Annex 3
Evaluation of test measurement procedures for PM for heavy-duty vehicles

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CONTENTS

A3.1 Introduction and overview of Tasks 3 and 4

Tasks 3 and 4 are entitled "Evaluation of test measurement procedures for PM for heavy-duty (Task 3) and light-duty (Task 4) vehicles. Clearly there is scope for considerable overlap between these two tasks. A high level summary of 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 this annex 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 all vehicle 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.

Hence it is seen that the first experimental study in Task 3 investigated two light-duty vehicles although the task is nominally focussed on heavy-duty vehicles. For clarity, these are reported in Annex 4, along with the other light-duty vehicle studies.

This annex reports the prioritisation of test procedures for heavy-duty vehicles (Section A3.3), the four experimental investigations listed above and then draws conclusions and recommendations from these.

A3.2 Objective and starting point

The objective of this task was to assess the potential effectiveness of candidate loaded and unloaded tests procedures for heavy-duty vehicles.

The conclusions and recommendations from the Phase 2 report[1], which provide the reasons for this task, were:

Conclusion 1 PM is an issue in terms of air quality.
Conclusion 2 Smoke is a reasonable proxy for PM provided it is recognised that smoke is a concentration measurement whereas PM is accumulated mass flux.
Conclusion 3 Anticipated smoke levels for Euro IV light-duty vehicles are around 0.1 m^{-1}.
Conclusion 4 There is concern that for vehicles with electronic control systems (virtually all Euro III and IV specification vehicles) the unloaded test is further decoupled from being representative of on-the-road driving.
Conclusion 5 Cost effectiveness of in-service testing of PM emissions for HDVs is much greater than for LDVs.

Recommendation 6 Improvement on the 2.5/3.0 m^{-1} pass/fail limit be sought (these were the current limits at the time of writing the Phase 2 report).
Recommendation 8 The relationship between emissions over drive cycles on a dynamometer and FAS tests needs to be investigated to establish the relevance/potential of FAS testing to modern electronically controlled diesel vehicles.
Recommendation 10 A steering group should practically assess the viability of the test options.

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[1] Low Emission Diesel Research CP17/18/770 – Phase 2 Report, AEAT/ENV/R/0629 Issue 3, June 2001

A3.3 Feedback from steering group

A3.3.1 STEERING GROUP PRIORITISATION OF POSSIBLE TEST PROCEDURES

Recommendation 10 of the Phase 2 report for this project suggests a steering group should be convened to assess the practicality of the in-service test procedure options. The steering group comprised people from:

- DfT's Vehicle Standards and Engineering Division,
- DfT's Licensing, Roadworthiness and Insurance division,
- VOSA's Testing Standards Policy and Strategy group and
- AEA Technology's Engines and emissions team.

The three options considered were:

- on-the-road driving,
- loaded testing using a chassis dynamometer and
- unloaded testing.

The final report from Phase 2 gave a matrix of four possibilities[2], detailing positive and negative aspects of the options. It included using the vehicles' brakes to provide a load – an option that was discounted by the Low Emission Diesel Research Project's Board as not being practical.

The steering group used its knowledge and experience to narrow down the viable possibilities. The framework/structure used for making the prioritisation is shown in Figure A3.1.

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[2] Tables on pages 20 and 30 of Low Emission Diesel Research CP17/18/770 – Phase 2 Report, AEAT/ENV/R/0629 Issue 3, June 2001

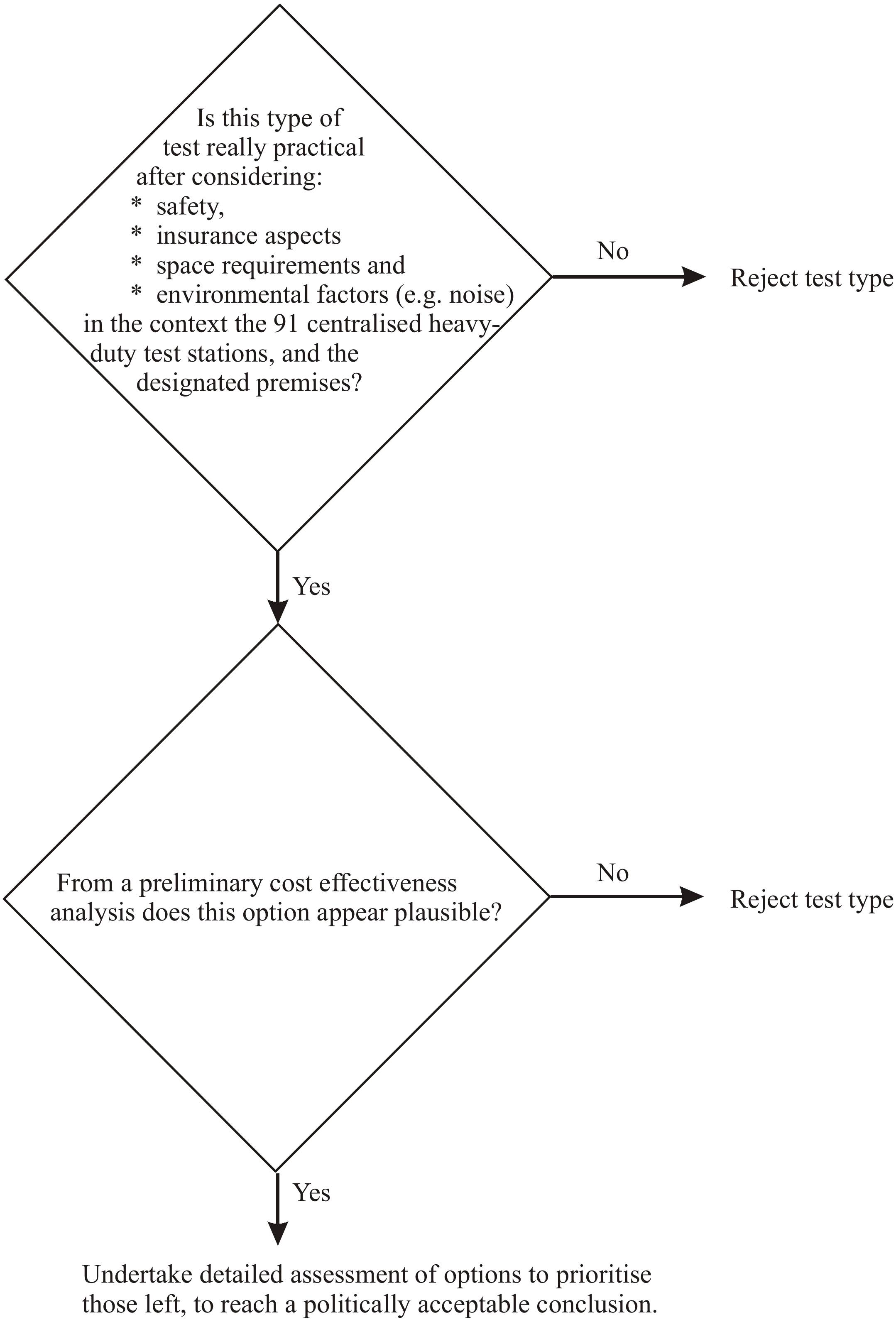

Figure A3.1 Framework for deciding on viability of various testing options

A3.3.1.1 On-the-road driving

Superficially, on-the-road driving appears to be technically the most attractive option in terms of potentially being the most representative of PM emissions from real vehicles on the roads. Further, some of the difficulties encountered when considering the testing of light-duty vehicles, principally caused by there being around 15,000 test centres in a wide variety of environments, are overcome by there being only 91 heavy-duty vehicle test stations. However the issues of:

- safety,
- insurance,
- space requirements and
- environmental considerations (including noise)

do remain and would need to be satisfactorily addressed.

In addition to these issues, for heavy-duty vehicles there is the factor that type approval is granted to engines, when tested on an engine dynamometer, rather than to vehicles. Consequently, two vehicles fitted with the same engine could perform quite differently over the same real-world vehicle drive cycle dependent on the gearboxes fitted to each. For light-duty vehicles each different vehicle would need to be type approved against the vehicle based standards.

For rigid vehicles, which account for around 50% of all heavy-duty vehicles, their PM and smoke emissions when driven on the road would be greatly influenced by the vehicle's load. It would not be practical to always test vehicles at a constant weight. For tractor units the uncoupling of the trailer, or its replacement with a standard trailer would overcome this problem.

The issues raised above are peculiar to heavy-duty vehicles, and further reduce the prospect of producing a fair, reproducible, improved test by replacing an unloaded test with an on-road drive cycle. The variability caused by changes in load are in addition to test variability caused by:

- variable weather conditions, principally wind strength, but also temperature, pressure and humidity,
- variable road surfaces,
- variable road conditions, e.g. dry/wet/icy.

On balance the steering group felt that despite the superficial attractiveness of on-the-road loaded testing, it would not be possible to devise a simple, equable test appropriate for all vehicle types that would cost effectively deliver significant additional emissions benefit, and be in keeping with the current type approval procedures.

A3.3.1.2 Dynamometer testing

Dynamometer testing overcomes many of the issues that contribute to the high variability anticipated for a roadworthiness emissions test based on an on-the-road driving procedure. It also overcomes many of the practical issues that makes on-the-road driving only marginal as a practical option (e.g. insurance and environmental issues and the space requirements). Whilst there remain significant safety challenges, it is believed that these could be managed such that the risk of injury to people, or damage to a vehicle or test facility, from a dynamometer test could be made acceptably low.

However, as was noted in the cost effectiveness analysis presented in the Phase 2 report, this is a more expensive option. Table A5.13 (in Appendix 5 of the Phase 2 report) predicts an **increased** cost per test of £18.38 and £17.68 for 2005 and 2015, respectively. Whilst these increases are only around three-quarters of those found for light-duty vehicles, it is, nevertheless, a significant additional cost. (The principal reason for the smaller increased cost is the smaller number of dynamometers that would be required, and the higher utilisation in terms of the average number of vehicles tested per dynamometer per year.) The Appendix also calculates that the "emissions saving potential", i.e. the maximum emissions savings that would occur if all excess emitters were detected and rectified, is diminishing as measured in ktonnes/year with more modern technology. This is principally a consequence of improved design leading to both lower emissions from new vehicles, lower "excess" emissions when faults occur and improved vehicle durability.

The primary technical reason for choosing loaded testing on a dynamometer, relative to unloaded testing, is the premise that the former will better correlate with on the road emissions. A reason cited for the continued, or even diverging, poor correlation between the PM emissions from unloaded tests and on-the-road driving is the introduction of electronic control units, breaking what was a mechanical link between the accelerator and the fuelling rack. However, alongside the engine control computer there has been a proliferation of other electronic systems, e.g. antilock-brake systems. Many modern vehicles on a single roll dynamometer immediately flag up the "unusual" axle rotation pattern that is occurring and often revert to a "limp-home" or another "safer" set of engine maps. Consequently, the author has serious concerns as to how much of an improved correlation would be afforded by a simple dynamometer, particularly for future technologies. As a result, it appears likely that the fraction of the "emissions savings potential" that would be delivered by dynamometer testing is likely to be less than that initially anticipated, unless more sophisticated, and hence expensive, dynamometers were to be used.

The conclusion is therefore: a preliminary cost effectiveness analysis of using dynamometers for an in-service IM test for heavy-duty vehicles indicates there would be insufficient emissions savings to outweigh the increase in test cost, and consequently this testing option is rejected.

A3.3.1.3 Unloaded testing

As a consequence of the considerations summarised in the preceding two sub-sections, the steering group's decision was that for heavy-duty vehicles, as for light-duty vehicles, AEA Technology should focus on developing an unloaded test.

Experimental investigations on light-duty vehicles, described in Annex 4, had researched two theories:

1. That the correlation between PM emissions over a loaded drive cycle and the peak smoke emissions during a FAS test is still poor for the latest technology light-duty vehicles when considering all different vehicle types.
2. That there is some correlation between PM emissions over a loaded drive cycle and the peak smoke emissions during a FAS test for light-duty vehicles for a single vehicle type as a function of the vehicle's state of repair/maintenance.

It was presumed that the findings from these investigations applied similarly to heavy-duty vehicles. Consequently, the objective of the research for this task was to examine the sensitivity of the FAS test result to various components of the FAS test procedure.

A3.4 The dependence of FAS test result on test procedure parmameters

Following the prioritisation of the options by the project's Steering Group, the fundamental test procedure looks likely to be similar to the current free acceleration test. Consequently, the experimental work investigations focussed on the issues below.

1. What are the smoke emissions from modern low-emission diesel vehicles?
2. How sensitive is the test result to various details of the procedure?
3. How sensitive is the answer obtained to various parameters controlled by the tester? and as a corollary to this, is there a demonstrable case for measuring, and possibly even controlling, further test parameters?
4. What is the likely effect of the agreed change in the pass/fail limits from 3.0 to 1.5 m^{-1} for HDVs?
5. What is the embryonic recommended pass/fail limit based on the limited quantity of practical testing available within this phase of the project?

A3.4.1 BASIC METHODOLOGY

The details of the experimental investigation were determined by the five questions posed above and the overall agreed size of the budget for this task.

A3.4.1.1 Vehicles studied

The range of heavy-duty vehicles to be studied encompassed rigids and tractor units for articulated vehicles – plus potentially PSVs. Engine sizes were selected to cover the range of those in the parc, i.e. 4 to 12 litres. The details of vehicles studied are given in Table A3.1.

It is notable that all the vehicles tested had potentiometers integral to their accelerator, i.e. depressing the accelerator sent electronic signals to the ECU rather than mechanically changing the position of the fuelling control rack.

Table A3.1 Details of the vehicles studied

Vehicle[3]	Vehicle type	Year of manufacture	Comments	Mileage	Engine
Vehicle 18	Small rigid	2003	Euro III spec	8,092 km	3.9 litre, 127 kW (170 hp)
Vehicle 19	Small rigid	2000	Euro III spec	70,940 km	4.25 litre, 110 kW (150 hp)
Vehicle 20	Large rigid	2003	Euro III spec	17,028 km	6.0 litre, 176 kW (235 hp)
Vehicle 21	Large rigid	2002	Euro III spec	223,550 km	6.37 litre, 170 kW (231 hp)
Vehicle 22	Rigid	2004	Euro III spec	286 km	9.0 litre 285 kW (380 hp), with manual gearbox
Vehicle 23	Tractor unit	2003	Euro III spec	69,370 km	12.0 litre 285 kW (380 hp), with manual gearbox
Vehicle 24	Tractor unit	2003	Euro III spec	84,710 km	12.0 litre 255 kW (340 hp), with semi-automatic gearbox
Vehicle 25	Tractor unit	late 2000	Euro III spec	339,170 km	12.0 litre, 309 kW (420 hp)
Vehicle 26	Tractor unit	2001	Euro III spec	150,025 km	12.6 litre, 322 kW (430 hp)
Vehicle 27	Tractor unit	late 2002	Euro III spec	178,891 km	12.6 litre, 315 kW (430 hp)

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[3] Vehicles used in this Phase 3 study are given a unique identifier, irrespective of the tasks(s) they were studied in. Hence Vehicles 1 and 2 in this table is the same vehicle as Vehicles 1 and 2 in Table A1.1 of Annex 1 etc.

A3.4.1.2 Parameters to be studied.

Five parameters were identified as very probably having a significant influence on the particulate/smoke emissions from vehicles during a free acceleration test. 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 oil or water temperatures);
- pre-conditioning the vehicle immediately prior to the test;

Some of these (accelerator pedal depression rate and extent, and engine temperature) had been shown to be important from a previous study[4]. However, the changes in diesel technology mean that this sensitivity needs to be reassessed for modern low emission diesels.

In more detail, the principal questions associated with each of the five parameters identified were formulated, together with an approach for their investigation. These were:

Rate of accelerator depression:

Answers sought: If the tester does not depress the accelerator fully within 1 second what effect does this have on the FAS reading obtained?

Approach adopted: Quantify the variations in smoke that occur for variations in the rate of accelerator depression.

Extent of accelerator depression:

Answers sought: If the tester does not fully depress the accelerator what effect does this have on the FAS reading obtained?

Approach adopted: Quantify the variations in smoke that occur for variations in the extent of accelerator depression using solid blocks to physically prevent the accelerator from being fully depressed.

Weather conditions:

Answers sought: Do variations in ambient conditions affect the FAS result obtained?
Do variations in ambient temperature affect the FAS result obtained?

Approach adopted: We have very little/no control over pressure and humidity.
Five vehicles both were tested both indoors and outside, giving measurements at two distinctly different temperatures.

Preconditioning of the vehicle:

Answers sought: Is the current preconditioning cycle specified in the UK testers' manual satisfactory?
For LDVs, how does the effectiveness of the preconditioning specified by the UK testers' manual compare with that recommended by the German research?

Approach adopted: For the majority of vehicles tested use the preconditioning specified in the UK testers' manual, then do FAS testing to see if there is further conditioning.
For two vehicles put them into a controlled "dirty" state and compare the FAS results from the 2 preconditioning methods.

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[4] "Diesel smoke test procedures and meter specification", report for DfT (DoT ref DPU/9/33/19) JOW Norris, Oct 1997

Engine temperature effects:

Answers sought:	Is the current direction specified in the UK testers' manual satisfactory for HGVs? Is there a period during the warming up of a vehicle when the indicated water temperature is significantly below the oil/engine temperature? If so does this affect the FAS result?
Approach adopted:	For a small number (2 or 3) of HGVs monitor oil & water temperature during warm up, taking FAS readings along the way.

A3.4.2 EXPERIMENTAL PROGRAMME

A3.4.2.1 Smokemeter

The preceding section described the parameters identified as very probably having a significant influence on the particulate/smoke emissions from vehicles during a FAS test, and the principal questions associated with these. A key measurement in the experimental programme is that of smoke opacity during the FAS test. VOSA requested a Crypton Technology "Dieseltune DX250" smoke meter be used. This is because this meter is fully compliant with the most recent VOSA diesel smokemeter specification, it has been certified against the UK reference meter and it is the meter that the centralised VOSA test stations currently use for roadworthiness emissions testing on heavy-duty vehicles.

A "portable" DX250 was kindly lent to AEA Technology by the manufacturers, Crypton Technology. This comprised both the smoke head and its associated control unit which are linked to a notebook PC. The PC ran the DX250 smokemeter program "UK MOT 2002". It is the combination of the hardware and this software that comprises the "certified smokemeter package". The PC logged data from the smoke meter's control unit at 25 Hz. It also provided the prompts for the tester, processed the smoke opacity using Bessel filter algorithms as specified in Directive 99/96/EC, and displayed the resulting smoke value (in units of m^{-1}). Additionally, it had the capability of saving the logged data on the PC's hard disc.

A3.4.2.2 Engine speed

A second important parameter in the measurement campaign is that of engine speed. Given the inaccessibility of many truck engines, tachometers that use sensors attached to the injector's fuel pipe or their electric wires (for electronic injectors), that were successfully used under the bonnet of light-duty vehicles, are not appropriate. Consideration was given to:

- using a stop watch and visual timing of when the vehicle's tachometer indicates the governed speed has been reached,
- using a measurement of exhaust gas velocity, or
- using a measurement of exhaust gas temperature.

It was appreciated that none of these options was ideal.

In addition to the loan of the smoke meter, Crypton Technology kindly lent us a tachometer, model CDSS3. This derives engine speed by monitoring the alternator ripple voltage across the battery. It has a signal output that can drive/be recorded by the DX250 Dieseltune smokemeter. In addition to displaying the engine speed, the controlling PC also logged it at 25 Hz. (The data from the CDSS3 was only updated once each engine cycle, i.e. at 600 rpm this would be 5 times a second. Hence the logged data contained several records at each engine speed.) These files were an important data base linking the response of the engine in terms of its speed to the smoke emitted during free acceleration tests.

A3.4.2.3 Accelerator position sensor

Questions posed in Section A3.4.1 were: What is the effect on the FAS measurement if the tester either depressed the accelerator slowly or incompletely? To quantify the accelerator pedal's movement an analogue output position transducer was connected to the accelerator pedal and anchored to some suitable static support within the vehicle cab. Calibration for each vehicle, indeed for each series of experiments, was achieved by noting the sensors output voltage at idle and full depression. These outputs were assigned to 0% and 100% depression, and, because of the linear response of the sensor, a linear mapping was used for intermediate values.

A3.4.2.4 Other sensors

In addition to the smokemeter, engine speed and accelerator pedal position the following parameters were also recorded:

• exhaust gas temperature,	continuously
• engine oil temperature,	continuously
• air temperature,	continuously
• barometric pressure,	for each set of measurements
• ambient temperature and humidity,	for each set of measurements.

The first three of these, plus the output from the accelerator position sensor, were recorded at 50 Hz using a data logger separate from that which recorded the smoke meter's output. Concequently, for each free acceleration test relevent data were recorded on two separate systems.

A3.4.2.5 Data analysis

Figure A3.2 shows the smoke opacity, engine speed and accelerator position profiles for a representative FAS test.

Smoke opacity

The conversion of the raw data, as illustrated in Figure A3.2, into the reported "peak smoke" value was undertaken by the UK MOT 2002 software associated with the DX250 smokemeter.

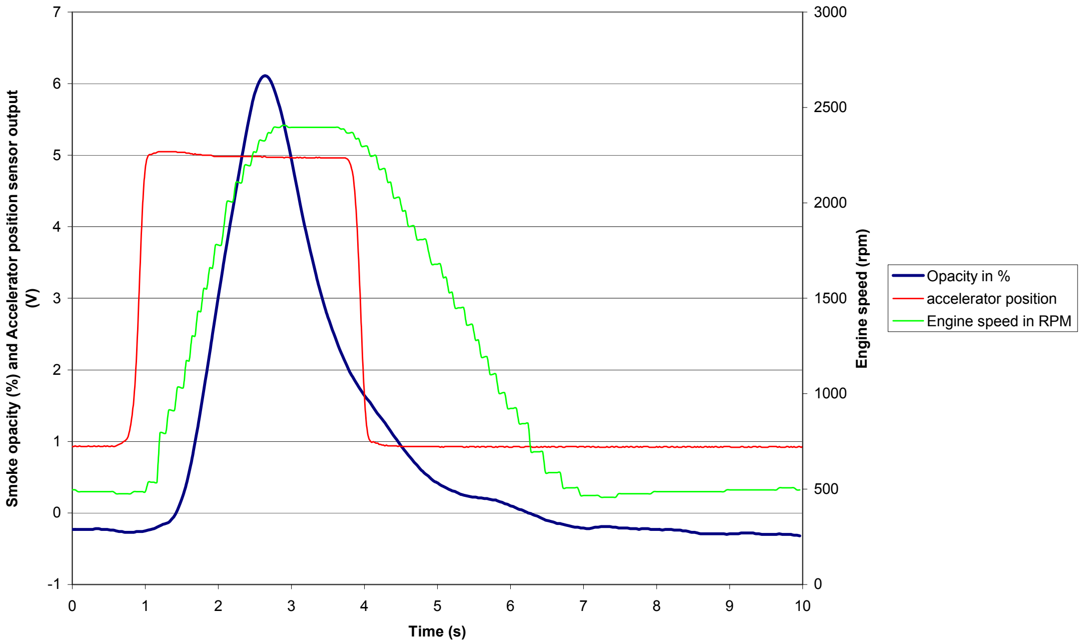

Figure A3.2 Typical smoke opacity, engine speed and accelerator position record

Engine speed

The requirement is to quantify the time taken by the engine to accelerate from low idle to its maximum (governor limited) upper speed. This should be achieved using a methodology that is insensitive to noise on the signal.

The engine speed at idle (n_{lo}) was calculated from the average of around 10 data records (i.e. 0.4 s) at the start and end of each FAS test. Similarly, the maximum engine speed, usually the governor limited speed (n_{hi}) was calculated from the average of around 25 – 50 data points (i.e. 1.0 to 2.0 s duration) within the plateau region. This eliminates the brief overspeed that occurs during the final part of the acceleration, and is more representative of the governed speed than simply taking the maximum value of the speed recorded in the data file.

The increase in engine speed during the FAS test is taken as $n_{hi} - n_{lo}$.

The algorithm used to compute the time for the engine to accelerate was taken as the interval between the engine speed increasing from 2.5% to 97.5% of the range above the low idle speed. Mathematically this can be expressed:

$$t_{accel} = t[n_{lo} + 97.5\%(n_{hi} - n_{lo})] - t[n_{lo} + 2.5\%(n_{hi} - n_{lo})].$$

The purpose of selecting thresholds just above the idle and just below the top speed is to project them out from the signal noise, making it unequivocal when the thresholds are reached.

Accelerator pedal position

The requirement is to quantify the time taken by the engine to depress the accelerator pedal in a manner that is insensitive to noise on the signal. Additionally, for partial depression of the pedal, it is to quantify the extent to which the pedal was depressed.

The initial (d_{lo}) and plateau (d_{hi}) pedal positions were calculated by taking mean values over a minimum of 10 data points. The final pedal position (following its release) was also calculated to confirm that the anchored part of the sensor had not moved during the acceleration, as would be evidenced by a shift in baseline.

Analysis of the data from a series of accelerations to investigate the effects of incomplete or slower accelerator pedal depression indicated:

- governor limited speeds were reached for incomplete, e.g. only 60%, accelerator pedal depression for many vehicles,
- when varying the rate of accelerator pedal depression, particularly for slower accelerations, the rate of depression sometimes decreased in the last quarter of the movement,
- for slower accelerations the engine reached its governed speed before the accelerator was fully depressed.

The consequence of the above is that the time taken to go from 2.5% to 97.5% of the depression range was not the optimum quantification of the accelerator depression time. Instead the time taken to go between 2.5% and 75% of the depression range was used and is that reported here. Mathematically, the pedal depression time, t_{dep}, can be expressed:

$$t_{dep} = t[d_{lo} + 75\%(d_{hi} - d_{lo})] - t[d_{lo} + 2.5\%(d_{hi} - d_{lo})]$$

where:

$$d_{lo} = [d_{lo}(\text{initially}) + d_{lo}(\text{finally})]/2.$$

A3.5 Results from FAS tests

A3.5.1 HEAVY-DUTY VEHICLES

A3.5.1.1 Rate of accelerator pedal depression

Varying the time taken to fully depress the accelerator would be expected to vary the time it takes for the engine to accelerate up to it governor limited speed, and consequently the smoke produced by the engine. Figure A3.3 and A3.4 show these two effects for nine of the heavy duty vehicles tested. (No equivalent data were collected for Vehicle 21 because its emissions were too low for the collection of meaningful data and on many free accelerations the smoke meter was not triggered to record data, see Figure A3.10).

Observations from the data are:

- When depressing the accelerator pedal by hand, complete depression typically took between 0.15 and 0.20 seconds. This was believed to represent "operation of the accelerator control quickly but not violently", as required in the MOT testers' manuals.
- The form of a typical graph shows that there is a depression speed above which, i.e. for a more rapid depression, the ECU takes control and limits the rate at which the fuelling is increased. This, in turn, limits the acceleration of the engine and the smoke emitted.
- Values for this threshold depression speed times are:

Vehicle	Time above which smoke values decrease significantly	Time above which engine acceleration time increases significantly
Vehicle 18	0.7 s	2.5 s
Vehicle 19	smoke values too low to give a meaningful threshold	4 s
Vehicle 20	0.6 s	> 2.5 s
Vehicle 22	3.0 s	4 s
Vehicle 23	2.6 s	2.8 s
Vehicle 24	3.0 s	3.2 s
Vehicle 25	1.5 s	1.5 s
Vehicle 26	1.5 s	1.5 s
Vehicle 27	1.6 s	1.4 s

- These thresholds are much longer that the standard time testers take for complete depression.

The conclusion from these observations is that for the pedal depression time used for correctly executed FAS tests extending to considerably longer times, the engine's ECU controls the rate of engine acceleration. Hence variability due to tester's style is virtually removed. For two vehicles (22% of sample) there was a significant reduction in FAS test result as the depression time increased from 0.2s to 1.5s of 80% ± 30% and 50% ± 10%. This is in marked contrast to a conclusion reached from studying vehicles with mechanical fuelling systems which found that changing the rate of accelerator depression from 0.7s to 1.5s led to variations of up to 500% in FAS result[5].

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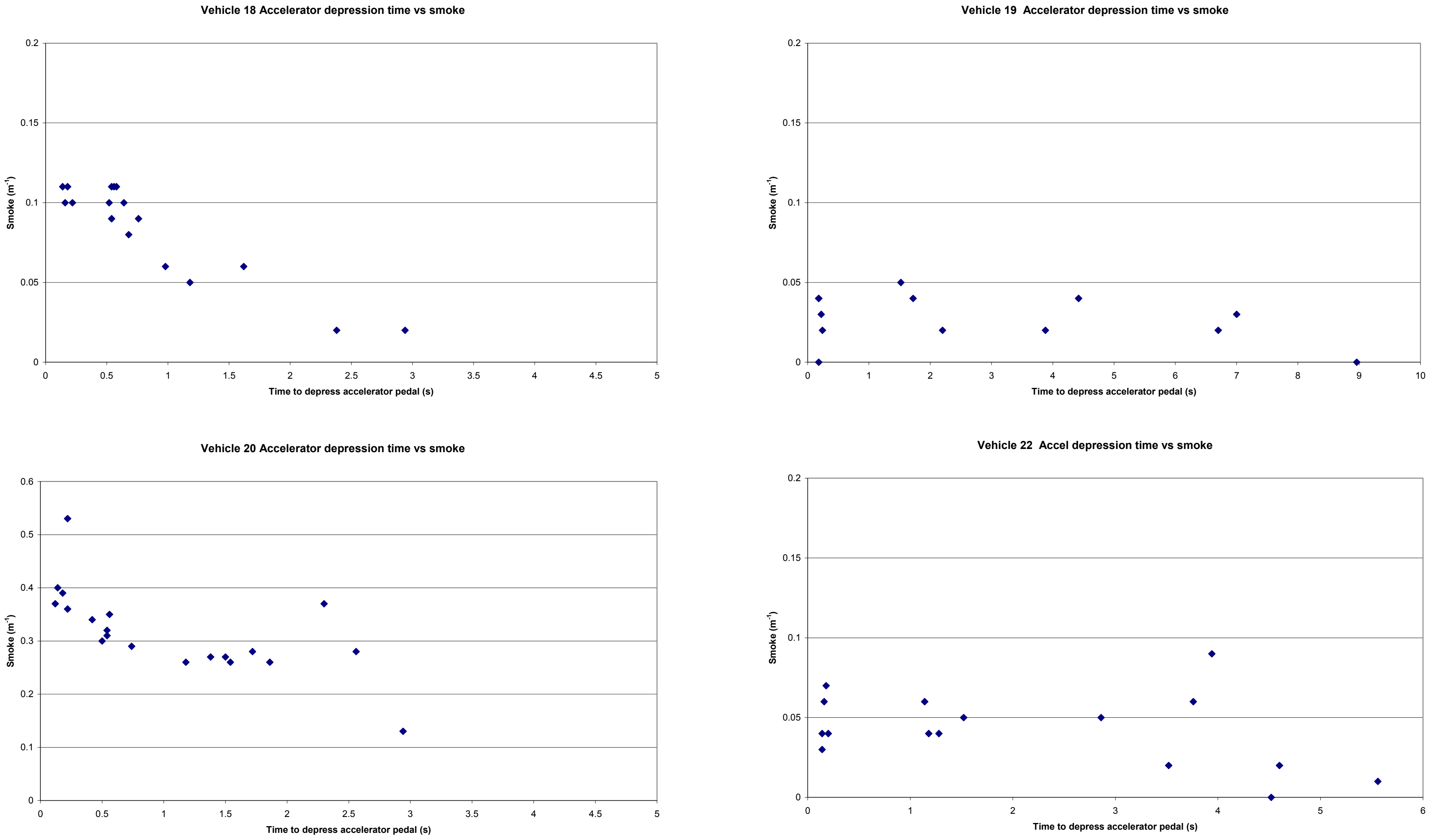
[5] Second point in Section 8.3.1, "Diesel smoke test procedures and meter specification", report for DfT (DoT ref DPU/9/33/19) JOW Norris, Oct 1997.



Vehicle 18 Accelerator depression time vs smoke

Vehicle 19 Accelerator depression time vs smoke

Vehicle 20 Accelerator depression time vs smoke

Vehicle 22 Accel depression time vs smoke

Figure A3.3 Effect of accelerator depression time on free acceleration smoke result (part 1)

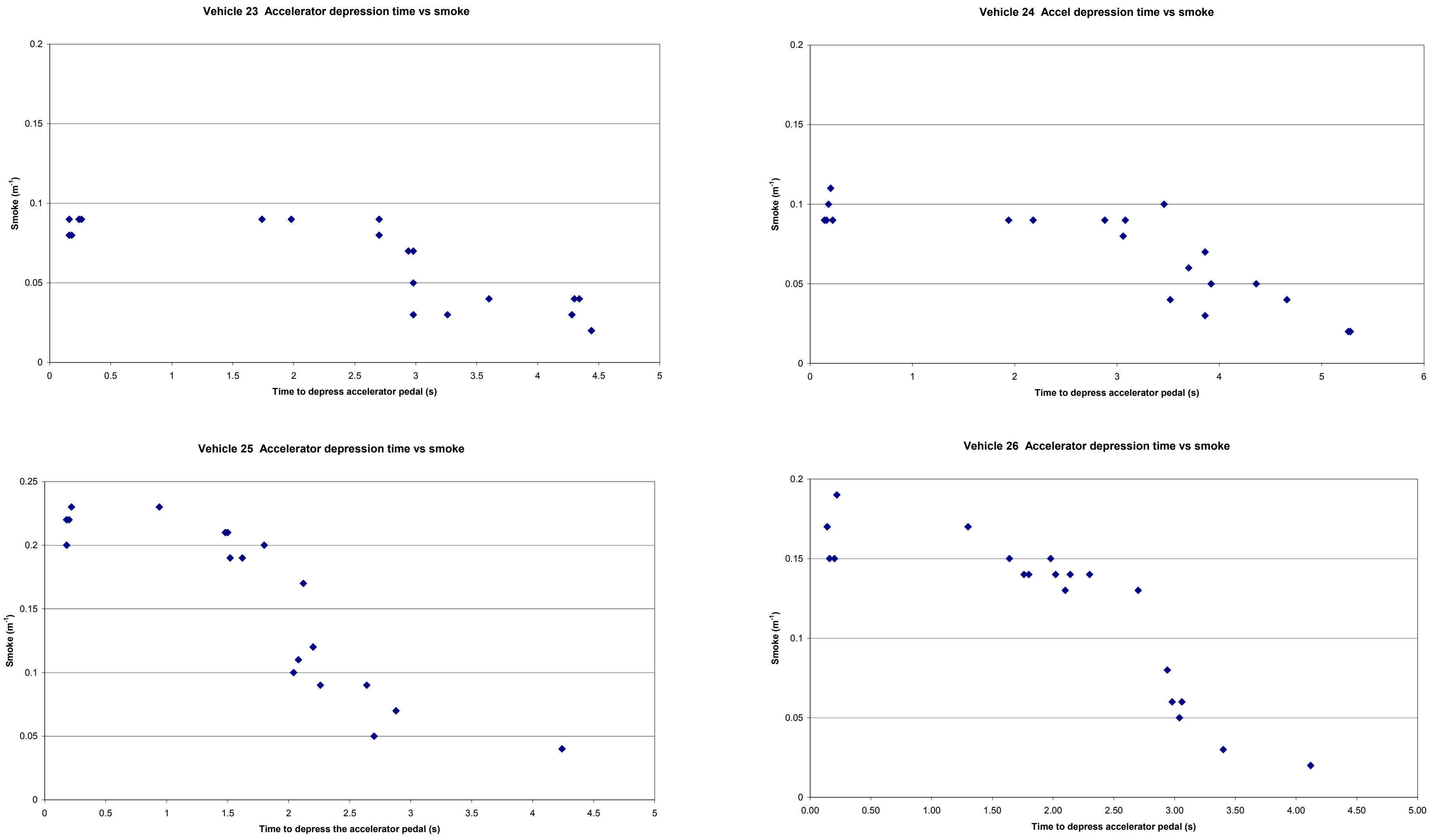


Figure A3.3 Part 2

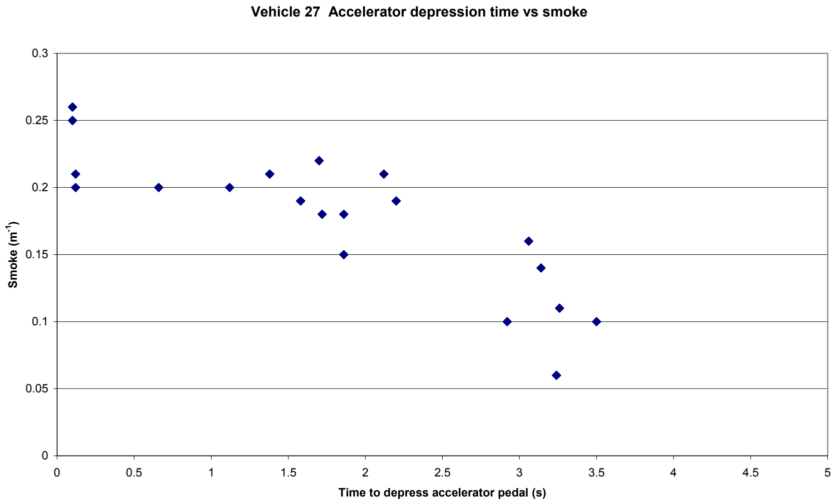


Figure A3.3 Part 3

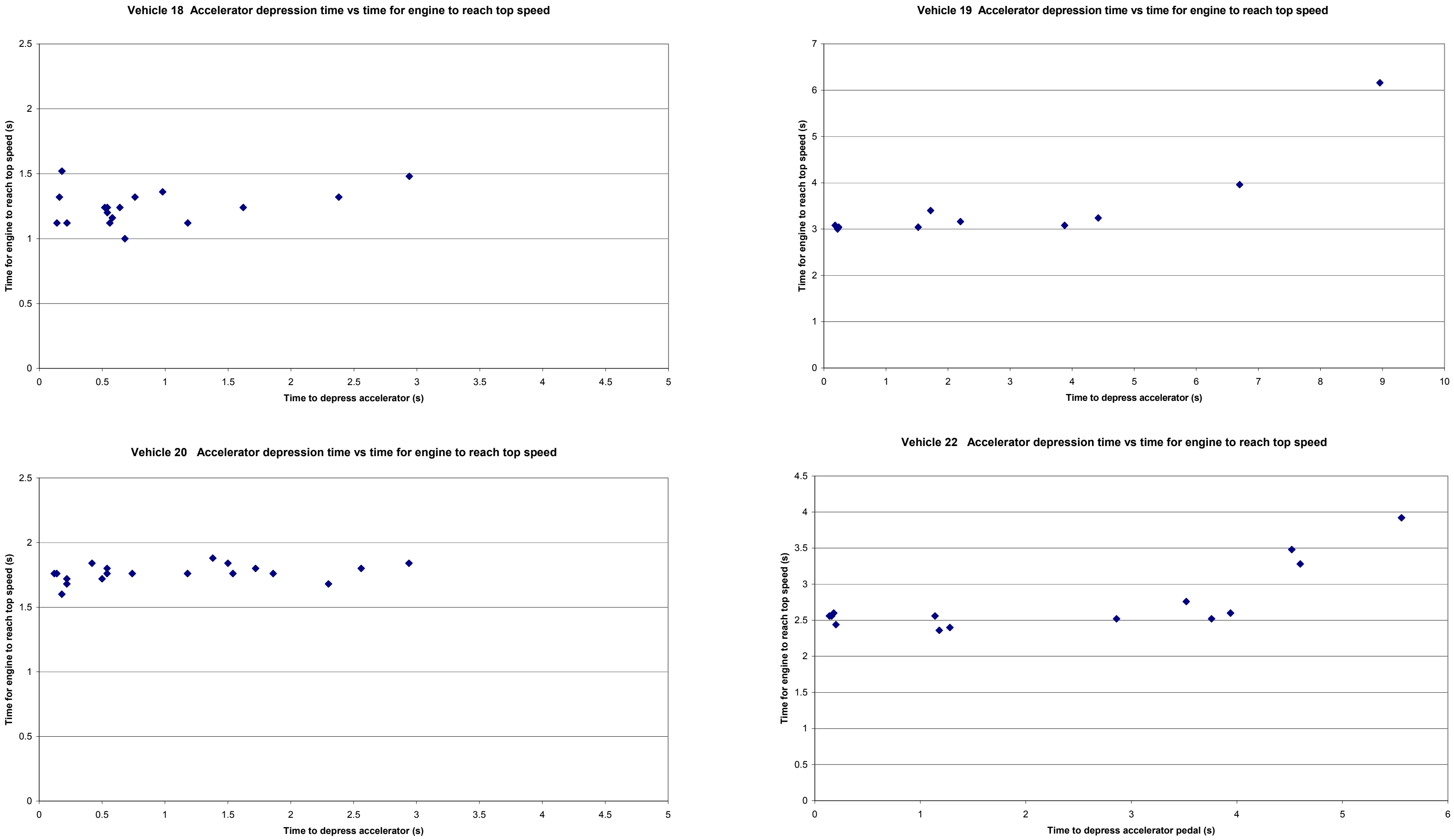
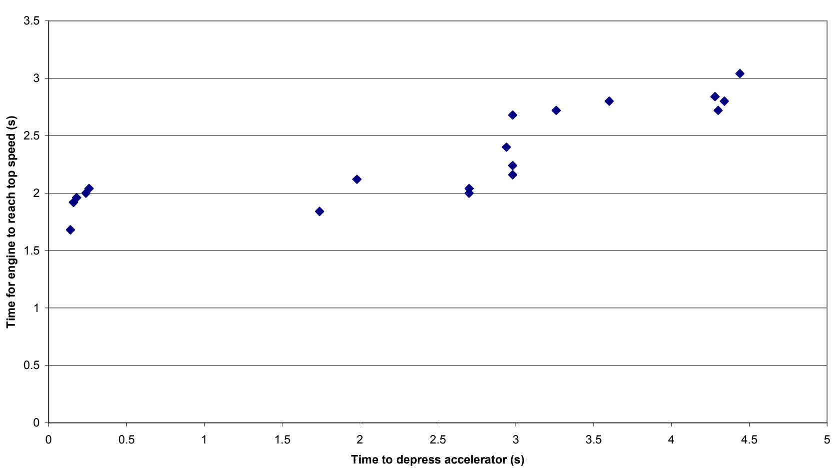
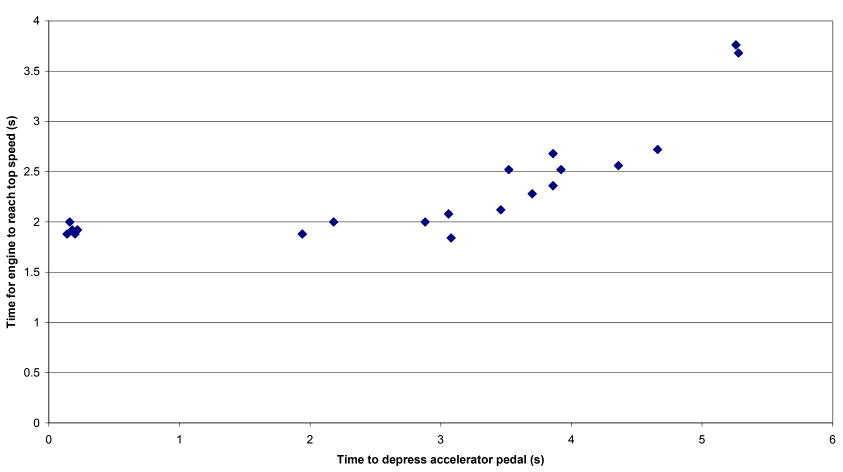
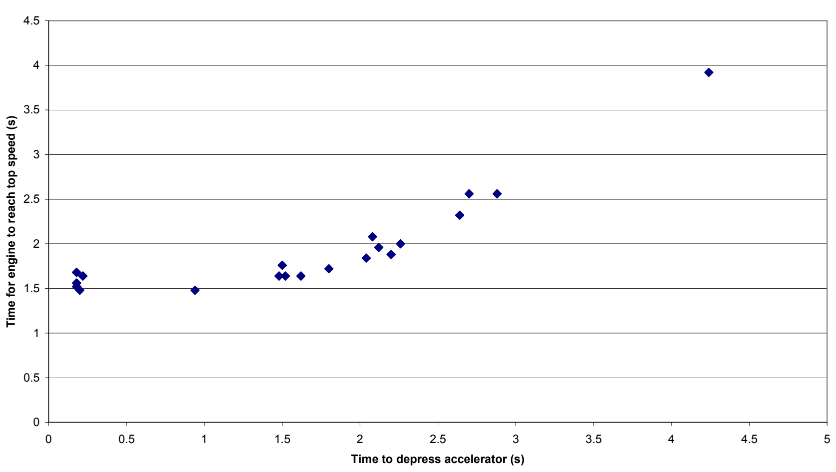


Figure A3.4 Effect of accelerator depression time on time taken by engine to reach top speed (part 1)


Vehicle 23 Accelerator depression time vs time for engine to reach top speed


Vehicle 24 Accelerator depression time vs time for engine to reach top speed


Vehicle 25 Accelerator depression time vs time for engine to reach top speed

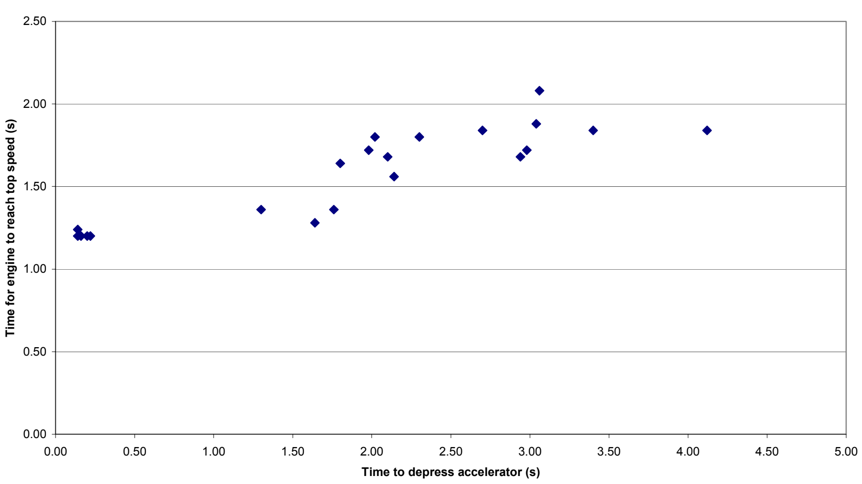

Vehicle 26 Accelerator depression time vs time for engine to reach top speed

Figure A3.4 Part 2

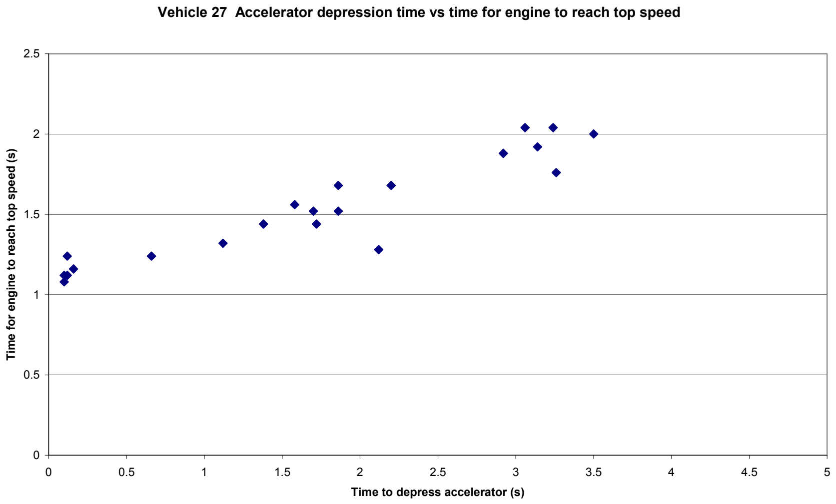


Figure A3.4 Part 3

A3.5.1.2 Extent of accelerator pedal depression

Incomplete depression of the accelerator might be expected to vary the time it takes for the engine to accelerate up to it governor limited speed, and consequently the smoke produced by the engine. In addition, for the smaller amounts of pedal movement the engine may no longer reach its governed speed. Practically this was investigated by using blocks to physically restrict distance the accelerator could be depressed. Depression to the revised limit occurred rapidly, i.e. in 0.15 to 0.2 s.

Figure A3.5, A3.6 and A3.7 show the smoke produced, the engine acceleration time and the engine’s plateau speed as the extent of the accelerator pedal depression was varied for eight of the heavy duty vehicles tested. (No equivalent data were collected for Vehicles 21 and 22 because their emissions were too low for the collection of meaningful data and on many free accelerations the smoke meter did not trigger to record data).

Observations from the data are:

- As the extent of accelerator pedal depression reduces from 100% the time taken for the engine to reach its maximum speed, the density of the smoke produced and the maximum engine speed reached remain constant until further reductions in the extent of depression cause deviations from their plateau values.
- The value of the % depression required before deviations occur from the plateau values are tabulated below.

Vehicle	Threshold depression extent below which smoke values decrease significantly	Threshold depression extent below which engine acceleration time increases significantly	Threshold depression extent below which engine top speeds decrease significantly
Vehicle 18	<40%	<40%	35%
Vehicle 19	50% though poorly defined as smoke values so low	<40%	50%
Vehicle 20	<50%	no threshold observed down to 30%	70%
Vehicle 23	60%	55%	60%
Vehicle 24	55%	55%	55%
Vehicle 25	65%	65%	60%
Vehicle 26	60%	50%	47%
Vehicle 27	60%	55%	45%

- These thresholds are much less than 100%. Hence a genuine mistake by a tester that led to him only depressing the pedal to, for example, 75% of its full extent would not affect the FAS test result.

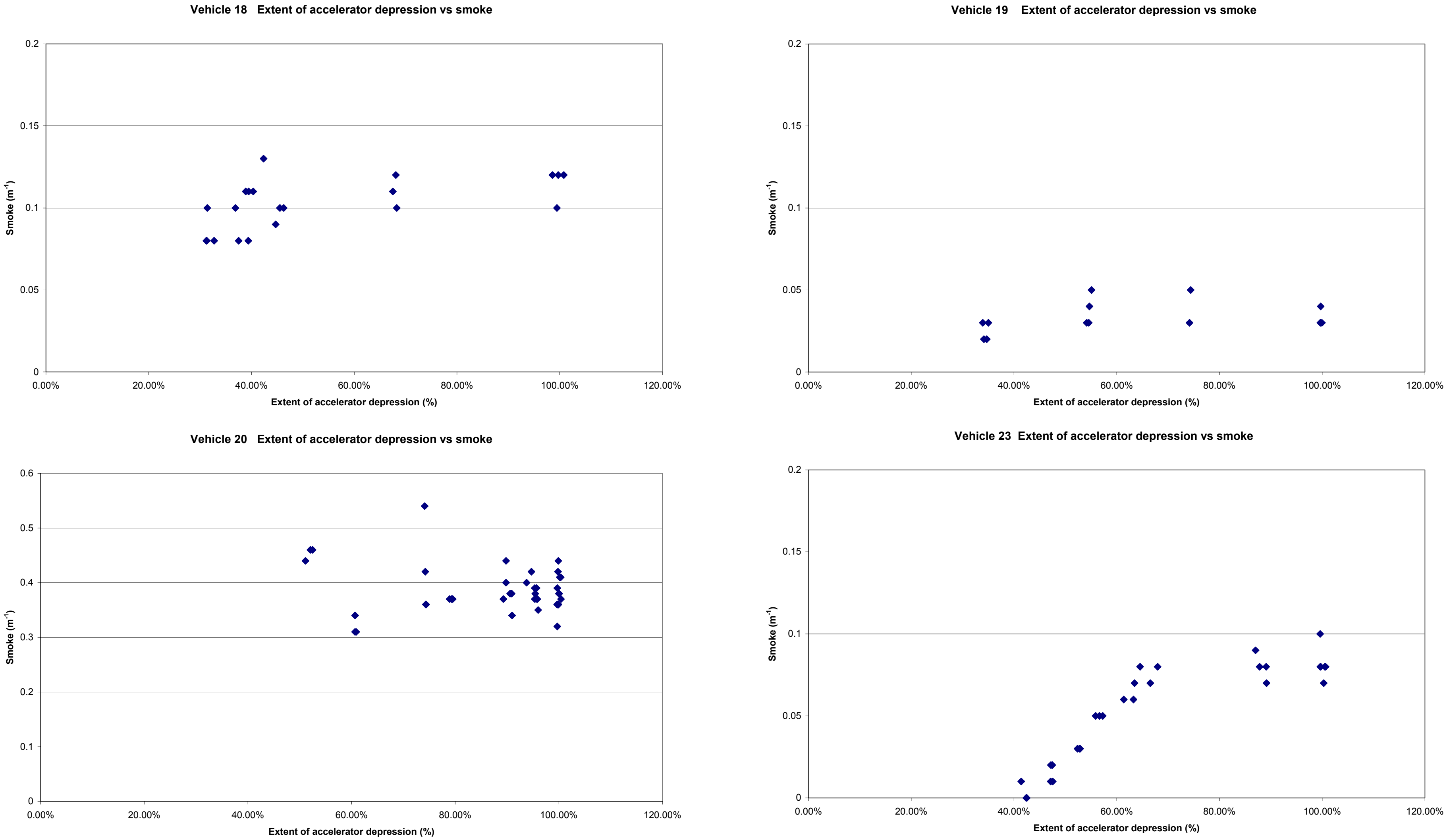


Figure A3.5 Effect of accelerator depression extent on free acceleration smoke result (part 1)

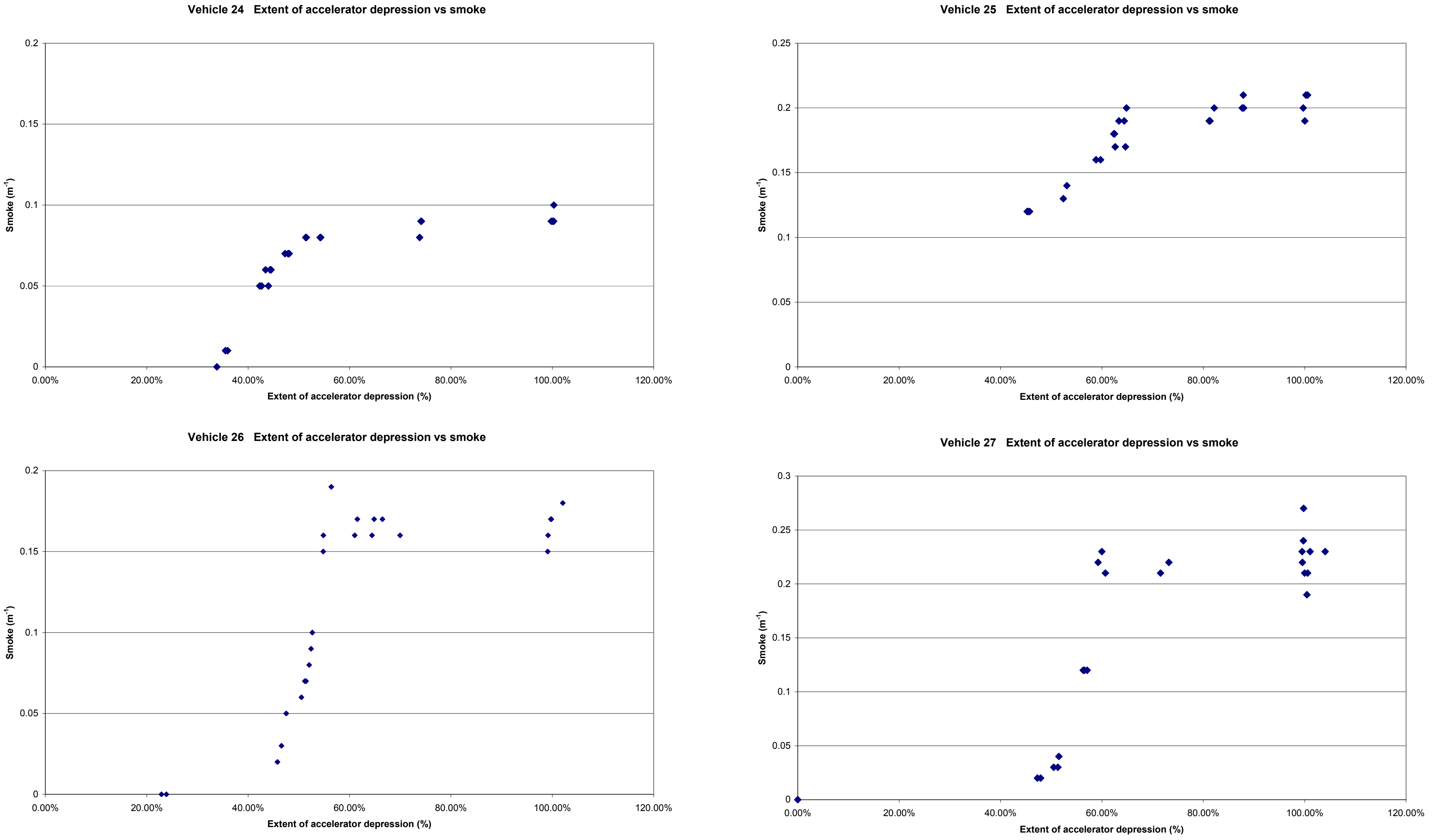


Figure A3.5 Part 2

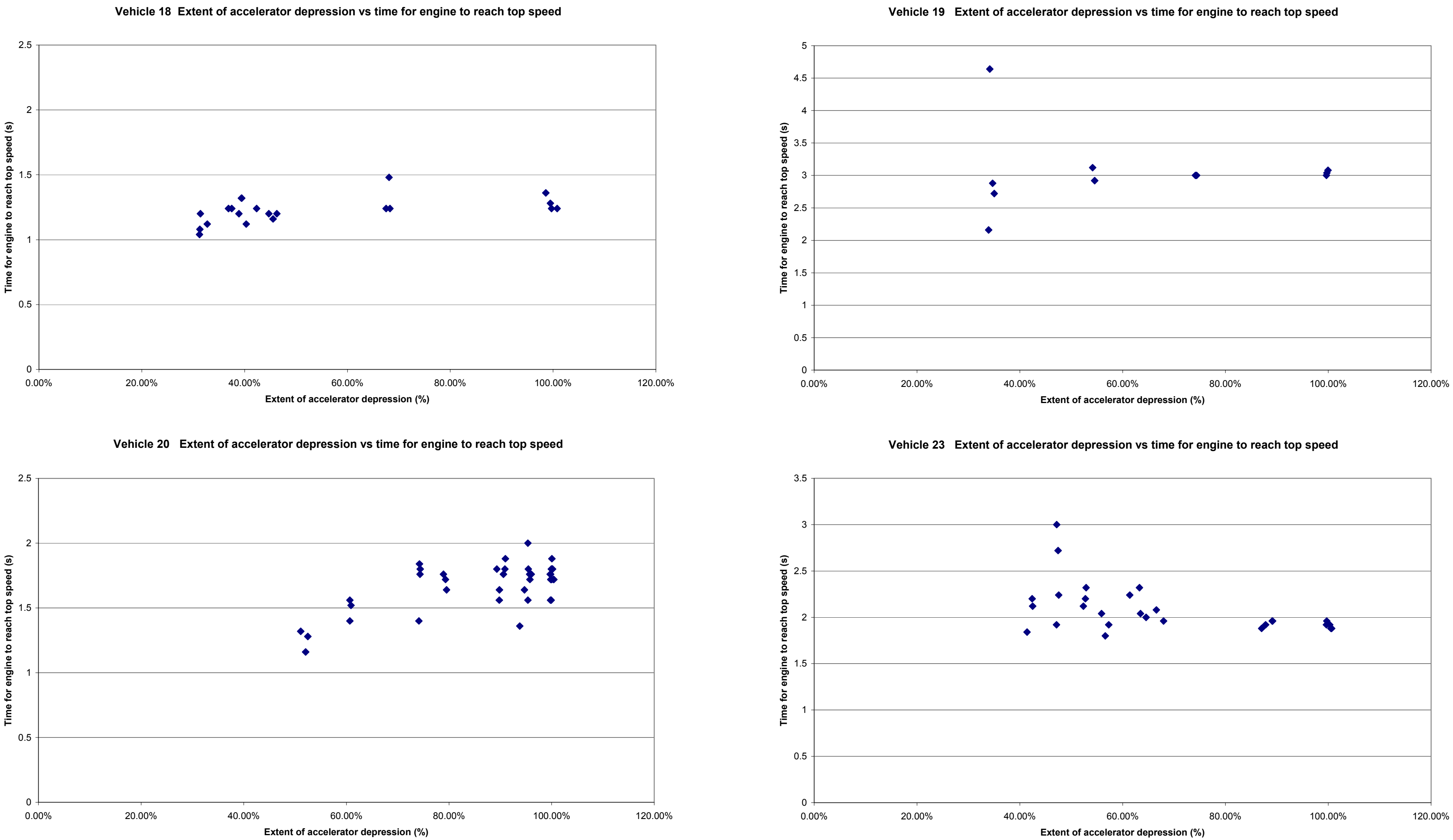
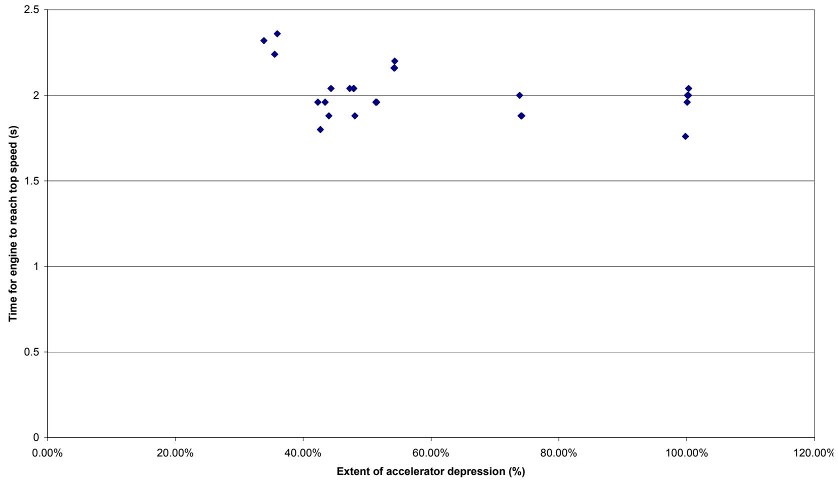
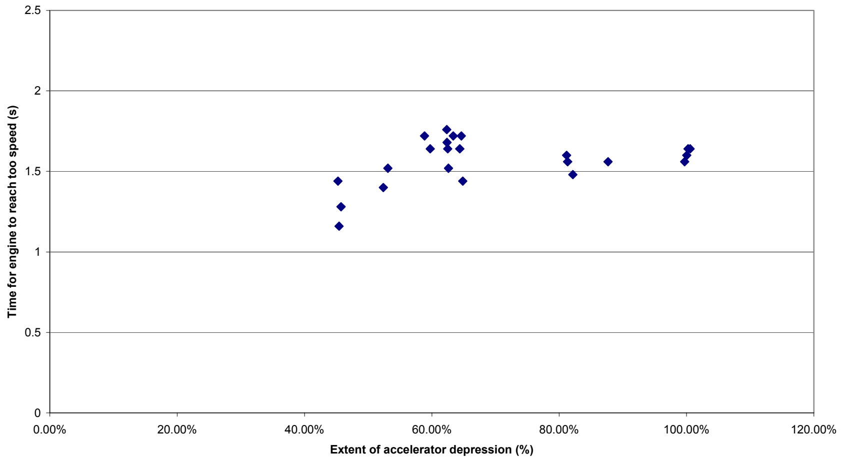


Figure A3.6 Effect of accelerator depression extent on time taken by engine to reach top speed (part 1)

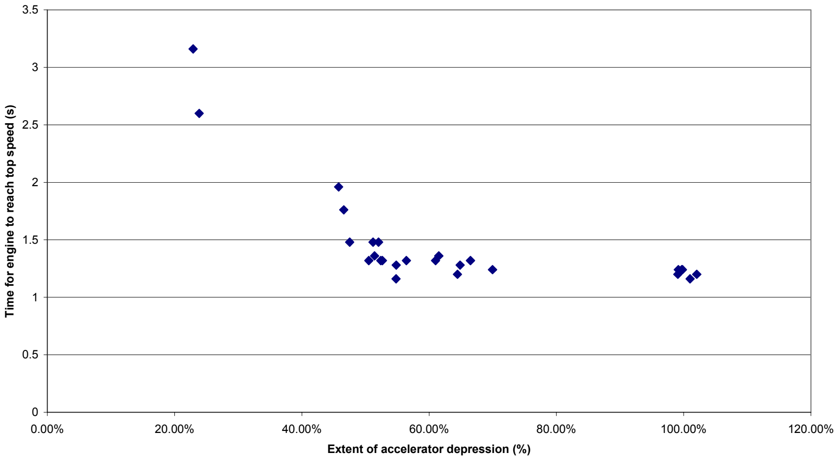
Vehicle 24 Extent of accelerator depressions vs time for engine to reach top speed



Vehicle 25 Extent of accelerator depression vs time for engine to reach top speed



Vehicle 26 Extent of accelerator depression vs time for engine to reach top speed



Vehicle 27 Extent of accelerator depression vs time for engine to reach top speed

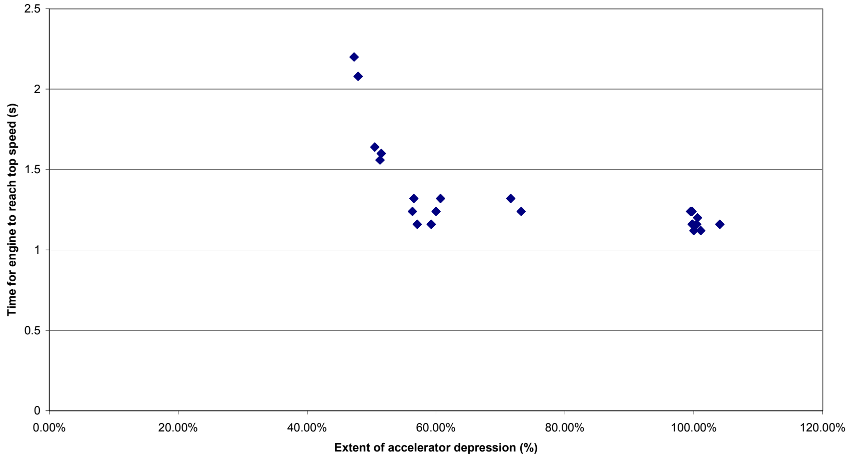


Figure A3.6 (Part 2)

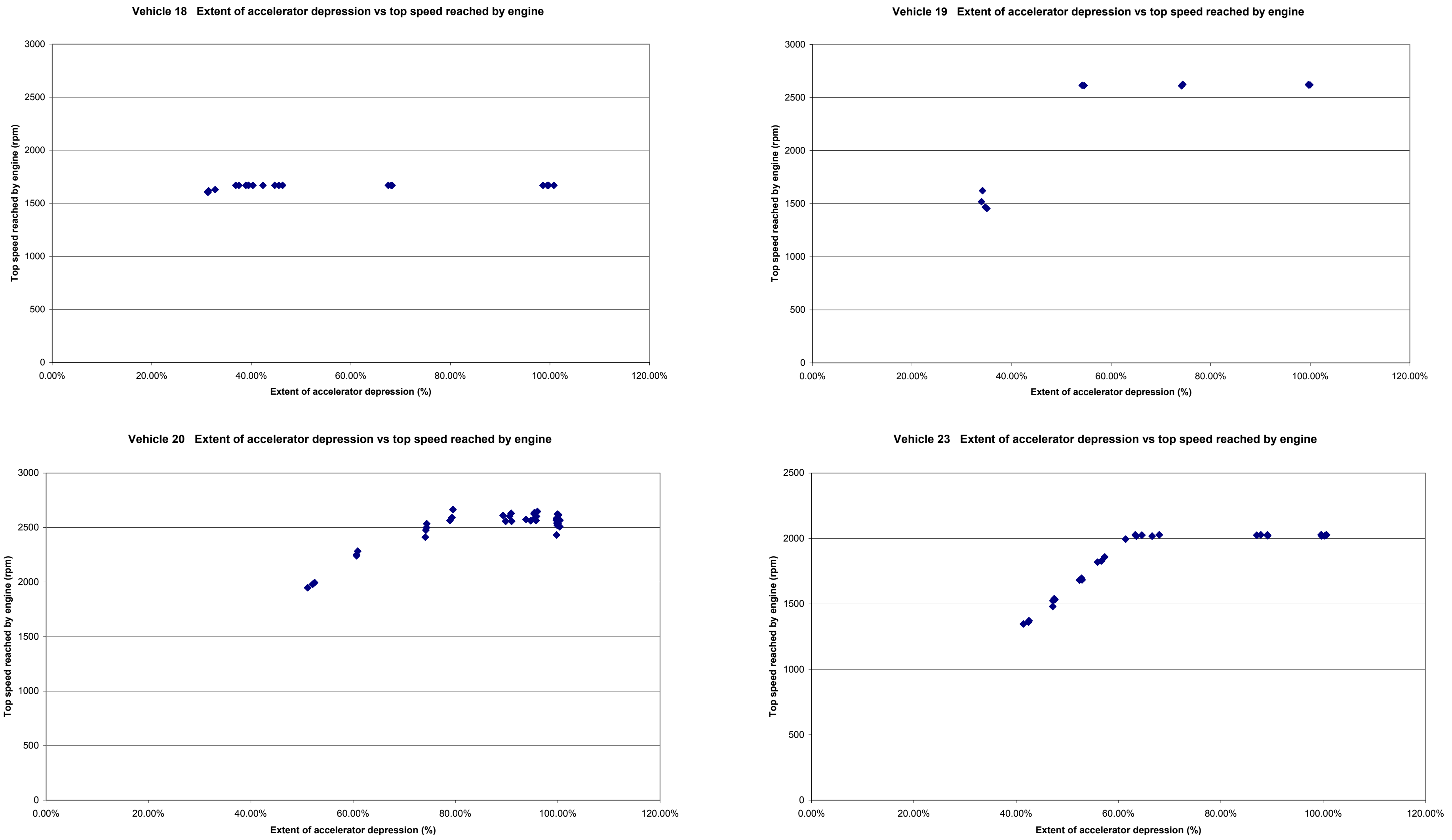


Figure A3.7 Effect of accelerator depression extent on top speed reached by engine

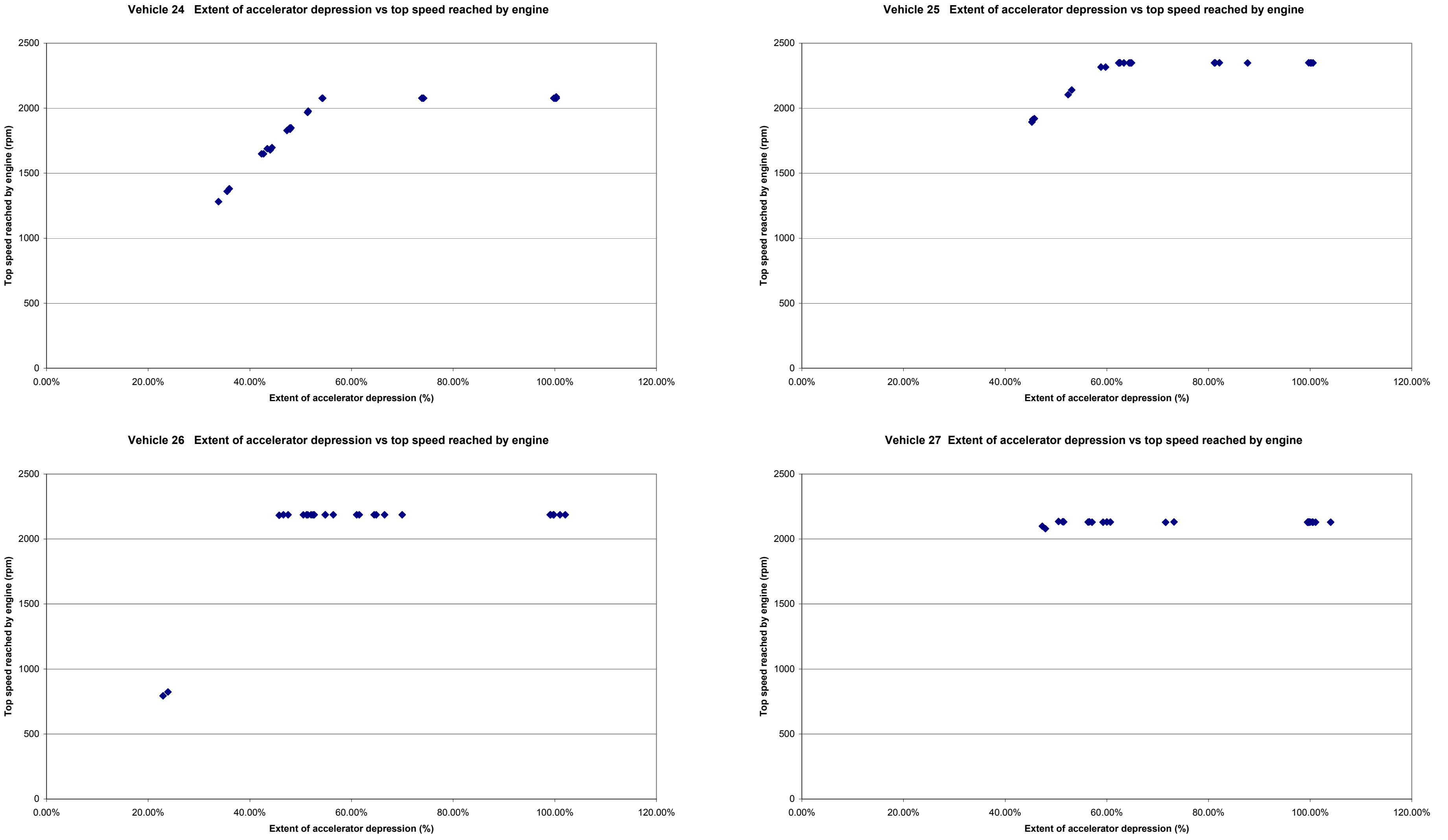


Figure A3.7 Part 2

A3.5.1.3 Effects of ambient temperature

The result of a FAS test might be influenced by ambient conditions (temperature, pressure or humidity). However, it was appreciated that we had no ability to significantly influence pressure or humidity. For 3 of the ten heavy-duty vehicles the effect of ambient temperature was studied by taking measurements within a heated test building, moving the vehicle outside with all the test equipment and retesting. The move typically took 15 – 30 minutes during the majority of which the vehicles engine was turned off.

Figure A3.8 shows the smoke values from successive free accelerations either side of the move. Visually the change in ambient temperature appears to have had no marked effect on smoke emissions. A more quantitative analysis is summarised in Table A3.2 which lists the means and their standard deviations of the peaks for each ambient temperature, omitting those highlighted with a "*" in Figure A3.8[6]. These data indicate "no significant difference" between the mean smoke values for the two ambient temperatures.

Table A3.2 Effect of changing ambient temperature

	Warm ambient test		**Cold ambient test**	
Vehicle	FAS test result (m^{-1})	Temperature (Humidity)	FAS test result (m^{-1})	Temperature (Humidity)
Vehicle 18	0.100 ± 0.006	21.1°C (33%)	0.092 ± 0.012	9.2°C (68%)
Vehicle 20	0.388 ± 0.020	26.4°C (35%)	0.360 ± 0.023	15.2°C (55%)
Vehicle 26	0.171 ± 0.011	29.2°C (30%)	0.165 ± 0.010	12.8°C (82%)

However, although the small differences are within the standard deviation of the data, the following points are noted:

- for all three vehicles the mean smoke values for cold ambient temperatures is a little **smaller** than for warm,
- the change is in the region 3.5 – 8.0 %,
- the changes in air density between the two conditions (detailed in Table A3.2 on a run by run basis) are in the range 3.9 – 5.7 %.

Consequently, the errors in the measurement of smoke density limit the size of an ambient temperature effect to being less that 5% per 10 degrees. But there are scientific grounds for anticipating a change of around 3.7% per 10 degrees, or 7.5% for a testing range of 15°C ± 20°, i.e. between -5°C and 35°C. This is probably too small to be significant. However, if subsequent improvements in accuracy merit, it would be relatively simple to incorporate appropriate compensation into a smokemeter. This would require an additional thermocouple to measure the ambient temperature and the application of a simple correction algorithm.

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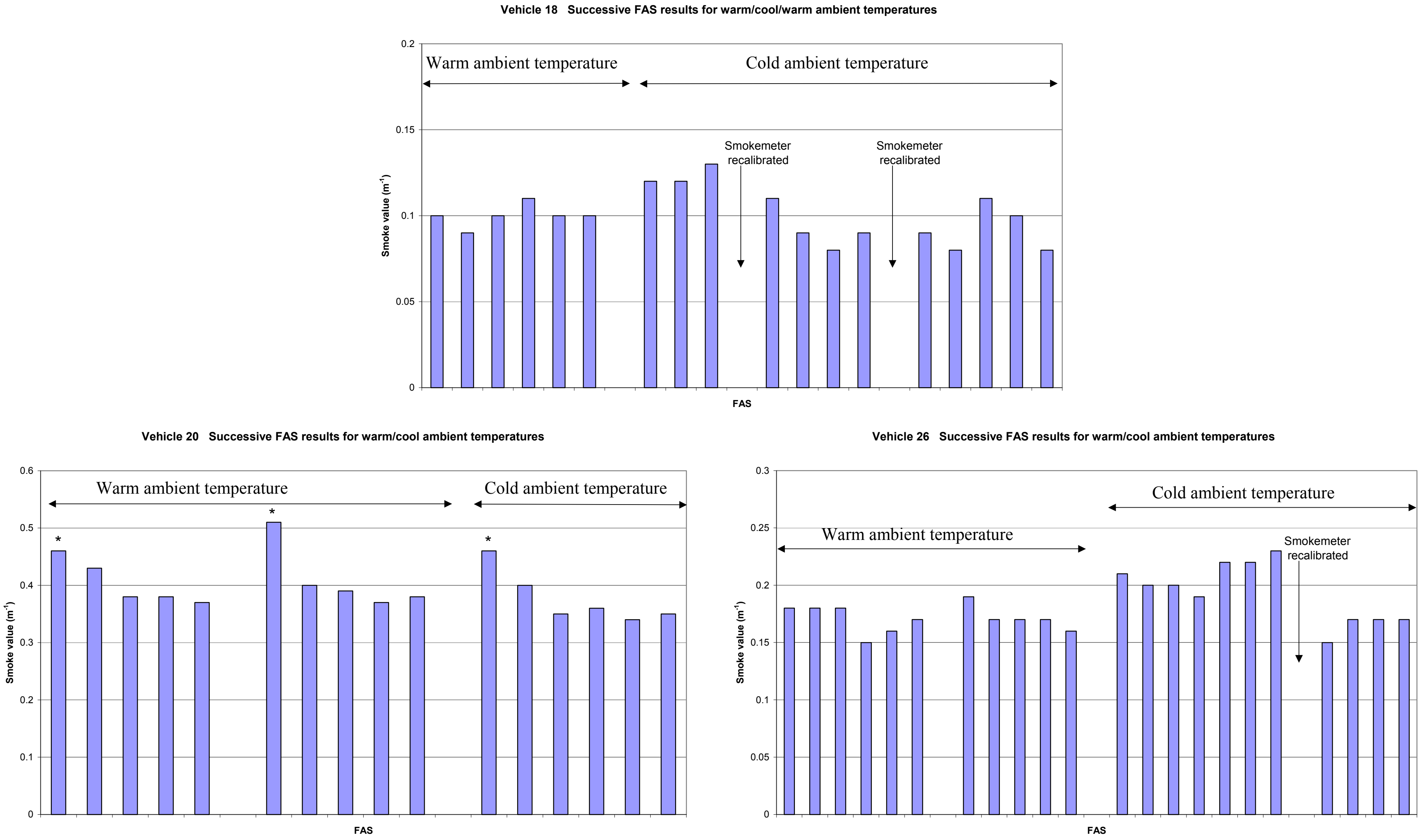
[6] Peaks were rejected if they appeared to be atypical, either being anomalously large due to preconditioning effects, see Section 4.1.5, or because of meter drift.



Vehicle 18 Successive FAS results for warm/cool/warm ambient temperatures

Vehicle 20 Successive FAS results for warm/cool ambient temperatures

Vehicle 26 Successive FAS results for warm/cool ambient temperatures

Figure A3.8 Smoke values from successive FAS tests for vehicles in warm/cold ambient environments

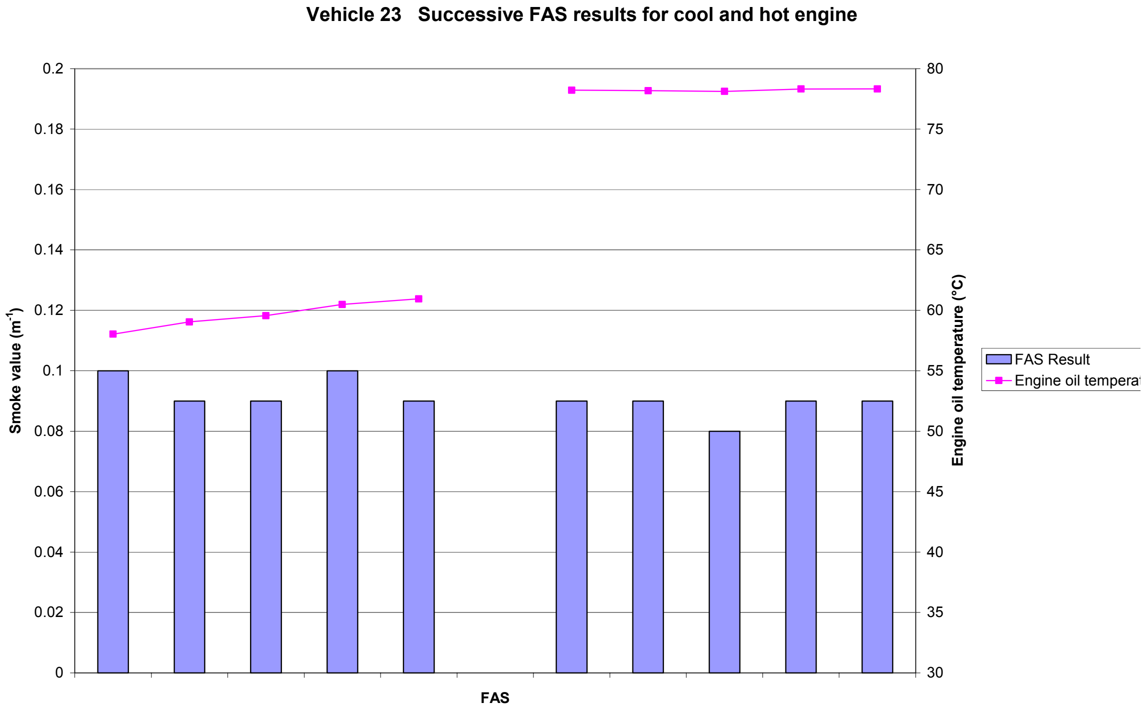
A3.5.1.4 The effect of engine temperature

The investigation 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 this effect proved the most difficult to study within the constraints of the current project. The vehicles studied on the Harwell site were not suitable because by the time they had been driven the twenty plus miles from the owners premises they were thoroughly warmed up. Of the other seven vehicles, three had smoke levels too low to give any meaningful measurements from this effect. The ideal study involves recording the engine's oil temperature, for example using a thermocouple in the engines sump introduced through the oil dipstick access tube. For two further vehicles the oil dipstick was inaccessible, it being under the driver's cab. It was found that attaching a thermocouple to the underside of the sump, even when covered with thermal insulation, gave poor measurements of the engine's oil temperature. Figure A3.9 shows data taken from the remaining two vehicles (both 12 litre tractor units) as they warmed up. For all the FAS measurements shown the engine temperature indicated in the driver's cab was in the "normal" region. It is emphasised that this is a very limited amount of data, and it may be unrepresentative. Given this caveat the data indicates as follows.

- The normal operating temperature of the oil in the sump, under idle conditions, is around 76 – 79 °C.
- FAS measurements made when the engine oil was around 61 – 68 °C are statistically indistinguishable from those at the normal operating temperature.
- FAS tests done when the engine oil was around 58 – 61 °C gave results just above those for the normal operating temperature (0.094 ± 0.005 m^{-1} relative to 0.088 ± 0.004 m^{-1}).
- FAS measurements made when the engine oil was around 51 – 54 °C (around 22 – 28 °C below the normal operating temperature) are around 33% higher (0.130 ± 0.020 m^{-1} relative to 0.092 ± 0.008 m^{-1}).

Consequently, from this limited data it appears that for engine oil temperatures up to 18 degrees below the normal operating temperature FAS results are unaffected.



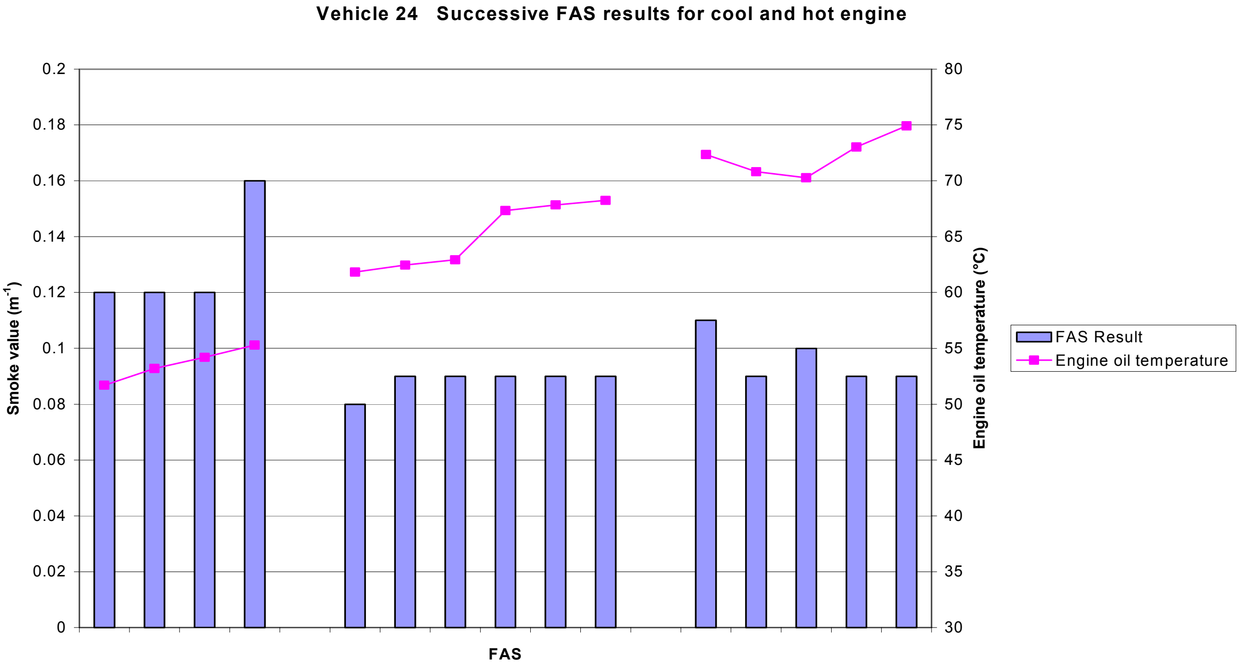


Figure A3.9 The effect of engine oil temperature on FAS test result

A3.5.1.5 The influence of vehicle preconditioning

The principal question researched in this portion of the investigation was: Is the current preconditioning cycle specified in the UK testers' manual satisfactory? Figure A3.10 shows the first group of FAS test results obtained 6 of the 10 vehicles, with Figure A3.8 and Figure A3.9 showing the first group for the remaining four vehicles (either in the context of varying ambient or the engine's oil temperature). Each set of data was recorded following the standard preconditioning of a 30 second purge at the governor limited speed.

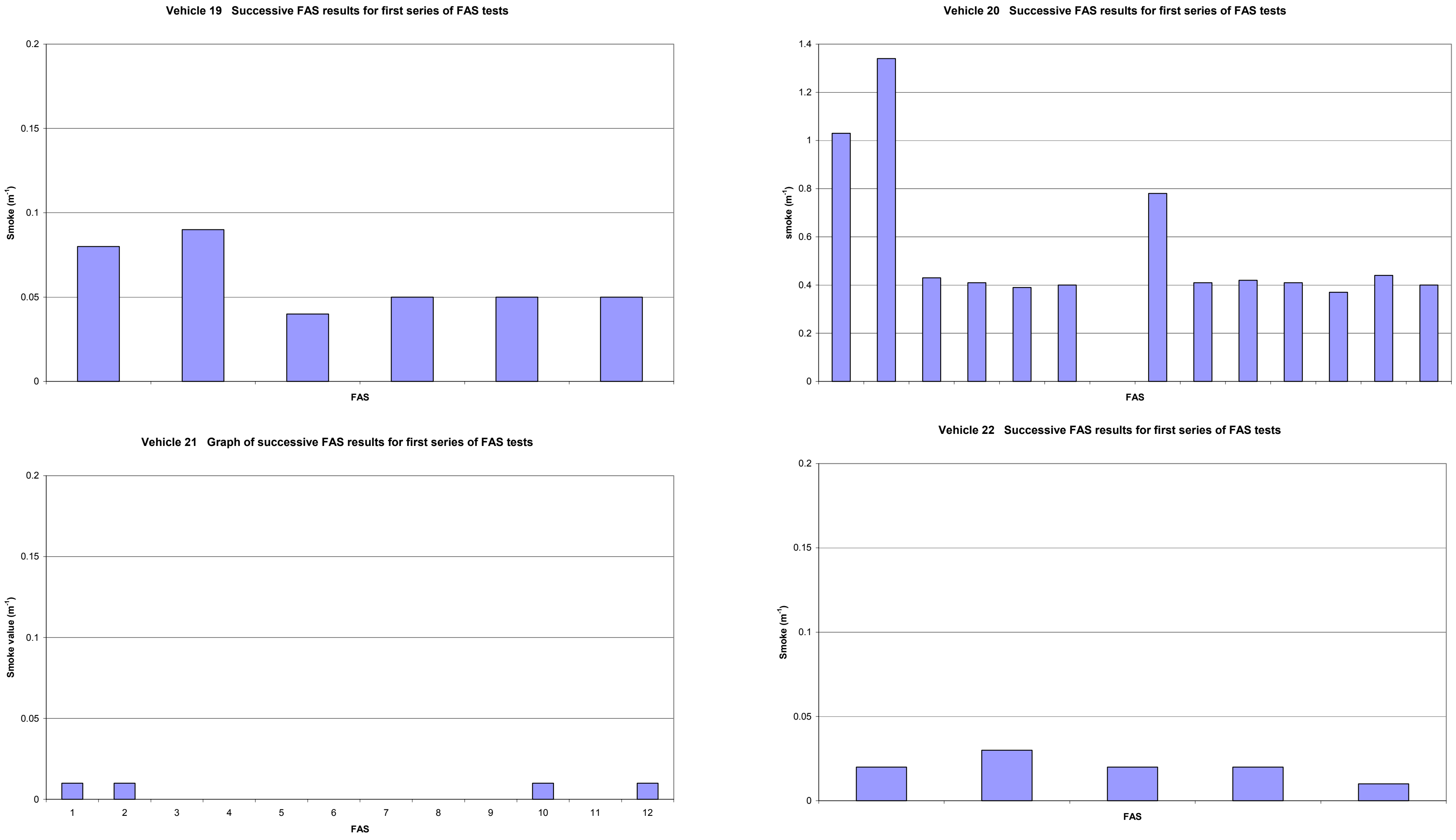


Figure A3.10 The smoke density from the first series of FAS tests for each vehicle (Part 1)

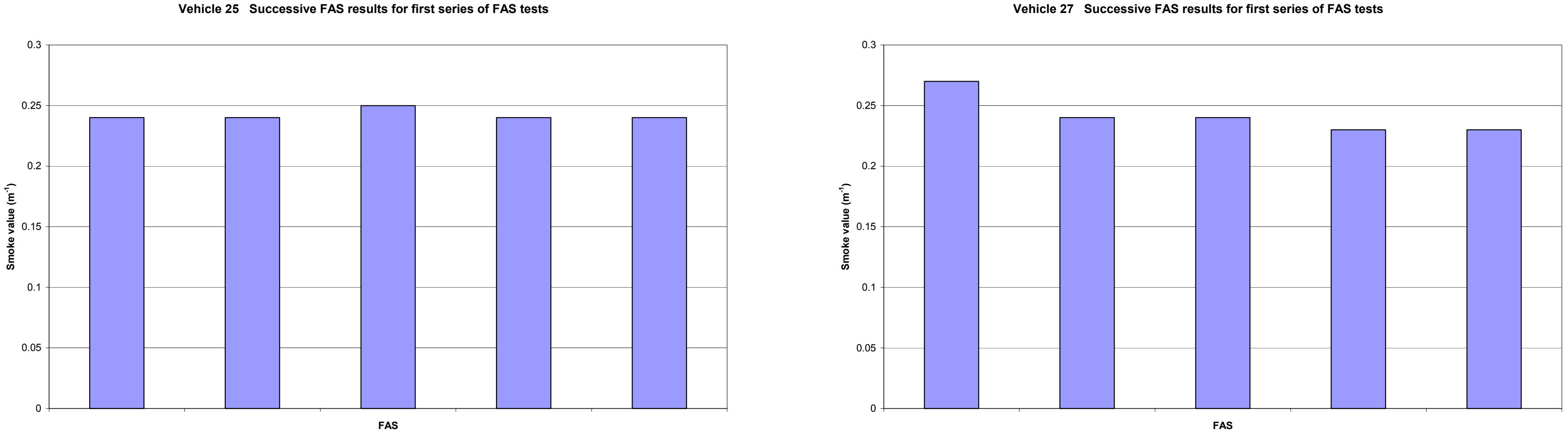


Figure A3.10 Part 2

From the figures it is seen that generally these indicate no major reduction in smoke density with successive free accelerations. The data for Vehicle 21 includes 8 accelerations where the meter reported 0.00. Vehicle 19 may have shown a small effect but the smoke levels are too small to say categorically whether this was the case. The small effect seen for Vehicle 24, see Figure A3.8, was ascribed to the deliberately cool oil temperature rather than to preconditioning effects.

The one clear exception to this is Vehicle 20. This was seen in the first series of FAS tests, see Figure A3.10, and the study on ambient temperatures, see Figure A3.8. It was noticed that when the vehicle had been left idling for some time (e.g. 10 minutes) the next free acceleration generated considerable quantities of bluish/grey smoke. Two further investigations were conducted with this vehicle to study:

- how the FAS result was affected by the time interval between successive accelerations, and
- how effective the current preconditioning procedure was at clearing up the exhaust after the vehicle had been standing idle.

Figure A3.11 shows the results from the first of these investigations. The peak smoke meter value, as reported by the DX250 smokemeter, was measured for successive FAS tests when the interval between the start of successive accelerations was carefully controlled to lie between 12 and 60 seconds. The figure shows how even when the interval is increased to 40 s there is no significant increase in the smoke value. However, for an interval of 60 s there was around a 70% increase.

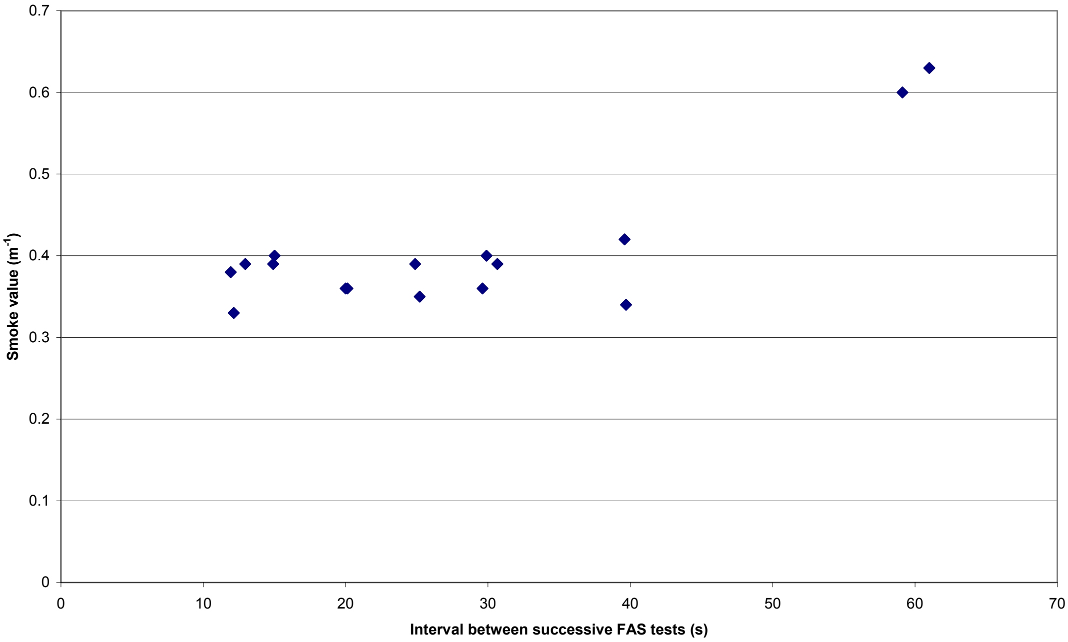


Figure A3.11 Effect of changing the interval between successive accelerations on FAS results

Figure A3.12 shows the effect of the sequence:

- after the end of series of FAS tests leave the engine idling for 7.0 minutes,
- (standard preconditioning of 30s at governor limited speed for one data set),
- series of standard FAS tests.

The two series of columns are for the series with and without preconditioning. Without preconditioning the first FAS result was 2.61 m^{-1}. The vertical scale has been expanded to show the relative size of all but this first peak. The figure shows that for this vehicle 2 to 3 conditioning FAS's were required before stable smoke levels were recorded in the absence of preconditioning, but only one was required if the preconditioning cycle was used.

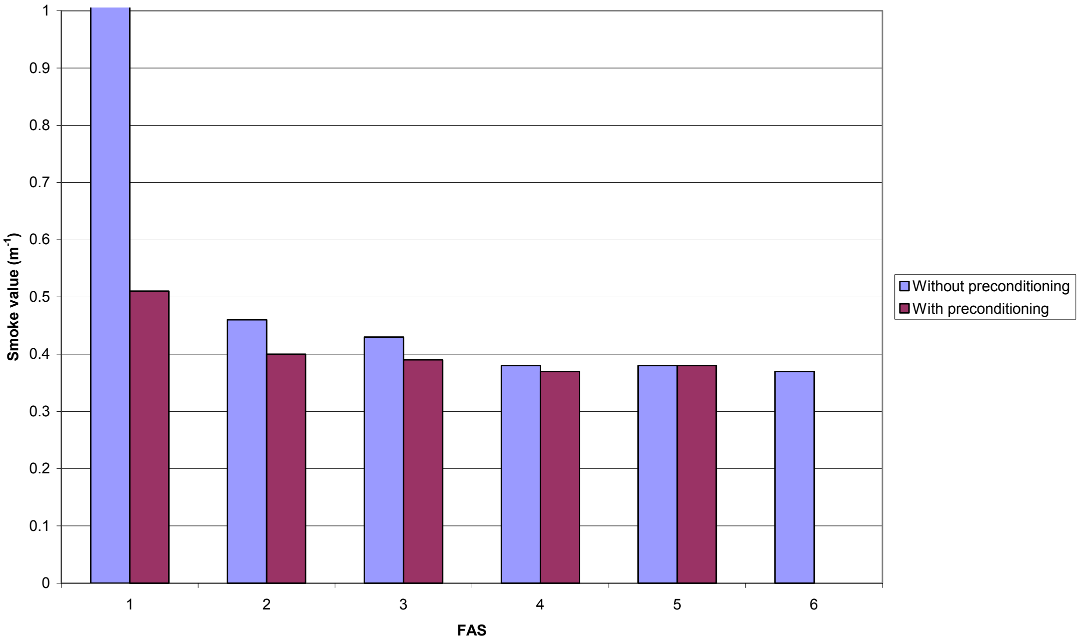


Figure A3.12 Smoke values from successive FAS tests for "dirty" vehicle with and without preconditioning.

A3.5.1.6 Further consequences of the introduction of electronic control

The same changes in technology which strengthens the case for using a FAS test as the basis of a roadworthiness emissions test on one hand, Recommendation 1, also has other consequences.

For Vehicle 18, a smaller rigid heavy-duty vehicle, the governor limited engine speed under no-load conditions was around 1,600 rpm, see Figure A3.7. It was noted that this was anomalously low for this size of engine, with a speed of around 2,750 rpm being anticipated. Putting the vehicle into gear, or releasing its handbrake, had no effect. However, when driven on the road its governor limited engine speed was around 3,000 rpm.

In further ad-hoc studies it was found that engine acceleration times for some of the other vehicles were very similar for:

- a free acceleration when stationary,
- a free acceleration when rolling at, for example, 20 kph, and
- pulling away from stationary in first, or the crawler, gear.

Further, visual inspections indicated that there was no noticeable change in smoke emissions for any of these. Such observations suggest the electronic control system programs operate over a wide envelope, not just at idle. These observations substantiate the claims of vehicle manufacturers that the introduction of such control programs is:

- to reduce wear and tear, and the risk of damage, to vehicle engines,
- to reduce fuel consumption, and
- to reduce environmental impact (both through emissions and noise)

not to defeat the FAS test.

A3.6 Conclusions on sensitivity of FAS test to procedure used

This task of the Phase 3 programme has generated much data pertinent to the FAS testing of diesel vehicles. In terms of the dependence of the FAS measurement on various key parameters, the conclusions and resulting recommendations are as follows.

- There is a large difference in the relationships relative to a study undertaken around 8 years ago. This is caused by 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).

- 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 depressions 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.

- 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).

Recommendation 1
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 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 2
There is no case for introducing further functionality into the test meter to filter out incorrect tests due to anomalous rates or extents of accelerator pedal depression.

This is 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 $-5°C < T < 35°C$. Hence the variations in the ambient temperatures likely to be encountered at test stations in the UK cause insufficient changes in FAS test results to warrant introducing a correction for this.

Recommendation 3
It is not necessary to introduce a correction for variations in the ambient temperatures into the measurement meter/procedure.

- The dependence of the FAS test result on oil temperature of HGVs was measured on a very limited sample (2 vehicles). Although it is clear that for heavy-duty engines oil temperatures do lag behind the engine's coolant temperature during the warm up cycle, the data showed no significant difference when the vehicles' oil temperature was around 18° below its normal operating temperature. A 33% increase in smoke value was seen when the oil temperature was 25° below the normal operating temperature. Consequently the current procedure appears sufficient.

Recommendation 4
There us no need to change the testers' criterion of checking the engine's coolant temperature is at its normal operating temperature.

- 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.

Recommendation 5
For heavy-duty vehicles the current preconditioning cycle specified in the UK testers manual need not be changed.

In addition to the issues specific to the details of the test procedure, this investigation has highlighted other issues. Concluding comments can be drawn regarding these.

It was noted in Section A3.2.1.1 that for heavy duty vehicles, unlike light-duty vehicles, there is the additional factor that type approval is for engines and not vehicles. This is a further barrier to the development of any vehicle based test (e.g. using on the road driving or a dynamometer). Further, it causes significant difficulties when considering the practicalities of in-use compliance testing, as this is now within the framework of EU type-approval for light-duty vehicles.

Recommendation 6
Consideration should be given, in consultation with manufacturers and the governments of other member states, to the case for having, as a minimum, a rudimentary loaded vehicle test to augment the current engine based type approval regulations. This may provide an "as new" vehicle standard against which a future roadworthiness emissions test can be assessed.

A further conclusion drawn from this task is that the FAS result for modern electronically controlled diesel vehicles is low. Figure A3.13 shows a distribution profile of the FAS results from the 10 vehicles studied. 60% of the vehicles had smoke values $\leq 0.10\ m^{-1}$. It is noted that the pass/fail limit for these vehicles is $3.0\ m^{-1}$ (all vehicles were turbo-charged).

Figure A3.13 serves to illustrate the mismatch between vehicles' actual emissions performance and the current pass/fail standard. It is anticipated that the introduction of the Euro 4 standard (where the PM emission levels reduce from 0.10/0.16 g/kWhr to 0.02/0.03/ g/kWhr for the ESC/ETC cycles, respectively) combined with lowering the pass/fail standard for the roadworthiness emissions test to $1.5\ m^{-1}$ will not improve this mismatch.

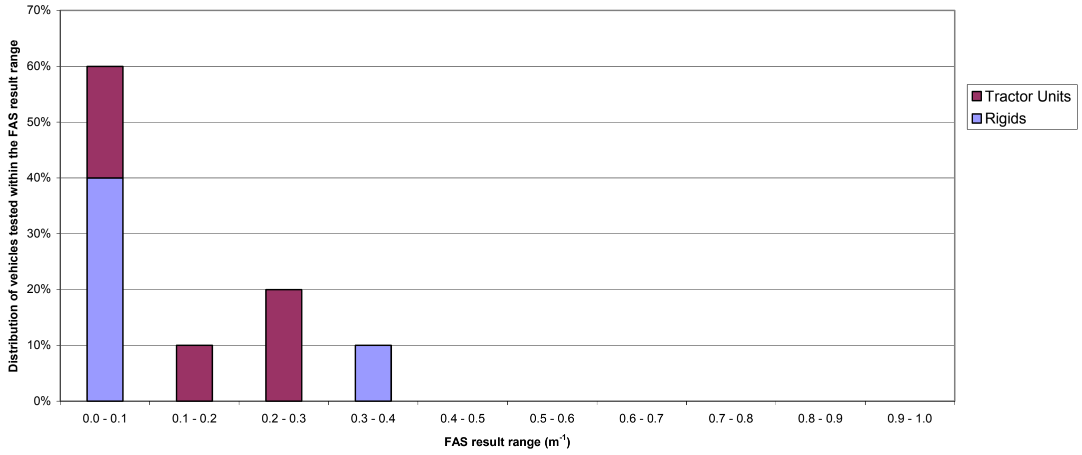


Figure A3.13 The distribution profile of the FAS results for the heavy-duty vehicles tested

A further surprise appeared when the measured FAS values were compared with that plated on the vehicles. For many vehicles this parameter, which was measured at the time of type approval of the engine, is plated on the engines' ECUs. It could only be seen when the vehicle's cab was tipped, an activity prohibited under the conditions of access to many of the vehicles. Consequently there are only data for 5 of the 10 vehicles. These are shown in Figure A3.14.

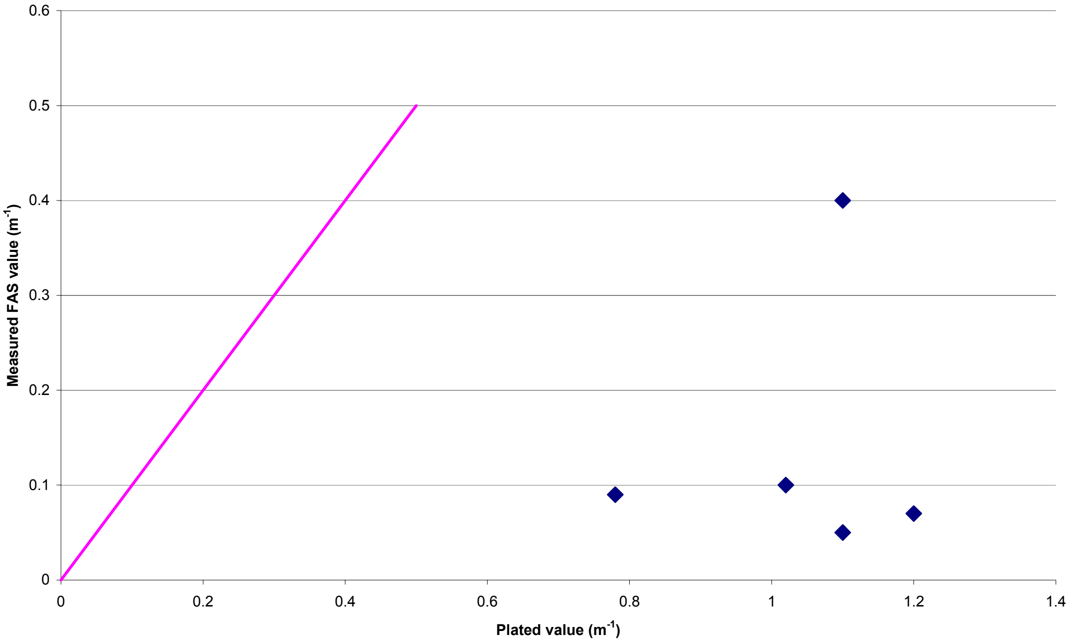


Figure A3.14 Comparison of plated and measured FAS smoke values for 5 heavy-duty vehicles

If the type approval measurements were directly transferable, and no degradation had occurred, the result would be a straight line of gradient 1.00 (as is added to the graph. Assuming some degradation had occurred the measured FAS values would exceed the original values, giving data points above the line. In practice all points lie significantly below the line. Two sets of illustrative data are tabulated below.

	Vehicle 4	Vehicle 6
Plated FAS value	1.10 m^{-1}	0.78 m^{-1}
Actually measured FAS value	0.05 m^{-1}	0.09 m^{-1}
Odometer reading	223,550 km	69,370 km

From the preceding discussion it is concluded that:

- the current FAS test pass/fail limits are inappropriate as for identifying vehicles seriously in need of repair or maintenance, and
- whilst moving to vehicle specific limits appear attractive, it is not appropriate to use the value plated on the vehicles at the time of type approval.

In summary, the research has highlighted that vehicle technology has fundamentally changed the emissions characteristics of modern electronically controlled heavy-duty diesel vehicles. Overall it is concluded that, in the context of constraining test procedures to unloaded tests, the case for using a FAS test has strengthened with the introduction of electronically controlled fuelling systems. Further, in terms of the rate and extent of accelerator pedal depression, ambient temperature, warm-up procedure and preconditioning, the procedure currently specified and pre-programmed within smoke meters is adequate.

A3.7 Survey of current FAS test

A3.7.1 OBJECTIVES AND APPROACH

The objectives of activity were to undertake a data collection exercise to establish:

- the age of the 1.0 – 1.5% of vehicles failing the current roadworthiness emissions test at VOSA test stations,
- the average values from the FAS test for new, electronically controlled, heavy-duty diesel vehicles.

These was achieved by collecting representative data from VOSA operated test stations from vehicles being presented for test. These were then analysed to answer the questions implicit in the two aspects of this task's purpose.

The target number of vehicles to be included in the data set was 1,000 – 2,000.

A3.7.2 DATA COLLECTION AND FILTERING

The data sets from the GVTSs were collated by VOSA and passed to AEA Technology as an Excel spreadsheet. Key fields in the information that were recorded for each vehicle were:

- Vehicle type,
- Registration number,
- Odometer reading, and
- Test number and smoke value (m^{-1}) for each FAS measurement undertaken
- Final FAS result as calculated by the GVTS's smoke meter.

The database provided by VOSA contained 2448 entries.

These 2448 entries were filtered by:

- removing entries which did not have a valid registration plate
- removing duplicate entries (same vehicle registration plate and smoke values)
- removing second or subsequent tests on same vehicle (same vehicle registration plate)
- removing vehicles with non-standard UK registration plates (e.g. using the Irish system)
- removing vehicles whose registration plate looks as though it probably is a personalised one and therefore does not indicate the age of the vehicle
- removing vehicles which were being tested for an RPC.

This left 2025 entries.

These were then manually assigned an age, from their registration plate, and a pass/fail flag dependent on the result from the FAS test.

A3.7.3 FINDINGS AND DISCUSSION

A3.7.3.1 Vehicles that failed the test

From the filtered data set of 2025 entries it was found that 28 vehicles failed their first or only FAS test. This is 1.38% of those tested.

Of these 28 vehicles the maximum smoke value was 8.07 m^{-1} and the minimum value was 3.02 m^{-1}. There was 1 vehicle whose FAS was 3.00 (just pass) and
10 whose FAS lay between 2.91 and 3.00
12 whose FAS lay between 2.81 and 2.90
12 whose FAS lay between 2.71 and 2.80 etc

Figure A3.15 shows the age distribution of the vehicles that failed the test (the blue columns, on the left of each pair). The youngest such vehicles were between 4 and 5 years old (2 vehicles failed). The ages with the largest number of failures were 5-6 and 7-8 years old, where there were 4 failures in each year group.

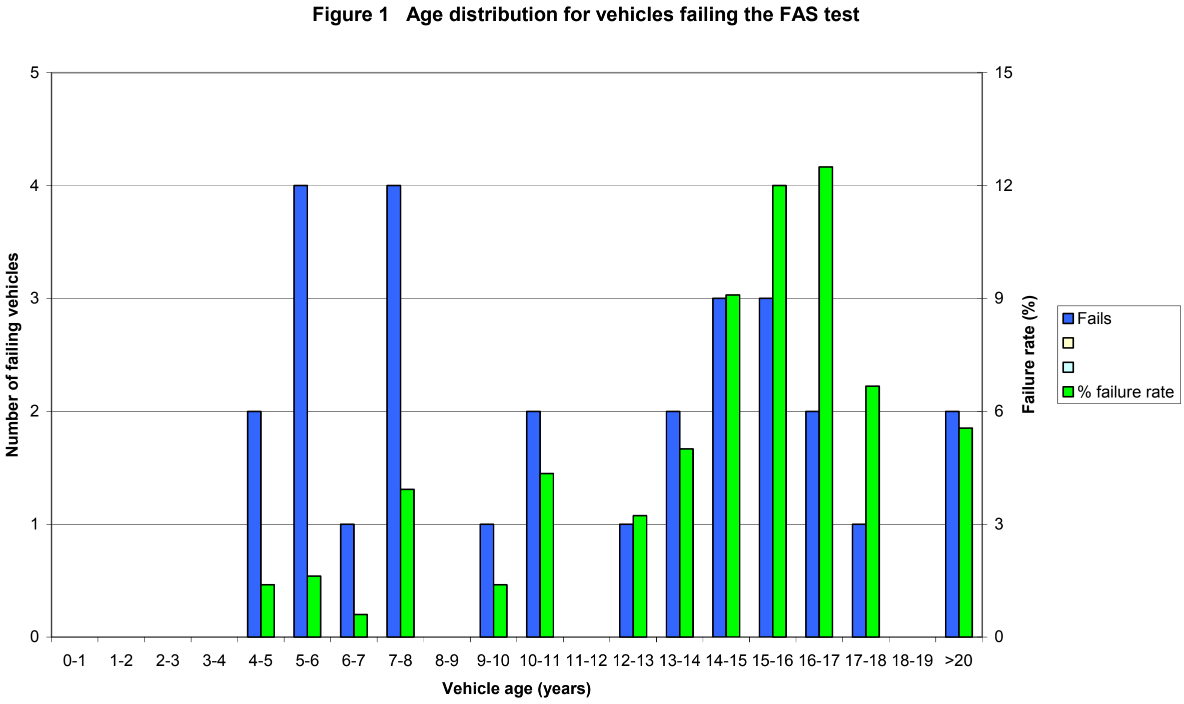


Figure A3.15 Age distribution for vehicles failing the FAS test

However, this analysis does not take into account the number of vehicles tested in each age group. The right hand column of each pair (green) gives the failure rate of each age group as a percentage (the right-hand axis), i.e. taking into account the number of vehicles tested in each age group. From these data the highest failure rate occurred for vehicles in the 15-16 and 16-17 years old age group where around 12% (i.e. 1 in 8) of vehicles failed. For the 5-6 and 7-8 years old age groups failure rates were 1.4 and 3.9% respectively.

The vehicles that failed the FAS test have also been analysed using the implementation dates of the various emissions standards to categorise vehicles. The results of this analysis are given in Table A3.3. This shows a steady reduction in the vehicle failure rate as a function of successive emissions standards. It is believed that the dominant reason for this reduction not the increasing average age of each sample group, but is indeed the change in emissions standard itself.

Table A3.3 Analysis of FAS test failures by introduction date of the different Euro standards

Standard	Introduction date	Number of vehicles which failed FAS test	% of vehicles tested which failed FAS test
pre-Euro 1		16	5.39%
Euro 1	1/10/93	5	1.61%
Euro 2	1/10/96	7	0.74%
Euro 3	1/10/2001	0	0.00%

A3.7.3.2 FAS test distribution functions

The second objective of this activity was to find the FAS test distribution profile for modern, electronically controlled heavy-duty vehicles. This was achieved by sorting the filtered data according to vehicle age, and then analysing specific portions of the data set.

Figure A3.16 shows the FAS test emissions levels for heavy-duty vehicles >5 years old from the data collected in this study (the left hand, blue column). The right hand, green columns show analogous data from the 1999 NAO report on Vehicle Emissions Testing.

Figure 2 FAS test emissions levels for heavy-duty vehicles >5 years old

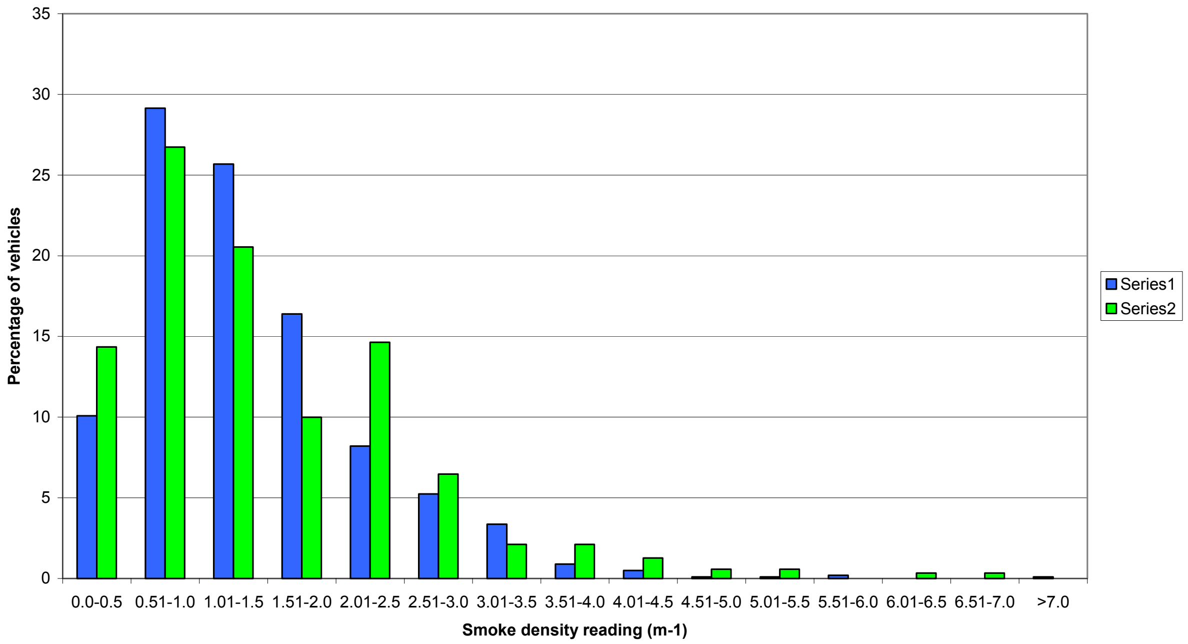


Figure A3.16 FAS test emissions levels for heavy-duty vehicles >5 years old

The following systematic differences exist between the two data sets.

- The NAO data were collected in August 1998, at which time vehicles manufactured in 1998 would be new. The AEA Technology data includes vehicles manufactured in 1998, and earlier, but these vehicles are now 6 years old.
- The AEA Technology data will include fewer pre-Euro 1 vehicles, manufactured before 1993, than the NAO data as a proportion of those tested in 1998 will have been scraped in the intervening years.

Notwithstanding these differences the similarity between the two profiles is striking.

Figure 3 FAS test emissions levels for heavy-duty vehicles >5 years and <3 years old

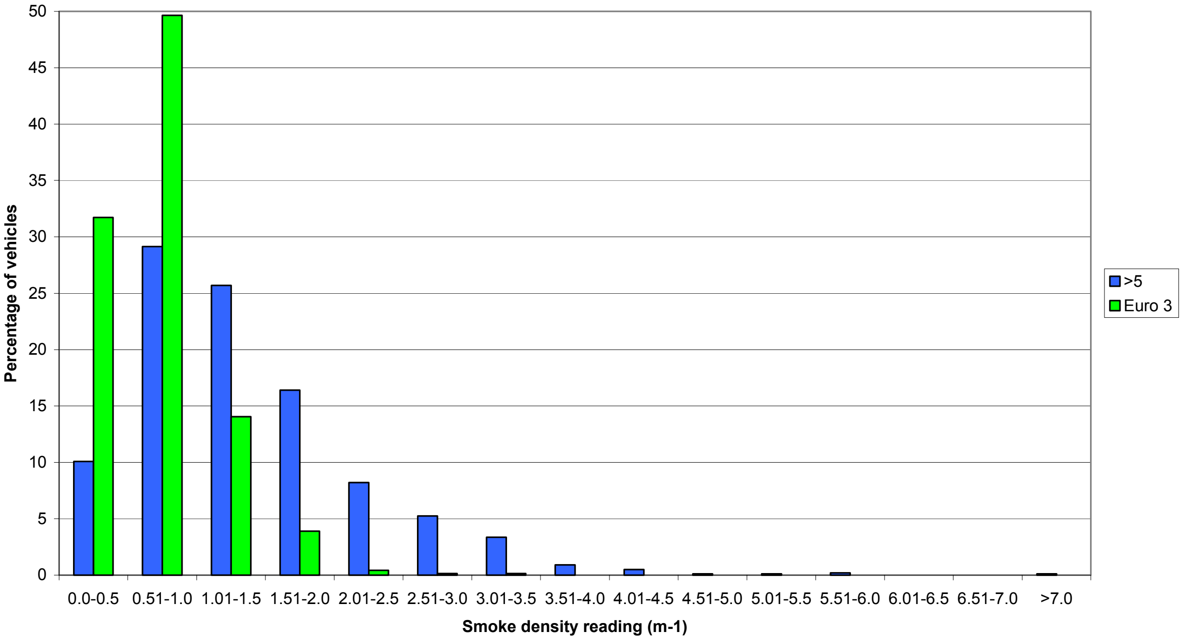


Figure A3.17 FAS test emissions levels for heavy-duty vehicles >5 years old and < 3 years old

Figure A3.17 displays the same data (the FAS test emissions levels for heavy-duty vehicles >5 years old) plotted alongside the equivalent data for vehicles < 3 years old (registration plates Y or later). The difference between the two data sets is marked. >95% of the newest vehicles tested had FAS test levels < 1.5 m^{-1}. For vehicles > 5 years old this figure was around 65%, with the FAS test level for 95% of vehicles being just over 3.0 m^{-1}.

The data collected has also been analysed using the implementation dates of the various emissions standards to categorise vehicles. This is a simplification because, for example, vehicles produced in the first half of 1996 had to meet the Euro 1 standard, but some would have met the Euro 2 standard in anticipation of its introduction in the autumn of 1996. The results of this analysis are given in Table A3.4.

Table A3.4 Analysis of FAS test results by introduction date of the different Euro standards

Standard	Introduction date	Mean FAS test result from these data	Standard deviation (as % of mean FAS test result)	Type Approval standard
pre-Euro 1		1.50 m^{-1}	74%	
Euro 1	1/10/93	1.10 m^{-1}	85%	0.36 g/kWhr (R49)
Euro 2	1/10/96	0.76 m^{-1}	71%	0.15 g/kWhr (R49)
Euro 3	1/10/2001	0.44 m^{-1}	65%	0.10 g/kWhr (ESC)

A principal objective of the additional research (Phase 3a) was: to obtain practical data that indicates an appropriate pass/fail limit value for the free acceleration smoke test. The data in Figure A3.17 and Table A3.4 strongly support the opinion expressed in earlier reports by the author that the 3.0 m^{-1} pass/fail limit for turbo-charged heavy-duty vehicles that was introduced for all vehicle types, including pre-Euro 1, is increasingly irrelevant for Euro 3 vehicles[7].

Looking to the future, the introduction of the Euro 4 standard (1/10/2006) involves a five fold reduction in PM emissions. The Directive 2003/27/EC amends the Roadworthiness Directive (96/96/EC) reducing the pass/fail limit for vehicles meeting the Euro 4 standard to 1.5 m^{-1}. The data presented here suggests this is very likely to be too high to detect vehicles that are not being appropriately maintained.

A3.7.4 FUTURE PASS/FAIL LIMITS

The drafting of Directive 2003/27/EC involved consultation with member states who, in turn, undertook regulatory impact assessments and consulted with industry. From discussions that have occurred during this work it is believed that resistance to a 1.5 m^{-1} FAS test limit for Euro 3 vehicles occurred because:

1. it would have involved the retrospective imposition of a standard that vehicles were not designed to meet at the time they received their type approval certification, and
2. **some** vehicles would have not passed this test despite being fully compliant with all aspects of the type approval certification.

Issue 2 is a consequence of having a single pass/fail value for all vehicle types.

A possible way of overcoming this would be to have vehicle type specific limits of the type:

- generic pass/fail value applicable to the **majority** of vehicles, and
- manufacturer declared higher limits for **some** vehicles that fully meet the type approval emissions standards.

The generic pass/fail limit should reflect:

- actual FAS test performance of new vehicles relative to their regulatory PM emissions over the type approval cycles,
- suitable age related degradation rates,
- the statistical variability of the FAS test performance caused by vehicle-vehicle variability,
- the statistical variability of the FAS test performance caused by test-test variability (including preconditioning effects)
- the accuracy and the precision of the meters used to obtain the FAS test value.

This approach seeks to apply an equable transferable standard between type approval process and the roadworthiness test that better reflects the actual emissions of vehicles than a single pass/fail value for all vehicle types.

It is noted that the values currently plated on the **engines** of heavy-duty vehicles bears little relationship to the FAS test result from **vehicles** (see Section A3.6, including Figure A3.14 of this annex).

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[7] Low Emissions Diesel Research – Phase 2 Report for VOSA, Report AEAT/ENV/R/0629, June 2001 (second dot point in Section 3.6 on page 39).

A3.8 Identification of faults and their frequency

A3.8.1 OBJECTIVES AND APPROACH

The objective of this activity was to establish the faults that occur most commonly with modern heavy-duty diesel vehicles, and their prevalence. The subsequent activity was to find the effect of these faults on the vehicles' PM emissions.

This was achieved by using a questionnaire to ask
- manufacturers,
- those who service heavy-duty diesel engines and
- fleet operators

what faults are occurring and how frequently they occur.

The primary purpose of contacting the manufacturer's head offices was to obtain their support for the study, and their agreement about contacting their franchised services centres rather than in anticipation that they would be appropriate teams to complete the questionnaire.

Once equipped with the agreement of the OEM, or even provided with an introduction, the Service Managers of franchised workshops/service centres were approached. The briefing note and a questionnaire were either posted with a stamped addressed return envelope, or e-mailed, to those who agreed to participate in the survey.

Fleet operators were also contacted because it was believed many vehicles are serviced and repaired within fleet workshops rather than in OEM's franchised workshops. It was also anticipated that there may be some systematic differences between the questionnaires completed by the two types of workshop.

A3.8.2 BRIEFING NOTE AND QUESTIONNAIRE

A one page briefing note describing the aims of the project and the information sought was prepared and agreed with VOSA.

A questionnaire was devised in consultation with some key people (engineers and service managers). The confidentiality of the information provided by companies is important so consequently some comments in this report have to be non-specific.

It also became apparent that the questionnaire would need to strike a balance between the level of detail that could be obtained and the need to get organisations to voluntarily provide the information. A further compromise reached involved the way service departments categorise their work and the very specific emissions related data we were seeking. (For example we did not need to hear about problems with vehicles braking or lighting systems but to ask specifically for "faults that might affect emissions" would be insufficiently robust.) The questionnaire used for the franchised dealers of OEMs is given in Appendix 1 to this annex.

The approach used was to emphasise that the survey was limited to

- heavy-duty vehicles only, i.e. those whose annual roadworthiness check was undertaken at one of the GVTSs, **and**
- vehicles that used electronic control units (as opposed to mechanical fuelling systems) **and**
- faults that were associated with the engine.

The questionnaire was in three principal sections:

Section 1 –	quantification of the number of modern. heavy-duty diesel engined vehicles looked after by a centre and how often vehicles with engine faults are encountered.
Section 2 –	a more detailed breakdown of the frequency of engine faults diagnosed sub-divided into nine categories.
Section 3 –	A ranking of components that may fail and lead to the four faults that have the largest impact on emissions.

Overall, Sections 1 and 2 enables a fault frequency in units of **number of faults encountered per year/100 vehicles** to be calculated.

A3.8.3 CONTACTS

A3.8.3.1 Contacts with OEMs

As noted in the previous section, the need for confidentiality was emphasised on a number of occasions, and consequently some comments in this report cannot be specific.

The report prepared for DG ENTR on a Survey of Future Emission Control Technologies[8] states that there are seven major heavy-duty engine manufacturers in Europe. Together these built 99% of the 417,235 heavy-duty trucks and 82% of the 35,314 buses produced in the EU in 2000. With the MAN and ERF and the use of Cummins engines in many ERF built vehicles, information from a MAN-ERF dealership provides information on both MAN and Cummins engines.

Six of the largest of the OEMS were approached to establish if they were willing to complete the questionnaire. Some endorsed our enquiry and spoke to some of their franchised servicing centres on the project's behalf. Others agreed that we could approach their franchised servicing centres, and some declined to take part in the survey.

Group service managers at a number of OEM franchised servicing centres were subsequently contacted, either by the AEA team or directly by their head office. The majority of those contacted agreed to take part in the survey. The briefing note and questionnaire were sent out to eleven these (either by mail or e-mail).

The target was that at least two thirds of the questionnaires sent out be returned. In practise eight of them (73%) have been returned.

A3.8.3.2 Contacts with fleet operators

Help in the identification of potential contacts, via VOSA, from Geoff Day of the Freight Transport Association and Colin Copelin of the Confederation of Passenger Transport is gratefully acknowledged.

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[8] Study on Emission Control Technology for Heavy-duty Vehicles, Final report Volume 1: Survey of future emission control techniques, Contract No ETD/00/503430, DG ENTR (Enterprise), by MIRA Ltd, PBA, LAT/AUTh, TU Graz, TNO Automotive and Vito, May 2002

Within the project it was intended that the survey should include representative numbers from all heavy-duty vehicle types in the fleet, i.e. tractor units, rigids and PSVs. One way of targeting data from specific vehicle types is to obtain information from fleet operators who use that vehicle type (e.g. bus companies for PSVs and local authorities for dustcarts, a rigid vehicle with an atypical stop/start drive cycle). This led to the following fleet operators being contacted. Inclusion of an organisation in the list below means that contact was made at an appropriate level within the organisation (e.g. fleet manager). The outcome of the discussions may be one of three possibilities:

- the fleet is maintained in-house and the organisation agrees to participate in the survey,
- the fleet is maintained in-house and the organisation declines to participate in the survey, and
- the fleet's maintenance is contracted out.

Large multi-centred fleets

3663
ASDA
British Telecommunications plc
Exel
Hoyer Ltd
J Sainsbury plc
John Lewis Partnership
Royal Mail
Wincanton

Smaller single centred fleets

Dawson Truck Rental
Timbmet
Verran Freight Group

Bus and coach fleets

Oxford Bus Company
Thamesdown Transport Ltd
Reading Transport Ltd

Local authorities

Oxford City Council
London Borough of Hounslow Council

Discussions with the organisations listed above revealed that there has been a major change in recent years where servicing, repair and maintenance are now undertaken predominantly by OEM franchised workshops/repair centres rather than in-house. Fleet managers cite the increasing technological complexity of vehicles, and complying with Operator Licence conditions as two drivers for this. Arrangements for this include:

- contract hiring of vehicles from OEMs which includes repair and maintenance
- purchase of vehicles in association with contracts where the OEM provides the repair and maintenance.

Whilst the first option has long been favoured by small fleet operators it is increasingly being adopted by the larger fleets. An example of this appeared in the "News" section of the Scania web-site which carried the following item:

Asda Places Major Order for Scania R-Series Trucks - Supermarket retailer ASDA is to incorporate 196 Scania R-series trucks into its UK distribution fleet in a major order scheduled to be fulfilled during November 2004…………… ASDA's Fleet Contracts Manager, Chris Strutt said "The other factors influencing our choice of truck are aftersales care – which the Scania UK dealer network consistently provides to an extremely high standard – and driver acceptability, ……….. The 196 new ASDA vehicles are being supplied on 50 month contracts, which include all repair and maintenance……….[9]

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[9] Web-site http://www.scania.co.uk/, Home page, October 2004.

An interesting variation on the second dot point above was provided by a large supermarket chain. Their fleet manager said that when they buy 200 tractor units at once they can, as part of the contract, negotiate for the OEM to equip and run the inspection, servicing and repair workshop housed in the supermarket's premises adjacent to a large distribution warehouse.

The net result is that within the UK there is a fleet wide shift towards OEMs undertaking repair and maintenance and away from in-house capabilities.

Another example of these trends was provided by interactions with the UK section of one of the world's largest logistics companies. They told me that much of their vehicle maintenance was out-sourced. Notwithstanding they provided contact details of one depot whose vehicle maintenance was in-house. When contacted this depot revealed that its workshops were closed down 2 months earlier, and the maintenance of its fleet was now also out-sourced.

A3.8.4 FREQUENCY OF ENGINE FAULTS

A3.8.4.1 OEM Franchised centres

Eight completed questionnaires were returned, two each from four different OEMs.

Section 1 of the questionnaire sought to establish the frequency of repair of "modern" vehicles with engine faults (in units of faulty vehicles/100 vehicles/year). For OEM franchised centres this was done by establishing how many vehicles were looked after by each service centre by finding how many "modern" heavy-duty vehicles were serviced during a typical week, and the frequency of servicing. From these data the number of vehicles looked after can be calculated. The number of vehicles with engine faults that were repaired each year was also estimated by the service centres. This allowed a fault frequency to be calculated (in units of faulty vehicles/100 vehicles/year).

Answers varied between 13 and 100, with three of the OEMs reporting both a higher (80 – 100 faults/100 vehicles/year) and a lower (<60 faults/100 vehicles/year), whereas the fourth OEMs two service centres both reported <35 faults/100 vehicles/year.

The mean aggregated failure rate (calculated by summing all vehicle numbers and all faults/year over the 8 replies and dividing one by the other) was 70.8 engine faults/100 vehicles/year. The failure rate calculated from taking the mean (and standard deviation) of the failure rates from each of the 8 replies was 53 (± 33) faults/100 vehicles/year.

However, it became apparent in the subsequent activity (in which the FAS test result was measured for faulty vehicles) that significantly fewer faults were occurring than was anticipated. Without exception the service centre managers expressed surprise at this. (Further discussion on the possible reasons are given in Section A3.8.7, in the context of the activity of gathering the FAS data.) Consequently four of the eight original organisations completed a second questionnaire at the end of the study. The difference is marked with the mean fault rate having been reduced by a factor of 3. In summary for the four centres:

	Original questionnaire	Final questionnaire
Maximum fault rate reported	100 faults/100v/yr	35 faults/100v/yr
Minimum fault rate reported	33.3 faults/100v/yr	16.6 faults/100v/yr
Mean fault rate over 4 organisations	75 faults/100v/yr	25 faults/100v/yr.

A3.8.4.2 Fleet service centres

It proved more difficult to find fleet operators who undertook their own maintenance than was expected (as discussed in Section 3.3.2). However, with perseverance six organisations from within the list given in Section 3.3.2 were identified who agreed to participate in the survey. These fleets can be categorised by size into large (>100 vehicles) medium (between 25 and 100 vehicles) and small (<25 vehicles). Those involved in the survey comprised 2 large fleets, 1 medium sized fleet and 3 small fleets. Two of the small fleets had operated too few vehicles for too short a time to be able to report anything other than a random (stochastic) distribution of faults. Further, given the reciprocal relationship between the number of faults per 100 vehicles per year and fleet size, these data were not included in this analysis.

Relative to the OEM franchised centres it is easy to define how many vehicles were looked after by a fleet service centre, it is the fleet size except for the largest fleets where several centres service the whole. Figure A3.18 shows the data for the eight franchised centres and the four fleets. For three of the four fleets the fault frequency lies between 22 and 80 faults /100 vehicles /year. There is one outlier where the overall result is dominated by the large number of electrical system faults reported (1 a day) which alone raises the fault frequency to >1,000 faults /100 vehicles /year. (This illustrates the difficulties introduced by including the data from the smallest fleets.)

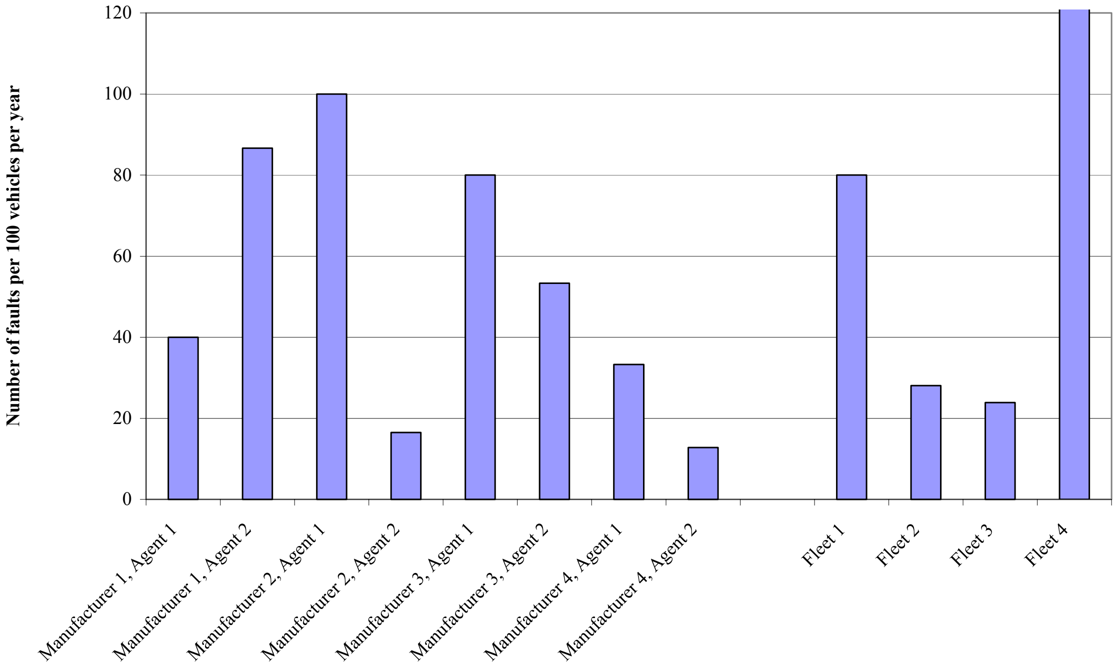


Figure A3.18 Vehicle fault frequencies for service centres and fleets

A3.8.5 ANALYSIS OF ENGINE SYSTEMS THAT FAIL

The questionnaire was designed to optimise the probability of its being completed (by being as simple as possible) whilst at the same time providing a level of detail appropriate to the research. Hence, recipients were asked to constrain their answers to “engine faults for modern, heavy-duty vehicles”. The “engine” was considered as comprising 9 different systems, in Section 2 of the questionnaire. These are listed in Table A3.5 below, and form the basis of the following analysis.

Table A3.5 Categorisation of engine faults, and their potential influence on emissions

Engine systems	Potential influence on emissions
Fuel system (from fuel tank to injector)	**High**
Air inlet system (from air filter to inlet manifold)	**High**
Electronic systems (ECU, wiring harness, engine sensors etc.)	**High**
Valve train faults (valve timing, cam shaft, valve operation etc.)	**Medium**
Exhaust system (exhaust manifold through to tail pipe but excluding traps filters etc which are the next item)	**Low**
Emission control systems (if fitted – e.g. EGR, traps, filters etc.)	**High**
Block and bottom end faults (crankshaft, con rods, pistons, rings, liners etc.)	**Low**
Lubrication systems (oil pump, filtration etc.)	**Low**
Coolant system (leaks, radiator etc.)	**Low**

It is appreciated that faults in different systems could have markedly different effects on emissions. The right-hand column of the table gives a category for the potential effect of a fault on the vehicles' emissions (using a high, medium or low ranking).

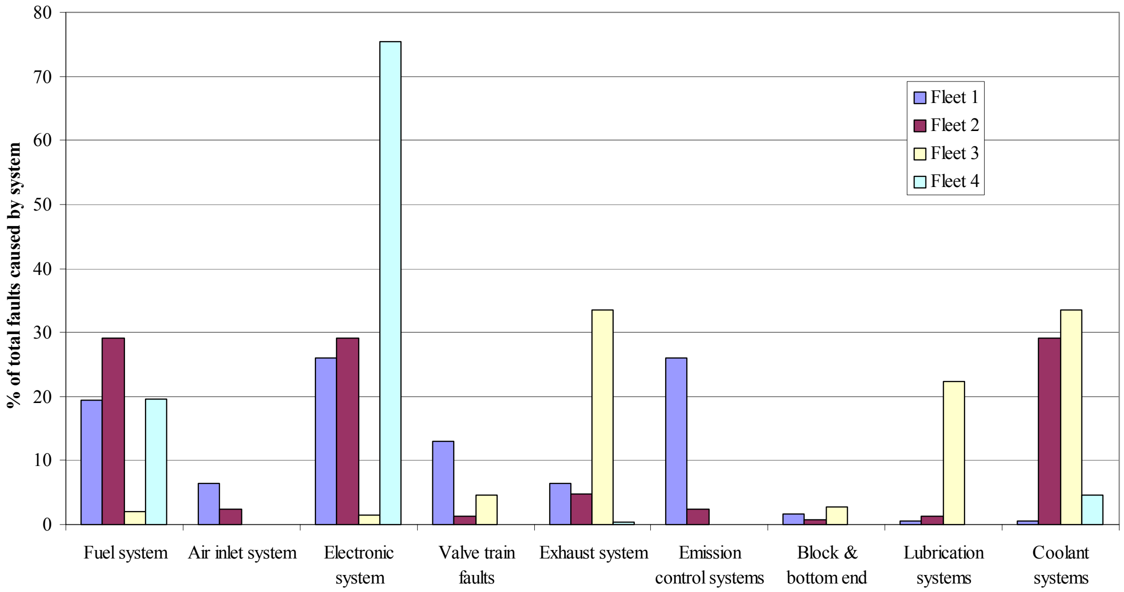
The proportion of faults due to different engine systems for OEM and fleet service centres are plotted as columns in Figure A3.19.

This format of analysis means that the height of all the columns for each organisation adds up to 100%, irrespective of the overall frequency of faults occurring. There is considerable variation in the organisations views about the relative failure rates. Some appear systematic, for example both agents for Manufacturer 1 felt that fuel system faults accounted for around 30% of the faults they encountered, a figure considerably above the average of 19% whereas the views of the two agents for Manufacturer 4 differed widely between 5% and 42%.

The emission control systems category (i.e. EGR and/or particulate traps) is unique in that it is the only system that **may** be applied to an engine, whereas all the other eight categories definitely are present. There are few vehicles in the fleet that were manufactured with either EGR systems of particulate traps fitted. Consequently the vast majority of OEM franchised centres reported rarely seeing vehicles with these systems fitted, and even more rarely encountering faulty emission control systems. In contrast, it has been a policy decision of some fleet owners, e.g. some bus companies, to retro-fit particulate traps to the majority, or all, or their fleet. Consequently, fleets report a much higher proportion of faults.

An overall picture can be obtained by summing data which was done in two ways. Firstly, by adding together the proportions in Figure A3.19, so that the result for X organisations sum to X hundred percent. This means each organisation contributes equally to the answer, irrespective of the number of vehicles they maintain. The second method was to add together the actual numbers of faults seen per year as reported by each organisation, and then to renormalise. This approach has the advantage of giving more weight to organisations maintaining larger fleets since these organisations encounter more faults. However, it has the disadvantage that a single response, e.g. from the fleet manager who reported having to repair an electronic system fault daily, can distort the whole picture.

Proportion of faults due to different engine systems for fleets



OEM Proportion of faults due to different engine systems for OEM franchised service centres

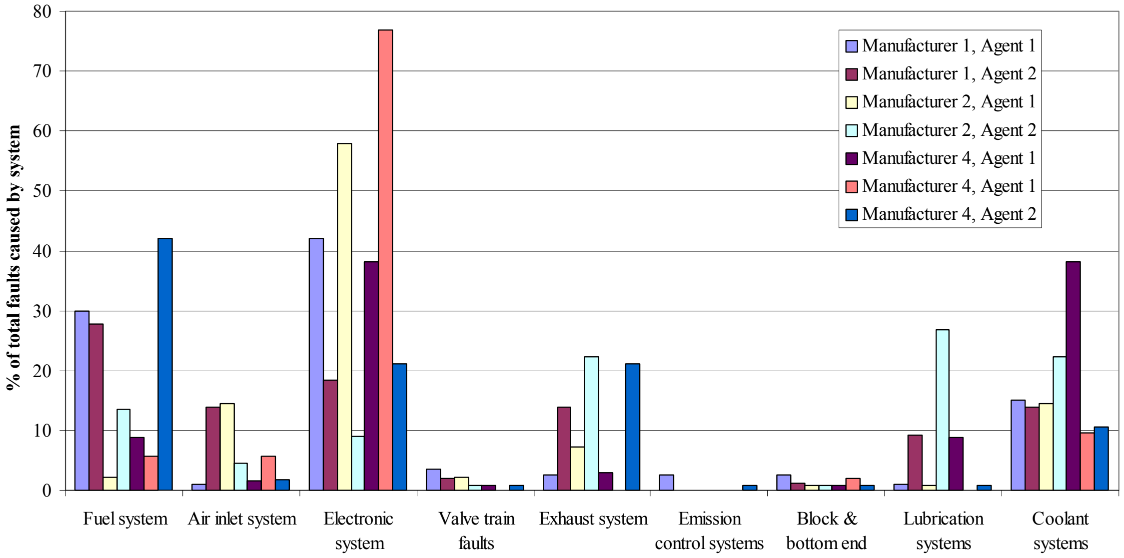


Figure A3.19 Proportion of faults due to different engine systems

Figure A3.20 shows the results of these summations for the OEM franchised repair centres, top half, and fleet repair centres, bottom half as pie charts. The chart on the left of each pair is the result obtained when each organisation contributes equally to the whole, and the chart on the right is from summing the actual numbers of faults per year reported by each organisation.

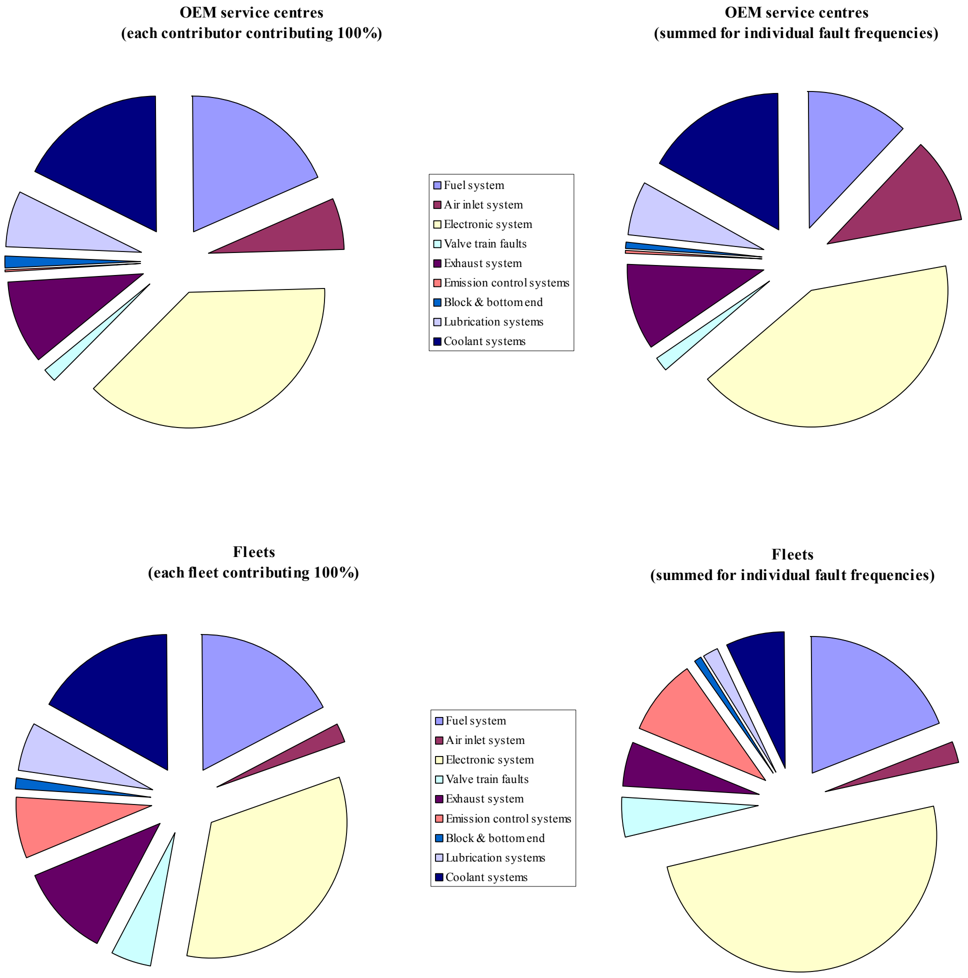


Figure A3.20   Proportion of faults reported for different engine systems

Faults with electronic systems are the largest segment in all four charts, typically accounting for around 40% of all faults.

Fuel systems, coolant systems and exhaust systems are generally the next highest contributors, each accounting for around 15% of all faults.

Emissions control systems, engine block and bottom end, and valve train faults are the smallest contributors reported by the OEM franchised centres, in total contributing <5% of the whole. For the fleet service centres, air inlet systems replace emission control systems as an area where very few faults are encountered.

Figure A3.21 shows similar data to than in Figure A3.18 and 3 for the revised assessment from one of each of the franchised repair centres of all four manufacturers.

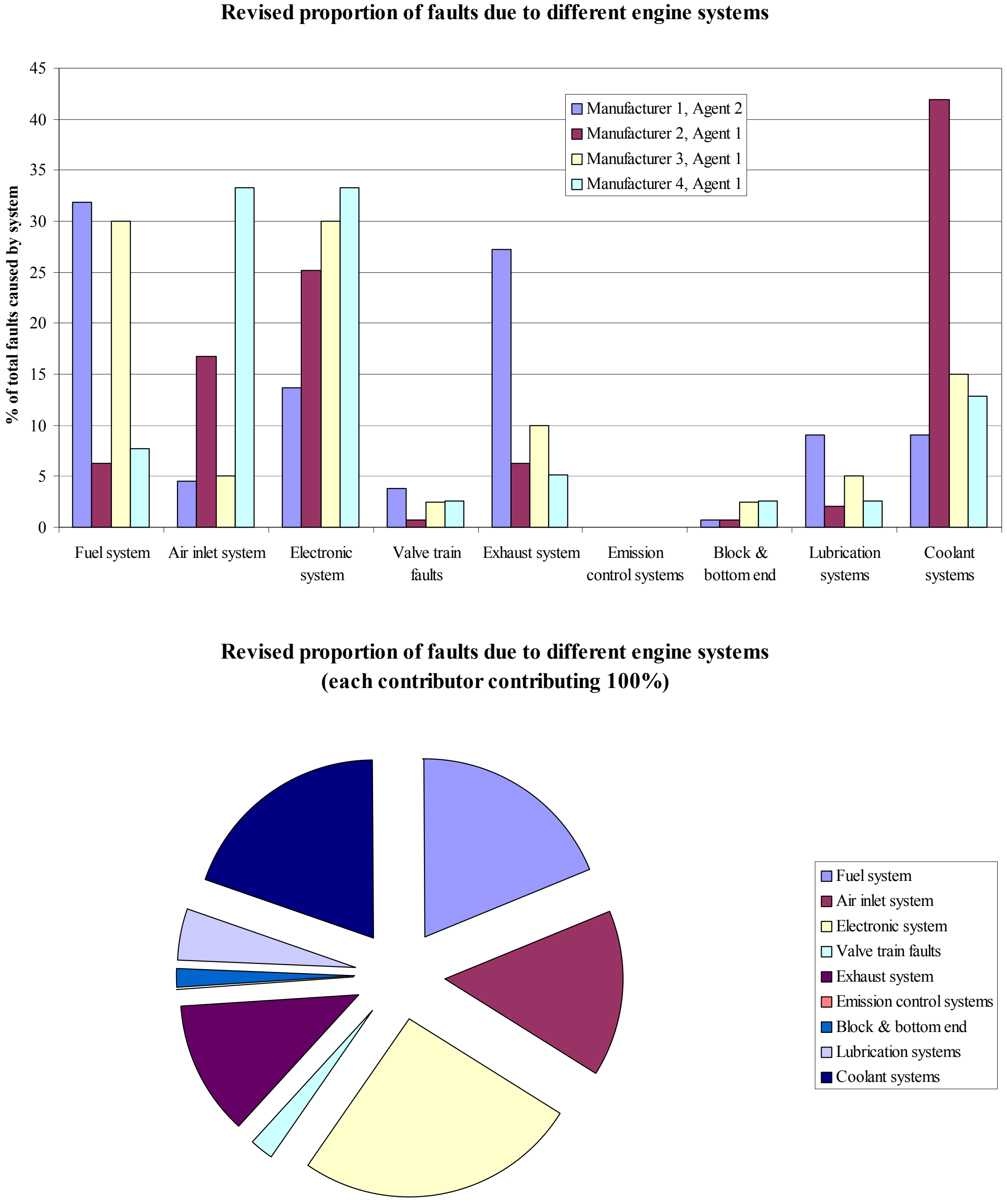


Figure A3.21 Revised proportion of faults reported for different engine systems

The most significant increase was observed for air inlet system faults, which has grown to be comparable to the frequency for fuel, coolant and exhaust systems. Two of the four agents attributed this to a sudden recent increase in the number of turbo-compressor failure they were having to repair.

A3.8.6 ANALYSIS OF COMPONENTS THAT FAIL

There are four engine systems that, when faulty, have a high potential influence on emissions (see Table A3.5), namely fuel, air inlet, electronic and emission control systems. Section 3 of the questionnaire sought a ranking of these by the organisation completing it. The purpose of this was to try to gauge from the experience of those most closely involved in repairing vehicles, exactly which components fail the most frequently. The components options provided for each engine system Table A3.6.

Rankings were provided by seven OEM franchised and three fleet repair centres (some organisations had too few faults to be able to provide a ranking of the options). These data are plotted in Figure A3.22. In this figure a high number represents a more commonly encountered fault, hence the higher the columns for a particular component the more problematic it is reported to be. If an organisation marked two or three components with the same ranking then each component is assigned the same value. Hence Agent 1 of Manufacturer 1, when considering air inlet system faults, ranked turbo units, leaks on high pressure side of turbo and intercooler faults all as equally least common. Hence rather than these three faults receiving rankings of 3, 4 and 5, each was given a ranking of 4.

Table A3.6 List of components that may fail categorised by engine system

	Mean	Variability
Fuel system faults (rank 1 to 4)		
Fuel quality problem (e.g. dirty fuel or blocked fuel filter)	2.40	1.29
Fuel system leaks	2.70	0.86
Fuel pump fault	2.40	1.15
Fuel injector fault	2.50	1.25
Air inlet system faults (rank 1 to 5)		
Blocked or semi-blocked air filter	2.83	1.41
Inefficient/faulty turbo compressor	3.83	1.17
Leak/fault in air pipework on high pressure side of turbo compressor	3.61	1.22
Problems with intercooler	3.11	0.93
Problems with inlet manifold	1.61	0.99
Electronic systems faults (rank 1 to 5)		
Electronic control unit fault	2.95	1.50
Faulty accelerator position sensor	3.30	0.82
Faults with other sensors (e.g. boost pressure)	3.10	1.78
Wiring harness faults	2.90	1.74
Faults with other sensors	2.75	1.09
Emission control system faults (rank 1 to 6)		
Blocked or semi-blocked filter		
Break up of particulate trap or filter		
Other particulate trap or filter faults		
Stuck EGR valve		
Other EGR system faults		
Faults with other emission control systems (in comments column please specify system)		

Considering air inlet system faults: the inlet manifold is reported to fail least often. It was adjudged the most reliable component in the air inlet system (possibly with others) in nine of the ten responses.

From Figure A3.22 it is seen that order, in increasing reliability, for the other faults, is:

(semi) blocked filter < intercooler < turbo unit ≈ leak on HP side of turbo.

A similar order can be deduced by calculating the average ranking (i.e. taking the arithmetic mean of the ranking values). Answers will lie between 1 and 5 for the air inlet system (because there are 5 options). The variability[10] of these data gives a measure of the degree of consensus on a ranking. It will equal zero if all respondents give the same ranking. These data, the means and variability, are given in Table A3.6.

The ranking of the electronic system components in the order they are most commonly found to be faulty is less conclusive than was the case for the air inlet system. For the latter the minium and maximum mean rankings were 1.6 and 3.8, spread around the 3.0 mid-point. For the electronic systems the minimum and maximum mean rankings were 2.75 and 3.3, values much closer to 3.0. This means there is no consensus view that any specific components are problematic, whilst others are reliable. One possible pattern is that 5 of the seven OEM franchised repair centres reported ECUs were the least, or second least likely component to be faulty. Opinions were split regarding the reliability of wiring harnesses and "other" sensors with no clear prioritisation emerging. The component that was adjudged to be the least reliable was the accelerator position sensor, although the margin for this is small in the context of the rankings.

The ranking of fuel system faults is even less conclusive. For the four options provided a ranking of 2.5 is the mid-point with deviations from this representing more frequently faulty (for ranking > 2.5) or more reliable (ranking < 2.5). The mean of the rankings for the four components lay between 2.40 and 2.70. Evaluation of the data in Figure A3.22, in terms of an OEM or fleet based pattern, or an individual manufacturer finding one component specifically problematic, yielded no clear preferences or patterns.

There were insufficient data for failures of emission control systems for an analogous column graph to be drawn. However, it was noteworthy that four of the five organisations providing any data in this section ranked stuck EGR valves as the most commonly occurring fault. The fifth organisation ranked stuck EGR valves as the second most commonly encountered fault, behind (semi) blocked diesel particulate filters.

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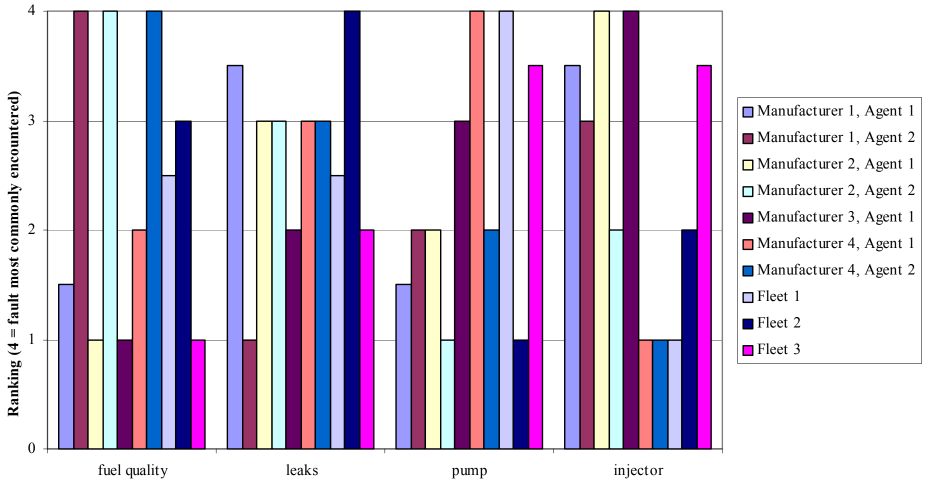
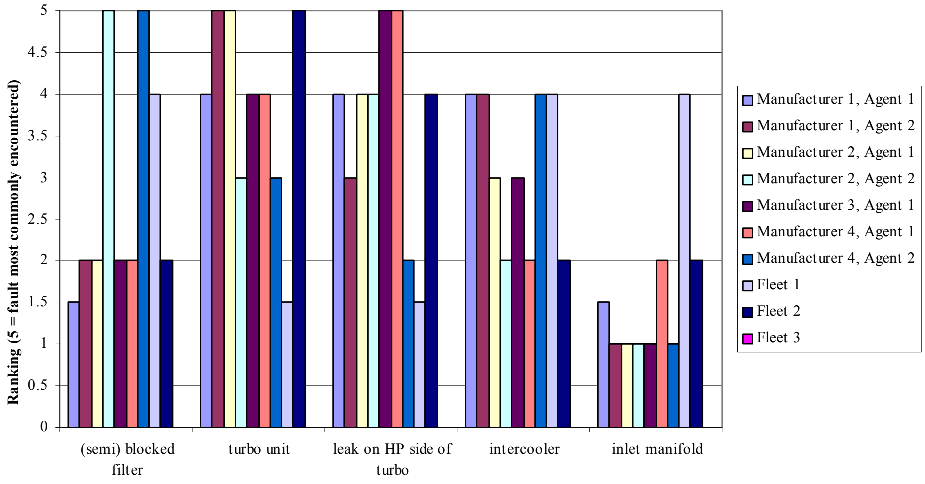
[10] the term variability is used because the ranking data are not a normally distributed set of independent measurements, and consequently the term "standard deviation" is inappropriate as a descriptor for the variations seen.

Ranking of fuel system components in order of how commonly seen



Ranking of air inlet system components in order of how commonly seen



Ranking of electronic system components in order of how commonly seen

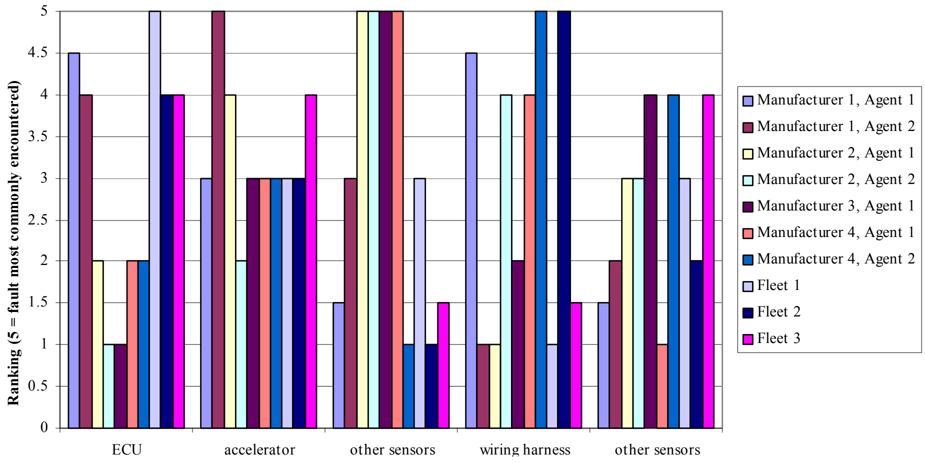


Figure A3.22 Ranking of engine system components on order of how commonly they fail

A3.8.7 CONCLUSIONS AND DISCUSSION

The questionnaire was generally successful in providing a quantification of what faults are occurring and how frequently. Overall the best estimate appears to be that heavy-duty engines fail at a frequency of around 10 – 40 faults /100 vehicles /year.

Further generalisations are as follows.

- 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 12 – 18 faults /100 vehicles /year.

However the pursuit of these general conclusions has highlighted some important issues.

1. The technology continues to evolve rapidly.

It became evident that the current overall failure rate is declining, it currently being substantially lower than it was a year ago.

2. Rates of failure are affected by service centres' experience and remedial actions.

A specific example of this was two fleet owners who listed (semi) blocked filters as the most and least commonly encountered emission control systems. (Both fleets were using retro-fitted diesel particulate filters.) When this was discussed with the fleet manager who reported it was not a problem it became apparent that initially it had been a major challenge for them too. However, by working with the trap supplier, installing sensors to monitor the start of blocking, and modifying their maintenance schedule to include the checking of the diagnostic sensor regularly, blocked filters ceased to be a fault that made vehicles unserviceable. Hence their response to the questionnaire.

A second example was a connector which, the service centre manager concluded, was incorrectly specified for its role. He had circumvented this weakness for the vehicles he maintained, and consequently what had been a regular source of faulty engines ceased to be so.

3. The reported failure rates are biased towards the challenges faced by service centres during the last three months.

An example of this is that two of the four centres reported that they had suddenly seen a large increase in turbo-compressor failures. This is probably a faulty batch of units, possibly symptomatic of manufacturing or QA difficulties, being supplied to the industry. These units had previously been viewed as reliable

4. Faults often occur in batches, see the example above.

Service centres report how one can go 12 months without seeing a particular fault, and then several occur together.

5. The reported failure rates van be influenced by overall workshop activity, not just the failures of modern, heavy-duty diesel vehicles.

Several service centres commented that there was a significantly lower failure rate for heavy-duty vehicles, relative to the larger light-duty vans (3.5 tonne vehicles). Since they sell and maintain both, this can bias their opinion on the failure rates they reported in the questionnaire.

The feedback from the service centres regarding which specific components most commonly lead to faults was valuable in demonstrating that over the fleet as a whole no single component dominates either fuel, air inlet or electronic system faults. One component, the inlet manifold, was found to be of low significance, but this consensus was the exception. The conclusion may be explained by the combination of commercial and operational pressures that lead OEMs to a culture of continual improvement. This means components whose reliability is as some time clearly below that of others are re-engineered or otherwise improved, and then become much more reliable.

A3.9 Effect of faults on emissions

A3.9.1 OBJECTIVES AND METHODOLOGY

The objective of this activity was, having established the nature and prevalence of faults that occur with heavy-duty diesel vehicles, to find the effect of these faults on their PM emissions. There are two aspects to this

- the effect of faults on PM emissions during on-the-road driving, and
- the effect of faults on PM emissions during a FAS test.

It was agreed by the customer that the first of these was outside the scope of the current project. It is the findings from research into the second aspect that are reported here.

Although the objective of the activity is easily stated, its undertaking proved challenging as will be described.

The original plan was to follow up some of the organisations approached with the questionnaire to have them participate in this exercise. It was envisaged 3 OEM franchised service centres and 2 fleet operators would gather data on up to 80 faulty vehicles over a period of 8 weeks. The majority of the data (75%) was to be gathered by the participating organisations with the remainder (25%) collected by the AEA Technology team using a standard smoke meter and a standard procedure (to provide some quality assurance regarding the results).

The first major departure from this plan came with visits to the two fleets most likely to be suitable participants. Whilst they were content to participate the number of faults being reported was quite low. This was partially a consequence of fleet size combined with their reported failure rate of around 26 faults/100 vehicles/year leading to a prediction of seeing, on average, one fault a fortnight. More serious was that the vast majority of vehicles from both fleets had been retrofitted with traps and it was not possible to undertake FAS tests measuring the smoke opacity of exhaust gases upstream from the trap. Consequently, a fault that did lead to a significant increase in PM emissions pre-filter, would probably lead to little difference post-filter. Further, given that the majority of heavy-duty vehicles in service are not fitted with traps, and that the current plans of most OEMs is that Euro 4 standards will also be achieved without the fitting of traps, it was apparent that any data collected would be unrepresentative of the vast majority of the current, and medium term future, fleet. Consequently it was agreed with VOSA to increase the number of OEM franchised service centres that collected data, and not to use any fleet service centres.

Five OEM franchised service centres, representing four different OEMs, kindly agreed to participate in the data gathering exercise. It was agreed with them that the data they provided would be in confidence, and reported in terms of Fault X led to effect Y. It was also evident that there is strong pressure on the service centres to get vehicles repaired and back on the road. This is sufficiently severe for some centres to operate a 5-day, 3 shifts per day pattern of working. Whilst these centres agreed to take FAS measurements before and after repair it was not practicable to ask that they delay work so that measurements could be made by AEA Technology staff. Insistence on this would have introduced unacceptable delays in vehicle repair whilst the AEA Technology team were notified and physically travelled to the service centre to take the readings. Hence the organisation would have withdrawn from the project. Consequently, the vast majority of data were collected by the franchised dealers with only two data sets being collected in the presence of AEA Technology staff. Notwithstanding, scrutiny of the data leads the author to the opinion that there is no reason to doubt the quality of any of the data collected.

A further departure from the original task plan arouse because a combination of illness and being asked to assume temporary responsibility for some other service centres meant that a key person in one organisation was not able to control data collection as anticipated, thereby greatly reducing the amount of data that could be collected. Hence the data were collected, in essence, from four service centres.

Despite the above challenges, the sizes of the participating organisations and the frequency of faults they reported in the questionnaire led to the expectation that they saw around 1,000 faulty engines per year. Given that 60% of the faults are in engine systems of interest, in 8 weeks the anticipated number of faulty vehicles was 96.

Around 4 weeks into the planned data collection exercise, i.e. half way, all five participating service were expressing genuine surprise at the low numbers of failures they were finding. Discussions with them and subsequent activities and discussions lead the author to the opinion that this reflects what is actually happening rather than a systematic under-reporting of faults. The change in plan agreed with the participating organisations and VOSA was to extend the data collection period from 8 weeks to 4 months (17 weeks).

At the end of this period only 14 faulty vehicles had been seen, plus two data sets were collected from a vehicle in which faults seen in earlier vehicles were reproduced. Also, the parts of the questionnaire concerning fault frequencies was completed again by the four service centres to revise the data in the context of their recent experience. This led to a downward revision in the frequency of faults by a factor of 4 (see Section 3.4.1). Hence the four organisations were now estimating:

around 250 engine faults per year
around 60%, i.e. 150 faults/year for the key engine systems of interest,
hence around 50 faults in 4 months for the key engine systems.

The service/repair centres reported that between 25% and 50% of faults are actually fixed in their workshops, with the remaining 75% to 50% being fixed by the roadside or at the operators' site. These data would predict between 12.5 and 25 faults occurring in the four month period of the study. The number of faulty vehicles is within this range, although to the lower end of the range.

The undertaking of off-site repairs does introduce some bias to the findings because some repairs are easier to effect off-site than others. These include many of the electronic system faults, where rectification is simply the fitting of a replacement sensor or the maintenance of a connector.

A3.9.2 DATA COLLECTED

The results obtained are tabulated in Table A3.7.

Table A3.7 Summary of faulty vehicles studied

			FAS when	
Vehicle type size	Faulty system	Repair	faulty	repaired
Tractor unit (420hp)	Fuel quality	replaced blocked fuel filters drained & replaced contaminated fuel	3.36 m^{-1}	0.27 m^{-1}
Tractor unit (420hp)	Fuel injector	replaced defective No 3 injector	2.02 m^{-1}	0.27 m^{-1}
Rigid (180 hp)	Fuel injector	replaced defective No 1 injector	1.93 m^{-1}	0.21 m^{-1}
Rigid (180 hp)	Fuel system - lack of power, excessive smoke	replaced all 4 injectors, replaced fuel filters and air filter, adjust valve clearances	2.10 m^{-1}	0.19 m^{-1}
Rigid	Fuel system - lack of power	replaced fuel filter	Would not start	
Rigid (220 hp)	Electronic – ECU light on, stalling	replaced faulty throttle potentiometer	0.92 m^{-1}	0.32 m^{-1}
Tractor unit (435hp)	Loss of power	replaced ECU unit	0.15 m^{-1}	0.15 m^{-1}
Tractor unit (380hp)	Electronic – ECU light on	new manifold air intake temperature and engine position sensors fitted.	0.06 m^{-1}	0.09 m^{-1}
Tractor unit (420hp)	Electronic – ECU light on	restored connection to engine speed sensor	0.35 m^{-1}	0.30 m^{-1}
Tractor unit (420hp)	Electronic – ECU light on	restored connection to injector setting solenoid	0.16 m^{-1}	0.30 m^{-1}
Tractor unit	Electronic – ECU light on	replaced ECU unit	Would not start	
Rigid	Electronic – ECU light on	replaced ECU unit	Would not start	
Rigid (150 hp)	internal water leak	remove cylinder head, reface head and replace gasket	1.34 m^{-1}	1.30 m^{-1}
Rigid (230 hp)	Coolant	replaced water pump	0.16 m^{-1}	0.15 m^{-1}
Tractor unit (410hp)	None	routine service	0.70 m^{-1}	0.94 m^{-1}

The effect of faulty fuel system components on the FAS result are shown as a column graph in Figure A3.23. Leaving aside fuel system leaks, Table A3.6 contains three faults: fuel quality, fuel injector and fuel pump faults. No faulty fuel pumps were encountered. However, vehicles that were faulty because of poor fuel quality, or with injector faults, or both, were encountered. These vehicles were reportedly smoky before repair. Their FAS test results, Figure A3.23, supports this observation with FAS levels typically falling from 2.0 m^{-1} or greater to around 0.25 m^{-1}. From Table A3.7 it is seen that these four vehicles comprise two 4 cylinder 180 hp engines and two 6 cylinder 420 hp engines. Indeed replacing an injector led to a very similar change in FAS results whether on a 180 or a 420 hp engine. The "lack of power" (possibly fuel starvation) was so severe for one vehicle that it could not be started, and consequently no FAS data are available.

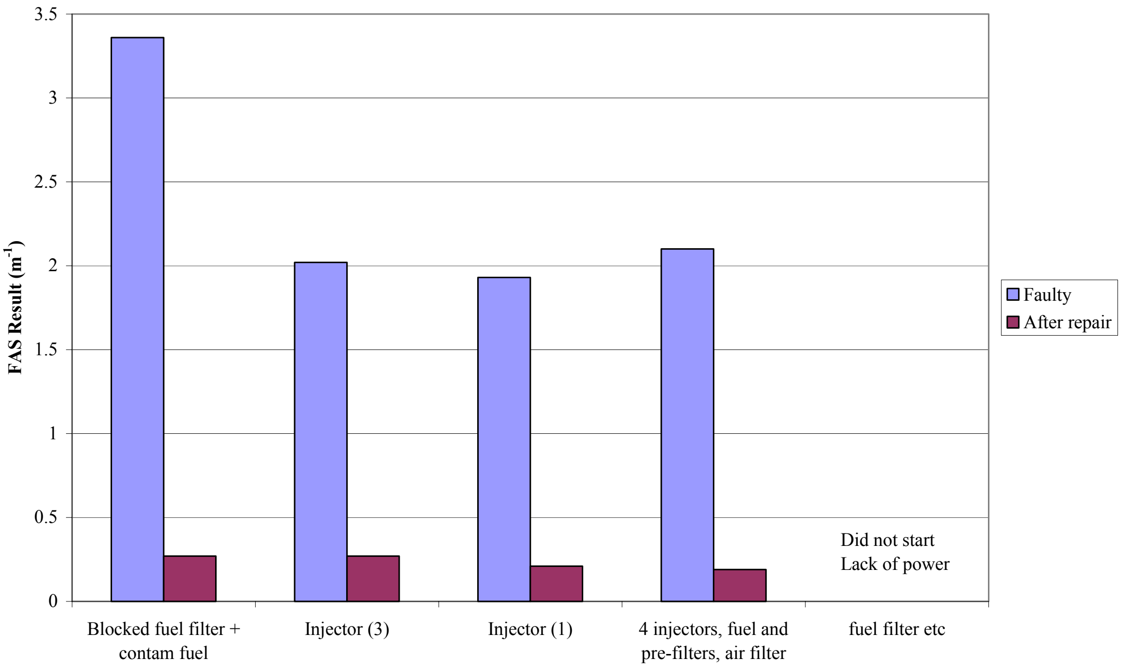


Figure A3.23 Effect of faulty components on FAS result

Figure A3.24 shows analogous data for five vehicles with faulty electronic systems. Again, somewhat fortuitously, these cover four of the five faults listed in Table A3.6 (no vehicles with a faulty wiring harness were seen). The effect of these faults on FAS results is distinctly different from that seen for the faulty fuelling systems.

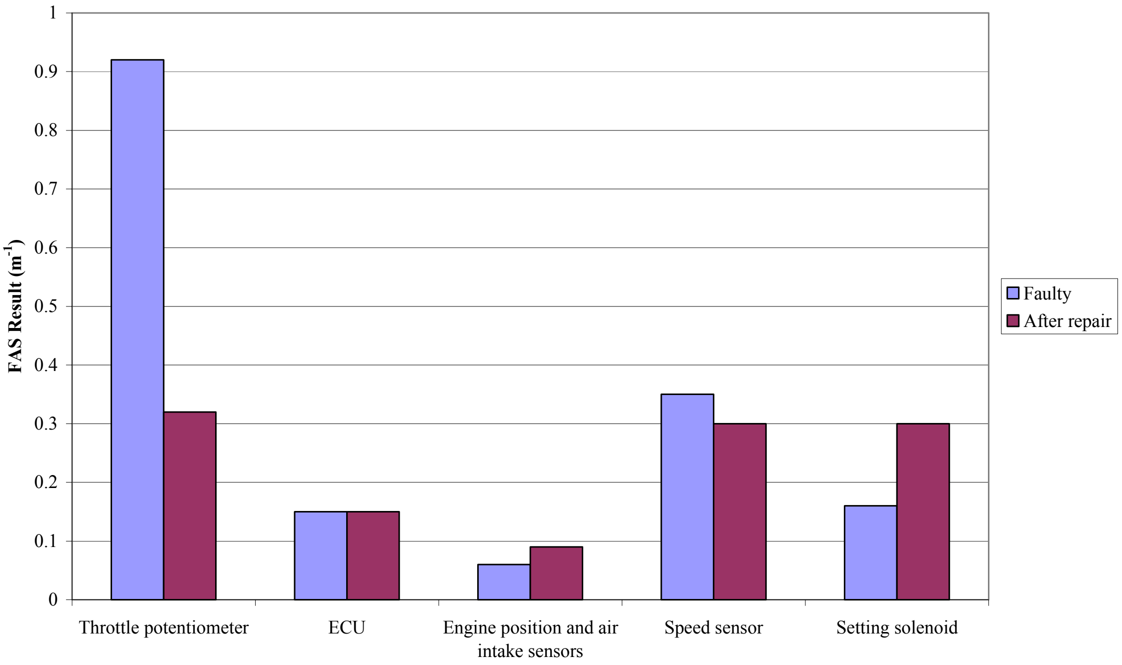


Figure A3.24 Effect of faulty components on FAS result

A 220 hp rigid vehicle with a faulty accelerator potentiometer gave FAS results of around 0.92 m^{-1} and 0.32 m^{-1} before and after repair. That fault aside, none of the other four faults led to changes of greater than 0.15 m^{-1} in the FAS result. Indeed two faults led to reductions in FAS result. This was explained by the engineers as the ECU responding to the presence of a fault by reducing fuelling levels.

The loss of the "speed sensor" signal represents an interesting fault. This is one of two sensors which continually update the ECU with the engine's position. It is used to confirm the engine's position and all times, and provides the timing for the fuel injection. The loss of this signal caused the "check engine" light to become illuminated, and the engine to advance its timing to protect itself. (It is the controlling of this timing that has been a major factor in enabling automotive technology to reduce PM emissions and to improve fuel economy, but at the expense of increasing NO_X emissions. Hence the effects on emissions, including FAS results with the attenuation of this benefit is of interest.) The ECU also reduced fuelling levels (again to limit power thereby protecting itself). The net effect of all these changes was a 0.05 m^{-1} increase in the FAS result.

One vehicle had two faults simultaneously: faulty engine position and air intake sensors . Again the "check engine" light was illuminated. In this case the revised engine mapping within the ECU led to a FAS result of 0.06 m^{-1} when faulty relative to 0.09 m^{-1} when repaired.

In addition to the five vehicles shown in Figure A3.24 there were a further two reported with electronic system faults. Both were repaired by replacing their ECUs and neither vehicle would start in their faulty state. Consequently no FAS data were available prior to repair, and these vehicles are not included in Figure A3.24.

Table A3.7 contains data from three further vehicles. One was in for a routine service and was monitored to provide some data for the question: What are the FAS emissions either side of a service. The vehicle's "check engine" light was not on. However, its post-service FAS result was higher than the pre-service result.

A further vehicle had a water leak from its cylinder head. This was repaired by removing it (a single block on this 150 hp, 4 cylinder rigid truck), it was refaced and refitted using a new gasket. This fault led to a negligible difference in its FAS values. The final fault vehicle encountered was running hot because of coolant loss. This was repaired by replacing the water pump. Again this fault, as would be expected, led to negligible difference in its FAS values.

Unfortunately no vehicles came into any of the service centres with air inlet system faults. During the period when data were collected some faults did occur but these were repaired by the roadside. The faults were several failed turbo compressors and pipe-work on the high-pressure side of the turbo compressor becoming detached (blowing off from the connecting flange). The absence of data is unfortunate because it is anticipated that such faults could cause a potentially large increase in PM emissions. (Indeed this is what was observed for light-duty vehicles; see definition and data for faults in Tables A4.3 and A4.4 of Annex 4.) However, the experience of repair centre managers is interesting –

- for disconnected pipe-work the general experience is that the truck suffers a major loss of power **but does not smoke**. The reason for this is that there are sufficient sensors, e.g. air flow and boost pressure sensors, and appropriate ECU programming such if this fault occurs the ECU prevents over-fuelling from occurring.
- for turbo compressor failure, e.g. due to a broken impellor, again the general view was that little black smoke results. However, in this case any black smoke would probably be hidden by substantial quantities of oil generated smoke as oil that normally lubricates the turbo's bearings, leaks or is blown into the exhaust manifold.

Indeed there are reports of many litres of oil being drained from the silencer/exhaust system as part of the repair activities following a turbo compressor failure.

A3.9.3 CONCLUSIONS AND DISCUSSION

Researching the effects of faults on emissions proved on of the more challenging, with it proving surprisingly difficult to find heavy-duty vehicles with faulty engines (not least to the participating franchised service centres). A number of changes had to be made, relative to the original plan, in response to circumstances. Despite these challenges, overall the primary objective of finding the effects of faults that occurred during normal operation on the FAS test result was met, albeit with less data than ideal.

Whilst there were surprisingly few faulty vehicles found, the data collected does appear to be consistent, illustrating key trends. The changes in FAS result caused by types of faults appears to be largely independent of engine size, with the same trends being observed for smaller 4-cylinder, e.g. 180 hp, engines and larger 6-cylinder, e.g. 420 hp, engines.

Both fuel quality and injector faults consistently led to large changes in FAS result from around, or greater than, 2 m^{-1} for the faulty vehicle to around 0.3 m^{-1} for vehicles when repaired. In contrast, for electronic system faults, where four of the five anticipated categories were encountered, 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.

A3.10 Overall conclusions and recommendations

A3.10.1 TYPES OF TEST PROCEDURES TO BE CONSIDERED

A steering group debated the advantages and challenges for different types of test procedure in the context of likely cost effectiveness and practical considerations. The conclusion from this debate is embodied in the recommendation below.

Recommendation A3.1
Only unloaded test procedures should be considered for the in-service testing of heavy-duty vehicles.

Unloaded test procedures could involve running the engine at a steady speed (as for the two speed idle test for SI light-duty vehicles fitted with three way catalysts) or transient testing. Unloaded transient testing has been found to better reflect PM emissions over loaded drive cycles, although the correlation between the two is poor. This led to the second recommendation below.

Recommendation A3.2
The focus of research should be on FAS testing for modern heavy-duty vehicles.

Research focussed on addressing four issues:

- evaluating the sensitivity of the FAS test result from heavy-duty vehicles to several important parameters,
- evaluating the effectiveness of the current FAS procedure based test programme, particularly with respect to vehicles designed to different emission standards,
- evaluating what faults occur in modern heavy-duty vehicles, and the frequency of their occurrence,
- evaluating the effects of faults on FAS test results.

A3.10.2 SENSITIVITY OF FAS TEST TO PROCEDURE USED

The sensitivity of FAS test results from heavy-duty vehicles to the rate and extent of accelerator pedal depression, ambient temperature, warm up procedure and preconditioning was investigated. The results obtained are reported in Section A3.5 of this annex, and discussed in Section A3.6, together with the conclusions that follow directly from the results. Five recommendations were also made. These can be summarised by the two recommendations below.

Recommendation A3.3
The case for using a FAS test as check of PM emissions has improved with the marked lower variability of test results for vehicles with electronically controlled (as opposed to mechanically controlled) fuelling systems.

Recommendation A3.4
There is no case for introducing further functionality into the test meter to control, or compensate for, variations in the rate and extent of accelerator pedal depression, ambient temperature, warm up procedure or preconditioning.

A3.10.3 SURVEY OF CURRENT FAS TEST PERFORMANCE

The previous section concluded that there were a number of positive aspects regarding the currently used FAS procedure. This led to the realisation that likely improvements would be focussed on better identifying excess emitting vehicles by changing the pass/fail limit. Before either new limits can be proposed or a cost effectiveness analysis could be undertaken, an audit of the current test's performance, and the collection of baseline FAS measurements from appropriately maintained vehicles is required.

FAS test results from around 2,450 tests were collected by Government Vehicle Test Stations (GVTS) staff to form the input data for this study. After filtering the data to leave the first valid test of a vehicle whose age could be calculated from their registration plate, 2,025 entries were left.

It was found 28, 1.38% of those tested failed the emissions (smoke) test.

The failure rate by emissions standard ranged from 0% for Euro 3 vehicles, through 0.74% for Euro 2 vehicles to 5.39% for pre-Euro 1 vehicles. Further the average smoke result decrease from 1.50 m^{-1} for pre-Euro 1 vehicles to 0.44 m^{-1} for Euro 3 vehicles. It was concluded as follows.

- The current 3.0 m^{-1} limit (2.5 m^{-1} for vehicles without a turbo) is too high to detect the vast majority of modern vehicles that excess emitters because of a lack of maintenance or repair.
- The 1.5 m^{-1} limit to be introduced into the UK in 2008 for Euro 4 vehicles is unlikely to improve detection rates.
- The use of a single pass/fail value for all vehicle types is a barrier to the equable testing of vehicles as a means of identifying a higher proportion of the excess emitters.

The principal recommendation from this study is as below.

Recommendation A3.5
The actual failure rates found for the current test procedure, broken down by emissions standard, should be used in the cost effectiveness analysis of Annex 5.

A3.10.4 IDENTIFICATION OF FAULTS AND THEIR FREQUENCY

This study is described in Section A3.8, with its conclusions and discussion contained in Section A3.8.7. The study, which involved sending questionnaires and interviewing workshop managers from OEM franchised service centres and fleet service centres, proved valuable in revealing some recent trends within the freight and heavy-duty vehicles industries.

First and foremost, situations are changing and are doing so relatively rapidly. For example there is a shift away from fleets servicing and repairing vehicles in their own workshops towards centralised, OEM franchised, service centres. Failure rates are also changing, with them being significantly lower now (January 2005) than they were a year ago. Overall best estimates are that heavy-duty engines are currently becoming faulty at a rate of around 10 – 40 faults /100 vehicles /year.

Further generalisations are as follows.

- 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). Gernerally 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 12 – 18 faults /100 vehicles /year.

A3.10.5 EFFECTS OF ENGINE FAULTS ON EMISSIONS

This study is described in Section A3.9, with its conclusions and discussion contained in Section A3.9.3.

The basic approach was for OEM franchised service centres to undertake FAS tests on vehicles with faulty engines before and after repair. The principal finding was that it proved very difficult to find many faulty vehicles. Indeed, the managers of the service centres were predicting around 2 – 5 faulty vehicles a week when the agreements with the were set up, and they believed the 8 week data collection period to obtain data from 16 – 20 faulty vehicles per service centre was eminently achievable. They were all very surprised to find that they could not reach even half these numbers in 17 weeks. Hence a conclusion from the study is that modern electronically controlled diesel vehicles are increasingly reliable.

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 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.

A3.10.6 TECHNICAL OPTIONS FOR COST EFFECTIVENESS ANALYSIS

The preceding section has shown:

- engines in modern heavy-duty vehicles are increasingly reliable,
- in-service testing of such vehicles should use an unloaded procedure – a free acceleration test is the most relevant,
- some (but far from all) engine faults lead to big increases in FAS test result (whether there are corresponding increases in PM emissions over loaded drive cycles is not known),
- the present in-service emissions test currently fails around 1.38% of all vehicles, ranging from >5% for pre-Euro 1 vehicles to 0% for Euro 3 vehicles,
- the results from FAS tests on modern, electronically controlled vehicles are more reliable, show less variability, than for older vehicles with mechanical fuelling systems,
- the current description/specification of the FAS test procedure successfully controls key parameters.

The current in-service test comprises three principal components: the procedure, the instrument used and the pass/fail limit. Given the conclusions that the procedure is currently “satisfactory” and that the meters used are appropriate for the current pass/fail limit, improvements rely on better tailoring the pass/fail limits to identify vehicles that are in need of repair or maintenance.

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 as too is the option of ceasing emissions testing for Euro 4 and later vehicles.

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:	Further stepwise decrease in pass/fail limit that applies to all vehicles.
Option PH4:	Introduce vehicle specific pass/fail limits for each type of vehicle.
Option PH5:	Further stepwise decrease in generic pass/fail limit plus 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.

The cost effectiveness of these six options is calculated in Annex 5

Annex 3 - Appendix 1

Questionnaire sent to OEM franchised repairers

Date:		Organisation:	
Name:		Address:	

Scope of study

The questions asked in all the sections are only concerned with **heavy-duty diesel vehicles that are equipped with electronic control.** In the sections below these are referred to as "modern" heavy-duty vehicles to contrast them from older vehicles whose fuel injection was controlled by a mechanical system.

Section 1 – Numbers of vehicles booked in to workshop

Background – it is assumed that the heavy-duty diesel vehicles that are equipped with electronic control passing through the workshop can be categorised into those:

- requiring routine maintenance
- that broke down on the road
- in for repair of non-engine faults (e.g. lights, wipers, electrical faults, windows, clutch, brakes etc.)
- in for repair of engine faults (e.g. the list given in section 2).

The purpose of this categorisation is estimate the number of such vehicles you routinely maintain, and to determine/project out faults which have an influence on emissions.

For those requiring routine maintenance

How many "modern[11]" heavy-duty vehicles do you have booked in during a typical week?	
How many times is a typical vehicles booked in each year (eg ¾ are seen twice /year, ¼ are seen three times /year)?	

How many "modern[1]" heavy-duty vehicles with engine faults do you estimate you repair a year?	

---

[11] i.e. engines equipped with electronically controlled fuel injection systems

Section 2 - Frequency of engine faults

Types of engine faults	How often do you see these faults (e.g. once a month, 2/year etc)
Fuel system (from fuel tank to injector)	
Air inlet system (from air filter to inlet manifold)	
Electronic systems (ECU, wiring harness, engine sensors etc.)	
Valve train faults (valve timing, cam shaft, valve operation etc.)	
Exhaust system (exhaust manifold through to tail pipe but excluding traps filters etc which are the next item)	
Emission control systems (if fitted – e.g. EGR, traps, filters etc.	
Block and bottom end faults (crankshaft, con rods, pistons, rings, liners etc.)	
Lubrication systems (oil pump, filtration etc.)	
Coolant system (leaks, radiator etc.)	

Section 3 – Ranking of faults

For 4 of the 9 categories listed in Section 2 a list of possible faults has been made. These are listed in the 4 following tables. For each table please rank/order the possible faults by writing **1** in the second column against the fault you encounter most commonly, writing **2** in the second column against the fault you encounter the next most commonly, etc. For faults that you virtually never encounter, please leave the ranking column blank.

Fault	**Ranking** Most common – rank 1 less common – rank 2,3,4 etc. very rarely seen – leave blank	**Any additional comments you may wish to make**

Fuel system faults (rank 1 to 4)

Fuel quality problem (e.g. dirty fuel or blocked fuel filter)		
Fuel system leaks		
Fuel pump fault		
Fuel injector fault		

Air inlet system faults (rank 1 to 5)

Blocked or semi-blocked air filter		
Inefficient/faulty turbo compressor		
Leak/fault in air pipework on high pressure side of turbo compressor		
Problems with intercooler		
Problems with inlet manifold		

Electronic systems faults (rank 1 to 5)

Electronic control unit fault		
Faulty accelerator position sensor		
Faults with other sensors (e.g. boost pressure)		
Wiring harness faults		
Faults with other sensors		

Emission control system faults (rank 1 to 6)

Blocked or semi-blocked filter		
Break up of particulate trap or filter		
Other particulate trap or filter faults		
Stuck EGR valve		
Other EGR system faults		
Faults with other emission control systems (in comments column please specify system)		

Section 4 – Assessing interest regarding further studies

The question below is seeking whether your organisation might be able to help with a further study that involves measuring the “smoke” emissions from a vehicle using a standard free acceleration test. It does not commit your organisation to anything.

Do you as a matter of routine measure the smoke emissions of serviced/repaired vehicles using a FAS test and a standard smoke meter?	Y / N