

Report

**Low Emission Diesel Research
CP17/18/770**

Phase 3 - Report

Report to Vehicle and Operator Services Agency
(VOSA)

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Executive Summary

Background and scope

This report describes work undertaken for the UK's Vehicle Operator and Services Agency (VOSA) under the third phase of a project entitled "Low emission diesel research". The project is concerned with the in-service testing of modern diesel vehicles. The first two phases, both desk based studies, concluded that the current test regime had weaknesses (Phase 1) and proposed alternative test procedures (Phase 2). These were focussed on the two pollutants particulate matter (PM) and oxides of nitrogen (NO_x) that are both emitted in significant quantities by diesel vehicles and are key species regarding air quality. The primary focus of this Phase 3 study is to provide an initial evaluation of the options recommended from the Phase 2 study.

Conclusions of earlier phases of the study indicated that whilst current in service testing of light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) does monitor PM emissions, the current regime is not ideal in identifying excess emitters powered by Euro 2 and newer engines and there is the potential for changes to the testing regime to offer cost effective emissions savings of this pollutant. Secondly, whilst there is no current in service test for NO_x emissions, for LDVs new testing regimes offer the potential for cost effective emissions savings of this pollutant.

Test procedure options

A steering group, comprising people from within DfT, VOSA and AEA Technology, concluded that for both LDVs and HDVs only unloaded tests should be considered (as opposed to on-the-road driving or loaded testing using dynamometers) for all proposed in-service testing.

Procedure for PM testing

For PM test procedures, further evaluation concluded a transient test was the best option (as opposed to a test at a constant engine speed). The current FAS test procedure was assessed. The variability in its results introduced as a result of various factors were investigated. (These included the rate and extent of accelerator depression, ambient and engine temperatures and preconditioning.) The study has concluded that for both HDV and LDV the change to electronic control of fuelling (replacing mechanical fuelling systems) has very greatly reduced the variability in test results occurring as a result of testers' actions. For HDVs this study recommended that no changes to the current procedures were required. For LDVs minor changes to the existing procedures were recommended to avoid unnecessary repeat testing and to reduce the effect of poor preconditioning.

Instrumentation for PM testing

The study concluded that the current meters used for in service testing are totally adequate for the existing pass fail limits and for those to be introduced for Euro 4 vehicles in 2008. However should more stringent limits be applied more sensitive meters may be required. Of the instruments/methods investigated the advanced opacimeter offered improvements in sensitivity over the current method, with the filter paper reflectometer approach being more sensitive than current instrumentation but more difficult to apply in practical aspects. The QCM instrument was not tested because of instrument failures. However we believe that the immaturity of the product at the time of

the study rather than inherent problems with the technique were responsible. Light scattering instrumentation was assessed and found to be the least suitable of the four instrument types assessed.

Pass/fail limits for PM testing

Investigations of the current level of failures on PM emissions for HDVs indicated that virtually no Euro 3 vehicles were failing the test. For LDVs the current universal pass/fail limit in the FAS test does not correlate well with estimated on road emissions and is not demanding for many vehicle types. The current test regimes are therefore poor in identifying excess emitters. Given the improved suitability of the FAS test procedure as an appropriate procedure, and the satisfactory performance of the current meters at policing pass/fail limits of 1.0 m^{-1} and above, the focus for improvement lies in the selection of appropriate pass/fail limits that meet the objectives of the in-service test programme.

Possible options may be summarised as introduction of lower pass/fail limits universally for all vehicles, lower vehicle type specific pass/fail limits or a mixture of the two approaches. The cost effectiveness (pounds spent per kg of PM saved) of these various options of changing the pass/fail limits for PM were investigated against a 'no change' base line. In addition to the cost effectiveness, the errors of commission (incidence of incorrectly failed vehicles) was considered. The study concluded that for both HDV and LDV the option of a degree of vehicle specific pass/fail limits coupled with improved instrument sensitivity would provide the most cost effective PM emissions savings whilst minimising the errors of commission.

Procedures for NO_x testing of LDVs

Phase 2 of the study had recommended developing a test to check the continued operation of exhaust gas recirculation (EGR) units, the NO_x abatement technology fitted to nearly all LDVs as this is the fault likely to lead to excess NO_x emissions. Two possible diagnostic techniques were assessed. These were the use of 4-gas analysers and thermometry.

Investigations into the potential use of thermometry to detect malfunctioning EGR valves proved that the technique was insufficiently sensitive, and not universally applicable to all vehicle types. For two of the nine vehicles used the EGR unit was inaccessible, squeezed between the engine and the bulkhead. In addition for all seven passenger cars used the presence of engine covers meant some dismantling was required prior to taking measurements. Overall it was adjudged that the technique was not an appropriate foundation upon which a practical in-service test could be developed.

The use of 4-gas analysers to identify EGR faults was shown to be feasible over a wide range of vehicles. These represented approximately 50% of the current UK sales of LDVs, by engine type, there being no vehicles used for which this approach does not work. The study identified three possible tests as potential pass/fail test regimes: a 2 engine speed (unloaded) test using the same engine speeds for all vehicles; a 2 engine speed test with using engine speeds tailored to each vehicle type, and a test based on changes at idle only which would also be tailored to each vehicle type.

The study went on to investigate the cost effectiveness of these options and the potential for errors of commission. All three options using 4 gas analyser testing to identify EGR faults in LDVs provided similar potential emissions savings (around 0.4 ktonne/yr NO_x). In terms of both cost effectiveness and errors of commission, the use of a test based on changes at idle represented the most attractive option.

Instrumentation for NO_x testing of LDVs

The procedures described above rely on the tailpipe measurements of CO₂ and O₂ concentrations because these change markedly with changes in EGR rate (as do NO_x concentrations). The instrumentation required for this is a 4-gas analyser of the type currently in use at MoT centres for petrol-fuelled vehicles. Discussions with a large manufacturer of such instruments indicated no significant barriers to their use being extended to the proposed procedure.

In-service testing of HDVs for NO_x control

Phase 2 also identified that for HDVs the fault most likely to result in excess NO_x emissions was failure of NO_x abatement technologies. However, because virtually no vehicles were fitted with such technologies and because there was no consensus view on the technologies that would be used in the future it was concluded that a watching brief be kept on their development and implementation, but no further research be conducted at this time.

The majority of manufacturers now anticipate the use of selective catalytic reduction (SCR) as the NO_x abatement technology to meet Euro 4 and 5 standards. This report recommends that with this choice made, the time is now right to consider in-service testing of these vehicles with a view to reducing potential excess NO_x emitters.

Concluding summary

Overall the project has considered the current in service strategies for reducing PM and NO_x emissions, has provided mechanisms to improve the existing PM test methods. It has also demonstrated the feasibility and cost effectiveness of reducing excess LDV NO_x emissions using instrumentation currently in place at UK test centres. In recommendations for further work on PM emissions, this report has presented options to help define what are appropriate pass/fail limits for PM for LDV and HDV and has presented methods by which more sensitive instrumentation might be evaluated to determine its suitability at these levels. For NO_x emissions, the report has indicated how the potential test checking EGR function in LDVs might be progressed. For HDVs the report recommends that with the choice regarding NO_x abatement technology having now been made, , the time is now right to consider in-service testing of these vehicles with a view to reducing potential excess NO_x emitters.

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1 Introduction

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

Before a new vehicle can be approved for sale in the EU it must meet certain standards for exhaust emissions as specified by EU directives. These standards are vehicle type specific and have evolved over time with improvements in engine design allowing lower limits to be achievable. Once in service, a vehicle's condition degrades and emissions generally increase above the original levels. Timely maintenance reduces the extent of this degradation.

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

An initiative to promote the acceptance of environmentally friendly vehicles was the "Cleaner Vehicle Task Force" (CVTF) 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 was 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, listed in their report entitled: "Technical solutions for reducing the emissions from in-use vehicles"¹, are incorporated as an input into this project.

In-service emissions testing is one of several measures designed to reduce pollution from vehicle emissions. The Vehicle and Operator Services Agency (VOSA) (formerly the Vehicle Inspectorate) is directly responsible for the emissions testing of heavy goods and public service vehicles, and the roadside testing of all vehicles. VOSA also oversees the testing of passenger cars and light goods vehicles (the MoT test) which is carried out by 18,600 private garages around Britain.

The National Audit Office (NAO) completed a study of the effectiveness of the regime for in-service testing of vehicle emissions in Britain, publishing its findings in May 1999 in a report entitled Vehicle Emissions Testing. Its main findings and recommendations, specifically those concerning the testing of diesel-engined vehicles, are also incorporated as an input to this project.

¹ Technical solutions for reducing emissions from in-use vehicles, report of Technology and Testing working group of the Cleaner Vehicles Task Force, UK Department of Trade and Industry, March 2000.

The "Low Emission Diesel Research" project has been commissioned by VOSA to provide advice to the UK Government's Department for Transport (DfT), and, through reciprocal arrangements, the European Community on

- appropriate in-service/test limits for both heavy-duty and light-duty low emission diesel-engined vehicles, and
- appropriate test procedures and equipment for use both in the annual roadworthiness test and at the roadside; in particular:
 - to check if the emissions control equipment is functioning correctly (on both new and retro-fitted vehicles) and
 - to ensure a meaningful test of EURO 1, 2, 3 and 4 specification engines.

The first Phase of this project was the **Definition and identification of an "Excess Emitter" vehicle at annual test**. Its principal conclusions were:

- a cost-effective savings potential exists for NO_x;
- currently there is no in-service NO_x test;
- a cost-effective savings potential exists for PM;
- the current testing regime (meter/procedure/limits) is far from ideal for identifying PM excess emitters powered by Euro 2, and later, specification engines.

The overall conclusion reached was that, because of the future savings potentials for both NO_x and PM emissions, consideration should be given as to the instruments and test procedures that might be used to ensure maintenance of these potential savings throughout vehicle life and to convert both these savings potentials into a real improvement in air quality. That was the purpose of the Phase 2, desk based study, which evaluated the options for NO_x and PM measurement, and also the options for the in-service testing of heavy-duty gas engines.

The Phase 2 study entitled **Assessment of alternative test procedures** made a number of recommendations, summarised below.

1. At present (June 2001) there is not a strong cost effective justification for including NO_x emissions checks in the in-service testing of heavy-duty vehicles. However, this might change with the introduction of NO_x abatement technologies, required to meet post-Euro 3 emissions standards. Consequently the direction of NO_x abatement technologies should be periodically reviewed so that, if appropriate, tests to confirm their effective operation can be researched.
2. At present (June 2001) it is appropriate, and timely, to evaluate in-service test procedures for light-duty vehicles fitted with exhaust gas recirculation (EGR) systems so that the reduction in NO_x emissions provided by this system continues to occur in use.
3. The applicability of using the 4-gas analysers currently employed in test stations for the in-service testing of petrol-fuelled vehicles should be evaluated.
4. Improvements to the current in-service PM test for all vehicles should be sought. (The current test comprises an unloaded free acceleration, opacimeter and 2.5 or 3.0 m⁻¹ pass/fail limits.
5. A steering group should critically assess the practicalities of the test procedure options (dynamometer, on-the-road and unloaded testing) weighing the technical advantages and disadvantages tabulated in the Phase 2 report with other issues, and taking into account decisions regarding probable test procedures for light-duty spark ignition vehicles.
6. Representative instruments of four different types (i.e. filter paper reflectometry, quartz crystal microbalance, advance opacimeters and light scattering) should be

evaluated to assess their accuracy and sensitivity for measuring PM emissions from modern diesel engines.

7. For gas fuelled heavy-duty vehicles a minimal test is currently appropriate because of the large difference between the type approval standards and the emissions actually produced from a new gas fuelled vehicle.

A further theme running through the recommendations was that any changes or additions to test procedures should be kept as simple as possible, deliberately minimising the investment required. This is because benefits are expected to be short lived as the development of on-board diagnostic (OBD) systems will identify some vehicles requiring maintenance prior to an in-service test.

This Phase 3 study is primarily a practical evaluation of the recommendations that came from Phase 2. It comprises five principal activities:

- Task 1 – a practical evaluation of test measurement techniques for the in-service testing of NO_x from light-duty vehicles with EGR systems (Chapter 2 and Annex 1),
- Task 2 – practical investigations into PM instrumentation (Chapter 3 and Annex 2),
- Task 3 – a practical evaluation of test measurement procedures for in-service testing of PM emissions from heavy-duty vehicles (Chapter 4 and Annex 3),
- Task 4 – an analogous practical evaluation but for PM from light-duty vehicles (Chapter 5 and Annex 4)
- Task 5 – a cost effectiveness analysis of the technical test options recommended from Tasks 1, 3 and 4 (Chapter 6 and Annex 5).

So as to keep the main report to a manageable size, it summarises the objectives and scope of each task, and the methodology used and the principal results obtained. These are discussed within the context of the project as a whole, and recommendations reached. The details of the evaluations and analyses are described in five stand alone annexes to the report, some of which contain appendices, e.g. of tabulated data. The correlation between the chapters, their subject matter, and the associated annex are listed above.

2 The evaluation of test measurement techniques for NO_x

A detailed description of the activities undertaken during this portion of the project is given in Annex 1. Frequent cross referencing to this annex occurs to guide those readers who wish to know further details.

2.1 OBJECTIVE AND SCOPE OF THIS TASK

The context of this piece of work comes directly from conclusions of Phase 2 of this project: that failure of NO_x abatement technology is the principal mechanism that would lead to excess NO_x emitters and therefore it is timely to develop a test for light-duty vehicles fitted with EGR systems. It was also concluded that tests to be considered should be constrained to be simple and unloaded from cost effectiveness considerations and because of the development of ODB systems (which have the potential to reduce the cost effectiveness of a test by identifying some of the vehicles requiring maintenance).

The Phase 2 report recommended "the applicability of using the 4-gas analysers currently employed in test stations for the in-service testing of petrol fuelled vehicles should be investigated, both to confirm this technical approach and to establish the modifications to the meters that would be required for this change of purpose. In addition VOSA requested consideration be given to using thermometry, specifically a non-contact instrument, to confirm exhaust gas flows through the recirculation pipe-work under some circumstances and not under others, thereby confirming the EGR system is operational.

The objectives of this task were:

- to investigate whether either/both of the proposed approaches might work in principle,
- to consider the practicality of an in-service test based on either principle in terms of
 - the ease and reproducibility of testing,
 - the ease of identifying defective vehicles,
 - the likelihood of incorrectly identifying vehicles which are not defective, errors of commission,
- to calculate the applicability of the approaches to the vehicle fleet and
- to undertake a first iteration of determining an appropriate test procedure and its associated pass/fail limits.

At the outset it was recognised that the number of vehicles that would be tested would be limited, and emphasis was placed on selecting vehicles that were representative of the fleet as a whole. Criteria for vehicle selection included:

- an emphasis on modern vehicles,
- the need to test both passenger cars (including heavier vehicles) and light commercial vehicles
- the need to test vehicles whose manufacturers were based in Europe, USA and Asia.

2.2 METHODOLOGY USED AND SUMMARY OF RESULTS

The two approaches for checking EGR functionality were investigated separately and at different times.

2.2.1 Assessment of approach using 4-gas analysers

The principal questions that were investigated regarding this approach were as below.

- a) Does it actually work?
- b) What is the likelihood of this approach forming the foundation of an in-service test?
- c) What might the form of the resulting in-service test be?
- d) What is the approaches applicability to the vehicle fleet?

Whether or not the approach of measuring exhaust gas concentrations using 4-gas analyser actually works was assessed by studying, in considerable detail, the exhaust gas composition for eight different vehicle manufacturer/models (selected using the criteria described in the previous section). The primary results were a mapping of exhaust gas concentrations (CO_2 , O_2 and for some vehicles NO_x) as a function of engine speed. A generic description of the vehicles, and the test arrangements used are given in Section A1.2 of Annex 1. It was found that there was some hysteresis in the results, and hence concentrations recorded when the engine was gently accelerating were separated from those obtained when the engine was gently decelerating. Also, for two of the eight vehicles it was confirmed that the discontinuities observed were caused by the EGR unit varying the quantity of gas recirculated by repeating test cycles with the EGR unit fixed in one position. Figure 1 (taken from Figure A1.2 of Annex 1) shows CO_2 and O_2 concentrations as a function of engine speed for one vehicle with its EGR unit functional and disabled. A clear step in exhaust gas composition is seen at 2,500 rev/min as the EGR unit switches from allowing exhaust gas to recirculate (for engine speeds less than 2,500 rev/min) to preventing exhaust gas from recirculating (for engine speeds above 2,500 rev/min). Whilst Figure 1 is for one of the clearer examples, the effects of changes in exhaust gas recirculation rates were observed for all eight vehicles, demonstrating that this approach does successfully check EGR functionality for all eight vehicles assessed.

The issue of the hysteresis in the gas concentrations observed when the engine was gently accelerating and decelerating was considered. One measurement that may show less hysteresis is that of exhaust flow rate (as a function of engine speed). This hypothesis was investigated using a Pitot tube to measure the velocity of the exhaust gases in the tailpipe as a function of engine speed. These investigations are described in Section A1.3.2 of Annex 1. They concluded that whilst discontinuities in Pitot pressure/engine speed plots were observed, and could, in principle, be used to confirm the correct operation of the EGR unit, signals were generally more difficult to interpret than those from the exhaust gas composition measurements.

A completely unexpected observation was the change in exhaust gas composition that occurs when the accelerator is touched for a vehicle at idle. The majority of vehicles switch from having no EGR (CO_2 concentrations around 2%) to high EGR rates (CO_2 concentrations $>3\%$) swiftly for around 30 – 90 seconds. Figure 2 shows this phenomenon for two vehicles, Vehicle 1 where the EGR is subsequently turned off gradually, and Vehicle 4 where the EGR on to off transition is much more abrupt. This offers the prospect of a simple test that is applicable to most vehicles, using 4-gas analysers, when vehicles are at low idle.

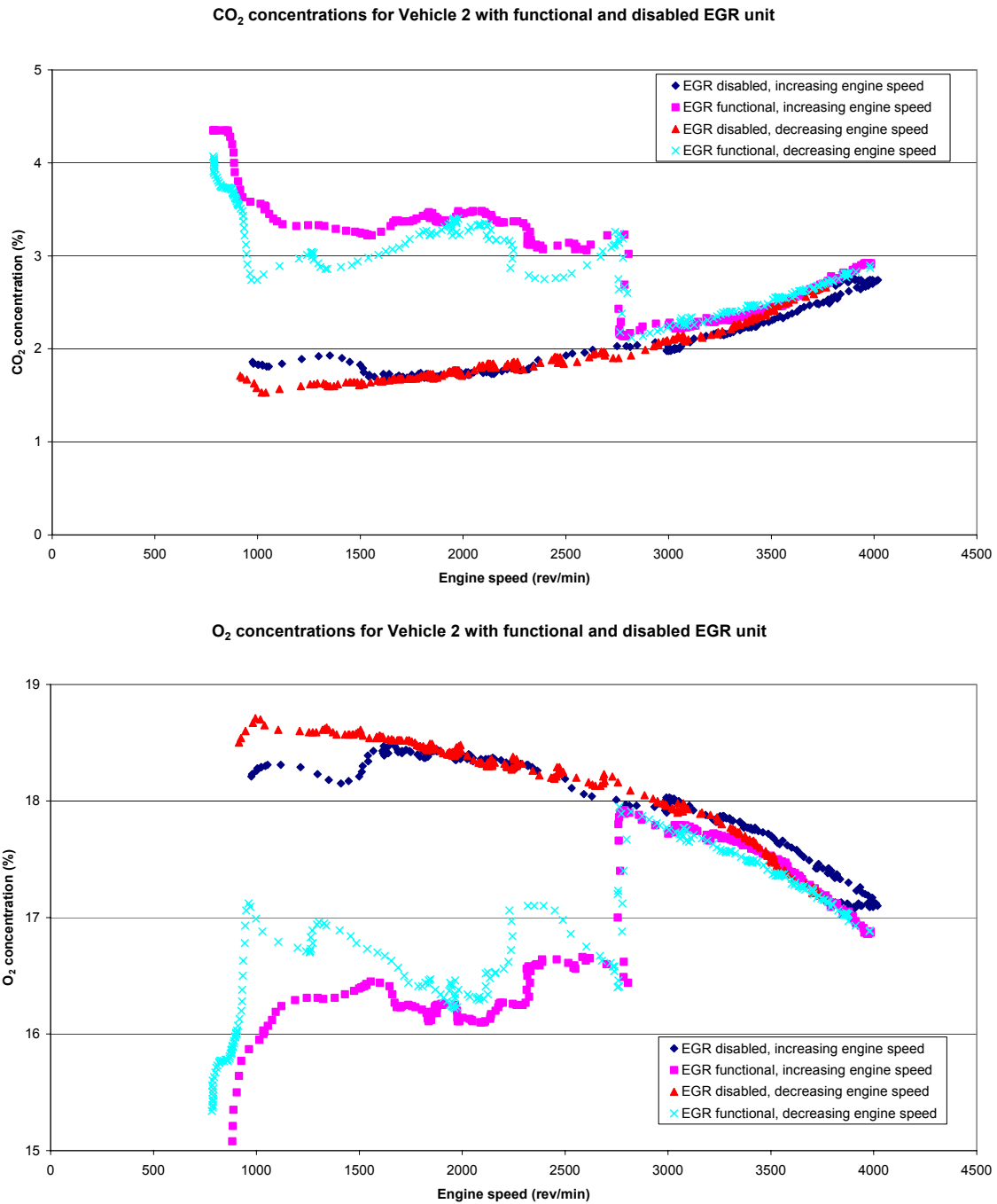
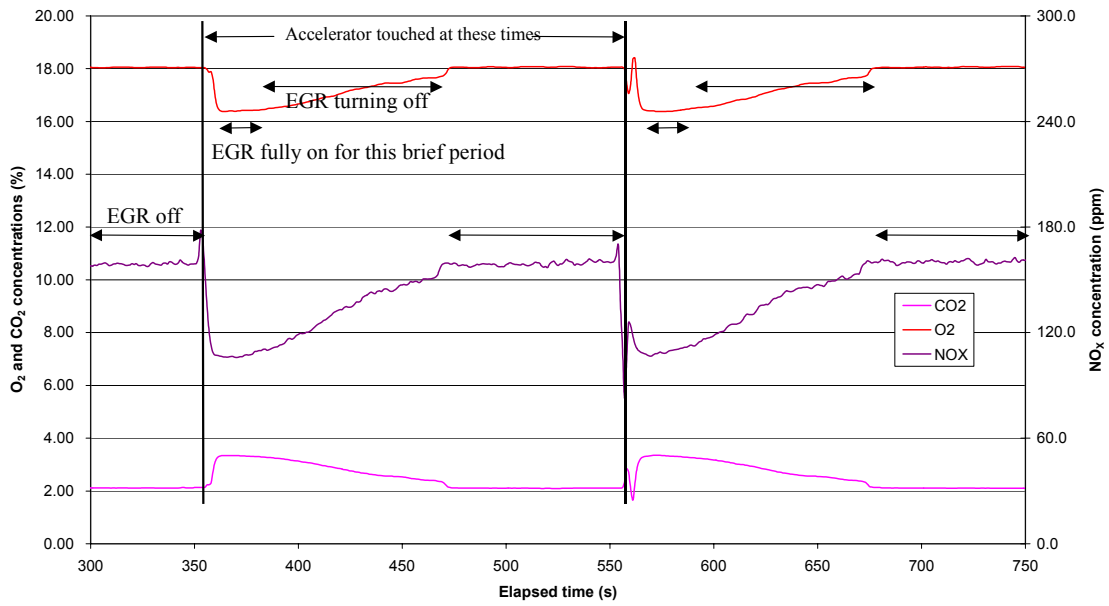


Figure 1 Illustrative example of CO₂ and O₂ tailpipe concentrations as a function of engine speed from a vehicle fitted with an EGR system

The investigations undertaken indicate that there is an excellent likelihood of the use of 4-gas analysers, when combined with an appropriate test procedure, forming the foundation of an in-service test.

Vehicle 1, Emissions at idle when EGR functional



Vehicle 4, Emissions at idle when EGR functional

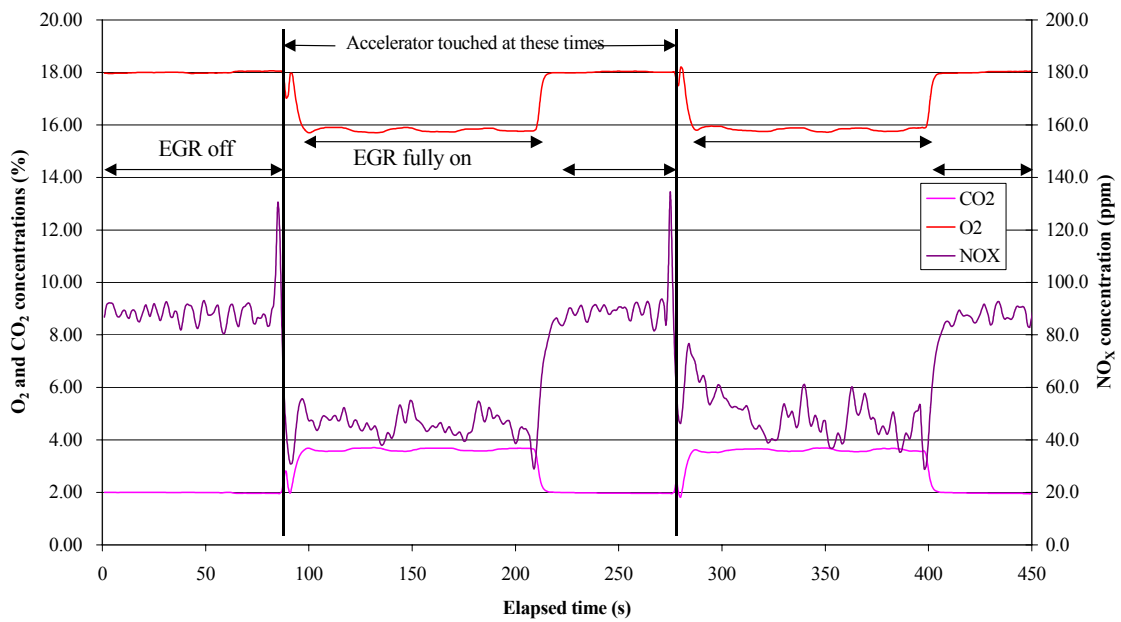


Figure 2 Illustrative example of CO₂ and O₂ tailpipe concentrations at idle from two vehicles fitted with EGR systems

2.2.2 Assessment of approach using thermometry

The principal questions to be answered for this potential approach are as below.

- a) Does the approach work?
- b) What is the likelihood of it forming the foundation of an in-service test?

The validity of the approach was assessed by studying three vehicles in detail. Full details are given in Section A1.4.2 of Annex 1. The results were not encouraging. In summary they were:

For vehicle 2 – the approach failed because the EGR pipe-work to be monitored was hidden between the engine and the bulkhead.

For vehicle 6 – the approach failed because the EGR control valve was directly onto a manifold that had a large thermal mass. Both a non-contact thermometer and a thermocouple configured to measure surface temperatures indicated changes caused by EGR switching between high and no recirculation were too small to be measured sufficiently accurately to form the basis of an in-service test.

Vehicle 9 – the approach worked. However, the signal to noise ratio of the measurements were not sufficiently high to convincingly demonstrate the practicality of this approach.

The general applicability of the approach was considered by augmenting the data from the three vehicles described above with observations from a further six vehicles, selected according to the criteria given in Section 2.1. Of the six additional vehicles, the EGR unit was totally hidden in one of them. Overall this limited study suggested this approach was not applicable to around a third of vehicles.

An additional difficulty noted was that for all seven passenger cars (although not for the two light commercial vehicles) an engine cover had to be removed to gain line-of-sight access to the EGR pipe-work (although even then it was not always visible). This, albeit modest, dismantling of part of the vehicle in order to undertake an in-service test is contrary the current policy of the in-service testing regime.

2.2.3 Assessment of applicability of approaches

Estimates were made of the proportion of the diesel fleet which were examined in the preceding two assessments. These were calculated from the sales of diesel vehicles in 2002 provided by the SMMT. From analysis of this data base it was found as follows.

- The six current passenger car models tested using 4-gas analysers comprised 16.5% of total sales in 2002.
- The six manufacturers whose models were tested sold 44.7% of total 2002 sales.
- The six engines fitted to the models tested were fitted to 47.6% of all vehicles sold in 2002.

In addition, although Vehicle 9 was not fully assessed using a 4-gas analyser, its behaviour at idle (studied as part of the assessment of the thermometry approach) mirrored the mapping of other vehicles tested. If this vehicle is added to give 7 passenger cars assessed, then the seven models comprise 18.7% of total sales and the seven manufacturers share of total 2002 sales was 54.8%.

The above data, combined with the fact that none of the vehicle studied were not suitable for testing with a 4-gas analyser, indicates that this approach is widely applicable for the current fleet.

2.2.4 Effect of EGR failure on NO_x emissions over Type 1 drive cycle

A further practical assessment measured the excess NO_x emissions that occur over the Type 1 regulatory cycle when a vehicle's EGR unit is disabled. This was obtained by measuring vehicles with their EGR units operational and disabled. The increase in NO_x emissions ranged from 34% to 138%, with an average of 87%. It is this average figure that is used in the cost effectiveness analysis reported in Chapter 6 (and Annex 5).

2.3 RECOMMENDED TECHNICAL TESTING OPTIONS TO BE ASSESSED.

The baseline option can be taken as "change nothing". It might be presumed that because there is currently no in-service test for NO_x emissions (the only test for diesel vehicles being the free acceleration **smoke** test) that current savings were zero. However, other studies in this phase of the project have shown that a vehicle with an EGR unit stuck either open or nearly fully open, has a much higher FAS result than a vehicle whose EGR unit operates correctly. Further, if the EGR unit is stuck in an intermediate position it is likely to generate some excess NO_x emissions. Hence the current FAS test does generate some NO_x savings. (The magnitude of this is calculated in Chapter 6, cost effectiveness analysis).

A consequence of the above is that a lowering of FAS limits would be expected to cause an increase in the number of vehicles with defective EGR units being identified and repaired.

The assessment of a potential in-service test using thermometry concluded that whilst the primary principle is proven, the implementation of the technology, the need to remove covers from the engine and the challenges involved in practically implementing a test based on this principle, means that it is a poor option relative to the alternative of using a 4-gas analyser. Consequently it is recommended that this option for the in-service testing of EGR units fitted to light-duty vehicles is not considered further.

The assessment of using a 4-gas analyser, specifically monitoring CO₂ and O₂ tail-pipe concentrations as a diagnostic check for EGR functionality demonstrated that this principle is sound. However, the mapping of exhaust gas concentration from idle to, for example, 3,500 rev/min is too complex to be recommended as the procedure to be used for an in-service test.

One alternative is to use a test that takes measurements at two engine speeds (one when a large amount of recirculation occurs and the other selected for when negligible recirculation occurs). This could be implemented using either the same engine speeds for all vehicles, or optimum engine speeds determined on a vehicle type basis. Whilst the latter is the more complex, it is likely to more successfully identify malfunctioning EGR units, and to produce fewer errors of commission. Figures A1.6 and A1.7 of Annex 1 show the tailpipe O₂ and CO₂ concentrations for these two testing options.

A second alternative would be to use a test at idle, measuring O₂ and CO₂ concentrations before the accelerator is lightly touched. This test is inherently simpler, quicker, and has better signal to noise characteristics than for measurements at engine speeds above idle. Its primary weakness is that a single answer is not appropriate to all vehicle types.

In terms of choosing between the two engine speed or low idle possible test procedures, the author favours the latter because, on the basis of the data reported in Annex 1:

- the changes in O₂ and CO₂ concentrations, caused by the EGR unit changing the amount of exhaust gas recirculated, are easier to see,
- the above implies an in-service test based on the low idle approach would lead to fewer incorrect failures (errors of commission),
- the test is simpler for the MoT tester to conduct.

The last point is reflected in a lower time required, and hence a lower cost per test (see the cost effectiveness analysis of Annex 5).

The above discussion can be summarised by the five testing options for NO_x listed below. These are the options whose cost effectiveness is evaluated in Chapter 6 (and Annex 5).

- Option N1: Change nothing – i.e. continue to test for smoke using the current free acceleration test with its pass/fail limits.
- Option N2: Adapt the current roadworthiness smoke test, as described in Option PL2 in Section 5.5 for PM testing of light-duty vehicles. Do not introduce an additional test procedure.
- Option N3: Introduce a new procedure, using 4-gas analysers and a 2 speed unloaded test that is the same for all vehicles fitted with EGR.
- Option N4: Using 4-gas analysers, introduce new procedures, based on a 2 speed unloaded test, that are vehicle type specific for all vehicle types fitted with EGR.
- Option N5: Using 4-gas analysers, introduce new procedures based on changes at idle only, that are vehicle type specific and apply to most vehicle types fitted with EGR.

3 Details of practical investigations into PM instrumentation

A detailed description of the activities undertaken during this portion of the project is given in Annex 2. Cross referencing to this annex occurs to guide the reader to further details if required.

3.1 OBJECTIVES AND SCOPE OF THIS TASK

A recurring theme in the project as a whole has been that modern diesel vehicles produce lower levels of polluting emissions. In parallel with this is the appreciation that current smoke meters might cease to adequately measure smoke, as a proxy for PM, from these low emission vehicles. The primary focus of this task was to practically assess four, potentially more sensitive, types of instrumentation, reporting on their strengths and weaknesses. The studies undertaken have:

- quantified the sensitivities of four different measurement concepts,
- investigated and reported on the applicability of these measurement concepts in terms of the concentration range of PM they can quantify,
- considered the practical aspects of using the possible measurement concepts, including the apparent potential for the instrument concepts to be developed further.

The task was not to assess specific instruments to declare a "winner". Nor was it intended to demonstrate correlation over a wide range of vehicle types and PM emission levels. It was intended to identify possible contenders, and to eliminate others.

The instrument types to be investigated were an output from Phase 2. This identified

- an advanced opacimeter
- filter paper reflectometry
- a light scattering meter and
- a quartz crystal microbalance.

as four instrument types that have, potentially, improved sensitivity relative to current instruments, and, from a preliminary paper study, were likely to be suitable for the requirements of in-service testing. In addition to the four new instrument types assessed studies also included, in parallel where possible,

- a UK reference smoke meter (i.e. a Bosch RMT 430 smoke tube + Edit Associates software), and
- a Celesco 107 research opacimeter.

These last two instruments provided reference measurements.

3.2 METHODOLOGY AND RESULTS

The instruments were characterised against seven assessment criteria. These were:

1. fundamental precision of instrument by characterising the noise level when sampling "fresh air"
2. stability over a period of around 2 minutes
3. response to a "pulse" of clean hot air

4. response to oxides of nitrogen
5. response to liquid droplet aerosol
6. response to range of PM charges that ranged from moderately high (1.5 m^{-1}) to very low ($< 0.05 \text{ m}^{-1}$)
7. effect of a moderately high PM charge on shifting the baseline between preceding and subsequent test results from a low emission vehicle.

The vehicles used to generate transient smoke samples were chosen to cover the range 0.05 m^{-1} to 1.5 m^{-1} , with a deliberate bias towards modern technology passenger cars with FAS emissions less than 0.4 m^{-1} . These criteria provide the more severe test for instrumentation. In practice the FAS test results for the vehicles selected ranged from $0.026 \pm 0.011 \text{ m}^{-1}$ to 1.37 m^{-1} , a dynamic range in excess of 50, with all values less than the new FAS pass/fail limit of 1.5 m^{-1} , specified in Directive 23/2003/EC.

Section A2.2.4 of Annex 2 systematically discusses the results for the eight assessment criteria for each of the six instruments. The annex contains sections on

- reasons for selecting this generic type of instrument
- measurement principles and instrument configuration,
- results (including calibration, noise/background signals, effects of NO_2 , temperature and droplets, and signals from free acceleration tests on vehicles).

Unfortunately no new data were collected for the QCM because AEAT's QCM failed prior to the start of measurements and could not be repaired. A replacement instrument, hired from the instrument's manufacturer's agents also failed and could not be repaired. These experiences reveal more about the instrument's maturity than its potential use for in-service testing. Indeed, since the experimental work on this task was completed Sensors Inc, a supplier of gas analysers and smoke meters in the automotive aftermarket, have secured worldwide manufacturing and distribution rights to QCM instruments using technology patented by Booker Systems, the sole European QCM instrument manufacturer. A paper at a recent conference², a press release from Sensors Inc³ and the recent commercial activity all indicate that others consider QCM instruments as potentially suitable for in-service testing. It appears this project was too early to have access to a robust instrument for assessment.

The data for the other 5 instruments is summarised in Table 1 (Table A2.5 from Annex 2). These will be discussed in the next section.

3.3 DISCUSSION AND RECOMMENDATIONS

It is important to remember that the purpose of the meter used for in-service testing is to measure the emissions from a vehicle **relative to a pass/fail standard** rather than to accurately measure what vehicle actually produce. (The latter could be more than an order of magnitude below the standard).

² 7th ETH conference on combustion generated nanoparticles, "Particulate matter mass measurement from a heavy duty diesel engine using 2007 CVS PM sampling in parallel to QCM and TEOM". Southwest Research Institute, San Antonio, US and the US Environmental Protection Agency, August 2003

³ Press release on the Semtech QCM on 23rd November 2003 to ThomasNet[®] Industrial News Room entitled "Particulate analysers are suited for in-use measurements, See web-site <http://news.thomasnet.com/fullstory/28419>

Table 1 Summary of results from different measurement instrumentation

	Advanced opacimeter	Filter paper reflectometry	Light scattering	Bosch reference meter	Celesco 107 smoke meter
Background noise level	$0.55 \times 10^{-3} \text{ m}^{-1} \text{ Hz}^{-0.5}$	<10%	$7 \text{ } \mu\text{g}/\text{m}^3$	$2.1 \times 10^{-3} \text{ m}^{-1} \text{ Hz}^{-0.5}$	$0.4 \times 10^{-3} \text{ m}^{-1} \text{ Hz}^{-0.5}$
LOD	$4 \times 10^{-3} \text{ m}^{-1}$	10%, $2.5 \times 10^{-3} \text{ m}^{-1}$	$18 \text{ } \mu\text{g}/\text{m}^3$	$16 \times 10^{-3} \text{ m}^{-1}$	$3.2 \times 10^{-3} \text{ m}^{-1}$
Effect of NO ₂ /100 ppm NO ₂	$1(\pm 0.2) \times 10^{-3} \text{ m}^{-1}$	None	$3 \text{ } \mu\text{g}/\text{m}^3$	$6(\pm 2) \times 10^{-3} \text{ m}^{-1}$	$9(\pm 0.5) \times 10^{-3} \text{ m}^{-1}$
Effect of hot air (/100°)	$<1 \times 10^{-3} \text{ m}^{-1}$	None	$80 \text{ } \mu\text{g}/\text{m}^3$	$<10 \times 10^{-3} \text{ m}^{-1}$	$-10 \times 10^{-3} \text{ m}^{-1}$
Effect of water droplets	$<1 \times 10^{-3} \text{ m}^{-1}$	None	$350 \text{ } \mu\text{g}/\text{m}^3 / 10^{-3} \text{ m}^{-1}$ on the Celesco	small, $<0.015 \text{ m}^{-1}$	Up to $35 \times 10^{-3} \text{ m}^{-1}$
Diesel smoke	Calibrated against Bosch meter	See Figure A2.3 of Annex 2	See Figure A2.5 of Annex 2	Reference values	

From the data obtained it can be deduced that neither the QCM nor the light scattering instrument can currently be recommended for consideration for the in-service testing of diesel exhaust during a FAS test.

The filter paper reflectometry and advance opacimeter have both been shown to have higher sensitivities than the Bosch reference meter (by factors of 4 and 6.4, respectively from Table 1). The two approaches are quite different, one measuring an accumulation of PM whilst the other measures smoke in real time. Both approaches have their merits and drawbacks.

It is noted that the current meter specification given in the type approval test specification (Directive 99/69/EC) is based on real time smoke measurements. It is also noted, particularly in the context of decentralised testing, that to change instrument type requires training and other setting up costs significantly beyond those incurred when upgrading an instrument to its latest model. These considerations bias against the filter paper reflectometry approach.

The crucial question is: **What instrument specification is required in the future?** It has been noted several times that the role of the instrument **is not** to measure how cleaner vehicles perform, but to measure vehicles exhaust smoke relative to a pass/fail limit. Consequently, consider a vehicle fitted with a particulate filter whose real FAS peak is, for example, 0.02 m^{-1} , that is tested using the standard (not RPC) emissions test. The meter used is required to have adequate precision and accuracy to gauge whether the vehicle's emissions are greater than, or below, the 3.0 m^{-1} pass/fail limit. Hence **current meters are totally adequate for this task**. From 2008, when the pass/fail limit is reduced to 1.5 m^{-1} for Euro 4 vehicles, the current meters remain totally adequate for this task.

If, however, the pass/fail limit for some vehicles was reduced to, for example, 0.3 m^{-1} , then the suitability of current meters would become more marginal, and a more sensitive meter might be required.

4 The evaluation of test measurement procedures for PM for heavy-duty vehicles.

4.1 INTRODUCTION AND OVERVIEW OF PM PROCEDURE STUDIES

This chapter reports on studies undertaken evaluating potential in-service test measurement procedures targeted at checking PM emissions from heavy-duty vehicles.

Phase 3 of the Low Emission Diesel project contains two related studies entitled Tasks 3 and 4 are entitled "Evaluation of test measurement procedures for PM for heavy-duty (Task 3) and light-duty (Task 4) vehicles. A summary of the activities undertaken for both tasks is:

- prioritisation of possible test procedures,
- experimental investigations, and
- recommendations and conclusions.

The prioritisation of possible test procedures, described in detail in Section A3.3 of Annex 3 (covering HDVs) and Section A4.2 of Annex 4 (covering LDVs) was undertaken by VOSA, DfT and AEA Technology personnel. They concluded that *AEA Technology should focus on developing an unloaded in-service test for both light-duty and heavy-duty vehicles*. The adoption of a common approach to in-service PM testing for all vehicles testing led to further overlap between the two tasks.

The experimental investigations undertaken were:

- Task 3 – A study of FAS testing to understand the sensitivity of the smoke result to a number of parameters. This study included two light-duty vehicles, alongside ten heavy-duty vehicles.
- Task 3 – An audit of FAS emissions from modern, low emission diesel vehicles, which was extended to cover the whole fleet.
- Task 3 – An assessment of the nature and prevalence of faults encountered in the field by heavy-duty vehicles.
- Task 3 – An assessment of the effect of the faults identified on the FAS result from heavy-duty vehicles.
- Task 4 – A study of the correlation between PM emissions over drive cycles and FAS test results for light-duty vehicles.
- Task 4 – A study of the correlation between PM emissions over drive cycles and FAS test results with the state of vehicle maintenance for light-duty vehicles.

The overall objective of this chapter was to assess the potential effectiveness of candidate test procedures for heavy-duty vehicles, thereby prioritising options.

4.2 EXPERIMENTAL STUDY OF FAS TESTING OF MODERN HEAVY-DUTY VEHICLES

The project's Steering Group's review of the generic options concluded that only unloaded test procedures should be considered. (Section A3.3 of Annex 3 contains more details on this.)

Possible unloaded tests range from steady state conditions (at an engine speed which could range from low-idle to the engine's governor limited maximum) to transient tests. The most extreme transient test is the free acceleration test, when the accelerator is rapidly depressed to its maximum extent.

At the start of this research the use of a FAS test as a diagnostic check for PM emissions from heavy-duty vehicles appeared to have several drawbacks⁴. These include:

- poor correlation between FAS results and on-the-road PM emissions,
- suspicions that the FAS result is very dependant on test procedure details, weather conditions at the time of the test and the vehicle's operating temperature,
- issues regarding preconditioning.

These three concerns affect the appropriateness of the FAS test as the basis of an in-service test to check PM emissions. The answers to them are a precursor to the setting of appropriate pass/fail limits. The first issue was investigated for light-duty vehicles, and the findings are reported in the next chapter. Results from research into the second and third issues are reported in this chapter.

Five parameters were identified as very probably having a significant influence on particulates/smoke emissions during a free acceleration test (particularly given the conclusions from the earlier study⁴. These were

- the rate at which the accelerator pedal is depressed; and
- the extent to which the accelerator pedal is depressed.
- weather conditions (specifically atmospheric pressure, temperature and humidity)
- engine temperature (including the issue of whether it matters if one monitors engine oil or water temperatures);
- pre-conditioning the vehicle immediately prior to the test.

Ten heavy-duty vehicles were used for the study. These comprised five rigid vehicles and five tractor units. The rigids ranged from 7.5 tonne local delivery trucks to a large curtain trailer. Engine sizes ranged from 4 to 12 litres. The ten vehicles were made by five different manufacturers. Three vehicles were tested at AEA Technology's facilities, a further three at the central head-quarters of a heavy-duty vehicle manufacturer, and the remaining four at the sites of truck hire companies.

Details of the vehicles (Table A3.1), the experimental design and equipment used (Section A3.4.2) and the methodologies used to analyse the data (Section A3.4.2.5) are all described in detail in Annex 3.

The variability of the FAS test result introduced by variations in the rate of, and extent of, accelerator depression were found by plotting smoke meter readings (from a Crypton DX 250, the meter used by VOSA in the Government Vehicle Test Stations), the time taken for engines to accelerate to their maximum speed and the value of the maximum

⁴ These observations were conclusions reached by a DfT study entitled; "Diesel smoke test procedures and meter specification", DPU/9/33/19, AEA Technology (JOW Norris), AEAT-3340, October 1997.

speed against either the rate, or the extent, of accelerator depression. The range of primary parameter (rate or extent of accelerator depression) was much more than those reported in the earlier study. Some typical results are given in Figures A3.3 to A3.7 of Annex 3.

The effect of ambient temperature was studied on three vehicles (2 rigids and 1 tractor unit) at AEA Technology's Harwell facility. Vehicles were tested indoors (where a number of heaters raised the ambient temperature) and outdoors. This approach allowed the same vehicle to be tested at two distinctly different ambient conditions (the temperature differences ranged from 11.2 to 16.4°C) within 30 minutes. (For further details see Section A3.5.1.3 of Annex 3).

The effect of engine temperature focussed on whether a heavy-duty vehicle could appear to be at its normal operating temperature and yet give an anomalous smoke value from a FAS test because it was not fully warm. This can arise because vehicle testers often use the engine temperature indicator in the driver's cab to decide whether or not a vehicle is at its normal operating temperature. This monitors the engine's coolant (water) temperature. However, it is known from previous studies that for heavy-duty (large) engines the engine oil temperature often lags behind the water temperature. (This effect is very much less pronounced for light-duty engines.)

In practice operational and technical constraints meant that only two vehicles, both 12 litre tractor units, were tested to investigate this phenomenon.

In contrast, the effect of preconditioning by studying FAS results from successive FAS tests was undertaken on all ten heavy-duty vehicles. The principal question addressed was: is the current preconditioning cycle specified in the UK manual satisfactory, or should it be amended?

4.3 CONCLUSIONS, DISCUSSION AND RESULTING RECOMMENDATIONS FROM STUDIES ON FAS TESTING OF HDVS.

The data collected and described in Annex 3, and summarised in the previous section, lead to the conclusions listed below.

The data in the figures illustrate an important change that has occurred with the introduction of electronically controlled vehicles. It was seen for all ten heavy-duty vehicles tested, for the light-duty vehicles tested (reported in the next chapter) and is reported by a German researchers⁵. The replacement of mechanical fuelling systems by electronic systems, i.e. the replacing of the direct cable linkage between the accelerator pedal and fuelling rack by an electrical signal to an electronic control unit (ECU), has led to a large reduction in the sensitivity of FAS results to the rate and extent of accelerator depression. For modern electronically controlled vehicles there is a plateau in the relationship between the rate and extent of accelerator pedal depression and the rate at which the engine accelerates from low idle to its governor limited speed. This occurs because for depression rates faster than a threshold time, or beyond a threshold extent of pedal movement, the ECU limits the rate of increase of fuelling irrespective of the driver's action.

⁵ Research project FE 85.007/1999, Exhaust test- performance check / part 2 Diesel, DEKRA, TÜV Rheinland, RWTÜV,

For heavy-duty vehicles these thresholds were around 1.5 seconds and 70% (depressing the accelerator either in a shorter time or beyond 70% led to an engine response indistinguishable from its acceleration at these threshold conditions).

It is worthwhile noting just how significant this change is. A previous DfT funded study entitled "Diesel smoke test procedures and meter specification"^(Reference 4) results for four heavy-duty vehicles using a Hartridge Mk III smoke meter (the reference meter of the time) using normal and slower rates of accelerator depression. (Both these depression rates could reasonably be described as valid tests which were carried out on an engine dynamometer.) The mean results are listed in Table 2⁶.

Table 2 Variability of FAS result on accelerator depression rate

Engine	Fuelling system	Mean FAS for normal depression rate	Mean FAS for slower depression rate	Change normal/slower
T440	Mechanical	1.89 m ⁻¹	1.68 m ⁻¹	+ 12%
Phaser	Mechanical	0.66 m ⁻¹	0.50 m ⁻¹	+32 %
Eagle	Mechanical	1.85 m ⁻¹	0.30 m ⁻¹	+ 517%
DDC series 60	Electronic	1.21 m ⁻¹	1.16 m ⁻¹	+ 4%

With hindsight, this study showed (albeit on a sample of one) how the introduction of electronic control changed the variability of the FAS result. (Analogous testing of light-duty vehicles gave the change, Normal/Slow depression rates, as around + 100% for six vehicles.)

The above observations lead to the key conclusion that the case for using a FAS test to indicate the state of a vehicle's maintenance is significantly strengthened by the marked reduction in the test's result variability caused by the tester. This is because the tester's actions are tantamount to instructing the engine's controlling systems to undertake a pre-programmed sequence.

Recommendation 1

There is no case for introducing further functionality into the test meter to control the range and extent of accelerator depressions because the range of accelerator depression times and extents within which the variations made by the tester cause no change in the vehicle's acceleration, are sufficiently wide for it to be assumed that all honest attempts to perform a FAS test are within this envelope.

The dependence of the FAS test result on ambient temperatures was measured as less than 5% per 10 degree change. Theoretical considerations suggest it may be 3.7% per 10 degree change, giving a maximum deviation from the mean of 7.5% over the range -5°C < T < 35°C.

Recommendation 2

There is no case for the introduction of a correction for ambient temperature into the measurement meter/procedure because temperature variations likely to be encountered at test stations in the UK cause insufficient changes in FAS test results to warrant this.

The dependence of the FAS test result on oil temperature of heavy-duty vehicles was measured on a very limited sample (2 vehicles). The data showed no significant

⁶ See Tables 6 – 9 of Appendix 3 of report for DfT (ref DPU/9/33/19) JOW Norris, Oct 1997

difference when the vehicles' oil temperature was around 18° below its normal operating temperature, but a 33% increase in smoke value when the oil temperature was 25° below the normal operating temperature. It is believed unlikely that the engine's water temperature would indicate it is at its normal operating temperature if the oil temperature were still 25° below the normal operating temperature. Hence, the current check is sufficient.

Recommendation 3

It is recommended that the instructions for checking the engine's coolant temperature is at its normal operating temperature (as described in the current testers' manual) is not changed because it appears sufficient not to lead to large variations in FAS result.

For heavy-duty vehicles the current preconditioning cycle specified in the UK testers manual appears satisfactory since 9 of 10 heavy-duty vehicles studied showed little to no further reductions in smoke opacity within a series of FAS tests after this preconditioning cycle had been used. The exception was for a vehicle that was probably faulty, and even in this case the preconditioning procedure was shown to markedly reduce variability even if it did not totally eliminate it.

Further analysis of this, and justification for the recommendation below are given in Chapter 5, from studies on light-duty vehicles.

Recommendation 4

For heavy-duty vehicles the current preconditioning cycle specified in the UK testers manual need not be changed.

4.4 AUDIT OF CURRENT FAS TEST

Having established that some of the perceived weaknesses in the use of a FAS test as a diagnostic check for PM emissions are no longer warranted for modern heavy-duty diesels, research moved on to establishing the effectiveness of the current FAS test. (Full details of this are given in Section A3.7 of Annex 3.) This was achieved by the collection of the FAS test results from around 2,500 HDV tests from four government vehicle test stations (GVTS). The data were filtered to remove data sets associated with vehicles that were being retested, were duplicate tests, or were being tested for an RPC. Further data filtering left 2,025 data sets for vehicles whose age could be inferred from their registration plate.

Analysis of these data led to the conclusion that the current failure rate for the emissions test was 1.38%. This value is within the 1.0% to 1.5% range that VOSA anticipated.

The data were categorised by age. One interesting observation was that the distribution of the FAS results for all the vehicles greater than 5 years old, i.e. manufactured in 1998 or earlier, was **extremely similar** to the distribution reported by the NAO from a survey undertaken in August 1998. This strong similarity increases confidence that the data collected here are a reproducible and representative sample, and observations made from these are real trends.

The data were further categorised, by age, into the various emissions standards (pre-Euro 1 to Euro 3). For each group the number of vehicles that failed, the percentage this represents of the group and the mean FAS values were calculated. The results are tabulated in Table 8 (in Section 7.2 of this main report), and show failure rates (and mean FAS results) decreasing from 5.39% (and 1.50 m⁻¹) for pre-Euro 1 vehicles through 0.74% (and 0.76 m⁻¹) for Euro 2, to 0.0% (and 0.44 m⁻¹) for Euro 3 vehicles.

Overall these data show that the current test identified no failing Euro 3 vehicles, and it indicates that the pass/fail limit is an increasingly long way from the mean FAS result.

4.5 IDENTIFICATION OF FAULTS AND THEIR FREQUENCY

The objective of this portion of the research was to establish which faults occur most commonly in modern heavy-duty diesel vehicles, and to quantify their frequency. (The details of the research is contained in Section A3.8 of Annex 3). The basic tool used to obtain these data was a questionnaire (see Appendix 1 of Annex 3). The questionnaire was directed at those who service HDVs within the franchised dealer network and fleets.

Before individual franchised service centre managers were contacted, agreement was sought from the OEM's head (UK) office that they were willing to participate in the survey. Such permission was received from four of the six principal OEMs. Two to three service centres for each OEM was contacted and replies were received from around two thirds of these. Hence on this basis it is believed the data collected is representative across the OEMs.

The fleet managers of around 17 fleets were contacted, ranging from some of the largest, e.g. Wincanton Logistics, Hoya Ltd to local authorities and bus companies. The reason behind contacting such a diverse range of fleet operators was to try to investigate if particular vehicle operating cycles, e.g. for buses or dust carts, led to different faults occurring relative to fleets where vehicles principally drove on motorways or trunk roads. The first findings were that many fleets have, in recent years, changed their servicing and repair arrangements, away from in-house workshops to the franchised dealers. Whilst there are several reasons for this, the increasing complexity of modern HDVs is certainly a significant contributory factor, if not the major one. Consequently, although 17 fleets were contacted only 6 organisations with their own workshops were identified.

All those who replied to the questionnaire were assured their answers would be treated confidentially. Consequently, the data reported here is in generic terms. Given the objective of obtaining data pertinent to the whole HDV fleet, this does not detract from the value of the data collected.

From the questionnaire the number of engine faults seen, expressed as faults per 100 vehicles per year, could be calculated. For the eight responding OEM service centres the mean of the failure rates was 53 ± 33 faults /100 vehicles /year. For a subset of four service centres, the four used to obtain the data described in the next section, the mean was 75 faults / 100 vehicles /year. However, after four months of studying faulty vehicles (see next section) the workshop managers universally expressed surprise at the low failure rates. Consequently, these four service centres completed a second questionnaire, and the revised fault frequency was 25 faults /100 vehicles /year, i.e. a factor of three lower. This lower figure is believed to be the more accurate, and this exercise demonstrated the changing nature of the frequency at which faults are occurring.

The questionnaire subdivided the engine into nine systems, and asked respondents to estimate the frequency of failure for each system. Figure 3 shows the revised replies

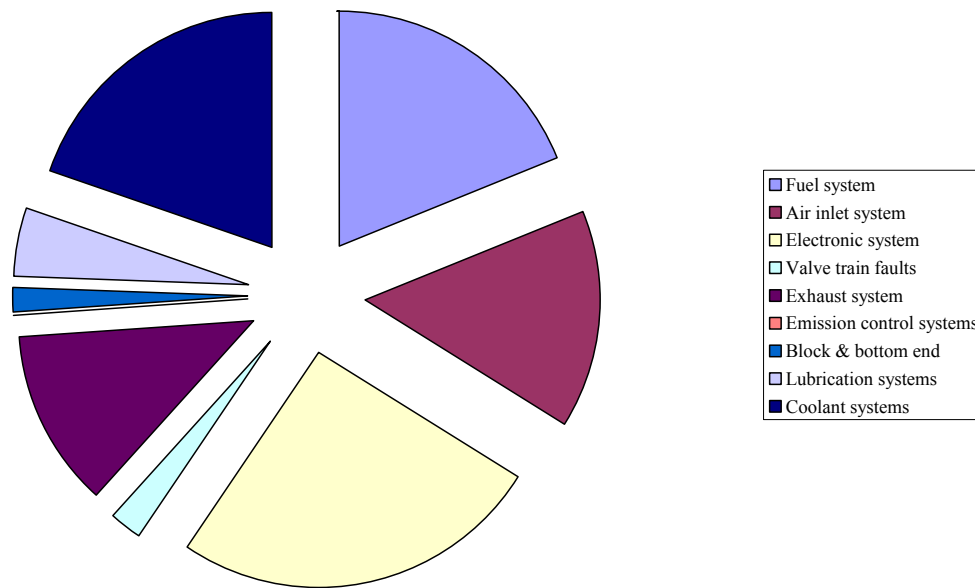


Figure 3 Proportion of faults due to different engine systems (each contributor contributing 100%)

from the four franchised OEM service centres at the end of the project as a pie chart. The legend on the right of the figure lists the nine engine categories. Earlier data had quite similar proportions, except for a larger proportion of electrical system faults (40% rather than 25%).

Four of the engine systems were presumed to have the potentially largest effect on PM emissions: fuel, air inlet, electronic and emissions control (traps, filters and EGR) systems. Each system can be sub-divided into a number of components, e.g. fuel system faults were sub-divided into:

- fuel quality problems
- fuel pump faults
- fuel system leaks
- fuel injector faults.

The questionnaire asked for a ranking of faults (from 1 to 4 in this case because there are four options). If all replies had said fuel leaks were the most commonly encountered problem (and hence given a rank marking of 4) and fuel pump faults the least commonly encountered (and hence given a rank marking of 1) then the arithmetic means of the replies would lie between 1 and 4. In practice they lay between 2.4 and 2.7, all very close to the 2.5 mid-point. The conclusion from such a result is that no fault dominates the failures. Reasons for this, and the dynamic nature of component failure frequencies are discussed in Section 3.8.7 of Annex 3. Similar analysis of data for air inlet and electronic system faults gave no clear differentiation except that air inlet manifolds were identified as a component that is fault very infrequently.

4.6 EFFECTS OF FAULTS ON EMISSIONS

This research followed directly on from the previous section. Its objective was to find the effect of faults on FAS test results. This was achieved by asking vehicle repairers to undertake a FAS test before and after repairing a faulty engine.

It was not possible to collect any data from fleet operators. Several attempts to do this were made but were unsuccessful because:

- the engine failure rate reported, when scaled by the fleet size, led to an anticipated fault frequency of around one per fortnight, too low for the study,
- the majority of the vehicles in the fleets were fitted with after-treatment devices, principally diesel particulate filters. The presence of these would hide any change in "engine emissions" from a FAS test for a faulty engine.

Consequently, data were collected from five OEM franchised service centres, covering four OEMs. As noted in the previous section the number of faulty vehicles encountered was low – surprisingly low according to all the five centres' managers. Consequently, the period of data collection was more than doubled from 8 to 17 weeks. Despite this only around 15 sets of data were collected.

Figure 4 gives the FAS data for fuel and electronic system faults. The two patterns are distinctly different. Both fuel quality and injector faults led to large changes in FAS results, from around 0.3 m^{-1} in the well maintained vehicle to 2 m^{-1} when faulty. In contrast for the electronic system faults only one, (a faulty accelerator potentiometer) led to a significant increase in FAS result. The remaining four led to only small changes, with two vehicles having slightly lower FAS results when faulty than when repaired. This illustrates the ability of the controlling ECU to identify faults and to alter the fuelling map in such a way so that PM emissions are not greatly altered.

No vehicles with faulty air inlet systems were seen. However, discussions with service centre managers indicated that the combination of the sensors within a modern engine, and the programme within its controlling ECU lead to the qualitative assessment that like electronic system faults, air inlet system faults generally lead to little change in FAS result.

4.7 OVERALL CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions from the studies on the options for in-service PM testing of heavy-duty vehicles as be summarised as follows.

1. Only unloaded test procedures should be considered.
2. Transient unloaded testing is more appropriate than testing at a steady engine speed. This constrains possible test procedures to free acceleration, or free acceleration like, tests.
3. For modern electronically controlled heavy-duty diesel vehicles there is markedly less test-to-test variability in the results from free acceleration tests caused by inconsistency in the rate or extent of accelerator pedal depression relative to diesels with mechanical fuelling systems.
4. The currently specified procedure for the free acceleration smoke (FAS) test, and the associated meter specification are satisfactory in many respects. Hence recommendations 1 to 4 of Section 4.3 affirm current practice.

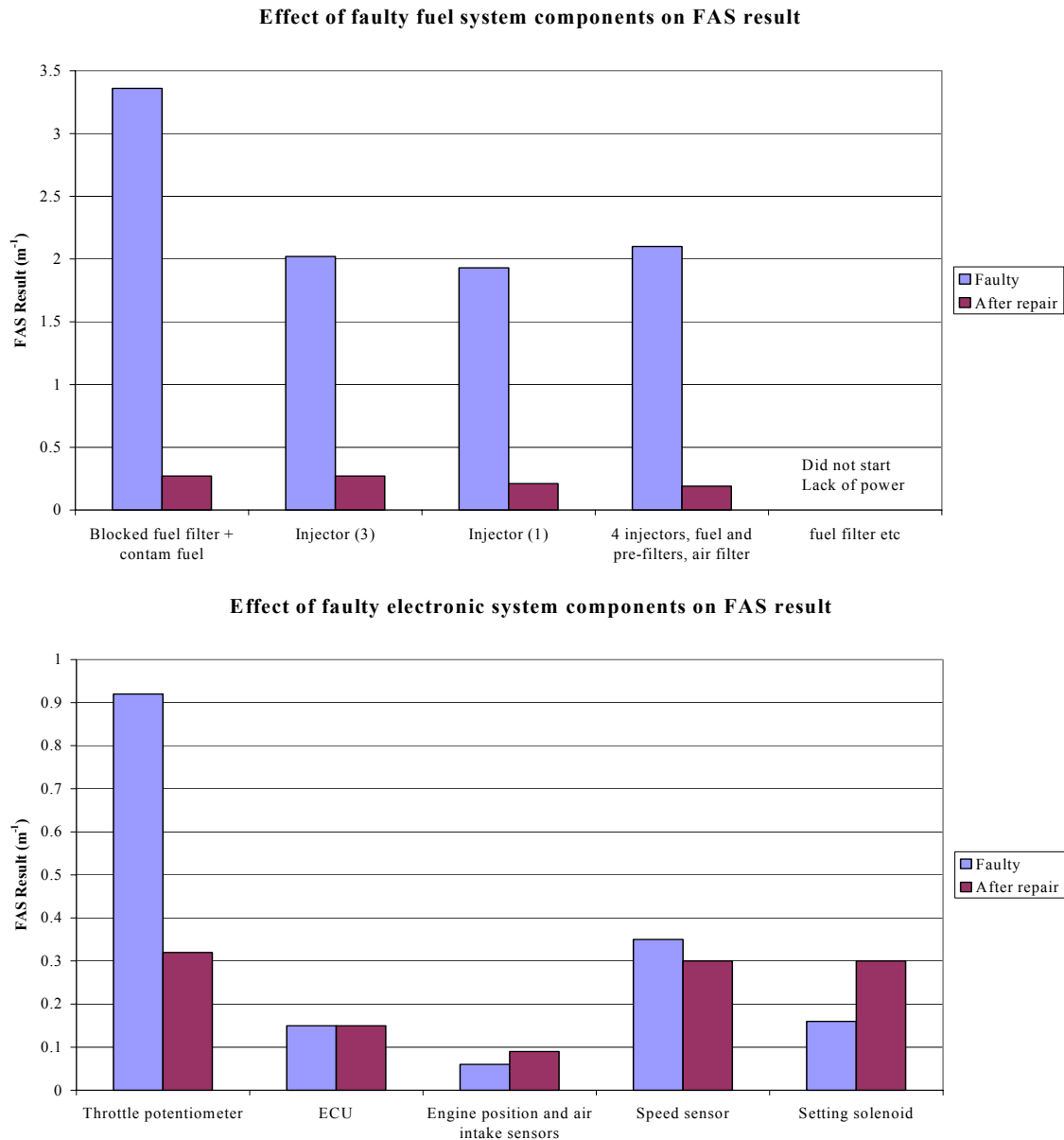


Figure 4 The effect of faults on FAS results

5. The current FAS test identifies an average of around 1.4% of all vehicles presented for test as failures.
6. The average figure above masks failure rates which range from 5.4 for pre-Euro 1 vehicle to 0.0% for Euro 3 vehicles.
7. An analysis of the nature and prevalence of engine faults in heavy-duty engines found a failure rate of around 25 ± 15 faults /100 vehicles /year.
8. The failure rate is a dynamic number. It has decreased notably, possibly by a factor of 3, over the past 12 months.

9. Of the engine systems likely to lead to increases in PM emissions, electronic, fuel and air system faults makeup around 60% of all faults.
10. In terms of the components that fail, there was little consensus view, with all components reportedly failing at similar rates. The exception was air inlet manifold which failed rarely. It was also noted that failure rates changed with time.
11. Faults caused by poor fuel quality or faulty injectors were found to cause large increases in FAS emissions (from 0.3 m^{-1} to around 2 m^{-1}).
12. In contrast, electronic system faults generally cause little change in FAS emissions.
13. Air inlet system faults too are reported to cause little change in FAS emissions.
14. The effects of fuel, air inlet or electronic system faults on PM emissions over drive cycles are not known

Overall the FAS test procedure has been shown to be better suited to reproducibly testing modern electronically controlled heavy-duty vehicles relative to the older, mechanically controlled vehicles. The current test regime, however, appears poor at identifying excess emitters. The crux of the improvement required distils down to the options for changing the pass/ fail limits for the FAS test. The plausible technical options range from do nothing, through continuing use a universally applied limit, to tailoring the pass/fail limit to each vehicle type. In addition, the option of "improving" the smoke meters' sensitivity is also included.

The six options are summarised as:

- Option PH1: Change nothing – i.e. continue to test for smoke using the current free acceleration test, equipment and pass/fail limits, including the new lower limits to be introduced as described in EU Directive 2003/27/EC.
- Option PH2: Cease emissions testing at the annual roadworthiness test for Euro 4 and later vehicles.
- Option PH3: Reduce the pass/fail limit that applies to all Euro 4 (and later) vehicles in a further step.
- Option PH4: Introduce vehicle specific pass/fail limits for each type of vehicle.
- Option PH5: Reduce the generic pass/fail limit that applies to all Euro 4 (and later) vehicles in a further step plus introduce the option that manufacturers can declare a higher value for vehicles that meet the type approval emissions specification in all other respects.
- Option PH6: Change from smoke meter to a more sensitive meter.

These technical options are offered in the context of increasingly low engine failure rates, and the finding that in modern diesel vehicles a considerable number of engine faults lead to little or no increase in smoke emissions because the controlling computer adapts the fuelling mapping to compensate for the faults it has sensed.

These technical options, and fault frequency data, are used as inputs into a cost effectiveness analysis, Chapter 6 (Annex 5).

5 The evaluation of test measurement procedures for PM for light-duty vehicles.

5.1 OBJECTIVE AND SCOPE OF TASK

This chapter is closely linked with the previous one because its focus is on evaluating potential in-service test measurement procedures targeted at checking PM emissions from light-duty vehicles. It reports data collected during three studies:

- a study of FAS testing to understand the sensitivity of the smoke result to four parameters,
- a study of the correlation between PM emissions over drive cycles and FAS test results for light-duty vehicles, and
- a study of the correlation between PM emissions over drive cycles and FAS test results with the state of vehicle maintenance for light-duty vehicles.

These three studies were conducted in the context of the important conclusion reached by the Low Emission Diesel project's steering group that **for light-duty vehicles the only in-service testing procedures to be pursued were unloaded procedures.** (Section A4.2 of Annex 4 gives further details regarding the options considered and the reasons for reaching the above conclusion.)

5.2 DEPENDENCE OF THE FAS TEST RESULT ON PARAMETERS

5.2.1 Methodology and results

The sensitivity of FAS results to the rate and extent of accelerator pedal depression were investigated, together with the effects of ambient temperature and vehicle preconditioning. Data from similar investigations by German researchers has been published^(ref 5). Consequently, the strategy used was to study only two light-duty vehicles and to see whether the findings were consistent with those reported from the German studies. If they were not then the differences would be investigated further. (The influence of engine temperature was not investigated here because, whilst it is known that the FAS test result does depend on engine temperature, testing according to the testers' manual reduces this to an acceptable level^(ref 4).)

The dependence of FAS result (smoke) and the time taken for engines to accelerate to their top speed, as a function of the rate and extent of accelerator depression, were in-line with the German findings. (Full details are reported in Sections 4.3.1.1 and 4.3.1.2 of Annex 4.) They showed that there is a threshold time for the rate, and extent of depression, beyond which the FAS test result is constant (as too is the time taken for the engine to reach its top speed). For the two vehicles studied the time threshold was around 1.5 seconds. The extent the accelerator had to be depressed was 45% for Vehicle 1 and 70% for Vehicle 2. (Hence for both vehicles, depressing their accelerators to at least 70% of its travel was sufficient to lead to there being no difference in the FAS results recorded.)

The effect of ambient temperature on the FAS result was studied by undertaking FAS tests initially within a garage area, then outside and finally back in-doors. This approach was useful because it was found that the mean smoke result decreased for successive groups of FAS tests. This testing methodology enabled the systematic reduction to be taken into account when deconvoluting the effect of ambient temperatures. Figure A4.7 (Annex 4) shows the FAS results in the context of the ambient temperature at the time of testing. Overall, ambient temperature changes of 15 ± 2 °C led to less than 0.03 m^{-1} change in the mean FAS values for both Vehicle 1 (whose mean FAS value was around 0.3 m^{-1}) and Vehicle 2 (whose mean FAS value was around 0.7 m^{-1}).

The effect of preconditioning was known from previous experience to be a more significant issue for light-duty vehicles relative to heavy-duty vehicles. It was found that introducing an EGR fault (i.e. fixing the EGR valve open to allow maximum EGR) led to a FAS result of greater than 9 m^{-1} , i.e. a very smoky vehicle. This provided a method of making an engine's exhaust system dirty in a controlled and reproducible way, thereby emulating a vehicle in need of preconditioning. The test methodology used was:

1. to start with a fully warmed up vehicle following some FAS tests,
2. then fix the EGR valve fully open,
3. to do 5 free accelerations to dirty the vehicle's exhaust system,
4. to restore the EGR valve to its normal automated mode of operation and
5. to measure around 10 successive FAS for this dirtied vehicle.

This sequence was repeated with step 5 being preceded by a standard preconditioning /purge cycle as specified in the MoT testers' handbook. The results for the two vehicles tested are shown in Figure 5. (Full details of this study are described in Section A4.3.1.4 of Annex 4).

5.2.2 Conclusions discussion and recommendations

The results from this research and from the German studies on the sensitivity of FAS test result on the rate and extent of accelerator pedal depression show that for modern electronically controlled light-duty vehicles there is a plateau in the relationship between the rate and extent of accelerator depression and the resulting FAS value (and the rate at which the engine accelerates). This is the same conclusion that was reached for heavy-duty vehicles and the reasons for this are those discussed in the context of heavy-duty vehicles.

The consequence of this finding is that, as for heavy-duty vehicles, the case for using a FAS test to indicate the state of a vehicle's maintenance is strengthened by the marked reduction in the variability of the test result on the tester's actions. This is because the testers actions are tantamount to instructing the engine's controlling systems to undertake a pre-programmed sequence.

The significance of this change should not be underestimated. In an earlier study, on light-duty vehicles with mechanical fuelling systems, the effect of slowing down the rate of accelerator depression over six vehicles was to lead to a reduction in smoke result of, on average, a factor of two⁷. It varied between vehicles from a factor of 1.1 to 2.7. For modern vehicles such a reduction would cause no change relative to that seen from a "normal, swift" accelerator depression rate. **Hence a major source of FAS test-to-test variability has been removed with the change in fuelling system technology.**

⁷ See data from Hartridge Mk III tabulated in Appendix V.5 of "Diesel smoke test procedures and meter specification", report for DfT (DoT ref DPU/9/33/19) JOW Norris, Oct 1997

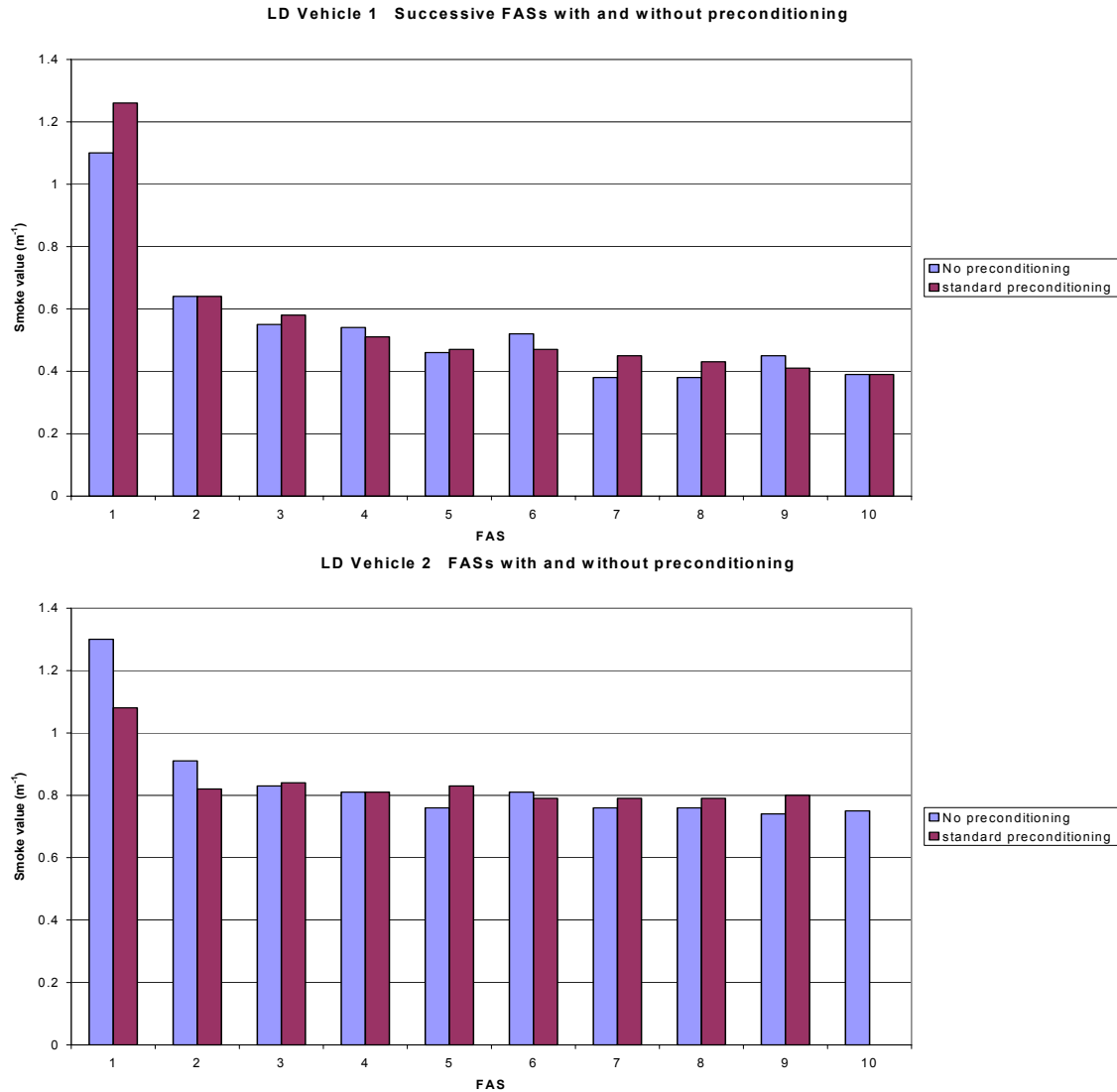


Figure 5 Successive FAS tests on "dirty" light-duty vehicles with and without preconditioning

These observations lead to the recommendation below:

Recommendation 1

There is no case for introducing further functionality into the test meter to control the range and extent of accelerator depressions because the range of accelerator depression times and extents within which the variations made by the tester cause no change in the vehicle's acceleration, are sufficiently wide for it to be assumed that all honest attempts to perform a FAS test are within this envelope.

The dependence of the FAS test result on ambient temperature changes was observed to be less than 0.03 m⁻¹ for a 15°C change. For the two vehicles tested this amounts to <7% and <3% change in FAS result per 10°C change in ambient temperature for the two vehicles tested. This leads to the Recommendation 2.

Recommendation 2

There is no case to introduce a correction for ambient temperature into the measurement meter/procedure because temperature variations likely to be encountered at test stations in the UK cause insufficient changes in FAS test results to warrant this.

The dependence of FAS test result on vehicle preconditioning is more marked. The data collected indicate the high probability that vehicles presented for testing will not give a constant set of FAS results, even after preconditioning according to the MoT testers' manual.

A primary objective of testing is to identify vehicles above the threshold (those that require maintenance or rectification) but to do so using the minimum number of FAS tests, thereby minimising the likelihood of damaging the vehicle's engine. Consequently, it should be remembered that anomalously high FAS results are only a problem if one is considering failing a vehicle – if all the FAS results are below the pass/fail limit then their variation is not an issue. If some are above the pass/fail limit then a specification is needed to filter out "anomalous" peaks. This is exactly what Section 5.1.6 of VOSA's Diesel Smoke Meter Specification⁸ does. This reads: *Calculate, continuously and automatically, the arithmetic mean of the latest 3 readings. If any of the 3 readings is less than 75% of the mean smoke level then that individual reading shall be rejected (for the purpose of this average only) and no mean value shall be displayed.*

When this filtering is applied to the data plotted in Figure 5 it is found it does go some way towards eliminating anomalous peaks from the data (discussed in detail in Section A4.4 of Annex 4). However, as discussed in the annex, there is scope for fine tuning this. Consequently two recommendations are made. The first, Recommendation 3, is intended to prevent further, unnecessary FAS tests from being carried out on a vehicle whose emissions are below the pass/fail standard. The second, Recommendation 4, is intended to fine tune the current data filtering to remove "anomalous" data points, specifically targeting unrepresentatively high values caused by insufficient "preconditioning".

Recommendation 3

The wording of Paragraph 5.1.6 of the VOSA MoT Smoke Manual specification should be amended to read: Calculate continuously and automatically the arithmetic mean of the latest 3 readings. If **the mean reading is above the pass/fail limit for the vehicle and** any of the 3 readings.....

Recommendation 4

The wording of the second half of the second sentence should be amended to read: any of the 3 readings is **more than 15%⁹* or 0.1 m⁻¹ (whichever is the greater) from** the mean smoke level then that individual reading should be rejected (for the purpose of this average only) and no mean value shall be displayed.

⁸ VOSA Specification for diesel smoke meters, MOT/05/01/01

⁹ It is recommended that further studies be undertaken to check/confirm that this is an appropriate margin for error.

5.3 CORRELATION BETWEEN PM EMISSIONS OVER DRIVE CYCLES AND FAS TEST RESULT

5.3.1 Objective, methodology and results

Numerous previous studies had concluded that the correlation between PM emissions over the Type 1 drive cycle and the FAS result was very poor over a wide range of vehicles. (See for example "Diesel smoke test procedures and meter specification", report for DfT (DoT ref DPU/9/33/19, reference 4). This was in addition to studies that showed the reproducibility of the FAS test was also poor with variation in the way the procedure was applied leading to large (>100%) variations in test result. However, it has become apparent that the change from mechanically controlled fuelling systems to electronically controlled fuelling systems has led to a step improvement in the reproducibility of the FAS test. The objective of this portion of the research was to investigate the correlation between PM emissions over drive cycles and FAS test results for modern, electronically controlled light-duty vehicles to see whether this correlation had changed.

The approach used was to measure the PM emissions over the Type 1 (NEDC) regulatory cycle (using the regulatory filter based method). Each vehicle was given a FAS test after it had completed the drive cycle (i.e. when it was fully warm). Figure 6 shows the results obtained with the PM emissions (vertical axis) plotted against FAS test results (horizontal axis).

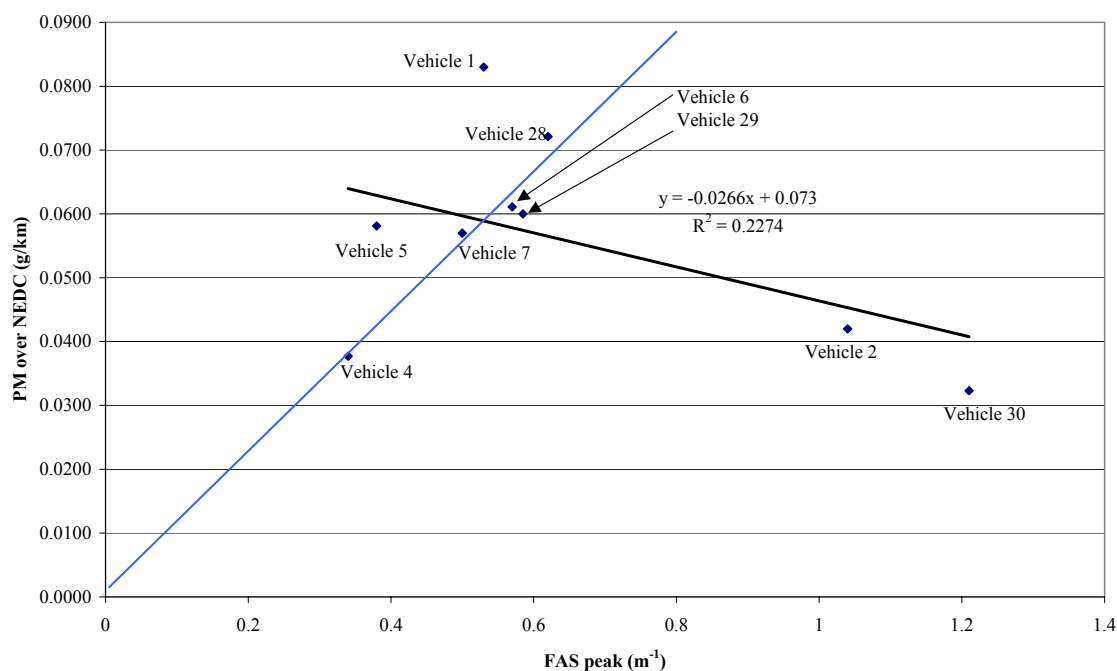


Figure 6 Correlation between PM emissions and FAS peak smoke with 2 analyses

5.3.2 Conclusions and discussion

Even though the number of vehicles tested is relatively small, the overall correlation remains poor, with a regression analysis, the black line, giving an unrealistic gradient.

The blue line was drawn by eye through the origin. Five of the nine vehicles lie close to this. Two vehicles lie above the line, which means that their PM emissions over the NEDC were higher, in relation to their FAS results, than for the five vehicles close to the

line. One of these vehicles was the only Euro 2 specification vehicle in the group of nine, whilst the other was a large (heavy) passenger car (Class III, weight >1760 kg).

The most significant deviations from the blue line occur for Vehicles 2 and 30 (which were the same model). These both gave FAS results > 1.0 m⁻¹ although their PM emissions over the Type 1 drive cycle were well within the 0.05 g/km Euro 3 standard. The fact that there were two vehicles, and other similar but unreported measurements from further vehicles of this type, indicates that this is not a rogue result. Further, there are other vehicle types that are known to have FAS results well to the right of the blue line.

The conclusions drawn from this investigation are:

1. The correlation between PM emissions over the regulatory loaded drive cycle and the peak smoke values obtained during a FAS test remains poor.
2. A universal pass/fail limit designed so as not to unfairly fail vehicle which meet the type approval PM emissions standard would have to be set at a smoke density above that of the **highest** vehicle type.

These conclusions lead directly to the recommendation below

Recommendation 5

Consideration is given to devising a pass/fail limit that is more equable for all vehicle types, at the same time being a more demanding assessment for the majority of vehicles.

5.4 CORRELATION BETWEEN PM EMISSIONS AND FAS TEST RESULT AND STATE OF VEHICLE REPAIR

5.4.1 Objective, methodology and results

The previous two sections have shown:

- a great improvement in the reproducibility of FAS tests for electronically controlled diesel vehicles, since results are much less affected by variability in the testers' actions,
- the correlation between the more reproducible FAS test results and PM emissions over the Type 1 drive cycle over all vehicle types remains very poor.

However, the purpose of an in-service emissions test is to identify vehicles requiring repair and/or maintenance. Consequently a crucial question is: for individual vehicles what is the correlation between their PM emissions over loaded cycles, and FAS result, and the state of vehicle repair. If it is found that faults (or even only some faults) that lead to increases in PM emissions on the road also lead to increased FAS emissions then there is the basis for continuing with, and refining, the in-service test. Somewhat surprisingly virtually no data on this could be found in the literature. The primary objective of this portion of the research was to investigate the above possible correlation.

The methodology was to find the most common faults encountered with modern diesel engined light-duty vehicles, and to test representatively faulty vehicles. The result of a small survey amongst OEM franchised garages was the consensus list:

- faulty air mass meter (noticed by customers as a reduction in power and sometimes increased smoke)
- faulty pressure or temperature sensors
- EGR faults (usually a stuck valve)
- faulty throttle position sensors (usually badly fitted rather than broken)

- injector faults (usually caused by contaminated fuel rather than faulty units) and
- all the garages surveyed said that ECU faults are very rare.

Five faults were investigated, as listed in the table below:

Table 3 Vehicles whose PM and FAS were measured in normal and defective states

Vehicle	Emissions standard	Fault induced
Vehicle 3 -Fault A	Euro 2	Need of general servicing plus sticking EGR
Vehicle 7 -Fault B	Euro 3	Turbo waste-gate disabled
Vehicle 28 -Fault C	Euro 3	Leak from hose on high pressure side of turbo-compressor
Vehicle 30 -Fault D	Euro 3	EGR valve fixed in a semi-open position
Vehicle 30 -Fault E	Euro 3	Faulty air mass flow sensor fitted

For each vehicle the PM emissions over the ECE and EUDC components of the NEDC were measured, together with a FAS test, when the vehicle was in its normal/rectified and faulty states. From these PM emissions measurements, the PM emissions for the combined cycle can be calculated. The data is tabulated in Table A4.4 of Annex 4. From these data the change in PM and FAS emissions caused by a fault can be calculated (see Table A4.5 of Annex 4). These changes are shown, as columns, in Figure 7. (Changes in NO_x were also measured and reported in Annex 4 because of the importance of this pollutant.)

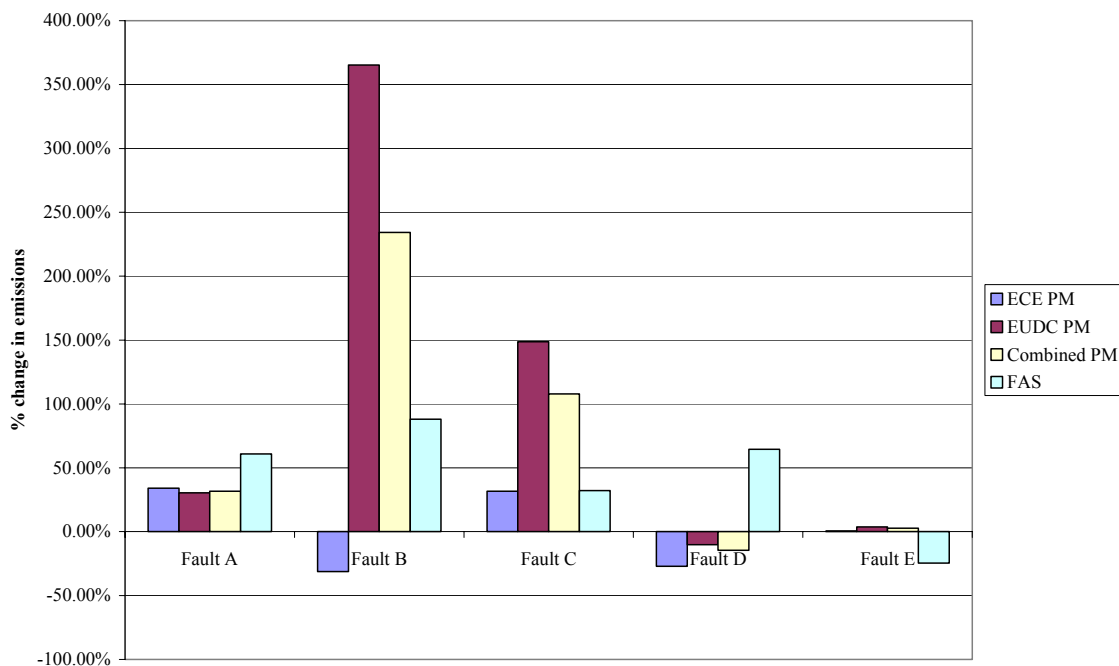


Figure 7 Changes in emissions caused by introducing faults

5.4.2 Conclusions and discussion

An important message to be drawn from Figure 7 is that the effect on the PM emissions over the two components of the NEDC varies from fault to fault (compare the heights of the first two columns in the figure). For example, detaching the turbo waste-gate control line on Vehicle B caused a **30% decrease** in PM emissions over the ECE cycle component of the NEDC cycle, but a **365% increase** over the EUDC. This leads to the important conclusion that it is naïve to believe that Fault X leads to a change Y in PM emissions over all loaded cycles: **The change in PM emissions depends both on the fault and the speed/time characteristics of the drive cycle.**

The FAS test only probes PM emissions over a very limited area of the engine's performance map whilst a specific drive cycle is a weighted average of PM emissions over a wider range of speeds and loads. The effect of different faults on the PM emissions at different portions of the engine's speed/load map can be explained for the most part. This is done on page A4.24 of Annex 4.

Overall, it is evident that the result of a FAS test is not a proxy for PM emissions over the loaded regulatory cycle (the NEDC) but is best viewed as a diagnostic test that has a range of sensitivities to different faults. It sometimes under reports the change in PM emissions over the NEDC (e.g. as for Faults B and C) and sometimes over reports them (e.g. Faults A and D).

In summary, this leads to the recommendation below:

Recommendation 6

The FAS test should continue to be used as an in-service check of PM emissions appreciating it is a diagnostic test that has variable sensitivity to different faults.

5.5 OVERALL CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions from the studies on the options for in-service PM testing of light-duty vehicles as be summarised as follows.

1. Only unloaded test procedures should be considered.
2. Transient unloaded testing is more appropriate than testing at a steady engine speed. This constrains possible test procedures to free acceleration, or free acceleration like, tests.
3. For modern electronically controlled light-duty diesel vehicles there is markedly less test-to-test variability in the results from free acceleration tests caused by inconsistency in the rate or extent of accelerator pedal depression relative to diesels with mechanical fuelling systems.
4. The currently specified procedure for the free acceleration smoke (FAS) test, and the associated meter specification are satisfactory in many respects. Hence recommendations 1 and 2 affirm current practice.
5. There is scope for fine-tuning the test to prevent some unnecessary testing and to reject some anomalous FAS results beyond those that are already rejected by the current specification (Recommendations 3 and 4).

6. The correlation of FAS results with PM emissions over the regulatory Type 1 drive cycle remains poor. This fact, when combined with the choice of using a universal pass/fail FAS result threshold, to identify vehicles requiring attention, is problematic. The resulting recommendation (5) is that consideration is given to devising a pass fail limit that is more equable for all vehicle types, whilst at the same time being a more demanding assessment of the state of a vehicle's maintenance for the majority of vehicles.
7. Notwithstanding Conclusion 6 above, studies on faulty /repaired vehicles show some modest correlation between changes in FAS test result and the PM emissions over the Type 1 test.
8. However, faults do not cause a constant increase in PM emissions across all drive cycles. This leads to the FAS test being a diagnostic test that has a range of sensitivities to different faults (Recommendation 6).

The crux of the improvement required distils down to the options for changing the pass/fail limits for the FAS test. The plausible technical options range from do nothing, through continuing use a universally applied limit, to tailoring the pass/fail limit to each vehicle type. In addition, the option of "improving" the smoke meters' sensitivity is also included.

The five options are summarised as:

- Option PL1: Change nothing – i.e. continue to test for smoke using the current free acceleration test, equipment and pass/fail limits, including the new lower limits to be introduced as described in EU Directive 2003/27/EC.
- Option PL2: Reduce the pass/fail limit that applies to all Euro 4 (and later) vehicles in a further step.
- Option PL3: Introduce vehicle specific pass/fail limits for each type of vehicle.
- Option PL4: Reduce the generic pass/fail limit that applies to all Euro 4 (and later) vehicles in a further step plus introduce the option that manufacturers can declare a higher value for vehicles that meet the type approval emissions specification in all other respects.
- Option PL5: Change from smoke meter to a more sensitive meter.

These are the options whose cost effectiveness is assessed in the next chapter (details in Annex 5).

6 Cost effectiveness analysis

6.1 OBJECTIVES AND SCOPE OF ANALYSIS

A full description of the cost effectiveness analysis, and the assumptions on which it is founded, is given in Annex 5.

This cost effectiveness analysis builds on those described in the reports on Phases 1 and 2 of this project. However, in this iteration the scenarios analysed are specifically those options which arise from Tasks 1, 3 and 4, see Chapters 2, 4 and 5 of this report.

The overall approach and methodology follows that used, reviewed and agreed, during the earlier phases of the project where annual costs of, and savings generated by, the various options were calculated.

The input data has been updated, such that the latest vehicle stock, vehicle activity and emissions factor databases are used. These are drawn from those used to calculate the National Atmospheric Emissions Inventory (NAEI) for 2003 (i.e. are those used for calculations made in autumn/winter 2004). These databases contain both current and projected data, updated to include current best understanding. For example, the databases take into account the increased penetration of diesel fuelled vehicles into the passenger car market, and latest analyses on vehicle emission factors and degradation rates. The use of these databases means that this cost effectiveness analysis is built on exactly the same assumptions and foundation data as is used to provide other government departments, principally DEFRA, with information. Other inputs, for example assumptions regarding the number of test stations, the time required for testing and the cost of this per minute, have been reviewed with VOSA and updated.

The range of scenarios modelled has contracted in-line with evolving views on the nature of future in-service testing programmes, and the evolution of vehicle technology. For example, this analysis does not consider dynamometer testing because cost effective and practicality considerations from the Phases 1 and 2 analyses led to the conclusions that these should no longer be considered in this project. Similarly, the Phase 2 cost effectiveness analysis considered scenarios where heavy-duty vehicles might meet Euro 4 standards using either particulate traps or by incremental reductions using current technologies. Most manufacturers now indicate that traps will not be required, and consequently this analysis only considers the single technological approach.

A further significant change relative to the Phase 2 cost effectiveness analysis concerns the vehicles to be tested. It had been assumed that any changes to the in-service emissions test would apply to all vehicles presented for testing. However, the recent amendment to the EU directive on roadworthiness testing (Directive 2003/27/EC) introduces changes to pass/fail limits for FAS testing of Euro 4 vehicles, and those which meet later emissions standards. Consideration was given by the Commission to applying the tighter pass/fail limits to older vehicles, but negotiations concluded that retrospective application of limits should not occur. This is an important precedent that has been adopted across the European Community. Its implications within this project are that any changes to the in-service emissions test would **only apply to Euro 4, and later, vehicles.**

The impact of this change is not immediately apparent from the Tables in Appendix 5 of the Phase 2 report because the emissions listed, and the emissions savings potential derived from these, are not sub-divided by Euro standard. By way of illustration, the

relative PM emissions from HGVs (rigids and artics) are given below in Table 4.

Table 4 Relative PM emissions from heavy-goods vehicles

Year	PM emissions from pre-Euro 4 vehicles	PM emissions from Euro 4, and later, vehicles
2005	6.08 ktonnes	0.00 ktonnes
2010	2.43 ktonnes	0.60 ktonnes
2015	0.47 ktonnes	1.13 ktonnes

These data highlight the large reduction in PM emissions predicted from Euro 4 and later vehicles, which is primarily a consequence of the five-fold reduction in the PM standards between Euro 3 and Euro 4 HDVs. Thus the PM emissions that might be saved from an improved emissions test that applies to Euro 4 and later vehicles only are correspondingly less than if an improved test were applied to the whole fleet.

6.2 METHODOLOGY AND RESULTS

The overall methodology remains:

- calculate the costs for implementing an option (Section A5.3 of Annex 5)
- calculate the emissions saved by rectifying the vehicles identified by the test (Section A5.4 of Annex 5)
- calculate the cost effectiveness (£ to be spent for each kg saved) for an option (Section A5.5 of Annex 5).

The calculation of costs, both for setting up and per test, were calculated using the revised input data. The setting up costs comprise those incurred centrally and those incurred by each test centre. The centrally borne costs were estimated and found to be small in comparison with the annual scheme's costs (especially when amortised over a 5-year in-service test lifetime). However, the costs do not convey the challenge of resourcing the implementation of a new test scheme from within VOSA and DfT.

The calculation of the emissions saved follows the approach used, reviewed and agreed from the Phase 1 and Phase 2 cost effectiveness iterations. Again revised input data were used, i.e. from the latest (autumn 2004) NAEI calculations). Some data on the emissions of the fleet as a whole, the numbers of excess emitters, the effectiveness of various test scenarios at detecting these and the fraction of the excess emissions that are reduced by rectification of the identified vehicles were obtained from the practical studies reported in Chapters 2, 3 and 4 (especially regarding NO_x emissions from light-duty vehicles and PM emissions from heavy-duty vehicles). Notwithstanding the research undertaken, some poorly quantified parameters and unknowns remain, and consequently the calculations of the emissions savings predicted by the scenarios does contain uncertainties. The other important conclusion drawn from the results from studies reported in Chapters 2, 3 and 4 is that advances in diesel technology are leading to major changes in the nature and frequency of faults, and on the magnitude of the emissions changes caused by faults. All these factors are discussed in more detail in Chapter 4 of Annex 5.

From the calculations of costs and emissions saved for the various technical options the cost effectiveness (£ to be spent per kg of emissions saved) can be calculated. The results are summarised in Tables 3 – 5 (taken from chapter 5 of Annex 5). An estimate of the number of errors of commission is also included in the tables for each technical scenario because this is a further vital parameter when assessing the attractiveness of options.

Table 5 Cost effectiveness calculations for PM emissions from light-duty vehicles

Option	Vehicles tested	Costs	Savings (ktonnes)	Cost effectiveness £ / kg	Errors of commission
PM emissions from light-duty vehicles in 2005					
PL1 – change nothing	All vehicles	£48,843,557	0.1009	£484	0.0%
	Euro 4 only	£0	0.0	N/A	
	Incremental costs	N/A as this is the baseline case			
PM emissions from light-duty vehicles in 2010					
PL1 – change nothing	All vehicles	£70,236,397	0.0262	£2,684	0.0%
	Euro 4 only	£26,382,118	0.0018	£14,464	0.0%
	Incremental costs	N/A as this is the baseline case			
PL2 – Lower limit for all vehicles	Euro 4 only	£26,382,118	0.0608	£434	1.5%
	Incremental costs	£0	0.0590	N/A	1.5%
PL3 – Vehicle specific limits	Euro 4 only	£32,035,429	0.0681	£470	0.1%
	Incremental costs	£5,653,311	0.0663	£85.31	0.1%
PL4 – Lower default + Vehicle specific exemptions	Euro 4 only	£32,035,429	0.0608	£527	0.1%
	Incremental costs	£5,653,311	0.0590	£95.86	0.1%
PL5 – better meter + Option PL3	Euro 4 only	£48,646,429	0.0681	£714	0.075%
	Incremental costs	£16,611,000	0.0000	N/A	0.075%
PM emissions from light-duty vehicles in 2015					
PL1 – change nothing	All vehicles	£90,364,484	0.0101	£8,937	0.0%
	Euro 4 only	£70,666,883	0.0034	£20,850	0.0%
	Incremental costs	N/A as this is the baseline case			
PL2 – Lower limit for all vehicles	Euro 4 only	£70,666,883	0.1130	£625	1.5%
	Incremental costs	£0	0.1096	N/A	1.5%
PL3 – Vehicle specific limits	Euro 4 only	£85,809,787	0.1265	£678	0.1%
	Incremental costs	£15,142,904	0.1231	£123	0.1%
PL4 – Lower default + Vehicle specific exemptions	Euro 4 only	£85,809,787	0.1130	£760	0.1%
	Incremental costs	£15,142,904	0.1096	£138	0.1%
PL5 – better meter + Option PL3	Euro 4 only	£102,420,786	0.1265	£809	0.075%
	Incremental costs	£16,611,000	0.1231	N/A	0.075%

Table 6 Cost effectiveness calculations for PM emissions from heavy-duty vehicles

Option	Vehicles tested	Costs	Savings (ktonnes)	Cost effectiveness £ / kg	Errors of commission
PM emissions from heavy vehicles in 2005					
PH1- change nothing	All vehicles	£2,219,861	0.0994	£22.32	0.0%
	Euro 4 only	£0	0.0	N/A	
	Incremental costs	N/A as this is the baseline case			
PM emissions from heavy vehicles in2010					
PH1 - change nothing	All vehicles	£2,246,476	0.0215	£104.40	0.0%
	Euro 4 only	£896,016	0.0012	£758.90	0.0%
	Incremental costs	N/A as this is the baseline case			
PH2 - Cease testing Euro 4 vehicles	Euro 4 only	£0	0.0000	£434	0.0%
	Incremental costs	-£896,016	-0.0012	N/A	0.0%
PH3 - Lower limit for all vehicles	Euro 4 only	£896,016	0.0095	£94.10	1.0%
	Incremental costs	£0	0.0083	N/A	1.0%
PH4 - Vehicle specific limits	Euro 4 only	£1,232,022	0.0107	£115.53	0.04%
	Incremental costs	£336,006	0.0095	£35.43	0.04
PH5 - Lower default + Vehicle specific exemptions	Euro 4 only	£1,232,022	0.0095	£129.39	0.04%
	Incremental costs	£336,006	0.0083	£40.28	0.04
PH6 - better meter + Option PH4	Euro 4 only	£1,877,636	0.0107	£176.07	0.015%
	Incremental costs	£645,614	0.0000	N/A	0.015%
PM emissions from heavy vehicles in2015					
PH1 - change nothing	All vehicles	£2,267,538	0.0055	£412.73	0.0%
	Euro 4 only	£1,727,136	0.0022	£785.49	0.0%
	Incremental costs	N/A as this is the baseline case			
PH2 - Cease testing Euro 4 vehicles	Euro 4 only	£0	0.0000	£434	0.0%
	Incremental costs	-£1,727,136	-0.0022	N/A	0.0%
PH3 - Lower limit for all vehicles	Euro 4 only	£1,727,136	0.0177	£97.40	1.0%
	Incremental costs	£0	0.0155	N/A	1.0%
PH4 - Vehicle specific limits	Euro 4 only	£2,374,812	0.0199	£119.58	0.04%
	Incremental costs	£647,676	0.0177	£36.67	0.04
PH5 - Lower default + Vehicle specific exemptions	Euro 4 only	£2,374,812	0.0177	£133.93	0.04%
	Incremental costs	£647,676	0.0155	£41.70	0.04
PH6 - better meter + Option PH4	Euro 4 only	£3,020,426	0.0199	£152.09	0.015%
	Incremental costs	£645,614	0.0000	N/A	0.015%

Table 7 Cost effectiveness calculations for NO_x emissions from light-duty vehicles

Option	Vehicles tested	Costs	Savings (ktonnes)	Cost effectiveness £ / kg	Errors of commission
NO_x emissions from light-duty vehicles in 2005					
N1 - change nothing	All vehicles	£0	0.0192	N/A	N/A
	Euro 4 only	£0	0.0	N/A	N/A
	Incremental costs	N/A as this is the baseline case			
NO_x emissions from light-duty vehicles in 2010					
N1 - change nothing	All vehicles	£0	0.0184	N/A	N/A
	Euro 4 only	£0	0.0085	N/A	N/A
	Incremental costs	N/A as this is the baseline case			
N2 - Lower FAS limit	Euro 4 only	£0	0.1356	N/A	N/A
	Incremental costs	£0	0.1271	N/A	N/A
N3 - 4-gas analysers, 1 test for all	Euro 4 only	£26,458,781	0.4026	£65.72	2%
	Incremental costs	£26,458,781	0.3941	£67.13	2%
N4 - 4-gas analysers, vehicle specific procedure and limits	Euro 4 only	£33,312,092	0.4153	£80.20	0.5%
	Incremental costs	£33,312,092	0.4069	£81.08	0.5%
N5 - 4-gas analyser + low idle test	Euro 4 only	£22,005,470	0.3602	£61.09	0.15%
	Incremental costs	£22,005,470	0.3518	£62.56	0.15%
NO_x emissions from light-duty vehicles in 2015					
N1 - change nothing	All vehicles	£0	0.0189	N/A	N/A
	Euro 4 only	£0	0.0154	N/A	N/A
	Incremental costs	N/A as this is the baseline case			
N2 - Lower FAS limit	Euro 4 only	£0	0.2469	N/A	N/A
	Incremental costs	£0	0.2314	N/A	N/A
N3 - 4-gas analysers, 1 test for all	Euro 4 only	£67,580,348	0.7329	£92.21	2%
	Incremental costs	£67,580,348	0.7174	£94.20	2%
N4 - 4-gas analysers, vehicle specific procedure and limits	Euro 4 only	£83,923,252	0.7560	£111.01	0.5%
	Incremental costs	£83,923,252	0.7406	£113.32	0.5%
N5 - 4-gas analyser + low idle test	Euro 4 only	£53,637,445	0.6557	£81.80	0.15%
	Incremental costs	£53,637,445	0.6403	£83.77	0.15%

6.3 CONCLUSIONS AND DISCUSSION

6.3.1 Current test

From Tables 3 to 5 it can be seen that the current test is providing some PM abatement (see Option PL/H1 – change nothing for 2005) at a cost effectiveness of 484 £/kg and 22.32 £/kg for light-duty and heavy-duty vehicles. However, in 2010 and 2015 as vehicles become cleaner despite the lowering of the FAS pass/fail limit to 1.5 m⁻¹ for Euro 4 (and later) vehicles the pounds spent per kg PM saved is predicted to rise sharply to around 9,000 £/kg and 413 £/kg for all light-duty and heavy-duty vehicles, respectively, in 2015.

However, these 2015 values still contain considerable contributions from pre-Euro 4 vehicles: for Euro 4 (and later) vehicles only the cost effectiveness are around 21,000 £/kg and 800 £/kg for light-duty and heavy-duty vehicles, respectively.

Whilst the 3.0 m⁻¹ (pre-Euro 4) and 1.5 m⁻¹ (Euro 4 and later) pass/fail limits produce very little emissions savings, they are forecast not to fail vehicles incorrectly.

6.3.2 PM savings generated by options involving lowering of pass/fail limits

The three options considered can be summarised as:

- a) introduce lower pass/fail limits that universally apply to all vehicles,
- b) introduce pass/fail limits that are vehicle type specific, or
- c) a mixture of a) and b) above.

Relative to the “do nothing” option the cost per kg of PM saved is predicted to be around 30 times lower for light-duty vehicles and around 6 times lower for heavy-duty vehicles. However, all three options have somewhat similar cost effectiveness. The principal difference between them is that the introduction of a significantly universal pass/fail limit, although it generates more emissions savings it does so at the cost of a significant rate (1.0 – 1.5%) of incorrectly failing satisfactory vehicles. The tailoring of pass/fail limits suitable for each (option b) or groups (option c) of vehicle types is estimated to reduce the number of incorrectly failed vehicles by around a factor of 15 whilst providing similar benefit in emissions saved.

The increased cost of opting for higher specification instrumentation does not generate increased emissions savings for the range of pass/fail limits likely. It does, however, reduce the number of vehicles incorrectly failed, but at a modest cost.

6.3.3 NO_x savings from light-duty vehicles

Option	Vehicles tested	Costs	Savings (ktonnes)	Cost effectiveness £ / kg	Errors of commission
PM emissions from heavy vehicles in 2005					
PH1- change nothing	All vehicles	£2,219,861	0.0994	£22.32	0.0%
	Euro 4 only	£0	0.0	N/A	
	Incremental costs	N/A as this is the baseline case			
PM emissions from heavy vehicles in 2010					
PH1 - change nothing	All vehicles	£2,246,476	0.0215	£104.40	0.0%

	Euro 4 only	£896,016	0.0012	£758.90	0.0%
	Incremental costs	N/A as this is the baseline case			
PH2 – Cease testing Euro 4 vehicles	Euro 4 only	£0	0.0000	£434	0.0%
	Incremental costs	-£896,016	-0.0012	N/A	0.0%
PH3 – Lower limit for all vehicles	Euro 4 only	£896,016	0.0095	£94.10	1.0%
	Incremental costs	£0	0.0083	N/A	1.0%
PH4 – Vehicle specific limits	Euro 4 only	£1,232,022	0.0107	£115.53	0.04%
	Incremental costs	£336,006	0.0095	£35.43	0.04
PH5 – Lower default + Vehicle specific exemptions	Euro 4 only	£1,232,022	0.0095	£129.39	0.04%
	Incremental costs	£336,006	0.0083	£40.28	0.04
PH6 – better meter + Option PH4	Euro 4 only	£1,877,636	0.0107	£176.07	0.015%
	Incremental costs	£645,614	0.0000	N/A	0.015%
PM emissions from heavy vehicles in2015					
PH1 - change nothing	All vehicles	£2,267,538	0.0055	£412.73	0.0%
	Euro 4 only	£1,727,136	0.0022	£785.49	0.0%
	Incremental costs	N/A as this is the baseline case			
PH2 – Cease testing Euro 4 vehicles	Euro 4 only	£0	0.0000	£434	0.0%
	Incremental costs	- £1,727,136	-0.0022	N/A	0.0%
PH3 – Lower limit for all vehicles	Euro 4 only	£1,727,136	0.0177	£97.40	1.0%
	Incremental costs	£0	0.0155	N/A	1.0%
PH4 – Vehicle specific limits	Euro 4 only	£2,374,812	0.0199	£119.58	0.04%
	Incremental costs	£647,676	0.0177	£36.67	0.04
PH5 – Lower default + Vehicle specific exemptions	Euro 4 only	£2,374,812	0.0177	£133.93	0.04%
	Incremental costs	£647,676	0.0155	£41.70	0.04
PH6 – better meter + Option PH4	Euro 4 only	£3,020,426	0.0199	£152.09	0.015%
	Incremental costs	£645,614	0.0000	N/A	0.015%

Table 7 indicates that the current in-service test programme, FAS test only for diesel vehicles, **does** produce a small NO_x emissions savings because this test does detect some excess NO_x emitters, albeit only a few.

A revised FAS test is predicted to increase this to around 32% of the excess NO_x emissions from Euro 4 and later light-duty vehicles (see Section 4.5 of Annex 5).

An alternative approach using 4-gas analysers and unloaded tests has been demonstrated. The options proposed can be summarised as:

- a) use a 2 engine-speed idle test + limits that apply to all vehicles,
- b) use a 2 engine-speed idle test + vehicle type specific limits, or
- c) use a low idle test.

The cost effectiveness of these options follow the order:

Option b > Option a > Option c i.e. Option c is the most attractive.

In terms of errors of commission these follow:

Option a > Option b > Option c i.e. Option c is the most attractive.

Hence both criteria indicate Option c, the use of a low idle test with a 4-gas analyser is the best option.

7 Conclusions, recommendations and future work

7.1 NO_x AND LDVS

A detailed report of the conclusions and recommendations reached from the evaluation of measurement techniques for NO_x is given in Section A1.5 of Annex 1, and is summarised in Chapter 2 of this main report.

The principal finding was the positive confirmation that the monitoring of tailpipe O₂ and CO₂ concentrations, using 4-gas analysers based on those already in use for the testing of SI light-duty vehicles fitted with advanced emission control systems, is a viable foundation for an in-service to check the functionality of EGR systems. (It is argued that the use of thermometry, though technically possible, is not a practical option.)

Two possible test procedures are proposed:

1. taking measurements at two different (possibly vehicle type specific) engine speeds for an unloaded engine, or
2. taking measurements at low idle.

A further finding was that the current (free acceleration smoke) and potential future PM emissions check does detect some malfunctioning EGR units.

Five different scenarios were evaluated in the cost effectiveness analysis ranging from the "do nothing" option to scenarios encompassing the two possible test procedures above. These predict a cost effectiveness of between £60 and £115 /kg NO_x saved (dependent on the timeframe and the scenario). In parallel with the cost effectiveness analysis, estimates were also made regarding the numbers of vehicles that would be incorrectly failed (errors of commission).

On the combined basis of cost effectiveness, practical considerations and minimising the errors of commission the "idle" based test using a 4-gas analyser is the most attractive option.

7.2 PM AND BOTH LDVS AND HDVS

Detailed reports of the conclusions and recommendations reached from the evaluation of test measurement procedures for PM from heavy-duty and light-duty vehicles are given in Sections A3.6, A3.8.7, A3.9.3 and A3.10 of Annex 3 (for HDVs) and A4.4 of Annex 4 (for LDVs). Because of the very significant overlap between testing option for both types of vehicles, they will be considered together.

The first issue addressed was: given the results from the Phase 2 studies, including the cost effectiveness analysis, practical (and political) considerations, what options for the test procedure should be pursued? A steering group comprising people from DfT's Vehicle Standards and Engineering and Licensing, Roadworthiness and Insurance divisions, VOSA's Testing Standards Policy and Strategy team, and AEA Technology's

Engines and Emissions team considered the potential options. These were: on-the-road driving, loaded testing using a chassis dynamometer and unloaded testing. The outcome of the debate was the decision that for both LDVs and HDVs attention should focus only on developing an unloaded test.

Possible unloaded tests range from steady state conditions (e.g. the two engine speed unloaded test described in the previous section as a possible procedure for checking EGR functionality and thereby NO_x emissions) to transient tests. The transient test with the highest accelerations is the free acceleration test, when the accelerator is rapidly depressed to its maximum extent. Previous studies had shown that during on-the-road cycles PM emissions are highest under transient accelerations. Hence a free acceleration test appears to be the most appropriate option. However, previous studies have also shown that free acceleration smoke (FAS) tests correlate poorly with PM emissions over loaded drive cycles.

A major weakness of the FAS test was found to be the dependence of the test result on the exact details of how the test procedure was undertaken (critically the rate and extent of accelerator depression). Halving the rate from the normal "swift rate of depression" led to changes in smoke emissions of up to 500% for HDVs and a mean change in excess of 200% for LDVs. Such large variations in FAS test result from such small changes in test procedure, particularly when combined with the poor correlation between FAS test results and PM emissions over drive cycles, seriously weakened the case for FAS testing.

Given this historical context the evaluation of test measurement procedures for checking PM emissions comprised:

- evaluation of sensitivity of FAS results to key parameters (HDVs & LDVs)
- evaluation of correlation between FAS results and PM emissions over regulatory cycle (LDVs)
- evaluation of correlation between FAS results, PM emissions and the state of vehicle maintenance (LDVs)
- an assessment of the nature and frequency of faults encountered in the field (HDVs)
- an assessment of the effects of faults encountered in the field on FAS results (HDVs)
- an audit of FAS results from current test procedure applied to current fleet (HDVs).

The evaluation of the sensitivity of FAS results to key parameters considered:

- the rate and extent of accelerator depression,
- the effect of ambient temperature,
- the effect of engine temperature (HDVs only)
- the influence of vehicle preconditioning.

The conclusions were that for both LDVs and HDVs the transition from mechanically to electronically controlled fuelling systems has greatly reduced the sensitivity of the FAS test result to changes in the exact details of how the procedure was undertaken. In particular the FAS test result, and the time taken for an engine to accelerate to its top speed, as a function of both the rate and extent of accelerator depression now has a plateau region within which variations make no difference. The on-set of this plateau region is around 1.5 seconds depression rate and less than 70% depression extent.

Discussion with, and observations and measurements of, testers indicate that a "normal" FAS test comprises 100% depression in around 0.7 seconds. What the conclusions reveal is that changes in FAS test result only start occurring when the accelerator is depressed **less than** 70% of its full extent in **greater than** 1.5 seconds. Consequently, it is reasonable to presume that all honest attempts at conducting a FAS test lie within

the plateau thresholds. This leads to the important recommendation that no additional functionality need be introduced into the meter to control these parameters (Recommendations 1 in Sections 4.2 and 5.2).

It was also concluded that effects of ambient temperature, engine temperature or preconditioning (HDVs only) that are within the bounds that might be anticipated in the field, or are as specified in the current MoT testers' handbook, do not lead to sufficient variability in the FAS result to warrant recommendations to change the current procedure.

The one exception is the preconditioning of LDVs where some changes to the smoke meters' specification are recommended

- to prevent further unnecessary testing, and
- to fine tune the current data filtering algorithm to remove "anomalous" data points, specifically targeted at removing unrepresentatively high values caused by insufficient preconditioning.

Overall, these findings and conclusions strengthen the case for the continued use of FAS testing.

The evaluation of the correlation between FAS test results and PM emissions over the regulatory, loaded drive cycle for LDVs showed that the change to electronic fuelling systems in modern diesel vehicles had not led to an improved correlation. Although analogous data were not collected, there are no grounds for believing that the correlation would be any better for heavy-duty vehicles.

The study also highlighted the difficulties associated with having a universal pass/fail limit, i.e. one that applies to all vehicle types. The associated recommendation was that consideration be given to devising a pass/fail limit that is more equable for all vehicle types, at the same time being a more demanding assessment for the majority of vehicles (see Section 5.3).

However, the primary purpose of an in-service emissions test is to identify "excess emitters" in need of repair or maintenance. Consequently, the change in FAS test results, relative to the change in PM emissions over drive cycles, as a function of the vehicle's state of repair is of prime interest. This was evaluated for five faults introduced into modern diesel passenger cars.

The major conclusion from this evaluation is that it is naïve to believe that fault X leads to a change Y in PM emissions for all loaded cycles: the change in PM emissions depends both on the fault **and** the speed/time characteristics of the drive cycle. (This was starkly shown for a vehicle whose turbo waste-gate line was disconnected. This led to a 30% decrease in PM emissions over the ECE cycle and a 365% increase over the EUDC.) In contrast the FAS test only probes PM emissions over a very limited area of the engine's performance map, albeit one where the highest levels of PM emissions may occur.

For heavy-duty vehicles an assessment of the nature and frequency of fault encountered in the field was undertaken. Key conclusions from this study were as follows.

- The answers are dynamic, i.e. the types and frequency of fault changes with time.
- Best estimates for the current rate of engine failure (i.e. at winter 2004/5) are 25 ± 15 faults /100 vehicles /year.
- The engine system most often found to be faulty is the engine's electronic system (ECU, sensors or wiring). This is currently estimated to be the cause of around 25% of vehicles faults.
- Fuel, coolant and exhaust systems are generally the next most commonly encountered faults, each contributing around 17% of all faults.

- Engine block and bottom end and valve train faults are the smallest contributors.
- Too few vehicles are fitted with emission control systems for all responding organisations to have experience of their reliability. OEM franchised service centres rarely see such vehicles, whereas fleet owners may have retro-fitted systems to their fleet (e.g. particulate traps).

Of the nine categories of engine faults, four lead to the potentially largest increases in excess PM emissions. These are air, fuel and electronic systems, and, if fitted, faults associated with emission control systems (e.g. filters or EGR systems). Generally these were found to comprise around 60% of all the engine faults encountered. Hence the frequency of faults potentially causing excess PM emissions is estimated to be 15 ± 9 faults /100 vehicles /year.

The evaluation then progressed to measuring the effects of different types of engine faults on FAS test results. Attention focussed on the four categories of engine faults which potentially lead to the largest increases in excess PM emissions: electronic, fuel, air inlet and emission control (traps, filters and EGR) systems. The principal findings were:

- both fuel quality and injector faults consistently led to large changes in FAS smoke from around, or greater than, 2 m^{-1} for the faulty vehicle to around $0,3 \text{ m}^{-1}$ for vehicles when repaired,
- of the four types of electronic system faults, only one (a fault accelerator potentiometer) led to a significant increase in FAS result, the remainder four led to only small changes,
- whilst no quantitative data were collected for vehicles with faulty air inlet systems, discussions with service centre managers indicated that the combination of the sensors within a modern engine, and the programme within its controlling ECU lead to air inlet system faults causing little change in FAS result.

The principal value of this information is as an input into the debate of the value and role of FAS testing of heavy-duty vehicles as a mechanism for identifying poorly maintained vehicles and ensuring their rectification. Important data missing, that prevents the estimation of the effect of detection rates on PM emissions savings, is the PM emissions from vehicles with these faults over loaded drive cycles. Collection of this data was outside the scope of the current study.

Overall the research has shown that the result of a FAS test is not a proxy for PM emissions over the regulatory drive cycles. It is best viewed as a diagnostic test that has a range of sensitivities to different faults. It sometimes under reports the change in PM emissions over the NEDC and sometimes over reports them.

This might be hard to accept by those who want the FAS test to be a proxy test for the type approval standard. The author strongly believes that it is wrong to consequently dismiss the FAS test as being of no value. The fact that it can not detect all faults that lead to increased PM emissions with the same effectiveness does not negate its ability to detect some faults, thereby presenting an opportunity to identify and have some excess PM emitting vehicles rectified.

This is exactly analogous to status of the roadworthiness emissions test for SI vehicles. For example, the two speed emissions test is not able to identify vehicles whose cold start emissions are excessive because it is a test carried out when the vehicle is operating at its normal operating temperature. This weakness does not diminish the current test's ability to detect some vehicles with defective closed loop fuelling systems, forcing rectification and thereby improving air quality.

In summary, this leads to the recommendation: The FAS test continues to be used as an in-service check of PM emissions appreciating it is a diagnostic test that has variable sensitivity to different faults.

In the context of the recommendation above a crucial question is: What is the efficiency of the current in-service test regime, particularly regarding modern diesel vehicles. This was evaluated by auditing the effectiveness of the current test, though only for HDVs. Emissions testing data were collected from a number of government vehicles test stations. When filtered these provided 2,025 test data-sets. The overall failure rate was 1.38%.

Vehicles were assigned to an emissions standard based on their age (deduced from their registration plate). From analysis of the database the following information was found.

Table 8 Analysis of FAS test results and failures by introduction date of the different Euro standards

Standard	Introduction date	Mean FAS test result from these data	Number of vehicles which failed FAS test	% of vehicles tested which failed FAS test
pre-Euro 1		1.50 m ⁻¹	16	5.39%
Euro 1	1/10/93	1.10 m ⁻¹	5	1.61%
Euro 2	1/10/96	0.76 m ⁻¹	7	0.74%
Euro 3	1/10/2001	0.44 m ⁻¹	0	0.00%

These data strongly support the view that the 3.0 m⁻¹ pass/fail limit for current turbocharged HDVs, and the new 1.5 m⁻¹ limit to be introduced for Euro 4 standard vehicles in 2008 is not effective at detecting poorly maintained vehicles.

To recap, the preceding conclusions and discussions – the current in-service emissions testing programme is increasingly ineffective at identifying excess PM emitters. This is within the context of diesel vehicles becoming both cleaner and more reliable (failure rates for HDVs have been quantified). The current in-service emissions test comprises three principal components:

the test procedure + the instrumentation + pass/fail limits.

Research has shown that the current test procedure (the free acceleration smoke test) is the most appropriate of the unloaded test options. It is a useful diagnostic check for some, but not all, engine faults that lead to excess PM emissions. It is concluded that there is little need (or scope) for changing (or improving) the procedure (except for a few minor changes regarding data processing). Indeed the current procedure has been shown to have greatly improved for modern electronically controlled diesels.

Instrumentation is discussed in more detail in the next section of this chapter. A central fact is that for appropriately calibrated instruments improving sensitivity does not affect the number of vehicles above or below the pass/fail limit. The meter's sensitivity/precision does affect the number of vehicles that inappropriately fail the test, and also the number of failing vehicles that are adjudged to pass the test. Hence changing instruments will not change the detection rate.

This leaves the pass/fail limit as the only component whose alteration will change detection rates.

The studies have demonstrated that a universal pass/fail limit is problematic. This is because if it is designed so as not to unfairly fail vehicles which meet the type approval PM emissions standard, it has to be set at a smoke value above that of the vehicle type which gives the highest FAS value when in its "appropriately maintained" state. This gives the vast majority of vehicles a large range within which it can degrade before it becomes a fail at the in-service test, by which time its PM emissions over loaded cycles are generally far in excess of those of a well maintained vehicle.

The options for changing the pass/fail limit can be categorised as:

- a) do nothing,
- b) a further decrease in a universal limit,
- c) move to vehicle type specific limits,
- d) a decrease in the default limit with higher limits for those vehicle types whose FAS result is greater than the new default limit even when the vehicle's PM emissions are within the regulatory (type approval) limits.

These options apply to both light-duty and heavy-duty vehicles. Their cost effectiveness were analysed in Chapter 6 (Annex 5).

An important additional question is: if a new test standard is introduced, what vehicles should it apply to? Discussions and debate within the project's steering group, led to the conclusion that any new test standards should only apply to Euro 4, and later specification, vehicles.

The cost effectiveness analysis confirmed the poor anticipated performance of the current FAS test as it deteriorated from £22.32 expenditure required for each kg of PM saved from heavy-duty vehicles in 2005 to around £760 /kg PM in 2010 for Euro 4 HDVs. For LDVs the change was from around £484 £ /kg in 2005 to £14,500 /kg in 2010 and £20,850 /kg in 2015. Very broadly, the three options involving lower limits (b) to d) above) all lead to similar improved cost effectiveness, i.e. to £140 ± £30 /kg for HDVs and £480 ± £50 /kg for LDVs, both in 2010. However, the three options are predicted to have markedly different error rates, with the lower universal limit forecast to incorrectly fail 1.0% (or 1.5%) HDVs (LDVs) of **all** vehicles tested. These incorrect failure rates are greatly reduced (by estimated factors of at least 15) by tailoring the pass/fail limit to different vehicle types.

7.3 INSTRUMENTATION FOR PM MEASUREMENT

In parallel with the evaluation of test procedures for PM measurement from light-duty and heavy-duty vehicles, research into the options for PM instrumentation were undertaken. The driver for this activity was concern that the current meters may become inappropriate for the measurement of low emission diesels.

Four different instrumentation types were selected for evaluation, not with a view to declaring a winner, but of better characterising their strengths and weaknesses based on practical experience. The instrument types, and the two reference meters used were:

- an advanced opacimeter,
- filter paper reflectometry,
- a light scattering meter,
- a quartz crystal microbalance (QCM),
- a Celesco 107 opacimeter and
- a Bosch RTM 430 smoke tube with software to configure it as a UK Reference Smoke meter.

Instruments were characterised according to their intrinsic performance and their response to potential interferences (clean hot air, liquid droplet aerosol and NO₂).

It was concluded that neither the QCM nor the light scattering meter are currently instrumentation that can be recommended for consideration for the in-service testing of diesel exhaust during a FAS test. In contrast the filter paper reflectometry and advance opacimeter have both been shown to have higher sensitivities than the Bosch reference meter (by factors of 4 and 6.4, respectively). The two approaches are quite different, one measuring an accumulation of PM whilst the other measures smoke in real time. Both approaches have their merits and drawbacks.

The critical question is: What instrument specification is required for the future? It is important to remember that the purpose of the meter used for in-service testing is to measure the emissions of a vehicle relative to a pass/fail standard, rather than to accurately measure what the vehicle actually produces. Hence currently meters are required to have adequate precision and accuracy to measure whether a vehicle's emissions are greater than, or below, the 3.0 m⁻¹ pass/fail limit. From 2008 this limit will be reduced to 1.5 m⁻¹ for Euro 4 vehicles. It is concluded that the **current meters are totally adequate for measuring both these standards.**

If, however, the pass/fail limit for some vehicles was reduced to, for example, 0.3 m⁻¹, then the suitability of current meters would become more marginal, and a more sensitive meter might be required.

7.4 UNCERTAINTIES AND FOCUS FOR FUTURE WORK

7.4.1 NO_x from light-duty vehicles

The first activity that will occur is an evaluation of this report by VOSA, DfT and other advisors to decide whether or not:

- generically, it is appropriate to consider NO_x testing of light-duty vehicles further.
- If so, which of the three options should be pursued.

If it is assumed that the answer to the above questions is to consider some form of testing further, then it is recommended that the activities listed below are undertaken:

- Extend the assessment of the validity of the approach to a wider range of models.
- Assess the variation in gas concentrations measured for different vehicles of the same type.
- Talk to different vehicle manufacturers about the prospect of using this approach to check EGR functionality.
- Talk to meter manufacturers about modifications that may be required to the current 4-gas analysers.
- Undertake field trials to
 - assess reaction of testers to the potential new test, and
 - collect data on how many vehicles actually have fault EGR systems.
- Further consideration of the vehicle emissions standards that a potential test might be applied to.

7.4.2 PM from light-duty and heavy-duty vehicles

Again the first activity will involve reviewing this report and prioritising the technical options (from do nothing to improve pass/fail limits by.....). Hence the activities listed below presume a decision to proceed further.

A vital parameter, hitherto not investigated, is the distribution of FAS test results from vehicles of the same type, or similar age and mileage, that are appropriately maintained. This is because the setting of a pass/fail limit will, in part, be determined by this distribution.

For light-duty vehicles this data may be known and obtainable from manufacturers. Also the computerisation of in-service testing will record data which could be analysed to find the required distributions. In addition, there is the less attractive option of collecting this data within the current, non-computerised system from selected test centres.

For heavy-duty vehicles there are probably sufficient entries in the data collected from the GVTSSs. However, this data contains the vehicle's manufacturer and the vehicle's registration number. It does not contain the vehicle's model and/or type information. This could be obtained by cross referencing the existing database registration number with information held by DVLA.

A further issue to be debated/decided is that of how vehicle type specific, default or exemption limits would be set. It is envisaged this would involve discussions/debates with manufacturers. However, such approaches should emphasise that this is quite different from changes to type approval emissions standards. Its objective is to ensure vehicles are appropriately maintained, a burden not on the manufacturers but on the vehicle owners/operators.

Recommendations about the activities required to produce new limits cannot be made in the absence of a decision regarding the basis of their quantification.

7.4.3 Instrumentation for PM measurement

If the decision were taken that a limit less than 1.5 m^{-1} be developed then it is recommended that a statistical analysis be undertaken to obtain the relationship between the meter specification and the number of incorrect fails (errors of commission) and passes (errors of omission) that would result. This would provide data against which a decision as to which meter options are optimal can be made.

7.4.4 NO_x from HDVs

The Phase 2 report concluded as follows.

1. It was inappropriate to attempt to measure NO_x emissions using loaded proxy cycles to emulate emissions from the type approval loaded cycles for either LDVs or HDVs.
2. In-service NO_x testing should consist of a diagnostic check of key systems (or components) whose failure would lead to excessive NO_x emissions. This reduces to checking NO_x abatement technology fitted to vehicles continues to function correctly. It is emphasised this is a technology dependent diagnostic check.
3. For LDVs the predominant NO_x abatement technology fitted to vehicles was EGR, at the time of writing the Phase 2 report (June 2001).
4. For HDVs there was neither any significant quantity of vehicles in the fleet fitted with NO_x abatement technology, nor any consensus on the technology that would be introduced.

The recommendation that followed Conclusion 4 above, was: At present there is not a strong cost-effectiveness justification for including NO_x emissions checks in the in-service testing of heavy-duty vehicles. However, this situation might change if in-use NO_x emissions become dependent on the effective operation of NO_x abatement technologies developed to meet the likely lower emissions standards anticipated for Euro V and beyond. In the meantime the direction of NO_x abatement technology strategies should be monitored so that appropriate tests for their effective operation can be considered.

Now it is evident that the majority of HDV manufacturers anticipate using selective catalytic reduction (SCR) as the NO_x abatement technology. Further, many manufacturers anticipate introducing SCR and careful control of fuel injection timing as the technological solution to meeting Euro 4 standards (as opposed to the widespread use of diesel particulate filters). Consequently vehicles fitted with prototype SCR systems are now undergoing field trials.

The consequence of this is the subsequent recommendation that the time is now right to consider in-service testing of vehicles fitted with SCR systems.

The approach recommended is the phased approach adopted for research into other aspects of in-service testing:

Consideration of options

A desk based study which involves familiarisation with the systems and technology being trialled. Primary objectives would be:

- to consider the approaches to testing that may be appropriate, and
- to recommend which approaches appear to be the more promising.

(This activity is analogous to the Phase 2 studies of the present project, and may involve a small amount of practical work.)

Evaluation of options

An experimentally based study whose primary objective is to evaluate if the approaches recommended from the "Consideration of options" phase above actually work. This activity would be analogous to this Phase 3 study in the present project.

8 Glossary

COV	Coefficient of variance
CVTF	Cleaner Vehicle Task Force
DfT	UK Department of Transport
DEFRA	UK Department for Environment food and rural affairs
DVLA	Driver and Vehicle Licensing Agency
ECU	Electronic control unit, also called the PCM
EGR	Exhaust gas recirculation
EUDC	Extra-urban driving cycle
Euro 1	The emissions standard specified in Directive 91/441/EEC
Euro 2	The emissions standard specified in Directive 94/12/EC
Euro 3	The emissions standard specified in Stage A of Directive 98/69/EC
FAS	Free acceleration smoke
GVTS	Government vehicle test station
HDV	Heavy-duty vehicle
JCS	Joint Commission Study (A study on inspection of in-use cars by the EC DGs for Environment (DG XI) Transport (DG VII) and Energy (DG XVII))
LDV	Light-duty vehicle
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)
OBD	On-board diagnostics
OEM	Original equipment manufacturer
QCM	Quartz crystal microbalance
SCR	Selective catalytic reduction
SMMT	Society of motor manufacturers and traders
VCA	Vehicle Certification Agency (the UK's national approval authority for new road vehicles, an executive Agency of the Department for Transport)
VOSA	Vehicle Inspectorate (an executive agency of the Department for Transport)

9 References and footnotes

- 1 Technical solutions for reducing emissions from in-use vehicles, report of Technology and Testing working group of the Cleaner Vehicles Task Force, UK Department of Trade and Industry, March 2000.
- 2 7th ETH conference on combustion generated nanoparticles, "*Particulate matter mass measurement from a heavy duty diesel engine using 2007 CVS PM sampling in parallel to QCM and TEOM*". Southwest Research Institute, San Antonio, US and the US Environmental Protection Agency, August 2003
- 3 Press release on the Semtech QCM on 23rd November 2003 to ThomasNet[®] Industrial News Room entitled "Particulate analysers are suited for in-use measurements, See web-site <http://news.thomasnet.com/fullstory/28419>
- 4 These observations were conclusions reached by a DfT study entitled; "Diesel smoke test procedures and meter specification", DPU/9/33/19, AEA Technology (JOW Norris), AEAT-3340, October 1997
- 5 Research project FE 85.007/1999, Exhaust test- performance check / part 2 Diesel, DEKRA, TÜV Rheinland, RWTÜV
- 6 See Tables 6 – 9 of Appendix 3 of report for DfT (ref DPU/9/33/19) JOW Norris, Oct 1997
- 7 See data from Hartridge Mk III tabulated in Appendix V.5 of "Diesel smoke test procedures and meter specification", report for DfT (DoT ref DPU/9/33/19) JOW Norris, Oct 1997
- 8 VOSA Specification for diesel smoke meters, MOT/05/01/01
- 9 It is recommended that further studies be undertaken to check/confirm that this is an appropriate margin for error

Annexes and appendices

CONTENTS

Annex 1	THE EVALUATION OF TEST MEASUREMENT TECHNIQUES FOR NO _x
Annex 2	DETAILS OF PRACTICAL INVESTIGATIONS INTO PM INSTRUMENTATION
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