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REPORT

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

Phase 2b Report

Identification of options for alternative test procedures

A report produced for DfT

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December 2002

Title	An In-Service Emissions Test for Spark Ignition (SI) Petrol Engines – PPAD 9/107/09: Phase 2b Report – Identification of the options for alternative test procedures
Customer	DfT
Customer reference	PPAD 9/107/09
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File reference	E&E/61021
Report number	EMStec/02/027
Report status	Issue 3

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Executive Summary

The UK Government's Department for Transport (DfT) have commissioned this phased project. Its focus is the in-service testing of petrol engined cars fitted with three-way catalytic converters. This report describes work undertaken in the second phase of the project which is predominantly focussed on how the current in-service test might be improved to become more cost effective, further reducing excessive pollutant emissions from SI vehicles.

This phase addressed the following topics:

- evaluating whether the fitting of OBD/OBM negates the need for the current in-service tailpipe test,
- evaluation of the considerations for λ, CO and HC measurement, i.e. improving the current test regime,
- evaluation of the considerations for NO_X measurement, i.e. extending the current test regime, and
- assessment of the in-service testing of gas fuelled light-duty vehicles.

The first of these topics was the subject of a separate report and is only summarised here. This document contains that summary and reports on the studies for the other three topics.

It had originally been planned to evaluate the considerations for particulate measurement (which may be appropriate for older vehicles that may be burning lubrication oil). However, following the finding from a parallel DfT-funded study that "oil burning does not appear to give rise to visible smoke on a vehicle fitted with a three-way catalyst" it was concluded that oil burning was no-longer a significant air quality issue. Consequently, this area of research was removed from the work programme and it was replaced by an increased emphasis on the subject of excess NO_X emissions (a significant air quality issue highlighted in the Phase 1 report).

The studies were undertaken in the context of the findings from the Phase 1 report, and consideration of the purpose and nature of the in-service test for SI engined vehicles. The studies led to a series of conclusions which, in turn, led to the following recommendations being made.

Pertaining to the purpose and nature of the in-service test for SI engined vehicles:

1. The UK in-service test should be considered as a series of diagnostic tests monitoring the continued correct operation of specific systems and components that are important in the control of the vehicle's emissions. As such it is not a pre-requisite that individual tests have a good correlation with the emissions from the Type 1 test over all vehicles, vehicle conditions and defects. This diagnostic test is distinctly different from, and complementary to, EOBD: it measures pollutant emissions directly, showing the combined effects of all the deterioration of all systems and components rather than inferring emissions performance from sensors' outputs.

Pertaining to the measurement of λ, CO and HC:

2. λ should continue to be checked as at present using a steady engine speed around 2,500 to 3,000 rev/min in an unloaded test. Consideration should also be given to the advantages and practicality of augmenting this check at a steady speed with a transient test (based on using repeated application of the brake pedal to introduce additional air into the engine and leading to an increase in engine speed).

3. Hydrocarbons should continue to be checked, as at present, for the calculation of λ. The pass/fail limit should be left unaltered at present. This should be reviewed following an analysis of the HC concentrations measured at test stations (which will become available from the computerisation of the MOT scheme).

4. CO should continue to be checked, as at present, for the calculation of λ. This test procedure, with the new limits, affords some checking for the integrity of the catalyst, and to a lesser extent, for catalyst activity.

5. Consideration should be given to the advantages and practicality of improved checking of catalyst activity through monitoring tailpipe CO concentrations using either of the two proposed improved test procedures.

Pertaining to the measurement of NO_X*:*

6. The concept of I&M generating NO_X emissions reductions, and thereby contributing to improvements in air quality, should be promoted. This is to correct the misconception that in-service testing may be irrelevant with regard to NO_X emissions.

7. Consideration should be given to the advantages and practicality of using one of the proposed unloaded tests combined with the measurement of tailpipe NO_X concentrations to assess the catalyst's NO_X reduction activity.

8. The probable £500 /meter price tag for augmenting the tailpipe measurement capability of the current garage exhaust gas analysers is sufficiently low for this possibility not to be ruled out. The principal challenge is to find an appropriate test procedure and there being appropriate cost effective benefits.

Pertaining to the in-service testing of gas fuelled vehicles:

9. Consideration should be given to discerning how the augmenting of type approved petrol fuelled vehicles to run on LPG can be better controlled so as to reduce the number of excess emitting LPG fuelled vehicles at source.

10. Consideration should be given to, as a minimum, checking the emissions of vehicles when fuelled by LPG if this fuelling option is fitted, and also applying any modifications accepted for use for the in-service emissions test of petrol fuelled vehicles equally to LPG vehicles.

Pertaining to the evaluation of the significance of OBD/OBM:

11. It is currently not appropriate to envisage augmenting the current UK in-service test with an EOBD system inspection. It is even less appropriate to consider replacing the current UK in-service test with an EOBD system inspection at present.

12. Further in-depth analytical and practical work should be commissioned to make good inadequacies in the currently available information. This should comprise studies to quantify the cost effectiveness and practicality of inspecting EOBD systems at the annual in-service test, thereby enabling the viability of various possible EOBD based inspection concepts to be assessed.

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Appendices

1 Introduction

Key issues addressed in Chapter 1

The chapter opens by reviewing the context of the project as a whole, i.e. DfT's need to critically assess the current in-service emissions test for SI vehicles, and some drivers and findings that shape the project's objectives.

The scope of the first phase of the project is summarised, together with the principal conclusions reached. These form the foundation for the objectives and work programme of this second phase of the project, which are also summarised.

Vehicles emit a cocktail of chemicals whose exact composition depends on the vehicles' fuel, the driving conditions (speed, load, rate of acceleration etc) and on the vehicles' condition (e.g. its 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 depends on the species and their concentrations. 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, it is stated 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.

One initiative to promote the acceptance of environmentally friendly vehicles is the "Cleaner Vehicles Task Force" which was launched by the Prime Minister in November 1997. The main work of the Task Force was 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 was 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 for Transport, DfT), oversees the testing of light-duty vehicles which is carried out by approximately 19,000 private garages around Britain. The VI is 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. The report concluded, amongst other things, “that there are some limitations with the current test techniques” and “that the DfT 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 Government’s Department for Transport. 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 led to the requirement to investigate whether for cleaner vehicles the current test adequately identifies vehicles whose emissions performance has deteriorated significantly. If it does not there may be a significant air quality benefit to be obtained from introducing a more effective test.

The programme of work designed to address these issues is phased. The first phase of the project was 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, including recommendations for minor modifications to improve the current test.

The overall conclusion reached was that the emissions from the vehicle fleet confirm the on-going requirement for an in-service test[1]. The current test has a high probability of identifying the most polluting vehicles. However, there are deficiencies with the test, and also it is not efficient at identifying excess emitters close to the threshold at which they are considered to become excess emitters. One unexpected finding was the relatively high number of excess NO_X emitters and the small reduction in NO_X emissions generated by repair.

The primary aims of this second phase of the project were:

- to investigate whether the likely impact of EOBD technology will be to remove the need for an in-service tailpipe test in the short/medium term, and
- to consider alternative test procedures to both improve the rate of detection of defective vehicles and to overcome some of the current test’s deficiencies.

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[1] An in-service emissions test for spark ignition petrol engines – Phase 1 report: Definition of an excess emitter and effectiveness of current annual test, J Norris, PPAD/9/107/09, AEA Technology report AEAT/ENV/R/0679, June 2001.

The first of these has been addressed in a separate report[2], whose executive summary is included in Chapter 7 of this report.

The second aim was achieved by considering, see Chapter 3, the purpose and possible improvements to the existing test for λ, CO and HC measurement, and then, see Chapter 4, possibilities regarding the introduction of testing by measuring gaseous NO_X concentrations.

The report also considers, in Chapter 5, the in-service testing of SI vehicles converted to run on liquefied petroleum gas (LPG) fuel.

So as to keep the main report a manageable size, appendices contain details regarding the instrumentation for NO_X measurement (App. 1), test procedures and equipment (App. 2) and the results from some practical investigations into NO_X emissions (App. 3).

A cost effectiveness analysis, started in the previous phase, is updated to include the information obtained during this phase of the work. The details of this are given in Appendix 4, and summarised in Chapter 6.

An area for research identified in the original ITT (PPAD9/107/09) was an evaluation of the considerations for particulate measurement. This was specifically in the context of whether particulate measurement is appropriate for older vehicles that may be burning lubrication oil. The conclusions from a parallel DfT-funded study was that “oil burning does not appear to give rise to visible smoke on a vehicle fitted with a three-way catalyst”[3]. Because of the dominance of such vehicles in the current fleet it was concluded that oil burning was no-longer a significant air quality issue. Consequently, the DfT removed this area of research from the work programme. (It was superseded by an increased emphasis on the subject of NO_X emissions following the unexpected finding of a relatively high number of excess NO_X emitters highlighted in the Phase 1 report (Reference 1)).

It is emphasised that this is the second 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.

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[2] An in-service emissions test for spark ignition petrol engines – Phase 2a report: evaluation of the significance of ODB/OBM, J Norris and A Reading, PPAD/9/107/09, EMStec report EMStec/02/026, September 2002.

[3] Detection of lubricating oil burning in vehicles fitted with three way catalysts, DCW Blaikley, CJ Dickens, EA Feest, AP Smith and AH Reading, DPU 9/33/30, AEA Technology report AEAT/R/PS/0006, March 2000.

2 Review of principal assumptions

Key issues addressed in Chapter 2

The requirement for this Phase 2 study is a consequence of conclusions reached in the Phase 1 study. However, around 18 months have passed since the latter was written. This chapter critically reviews the principal assumptions on which the objectives for this Phase 2 study were built, by specifically considering new information that has become available in the intervening period.

2.1 INTRODUCTION AND OBJECTIVES

The objective of this chapter is to critically review the principal assumptions on which the work programme for Phase 2 of this project are based. This is achieved by identifying the principal factors/assumptions involved, and considering any additional information that has become available, or changes that have occurred, in the eighteen months between the issue of the first draft of the Phase 1 report, and this report on the Phase 2 findings.

The objectives of the Phase 1 study were to establish:

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

Principal factors were identified as:

1. the emissions from vehicles in the context of the nation's Air Quality Strategy and standards,
2. the regulatory framework for the emissions standards, both at type approval, and for in-service roadworthiness testing,
3. the actual emissions from the vehicles on the UK's roads, i.e. their emissions distribution function,
4. the details of the current in-service test,
5. an assessment of the effectiveness of the current test at identifying excess emitters, and
6. a cost effectiveness analysis of potential emissions savings.

2.2 VEHICLE EXHAUST EMISSIONS

The Phase 1 study (reference 1) used the latest publicly available information to assess the impact of vehicle exhaust emissions on the nation's atmospheric emissions inventory, namely the National Atmospheric Emissions Inventory for 1998[4], which was the source of the data

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[4] UK emissions of Air Pollutants 1970 – 1998, JWL Goodwin, AEA Technology NETCen report AEAT/R/EN/0270, August 2000

contained in Appendix 1 of Reference 1. The most recently available data currently on the NAEI web site[5] is for 1999. Table 1 contains the data for seven of the species listed in the UK National Air Quality strategy for 1998 and 1999. (These are the seven species reviewed in the Phase 1 report and shown in Figures 1 and 2 of that report.) For each species the table contains the atmospheric emissions inventory from "road transport" and the percentage of the whole that this represents. Without going into details of the proportion of the emissions originating from petrol- and diesel-fuelled vehicles it can be seen that there has been a small reduction in the emissions inventory.

Table 1 NAEI data for 1998 and 1999

	1998		1999	
Species	Emissions from mobile sources (ktonnes)	% of mobile sources to whole inventory	Emissions from mobile sources (ktonnes)	% of mobile sources to whole inventory
SO_2	23	1.5%	12	1.0%
PM_{10} from combustion	35	17.8%	32	17.2%
PM_{10} (brakes and tyres)	5	2.5%	5	2.7%
NO_2	786	45.3%	714	44.5%
lead	591	65.2%	327	59.1%
CO	3507	70.7%	3293	69.2%
1,3 butadiene	5.9	88.1%	5.3	85.5%
Benzene	23.4	71.8%	21	70.7%

Those forecasting future emissions levels predicted this reduction[6]. It results from a reduction in average emissions per vehicle, a consequence of the vehicles becoming generically cleaner, off-set to some extent by the opposing influence of increasing traffic activity. The net change is the reduction seen.

The key points from Table 1 are that there has been no major change from the previous emissions inventory (especially regarding the two sensitive species of NO_X and PM_{10}), and there is the encouragement that lowering emission standards at type approval is producing improvements in air quality. Overall, the arguments presented in the Phase 1 report still apply regarding the role of an in-service test playing its part in keeping vehicle emissions low.

2.3 THE REGULATORY FRAMEWORK

No new emissions standards for new vehicles have been published in the last 18 months. The Stage A and Stage B levels of Directive 98/69/EC remain the current and the next, respectively, emissions standards in force for new vehicles.

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[5] Web site for NAEI is http://www.naei.org.uk/

[6] UK Road transport emission projections, TP Murrells, AEA Technology report number AEAT-5953, January 2000

The latest implemented Directive on roadworthiness testing remains Directive 96/96/EC and its amending Directives 1999/52/EC and 2001/09/EC. The pass/fail criteria for these directives are summarised in Table 2. However, the European Commission has been seriously considering tightening in-service limits. The original proposals were rejected by member states and have been revised. The principal revisions involve changing the vehicles to which the new limits apply from those meeting the emission standards in Directive 94/12/EC (Euro II) to Directive 98/69/EC Stage A (Euro III) for SI engined vehicles. The main provisions of this proposal are included in Table 2. This revised proposal was accepted at a meeting of the relevant Technical Adaptation Committee (TAC) on 3rd December 2002.

In terms of implementation, in the UK vehicles are tested annually from when they are 3 years old. Consequently, the new limits will only become relevant with effect from 1st January 2004, and then only for the newest vehicles in the fleet.

A detailed assessment/critique of these proposals is included in Chapters 3 and 6, in the context of the testing regimes proposed as part of this work and the cost effectiveness of in-service testing.

Table 2 The evolution of emissions limits for the roadworthiness test

	Directive 96/96/EC	Directive 2001/09/EC	Revised EC proposal
	All vehicles with an advanced emission control system (Euro I and later)	As for Directive 96/96/EC	All vehicles first registered after 1/1/2001, ie Euro III standard
High idle (>2000 rev/min)			
Lambda	0.97 – 1.03 or MSL*	0.97 – 1.03 or MSL*	0.97 – 1.03 or MSL*
CO	0.3%	0.3% or MSL*	0.2% or MSL*
HC	not specified	not specified	not specified
Low idle			
CO	0.5% or MSL*	0.5% or MSL* or EOBD check	0.3% or MSL* or EOBD check
Lambda and HC	not specified	not specified	not specified

MSL* = Manufacturer specified limits

2.4 THE DISTRIBUTION OF EMISSIONS FROM VEHICLES

No new significant data sets for the emissions from vehicles on the UK's roads have been found during the last 18 months.

Analysis of some EPA data of the emissions of defective US vehicles, measured over the US type approval cycle (FTP75) is discussed in Section 3 of Appendix 3 to this report. Generally the findings of this study support those of the JCS study, provided allowance is made for the different ways the vehicle samples were selected, and for some differences in the average characteristic between the US and UK vehicle fleets.

Consequently, the distributions discussed in the Phase 1 report (originating from the JCS study[7]) are not superseded.

2.5 DETAILS OF THE UK IN-SERVICE TEST AND ITS EFFECTIVENESS

The UK Vehicle Inspectorate have recently revised their MOT Testers Manual[8], such that it now includes the Basic Emissions Test (BET) discussed in Section 5.2.3, page 41, of the Phase 1 report. The primary aim of this test is to check a vehicle's emissions against generic limits, possibly before the oil is at its operating temperature, etc. Vehicles meeting these limits would also meet the limits of the full test, and consequently pass the test. Vehicles that fail to meet these limits are not failed, but are then tested using the full test. Consequently, the ultimate pass/fail criteria remain unchanged – what has altered is that for a vehicle with low pollutant emissions this fast pass route saves time.

Therefore, although there has been a significant change in terms of making the test simpler and quicker to administer for the cleaner vehicles, it does not fundamentally alter the number of vehicles failing the test, nor the test's cost effectiveness.

2.6 COST EFFECTIVENESS

The Phase 1 report contains the first iteration of a cost effectiveness analysis. The project's work programme includes a revision/extension of this with each successive phase. Therefore further discussion on this aspect of the Phase 1 report is contained in Chapter 6 and Appendix 4.

2.7 CONCLUSIONS

The six principal factors/assumptions that were used as the basis for the definition of the work programme for Phase 2 of this project on in-service testing of SI vehicles have been systematically reviewed. Additional information that has become available and changes that have occurred in the eighteen months since the issue of the first draft of the Phase 1 report, and this report on the Phase 2 findings, have been identified and assessed. None of these cause any substantial change to the objectives for this phase of the study as outlined in Chapter 1.

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[7] The inspection of in-use cars in order to attain minimum emissions of pollutants and optimum energy efficiency – Main Report, EC DGs for Environment (DG XI) Transport (DG VII) and Energy (DG XVII), LAT AUTh INRETS TNO TÜV Rheinland and TRL, May 1998

[8] MOT testers handbook, UK Vehicle Inspectorate, July 2002

3 Considerations for the measurement of λ, CO and HC

Key issues addressed in Chapter 3

Given that the Phase 1 report concluded that there was scope to improve the current in-service test, the options involving the measurement of λ, carbon monoxide and hydrocarbons are considered. These are preceded by a discussion on the philosophy of in-service testing generically, and the reasons for measuring tail-pipe λ, carbon monoxide and hydrocarbons specifically.

These lead to suggested revised or amended test procedures, together with the rationale for the revised tests.

The ITT contains a section entitled: *Evaluate the considerations for hydrocarbon, CO, NO_X and/or lambda (λ) measurement.* As a first step the fundamental question: “Is there a need to measure this species (or parameter)?” will be addressed. If the answer is affirmative then further questions to be addressed are: “Is the current test procedure satisfactory?” and “Is the current equipment satisfactory?” In this section hydrocarbon (HC), CO and λ are discussed. The aspects to be considered for NO_X are sufficiently large that this is covered in the following chapter.

Prior to considering the species on a case-by-case basis there is a discussion of the role and nature of in-service testing and the desirability of testing for the various possible gaseous species in the wider terms of key vehicular emissions systems.

3.1 THE ROLE, OBJECTIVES AND NATURE OF IN-SERVICE EMISSIONS TESTING

The general philosophy of type approval emissions regulation is to set standards for the average emissions over a tightly specified drive cycle and to police that they are being met. The regulations do not involve the details of the technology used to achieve these standards (except insofar as the standards need to reflect what is technologically feasible and is not unreasonably expensive).

The relative rates of emission of the regulated pollutants are well established as a function of drive cycle parameters and the characteristics of in-use driving patterns. For European type approval standards the principal parameters involved have been combined to form the regulatory drive cycle, the NEDC or Type I test. This combines urban and extra-urban driving styles, and the vehicle warm-up cycle starting from when the ignition key is turned. This driving cycle occupies a focal position regarding the emissions standards for European type approval, and is the cycle used to confirm conformity of production and also in-use compliance.

Other countries have developed similar cycles, e.g. US FTP cycle. The US have augmented this with supplementary cycles called the Air Conditioning Cycle and the High Speed High Load cycle, for evaluating emissions from vehicles in a way that takes into account some characteristics “local” to driving in the US. Within Europe the type approval Type I test (the NEDC) has been supplemented with the Type VI (-7°C start) test because of the importance of cold start emissions to the emissions inventory as a whole.

The role of an I&M emissions test is to ensure that vehicles used on the road are kept in a roadworthy condition in the interests of the environment. More specifically, an inspection programme should aim to identify vehicles with excessive emissions and require them to meet reasonable emission standards to reduce vehicle-related air pollution. Further this needs to be done in a cost-effective manner. The definition of excess emissions was discussed in the Phase 1 report of this work (reference 1) and is expressed as average emissions over the NEDC drive cycle relative to the type approval limit, after allowance has been made for reasonable deterioration. It is also a founding principle that an I&M test should be universally applicable and applied fairly. Therefore the challenge that faces an in-service roadworthiness emissions inspection programme is to devise a test that is both appropriate and cost effective.

In principle there are two approaches that might be used for an I&M test:
1. to devise a representative driving cycle (e.g. a loaded short test using a dynamometer) or
2. to use tailpipe emissions as a diagnostic test for checking the continued correct operation of key systems and components, devising appropriate loaded or unloaded test procedures on a case by case basis.

There is an important distinction between these two approaches in that for the first it is vital that emissions over the proxy I&M drive cycle **correlate well** with the emissions over the full cycle for all vehicles, vehicle conditions and defects. In contrast, the second approach requires a delineating emissions level to distinguish between correctly operating and fault systems or components. This emissions level will not necessarily detect other possible faults, and consequently will **not necessarily correlate well** with emissions over the full cycles for all vehicles, vehicle conditions and defects.

Research in the US has considered the first approach by devising the IM240 driving cycle as a tailored hot-start test to compliment the cold-start FTP type approval cycle. However, even for this test correlation with the FTP data is far from excellent. Lab-IM240 and Lane-IM240 relate to where the IM240 test is undertaken, respectively, either in a vehicle emissions laboratory or on an in-service test lane. The EPA found the following correlations.

Lab-IM240 – FTP 75 for CO and HC	Poor
Lab-IM240 – FTP 75 for CO_2 and NO_X	Good.
Lab-IM240 – Lane-IM240 for all species	Moderate.

The principal reason for the first two correlations is that the IM240 is a hot start cycle whereas the FTP75 is a cold start cycle, and the importance of the cold start contribution to the total CO and HC emissions is large, whereas the cold start contribution to the total CO_2 and NO_X emissions is much smaller. The EPA ascribe the only moderate correlation between the emissions results from the same test on the same vehicle but undertaken in different circumstances as being primarily caused by variations in the operating temperature of the vehicle.

A further factor is test cost. Approximate figures for the cost of the type approval FTP test, to the IM240 to an unloaded idle test are 400:10:1[9].

The above illustrates how in general it is difficult to find "loaded short tests" that correlate well with the full test. The differences between cold start testing and hot start testing being a key difficulty. The correlation reduces further for unloaded tests.

It is a fundamental proposition in this work that UK in-service testing has actually been based on the approach of using the tailpipe emissions test as a diagnostic test – although unfortunately it has frequently not been appreciated as such. It is also **a fundamental tenet that this is the approach most appropriate to the UK's in-service testing programme**.

When designing a diagnostic test a standard methodology is:
- identify the important systems or components whose satisfactory operation is vital to achieving the required objectives,
- prioritise those which are suitable for testing given the constraints of cost, time and practicality,
- devise tests which check the selected systems or components by defining the equipment required, the test procedure and the range of measured values that indicate the system or components checked are operating satisfactorily, and outside which they are viewed as faulty.

The strategy appropriate to developing an in-service test programme is, therefore:
- to identify the key systems required for a vehicle to meet emissions regulations,
- to identify the technologies and components underpinning these systems,
- to identify methods, where practical, of using tailpipe emissions to check the correct operation of these systems, technologies and/or components.

This is the basis used in this report for considering the appropriateness of testing various gaseous species, and recommending the test procedures that might be used.

A further important consequence of appreciating that the in-service emissions test is a diagnostic test is that it is **not universally applicable** unlike the pragmatic average emissions standards over the NEDC. This is because the first step in devising an appropriate diagnostic test is to identify the important systems or components whose satisfactory operation is vital to achieving the required objectives, and these change for different technologies. Therefore, whilst the type approval emissions regulation set standards for the average emissions over a tightly specified drive cycle and are not involved in the details of the technology used to achieve these standards, an in-service diagnostic emission test **does need to be tailored to the details of the technology used**. One interesting aspect of spark ignition automotive technology over the past 10 plus years is that there has been very little divergence in the technology used to achieve the emissions standards. However, that is changing with the introduction of directly injecting petrol into the combustion chamber, and with the development of lean burn engines.

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[9] Taken from Table 1 of report by Dr ED Rothman for US EPA available at http://www.epa.gov/otac/regs/im/rothman.pdf

3.2 OVERVIEW OF TEST REQUIREMENTS IN TERMS OF THE SYSTEMS AND COMPONENTS TO BE MONITORED.

3.2.1 Identification of the important systems and components used to control emissions

For a spark ignition engine to meet European emissions standards post 1992 (i.e. to meet Euro I levels and beyond) some key systems are required. These are:

- closed loop fuelling control to get the air/fuel ratio correct such that
  mean $\lambda = 1.00$ +/- 0.01,
  λ fluctuates between 0.98 and 1.02 at between 0.5 and 2.0 Hz,
- efficient ignition to cause combustion of the charge to generate power,
- an active three way catalyst that undertakes both oxidation and reduction of pollutants, and
- a system to control fuelling, and hence emissions, at idle.

Additionally there are systems and components for controlling emissions from cold engines:

- coolant temperature sensors to indicate to the ECU when the engine is warming up,
- additional fuelling maps within the ECU used during warm up, and
- secondary air injection increasingly fitted to vehicles.

The first three of these seven systems need to work under both steady state conditions, and transient conditions albeit with slightly relaxed margins of error, whereas the idle stabilisation system works, as its name suggests, at idle.

The technologies used within these systems include:

- the combination of oxygen sensors (often referred to a lambda sensors), in the exhaust manifold, feeding back the oxygen concentration to the electronic control unit (ECU) which trims the amount of fuel delivered through the electronically actuated petrol injectors by adjusting how long they are turned on for,
- an ignition system,
- a three way catalyst (a passive unit), and
- an idle stabilisation system.

No system on its own is sufficient to meet the type approval standards. For example, ignition and closed loop fuelling produces too much pollution in the absence of an effective catalyst, and a very active three-way catalyst which receives the wrong feed gas cannot efficiently process it. Therefore the ideal in-service test would correlate well with real (loaded) driving and would confirm that no misfiring was occurring, λ was correct and was being controlled to oscillate at the correct frequency, and the catalyst had appropriate activity for both oxidation and reduction. In addition, it would also check that the engine ran correctly at idle.

The issue of checking the systems and components used for controlling emissions during cold starting is challenging. Apart from (E)OBD systems checking the secondary air injection systems (if fitted) I&M programmes around the world have opted not to test these.

3.2.2 Closed loop fuelling control

The ratio of the quantity of air supplied relative to the theoretical requirement to obtain **total** oxidation of the fuel supplied in the combustion mixture is characterised by the parameter λ. Its quantification requires knowledge of the concentration of oxygen, and the concentrations of the oxidisable species, in the gas stream. In this report calculation of λ has followed the commonly accepted practice for in-service testing of using the Brettschneider equation (also known as the "simplified Lambda calculation") given in the VI MOT exhaust gas analyser specification[10]). Its format is:

$$\lambda = \frac{[CO_2] + \frac{[CO]}{2} + [O_2] + \left\{ \frac{H_{CV}}{4} \times \frac{3.5}{3.5 + \frac{[CO]}{[CO_2]}} - \frac{O_{CV}}{2} \right\} \times \{[CO_2] + [CO]\}}{\left\{ 1 + \frac{H_{CV}}{4} - \frac{O_{CV}}{2} \right\} \times \{[CO_2] + [CO] + K1 \times [HC]\}}$$

where [xy] = the concentration of species "xy" in % vol.

Leaving aside other parameters (K1, $H_{CV} = 1.7261$, and $O_{CV} = 0.0175$) which are constants, the important aspect is that **the calculation of λ involves measuring the concentrations of CO, CO_2, O_2 and HC.**

The importance of ensuring its value stays within reasonable limits is recognised within the EU directive on roadworthiness testing (96/96/EC and the amending directives 1999/52/EC and 2001/09/EC). Consequently, checking λ is within an appropriate range at the roadworthiness test is of value.

3.2.3 Efficient ignition system

Whilst the role of the closed loop fuelling system is to ensure that the correct air/fuel ratio is delivered to the combustion chamber it is the role of an efficient ignition system to provide a suitable igniting spark at the optimum time within the combustion cycle.

The fuel (petrol or LPG) for spark ignition vehicles is hydrocarbon. Whilst it is generally efficiently burnt to provide the power from the engine and leave low levels of unburned hydrocarbon, there are circumstances that lead to significant quantities of unburned hydrocarbon passing through the combustion chamber, and possibly out through the tail pipe. These are generally referred to a misfire and can range from a problem with a spark plug to the deliberate removal of an HT lead to a sparkplug with the aim of "beating" the test.

The Phase 2 study on EOBD (reference 2) noted that misfire is specifically addressed in EC Directive 98/69/EC. The reasons for this are that measurements indicate that 2% of misfire is sufficient to raise hydrocarbon emissions by 50% above the level of a Euro 3 compliant vehicle, and 17% of misfire is sufficient to cause permanent damage to the catalyst.

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[10] 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.

Consequently, the measurement of the HC concentration in the exhaust gas is a good diagnostic test to monitor for misfire.

3.2.4 Efficient catalyst system

The measurement of catalyst activity is well researched and standard test protocols have been established. The central question is how these principles might be applied to the testing of automotive catalysts. In terms of the test procedure this is discussed in Section 3.5.3.

The role of the automotive catalyst system, in association with the closed loop fuelling control is:

- to oxidise unburned hydrocarbons to carbon dioxide and water vapour,
- to oxidise carbon monoxide to carbon dioxide, and
- to reduce oxides of nitrogen to nitrogen.

The term "catalyst efficiency" rather than simply "catalyst activity" is used because detailed analysis indicates two mechanisms of catalyst failure (see Section 4.2.2 of reference 1)

- loss of catalytic activity – catalyst is unable to react feed gas sufficiently rapidly, and
- loss of physical integrity – not all the feed gas goes through the catalyst due to holes, break-up of monolith etc.

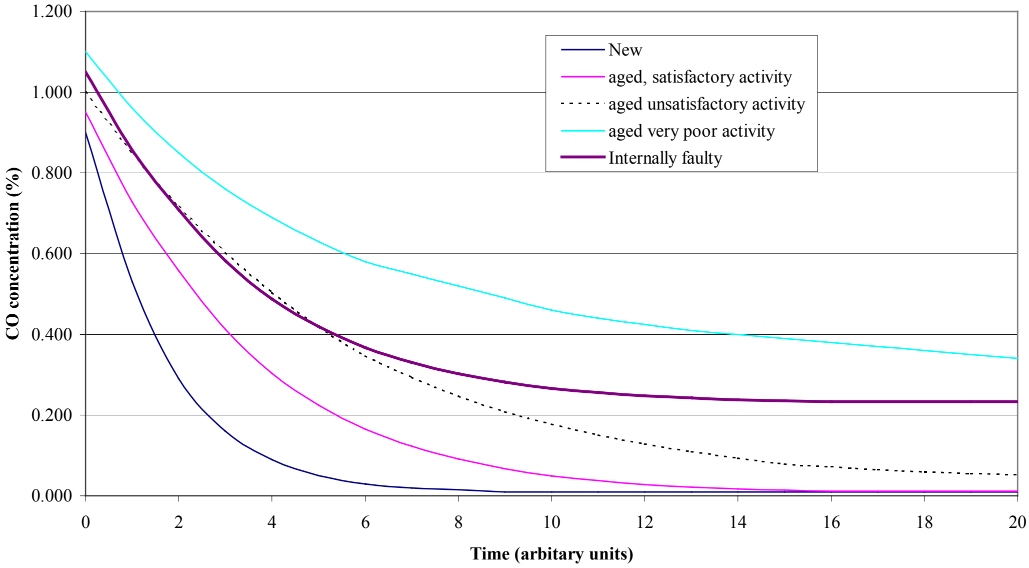

Figure 1 Schematic of CO concentration time profiles for some idealised catalyst systems

Figure 1 shows, schematically, the CO concentration time profile of five idealised catalyst systems as follows,

1. new catalyst,
2. aged catalyst retaining acceptable activity
3. aged catalyst with unacceptable activity

4. aged catalyst with even less activity than for 3
5. aged catalyst with acceptable activity, but with an internal fault affecting its physical integrity such that 15% of the feed-gas bypasses the active catalyst.

Equivalent data for HC concentration time profiles would be broadly similar but would involve much lower concentrations (typically a few tens of ppm of hexane). Therefore an appropriate diagnostic test for checking the catalytic oxidation activity and its physical integrity, would be to measure CO concentrations. However, the exact form of the procedure is a challenging issue discussed in Section 3.5.3.

An analogous measurement of NO_X would test the catalyst's activity to NO_X reduction. Again, the exact form of the procedure is a challenging issue and is discussed later.

3.2.5 Idle stabilisation system

When a vehicle is running at idle the plates within the throttle body are shut, cutting off the airflow through the normal route. Air is admitted instead via the idle air control passage and regulated by the idle air control valve. The position/degree of opening of the latter is under feedback control from the ECU (via a stepper motor) as too is the fuelling. A further refinement used by some vehicles is to use timing to further trim the idle speed.

These systems, primarily present to provide stable running at idle, do affect emissions and if faulty they can lead to excess pollutant emissions at idle.

3.2.6 Systems used during cold starting

The systems and components in this category are those that specifically impact on emissions during cold starting and are additional to the four covered previously. It is well established that the excess emissions on cold starting are a major contribution to the emissions over all the Type I cycle. Indeed a catalyst with poor activity alone can double these (see data in Table A3.7 of Appendix 3 to this report). However, catalyst activity has already been discussed because it is required to work effectively at normal engine operating temperatures too.

Further, of the three systems/components listed as being involved in determining emissions from cold starting, (coolant temperature sensor, additional fuelling maps within the ECU and secondary air injection) if the first was seriously defective it too would influence emissions when the engine is operating at its normal temperature (it would lead to overfuelling and excessive CO emissions).

Generally, the practicality of in-service testing, which is one factor influencing the cost effectiveness of various options, has strongly favoured a hot test. The time taken for a vehicle to cool down is many hours (Directive 98/69/EC specifies at least 6 hours). One study has shown this is generally insufficient[11]. Consequently a decision to test emissions from cold starting would involve a test station retaining the vehicle for at least 6 hours.

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[11] UG219 TRAMAQ – Cold start emissions Summary report, DCW Blaikley, AP Smith, EA Feest and AH Reading, AEA Technology report AEAT/ENV/R/0638, May 2001.

Testing at an intermediate temperature, i.e. between hot and cold starting, is also problematic. The US EPA considered the difference between Lane-IM240 and Lab-IM240 emissions[12] and concluded that of 6 sources of variation, poor control regarding the operating temperature of the vehicle, in particular its starting temperature, was the most critical.

To summarise, the importance of cold starting on emissions is unequivocal. However, the correct operation of some systems/components involved can be tested when the vehicle is hot. Further, the practical implications on the time a vehicle would be required by the test station to undertake a cold start makes this option unattractive. The data from test houses and from the US IM240 loaded test programme indicate variations in vehicle starting temperature significantly adversely affect the accuracy of emissions measurements.

It is therefore recommended that no attempt be made to monitor those systems and components which are used to control/reduce emission when starting from cold.

This recommendation would keep the UK in-service testing programme aligned with I&M programmes used world-wide which do not attempt to take cold start emissions measurements.

3.2.7 Summary

The key systems and components identified in Section 3.2.1 have been systematically considered. The gaseous species in the vehicle's exhaust that might be monitored as part of a diagnostic test to check the correct operation of these systems have been identified.

Table 3 Matrix of systems to be checked and the exhaust gas component(s) that might be used to check their correct operation

	CO_2	CO	HC	NO_X	O_2	Engine speed
Closed loop fuelling (λ) – steady running	✓	✓	✓		✓	
Closed loop fuelling (λ) – transient	✓	✓	✓		✓	✓
Efficient ignition			✓			
Catalyst integrity		✓	(✓)	(✓)		
Catalyst oxidation activity		✓	(✓)			
Catalyst reduction activity				✓		
Idle stabilisation		✓				✓
Cold starting	not applicable given the decision not to test these systems					

(✓) signifies that this exhaust gas component is affected by the system under consideration but the change in concentration, and the relatively smaller absolute concentrations involved make this species less attractive than the unbracketed, ticked species.

Given the above table as the rationale as to why it may be appropriate to measure the concentrations of various species, the details of possible diagnostic tests can be developed, in particular relevant test procedures.

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[12] Evaluation of on-board diagnostics for use in detecting malfunctioning and high emitting vehicles, E Gardetto and T Trimble, U.S. Environmental Protection Agency, EPA420-R-00-013, August 2000.

3.3 FURTHER DETAILS OF TEST REQUIREMENTS FOR λ

3.3.1 Objectives for λ

The objectives of testing for λ could be, with reference to Section 3.2.2 and Table 3:

- to check that λ controls very close to 1.00 for steady state running,
- to check that the feedback system allows λ to fluctuate at an appropriate frequency (between 0.5 and 2 Hz),
- to check λ during transient behaviour.

3.3.2 Possible test conditions for measuring λ

To meet the first objective of those listed in Section 3.3.1, the test conditions required are a steady state well above normal idle conditions. The current test is an unloaded test at a manufacturers' specified speed, typically 2500 – 3000 rev/min. It is reasonable to question if this is appropriate relative to a loaded steady speed. On balance the unloaded test appears to be a reasonable simulation for a loaded steady state with regard to checking λ, although this is not always the case see (Section 4.3.2).

The monitoring of λ to ensure it is varying at the correct frequency is problematic. In MOT testing one is restricted essentially to tailpipe testing. The effect of the catalyst, in particular its oxygen storage capacity (OSC), and silencers (most vehicles have more than one) is to significantly reduce and average out these oscillations. Therefore it is believed there is no practical way of measuring this parameter reliably, even if testers were equipped with a fast λ sensor.

The control of λ during transient conditions is very important for a vehicle achieving its type approval emissions. Indeed the whole art of mapping an engine to optimise both driveability and emissions is complex as the calibration engineers who undertake this will readily admit. Further, different vehicles are mapped differently. Therefore, unlike steady speed running where λ is close to 1.00 for all manufacturers, the different value/time characteristics of λ for different vehicles, rates of acceleration, load, initial engine speed etc. means it is extremely difficult to define test and pass/fail standards. Therefore, ignoring issues of the test equipment that would be required, the control of λ during transients, although important, does not appear a viable parameter that can be conveniently tested during an in-service inspection.

Whilst the two paragraphs above indicate that monitoring λ to meet the second and third objectives in Section 3.3.1 is problematic, the situation is probably not as bad as it may appear. In terms of the hardware involved it is the same oxygen sensor, fuel injectors and ECU that controls λ for all circumstances. Therefore, a steady speed test ensuring λ is controlled to around 1.00 does check these critical pieces of hardware. The principal failure/deterioration mode not assessed is if the time constant of the oxygen sensor were to change, i.e. it took longer to respond.

One suggestion for checking this aspect of the active feedback control is to perturb the engine when running at a steady speed. A test that has been considered, principally by Germany is to use the brake servo system as a means for injecting additional air into the engine's inlet manifold after the manifold air flow sensor by briefly depressing the brake pedal. This would change the air/fuel ratio making it leaner. A correctly operating active feedback system would be expected to detect the high λ, increase the fuelling, and restore λ to around 1.00.

The author has found no written description of the test. However, practical studies have produced some promising results (further details are given on page 4 of Appendix 2). The procedure used was to run the engine, unloaded at a high idle condition (e.g. 2800 rev/min). The brake pedal was then repeatedly depressed and released at around 1 Hz. No significant change in λ was observed. However, the engine's speed did rise noticeably. Initially it was though that this might have been caused by the tester inadvertently changing the position of the accelerator. When a mechanical device that, adjustably, partially depresses the accelerator by a constant amount (often colloquially known as a dead man's foot) was used to keep the accelerator position constant, the engine speed showed around a 200 rpm increase during the period of repeated braking. The engine's speed returned to its original high idle value on cessation of the braking.

The explanation for the above is that the engine is detecting the increase in air flow and is increasing fuelling to compensate too rapidly for there to be a clear change in λ. However, the increased air and fuel, under these no load conditions, leads to an increase in engine speed. An attractive feature of the test is that the key measurement parameter, engine speed, is a parameter already measured by garage exhaust gas analysers.

It must be emphasised that the above practical tests are very preliminary. However, this test does appear to be a potentially viable diagnostic to demonstrate the engine can actively control the air/fuel ratio – a key component in the overall strategies for controlling emissions. One issue to be quantified is the applicability of this approach amongst the fleet.

At low idle the vehicle control systems are radically different to those that apply under loaded running. This is because the throttle flap is shut, and consequently the idle air control circuit controls air. Checking that λ is within appropriate limits at idle is a potential way of checking that these systems are operating correctly.

3.3.3 Possible test equipment required to measure λ

Given the discussion above, and a steady-speed test, and given the Brettschneider equation, the equipment required is a 4-gas analyser that measures CO_2, CO, HC and O_2. The current equipment appears appropriate for this.

If it was decided to check the rapid active response of a vehicle's closed loop fuelling system by rapid braking, then the programming of the current garage exhaust gas analysers would need to be altered **but no additional sensor would be required**.

Consideration should also be given to the possible use of a dead man's foot rather than the tester's right foot. This would improve the accuracy of the measurement but at the cost of requiring additional time per test and the additional equipment.

3.3.4 Pass/fail limits for the measurement of λ

It appears that the current limits of 1.00 +/- 0.03 are reasonable for the vast majority of current vehicles.

3.4 FURTHER DETAILS OF TEST REQUIREMENTS FOR HC

3.4.1 Introductory comments for HC

Hydrocarbons are not one of the eight species for which targets were set in the UK's Air Quality Strategy. However, interest in hydrocarbon emission has grown as their role in the photochemical production of ozone (which is one of the eight species) has been appreciated. From the latest published NAEI for 1999[13], petrol fuelled cars fitted with TWCs are estimated to produce 3.5% of all hydrocarbons. However, methane comprises around 56% of the whole hydrocarbon inventory, and is predominantly from "natural" processes, e.g. agriculture. If methane is excluded, then vehicles fitted with three way catalysts are estimated to produce 7.8% of the total NMVOC inventory.

The fuel (petrol or LPG) for spark ignition vehicles is hydrocarbon. Whilst it is generally efficiently burnt to provide the power from the engine and leave low levels of unburned hydrocarbon, there are circumstances that lead to significant quantities of unburned hydrocarbon passing through the combustion chamber, and possibly out through the tail pipe. These are generally referred to a misfire and can range from a problem with a spark plug to the deliberate removal of an HT lead to a sparkplug with the aim of "beating" the test.

In addition to monitoring for misfire, the measurement of hydrocarbons is also required as part of the measurement of λ, as justified in the previous section.

3.4.2 Objectives for HC

The objectives of testing for HC, with reference to Table 3, are

- to measure HC as part of the measurement of λ, and
- to monitor for misfire.

3.4.3 Possible test conditions for measuring HC

For the first objective the test conditions are those discussed in section 3.3.2, i.e. steady engine speed of around 2500 - 3000 rev/min, unloaded test.

For the second objective –misfire can occur at any speed if the ignition system has a major fault, e.g. a broken HT lead will mean one cylinder does not fire irrespective of what the engine is doing. In which case the steady speed listed above is a good test regime.

However, some faults, e.g. HT leads whose conductivity had deteriorated (i.e. their internal resistance had increased beyond its specification) or a spark plug with too large a gap, would not cause misfire under all conditions. The voltage required to cause air to breakdown depends on the electrode separation and gas pressure, it being approximately proportional to pressure. Hence the phenomenon of high power misfire, i.e. misfires that are only apparent when the throttle is quite open, and cylinder pressures are higher that for low power. A 3000 rev/min unloaded test is unlikely to pick these up. A transient unloaded test, where the engine is accelerated against its own inertia, is more sensitive to this. However, the anticipated very

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[13] UK emissions of Air Pollutants 1970 – 1999, JWL Goodwin, AEA Technology NETCen report AEAT/ENV/R/0798, November 2001.

small number of vehicles with this defect suggests such an additional test would not be cost effective.

3.4.4 Possible test equipment required to measure HC

As noted for lambda, the current equipment, a 4-gas analyser that measures CO_2, CO, HC and O_2 appears appropriate for measuring at the steady state.

3.4.5 Pass/fail limits for the measurement of HC

If a vehicle registered 0.2% CO and 200 ppm HC on an MOT meter then the ratio of the mass fluxes is

CO : HC :: 1.0 : 0.32.

For the Euro III emission limits, 2.3 g/km CO and 0.20 g/km HC, then the ratio of these mass fluxes is

CO : HC :: 1.0 : 0.087.

i.e. HC level for the in-service test is 3.6 times higher, relative to CO, than the type approval limit.

This is also in keeping with the findings from the TRL study, where despite there being around 2.8% of vehicles presented for their MOT test failing on high CO, 0.4% of these also had high HC and 0.05% (1 vehicle) failed the test on high HC and λ.

Therefore the current pass/fail limit appears too high for modern vehicles. A number of options can be considered:

- reduce the pass/fail limit to make it more appropriate to vehicles fitted with advanced fuelling systems and three way catalysts,
- measure HC to calculate λ but cease to use it as a pass/fail criterion, or
- leave the pass/fail limit at its current value for the present because although it is of little benefit for the vehicle technologies currently being used, it may be a useful diagnostic measurement in the future.

On balance it appears that very little is to be gained from reducing the current limit values. Table 3 (on page 15) indicates the only system/component whose malfunction might be detected by the measurement of HC alone is the ignition system. In practice this is not a fault encountered often in isolation because a faulty ignition system usually rapidly leads to catalyst damage (for which the tests described in the next section are pertinent). This view is supported by the number of “excess emitters” in the current fleet as measured by the JCS study (reference 7) and as calculated in the Phase 1 report (see Table 6 on page 28 of reference 1). These data showed that the number of excess HC emitters is below half the number of excess emitters of NO_X or CO.

However, it is administratively easier to change an existing limit than to re-introduce a pass/fail limit if it were found to be required at a later date. Further, additional quantitative information on the HC emissions from the current fleet will become available with the introduction of the computerised MOT scheme.

Consequently, the recommendation reached here is that the pass/fail limit should be left unaltered at present. This should be reviewed following an analysis of the HC concentrations measured at test stations (which will become available from the computerisation of the MOT scheme).

3.5 FURTHER DETAILS OF TEST REQUIREMENTS FOR CO

3.5.1 Introductory comments for CO

There is no primary reason for measuring CO emissions because CO levels are not an air quality issue. However, as was seen earlier the measurement of CO concentration is required as part of the measurement of λ. Furthermore, the monitoring of CO is a potentially useful way of monitoring the oxidation activity of the catalyst, and the correct functioning of the vehicle's idle stabilisation system.

Whilst the basic combustion process converts oxygen in the air and the hydrocarbon fuel into carbon dioxide and water vapour, at the temperatures within the combustion chamber a dissociative equilibrium reaction occurs:

$$2CO_2 \Leftrightarrow 2CO + O_2$$

This leads to significant quantities of carbon monoxide inevitably being present in the exhaust gas. Furthermore, if there is overfuelling, i.e. $\lambda < 1.00$, then the combustion products include higher concentrations of CO as opposed to unreacted hydrocarbon.

Therefore, overall, measuring CO concentrations in tailpipe emissions can aid the monitoring of key vehicle systems.

3.5.2 Objectives for CO

The objectives of testing for CO, with reference to section 3.1, are:

- to measure CO as part of the measurement of λ,
- to use the measurement of CO to indicate "catalyst efficiency".

(See Section 3.2.4 for further details regarding the term "catalyst efficiency".)

3.5.3 Possible test conditions for measuring CO

To assess a catalyst's activity a frequently used approach is to supply feed-gas of a constant composition, at a constant rate, through a fixed volume of the catalyst under test. The temperature of the catalyst is increased at around 50 degrees /hour. The post-catalyst gas is analysed periodically (occasionally this is done continually). From the product analysis and a knowledge of the composition of the feed gas the extent to which the reaction has occurred can be calculated. This is usually plotted against catalyst temperature to give a characteristic "S" shaped curve. The parameter often cited is the temperature at which 50% reaction has occurred, known as $T_{50\%}$. Figure 2 shows some data from one such catalyst research programme (actually quantifying catalytic oxidation of methane).

Figure 2 Some activity assessment data from a catalyst development programme

From these data the order of reactivity is seen to be:
sample 10 > sample 9 ~ sample 2 > sample 7 > sample 6 > sample 3 > sample 5.

Two questions that arise from considering how catalyst research scientists approach the measurement of catalytic activity are:

- How does this approach contribute to understanding some of the weaknesses and deficiencies of the current test, and amend the test so as to improve it? and
- How might this approach be applied to automotive catalyst testing testing?

From Figure 2 it is seen that at 450°C all seven catalysts would have the same reactivity, giving around 100% conversion). If an in-service test involves running an engine at sufficiently high a speed, for sufficiently long, until the catalyst has “lit off” it is a truism that its activity is close to 100%, and such a test would not distinguish between catalysts. If it were a loaded, rather than an unloaded test, whilst the CO concentration would be higher, more exhaust gas would be produced at a higher temperature. Hence, although the catalyst would need to convert more CO, this would not provide a test that differentiated between active and less active catalysts.

There is a relatively narrow temperature window over which the catalyst switched from low to high activity. This leads to the relatively high number of initial failures which pass on retest. For catalyst 3, the first high idle test might raise its temperature to 330°C, at which temperature it is 20% efficient (and it fails the test). An immediate retest might cause the temperature to increase to 390°C, giving approximately 100% conversion, and leading to a test pass.

It is a feature of the current in-service test that the tester does not know where on the catalyst temperature axis a test starts from. It is also hypothesised that it is actually irrelevant. This is because to meet type approval regulations a vehicle has to produce less pollutant than the regulatory standard over the test (using whatever technology the manufacturer chooses). Therefore different vehicle manufacturers will design their catalysts to operate at different temperatures, and will locate them along the vehicle's exhaust system accordingly. It is argued that even if the catalyst's temperature was measured it would not help unless this was checked as a vehicle specific parameter (indeed as a catalyst specific parameter since many vehicles now have more than one catalyst).

Figure 1 (on Page 13) shows, schematically, the CO time profile for catalysts whose activity is varies from very good (the new catalyst) to very poor. Of the five representative conditions shown, only the first two are satisfactory in that they result in low emissions such that their vehicles are not excess emitters. The current in-service test would only lead to one of the other three being labelled a failure, and even for this catalyst (aged very poor) a tester who either preconditioned at a higher engine speed (to further increase the catalyst's temperature) or was willing to wait longer might pass this catalyst too. The conclusion reached is that the current test provides only a very poor measure of catalyst activity and is unable to differentiate between mediocre and poor catalysts although it can detect very poor ones.

Another aspect of catalytic health that is important to its ability to control emissions is that of its physical integrity. A well controlled vehicle operating within its design λ range may produce 1.5% CO concentration in its raw exhaust. The role of the catalyst is to convert this to CO_2. If the vehicle has an active catalyst but internal damage causes 15% of the exhaust flow to bypass the catalyst, then the tailpipe CO concentration cannot be less than 0.225%. The CO concentration/time profile of such a catalyst is that for the "internally faulty" trace in Figure 1. Such a vehicle would pass the current in-service test, but would be adjudged a failure of the pass/fail limit were reduced to 0.2%. This is discussed further in Section 6.3.2.

Two alternative approaches to the current test procedure are suggested here. The first is to try to use information in the time domain (i.e. utilising the information shown schematically in Figure 1, whilst the second changes the emphasis from "has the catalyst lit off? (despite uncertainties regarding the starting temperature etc.)" to "for a working lit off catalyst does it continue to operate even at the extreme (low idle) of its operating range?" It is recommended that consideration be given to the following modified, unloaded test.

1. Start the vehicle at an unknown catalyst temperature.
2. Go to high idle (2500 – 3000 rev/min) and pause at this condition. Check that λ is within limits. If it is not then the vehicle fails the test on poor λ control, and its catalyst activity need not be checked.
3. If λ is within limits, start monitoring CO concentration and the rate at which it is changing. This can be used to determine when the catalyst has lit off, and to monitor residual CO levels, thereby checking the catalyst's physical integrity. If the concentration is seen to fall but then "sticks" at a concentration greater than 0.3% (or 0.2%) CO then

either the catalyst's activity is very poor or there is an internal leak and the vehicle should fail.

4. At this point in the test you know the status of the catalyst – it has lit off, is of at least moderate activity and has no severe internal leaks.
5. Go to normal idle and pause. After X seconds (time to be determined) measure CO levels and idle engine speed to verify the idle stabilisation systems are operating appropriately. If CO concentration is above 0.5% (or 0.3%) then, because it is known that the catalyst had lit off, either there is an air/fuel ratio problem at idle or the catalyst's activity is so poor that it has "gone out". In both cases the vehicle should fail. Similarly, if the engine's idle speed is outside its agreed range this too suggests a fault and that the vehicle should fail.
6. Wait for Y seconds (time to be determined, but 60 – 180 seconds from leaving high idle are thought to be appropriate).
7. Return to high idle and check CO concentration after a short while (again time to be determined, but 5 – 10 seconds thought likely). If catalyst has gone out the vehicle should fail.
8. After the previous rapid high idle check, return to idle and switch off.

Stages 6 and 7 of this test are designed to check catalyst activity, albeit relatively crudely, but using a more scientific approach than that currently used. The basic premise is that any catalyst with sufficient activity to pass the type 1 regulatory test would remain lit when the vehicle idles for Y seconds. Indeed, a significant proportion of the current regulatory test involves brief periods at idle. Extending this for the in-service test is intended to make the test more discriminating, failing the poorer catalysts. It is also believed that pausing at low idle is more realistic and easier to incorporate into a test than turning the vehicle off for a similar period.

The alternative approach is to use the rate of change in CO concentration at high idle to infer catalyst activity. From Figure 1 it is seen that a measure might be the time it takes for the CO concentration to change from, for example, 0.8% to 0.3%, this being dependent on the catalyst's activity. For this approach, the pass/fail would be adjudged by signal processing incorporated, via software, into step 3 of the above procedure.

The criteria for selecting the preferred approach are as follows.

- Which test is the more effective at identifying excess emitters?
- Which test gives the fewer errors of commissions?
- Which test is the more cost effective to implement? and
- Which test is more immune to attempts to defeat it?

As yet there are insufficient data to make this judgement. Therefore it is recommended that the CO concentration data collected during the course of Stages 2 and 3 of the 8-stage test just described are also analysed to assess the relative strengths of the two approaches.

3.5.4 Possible test equipment required to measure CO

In principal, the current vehicle exhaust gas analysers already measure CO, so no additional sensors would be required.

However, both approaches proposed involve a degree of signal processing of information that changes with time. For these the CO measurement equipment would need to have an appropriate speed of response.
Also, for either approach, the new signal processing/drivers prompt software would be required to be incorporated into the meter systems.

3.5.5 Pass/fail limits for the measurement of CO

In terms of the pass/fail thresholds for CO concentrations the test proposed would be outside that specified by Directive 96/96/EC and therefore the pass/fail limits specified in this and its amending directives do not automatically apply. However, for both simplicity and for harmonisation an assessment should be made as to whether the current (Euro III and beyond) values of 0.3% and 0.5% (0.2% and 0.3%) for high and normal idle, respectively, would be appropriate.

Also, it should be apparent from the proposed test procedure that there are some timings, and associated parameters to be defined. It would be appropriate that the research to investigate these also generate data to confirm the above thresholds, or to suggest alternatives.

Further consideration on the effect of these pass/fail limits on the cost effectiveness of the in-service test is given in Section 6.3.2.

4 Considerations for the measurement of NO_X

Key issues addressed in Chapter 4

The desirability and practicality of measuring NO_X concentrations are considered in this chapter. Firstly, the question regarding whether repair and maintenance does reduce NO_X emissions is considered because if, as concluded by the JCS study it does not, then this undermines the case for specifically measuring NO_X concentrations.

Possible test conditions/drive cycles and the equipment options are then discussed.

4.1 INTRODUCTION

NO_X emissions are an enigma. Unquestionably there is an air quality requirement which provides a strong driving reason for controlling NO_X emissions from vehicles. For vehicles, NO_X is a regulated pollutant whose type approval limit value has been decreasing with successive standards. It is also controlled through the conformity of production and in-use compliance portions of the EU regulations, e.g. Directive 98/69/EC. However, currently the European in-service roadworthiness emissions test does not include the measurement of NO_X.

Phase 1 of this project concluded that, from the data available, a significant number of vehicles were emitting excessive quantities of NO_X (reference 1). A JCS study (reference 7), the main source of data, concluded that NO_X emissions were not reduced by maintenance. However, if an I&M programme is to be cost effective, then a pre-requisite is that identifying malfunctioning vehicles is the first step towards reducing their emissions. At the end of Phase 1 of this study, evidence had not been amassed to indicate that appropriate maintenance would reduce NO_X emissions.

This chapter considers the key technological aspects required for low NO_X emissions, and presents a number of hypotheses that might explain the findings of the JCS study of the (surprisingly) high number of excess NO_X emitters. It then contains details of practical work, and data analysis that shows that maintenance **does** reduce NO_X emissions. This being the case, the options for measuring NO_X as part of an in-service test are considered.

4.2 KEY TECHNOLOGIES AND HYPOTHESES AS TO THE ORIGINS OF THE JCS STUDY'S FINDINGS

The key technologies employed by the current generation of SI engine/vehicle manufacturers to reduce NO_X emissions to be within the type approval standards are:

- control of λ (the air/fuel ratio) to be very close to 1.00,
- varying the air/fuel ratio so that λ oscillated between around 0.98 and 1.02 at approximately 0.5 to 2 Hz,

- using a three way catalyst that contains a formulation to reduce NO_X when given the appropriate feed-gas composition,
- control of the ignition timing because advancing the timing produces higher NO_X concentrations in the exhaust gas,
- control of the operating temperature of oil and water within the engine because an overheating engine produces higher NO_X concentrations, and
- for some vehicle the use of exhaust gas recirculation (EGR).

Malfunction of these systems can lead to excess NO_X emissions.

Various hypotheses are proposed to account for the relatively high proportion of excess NO_X emitters noted in the JCS study. These are as follows.

1. The vehicles used for the JCS study were statistically not representative of Europe's fleet as a whole, and consequently the conclusion that the fleet contains a large percentage of excess NO_X emitters is incorrect.
2. The large percentage of excess NO_X emitters did exist at the time of the JCS study, but this is no longer the case.
3. The vehicles used for type approval are unrepresentative, low NO_X emitters, i.e. the NO_X emissions distribution function of the as new vehicles means a high percentage of these are "excess emitters" in their as new state.
4. During use the NO_X reduction activity of the catalyst deteriorates.
5. During use other key components deteriorate or fail (e.g. oxygen sensors or EGR units).
6. During use the ignition timing drifts.
7. During use a build-up of deposits within the combustion chamber leads to an increase in NO_X emissions.

The first of these seems unlikely because, independently, an EPA study found a similar large percentage of excess NO_X emitters within the US fleet (reference 11).

The second hypothesis is interesting. It is expected that the NO_X emission distribution function will change with time as technology matures, as new emissions standards are introduced and as the vehicle age profile alters. Notwithstanding, it is recommended that until strong evidence exists that the issue of excess NO_X emitters is no longer a problem it is assumed that there is an environmental concern that requires addressing.

The third theory appears unlikely because the conformity of production (COP) testing, which forms part of the regulatory inspection as detailed in Directive 98/69/EC, is designed to reduce this very possibility. The author is not aware of current COP testing providing data that suggests this is an issue. Furthermore, the introduction of in-use compliance testing further reduces the likelihood of this theory being applicable for the most modern vehicles.

The remaining four hypotheses pertain to the possible technical origins of the increase in NO_X emissions as vehicles age.

The last hypothesis on the list, the build-up of deposits within the combustion chamber leading to an increase in NO_X emissions, is an accepted phenomenon. It has been the study of considerable research (see for example references 14, 15 and 16). Generally it leads to

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[14] SI engine combustion chamber deposits and their effects on emissions, R Lees, SAE 1999-01-3583

increases in NO_X emissions of 15 – 25% relative to those for a clean engine during the first 200 – 500 miles of driving. After this the NO_X emissions stay at this upper level unless a major perturbation either leads to engine cleaning or additional deposit build-up.

Hypotheses 4 to 6 were investigated as described in the following section.

4.3 DETERMINATION OF EXCESS NO_X EMITTERS AND THEIR REPAIR

4.3.1 Experimental programme to identify excess NO_X emitters and to attempt their repair

The suggestion was made in the preceding section that for some vehicles that emit excessive levels of NO_X malfunctioning catalysts or oxygen sensors are responsible. A small experimental programme was undertaken to assess this. Further details, including the tabulated emissions data are given on pages 3 to 8 of Appendix 3. The programme comprised:

- identification of 6 high mileage vehicles that might be high NO_X emitters,
- measurement of their regulated emissions over several pertinent driving cycles,
- identification of those vehicles that emit over the type approval standard,
- change oxygen sensor and retest,
- change catalyst, and retest.

The 6 vehicles selected were from 5 different vehicle manufacturers and had between 70,000 and 157,000 miles on their odometers. One vehicle was a Euro II emissions specification, whilst the other 5 were type approved to Euro I standards.

The vehicles were tested using the following drive cycles/tests:

- cold start regulatory ECE + EUDC i.e. Euro I/Euro II cycle (these are the same),
- hot start regulatory ECE + EUDC,
- steady speed 50 kph,
- steady speed 120 kph,
- in-service MOT dual idle speed test, including NO_X measurement.

Two vehicles (a Euro I specification vehicle with 157,000 miles on its odometer and a Euro II specification vehicle with 70,000 miles on its odometer) gave NO_X emissions around 150% of their derived type approval standards[17]. The other four vehicles gave NO_X emissions less than 80% of their type approval standards.

For the older vehicle, changing its oxygen sensor led to no significant change in NO_X emissions over the type approval drive cycle. When its catalyst was replaced this led to

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[15] Literature search on the impact of combustion chamber deposits on engine performance, Co-ordinating Research Council (CRC) report CRC-595, October 1995

[16] A field validation study to determine in-use combustion chamber deposit levels, CRC report CRC-604, December 1997

[17] For Euro I and Euro II standards the emissions thresholds are specified for HC + NO_X. The NO_X only component is derived from this as explained in Appendix 3.

approximately a 57% reduction in its NO_X emissions such that they became within (were 65% of) the Euro I type approval standard.

Repairing the younger vehicle was more of a challenge. Neither replacing its oxygen sensor nor its catalyst led to improved NO_X emissions performance. Indeed, the replacement oxygen sensor was faulty and led to increased emissions, especially of CO which increased about 12-fold over the hot start ECE+EUDC test. The new catalyst was tested with the original oxygen sensor refitted, but this too showed no improvement that could be attributed to changing the catalyst.

Overall, this vehicle was an excess NO_X emitter for which the maintenance undertaken did **not** reduce NO_X emissions. However, the team are convinced that the vehicle was faulty (further supporting evidence for this is given in Appendix 3) and given more time, further diagnosis and appropriate rectification it is confidently predicted that its emissions would have been reduced.

4.3.2 Emissions performance of a vehicle which failed the MOT test on high λ

The purpose of this component of the experimental programme was to test the theory that vehicles that failed the MOT test because λ was **above** its upper limit for the high idle test, are excess NO_X emitters. An earlier study[18] had noted the significant number of vehicles in this category (around 2% of the vehicles presented for test) but had no data for their on-the-road emissions performance.

One vehicle fulfilling the criteria required was found. Its high idle λ value was around 1.21, above the manufacturer declared upper limit of 1.15 (which is itself considerably higher than the usual value of 1.03). However, when driven over the ECE+EUDC test, i.e. a regulatory Euro I Type I test, its HC and NO_X emissions were within the Euro I standard (the NO_X level was 62% of the standard). It was its CO emissions that were too high, around 190% of the standard.

The vehicle was over fuelling. Its oxygen sensor was changed, as too was its catalyst because inspection showed that this was damaged. Then the vehicle was retested. These changes led to a small decrease in CO emissions, and a small increase in HC and NO_X emissions. However, the pattern of the CO being over the standard, whilst the HC and NO_X were under it remained.

Ultimately the vehicle was repaired by a franchised dealer who, using their experience of this model, augmented the maintenance already undertaken by changing the ECU. Inspection of the ECU in the vehicle when it was presented for testing revealed it was that appropriate to a 2.0 litre engine, not the 1.6 litre engine in the vehicle. Under these conditions one would expect the output from the oxygen sensor to adjust the fuel trim (reducing fuelling) to the bottom end of the range available, but that still being insufficient adjustment to prevent over-fuelling.

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[18] An analysis of emissions data from the MOT test, TJ Barlow, RS Bartlett and ICP Simmons, S140C/VB, Transport Research Laboratory report PR/SE/474/98, August 1998.

The MOT test results on the vehicle fitted with its new oxygen sensor, catalyst and ECU gave λ at high idle of around 1.007 and overall a clear MOT pass.

To conclude, for this vehicle which failed the MOT test on high λ, NO_X emissions levels were not above their TA limit values over the type I test. However, the MOT test did correctly identify a vehicle whose emissions were outside those for an "appropriately maintained" vehicle and the subsequent vehicle repair resulted in reduced pollutant emissions. The results from this single vehicle led to a revised hypothesis: **some** vehicles failing the current in-service emissions test because $\lambda > 1.03$ (or manufacturer declared limit) are excess NO_X emitters. Further research is required to confirm or disprove this amended hypothesis.

4.3.3 Analysis of some US EPA data

An extremely useful database for this study has been found at the back of an EPA report whose primary objective was focussed on evaluating the use of OBD for in-service testing (reference 12). Further description and discussion of this report in the context of OBD in-service testing are to be found in a report on OBD which is part of this project (reference 2). The method used in the EPA study was:

- to identify and procure the vehicles to be tested,
- to measure their regulated emissions over the US type approval cycle, the FTP cycle,
- to measure their regulated emissions over the US in-service loaded test cycle, the IM240 test,
- to repair the vehicles following OEM published procedures (and in some cases in consultation with the OEM),
- to re-measure their regulated emissions over the FTP cycle,
- to re-measure their regulated emissions over the IM240 test.

The results of these emissions tests and the repairs undertaken form the database used for this analysis.

Graphs of the NO_X emissions data, presented in the style used by the JCS (reference 7) in their report, are presented in Appendix 3, together with the equivalent JCS data. Whilst the JCS found that NO_X emissions were not reduced to any significant extent by maintenance, the EPA data shows maintenance **did** reduce NO_X emissions, to 66% of their original value.

The analysis undertaken here then proceeded to consider the reduction in NO_X emissions on a vehicle by vehicle basis. Of the 199 vehicles whose emissions were measured it was found that:

39 of the vehicles were given no maintenance,
14 vehicles had no change in NO_X emissions,
105 vehicles showed a decrease in NO_X emissions (47 a decrease of ≥ 0.1 g/mile), and
41 vehicles showed an increase in NO_X emissions (7 an increase of ≥ 0.1 g/mile).

The key message from this part of the analysis is that the 34% reduction in NO_X emissions observed was **not** a consequence of an unrepresentatively small number of vehicles but was spread among those tested. A second conclusion is that maintenance/repair can lead to an increase in NO_X emissions, usually accompanying a reduction in CO emissions.

The EPA data also contains information on the repairs undertaken. The repairs/maintenance that led to the 47 vehicles having NO_X emissions that decreased by ≥ 0.1 g/mile are tabulated in Appendix 3. For these vehicles:

oxygen sensors repairs occurred in 16 cases,
catalyst repairs occurred in 10 cases,
EGR repairs occurred in 8 cases, and
wiring repairs occurred in 4 cases.

The conclusions from this analysis is that NO_X emissions can be reduced by appropriate repair and maintenance.

4.4 CONSIDERATION OF NO_X MEASUREMENT

4.4.1 Objectives for NO_X

To devise a test that is designed to assess appropriate key systems, thereby identifying excess NO_X emitting vehicles. The follow up repair and maintenance should produce a positive contribution to the nation's air quality.

4.4.2 Prioritisation of systems/components to be monitored

The key technologies listed at the beginning of section 4.2 are considered in turn to assess the potential emissions savings that might be generated by an appropriate diagnostic test.

- *control of λ (the air/fuel ratio) to be very close to 1.00*,
- *varying the air/fuel ratio so that λ oscillated between around 0.98 and 1.02 at approximately 0.5 to 2 Hz*,

These two aspects are covered under λ measurement in Section 3.2.

- *the efficiency of the three way catalyst to reduce NO_X when given the appropriate feed-gas composition*

The EPA data show how this is a key component whose failure is a significant contribution to excess NO_X emissions. TWCs comprise two distinct sections, often two separate catalyst monoliths, one for oxidising CO and HC and the other for reducing NO_X. There is no reason why deterioration should occur at the same rate for both catalyst systems. Consequently, assessing the oxidative activity of the catalyst system might not give an accurate indication of its reductive activity. Whilst there are some modes for common failure, e.g. a misfiring engine causing both to overheat and become less active, there are likely to be mechanisms that cause differential deterioration, e.g. the two catalysts will most probably have different susceptibilities to poisoning or ageing.

- *the control of the ignition timing*

This is an important system that influences emissions. It is one of the systems that is monitored within EOBD systems, such that faults that might occur are likely to be detected, and signalled to the driver via the malfunction indication lamp (MIL). Monitoring is via effect (e.g. knock detection), primary sensors (e.g. the signals from the crank shaft and cam shaft sensors) and through values computed by the ECU (e.g. the relative phase of the crank and cam shaft sensors has to remain plausible).

The timing used by the engine is determined by the position on the engine speed/load (fuelling) map and is modified by a number of other parameters (e.g. knock sensors, engine temperatures etc.). For a vehicle with an ignition timing fault the manufacturer's diagnostic fault code reader is a powerful tool for detecting and rectifying the fault. Devising an unloaded generic test to check specifically that the engine's timing system is operating correctly is a challenge that has yet to be addressed. On balance, the introduction of EOBD for all vehicles first registered after 1/1/2001 combined with the difficulty of devising a simple, representative in-service test leads to the recommendation that this parameter is not checked specifically at the in-service test.

- *control of the operating temperature of oil and water within the engine*

The sensitivity of NO_X emissions to engine fluid temperatures is not excessively large over plausible ranges. Further, vehicles usually contain both an engine coolant temperature sensor, whose output is displayed to the driver, and warning lights which become illuminated if the engine overheats. Because of these factors it is recommended that no additional in-service test is required.

- *exhaust gas recirculation (where fitted)*

Spark ignition engines are increasingly being fitted with EGR, particularly fitted to the second generation and subsequent 4 valve/cylinder engines. Also, these relatively modern engines are often in vehicles equipped with EOBD systems.

The experience from light-duty diesel engines, where EGR has been widely used for around a decade, is that the most commonly encountered fault is a sticking flap valve in the exhaust flow. Technology/engineering has matured reducing the frequency of this. The author's view is that the frequency of this happening in petrol fuelled vehicles is likely to be significantly smaller – a combination of technological maturity and the much lower particulate loadings in the exhaust of petrol vehicles. It is therefore thought that the cost effectiveness of a test to check for malfunctioning EGR systems would be relatively modest.
However, it is recommended that further consideration be given to this issue. The information required is:

- the fraction of the petrol fuelled existing fleet, and new sales, fitted with EGR
- the breakdown for the existing EGR fitted fleet into those fitted with EOBD and the remainder,
- an assessment of the likely frequency of faults, and
- a measurement of the increase in NO_X emissions caused by a malfunctioning/inoperable EGR system.

To summarise, of the six systems/components identified as being central to the NO_X emission strategies of current vehicles it is recommended that it is only appropriate to consider testing two of them at the in-service test. These are:

- confirming that λ is being appropriately controlled, and
- confirming the efficiency of the catalyst to reduce NO_X.

4.4.3 Possible test conditions for measuring NO_X

Of the two systems/components that the preceding section recommended are considered for checking at the in-service test, one (λ) has already been addressed in the preceding chapter. This leaves only the NO_X reduction catalyst activity to be considered here.

Using the same categorisation for test procedures as is used in Appendix 2, potential test procedures can be listed as:

- unloaded steady speed,
- unloaded transient,
- loaded steady speed, and
- loaded transient.

Table 4 summarises some positive and negative aspects of these options. Further, all of these tests were undertaken as an additional part of the experimental programme described in Section 4.3.1. Therefore the table includes these data to give an illustrative example of the NO_X emissions before and after replacing a vehicle's catalyst. The NO_X concentrations for the loaded tests were taken from the full flow dilution tunnel, and have been scaled to those in the raw exhaust from the CO_2 concentrations.

It should be remembered that the data in the table above is for concentrations in the raw exhaust, i.e. analogous to the measurements made in the current in-service test, and should not be confused with the more familiar mass flux measurements.

The reduction seen for the unloaded transient test is the greatest change seen for all the tests. Whilst this is encouraging it is not yet known if this is generally applicable.

It is also noticeable that the reduction for steady speeds (either loaded or unloaded) is smaller than for transients. This is because the catalyst not only reduces NO_X but also stores it during periods when the exhaust is NO_X rich for later reduction. (For example, for an acceleration followed by a sustained higher speed, some of the NO_X generated during the acceleration is reduced later when the NO_X concentrations are lower.)

Therefore, the recommendation from this study is that the unloaded test gives promising results, comparable to those from the loaded tests. However, there are insufficient data at this stage to be able to recommend one test in preference to another (i.e. transient as opposed to steady engine speed). Further investigation and prioritisation between these two possible options will need to be investigated further in Phase 3.

Table 4 Possibilities for test procedure for checking NO_X catalyst effectiveness

Test type	Test procedure	Positive aspects	Negative aspects	NO_X emissions before changing catalyst	NO_X emissions after changing catalyst
Unloaded steady speed tests	low idle (800 rpm) high idle (3000 rpm)	capital requirements small, relatively cheap and quick	issue of how representative it is	50 ppm 150 ppm	<10 ppm 100 ppm
Unloaded transient				300 ppm peak	40 ppm peak
Loaded steady speed tests	50 kph (4th gear) 120 kph (5th gear)	gives exhaust emissions more typical of on-the-road driving	requires dynamometer, takes additional time per test	330 ppm* 1040 ppm*	170 ppm* 740 ppm*
Loaded transient	accel hills on ECE 0-70 kph accel in EUDC 100 – 120 kph accel in EUDC	gives exhaust emissions even more typical of range of on-the-road driving styles	requires dynamometer, takes yet further additional time per test	1500 ppm* 1050 ppm* 1500 ppm*	350 ppm* 700 rpm* 1500 rpm*

* denotes that the NO_X concentration measurement was taken on the **dilute** gas within the full flow dilution tunnel, and the concentration in the raw exhaust was calculated by applying the instantaneous system dilution factor, estimated from the CO_2 concentration, to the dilute NO_X value.

4.4.4 Possible test equipment required to measure NO_X

Detailed information about the principal techniques used to measure NO_X concentrations in the exhaust gas of vehicles is contained in Appendix 1. The table overleaf contains a summary of this information.

In Europe only a 4-gas exhaust analyser is required to undertake the tailpipe test within the roadworthiness test, i.e. it does not require NO_X analysis. This is not the case in the US where many states also require measurement of NO_X. Consequently some of the companies manufacturing exhaust gas analysers for the US market, or looking towards possible future European requirements, offer 4-gas or 5-gas analysers.

Costs for European 5-gas analysers appear to be in the £2,000 - £5,000 range depending on detailed specification. For example, one analyser whose 4-gas version is an OIML Class 1 emissions analyser approved for UK MOT testing cost £3,000 for the 5-gas version. Other manufacturers are guarded about giving exact prices because, they argue, they are focussed on meeting the needs of in-service test stations, with their unit essentially programmed to give the tester a pass/fail judgement. The lack of a current test procedure and pass/fail limit means it is currently inappropriate to have this package priced. The system that is available treats NO_X emissions results similar to those for CO_2, where they are displayed and printed to aid fault diagnosis, but they are not used in the process of determining whether a vehicle has passed or failed the test.

Typical instrument specifications are for 0-4,000 ppm NO_X with a display resolution of 2 ppm, and an accuracy of around ± 30 ppm in the 0 – 1,000 ppm range. Where technical details were provided it was found that for garage exhaust gas analysers the use of an electrochemical cell was the favoured measurement principle.

To summarise, it appears that MOT type garage 5-gas vehicle exhaust analysers are available, and being further developed. The availability of such instrumentation does not, therefore appear to be a constraint on considerations regarding the merits of an in-service test for NO_X.

4.4.5 Pass/fail limits for the measurement of NO_X

Given that it was concluded that it is not possible at this stage to prioritise between two unloaded possible test procedures because of lack of data (Section 4.4.3) similarly it is not possible to recommend pass/fail limits. However, from the data in Table 4 it is likely that the pass/fail limit would lie in the range 100 – 1,000 ppm NO_X.

Table 5 The principal techniques used to measure NO_X concentrations in the exhaust gas of vehicles

Technique	Physical principle	Species measured and sensitivity	Typical cost	Other comments
NDIR (Non-dispersive infra-red)	absorption of specific energies in infra-red	NO (not NO_2 because of interference from H_2O) 0 – 500 ppm	£2,500	NDIR is the basis for the current garage exhaust gas CO, CO_2 and HC analysers
FTIR (Fourier transform infra-red)	absorption of specific energies in infra-red followed by FT	NO (not NO_2 because of interference from H_2O) 0 – 500 ppm	£25,000 - £35,000	Measures other gaseous species (CO, CO_2, HC but not O_2) simultaneously
Chemiluminescence	reaction of NO with ozone which makes light	NO (not NO_2 because it doesn't react with ozone to make light) 0 – 25 ppm to 0 – 2,500 ppm ranges	£5,000	Standard technique used by test houses. Requires source of ozone (e.g. either cylinder of air, oxygen or a pump) Ozone is toxic
Electrochemical cell	reaction of NO with oxygen to make electric current	NO (not NO_2 because it doesn't react with oxygen to make electric current) 0 – 1,000 ppm 0 – 4,000 ppm ranges	£500 - £1,500	Least mature technology; for which durability may be an issue. The approach favoured by many raw vehicle instrument manufacturers for garage exhaust gas analysers.

5 Gas fuelled vehicles

Key issues addressed in Chapter 5

The principal question addressed in this chapter is: What in-service test is appropriate for gas fuelled vehicles?

The following issues are considered:
- the technology employed by gas fuelled vehicles
- the current in-service test programme for gas fuelled vehicles. and
- the emissions from gas fuelled vehicles.

From these the deficiencies of the current testing programme, recommendation to overcome these and the challenges that require addressing are discussed.

5.1 INTRODUCTION AND TECHNOLOGY EMPLOYED

The addition of a gas fuelling system to a petrol fuelled spark ignition engined vehicle is colloquially known as conversion. This is something of a misnomer since it is actually augmentation: the converted vehicle being a bi-fuel vehicle, i.e. capable of running on either petrol or gas fuel. There are virtually no gas only fuelled road vehicles.

Vehicles can be adapted to run on natural gas or LPG. The former is predominantly (>95%) methane which at ambient temperatures it is a gas that cannot be liquefied by being compressed, and consequently is used either as compressed natural gas (CNG) or cryogenically liquefied natural gas (LNG). This makes its storage a challenge, and reduces its attractiveness for passenger cars given LPG as an alternative.

LP Gas (or LPG) stands for "Liquefied Petroleum Gas". It is the term widely used to describe a family of light hydrocarbons called "gas liquids". The most prominent members of this family are propane (C_3H_8) and butane (C_4H_{10}). Whilst LPG at ambient temperature and pressure is a gas, in contrast to methane LPG changes to a liquid when subjected to modest pressure or cooling. In liquid form the tank pressure is about twice the pressure in a normal truck tyre. The vast majority of "gas conversions" to passenger cars are to enable them to run on LPG.

Within Britain there are around 80,000 vehicles running on LPG with there being forecasts (assuming continuing fiscal incentives) that this number will increase to 250,000 by the end of 2005[19].

The principal components added to a standard petrol fuelled vehicle to effect this conversion are the gas fuel tank, a gas fuel injection system and its controlling ECU, an evaporator and a switch to select either fuelling mode. The ECU is often configured as an emulator of the vehicle's original ECU (that controls the petrol fuelling) applying multipliers to its output.

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[19] Data from LP Gas Association, Oct 2002 (www.lpga.co.uk)

The advantage of this approach is to make use of both the existing sensors (i.e. oxygen, air flow, pressure etc), and the experience and sophistication that is embodied in the petrol ECU.

There are an increasing number of bi-fuelled vehicles being produced by major vehicle manufacturers (including Vauxhall, Volvo, Renault, Ford, and Rover[20]) such that consumers can purchase a bi-fuelled vehicle from the showroom. However, these OEM approved LPG vehicles are, historically, "converted" by the OEM off the production line. In addition to ex-showroom bi-fuelled vehicles, many vehicles are converted to run on LPG by after-market converters.

In addition to OEM conversions, some vehicles are converted by subcontractors undertaking conversions specified and approved by the OEMs. These conversions are referred to as OEM approved conversions.

The LPG Association operates a voluntary "Approved Installer Scheme" that was drawn up in consultation with the DfT. Approval is granted to named candidate(s) working within a named company installing equipment as detailed on their training certificate(s).

A further scheme associated with LPG conversions is known as "PowerShift". This is a programme run by the Energy Saving Trust. The PowerShift Register is a buyer's guide to clean fuel vehicles. It allows vehicle buyers to make informed choices about the merits of the different clean fuel vehicles on offer and provides the basis on which PowerShift grants are offered (offsetting some of the costs of conversion). Grant criteria include conversion by an LPGA approved converter, and VCA witnessed emissions tests for the vehicle type over the European drive cycle.

However, a considerable number of conversions are also undertaken when there is no application for a Powershift grant, and indeed the converters are not on the LPGA approved installer scheme.

Consequently, the addition of LPG fuelling to a vehicle can be categorised as:

- OEM conversions,
- OEM approved conversions,
- Powershift registered or LPGA Approved Installer Scheme conversions, and
- other conversions.

5.2 CURRENT IN-SERVICE TESTING OF GAS FUELLED VEHICLES

Currently vehicles converted to run on gas are subjected to an annual roadworthiness test like all other vehicles. Relative to a single fuelled vehicle, this test contains some additional checks designed to ensure that the additional fuel tank, its associated pipe work and other critical components, are safe. The emissions check is that for a single fuel vehicle, i.e. high and low idle tests, **with the vehicle being tested using the fuel they are running on when presented.** Hence, this is a single test when the vehicle is either fuelled by petrol or gas.

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[20] Data from Global Autogas Industry Network (www.worldlpg.com/gain)

The pass/fail limits for CO at normal idle and for CO and λ at high idle are the same for both fuels. The tester is instructed to adjust the hydrocarbon limit for the different infrared absorption signatures of propane and hexane. (The upper limit for a petrol car is 200 ppm hexane, i.e. 1,200 ppm carbon, and for a gas fuelled car is 200/PEF ppm[21], i.e. still 1,200 ppm carbon).

In addition to the modified pass/fail limits for HC that should be applied to LPG fuelled vehicles, the appropriateness of the limits for λ also need to be considered. This arises because the stochiometric air/fuel ratio varies for different fuels:

fuel	petrol	propane	butane
stoichiometric air/fuel ratio	14.60	13.57	13.76.

However, in the context of the analysis of exhaust gases from nearly complete combustion, these variations may not be too great. What is required is an analysis of the sensitivity of λ to the various gas concentrations (CO_2, CO, HC and O_2) that are involved in calculating its value from the Brettschneider equation, as a function of the chemical composition of the fuel. It is anticipated that this may prove not to be a significant issue. If the analysis reveals that it is important, then different limits to λ might be appropriate for LPG vehicles to make them analogous to those of 1.00 ± 0.030 for petrol fuelled vehicles.

5.3 DEFICIENCIES OF THE CURRENT SYSTEM

The primary difficulty with the current in-service testing regulations is that bi-fuel vehicles are fitted with two fuel injection systems, one for each fuel, but only one is tested. This is only a significant deficiency if

- there is evidence that the two fuelling systems can deteriorate at different rates thereby affecting emissions
- and there is evidence that the number of bi-fuel vehicles and the fraction of these that are excess emitters is sufficiently large to have a detrimental impact on emissions, and thence air quality.

The EST, as part of its policing of the PowerShift programme, has an associated conformity of production programme (COP). The data from this strongly indicate that there is a difference between the emissions performance of bi-fuel vehicle when run on petrol and LPG, with the latter emitting higher concentrations of pollutants[22] (i.e. the number of COP failures for vehicles when fuelled by LPG is greater than for when they are fuelled by petrol). Two trends noted are that the rate of failures increases, i.e. average pollutant emissions increase, in the order:

multi-point sequential injection < multi-point injection < single point injection systems,
and OEM < OEM approved < non-OEM approved conversions.

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[21] PEF = Propane equivalence factor – a manufacturer declared calibration constant that enables the meters response to hexane and propane to be related. The value is usually in the region of, and just less than 0.5, e.g. 0.48.

[22] Private communication between the author and the EST, November 2002.

These trends generate issues to be resolved. In addition, the EST note that vehicles that fail the COP test often do so by a large margin. Therefore a further issue to be resolved is "Why?"

Whilst the EST have collected statistics from their COP programme, the author had been unable to find analogous data for in-use emissions performance. It is the author's opinion that in-use deterioration of emissions from gas fuelled vehicles is very likely to be greater than that from petrol fuelled vehicles. Reasons for this include the likelihood of a common problem that leads to the larger number of LPG COP failures relative to petrol. The origins of this may well lie in the combination of the quality of installation and the durability of the components, with some LPG conversions carried out to lower QA standards and using less technologically mature components.

Discussion by the author with a small sample of MOT testing centres revealed that (for what statistically is an unrepresentative sample) those that had tested bi-fuel vehicles had the vehicles presented running on petrol. For these vehicles the LPG system is therefore not checked. This appears to be the most serious deficiency of the current system. It is therefore recommended that consideration be given to checking the emissions of vehicles that can run on LPG, as a minimum when they are fuelled by LPG.

It is noted that the information above is a snapshot of that available at the time of writing (November 2002) and improvements in COP test performance following these poor early results are anticipated as the deficiencies highlighted are acted upon. Also, there is generally a lack of statistically validated available information. The author recommends it would be appropriate to consider gathering information on the in-service testing of vehicles capable of running on LPG, seeking:

- to establish the number of vehicles tested annually,
- the fuel the vehicle was using when offered for test, and
- the result of the test.

Other factors to be considered include the other changes and pressures on the decentralised test stations, and gauging their likely acceptance of being asked to provide "yet more information".

Notwithstanding the above caveats, given that LPG is usually promoted as a cleaner alternative fuel, it appears reasonable and equable that the standards for petrol vehicles should apply to gas fuelled vehicles, as they currently do for type approval. It also appears reasonable and equable that the same in-service test is used, i.e. for LPG converted vehicles fitted with closed loop fuelling systems and three-way catalysts, the "advanced emissions test" is appropriate. Furthermore, it is also recommended that consideration be given to checking the emissions of vehicles that can run on LPG, as minimum when they are fuelled by LPG. Extending these arguments, any changes recommended regarding the testing of petrol fuelled vehicles should equally apply to gas vehicles because Directive 98/69 EC applies equally to gas and petrol fuelled SI vehicles, and because of the very high degree of overlap between the technologies employed to meet these standards (closed loop fuelling, TWCs etc).

5.4 CONCLUSIONS, RECOMMENDATIONS AND DISCUSSION

The two recommendations from the preceding section are that **consideration be given to**

1. as a minimum, checking the emissions of vehicles when fuelled by LPG if this fuelling option is fitted, and
2. applying any modifications accepted for use for the in-service emissions test of petrol fuelled vehicles equally to LPG vehicles.

It is emphasised that this report recommends that these options are considered, not that they are necessarily accepted. This is because there are a number of implications that need to be thought through, and decisions to be made by politicians. These implications include:

- possible increase in test cost (and who pays),
- actions to be taken to vehicles which fail the test because of poor maintenance,
- actions to be taken to vehicles which fail the test but which cannot comply despite maintenance, and
- guidelines for testers regarding attempts to thwart the testing programme.

5.4.1 Cost implications

It is believed the additional cost of testing an LPG vehicle would not be greater than the average cost of an emissions test for a post-1992 vehicle. This is valued at £4.04 /test for 1997/8 in the NAO report[23]. Since 1997/8 the modest increases expected for inflation are offset by the introduction of the “Basic Emissions Test”, such that a current average figure of £4.00 /test would appear to be a reasonable estimate.

The fiscal incentive for using LPG is currently around £0.36 /litre (based on petrol costing £0.74 /litre and LPG £0.38 /litre). For a vehicle owner travelling an average of 9,000 miles a year with a vehicle which travels an average of 8.0 miles /litre of petrol and requires the same **mass** of both petrol and LPG, this amounts to a saving of £192 /year if the vehicle runs totally on LPG. It appears reasonable that the owners of LPG bi-fuelled vehicles should be asked to pay the £4.00 additional annual test fee as part of their cost of ownership that provides such savings throughout the year. However, this decision would need to be taken by the appropriate politicians.

5.4.2 Actions to be taken for failures caused by poor maintenance

At first sight this appears straightforward: if a petrol fuelled vehicle fails the annual emissions test and appropriate repair/maintenance would restore its emissions to an acceptable level, the tester refuses to issue the vehicle with a test certificate until it has been fixed. It could be argued the same principles also apply to an LPG fuelled vehicle. The difficulty arises for vehicles that can pass an emissions test when running on petrol but fail when running on LPG. Should the vehicle be issued with a test certificate or not? An owner’s promise only to run the vehicle on petrol until it has been repaired and retested is unlikely to be acceptable.

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[23] National Audit Office report on Vehicle emissions testing, May 1999, HC 402

5.4.3 Actions to be taken for failures which despite maintenance cannot pass the emissions test

The situation becomes more complex for a vehicle which has been poorly converted to run on LPG, and no emissions check was carried out as part of the conversion. Later, at an annual emissions check, it is found that when running on LPG the vehicle fails the test. Further, unbeknown to the owner, the conversion is of insufficient quality for the vehicle ever to have passed the test.

One solution would be that all conversions need to be accompanied by an in-service test, including emissions, and the issuing of a test certificate. If this obligatory approach were to be adopted a change in regulations would be required. Alternatively, it could be embodied in a code of best practice, with the conversion being within the caveat emptor principle (much as it is now).

5.4.4 Implications for testers faced with attempts to thwart the test

Changes in the current test procedure could lead to adverse publicity regarding its fairness, and may lead to attempts to thwart the test. If the recommendation for a mandatory LPG emissions test for bi-fuel vehicles were implemented, responses would need to be prepared to a number of scenarios. For example, owners who present their vehicles for testing with an empty LPG tank (thereby making such an emissions test impossible, but not making the vehicle unusable). The responses formulated would also need to encompass the circumstances of genuine owners who had their vehicles converted but who subsequently decided not to use the LPG fuelling option (through, for example, experiencing poor driveability or difficulties in obtaining fuel).

To summarise, the driver of air quality, the reality of the emissions from converted vehicles, plus the principles of the in-service test being universally applicable and fair lead to the recommendation that vehicles converted to run on LPG should be subject to an emissions check when running on LPG as part of the annual roadworthiness check. However, there are a number of significant issues regarding the implementation of this recommendation that need to be thought through, and require political judgements to be made before such changes could be introduced.

6 Cost effectiveness of in-service testing

Key issues addressed in Chapter 6

The cost effectiveness of three different test procedure scenarios are calculated based on the emissions savings potential (maximum emissions that could be saved by the perfect in-service test) for the representative years 2005, 2010 and 2015.

The actual emissions saved in 1998 are calculated. Also, qualitative estimates are made of the actual quantities of emissions that might be saved by possible future tests.

6.1 INTRODUCTION

The first iteration of the cost effectiveness analysis undertaken in Phase 1 has been built upon. The peer reviewed methodology used in Phase 2 of the "Low Emission Diesels" project[24] has been used here also, so the results are comparable. It is emphasised that the data presented here are a cost effectiveness analysis, calculating the cost (£) to achieve a reduction of 1 ktonne of pollutant from an in-service test given a number of stated assumptions. As agreed with the DfT it is not a cost benefit analysis. This would require further judgements of "damage cost factors" to convert a reduction in emissions (k tonnes of pollutant) to benefits to society (£). By providing cost effectiveness data the data is more robust and can be used for calculating cost benefit analyses at later dates using the most appropriate damage cost factors combined with geographic distributions of pollutants.

The Phase 1 iteration considered only the costs of the current test programme. It calculated the emissions saved in 1998 from data on the test programme's performance and estimated the emissions savings potential of a "perfect" test for the years 2005, 2010 and 2015. From these the cost effectiveness of the existing test, and the maximum achievable for the three representative future years were estimated.

Despite the 18 months between the writing of the Phase 1 report and this Phase 2 report no significant changes have occurred to this first iteration "base case" except in one important respect: the NO_X savings of the current test were believed to have been underestimated by around a factor of five. This is because the JCS study (Reference 7) concluded that repair of defective vehicles produced negligible reduction in NO_X emissions whereas the modest experimental programme undertaken here and data from an EPA study (Reference 12) both indicate a larger reduction would be expected. The details of how the factor of 5 is calculated are given in Section 3.2 and Table A4.10 of Appendix 4.

In this iteration of the cost effectiveness alternatives to the current test programme are considered.

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[24] Low emissions diesel research – Phase 2 report, J Norris, CP17/18/770, AEA Technology report AEAT/ENV/R/0629, June 2001.

6.2 COST EFFECTIVENESS FOR A RANGE OF SCENARIOS

6.2.1 The scenarios

The primary focus of the Phase 2 study is to consider alternatives to the current test programme.

For the measurement of λ, CO and HC three scenarios have been selected.

Scenario 1 Base case

The meters used to measure λ, CO and HC are already available, i.e. no additional test equipment is required. Whilst there may be minor changes to the test procedure the time taken is unaltered from that required at present. Consequently the costs for this base case are those of the current in-service test programme. The incremental cost of this scenario is £0.

Scenario 2 Extended unloaded test

The meters used to measure λ, CO and HC are already available, i.e. as for Scenario 1 no additional test equipment is required. The test procedure is extended such that it takes a further 3 minutes per test.

Scenario 3 Loaded test

Again it is assumed no change to the test meters is required. However, this test involves a simple dynamometer to load the vehicle. It is assumed the **whole** cost of a low cost, air-cooled eddy dynamometer is carried by the tests. Further, because the dynamometer test is more complex than the unloaded test, it is assumed that the additional test time is 9 minutes (making a total emissions test time of 12 – 15 minutes, and a maximum throughput of 4 – 5 vehicles/hour/dynamometer).

For NO_X, because currently there is no measurement of NO_X this would inevitably require upgrading meters. However, given the existing meters with their analysis measurement benches and their computer control systems, this would involve a relatively modest sum – around £500 per meter. Three scenarios involving the measurement of NO_X were considered.

Scenario 1 Base case

This assumes the current (or a slightly modified) test procedure can be used, and consequently there is no change in the cost of the testing. Therefore the only incremental costs are those for upgrading the meters.

Scenario 2 Extended unloaded test

This scenario is analogous to Scenario 2 for λ, CO and HC measurement, where the test procedure is extended such that it takes a further 3 minutes per test. In addition to the change in test time there is also the need to buy meters to measure NO_X

Scenario 3 Loaded test

As for Scenario 3 for λ, CO and HC measurement, this scenario assumes a simple dynamometer is required. It further assumes that the duration of the test procedure is increased by 9 minutes (making a total emissions test time of 12 – 15 minutes). There remains the additional need to buy the meters to measure NO_X.

The first row of Table 6 lists the number of three way catalyst (TWC) tests expected per year (in thousands) for the four representative years used in this analysis.

Table 6 The total and incremental costs of testing for λ, CO and HC for various scenarios

	Year	1998	2005	2010	2015
Number of tests of TWC vehicles (1000s)		8,905	18,391	19,795	19,915
Scenario 1	Total costs Cost/test	£64.5 M (£7.30)	£134.3 M (£7.30)	£144.5 M (£7.30)	£145.4 M (£7.30)
Scenario 1	Incremental costs Incremental cost/test	£0.0 M (£0.00)	£0.0 M (£0.00)	£0.0 M (£0.00)	£0.0 M (£0.00)
Scenario 2	Total costs Cost/test		£181.8 M (£9.88)	£195.4 M (£9.87)	£196.6 M (£9.87)
Scenario 2	Incremental costs Incremental cost/test		£47.5 M (£2.58)	£50.9 M (£2.57)	£51.2 M (£2.57)
Scenario 3	Total costs Cost/test		£376.2 M (£20.45)	£396.5 M (£20.03)	£398.3 M (£20.00)
Scenario 3	Incremental costs Incremental cost/test		£241.9 M (£13.15)	£252.0 M (£12.73)	£252.9 M (£12.70)

6.2.2 The costs

The results of the cost analysis are tabulated in Table 6. For each of the three scenarios the cost of the possible test programme in £M, (and the cost per test, £) are tabulated in two cells. The first gives the total programme cost whilst the second gives the incremental cost relative to the continuation of the current test programme. The labour cost used is that pertinent to 1998 in all cases, i.e. no assumptions or account has been made with regard to inflation.

Table 7 gives the results of the analogous cost analysis for the measurement of NO_X emissions for the three NO_X measurement scenarios.

Table 7 The total and incremental costs of testing for NO_X for various scenarios

	Year	1998	2005	2010	2015
Scenario 1	Total costs Cost/test		£136.4 M (£7.41)	£146.6 M (£7.41)	£147.5 M (£7.41)
Scenario 1	Incremental costs Incremental cost/test		£2.1 M (£0.11)	£2.1 M (£0.11)	£2.1 M (£0.11)
Scenario 2	Total costs Cost/test		£183.9 M (£10.00)	£197.5 M (£9.98)	£198.7 M (£9.98)
Scenario 2	Incremental costs Incremental cost/test		£49.6 M (£2.70)	£53.0 M (£2.68)	£53.3 M (£2.68)
Scenario 3	Total costs Cost/test		£378.3 M (£20.57)	£398.6 M (£20.14)	£400.4 M (£20.10)
Scenario 3	Incremental costs Incremental cost/test		£244.0 M (£13.27)	£254.1 M (£12.84)	£255.0 M (£12.80)

6.2.3 The emissions savings potential

The emissions savings potential is an estimate of the maximum possible savings that could be generated from a "perfect" in-service test, as calculated using assumptions stated in Appendix 4. Consequently it is independent of test scenario. The emissions for the three principal regulated species, and also for benzene and 1,3 butadiene, as predicted in the NAEI are listed Table 8. The percentage of the emissions from "a well maintained fleet" that are predicted to be saved by the "perfect" test are tabulated adjacent to the species in the left hand column. The resulting emissions savings potential are given in the three right hand columns of the table.

Table 8 Emissions savings potentials, expressed as k tonnes

Species	NAEI emissions inventory projections (k tonnes)			Emissions savings potential ktonnes		
Year	2005	2010	2015	2005	2010	2015
NO_X (48.5%)	170.7	126.2	106.0	82.8	61.2	51.4
NMVOCs (26.2%)	132.0	117.7	110.9	34.6	30.9	29.0
Benzene (26.2%)	6.51	5.53	5.10	1.71	1.45	1.34
1,3 butadiene (26.2%)	1.37	1.06	0.93	0.36	0.28	0.24
CO Total sample (119.4%)	1,708	1,389	1,171	2,039	1,658	1,398
CO Random sample (9.8%)	1,708	1,389	1,171	167	136	115

6.2.4 The cost effectiveness

From the costs for the various testing regimes considered, and the emissions savings potential a cost effectiveness can be calculated. Since the Phase 1 report the DfT have changed their preferred units for quantifying cost effectiveness from grams saved per pound spent to pounds spent per tonne saved. This Phase 2 report calculates cost effectiveness in £/tonne, see Table A4.14 in Appendix 4.

Two important factors to be remembered when interpreting the data in that table are:

- The cost effectiveness values given are not exclusive because, for example, the cost required to save 1 tonne of benzene for the current test is **not the sole benefit**. The test also leads to savings for 1,3 butadiene, other hydrocarbons, CO and NO_X.
- The cost effectiveness presented in Table A4.14 is calculated from the emissions savings potentials, i.e. represent the maximum possible for a "perfect" in-service test.

A crucial question is "What proportion of the emissions savings potential is realisable?" The first column of Table 8 contains the percentage of the emissions from a well maintained fleet that are predicted to be saved by a perfect test, i.e. the sum of all the excess emissions from the excess emitter vehicles. Table 10 contains the savings that were achieved in 1998, as calculated from TRL data. Section 6.3.1, below, discusses how the in-service test failure rates have reduced from around 5% to 3% between 1998 and 2001/2, i.e. 60% of the 1998 values. It is therefore assumed that realistically achievable savings from improved test procedures are maintained at around 60% of the estimated percentage of the emissions that were saved in 1998. The percentages assumed are tabulated in the third column below. In the fourth column the percentage of the emissions savings potential that this represents is calculated. This is the value that enables the "Estimated realisable cost effectiveness" data of Table 9 to be related to the "Maximum cost effectiveness" data of Table A4.14 in Appendix 4.

Species	achieved in 1998	achievable in 2005 etc	% of the ESP[¶]
CO	44.5%	30%	25% of the ESP for the "Total" sample 300% of the ESP for the "Random" sample
HCs	24.5%	16%	60%
NO_X	15%	10%	20%

[¶] ESP = emissions savings potential

It is not surprising that the proportion of the emissions savings potential varies for different species. This arises because of the variability in success rates of reducing emissions following repair, and the variability in the vehicle fleet's emissions distribution function. The latter influences the rate of detection of excess emitters, with it being more difficult to reduce emissions for a pollutant where many vehicles are just over the limit (i.e. NO_X) relative to a pollutant where a few vehicles are significantly over the limit, and are easier to detect (i.e. CO and HC).

It would also be reasonable to apply different factors for different years or different test scenarios. However, such further manipulation of the data, in the author's view, merely serves to further obscure key trends apparent in the data. Further, if the assumptions were shown to be poor by the passage of time, they could give misleading conclusions to the detriment of good decision making. Therefore, in the absence of appropriate quantitative data to justify varying the factors for different years or different test scenarios no such amendments are undertaken.

Table A4.14 in Appendix 4 gives the maximum savings potential. Table 9 below gives the estimated realisable savings, based on the savings tabulated above being realised.

Table 9 Estimated realistically achievable cost effectiveness of emissions testing

2005	Scenario 1	Scenario 2	Scenario 3
CO (£/tonne)	265	360	745
NMVOCs (£/tonne)	6,467	8,756	18,120
benzene (£1000s/tonne)	130.9	177.2	366.6
1,3 butadiene (£1000s/tonne)	621.5	841.6	1,741.5
NO_X costs from λ, CO, HC test (£/tonne)	8,107	10,977	22,715
NO_X costs from NO_X test (£/tonne)	8,234	11,104	22,842
2010	Scenario 1	Scenario 2	Scenario 3
CO (£/tonne)	352	475	965
NMVOCs (£/tonne)	7,794	10,540	21,388
benzene (£1000s/tonne)	166.1	224.6	455.8
1,3 butadiene (£1000s/tonne)	860.2	1,163.1	2,360.3
NO_X costs from λ, CO, HC test (£/tonne)	11,806	15,965	32,396
NO_X costs from NO_X test (£/tonne)	11,978	16,136	32,568
2015	Scenario 1	Scenario 2	Scenario 3
CO (£/tonne)	420	565	1,150
NMVOCs (£/tonne)	8,355	11,297	22,889
benzene (£1000s/tonne)	180.4	244.5	495.4
1,3 butadiene (£1000s/tonne)	1,009.6	1,365.1	2,765.8
NO_X costs from λ, CO, HC test (£/tonne)	14,142	19,122	38,742
NO_X costs from NO_X test (£/tonne)	14,347	19,326	38,947

From Table 9 it is forecast that it becomes more expensive to save each tonne of a given pollutant for a given scenario as time passes. This is a consequence of vehicles becoming cleaner by design, the successive lowering of type approval standards and the scrapping of some of the older, more polluting vehicles. In addition, OEMs have increasing responsibilities (as embodied in the type approval regulations) regarding the durability of emissions control equipment during use. This reduces the rates at which pollutant emissions increase as vehicles age, thereby further reducing the opportunities for emissions savings.

The data in Table 9 can be argued to be systematically pessimistic, over calculating the cost of saving each ktonne of pollutant for two reasons. Firstly, it is emphasised that the savings quoted are **not exclusive** because the current test, and its related costs, leads to maintenance and thence pollutant savings of X ktonnes of CO **and** Y ktonnes of HC **and** Z ktonnes of NO_X. However, the cost effectiveness analysis presented in Table 9 assumes they are exclusive because it treats the in-service test programmes cost as if it only saved CO **or** HC **or** NO_X.

Secondly, it is emphasised that the cost effectiveness analysis presented here is for the emissions reductions predicted for **the UK fleet operating in the environment of there**

being an appropriate 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 gross polluters will not be rectified. 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 greater than this because of the cumulative effect of an increasing number of unrectified gross polluters. If no rectification occurred at all the savings potential would be 15X ktonnes. (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.) However, this represents an upper limit for the cumulative figure. In reality the cumulative savings potential would lie somewhere between 5X and 15X because some vehicles would be rectified. Over 10 years the savings would be between 55X and 10X, the latter figure being that implied by a simple additive yearly saving.

In terms of sensitivity, the relationship between the assumed efficiency of the in-service test and the resulting cost effectiveness is one of inverse proportionality. For example, if the NO_X savings achievable in 2005 etc were to double to 20% (twice the figure tabulated on page 45) the cost effectiveness figures in Table 9 would halve for each of the 3 years, and for each of the 3 scenarios. Conversely, if the test were less efficient and the NO_X savings achievable in 2005 etc were to be halved to 5% (half the figure tabulated on page 45) then the cost effectiveness figures in Table 9 would be doubled for each of the 3 years, and for each of the 3 scenarios.

6.3 EMISSIONS SAVINGS AS A FUNCTION OF TEST PROCEDURE

6.3.1 Emissions savings for the existing test

The savings actually achieved in 1998 are calculated in Appendix 4 and are summarised in Table 10.

It is noted that the number of vehicles failing the test is decreasing. The estimate from TRL for 1998 was around 5% for vehicles fitted with TWCs. This must have been virtually exclusively for vehicles meeting the Euro I emission thresholds. Data from the DfT's 28th edition of Transport Statistics of Great Britain (Table 3.13) gives the total number of petrol passenger cars failing the emissions part of the MOT test as around 6.5% for 1998. The lower figure reported by TRL almost certainly arises because that study considered exclusively vehicles fitted with TWCs, where as the 6.5% DfT figure is for all petrol cars. Therefore the 5% figure appears correct for that date.

Table 10 Emissions inventory and reduction of emissions achieved for 1998

Species	CO	NMVOCs	Benzene	1,3 butadiene	NO_X
1998 inventory for TWC petrol vehicles (k tonnes)[25]	1334 kt	98.7	5.8	1.0	146
Savings for the maintained fleet from TRL data	44.5%	24.5%	24.5%	24.5%	15.0%
Reduction in emissions achieved (TRL data)	1070 kt	32.0 kt	1.88 kt	0.33 kt	25.76 kt

The DfT Transport Statistics data for 2001/2 gives a failure rate of 3.1%. Again it is probable that the frequency of failure of the older, pre-Euro I, vehicles will be higher than for vehicles fitted with TWCs. However, the passing of time means that the pre-Euro I proportion of the fleet has diminished significantly, from just over 50% to between 20 and 25%. Therefore in this cost effectiveness analysis it is assumed that 3.0% of vehicles fail the in-service test on emissions.

6.3.2 Emissions savings from possible amended tests

This section is necessarily qualitative, and at best semi-quantitative. In order for it to be quantitative the information required would be the measurement of:

- the increased number of vehicles failed by the alternative tests, and
- the reduction in emissions over the Type 1 test cycle (the NEDC) caused by maintaining the identified vehicles.

For public acceptability, a further indication required would be an estimate of the number of vehicles incorrectly failed (the number of errors of commission).

The scenarios considered are the changing of the current in-service two speed idle test such that:

- the pass/fail threshold is reduced from 0.3% CO to 0.2% CO at high idle, and from 0.5% CO to 0.3% CO at low idle,
- the catalyst's oxidation activity measurement is improved,
- the catalyst's reduction activity is checked,
- vehicle emissions are measured over a loaded cycle using a dynamometer, and
- vehicles that can run on LPG are tested when fuelled by LPG.

Lowering CO thresholds to 0.2% and 0.3%

This is the proposal that was accepted by member states of the EC on 3rd December 2002.

It was seen in Chapter 3 that the principle effect of the CO check, in addition to providing a supporting measurement for the quantification of λ, is to check catalyst integrity and activity.

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[25] Emissions data in this Appendix on Cost Effectiveness are taken from the 1999 NAEI Road Transport Emissions Projections (Reference 13).

An engine operating at $\lambda = 1.00$ might produce an exhaust gas containing 1.5% CO. If this is fed to an active, warmed up catalyst with no leaks, a tailpipe CO concentration of <0.05% would be expected. If the catalyst's physical integrity had been compromised, such that 20% of the exhaust gas did not flow through the active catalyst, the tailpipe CO concentration would rise to 0.30 – 0.35% CO. This should just fail the current test. If 13% of the exhaust gas did not flow through the active catalyst, the tailpipe CO concentration would rise to 0.20 – 0.25% CO. This vehicle would be adjudged a pass by the current test and a failure by the new test.

With reference to Figure 1, on page 13, the trace labelled "aged very poor catalyst" would be adjudged a pass by a "patient" tester because the CO concentration is creeping down to a value of less than 0.3%. Such a vehicle would fail if the pass/fail threshold were lowered to 0.2%.

These examples serve to illustrate why more vehicles will fail the revised test, leading to a reduction in emissions for the lower limits. It also highlights the increasing challenge of vehicle not passing first time because the catalyst was not sufficiently hot. A further weakness of the revised test is the increasing size of the meter error relative to the pass/fail limit. This is specified in the OIML regulations as ± 0.06% for CO and this will, most likely lead to increases in both errors of commission and omission.

Overall, this change is predicted to lead to an increased number of failing defective vehicles with either internal leaks, or low activity catalysts. This diagnostic test, though based on CO measurement will force repair and maintenance of the failed vehicles, and will lead to further reductions in CO, HC and NO_X emissions, but by differing amounts for the different pollutants.

Improving the catalyst oxidation activity measurement

As noted above, and discussed in Chapter 3, the current test is a poor assessment of catalytic activity principally because of the issue of warming up the catalyst. This results in the need of a second test for a considerable number of vehicles. The revised test is expected to reduce both types of errors, and to detect an increased number of vehicles with inadequate catalysts. However, as noted earlier, a more quantitative assessment is not possible in the absence of further data.

Including a measurement of the catalyst reduction activity

The vehicle whose emissions results are reported in Table A3.7 showed high NO_X emissions but acceptable CO emissions. The possible additional test would lead to some additional failures, not least because it is in addition to the current testing programme. However, as noted in Chapter 4, further studies are required to quantify the likely benefits, and the number of errors of commission in the context of a test that has yet to be completely defined.

Loaded testing of vehicle emissions

The US experience with the IM240 test, which was carefully specified to mimic the FTP type approval test, is that the CO and HC correlations are poor between FTP and lab-IM240 tests.

Also, the correlation between lab-IM240 tests and lane-IM240 tests (i.e. those undertaken in the inspection lanes of test stations) is far from good.

A consequence of these findings is that in order to have an acceptably low number of errors of commission the pass/fail limits would need to be quite high. This would significantly reduce the number of vehicles identified as requiring maintenance, thereby reducing the savings generated by the test to well below the maximum possible.

The evidence and analyses presented here are that the current test is currently detecting around a third of the emissions savings potential, see Tables A4.12 and A4.13. Thus a perfect test would produce around three times the current savings. It was also found that the cost of introducing a dynamometer-based test relative to the current test is approximately in the ratio 3:1. For this non-perfect test the cost effectiveness would therefore be **less** than for the current test. However, the number of kilograms of NO_X that would be saved by the test would **increase** relative to the current test, but at a lower rate than the increase in costs.

There are two further assumptions that are important in weighing the cost effectiveness predicted for the dynamometer testing option. These are as follows.

- It is assumed that the emissions distribution function of the fleet remains as found by the JCS study. If it were to change because modern vehicles deteriorated less rapidly, then the emissions savings potential for all tests would be reduced.
- The costs given here were calculated assuming the dynamometers were annuitised over a ten-year period. If either this period was reduced, or the number of tests requiring the dynamometer were reduced (for example, if it was decided to test some of the currently eligible vehicles by only inspecting their EOBD systems) then the capital cost per test would increase.

The most likely direction of change for both these assumptions is such that they would lead to a higher cost being required for each tonne of pollutant saved for this possible testing programme.

Testing LPG vehicles when fuelled by LPG

If within a population there exists a sub-set whose average emissions are greater (deviate more significantly from the standard) than those for the whole, then the cost effectiveness of paying more attention to this sub-set is a lower cost/unit mass saved than for the whole. This was recognised in the NAO report (Reference 23) where in Part 2 of the report “Design and fitness for purpose of the emissions testing regime” alongside considering “Testing the right emissions” there was a section on “Testing the right vehicles at the right frequency”.

The evidence available, contrary to common perception, is that LPG fuelled vehicles are, as a sub-set, more polluting than their counterparts fuelled by petrol only. The cost effectiveness arguments that on balance favour a tailpipe test of some form for SI vehicles generically, are stronger for the testing of these vehicle when running on LPG.

6.4 TESTING TO MANUFACTURERS' SPECIFIED LIMITS

The Cleaner Vehicle Task Force was an initiative launched by the Prime Minister in November 1997 to promote the acceptance of environmentally friendly vehicles. It published its final report entitled *The way forward* in 2000. Recommendation 8 (Annex B) concerns improving the MOT emissions test. Under the column entitled Actions and Initiatives it states *The government is looking at ways to make manufacturer limit values more demanding*. The reason behind this is the expectation that tighter standards, based on model specific, rather than generic, limit values for the MOT test would lead to more defective vehicles being identified, and as a result of their repair, a larger reduction in emissions.

The manufacturer defined limit values could be on either a voluntary basis, as at present, or a compulsory basis.

6.4.1 Voluntary requirement for manufacturers to define limit values

This would be an extension of the current system with manufacturers having the option of declaring limit values for low idle CO concentration, maximum and minimum values for λ at high idle, plus limit values for CO and HC concentrations at high idle.

An analysis of the current limit values used for testing vehicles is given in Section 6.4.1 of the Phase 1 report (Reference 1) (see also Figure 17 of that report). It is notable that the values of the manufacturer declared limits are generally **less severe** than the default limits, see for example the λ ranges shown in Figure 17 - Part 4. For some vehicles there are very good engineering reasons for this. For example, many models of the Porsche 911 and 928 series use secondary air injection into the exhaust manifold which causes tailpipe emissions to be lean, and the value of 1.5 for the upper λ limit has a technical basis. The reasons for some of the tolerances that are wider than the default values are, however, less clear.

Therefore it is suggested that the voluntary requirement would lead, on average, to less demanding test limits. This, in turn, would lead to likely reduction in the effectiveness of the test.

6.4.2 Compulsory requirement for manufacturers to define limit values

This would require carefully defining the preferred scheme and then changing regulations, most probably at European Directive level. It would provide the opportunity to incorporate the appropriate road worthiness test limit values into the type approval regulations.

Two different possible approaches are:

- to set generic limits centrally and to ensure they can be met as part of the type approval process, and
- for vehicle types meeting the appropriate current emissions standards, measure the emissions from the "acceptable" vehicle and derive type specific in-service test limits from these.

In essence the latter amounts to using the in-service test limits as a transferable standard linking a vehicle type's performance at type approval and at the in-service test. One area for debate with this approach is the extent to which degradations in emissions performance that occur during the vehicles' lifetimes are mirrored by equivalent changes in in-service emissions.

The principal difference between the first approach and what occurs at present would be the incorporation of the in-service limits into the type approval process. However, this could be counter productive and problematic. The type approval standards are for accumulated emissions over an approximately 20 minute drive cycle, **and are technology independent**. As discussed in Chapter 3, the tailpipe check is actually a **technology dependent diagnostic test**. It might be envisaged that, for example, $\lambda = 1.00$ +/- 3% became part of the type approval test. The current divergence of emissions technology from $\lambda = 1.00$ +/- 3% + TWC to, for example, lean burn technology would not meet such a standard.

If the second approach were to be adopted then it is strongly recommended that the in-service value measured at the time of type approval is adjusted to reflect the extent to which the vehicle's emissions are within the emissions standard. This is to deter the adjusting of emissions to as close to the limit as possible, and to encourage vehicle manufacturers to make as clean a vehicle as they can.

For example, if the NO_X emissions of a particular Euro IV vehicle over the NEDC were 0.04 g/km (limit = 0.08 g/km) and the in-service test indicated X ppm NO_X. Then the in-service pass/fail limit would be X.(0.08/0.04).DF (the degredation factor agreed), i.e. 2X.DF. In contrast, a vehicle whose NO_X emissions were 0.08 g/km, and Y ppm for the type approval and in-service tests, respectively (i.e. only just managed to meet the standard) would have its in-service pass/fail limit set at Y.DF.

Overall, the benefit of testing to manufacturer specified limits would depend on the way it were implemented. Its key advantage is that it has the potential for providing more appropriate limits than the current generic ones if the appropriate implementation option were selected.

7 Evaluation of the significance of OBD/OBM

Key issues addressed in Chapter 7

The requirement to fit EOBD systems to all vehicles sold after 1st January 2001 has generated the possibility that the in-service test could be radically changed from a tail-pipe emissions check to an inspection of the EOBD system. This is the subject of a separate report, which is summarised in this chapter.

This Phase 2 study is focussed on considering how the in-service emissions test for spark ignition vehicles fitted with three way catalysts might evolve. One possibility is to replace a tail-pipe gaseous emissions check with a check of the European on-board diagnostics (EOBD) emissions monitoring system. Other possibilities include checking both gaseous emissions and the EOBD system, or continuing with the gaseous emissions test and not checking the EOBD system. Because of the importance of these possibilities on the Phase 2 project (not least because the first would remove the need for a tail-pipe emissions check) EOBD was considered first. This resulted in a report entitled "Evaluation of the significance of OBD/OBM" being published in September 2002. The remainder of this chapter comprises the edited executive summary from that report.

The objectives, legislative framework and the technical details of the European on-board diagnostics (EOBD) concept have been reviewed. So too have the reports on E(OBD) studies undertaken within Europe and the US. The principal objective of the study was to consider the options for using EOBD as part of the in-service test. Key conclusions from this, and their consequences, are as follows.

- The original regulatory purpose of an On Board Diagnostic (OBD) system is to ensure correct operation of the emissions control system of a vehicle, in use, during its lifetime. This is achieved by proxy, by monitoring emissions related components for deterioration and malfunction. An important consequence of this definition is the fact that EOBD was not primarily intended for roadworthiness testing. However, given the manner in which similar technological advances in the past (e.g. ABS) have subsequently become checked in the roadworthiness test, it might reasonably have been anticipated that the checking of EOBD systems would also be considered for inclusion in the annual test.
- In practice EOBD is a development/extension of manufacturers' engine diagnostics (extended to cover emissions). A consequence of this is that there is a range of levels of EOBD sophistication above and beyond the minimum requirements laid down within the EC directive.
- The experience of other European studies on EOBD indicate that there are some difficulties to be overcome both in the detection of excess emitters (i.e. error of omission) and in the success rate of ECU/EOBD (on-board) to scan tool (off-board) computer communications. The US experience, and that from the introduction of other new technologies, suggests this is partially caused by a current lack of maturity of EOBD technology and should be expected to improve with time.
- A further consequence of the newness of the technology is currently a poor level of quantification of its rate of detection of faulty vehicles, and hence the emissions savings that this rate of detection affords (a key element required to calculate its cost effectiveness).
- Within the current EOBD systems two technical options for reading the system are either to use the malfunction indication lamp (MIL) or to use a generic scan tool. Both approaches have weaknesses. Inspection of the MIL would currently not detect if the system had been reset. However, this could be overcome by extending the specification of the MIL to include a "system ready" component that is illuminated when the readiness codes are set. The use of a scan tool might be a test of variable severity for variable levels EOBD implementation for different vehicles. If it were found this were the case to an unacceptable degree further data processing could be added into an "MOT specific scan tool" to ignore less severe faults.

- Fundamental tenets of the current in-service test are that it should be a demonstrably cost effective programme that improves air quality, is universally applicable and is fairly applied. The findings of the study indicate that inspecting EOBD systems using either technical option above as part of the annual roadworthiness test would at present not comply with these tenets.

It is too early for data to be available to quantify the savings potential, and the number of errors of omission and of commission, that an EOBD inspection might provide. However, indicative data exists from a US EPA study which tested 194 vehicles whose MIL was illuminated. 70.1% of these vehicles had emissions **under** their appropriate FTP certification standard (the US equivalent of our type approval standard), i.e. 29.9% of these OBD failures were over their type approval emissions standard.

In the context of in-service testing, EU Directive 2001/09/EC allows for the use of EOBD inspection to replace the low idle CO test as part of a member state's roadworthiness testing programme. (The requirement to measure λ and CO at high idle remains unchanged.)

Overall, whilst it is agreed that EOBD has the potential to improve the effectiveness of in-service testing, the authors recommend that currently it is premature to propose augmenting the current UK in-service test with an EOBD system inspection. There is a body of evidence that indicates that many of the real problems that currently exist are principally caused by technical immaturity rather than more generic issues regarding concept or consistency of implementation. The technology requires time to mature. A corollary to this is the authors' view that to replace the current tailpipe emissions test with an EOBD system inspection would also be inappropriate at present.

Looking to the future, it is recognised that EOBD seems reasonably well formulated given the concept of monitoring in-use emissions through diagnostics and comparing these with emissions standards, as opposed to the direct measurement of exhaust gas composition. However, in comparison with other emissions regulations it is, in essence, a compromise necessitated by the technology available. If on-board emissions measurement (OBM) (the direct measurement of exhaust gas composition during use) were to advance to a stage of being a practical likelihood, then this should be considered as the primary technique used to monitor in-service emissions, i.e. superseding EOBD.

A more likely scenario is that it remains appropriate to consider the use of EOBD testing. Recommendations are made regarding the further in-depth analytical and practical work that is required to make good inadequacies of the currently available information on which to base recommendations on the viability of EOBD based inspection concepts. This comprises programmes of work to quantify the cost effectiveness and practicality of inspecting EOBD systems at the annual in-service test.

Estimates are given of a timeframe for the formulation and implementation of possible amendments to the roadworthiness directive to incorporate EOBD-based inspection concepts. On the assumption that it is prudent to wait until some experience from pilot studies is available it is difficult to see how the key data could be available before early 2006. Given the time required for debate and the reaching of a consensus position, it is estimated that the passing EC amending directives would occur not earlier than 2008.

8 Conclusions and recommendations

8.1 CONCLUSIONS

8.1.1 The role, objectives and nature of in-service testing

The primary objective of an in-service test programme is to support the type approval regulations by ensuring vehicles used on the road are kept in a roadworthy condition in the interests of the environment. The type approval emissions standards limit the total emissions that can be produced over a specified drive cycle that includes the vehicle warming up from the initial key on, and makes no assumptions about the technology used to achieve it. In-service tests can either be a representative proxy cycle, or a diagnostic test checking some key systems. The emissions from the former need to correlate well with the emissions over the full cycle for all vehicles, vehicle conditions and defects. The latter need not. Rather it should correlate with the performance of the key system/component it checks. Further, diagnostic tests are system/technology dependent.

The experience of the US who have used the IM240 test (which was specifically designed as a proxy short test for the FTP 75 type approval test) shows that for a range of reasons test lane-IM240 emissions correlate relatively poorly with the emissions from the full FTP 75 test. The unloaded UK in-service test is not designed as a proxy for the European type approval ECE+EUDC cycles. Therefore, the UK in-service test should be viewed as a diagnostic check.

This places the in-service test alongside EOBD as another diagnostic tool. However, there are important distinctions between the two. The in-service test measures pollutants directly, over the selected test procedures, to check the satisfactory operation of key emission control systems and components, whereas an EOBD system measures the output from sensors, during on-the-road driving, and relies on algorithms to infer the pollutant emissions.

One of the identified weaknesses of the EOBD concept concerns the ability of the algorithms to predict emissions in real complex situations where several systems have degraded to a degree. This weakness is circumvented in a tailpipe emissions test because the combined effects of all the degradations on emissions are monitored directly. (The challenge for an in-service tailpipe test is to devise appropriate drive cycles/procedures.)

The above also illustrates the complementary nature of these two diagnostic tools.

Key finding 1

The UK in-service test is best considered as a diagnostic test, undertaken using tailpipe emissions measurements that check key emissions control systems and components. As such it is technology dependent, not universally applicable, and would not be expected or need to correlate with emissions over the type approval cycles for all vehicles, vehicle conditions and defects. The tailpipe diagnostic test is distinctly different from, and complementary to, EOBD. Specifically in that the in-service tailpipe test measures pollutant emissions directly, showing the combined effects of all the deterioration of all systems and components.

The strategy appropriate to developing an in-service test programme is, therefore,
- to identify the key systems required for a vehicle to meet emissions regulations,
- to identify the technologies and components underpinning these systems,
- to identify methods, where practical, of using tailpipe emissions to check the correct operation of these systems, technologies and/or components.

The results of such an analysis generates a matrix of systems/components to be checked and the species in the exhaust gases that might be measured as part of checking their correct operation. This matrix is given in Table 11.

Table 11 Matrix of systems to be checked and the exhaust gas component(s) that might be used to check their correct operation

	CO_2	CO	HC	NO_X	O_2	Engine speed
Closed loop fuelling (λ) – steady running	✓	✓	✓		✓	
Closed loop fuelling (λ) – transient	✓	✓	✓		✓	✓
Efficient ignition			✓			
Catalyst integrity		✓	(✓)	(✓)		
Catalyst oxidation activity		✓	(✓)			
Catalyst reduction activity				✓		
Idle stabilisation		✓				✓
Cold starting	not applicable given the decision not to test these systems					

(✓) signifies that this exhaust gas component is affected by the system under consideration but the change in concentration, and the relatively smaller absolute concentrations involved make this species less attractive than the unbracketed, ticked species.

8.1.2 Considerations for lambda (λ)

The control of this parameter is a crucial part of the emissions control technology on most current vehicles. This will most probably not continue to be the case for the emerging lean burn technology.

Testing to confirm that λ is being controlled within narrow prescribed limits in an unloaded, steady engine speed high idle test is valuable. Replacing this with an equivalent loaded test is anticipated to identify only a few additional vehicles with defective closed loop fuelling control systems. This measurement requires exhaust gas analysers that measure the concentration of CO, CO_2 O_2 and HC at the tailpipe (and uses the Brettschneider approximation to calculate λ).

The addition of a transient test when repeatedly depressing the brake pedal (with the engine starting at the high idle condition) has been shown to lead to an increase in engine speed for vehicles with correctly operating closed loop fuelling systems. (This occurs because additional air is introduced into the inlet manifold via the brake servo, which rapidly leads to additional fuelling being supplied by a correctly operating fuelling system, generating more power and leading to an increase in the engines power and hence speed.) This could form the basis for an unloaded test of the transient behaviour of the closed loop fuelling system.

Key finding 2

The correct operation of the closed loop fuelling control system at steady speed is appropriately checked by ensuring λ is within a defined range using the current unloaded, high idle test. This could be extended to check its transient response is also satisfactory by the addition of a further unloaded test.

8.1.3 Consideration for HC

The measurement of tailpipe HC concentrations is required to calculate λ. It also affords a somewhat crude check for misfiring. The procedure and instrumentation are those determined by the procedure required by λ, i.e. the current unloaded, high idle test, and existing exhaust gas analysers. However the pass/fail limit for HC appears to be inappropriately high.

Key finding 3

The current pass/fail limit for HC (200 ppm hexane, or 1,200 ppm carbon equivalent) has been shown to be high relative to the type approval standards and the emissions of vehicles in the fleet.

8.1.4 Consideration for CO

There is no primary reason for measuring CO emissions. Its measurement is required for the calculation of λ, and it is potentially a useful way of checking catalyst health, and the correct functioning of the vehicle’s idle stabilisation system (together with the engine’s speed at idle).

The measurement as part of the λ calculation requires the procedure appropriate to that diagnostic test, i.e. unloaded steady engine speed at high idle. This procedure also checks, to some measure, the physical integrity of the catalyst, identifying vehicles whose catalyst is leaking internally or has broken up such that some exhaust gas bypasses the active part of the catalyst. The lowering of the pass/fail limit for CO at high idle from 0.3% to 0.2% is consistent with what appropriately maintained vehicles can achieve and is therefore reasonable. (There remains the question of the appropriateness of the specification of the accuracy and precision of the meters used to make these measurements.)

The current test will also identify loss of catalytic oxidation activity in the worst cases. However, it is a poor test of this, both because of its poor sensitivity and because of the large number of false first time failures that occur.

Key finding 4

The measurement of CO at high idle is required for the calculation of λ. The new lower limits will improve its ability to check catalyst integrity and identification of the worst cases of loss of catalytic oxidation activity.

The measurement of CO and engine speed, at low idle, checks the correct functioning of the vehicle's idle stabilisation system.

Two possible improved test procedures for the checking of catalyst activity and reducing the number of first high idle test failures are identified. They comprise:
- the use of the CO concentration/time profile to infer catalyst activity, or
- the measurement of whether the activity of a working, lit-off, catalyst remains at the unfavourable extreme (unloaded, normal idle) of the engine's operating range.

The limited data obtained show that both may provide the basis for an improved test, but as yet there are insufficient data to make firm recommendations. It was also concluded that measuring CO concentrations in a loaded steady speed test would not be a significant improvement on the current test, and that testing CO concentrations for a cold start is impractical for an in-service test.

Key finding 5

Two possible unloaded test procedures are proposed that would provide a better measure of catalyst activity. Insufficient data currently exist to enable the two possibilities to be prioritised, or indeed to confirm the effectiveness of either approach.

8.1.5 Consideration for NO_X

Key finding 6

A small practical study and the analysis of some US EPA data both show how maintenance does reduce NO_X emissions. This contradicts the conclusion reached by the JCS study.

It was also concluded that there are two principal systems/components important in the control of NO_X emissions for which an in-service check is appropriate:
- the closed loop fuelling system – discussed under λ measurement, and
- the catalyst's NO_X reduction activity.

Also, it is worth monitoring the increasing use of EGR by vehicle manufacturers as a system for reducing NO_X because it may be that it becomes appropriate to check this with an in-service diagnostic test.

The NO_X tailpipe emissions for several loaded/unloaded steady speed/transient tests were measured with one of the vehicles being tested with a poor and a new catalyst. The unloaded tests look promising showing larger, or comparable, reductions than their loaded counterparts (although the tailpipe NO_X concentrations were higher for the loaded tests).

Key finding 7

Unloaded procedures for checking the NO_X reduction activity of a vehicle's catalyst appear promising. The results from unloaded tests were encouraging, both at steady speed (i.e. high idle test) and transient (accelerating the engine against its own inertia from idle to around 3,000 rev/min in 5 – 7 seconds).

Finally, given the above conclusions that it was both worthwhile (in terms of the ability to reduce NO_X emissions) and feasible (in terms of the definition of a practical test procedure), the instrumentation required was considered. It was noted that garage exhaust gas analysers comprise a series of sensor benches and a microprocessor driven testers' prompt, signal analysis and display unit.

Key finding 8

To increase the capability of the current garage exhaust gas analysers to include the measurement of NO_X concentrations would only require the addition of a NO_X sensor into the existing systems, and some relatively minor software changes. The expectation is that the NO_X sensor would most probably be an electrochemical cell, and involve a cost of around £500 per meter.

8.1.6 Cost effectiveness

The cost effectiveness calculations reported in the Phase 1 study have been built on. The emissions savings potential for the years 2005, 2010 and 2015 have been revised, but are little changed from those calculated in the Phase 1 study because there have been no significant changes in the input assumptions or base data.

The cost of testing for λ, CO and HC has been calculated for three scenarios:
1. base case – a continuation of the current test programme at no incremental cost,
2. extended unloaded testing – increasing the current emissions test time by three minutes, and
3. loaded test – both increasing the current test time by 9 minutes and requiring the use of a dynamometer.

The cost of measuring NO_X concentrations has been calculated using the same three scenarios as for λ, CO and HC, but allowing for addition of NO_X measurement capability to the current exhaust gas analysers.

The cost effectiveness has been calculated using the above data. The units used have changed to pounds spent per tonne saved from grams saved per pound spent.

Dividing the in-service test programme costs by the emissions savings potential (the maximum savings that would be delivered by a "perfect" test) gives an upper limit to the cost effectiveness that could, in practice, ever be achieved. The savings that might realistically be achievable were estimated, and the resulting estimates of the realisable cost effectiveness of emissions testing was found to be as tabulated overleaf.

It is emphasised that each saving is **not exclusive**, i.e. **not the sole benefit**, because there will be associated reductions for other species.

Table 12 Estimated realistically achievable cost effectiveness of emissions testing

2005	Scenario 1	Scenario 2	Scenario 3
CO (£/tonne)	265	360	745
NMVOCs (£/tonne)	6,467	8,756	18,120
benzene (£1000s/tonne)	130.9	177.2	366.6
1,3 butadiene (£1000s/tonne)	621.5	841.6	1,741.5
NO_X costs from λ, CO, HC test (£/tonne)	8,107	10,977	22,715
NO_X costs from NO_X test (£/tonne)	8,234	11,104	22,842
2010	Scenario 1	Scenario 2	Scenario 3
CO (£/tonne)	352	475	965
NMVOCs (£/tonne)	7,794	10,540	21,388
benzene (£1000s/tonne)	166.1	224.6	455.8
1,3 butadiene (£1000s/tonne)	860.2	1,163.1	2,360.3
NO_X costs from λ, CO, HC test (£/tonne)	11,806	15,965	32,396
NO_X costs from NO_X test (£/tonne)	11,978	16,136	32,568
2015	Scenario 1	Scenario 2	Scenario 3
CO (£/tonne)	420	565	1,150
NMVOCs (£/tonne)	8,355	11,297	22,889
benzene (£1000s/tonne)	180.4	244.5	495.4
1,3 butadiene (£1000s/tonne)	1,009.6	1,365.1	2,765.8
NO_X costs from λ, CO, HC test (£/tonne)	14,142	19,122	38,742
NO_X costs from NO_X test (£/tonne)	14,347	19,326	38,947

8.1.7 Gas fuelled vehicles

The objective of this section of the report was to discern the in-service test appropriate for gas fuelled vehicles. The background of the factors influencing conversion to run on gaseous fuel, the technology used to achieve this, the in-use emissions from converted vehicles and the current in-service test procedure were all reviewed.

Key finding 9

Contrary to popular perception, and to what **could be achieved**, the current evidence is that **on average** petrol light-duty vehicles that have been converted to run on LPG are more polluting, and their emissions degrade more rapidly, than their petrol fuelled counterparts. It is emphasised that the conversions installed range widely from excellent to unacceptable in terms of their emissions performance.

The conclusion above would indicate that the cost effectiveness of the in-service test for these vehicles ought to be high. However, this appears not to be the case because vehicles are only required to be **tested using the fuel they are running on when they are presented** for testing.

Key finding 10

The in-service testing of vehicles converted run on gas fuels (principally LPG) appears inadequate to instigate repair and maintenance in many cases.

In terms of the technology, it appears that any modifications acceptable to the in-service test for petrol vehicles are very likely to be also appropriate for vehicles when running on gas.

However, before the in-service test for vehicles converted to run on gas can simply be changed to include testing when the vehicle is running on gas there are a number of implications to be thought through and decisions to be taken.

8.1.8 The influence of OBD

The requirement to fit EOBD systems to all vehicles sold post 1st January 2001 has generated the possibility that the in-service test could be radically changed from a tail-pipe emissions check to an inspection of the EOBD system. This is the subject of a separate report, which is summarised in this report.

Key finding 11

Whilst EOBD has the potential to improve the effectiveness of in-service testing for maintaining appropriately low pollutant emissions, it is currently (Dec 2002) premature to propose augmenting the current UK in-service test with an EOBD system inspection.

There are various reasons for the above conclusion and it is believed that technical immaturity rather than more generic issues regarding concept or consistency of implementation are the primarily cause of these.

Key finding 12

OBD is in essence a compromise necessitated by the technology available. On-board emissions measurement (OBM) may, in time, supersede OBD.

Notwithstanding, because EOBD has the potential to improve the effectiveness of in-service testing for maintaining appropriately low pollutant emissions the key question appears to be more of "**when are conditions right?**" and "**exactly what form should an in-service test take?**" rather than should OBD become part of the in-service test.

It was concluded that two possible developments that would prevent EOBD from becoming an appropriate part of an in-service test are as follows.
1. If it became evident as the technology matures that EOBD cannot meet it technical objectives. This appears unlikely given the experience in the US where OBD was introduced around 5 years earlier than in Europe.
2. If on-board emissions measurement (OBM) (the direct measurement of exhaust gas composition during use) were to advance to a stage of being a practical likelihood, then this should be considered as the primary technique used to monitor in-service emissions, i.e. superseding EOBD.

8.2 RECOMMENDATIONS

These follow from the twelve key findings highlighted in the previous section on a one-to-one basis.

1. The UK in-service test should be considered as a series of diagnostic tests monitoring the continued correct operation of specific systems and components that are important in the control of the vehicle's emissions. As such it is not a pre-requisite that individual tests have a good correlation with the emissions from the Type 1 test over all vehicles, vehicle conditions and defects. This diagnostic test is distinctly different from, and complementary to, EOBD, specifically in that it measures pollutant emissions directly, showing the combined effects of all the deterioration of all systems and components rather than inferring emissions performance from sensors' outputs.

2. λ should continue to be checked as at present using a steady engine speed around 2,500 to 3,000 rev/min in an unloaded test. Consideration should also be given to the advantages and practicality of augmenting this check at a steady speed with a transient test (based on using repeated application of the brake pedal to introduce additional air into the engine and leading to an increase in engine speed).

3. Hydrocarbons should continue to be checked, as at present, for the calculation of λ. The pass/fail limit should be left unaltered at present. This should be reviewed following an analysis of the HC concentrations measured at test stations (which will become available from the computerisation of the MOT scheme).

4. CO should continue to be checked, as at present, for the calculation of λ. This test procedure, with the new limits, affords some checking for the integrity of the catalyst, and to a lesser extent, for catalyst activity.

5. Consideration should be given to the advantages and practicality of improved checking of catalyst activity through monitoring tailpipe CO concentrations using either of the two proposed improved test procedures.

6. The concept of I&M generating NO_X emissions reductions, and thereby contributing to improvements in air quality, should be promoted. This is to correct the misconception that in-service testing may be irrelevant with regard to NO_X emissions.

7. Consideration should be given to the advantages and practicality of using one of the proposed unloaded tests combined with the measurement of tailpipe NO_X concentrations to assess the catalyst's NO_X reduction activity.

8. The probable £500 /meter price tag for augmenting the tailpipe measurement capability of the current garage exhaust gas analysers is sufficiently low for this possibility not to be ruled out. The principal challenge is finding an appropriate test procedure and there being appropriate cost effective benefits.

9. Consideration should be given to discerning how the augmenting of type approved petrol fuelled vehicles to run on LPG can be better controlled so as to reduce the number of excess emitting LPG fuelled vehicles at source.

10. Consideration should be given to, as a minimum, checking the emissions of vehicles when fuelled by LPG if this fuelling option is fitted, and also applying any modifications accepted for use for the in-service emissions test of petrol fuelled vehicles equally to LPG vehicles.

11. It is currently not appropriate to envisage augmenting the current UK in-service test with an EOBD system inspection. It is even less appropriate to consider replacing the current UK in-service test with an EOBD system inspection at present.

12. Further in-depth analytical and practical work should be commissioned to make good inadequacies in the currently available information. This should comprise studies to quantify the cost effectiveness and practicality of inspecting EOBD systems at the annual in-service test, thereby enabling the viability of various possible EOBD based inspection concepts to be assessed.

9 Glossary

CNG	Compressed natural gas
COP	Conformity of production
ECU	Electronic control unit, also called the PCM
EOBD	European on-board diagnostics
EPA	Environmental Protection Agency (a US government department)
EST	Energy Saving Trust
EUDC	Extra-urban driving cycle
Euro I	The emissions standard specified in Directive 91/441/EEC
Euro II	The emissions standard specified in Directive 94/12/EC
Euro III	The emissions standard specified in Stage A of Directive 98/69/EC
FTP	Federal test procedure (the US equivalent of the European NEDC), also known as the FTP 75
GDI	Gasoline direct injection
I&M	Inspection and maintenance
IM240	A 240 second duration dynamometer test used by some US states for their in-service testing
ISO	International Organisation for Standardisation (a world wide federation of national standards bodies)
JC	Joint Commission (A study on inspection of in-use cars by the EC DGs for Environment (DG XI) Transport (DG VII) and Energy (DG XVII)
Lambda (λ) sensor	Commonly used name for what is actually an oxygen concentration sensor (Section 3.3.2)
LPG	Liquefied petroleum gas
LPGA	Liquefied Petroleum Gas Association
MIL	Malfunction indication lamp
MOT	Ministry of Transport – the UK in-service test is colloquially known as the MOT test after the ministry responsible for its introduction
NAEI	National atmospheric emissions inventory
NAO	National Audit Office
NEDC	New European driving cycle (the Type 1 test specified in 98/69/EC – Section 3.4)
NMVOC	Non-methane volatile organic compounds (i.e. hydrocarbons less the methane component)

OBD	On-board diagnostics
OBD I, OBD II	The US standards for On-board diagnostics version 1, and 2 (Chapter 1)
OBM	On-board measurement
OEM	Original equipment manufacturer
OIML	Organisation Internationale de Métrologie Légale - the organisation that generates the currently used specification for vehicle exhaust gas analysers
OSC	Oxygen storage capacity – a characteristic central to the satisfactory performance of a three-way catalyst
TAC	Technical adaptation committee – an EC technical committee
TRL	Transport Research Laboratory,
TWC	Three-way catalyst
VCA	Vehicle Certification Agency (the UK's national approval authority for new road vehicles, an executive Agency of the Department for Transport)
VI	Vehicle Inspectorate (an executive agency of the Department for Transport)

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17 For Euro I and Euro II standards the emissions thresholds are specified for HC + NO_X. The NO_X only component is derived from this as explained in Appendix 3.

18 An analysis of emissions data from the MOT test, TJ Barlow, RS Bartlett and ICP Simmons, S140C/VB, Transport Research Laboratory report PR/SE/474/98, August 1998.

19 Data from LP Gas Association, Oct 2002 (www.lpga.co.uk).

20 Data from Global Autogas Industry Network (www.worldlpg.com/gain).

21 PEF = Propane equivalence factor – a manufacturer declared calibration constant that enables the meters response to hexane and propane to be related. The value is usually in the region of, and just less than 0.5, e.g. 0.48.

22 Private communication between the author and the EST, November 2002.

23 NAO report on Vehicle emissions testing, May 1999, HC 402.

24 Low emissions diesel research – Phase 2 report, J Norris, CP17/18/770, AEA Technology report AEAT/ENV/R/0629, June 2001.

25 Emissions data in this Appendix on Cost Effectiveness are taken from the 1999 NAEI Road Transport Emissions Projections (Reference 13).

Appendices

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