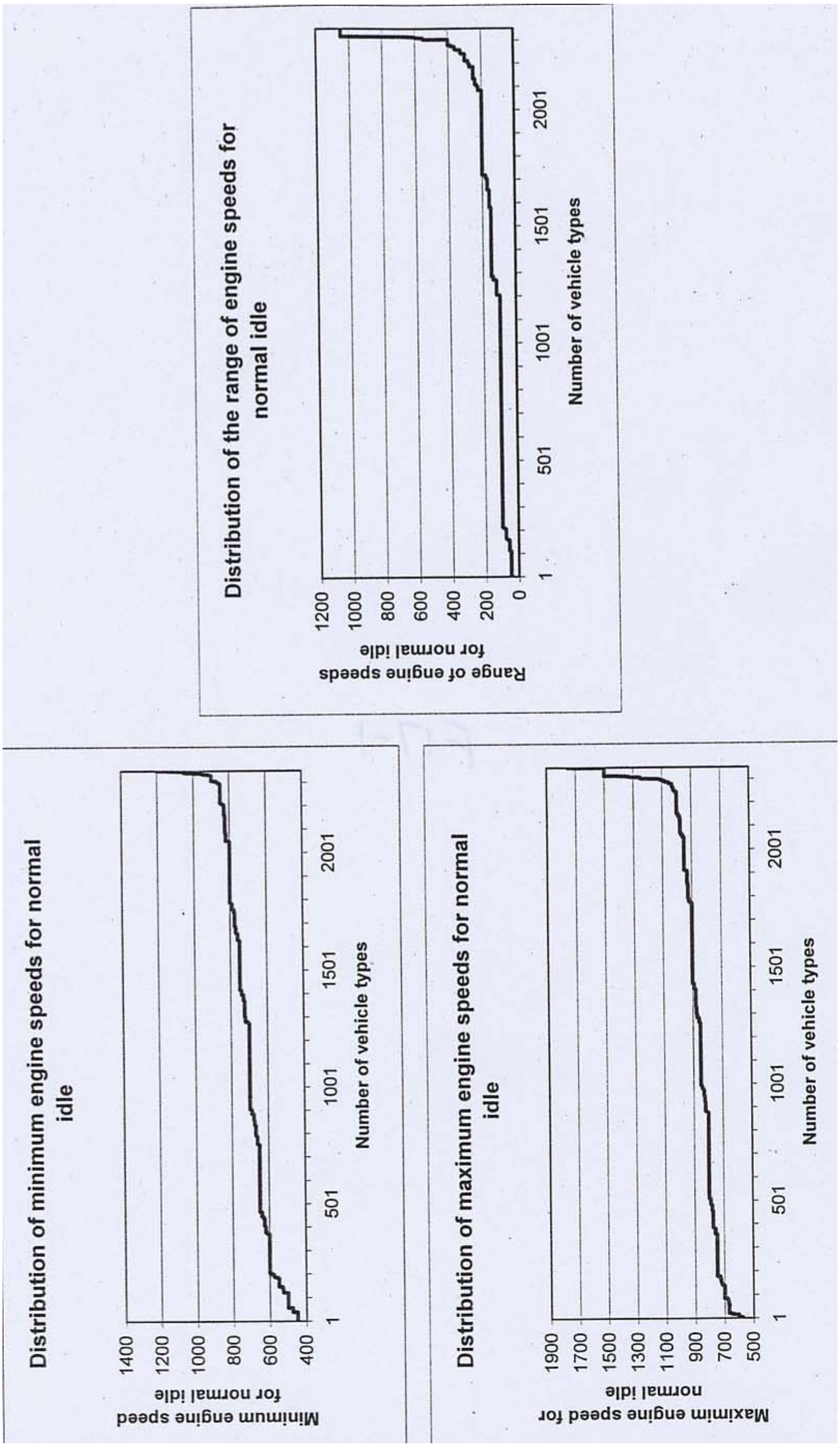

Figure 17 Profiles of the in-service limit values – Part 1

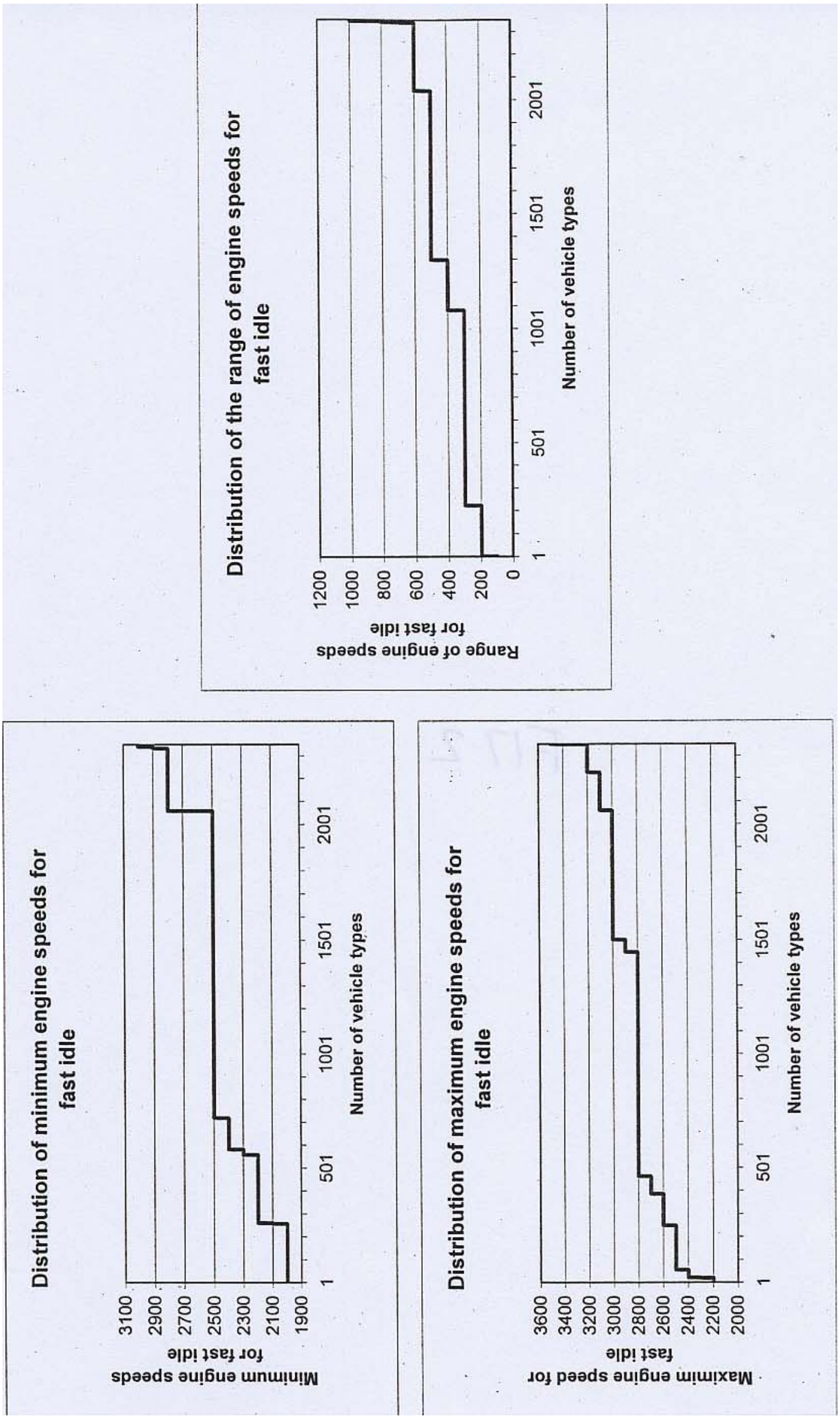

Figure 17 Profiles of the in-service limit values – Part 2

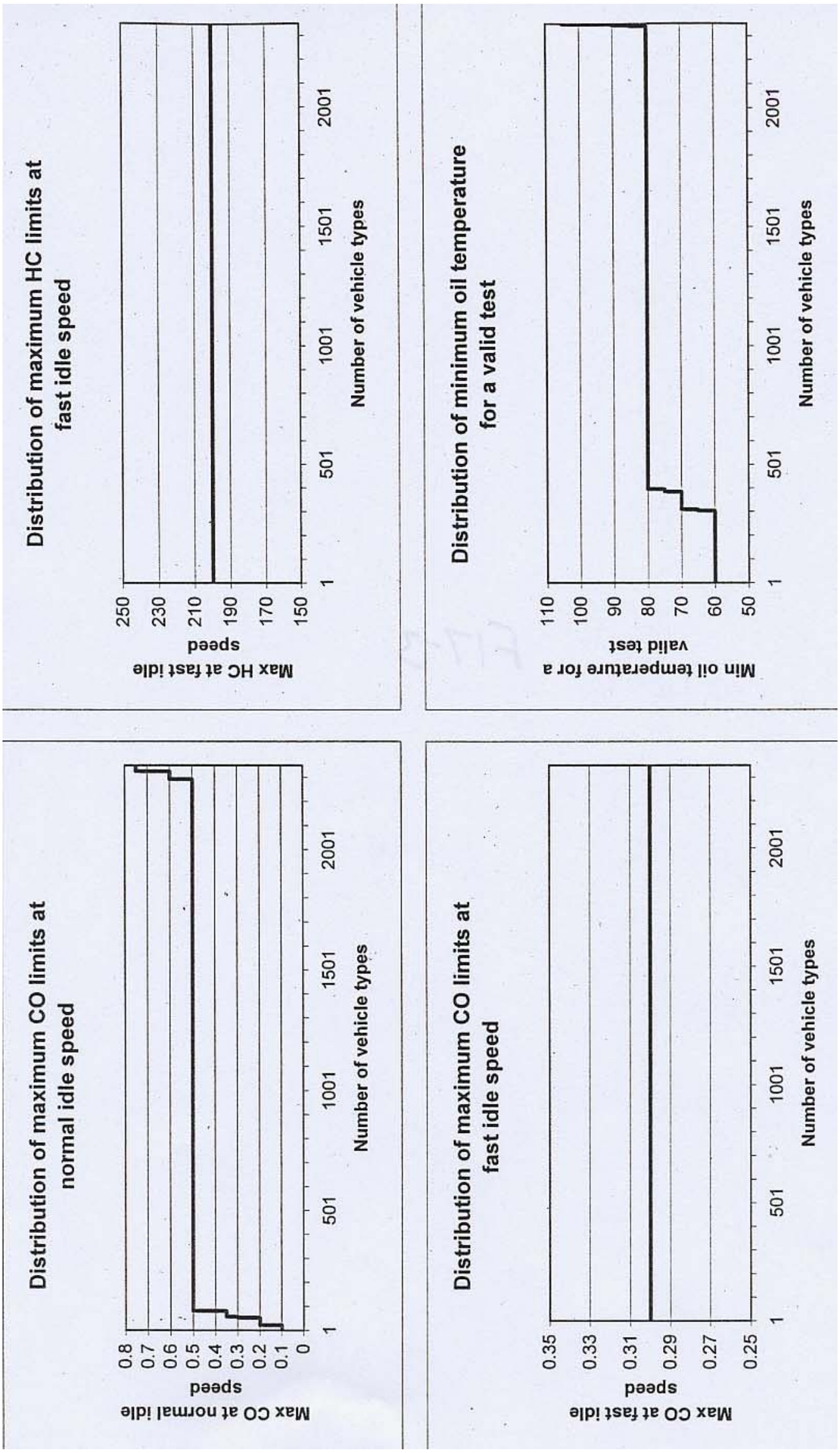

Figure 17 Profiles of the in-service limit values – Part 3

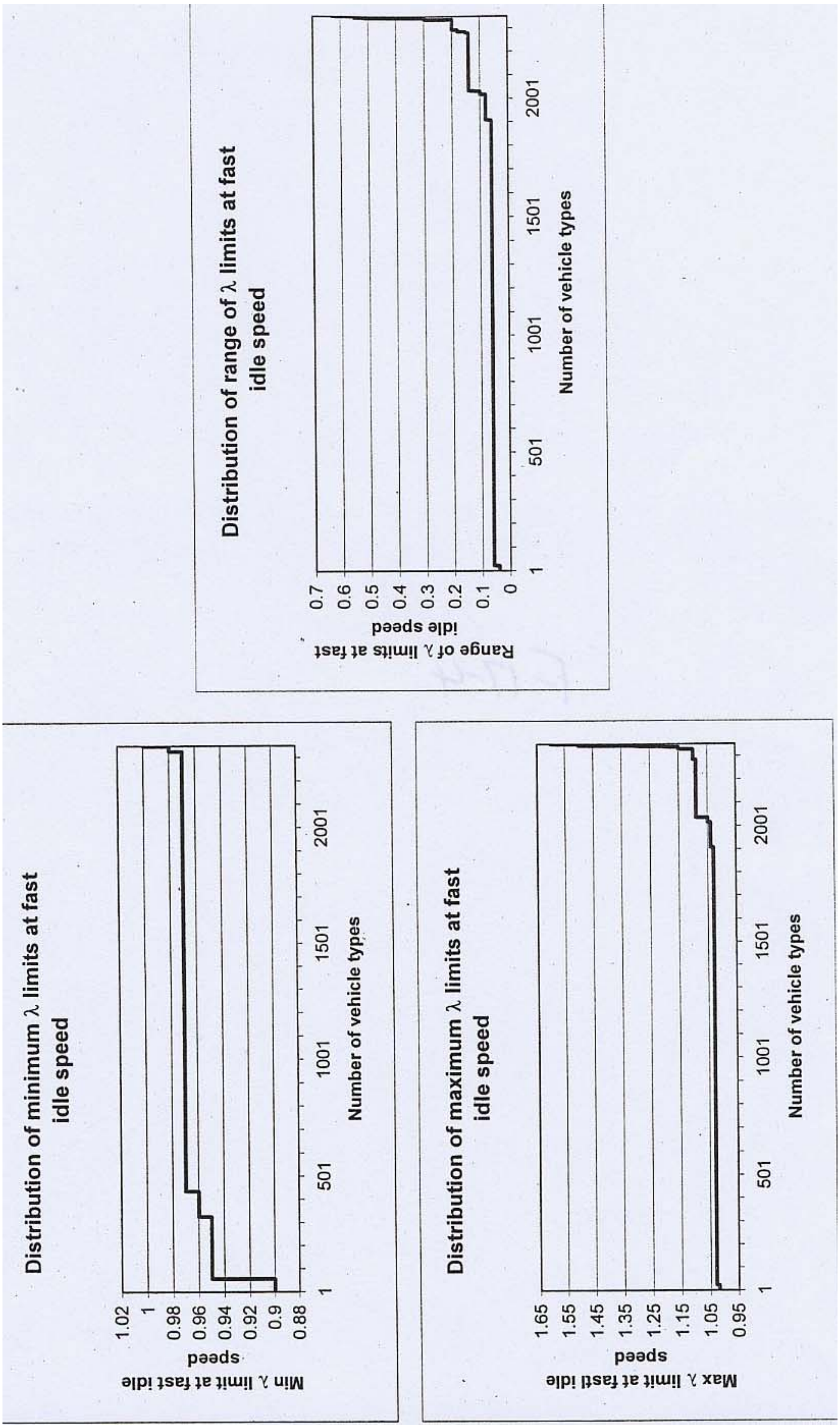

Figure 17 Profiles of the in-service limit values – Part 4

idle, and for the fast idle λ values, the range of values was also calculated, analysed, and is presented.

A word of caution is that all values are treated as equivalent, be it a Ford Escort, Vauxhall Cavalier, Maserati Ghibli or Rolls Royce Silver Seraph, i.e. no account has been taken of the relative popularity of different vehicles.

Table 9 Audit of current in-service limit values

Parameter	maximum	minimum	mean	most common
Normal idle - Max CO limit (%)	0.75	0.1	0.49	0.50
Engine speed, Normal idle - Min limit (rev/min)	1200	450	707	650,700
Engine speed, Normal idle – Max limit (rev/min)	1750	575	865	750,900
Fast idle - Max CO limit (%)	0.3	0.3	0.3	0.3
Fast idle - Max HC limit (ppm)	200	200	200	200
Fast idle - Min λ	1	0.9	0.966	0.97
Fast idle - Max λ	1.6	1.02	1.040	1.03
Engine speed Fast idle – Min limit (rev/min)	3000	2000	2438	2500
Engine speed Fast idle – Max limit (rev/min)	3500	2200	2842	2800
Min oil temperature (°C)	105	60	77	80
Range of engine speeds – Normal idle (rev/min)	1050	40	157	100
Range of engine speeds – High idle (rev/min)	1000	100	404	300,500
λ range	0.63	0.04	0.075	0.6

The upper and lower limits for the engine speed, both for normal idle and for fast idle, need to be sufficiently separated for testers to have a reasonable window in which to make the emissions measurements. It is inappropriate to comment on the low idle limits set by OEMs since this is primarily a function of the vehicle's technology. However, the >1000 rev/min range at normal idle for around 35 of the vehicle types does appear "generous".

For fast idle there are 7 vehicle types with a range of 1000 rev/min, and only 13 types with a range >600 rev/min. There is one vehicle type, the Toyota Paseo, where the manufacturer stipulates only a 100 rev/min range. Whilst there may be good reasons for this I suspect the vehicle testers would appreciate a larger, e.g. 200 rev/min, minimum range.

Another parameter that influences the ease of testing is the manufacturers' specified minimum oil temperature. Most (82.7%) manufacturers adopt 80°C, with 16.75 specifying a temperature below this, most usually 60°C. However, there are 11 vehicle types specifying a minimum temperature of >80°C, with two, Maseratis, specifying a minimum temperature of 105°C. This may be totally consistent with the normal operation of these vehicles (we have no first-hand experience of testing either of these models!). However, if this constraint were giving testers difficulties then some revision of the minimum oil temperature would be appropriate.

In terms of emissions limits, the normal idle CO values range from 0.1% to 0.75% with the vast majority, 94%, adopting the default 0.5% value. 80 vehicle types have a value less than 0.5%; with 57 between 0.1% and 0.3%. There are 25 vehicle types where the CO concentration equals 0.75% - further comments are made regarding this later.

The fast idle CO and HC limits are all currently 0.3% and 200 ppm by definition.

The values for minimum λ at high idle range from 0.90 to 1.00. 55 vehicle types have this λ limits as 0.90, 296 as 0.95 and a further 111 as 0.96. There are only two vehicles which have a minimum λ specified as > 0.98. These are the Kia Pride fitted with a feedback carburettor as the passenger car and van models. It is believed that there are sound technical reasons for this exception, and consequently this is not believed that this figure requires attention.

Turning to the maximum values specified for λ, these range from 1.02 to 1.6, with the vast majority being 1.03. A significant proportion (13.3%) have maximum values of λ of 1.09 or greater, with 22 vehicle types having λ >1.1. For some vehicles this is a consequence of their technology, e.g. the rotary engine in the Mazda RX-7 and the secondary air injection used by Porsche in some of their models.

6.4.2 Assessment of impact of extreme limit values

At normal idle the only parameter measured, and on which a vehicle can fail an emissions test, is the raw exhaust CO concentration. Vehicles for which manufacturers have declared values >0.5%, e.g. 0.75%, could clearly pass the test emitting around 50% more CO than other marginal vehicles. 19 of the 25 vehicle types in this category are manufactured by Proton. It would be interesting to have more information regarding the rationale behind these high values, and to know what the normal idle CO value measured at type approval was in comparison to that measured at in-service tests.

At fast idle the CO and HC concentrations are fixed.

The lower limit for λ at fast idle is not as flexible as it might appear. If a vehicle was on the pass/fail limit for other pollutants, producing 0.3% CO and 200ppm HC, the definition of λ, using the "simplified Lambda calculation" given in the VI MOT exhaust gas analyser specification[13], means that λ can not be less than 0.989. This occurs when the oxygen concentration is zero. If the oxygen concentration is higher than zero, then λ will be larger too. It is therefore difficult to see how a vehicle operating with a minimum λ value of less than 0.985 could pass the current test. Consequently it is believed that if manufacturers specify that λ could be below 0.97 it would **not** materially affect the number of excess emitters passing the test unless the manufacturer was able to declare a CO value of greater than 0.3%. Directive 2001/9/EC allows manufacturers to do just this.

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[13] See Appendix 3 – Calculation of Lambda value according to Brettschneider, in 4th revision of the VI's 1996 MOT exhaust gas analyser specification, 20/7/1999.

At the upper end of the range, a vehicle operating with λ >= 1.00 all the time will not be providing the catalyst with the reducing mixture to enable it to convert NO_X efficiently. However, because there are only two vehicle types which have a minimum λ specified as > 0.98 it is not believed that this figure is materially affecting the number of excess emitters passing the test either.

The upper limit for λ at fast idle varies from 1.02 to 1.6. Excluding effects like secondary air injection, if this were the cylinder charge it contains considerably more oxygen than is required for combustion. This both reduces the amount of CO and unburned hydrocarbon during combustion, and provides ample oxygen for the catalyst to complete the oxidation. Thus vehicles operating in this regime are unlikely to be excess emitters of either CO or HC. However, the combustion could produce significant quantities of NO_X, which for a mixture with a λ of 1.1 or greater, will be reduced by the catalyst with low efficiency. Whilst that is a distinct possibility, the data from the JCS study indicates that NO_X emissions from the vehicles sampled did not change with maintenance, suggesting that excess NO_X emissions caused by poor maintenance were very small (in contrast to CO and HC emissions).

6.5 THE SENSITIVITY OF THE METERS CURRENTLY USED

This section of the report will contain a brief description of the specification for the exhaust gas analysers, detailing the references that contain the detailed specification.

The current MoT exhaust gas analysers are four gas analysers measuring CO, CO_2 HC and O_2. From these concentrations λ is calculated and also displayed. The underpinning specification is given in VI's 1996 MOT Exhaust Gas Analyser Specification (4th Revision July 1999). However, this requires that analysers *meet all the requirements of the Organisation Internationale de Métrologie Légale – "Instruments for measuring vehicle exhaust emissions" OIML R99, Class 1 instruments*, with additional requirements defined in the VI specification. The OIML R99 specification was published in 1991 (the R99 is not indicative of the year it came into force) and is for a three gas analyser, CO, CO_2 and HC. Consequently, the VI specification includes the following details:

- Requirements for the oxygen analyser (section 4)
- Test procedure to be followed embodied in software (Appendix 1)
- Specification for the serial port (Appendix 2)
- Methodology for calculating λ (Appendix 3), and
- UK calibration requirements.

The fundamental requirements are given in Table 10.

Table 10 Principal aspects of the specification for 4-gas analysers

	CO	CO_2	HC	O_2
Range	0 – 5% vol	0 – 16% vol	0 – 2000 ppm vol	0 – 21% vol
Indication (equal to or better than)	0.01% vol	0.1% vol	1 ppm vol	0.02% vol (0-4%) 0.1% vol (4-21%)
Maximum permissible error (absolute)	± 0.06% vol	± 0.4% vol	± 12 ppm vol	± 0.1% vol
Maximum permissible error (relative)	± 3%	± 4%	± 5%	± 5%
Response time	95% of final value within 15 s for step change between zero and calibration gas			

A consequence of the above specification is that for the current in-service test the error, when expressed as a percentage of the pass/fail value is:

For normal idle	CO = 0.5 ± 0.06%	i.e. ± 12% of the limit
For high idle	CO = 0.3 ± 0.06%	i.e. ± 20% of the limit
For high idle	HC = 200 ± 12ppm	i.e. ± 6% of the limit
For high idle	$\lambda = 0.97 \pm 0.008$	i.e. ± 13% of the limit
For high idle	$\lambda = 1.03 \pm 0.008$	i.e. ± 13% of the limit.

The values for λ were calculated by compounding the maximum permissible error for all 4 gases in the direction that accentuated the error.

The difficulties caused by a meter having too poor an accuracy for the measurement it is intended to provide is that it generates errors of commission and omission. These are in addition to errors that occur from variability in the test procedure and poor correlation between the test procedure and the drive cycle it is intended to emulate.

Consider a vehicle whose emissions were exactly on the pass/fail limit, for example 0.50% CO at normal idle and was tested by a large number of meters. Because of the finite resolution of the meters display, and their accuracy, some would indicate a reading of 0.50% CO, some would indicate lower values and some higher. For a vehicle whose emissions were 0.49% CO again the three possibilities exist. The exact proportion in each category would depend on:
- the display resolution,
- the accuracy of the meters and
- the range of real readings offered to the meters.

For vehicles tested where the display reads 0.51% CO, or greater, such vehicles would incorrectly fail the test, i.e. be an error of commission.

The effect of varying meter accuracy can be demonstrated quantitatively. It is assumed that
- the accuracy of the meters follows a normal distribution function, such that 99% of meters are within the required specification, i.e. the errors listed above are 2.5σ
- the display precision is 0.01% CO
- the pass/fail limit is 0.50% CO, i.e. readings of 0.51% CO or greater constitute a failure.

The graph below shows the probability of a meter registering a failure for a vehicle whose real emission level is as depicted on the x-axis. Levels of meter accuracy relative to the 0.50% threshold of 6%, 13% and 20% are plotted, corresponding to the errors listed above. An additional line corresponding to 30% is included. (This would be the error using the current meters for CO at high idle if the pass/fail limit were reduced to 0.2% as some have suggested.)

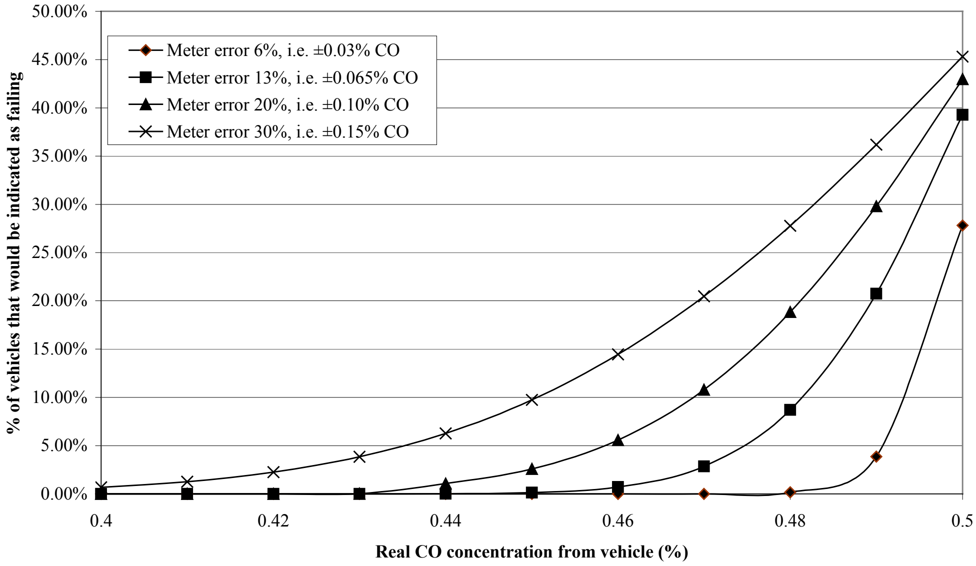

Figure 18 The influence of meter accuracy on the fraction of vehicles incorrectly failed

This analysis can be applied to the TRL data. The number of vehicles having a measured CO concentration at normal idle of 0.40 to 0.50 +/- 0.01 was found from the database. This was a total of 233 of the 2172 vehicles. These frequencies were then multiplied by the probability of a meter registering a failure, as calculated above, and summed. The results are:

Meter error as % of pass/fail limit	6%	13%	20%	30%
Number of error of commission (vehicles)	7.8	17.4	25.6	35.8
Number of error of commission (% of sample)	0.36%	0.80%	1.18%	1.70%

It must be remembered that these data are in the context of an overall failure rate of around 5%.

This is uncomfortably large for a 20% error, i.e. that appropriate when measuring the high idle CO level with the current meters. It is argued that in this context if evidence concluded that an in-service limit of 0.2% was appropriate to ensure that vehicles were correctly maintained, meter accuracy would need to improve, probably by a factor of two, to prevent a large number of error of commission, and the subsequent devaluing of the upgraded test's objectives.

7 Cost effectiveness analysis

Key issues addressed in Chapter 7

Changes that involve financial costs to the public need to be justifiable in terms of their cost effectiveness. This chapter provides a first iteration cost effectiveness calculation. It comprises:

- a generic review of the costs involved for various testing scenarios,
- calculation of the cost of the current testing regime, both currently and in the future,
- estimation of the cost to the motorist of repairing failed vehicles,
- estimation of the emissions savings for 1997/8 by the current test,
- predicting the emissions savings potential for future years if all excess emitter vehicles were detected (i.e. predicting the maximum benefit of an in-service test), and
- calculating the cost effectiveness, or maximum possible cost effectiveness, in units of g/£.

7.1 INTRODUCTION

The primary purpose of this project (as a whole) is to provide advice on in-service testing regimes as detailed in the introduction to this report. The advice must be in the context of the testing required/desirable, what is technically possible and could be implemented, and what is appropriate for vehicles that comply with recent and future European directives. In addition, the advice offered must be costed. The costs associated with testing are expected to be recovered via the fees charged and these fees have to politically acceptable. There is also the costs to motorists of incorrectly failing vehicles (retest fee, unnecessary maintenance etc.) to be considered. Therefore an analysis of the effectiveness of various testing options, in terms of the savings in pollutant emissions (measured in mass/year) and the cost of undertaking the testing options (calculated in £/year), is required. From these two numbers the cost effectiveness, in units of grams saved per pound spent, can be calculated.

The cost-effectiveness analysis presented here is the first iteration of a process that will be reviewed/recalculated during each phase of the project. It is intended to provide sufficient detail to enable the definition of the next activities of the programme, thereby preventing the project's resources being spent on pursuing inappropriate avenues.

The years chosen for the cost-effectiveness analysis are 1997/8, 2005, 2010 and 2015. These are selected because 1997 provides a convenient date for which there is both atmospheric emissions inventory data available and for which data from the JCS and TRL studies are relevant. 2005 is one of the earliest years in which the fruits of this project could potentially be harvested. 2010 and 2015 represent dates where the projected emissions inventory will be significantly affected by the adoption of the currently proposed changes in vehicle emissions standards. Together, this time-scale spans the current through to the future, thereby enabling the DTLR to conveniently evaluate the recommendations made in the context of the current testing position.

The pollutants for which an effectiveness will be calculated are CO, NO_X and HCs. Particulate matter, a challenging requirement, is not considered in detail until Phase 2 of this project, and consequently potential savings of this pollutant will not be calculated in this phase. Benzene and 1,3, butadiene, which are species for which there are national air quality standards, will also be estimated.

7.2 GENERIC CONSIDERATIONS

In general terms the cost of implementing a defined testing regime can be itemised to include:

1 Setting up costs
    1.1 purchase of the meters that meet the specification
    1.2 purchase of any vehicle testing equipment required to enable the specified procedure to be followed (this could range from none being required to the cost of a dynamometer)
    1.3 installation costs of any vehicle testing equipment required
    1.4 cost of training the testers on the use of new meters and undertaking a new procedure.

These one-off costs should be depreciated over an appropriate term, enabling an annual cost of interest on capital expenditure and depreciation to be calculated.

2 Annual costs
    2.1 servicing of the meters
    2.2 servicing of any vehicle testing equipment used by the specified procedure
    2.3 cost of refresher training for the testers.
    2.4 insurance costs.

3 Costs per test
    3.1 time taken by tester to examine vehicle and report findings
    3.2 cost of repair of failed vehicles by owners.

There is the question as to whether the cost of repair of failed vehicles by owners should be included in the cost effectiveness calculation because owners have a responsibility to maintain their vehicles and in-service testing is merely a measure to enforce this. In this study this cost is **not** included in the cost effectiveness calculation.

7.3 COST OF TESTING

The current in-service test regime the estimate by DTLR is that the average cost of testing a vehicle with a TWC is £7.30[14].

If it is assumed that:

- the cost per test remains at £7.30 / test (1997/8 costs),
- the ratio of the number of tests to the number of eligible vehicles remains constant at 941 tests/1000 vehicles (data from NAO report),
- the ratio of the number of eligible vehicles to the total number of gasoline vehicles in the fleet remains constant,
- the number of gasoline vehicles in the fleet is that given by the input data to the national atmospheric emissions inventory model,

then the cost of testing can be simply calculated, to give the result presented in Table 11.

Table 11 Estimated cost of testing gasoline vehicles

Year	1998	2005	2010	2015
Cost of testing	£139.95M	£142.48M	£150.83M	£159.04M

Further details of how these final figures are derived are given in Appendix 5.

7.4 COST OF REPAIR

In Chapter 4 it was found, from data that is admittedly a few years old, that around 5% of cars fitted with TWCs failed the emissions component of the annual road worthiness test. In Section 4.2 the frequency of the occurrence of faults was analysed. These data are the basis for calculating the cost of repair. The details of the methodology are given in Appendix 5. This gave an average repair bill of £195 per failing vehicle.

From the average number of tests, Table 1 of Appendix 5, assuming a continuing 5% failure rate and the average repair bill remaining at £195, the projected annual costs of repairing gasoline vehicle which fail the annual emissions test were calculated and are given in Table 12.

Table 12 Projected annual costs of repairing gasoline vehicles which fail the annual emissions test

Year	1998	2005	2010	2015
Cost of repairing vehicles	£186.92M	£190.29M	£201.45M	£212.41M

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[14] Private communication with DTLR VSE2, August 2001.

7.5 EFFECTIVENESS ANALYSIS

For 1997/8 the actual effectiveness of the current test regime can be estimated from the MoT test data given in the TRL report[15]. For future years what is calculated is the **savings potential** which is the savings to the Atmospheric Emissions Inventory that would be made if all target vehicles were correctly identified and then rectified. Given the imperfect nature of in-service testing, the savings that would be achieved are actually only a fraction of the savings potential.

The actual effectiveness or the "savings potentials" calculated here are the possible reductions in emissions predicted for a **year-on-year basis for the UK fleet operating in the environment of there being an in-service emissions test that is enforced**, i.e. as present. If one considers an alternative scenario of there being no annual in-service test there is the high probability that the majority of excess emitters will not be rectified because their driveability is unaffected, as discussed above, and because the environmental ethos would change. Currently the ethos is that emissions from vehicles **do** significantly affect health and that is why proper maintenance is required and policed during the annual MOT inspection. The abolition of an annual emissions test is likely to seriously undermine this tenet. Consequently, if the annual savings potential, as reported here, is X ktonnes per year, the savings over a five year period would not be 5X ktonnes but 15X ktonnes because of the cumulative effect of an increasing number of unrectified gross polluters. The 15X comprises X in the first year, 2X in the second, 3X in the third, 4X in the fourth and 5X in the 5th. Over 10 years the savings would be 55X rather than the 10X implied by a simple additive yearly saving.

Finally, it is emphasised that the "savings potentials" calculated here are **the reductions possible from an in-service test. They are not the possible savings over and above those achieved by the current test.**

7.5.1 Effectiveness analysis for 1997/8

The foundation for the calculation is the TRL study on nearly 2,200 MOT tests for cars fitted with TWCs. Details of the calculation are given in Appendix 5. Two key assumptions in they analysis were:

- vehicles whose high idle CO concentrations are above 0.3% are rectified such that on retest their CO concentration equals 0.3%, and
- the extent to which the high idle CO concentration is above 0.3% is equal to the excess emissions for the vehicle on-the-road.

Appendix 5 contains an assessment of the validity of this last point particularly in the context of the poor correlation between emissions for unloaded tests and those for loaded drive cycles. For example, this approach to calculating the emissions reduction also does not account for errors of commission in the failure statistics. An attempt is made to compute the relationship between the CO concentration in the raw exhaust at high idle and the CO emissions over the type approval cycle. The conclusion reached is that the 0.3% MOT pass/fail limit would correspond

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[15] An analysis of emissions data from the MOT test, TJ Barlow, RS Bartlett and ICP Simmons, Report to the DETR ref. PR/SE/474/98, Aug 1998.

to 4.29 g/km. However, the assumptions made, and the very significant differences between the two cycles means that this relationship has caveats attached regarding its validity.

On this basis analysis of the TRL data indicates that the existing I&M programme would have led to an emissions reduction of 44.5% of the original cumulative CO emissions total.

This is an interesting observation because the JCS study concludes: "if all the high emitters had been repaired the emission benefits would be approximately 50% for CO and 35% for HC"[16]. Further, examination of the key figure on which this is statement is based, the upper quartile of Figure 15 in the JCS report, reveals that even after maintenance a few (5) cars still had CO emission levels of greater than 20 g/km. If these were rectified to produce, say, 5 g/km, the emission benefits would have been around 57%.

Hence overall, the data from the TRL study is consistent with the JCS data if it is remembered that the JCS "Total" sample was skewed having a higher than average number of the highest emitters.

The percentage reduction for CO was converted into ktonnes saved. Further, the emissions reduction for other pollutants, caused by repairing the MoT failures was also estimated in ktonnes. Underpinning assumptions used in the calculations were:

- that the contribution to the NAEI of pollutants from mobile sources is that from the "well maintained" proportion of the fleet
- that the maintenance of the vehicles in the TRL study causes the same pro-rata emissions savings as was measured in the JCS study (over the NEDC) for hydrocarbons and NO_X.
- and that the savings calculated for hydrocarbons generically also applies to benzene and 1,3 butadiene.

Using the NAEI figures for the emissions from gasoline vehicles fitted with catalysts in 1998 (taken from the 1999 NAEI road transport emissions projections data) the reduction in emissions achieved were calculated to be:

Species	CO	NO_X	Benzene	1,3 butadiene	NMVOCs
Reduction in emissions achieved by current test	1,070 kt	4.68 kt	1.88 kt	0.33 kt	32.0 kt

7.5.2 Emissions savings potentials for 2005, 2010 and 2015

The calculation assumes the traffic activity used to calculate the emissions inventory. However, this may lead to systematic errors in the estimation of the emissions savings potentials. One potential source arises from the generalisation that older vehicles, whilst travelling fewer miles than new vehicles, tend to have a shorter average journey distance. As these are the very vehicles whose catalyst activity might be below standard, this would mean that the combined effect of the reduction in catalyst activity and the change in journey characteristics makes their excess emissions actually higher than would be calculated from fleet means.

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[16] taken verbatim from page 32 of JCS Main Report on *the inspection of in-use cars in order to attain minimum emissions of pollutants and optimum energy efficiency*, May 1998

The basic methodology adopted for each pollutant, is:

1. to select the model's parameters (possibly to fit some data)
2. to select the pass/fail criterion,
3. to compute the fraction of vehicles above and below the emissions pass/fail criterion
4. to compute the fraction of the total emissions from the vehicles above and below the emissions pass/fail criterion
5. to compute a new revised total of emissions if all failing vehicles (those above the threshold) emitted at a lower rate (e.g. the pass/fail level)
6. express the emissions reduction in terms of the percentage increase to the revised total of emissions for rectified vehicles
7. find the NAEI prediction for the selected pollutant for each selected year
8. multiply the NAEI figure by the emission reduction from 6 above, to convert from percentage of a normalised whole to ktonnes/year.

The details of the calculations are given in Appendix 5.

The emissions reduction was then expressed in terms of the percentage change of the revised total of emissions for the repaired vehicles, i.e.

$$(\text{Emissions}_{\text{before repair}} - \text{Emissions}_{\text{after repair}}).100 / \text{Emissions}_{\text{after repair}}.$$

The forecast NAEI emission figures for the three selected years, taken from the 1999 NAEI road transport emissions projections, are used to express the emissions savings potential in ktonnes. Details of the methodology used are given in Appendix 5.

If it is assumed that the repaired vehicles have average emissions of 67% of the pass/fail limit then the emissions savings potentials were calculated and are listed in Table 13.

Table 13 Emissions savings potential (in k tonnes/year)

Species	CO	NO_X	Benzene	1,3 butadiene	NMVOCs
Year	Total (Random)				
2005	2,039 (167)	82.8	1.71	0.36	34.6
2010	1,658 (136)	61.2	1.45	0.28	30.9
2015	1,398 (115)	51.4	1.34	0.24	29.0

For CO the emissions savings potential was calculated using the model's parameters for both the "Total" and the "Random" sample. The emissions savings potential for the latter are the figures in brackets

7.5.3 Cost effectiveness

From costs derived earlier, the cost effectiveness based on the savings potentials can be calculated. The results are tabulated in Table 14. Also included are the cost effectiveness of the existing regime, calculated for the savings that were estimated to have been generated in 1997/8 when divided by the in-service programmes costs for that year.

Table 14 Cost effectiveness achieved in 1997/8, and maximum possible for selected future years. All figures in g/£

	Cost effectiveness achieved	Maximum cost effectiveness that might be achieved		
	1997/8	2005	2010	2015
NO_X	31.8	581.2	405.9	323.1
NMVOC	273.7	242.7	204.5	182.6
Benzene	14.5	11.98	9.61	8.41
1,3 butadiene	4.0	2.53	1.84	1.54
CO “Total”	7,503	14,313	10,995	8,792
CO “Random”		1,175	902	722

It should be remembered that the cost effectiveness data for future years are the maximum possible cost effectiveness for all pollutants assuming the cost structure of the in-service testing regime remains unaltered.

Generally it is noticeable that cost effectiveness reduces in future years, because vehicles continue to become cleaner by design. As this happens the level of excess emissions from those vehicles which are poorly maintained decreases in absolute terms, and therefore becomes less significant in terms of achieving air quality targets. There are also wide boundaries on the savings potential for CO, dependent on which model will best represent the distribution of emissions in the future.

Again, it is emphasised that this is a preliminary cost effectiveness analysis based on a series of assumptions and caveats. It will be reviewed and revised in later phases of the project.

Finally, the savings predicted here can be compared with those given in the NAO report. In order to separate differences in prediction methodologies, and the difference between “emissions savings potential” calculated here and “predicted emissions avoided” calculated by the NAO, the comparison will be restricted to the year 1998. These are summarised in the table below:

Table 15 The amount of emissions avoided by the in-service test programme in 1998 (in k tonnes/year)

Species	NAO figures	This work
	1998	1998
Carbon monoxide	297	769
Nitrogen oxides	32	4.5
Hydrocarbons	24	38
Particulates	7	-

At first sight the data appear to be moderately similar, generally within a factor of 3. However, the are some substantial differences in methodology. The data from this work is the predicted savings for petrol fuelled vehicles with TWC technology. The data in the NAO report is for all road transport, i.e. it includes the non-catalyst petrol vehicles and the diesel fleet and is a measure of the effectiveness of the in-service test programme in its entirety.

The inclusion of diesel vehicles accounts for the larger values of NOX and particulates avoided as computed by the NAO relative to this work.

If the savings from non-catalyst vehicles were subtracted from the NAO data the difference between the two sets of figures for carbon monoxide and oxides of nitrogen increases greater than a factor of 5.

The NAO report computes the emissions avoided by multiplying an estimate of the annual emissions from the type of vehicle being considered by a reduction factor. The reduction factors used were gleaned from the JCS study, using the data from the "Random" sample. As has been discussed earlier there are reasons to believe these data are unrepresentatively low, and the estimate produced in this report from the TRL study using the results from more than 2,000 MOT tests is believed to be more representative.

Overall, the conclusion from these cost effectiveness calculations is that the available data indicates the current test is a valuable contribution to reducing emissions of pollutants, and to improving air quality. **It is remarked that this means that there is room for improvement on the current test, but that such savings are not guaranteed for future years.**

8 Conclusions and recommendations

Key issues addressed in Chapter 8

This chapter draws together the conclusions for this Phase 1 study and highlights four key findings, namely:

- the definition of an excess emitter vehicle,
- the percentage of vehicles emitting above these limits,
- the detrimental impact that poorly maintained vehicles are having on air quality, and
- the significant contribution that the current in-service test made to reducing carbon monoxide and hydrocarbon pollutant emissions in 1998.

The chapter also makes recommendations regarding minor changes that could be made to the current in-service test to increase the ease of testing or confidence in the results obtained. Recommendations are also made regarding specific issues it is recommended be addressed by the Phase 2 study.

8.1 CONCLUSIONS

8.1.1 Definition of an Excess Emitter

The two species of most concern to the nation meeting its air quality standards are NO_X and PM. Gasoline fuelled vehicles contribute significantly, 24% and 3.7%, to the total inventories. They also make major, greater than 60%, contributions to the National Atmospheric Emissions Inventory (NAEI) for benzene, 1,3 butadiene, carbon monoxide and lead. Further, the contributions are geographically localised in urban areas where air quality is generally poorer. Cold start emissions contribute 54% for CO, 16% for NO_X, 27% for hydrocarbons and 13% for PM_{10} to the urban inventory from petrol fuelled vehicles.

Key Finding 1

The definition of an excess emitter has been considered. That chosen reflects the principal issues noted above: the EU type approval standards, the in-use compliance standards and the important contribution cold emissions make to the inventory. The conclusion reached is that a vehicle is an excess emitter if its CO, HC or NO_X emissions are outside those of the European standard that applies when measured over the type approval drive cycle specified in directive 98/69/EC (the NEDC) after due allowance has been made for degradation at the rate of an additional 20% for each 50,000 miles (80,000 km) that the vehicle has been driven.

One caveat to the above definition is that it does not account for CoP scatter. More significantly, experience has shown that the emission levels over the NEDC cannot simply be related to levels on an idle test, i.e. there is a poor correlation between the emissions measured by the two tests.

On this basis vehicles would be excess emitters if their emissions exceeded the figures tabulated below (in g/km over the NEDC) after having travelled the number of km indicated.

For passenger cars meeting directive 91/441/EEC emissions limit values

Species	TA limit	40,000 km	80,000 km	120,000 km	160,000 km	200,000 km
CO	4.05	4.46	4.86	5.27	5.67	6.08
HC	0.65	0.72	0.78	0.85	0.91	0.98
NOx	0.46	0.51	0.55	0.60	0.64	0.69

For passenger cars meeting directive 94/12/EC emissions limit values

Species	TA limit	40,000 km	80,000 km	120,000 km	160,000 km	200,000 km
CO	3.28	3.61	3.94	4.26	4.59	4.92
HC	0.34	0.37	0.41	0.44	0.48	0.51
NOx	0.24	0.26	0.29	0.31	0.34	0.36

For passenger cars meeting directive 98/69/EC Stage A emissions limit values

Species	TA limit	40,000 km	80,000 km	120,000 km	160,000 km	200,000 km
CO	2.3	2.53	2.76	2.99	3.22	3.45
HC	0.2	0.22	0.24	0.26	0.28	0.30
NOx	0.15	0.17	0.18	0.20	0.21	0.23

8.1.2 Proportion of Fleet Emitting above Excess Emitter Threshold

A mathematical model that described the distribution of emissions over the chosen drive cycle has been developed. The model is based on the **log normal** distribution, and it predicts a distribution using two parameters, an arithmetic mean and a standard deviation of the population. The model was fitted to data from the JCS study. This study evaluated 192 cars fitted with closed loop fuelling and TWC systems. 135 were in the “Random” group which were augmented by a further 57 selected deliberately as “likely high emitters” to create the 192 large “Total” group. NO_X, HC, CO and CO_2 emissions were measured over the NEDC. These were the data to which the model was fitted. The quality of the fitting ranged from good to moderate. For CO, the pollutant for which emission distributions of the two JCS samples varied most, parameters were selected to produce distributions that bracket the “real” distributions.

The values of the model’s parameters that were adjudged to give the best fit are tabulated below. So too is the threshold (g/km over the NEDC) beyond which vehicles can be considered to be an excess emitter

	Model’s parameters		
Species (JCS data set)	mean emissions	standard deviation	Excess emitter threshold
NO_X	0.192 g/km	1.05	0.53 g/km
HC	0.22 g/km	1.00	0.75 g/km
CO (“Total” sample)	2.7 g/km	1.50	4.66 g/km
CO (“Random” sample)	2.7 g/km	0.95	4.66 g/km

Key Finding 2

From the model, using the parameters and excess emitter threshold values tabulated on the previous page, the percentages of vehicles emitting beyond various threshold levels were found to be:

	Excess emitter	Excess emitter +25%	Excess emitter +50%	Excess emitter +100%	Excess emitter +200%	Excess emitter +400%	Excess emitter +900%
NO_X	25.3%	16.3%	10.7%	5.3%	1.6%	0.24%	0.00%
HC	12.3%	8.1%	4.9%	2.0%	0.46%	0.05%	0.00%
CO (Total)	34.4%	27.0%	21.6%	14.5%	7.4%	2.6%	0.80%
CO (Random)	5.2%	2.5%	1.3%	0.39%	0.05%	0.00%	0.00%

Principal conclusions from this analysis are:

- the (surprisingly?) high number of vehicles (both found in the JCS study and duplicated by the model's predictions) whose emissions are above the NO_X standard,
- the fraction of excess NO_X emitters appears to be independent of the vehicle sample and the state of maintenance, with maintained vehicles having an emissions distribution nearly identical to that before maintenance,
- the reasons for the high proportion of excess NO_X emitters, and its insensitivity to maintenance is not currently known,
- the high degree of variability of CO emissions dependent on vehicle sample selection, with maintained vehicles having a very different emissions distribution relative to the same vehicles before maintenance.

Key Finding 3

The percentages of vehicles emitting beyond various thresholds is contributing to pollutant emissions and thereby affecting UK air quality. The most serious in terms of its direct detrimental contribution to health is NO_X. However, the reasons for the relatively high number of vehicles emitting above their type approval limit, and the apparent resistance of emission levels to maintenance, is not clear, see comments in the Recommendations Section of this chapter.

Atmospheric levels of other pollutants, most notably CO, although higher than they would be in the absence of vehicles, are currently viewed as being sufficiently low so as not to cause significant detrimental health effects directly. (However, hydrocarbons are significant, though in a complex manner, as an ozone precursor.) Consequently excess emitting vehicles are generally not preventing the nation from meeting its current air quality targets for species other than NO_X.

It has been shown that CO is a useful indication of the state of repair of petrol vehicles and as such it measurement, and its use to trigger maintenance, is an important strand in maintaining pollutant emissions from vehicle as low as reasonably achievable.

8.1.3 Reasons for Excess Emissions

An assessment of the likely degradation mechanisms and their impact on emissions performance was undertaken. The number of faults that lead to excess emissions for a vehicle with closed loop fuelling control and a three way catalyst (TWC) was found to be relatively small, vis:

- failure of the closed loop fuelling system,
- failure of the catalyst, or
- leakage in the exhaust system between the engine and the catalyst,

and sub-systems within these headings.

Attempts to quantify the rates of failure showed that there are serious difficulties in gathering unbiased, objective, statistically meaningful data. The general consensus for the frequency of faults influencing emission is in descending order:

- λ sensor faults
- catalyst internal integrity
- catalyst external integrity (corrosion or other leaks)
- others.

8.1.4 Effectiveness of Current in-service test

A major part of the study has been an assessment of the effectiveness of the current annual test at identifying excess emitters. The success criteria were that the test should:

a. maximise the likelihood of detecting the worst offenders, i.e. optimising the cost effectiveness of improving air quality and
b. minimise the number of vehicles erroneously identified as requiring maintenance.

The JCS study, which included measuring the emissions over both the type approval cycle and the two speed idle, in-service test concluded: *on the basis of the test results of the random sample, the short test legislated by directive 92/55/EEC was completely ineffective*, and *the efficiency of this test clearly increases with increasing share of excess emitters*. Also, *the λ test was found to aid in the identification of NO_X emitters but had the drawback of increasing the errors of commission.*

Analysis of the TRL study data gave a snapshot of the current test's effectiveness during the period June 1997 to July 1998. Around 31% of vehicles failed the first fast idle test, 26.5% failing because of high CO emissions with the vast majority having λ within its prescribed limits. With further preconditioning over 97% of these then passed. This observation raises serious questions on the value of the CO readings. Overall, 5.6% failed the complete test, 2.4% on high λ only, 3.2% on high CO (of which 1% failed on an additional factor too, e.g. low λ or high HC) and only one vehicle in the sample of 2,174 failed on neither low λ only nor high CO, (it failed on high HC and high λ).

Vehicles with high CO concentrations (greater than 2.0%) **and** $\lambda<0.95$ comprised 1.24% of the sample, and contributed 35.1% of the cumulative CO readings. There is a challenge in determining how large an impact this represents for the vehicles' on-the-road emissions. However, an analysis is presented to suggest that for these very high emitters a similar saving might be expected. Notwithstanding, these data indicate that for this statistically large sample the detection of a few high emitters is having a very clear impact on reducing emissions and improving air quality.

A corollary to this is that the emissions saved by the test accrues from the detection of a few vehicles well over the 0.3% pass/fail limit, and not from vehicles in the 0.3% - 0.5% range.

The current technical specification for the meters used for in-service testing is for a maximum permissible error of ± 0.06% vol for CO. A further conclusion is that this is a relatively poor accuracy for a pass/fail threshold of 0.3% CO and will contribute to the errors of commission. An analysis to quantify this concluded that the current meters would fail around 25% of vehicles whose true emissions were 0.29% CO, erroneously indicating values >0.30%. (If the pass/fail threshold were lowered to 0.20% then the percentage of vehicles, whose true emissions were 0.19% CO, incorrectly failed would increase to around 33%.)

Therefore this study:

- advocates caution in over interpreting data from vehicles close to the 0.3% CO level because of the influence of preconditioning and the accuracy of the current meter specification,
- does not recommend a relaxation of the limit, to a value greater than 0.3% currently used,
- nor does it recommend a tightening of the limit to a value less than 0.3%.

This last recommendation is made in the light of recent discussions within the EU on the possibility of reducing the high idle CO limit from 0.3% to 0.2%.

There is some evidence from a more recent VI study that overall average levels of emissions from TWC vehicles may be reducing.

Key Finding 4

Therefore, this review concurs with the JCS study's conclusions that that the current in-service test is better at detecting vehicles emitting significantly above the "excess emitter" threshold than vehicles only just over the threshold. However, in the context of its impact on air quality, the detection of a small number of high emitters in the fleet, and their subsequent rectification, is reducing CO and HC pollutant emissions and thereby improving air quality.

The report also reviews and assesses the current procedure and meter specification. It makes some recommendations regarding improvements that might be made, see next section.

A preliminary cost effectiveness analysis was also undertaken. The results of this analysis are tabulated below. The emissions savings for 1998 is that calculated to have occurred, whilst for the three future years it is emissions savings potential that is calculated. The significance of the savings, or savings potential, as a proportion of the total UK inventory predicted is included as a percentage within brackets. It is noted that potential savings, and the potential cost effectiveness, decrease with time as vehicles become cleaner.

Costs	1998	2005	2010	2015
	£139.95M	£142.48M	£150.83M	£159.04M
Emissions savings potential in ktonnes				
	1997/8	2005	2010	2015
NO_X	4.68 (0.3%)	82.8 (6.1%)	61.2 (5.2%)	51.4 (4.8%)
NMVOC	32.0 (1.6%)	34.6 (2.4%)	30.9 (2.2%)	29.0 (3.4%)
Benzene	1.88 (5.7%)	1.71 (9.0%)	1.45 (8.5%)	1.34 (8.9%)
1,3 butadiene	0.33 (4.8%)	0.36 (11.8%)	0.28 (11.8%)	0.24 (11.5%)
CO “Total”	1,070 (22.5%)	2,039 (62.2%)	1,658 (58.4%)	1,398 (52.0%)
CO “Random”		167 (5.1%)	136 (4.8%)	115 (4.3%)
Cost effectiveness in g/£				
	Cost effectiveness achieved	Maximum cost effectiveness that might be achieved		
	1998	2005	2010	2015
NOx	31.8	581.2	405.9	323.1
NMVOC	273.7	242.7	204.5	182.6
Benzene	14.5	11.98	9.61	8.41
1,3 butadiene	4.0	2.53	1.84	1.54
CO “Total”	7,503	14,313	10,995	8,792
CO “Random”		1,175	902	722

Where the two estimates for CO are based on JCS data representing extremes of a well maintained fleet (the “Random” sample) and a fleet with an atypically high proportion of very high emitters (the “Total” sample).

To summarise, this study concludes that emissions from gasoline fuelled vehicles do affect the nation’s air quality. The current in-service test regime is generating some (significant) benefit **but** there is scope for devising an improved test. The poor correlation between the current unloaded test and real drive cycles means that an improved test is unlikely to be simply a tightening of the current tests’ limits. This would most likely increase the errors of commission whilst generating minimal emissions savings.

8.2 RECOMMENDATIONS

The report makes recommendations in two distinct areas. Firstly, minor changes that might improve the current test, additional to the Basic Emissions (in-service) test that is being introduced, and secondly areas that the Phase 2 study should address.

8.2.1 Recommended changes to the current in-service test.

These are principally intended to increase the ease with which testers can test vehicles and to increase confidence in the answers indicated by instruments. It is emphasised that these are viewed as improvements in the current test procedure. They do not replace, or substitute for, trying to devise an improved test.

The recommendations are:

- modifications in the testers routine regarding oil temperature and vehicle identification
- modifications to the readouts of meters, changing both the precision displayed and the minimum reading value,
- modifications to the calibration of meters regarding the concentrations of the calibration gas and the frequency of zero checks.

It is recommended that the current pass/fail limits remain unaltered whilst this current research into an in-service test is progressing. If it were decided, in the fullness of time, to continue with the current test, albeit in a slightly modified form, then the pass/fail limits should be reviewed again using the information generated by this project to help define the optimum values.

8.2.2 Specific issues it is recommended that the Phase 2 study addresses

It is noted that there are a couple of elements that the ITT specified should be covered in this Phase 1 report that have not been addressed. These are the consideration of the use of type approval derived high idle limits and the effects of implementing generic limits. These are to be covered in the Phase 2 study.

The ITT stated that Phase 2 of the project should comprise 4 elements, namely:
Task 2.1 Evaluation the considerations for HC, CO, NO_X and or λ measurement.
This evaluation should aim to answer the following questions:

- What practical options exist for alternative in-service tests that more effectively identify excess emitters than the current test?
- Is there a need to measure HC emissions and NO_X directly?
- If there is what technologies are available for making these measurements?
- If there is how might NO_X can be measured at low engine loading levels?
- Again if there is the need, what are the likely costs of measuring NO_X and/or HC?

Task 2.2 Evaluation the considerations for particulate measurement.
This evaluation should provide advice regarding:

- whether particulate measurement is appropriate to screen older vehicles which may be burning lubrication oil;
- if particulate measurement is appropriate what technologies could practically collect a large enough sample of PM during an annual roadworthiness test;
- what might be an appropriate test procedure and measurement technology, especially if smoke obscuration is not an acceptable measure.

Task 2.3 Evaluation the significance of OBD/OBM.
This evaluation should aim to answer the following questions:

- How can the information from the OBD/ODM sensors be used in an in-service test?
- Is the information of sufficient integrity to negate the need for tail pipe testing?
- If the answer to the above question is yes, then what equipment/instrumentation would be required for emissions assessment purposes in vehicle test centres?

Task 2.4 Cost effectiveness and benefits.
The initial cost effectiveness study undertaken in Phase 1 should be revised.

The proposal by AEA Technology, accepted by the DTLR, addressed these four elements.

The results from the Phase 1 study confirm the need for the Phase 2 study to comprise the above four tasks. They also highlight some additional or specific aspects that it is recommended the Phase 2 study should be expanded so as to include:

1. the origin of the relatively high proportion of excess NO_X emitters,
2. further consideration as to why their emissions appear resistant to the effects of vehicle maintenance,
3. consideration of alternative test procedures to improve on the current in-service test.

Concerning item 3 above, it is recommended that aspects to be specifically addressed include:

- improving the correlation of the test to the emissions from vehicles over transient loaded cycles,
- introducing an improved assessment of catalytic activity
- improving (i.e. reducing) the currently high number of vehicles which fail the first high idle emissions test but after further preconditioning pass a second high idle emissions test,
- reducing what may be an unreasonably high number of inappropriate failures because of the high idle upper λ limit.

The above recommendations, taken together, emphasise the principal objective of the Phase 2 study, namely that it identifies options for alternative test procedures in the context of developments in automotive technology, and the role of the annual in-service test to ensure vehicles remain appropriately maintained.

Appendices

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