CITA Study No 4 - Influence of catalyst temperature on effectiveness of in-service testing - Final Report

E A Feest and D C W Blaikley

October 2001

E&E/DDSE/02/022 Issue 1

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Title	CITA Study No 4 - CITA Study No 4 - Influence of catalyst temperature on effectiveness of in-service testing - Final Report
Customer	CITA
Customer reference	
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File reference	
Report number	E&E/DDSE/02/022
Report status	Issue 1

AEA Technology plc
401.8 Harwell
Didcot
Oxfordshire
OX11 0QJ
Telephone +44-(0)1235-434422
Facsimile +44-(0)1235-436322

	Name	Signature	Date
Author	E A Feest		
Reviewed by			
Approved by	M McDonagh		

Executive Summary

This is the Final Report of Study No. 4 within the 2nd CITA Research Study Programme on Emissions Testing at Periodic and Other Inspections. The study is entitled 'Influence of catalyst temperature on effectiveness of in-service testing'.

Study No. 4 originally comprised two main work packages:

- a review of available information and
- a small experimental programme aimed at investigating some of the key relationships indicated by the review under conditions representative of the I/M test arena.

Following completion of the first of these work packages, the review, a presentation on the conclusions reached and the proposed experimental programme was made to the CITA Working Group 1. After discussion it was agreed that the proposed short experimental programme should not proceed as it would not add significantly to the existing body of knowledge, primarily because generalised conclusions could not be drawn from experiments on just one vehicle. This Final Report is therefore based on the review work package only.

The motivation for this work was to explore the technical options for minimising errors of commission in I/M tests resulting from inadequate control of catalyst system condition during the test. The technical review therefore focussed on the scope for:

- measurements (particularly thermal) to verify catalyst condition at the time of test;
- vehicle preconditioning to minimise the possibility of sub-optimal operation of the emissions control system.

The review comprised:

- a brief introduction to the characteristics of operation of catalyst systems;
- a review of available information related to the effects of temperature on emissions and to potential indicators of catalyst system performance;
- a summary of reported studies and regulations related to the influence of catalyst light off in the context of the development and operation of I/M tests;
- relevant results from recent AEA Technology work on the evolution of cold start emissions and on the influence of preconditioning (on road or in test sequence) on the condition and performance of catalyst systems.

The main conclusions of the review were as follows.

- Additional temperature measurements do not appear to have much potential as a means of assessing catalyst system condition prior to I/M tests. This is mainly because of the practical difficulties associated with intrusive measurements and of the complexities of the relationships between individual measurement parameters and the operation of specific emissions control systems.
- There may be scope for providing more prescriptive guidance on preconditioning to both the tester and the vehicle owner, although this would be difficult to specify on the basis of the limited experimental data currently available.
- There is a paucity of information available on the nature and magnitude of the normal ageing behaviour of catalyst-based emissions control systems.

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1 Introduction

This report was drafted as Deliverable D410/1 within Study No. 4 of the 2nd CITA Research Study Programme on Emissions Testing at Periodic and Other Inspections. Study No. 4 is entitled 'Influence of catalyst temperature on effectiveness of in-service testing'. This deliverable comprised a report on current knowledge and the definition of the experimental work proposed for Work Package 420 of the Study. It was submitted in draft form to the CITA Working Group 1's Chairman in June 2000 and formed the basis of a presentation to the Working Group 1 meeting in Essen in September 2001. At that meeting it was decided that the proposed short experimental programme would not add significantly to the existing body of knowledge, primarily because generalised conclusions could not be drawn from experiments on just one vehicle. This final version of the report now comprises the Final Report of the study, thereby satisfying deliverables D401/1 and D400/2. No new work was undertaken after submission of the draft report in June 2000 so the review takes no account of any literature which might have become available after that date.

The context of this study is that the emissions of catalyst-fitted vehicles are largely determined by the instantaneous condition of the catalyst system whereas the procedures for current I/M (Inspection & Maintenance, i.e. in-service) tests do not necessarily take account of the detail of this interaction. This situation may therefore be contributing to events, such as vehicles passing a second test soon after failing a first I/M emissions test, which might lead to the vehicle owners incurring avoidable costs or the credibility of the test with the public being undermined. Recent work (Ref. 1) on warm start effects has highlighted the sensitivity of catalyst light-off (and hence emissions reduction performance) to driving patterns. The main aim of this study is therefore to review relevant available technical information with a view to assessing possible ways of minimising anomalous test results due to catalyst light-off effects in future I/M test procedures – whether dynamometer-based or not.

2 Methodology

Given the limited budget of this study, the approach selected for the review task has therefore been to:

- make maximum use of recently published reviews,
- examine the significance of current, as yet unpublished, research activity,
- discuss with workers known to be active in the field.

The review does not therefore include a comprehensive review of all aspects of the effect of temperature on catalyst performance. Rather it attempts to focus down on those technical aspects most directly relevant to the I/M test requirements and practicalities.

3 Review of existing information

This comprises:
- introduction to the characteristics of operation of catalyst systems;
- a review of available information related to the effects of temperature on emissions and to potential indicators of catalyst system performance;
- a summary of reported studies and regulations related to the influence of catalyst light off in the context of the development and operation of I/M tests;
- a summary of relevant results from recent AEA Technology work on the evolution of cold start emissions and on the influence of preconditioning (on road or in test sequence) on the condition and performance of catalyst systems.

3.1 CATALYST SYSTEM TECHNOLOGIES

The use of catalysts to control vehicle emissions stems from air quality concerns in Japan and the USA. Oxidation (for carbon monoxide and hydrocarbon) catalysts were introduced in the USA in 1975, and three-way catalysts to include oxides of nitrogen (NO_x) control in 1981. In Europe, Directive 93/15/EC (Euro I) required passenger cars to be catalyst-equipped from 1993. However, catalysts were in use in many European countries before 1993.

The catalyst usually consists of a ceramic or metallic honeycomb substrate coated with fine precious metals particles dispersed in a high surface area ceramic-based washcoat. The catalyst is mounted in a stainless steel container using wire mesh and intumescent mat which must maintain a positive pressure between the substrate and container. Catalysts were traditionally mounted underfloor, often replacing the first silencer box. As a result of the increased emission control requirements, vehicle manufacturers have progressively incorporated exhaust systems that use close-coupled catalytic converters instead of, or in conjunction with, the underfloor converter. By placing the converter at the exhaust manifold, the catalyst can typically achieve its operating temperature more quickly thereby reducing cold start emissions.

In a vehicle that uses the current technology of a lambda sensor, electronically controlled fuel injection and a three-way catalyst, the engine's electronic management system receives inputs from a number of sensors. It uses these to find the fuel map appropriate to the engines current circumstances, and the fuel map determines the amount of fuel to be injected. This closed loop control is used to maintain the engine out exhaust gases within composition ranges required for effective catalyst operation.

The evolution of OBD regulations and the potential for making use of the arising vehicle technologies in improving the effectiveness of in-service emissions tests is being covered in a parallel Study within this Programme.

3.2 EFFECT OF TEMPERATURE ON EMISSIONS

Engines and catalysts warm up at different rates, and it is well documented that for a catalyst to work effectively it must both be above its 'light-off' temperature, and be supplied with an appropriate mixture of gases (i.e. the air/fuel ratio should be stoichiometric). The generally acknowledged view (Ref. 2) is that the time required for catalysts to attain their light-off temperature is considerably shorter than that required for the engine to warm up (e.g. 2 minutes for the catalyst rather than eight minutes for the engine). Experiments with pre-heated catalysts have resulted in only quite small improvements in emissions being seen for cold starts (Ref. 2). Therefore, the principal inhibitor to the catalyst operating efficiently under cold start condition is the cool engine providing gases that have too low an oxygen concentration for the catalyst to effect conversion, irrespective of whether the catalyst is above its light-off temperature or not.

Ambient air temperature affects cold start emissions by:
- changing the rate of cooling, and thereby the 'engine temperature' the vehicle has reached when it restarts,
- changing parameters involved in the combustion process.

For gasoline cars whose fuel system uses a carburettor, changes in ambient temperature would lead to different air/fuel ratios being supplied to the cylinders because the carburettor does not deliver fuel according to the air mass flowing through it, rather the volume of air. For these vehicles emissions are a function of ambient temperature, and similarly cold start emissions are also a function of ambient air temperature.

Modern technology gasoline cars, designed to meet the current type approval legislation, are equipped with an air flow meter, which is usually a hot film sensor measuring the mass of air delivered. The engine's control unit also senses the inlet air temperature and uses these data to control (via fuel maps) the appropriate amount of fuel to be added for the air/fuel ratio to remain within narrow limits, irrespective of climatic conditions. Further, for a hot engine, closed loop control between the lambda sensor and the fuel supplied also ensures compensation occurs for ambient conditions. Therefore, for the more recent vehicles, cold start emissions from a vehicle starting at the same initial 'engine temperature' are not significantly affected by climatic conditions generally, or ambient temperature specifically.

The time interval during which the engine is switched off is known as the soak time. During this period the engine (and its catalyst) cools so that on restart it is not at its normal operating temperature and produces excess cold emissions. There is clearly a soak time/cold start emissions relationship with "temperature" being the unifying parameter. In this relationship, the rate at which the engine cools, will be further complicated by a number of factors given in the following table.

Factors influencing the rate of cooling of a parked vehicle

Factor	Nature of effect
The engine size	Larger vehicles will have a smaller surface area/mass ratio and hence might be expected to cool more slowly.
Its mounting within the vehicle	The rate of cooling of a mid-vehicle mounted engine will differ from an engine mounted near an open grill under the bonnet.
Ambient temperature	Cooling rates are proportional to temperature gradients.
Ambient climatic conditions, especially wind speed	Forced cooling rates are higher than equivalent rates in calm conditions.
The geography of the parking venue	There will be different cooling rates for parking in an exposed position to within an enclosed space.
Parking direction	The rate of cooling of a vehicle will be different when parked with its bonnet facing the wind, and with its boot facing the wind and its bonnet on the lee side.

Ultimately, after a sufficient soak period, the engine reaches the ambient air temperature. It is well documented that the cold start emissions are strongly dependent on this temperature, increasing significantly for temperatures below 20°C (see for example Refs. 2-5).

One early study (Ref. 6) showed that transient hydrocarbon emissions appeared to increase approximately linearly with $\log_{10}$ of the soak length. However, emissions of CO (plus NO_x and fuel consumption data) did not support this mathematical relationship, and at this stage it would be prudent to treat this as an as yet unsubstantiated hypothesis, rather that the basis for predictions. There is also the question of the extent to which a study conducted in 1978 is representative of the current, or future, passenger car fleet. Boulter remarks in his review (Ref. 2) that few studies have addressed the effect of soak time, and the search of recent literature has revealed little further information.

Many tests have concentrated on measuring the excess cold start emissions that occur for a vehicle left to soak for 6 - 16 hours at 20-30°C (the conditions specified for Type Approval) and other studies have measured the excess cold start emissions (ECSE) from vehicles starting below 20°C. However, there are very few data from warm or tepid starts, i.e. ECSE from a starting temperature between ambient and the engine's normal operating temperature

TRL has reported some pertinent data, obtained from six catalyst and three diesel passenger cars, where each vehicle was fully soaked to ambient temperatures of -10, 0, 10, 20 and 30 °C and the second-by-second emissions from these vehicles tested over a TRL-defined test cycle (Ref. 2). The data for the average pollutant emissions from all 6 catalyst cars show a small increase in the CO_2 emissions for the cold starts relative to the equivalent hot start (i.e. in excess emissions) that increases from 4.4% for 30°C starting to 19% for -10°C starting. The figures for CO illustrate the importance of cold starting to CO emissions, the excess emissions rising from 8.6g for 30°C starting to 80g, (a 460% increase) for -10°C starting.

However, the excess NO_X emissions are relatively constant, small and negative (i.e. less NO_X is produced on cold start relative to an equivalent hot start). For the three diesel engines tested there are similar increases in CO_2 emissions, but the excess CO emissions range from around 3g for 30°C starting to 10g, (a 160% increase) for -10°C starting. For diesel engines TRL found the excess NO_X emissions are moderately small and positive (i.e. less NO_X is produced on cold start relative to an equivalent hot start). Overall, for CO, diesel-engined vehicles gave much lower excess cold start emissions than gasoline fuelled engines.

Catalyst performance can be affected by reversible deactivation of active sites by coking or by other deposits or adsorbed species. In cases where previous driving patterns have not provided the conditions for thermal desorbtion of such deposits, appropriate preconditioning to generate higher catalyst temperatures can be used to improve the catalyst efficiency.

Number-based or mass-based measurements of size-differentiated particulate emissions are not yet incorporated into the vehicle emissions regulatory framework although recent and current projects have been concerned with the practicalities associated with their inclusion (e.g. Ref. 7). In the event of these measurements cascading down into the I/M arena, peculiar transient temperature effects may have to be taken account of. For example, there is mounting evidence that the number flux of ultrafine particulate emissions from gasoline vehicles is significantly influenced by the burning off of lubricant deposits in the catalyst or elsewhere in the exhaust system. Their measured flux in the tailpipe emissions is thus strongly dependent on the vehicle operating conditions prior to test with deposited precursors being driven off from exhaust system internal surfaces as their temperatures are progressively increased. Measured values can therefore be dependent on the driving pattern or preconditioning immediately prior to the test.

3.3 INDICATORS OF CATALYST SYSTEM PERFORMANCE

3.3.1 Emissions measurements

In the context of the I/M objectives of this study some aspects of emissions measurements from catalyst systems need to be appreciated when interpreting thermal data.

Catalyst 'light–off'

A catalyst needs to reach a certain temperature, known as 'light-off', before it becomes operational. There are two commonly accepted definitions of light-off temperature:
- the temperature at which any emissions reduction is first seen,
- the temperature at which 50% emissions reduction of a particular pollutant is observed, i.e. T_{50}.

The latter assumes near 100% reduction at a higher temperature. We have observed (Ref. 8) that light-off can be quite sharp, i.e. a few tens of degrees can take the catalyst from 0 to 100% emissions reduction – hence T_{50} can be a convenient measure.

Whereas a measure of the inlet temperature may give a good guide to light-off temperature, it will not represent the operational temperature of the catalyst because of the exothermic reactions taking place. The exhaust temperature will be much closer to this but our experience (Ref. 8) has showed that this is still likely to underestimate the peak temperature for two reasons:

- heat losses from the catalyst body and exhaust pipework to the measuring point (even if this distance is minimised),
- the temperature differential between the catalyst surface and exhaust gases.

Thermocouples inserted into the catalyst would give a much better guide although even then the longitudinal and radial thermal gradients within a catalyst would have to be considered.

Catalyst light-off temperature is therefore not a simple parameter.

Ageing issues

The measurement of regulatory pollutant emissions is clearly the most direct indicator of the performance of the catalyst system. In the context of I/M testing the relevant indicators have to be formulated in the context of the performance deterioration processes taking place under normal and abnormal service conditions.

Catalyst durability, in terms of emissions limits at 50,000 and 100,000 miles, is already legislated for in the USA. Directive 98/69/EC (Euro III) brings stricter catalyst durability requirements for 80,000 km from 2000. 100,000 km requirements for Euro IV legislation (2005) are being discussed. It must be remembered that these durability requirements are coupled with increasingly challenging emissions limits.

Regulations for both original equipment and replacement catalytic converter type approval (Refs. 9,10) specify a default deterioration factor of 1.2 for the regulatory pollutants in the case of positive ignition engines and this could therefore be regarded as an indicator of anticipated deterioration in use.

There is evidence from laboratory studies using simulated exhaust streams (Ref. 8) that with ageing:
- the catalyst light-off (T_0) temperature rises,
- the light-off is more gradual,
- the percentage reduction by the fully-lit catalyst is reduced.

The magnitude of these effects has been studied recently (Ref. 22) in an onging programme of experiments on high-mileage fleet-aged catalysts which are emissions tested over the initial stages of the FTP cycle both as aged and after washing out the assumed contaminants. In these studies the ageing typically doubled the time to effective light-off.

Results from a recent study (Ref. 11), which included both I/M and chassis dynamometer emissions data for a high mileage vehicle fitted with its original catalyst and also with a new OE replacement catalyst, were consistent with these trends in ageing. They also indicated that a deterioration factor of 1.2 might be an underestimation of reality for ageing times in excess of the current 80,000 km regulatory requirement, although no statistical significance can be drawn from this single vehicle experience.

Catalyst activity might be reduced or ultimately destroyed by for example:
- coating of active surface sites, e.g. by coking,
- poisoning by lead, sulphur, zinc, phosphorus,
- mechanical or thermal shock damage.

A common cause of degradation is 'overfuelling', resulting in progressive irrevocable sintering of the high surface area active components, which could be caused by:
- engine misfire,

- lambda sensor failure due to either to dirt or to mechanical failure,
- air flowmeter or water temperature sensor failure,
- electrical contact failure, e.g. exposed connection at lambda sensor which suffers extreme conditions of hot/cold/wet etc.
- worn, dirty or malfunctioning fuel injectors.

Zinc and phosphorus, which mainly come from zinc dialkyl dithiophosphate (ZDP) and other materials found in engine oils, can give oxide deposits on the catalyst surface. Lead poisoning could result from the wrong choice of fuel at the pump but this possibility is being reduced as leaded fuel is being phased out. Sulphur poisoning from fuel sulphur is considered to be reversible.

Depending on the detail of the causal events, many of the above deterioration mechanisms can lead to reduced catalyst effectiveness without necessarily resulting in immediate or eventual catastrophic failure and this should perhaps be borne in mind when setting I/M procedures and thresholds.

3.3.2 Temperature measurements

Engine temperature measurements

For vehicle testing the commonly used measures of the engine's temperature are:
- the temperature of the engine's coolant water system,
- oil in the sump via the dipstick access point.

Publications often omit the practical detail of exactly where in the vehicle's system temperatures were measured: hence some care needs to be exercised in interpreting the available data. There has been some discussion in the literature regarding which is the more appropriate for predicting cold start emissions (see for example Refs. 2, 12-14). Plots of emissions changes against possible indicative temperatures were obtained by Joumard et al (Ref. 15). Such plots enabled the authors to determine minimum temperatures for which emissions could be considered steady. It was concluded that, of the two listed above, water temperature seemed to give the best indication of engine thermal conditions for the whole range of pollutants.

In a vehicle meeting current legislative requirements (that uses the current technology of a lambda sensor, electronically controlled fuel injection and a three way catalyst) the engine's electronic management system receives inputs from a number of sensors. It uses these to find the fuel map appropriate to the engine's current circumstances, and the fuel map determines the amount of fuel to be injected. One of the inputs is the "engine's temperature" and the temperature normally used is that indicated by a sensor located in the water cooling circuit within the block. Therefore it may be that the water temperature is directly associated with the amount of fuel injected, and consequently with the emissions leaving the engine.

Nevertheless, when modelling cold start emissions we have found that the water temperature heating profiles tend not to be as reproducible as those for the engine oil or the block (Ref. 1). Of the latter two, we prefer to use oil temperature as this is a parameter more normally measured and reported in the literature. It also removes any ambiguity as to where on the engine block the temperature was measured.

Exhaust gas temperature measurements

Exhaust gas measurements are used in R&D projects to investigate the operation of emissions control systems. Measurements close to the manifold give information on the engine out combustion conditions and the inlet temperatures for close-coupled systems. In Ref. 16 for example it has been shown that maximum inlet temperatures for close-coupled converters are not necessarily higher than for underbody converters. Measurements upstream and downstream of catalytic converters are used to monitor light-off phenomena (e.g. the work described in Section 4 below). Tailpipe gas temperatures have also been investigated as a potential indicator of catalyst light up. However in one of the studies summarised in sub-section 3.4 below there was no indication that this temperature alone could indicate that transition.

Catalyst temperature measurements

The most direct measure of catalyst temperature would be via temperature sensors within the catalyst brick(s) and this is the method adopted in the more rigorous R&D studies. Even without worrying about the most appropriate location(s), it is clearly inappropriate for I/M application because of the impracticality of non-destructive insertion and the unacceptability of retrofitting appropriately robust sensors or incorporating them during manufacture.

Arguably the next best option would be to measure the temperature at the centre of the exhaust face of the catalyst by means of a probe inserted through the tailpipe. This is essentially a special case of an exhaust gas measurement. This too is unlikely to be a viable option for I/M application because of the practicalities of access through the various complex exhaust system architectures encountered.

Catalyst container external temperature might be considered to be a practically viable option. However recent modelling and experimental validation work on catalytic converter cool down after engine shut off has highlighted the complexity of the relationships between internal gas flows, substrate temperatures, support mat temperatures, external air temperatures and flows and the container surface temperature (Ref. 17). This surface temperature may for example peak hundreds of seconds after engine shut off. This temperature is therefore unlikely to provide a reliable indicator of catalyst condition with respect to light-off unless used in conjunction with many other parameters. It does at least however give a lower limit to the temperature within the catalyst.

3.4 STUDIES AND REGULATIONS CONCERNED WITH THE DEVELOPMENT AND OPERATION OF IN-SERVICE TESTS

Regulations

The original EC Directive 92/55/EC established guidelines for common in-service testing standards throughout Europe. In it the only reference to preconditioning was that the initial CO test at idle be performed "after a suitable period of engine conditioning".

The current Directive 96/96/EC, amended by 1999/52/EC, lays out the minimum requirements for I/M within the European Union. With respect to positive-ignition (petrol) engines, it defines exhaust emission limits in terms of CO levels for three categories of vehicle: pre 1 October 1986, post 1 October 1986 and catalyst equipped with lambda-probe

control. For catalyst-equipped vehicles, the engine should be conditioned in accordance with the manufacturer's recommendations. Generally this means that the oil temperature should be at 80°C or above. 96/96/EC does not explicitly specify any of:
- ambient conditions (temperature, humidity),
- engine exhaust outlet temperature (other than through a minimum oil temperature),
- catalyst temperature (inlet, body, outlet),
- engine/catalyst preconditioning,
- time between engine preconditioning and test (relative cool down and heating rates of oil and catalyst),

all of which may affect the emissions results to a greater or lesser extent.

The UK Vehicle Inspectorate Executive Agency's 1996 MOT exhaust gas analyser specification includes requirements for the following test procedure prompts.
- During engine preconditioning, oil temperature should have reached manufacturer's specification (or 60°C as default) and if not the engine should be run at 2000-3000 rpm until that temperature is achieved.
- For the fast idle test, speed raised to fast idle during 10 seconds countdown and then maintained at fast idle during 30 seconds countdown.
- If fast idle test fails, then raise to 2000-3000 rpm during 10 seconds countdown and maintain for 180 seconds as an additional preconditioning.
- Prior to natural idle test, raise to appropriate fast idle speed during 10 seconds countdown and maintain over 30 seconds to stabilise catalyst.

We understand that during the consultation exercise preceding the adoption of the above specification the possibility of incorporating a measure of catalyst temperature was considered. It was rejected on grounds which included the practicalities of inserting a temperature probe to a relevant location within the exhaust system bearing in mind the range of exhaust system architectures.

In the UK, motorists are advised that wherever possible vehicles should arrive at the test station with the engine at its normal operating temperature, e.g. after a drive of around 8 km (Ref. 18), and the tester is advised to do the emissions test 'as soon as possible after driving on the road' (Ref. 23).

In the USA in-service test requirements vary from state to state from a requirement of no emissions testing through idle-based, steady state dynamometer and transient dynamometer tests.

For the IM240 test, which is based on a shortened form of part of the FTP Urban Driving Dynamometer Schedule, the latest technical report recommends the following advice on vehicle conditioning (Ref. 19).
- Queuing time. When the vehicle queue exceeds 20 minutes, a vehicle shall get a second-chance emission test if it fails the initial test and all criteria exhaust components are at or below 1.5 times the standard. At the state's discretion, second-chance testing may be granted if criteria exhaust components exceed any present level above the standard.
- Discretionary preconditioning. Any vehicle may be preconditioned by manoeuvring the vehicle on to the dynamometer and driving the 94 to 239 second segment of the transient cycle……. This method has been demonstrated to adequately precondition the vast majority of vehicles (SAE 962091).

The EPA consider that preconditioning remains the subject of debate: "…work done in Arizona has lead to what is called the AZ147 cycle. This cycle is based on a study that shows that the initial hill of the 240 cycle does not really function as a catalyst warm up due to low gas flow. The 147 drops the first hill and instead uses three second hills as the test" (Ref. 20).

Studies prior to adoption of UK in-service test procedure for catalyst equipped vehicles

A programme (Ref. 21), carried out by TRL on behalf of the UK Department of Transport, investigated some of the practicalities involved in applying an in-service test compliant with EC Directive 92/55/EC. The following results from that study have a bearing on preconditioning issues.

Emissions lab measurements were carried out on 56 vehicles subjected consecutively to:
- cold start UDC + EUDC test,
- IM240 transient cycle test,
- 5 engine speed x 5 engine load steady state test matrix,
- 2000 rpm idle test,
- 3000 rpm idle test,
- natural idle test,

with modal CO and HC+NO_x measurement made on all tests and with garage meter CO measurements made on idle tests and lambda measurements made on the fast idle tests. These experiments identified the need to ensure that under cold conditions both engine and catalyst are up to normal working temperature before emissions testing. Provisional recommendations were to:
- run engine until at normal running temperature,
- raise engine speed to about 2500 rpm and hold for 20 seconds,
- return to idle and check emissions,
- if emissions excessive, increase speed to 2500 rpm for 20 seconds,
- return to idle,
- increase speed to 3000 rpm for 20 seconds or until emissions stable.

Field trials were carried out on 270 vehicles in selected test stations using a test procedure which included:
- initial warm-up by running the engine until it reached its normal operating temperature,
- precondition the catalyst by raising engine speed to 3000 rpm for 60 seconds,

before executing the prescribed fast idle and natural idle emissions tests. Recommendations included the need for warm-up to be carried out without sample probe inserted to avoid condensation and HC hang-up problems.

The study included visits to German and Austrian test centres which revealed the following information relevant to preconditioning. German test practice involved:
- ensuring that the oil temperature (via probe) is not below manufacturer's specification, if necessary by increasing engine speed to 3000 rpm or higher at the discretion of the tester,
- giving a discretionary further higher engine speed preconditioning if the fast idle results are unacceptable to ensure catalyst is up to temperature.

Preconditioning problems included:
- the time taken for engine oil to reach the required temperature especially in winter and hence the tester's encouragement of the vehicle owner to idle their engines for about 10 minutes prior to the test,

- the possibility, during waiting prior to testing, of catalyst cool off without the engine temperature falling below the specified level.

There were still no guidelines for the preconditioning prior to a second fast idle test.

Some tests were carried out to investigate practicalities of achieving catalyst light-off at idle. 14 catalyst-fitted cars were tested after parking outside at temperatures down to 0°C for over 2 hours. The test cycle comprised 20 seconds at idle, then Crypton Emissions Analyser measurements at 30 second intervals over a period of 5 minutes at idle and then several minutes at 2500 rpm until light-off was indicated by low CO & HC emissions and finally 60 seconds at natural idle. Exhaust temperature (200mm into the tailpipe) and oil temperature (via sensor in dipstick hole) were logged continuously. These experiments showed that:

- the catalyst did not generally light up until the engine is subjected to a period of high idling,
- the exhaust temperature did not indicate light-off (e.g. via a sudden increase) whereas it did respond to changes in engine speed,
- oil temperatures corresponding to light-off (as indicated by emissions) ranged from <30 to >60°C.

Therefore, if a hot engine is left standing for several minutes prior to test the catalyst could cool down even though the engine is still hot. However, light-off is likely to be achieved quicker with a hot engine than with a cold engine.

Further field trials were then carried out involving 142 tests to a revised test procedure which included:

- an additional preconditioning sequence (raising engine speed at operator's discretion for up to 3 minutes until emissions within limits) before the optional second fast idle test,
- the inclusion of a minimum oil temperature requirement prior to test.

These trials indicated the value of the repeat fast idle test in avoiding errors of commission and identified some practical problems associated with oil temperature measurement.

3.5 RECENT RESULTS ON INFLUENCE OF VEHICLE PRECONDITIONING ON CATALYST PERFORMANCE

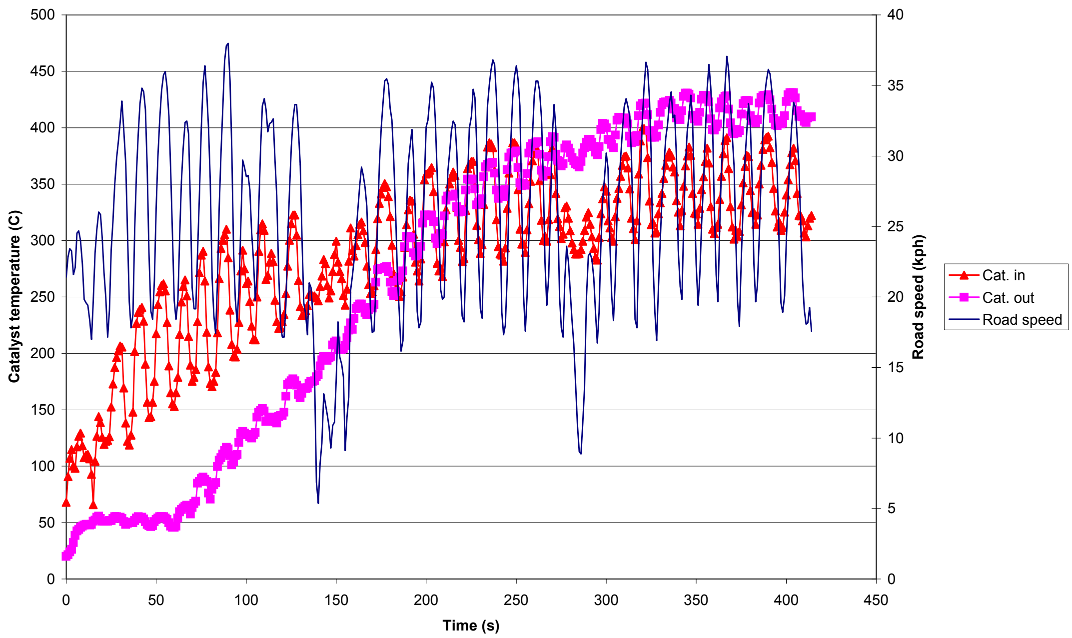
Traffic calming studies

AEA Technology undertook a campaign of vehicle emissions measurements aimed at determining the effect of various traffic management schemes on emissions of regulatory pollutants (Project UG127 in the DETR's TRAMAQ Programme). That campaign involved measuring emissions from a wide range of light duty diesel and gasoline vehicles over chassis dynamometer drive cycles simulating a series of real world routes before and after installation of traffic calming measures. For each vehicle and traffic management scheme, emissions measurements were typically made over the test sequence:
1 - without calming, 2 - with calming, 3 - with calming, 4 – without calming,
with a vehicle preconditioning sequence (usually EUDC) applied before the first and third tests. Whilst this procedure gave rise to consistent repeat results within the test sequence when diesel vehicles were tested, repeatability was not achieved in many cases when catalyst-fitted gasoline vehicles were tested. This was originally attributed to catalyst light-off temperature not being achieved or not being maintained over the test cycle. A more severe preconditioning (2 minutes at 120kph) had been tried to ensure catalyst light-off but this also failed to give the sought after reproducibility.

In an effort to understand and overcome this lack of reproducibility, vehicle preconditioning has been more fully investigated in a programme that involved experiments on a single vehicle drawn from the range of vehicles used in the previous measurement campaign. For these experiments, however, the vehicle was instrumented to monitor and log key operating parameters including pre- and post-catalyst temperatures as an indicator of catalyst performance. The experimental programme included on-road measurements over a traffic management scheme, chassis dynamometer emissions measurements over test schedules representative of those made in the earlier campaign and chassis dynamometer emissions measurements over test sequences aimed at understanding and optimising the test procedure.

Figure 1 shows the pre- and post-catalyst temperatures and road speed for a cold start drive three times over the raised humps speed curbing scheme at a village in Oxfordshire (the Sutton Courtenay calmed cycle). It took ~4 minutes for the catalyst exhaust temperature to reach the catalyst inlet temperature. Thereafter the catalyst exhaust remained at a higher temperature than the inlet, implying that once lit it was in continuous operation.

Figure 1. Catalyst temperatures and road speed after a cold start at Sutton Courtenay (calmed scheme with raised humps).



Figures 2 and 3 show the recorded catalyst inlet and outlet temperatures respectively over a Sutton Courtenay calmed cycle (average speed 25 kph) on the chassis dynamometer after preconditioning with an uncalmed cycle (average speed 35 kph, duration 5 minutes) and after 120 kph preconditioning and during real-world road work. It can be seen that the temperatures after preconditioning with the uncalmed cycle match the real-world road work quite closely, whereas the temperatures after the 120 kph preconditioning are significantly higher. Higher, i.e. worse and arguably more realistic, emissions were obtained using the slow speed preconditioning.

Figure 2.

Catalyst inlet temperatures for Sutton Courtenay calmed scheme

i) On chassis dynamometer after conditioning with an uncalmed (low speed) cycle

ii) On chassis dynamometer after conditioning with 2 min at 120 kph
iii) Real-world road-work

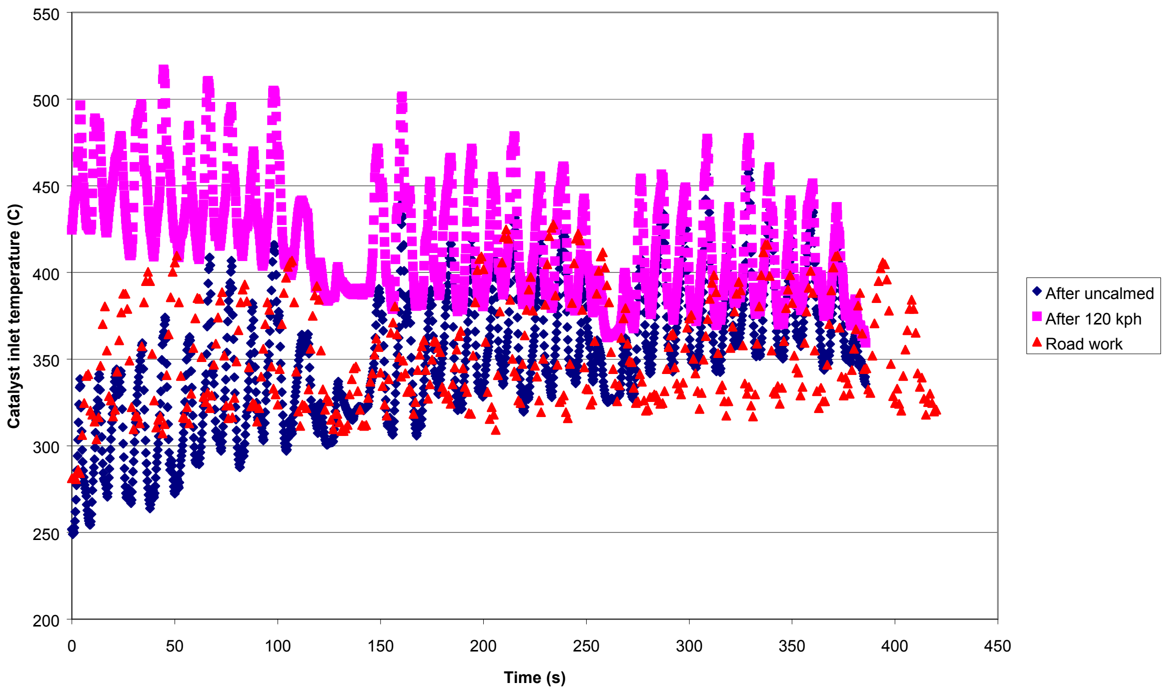
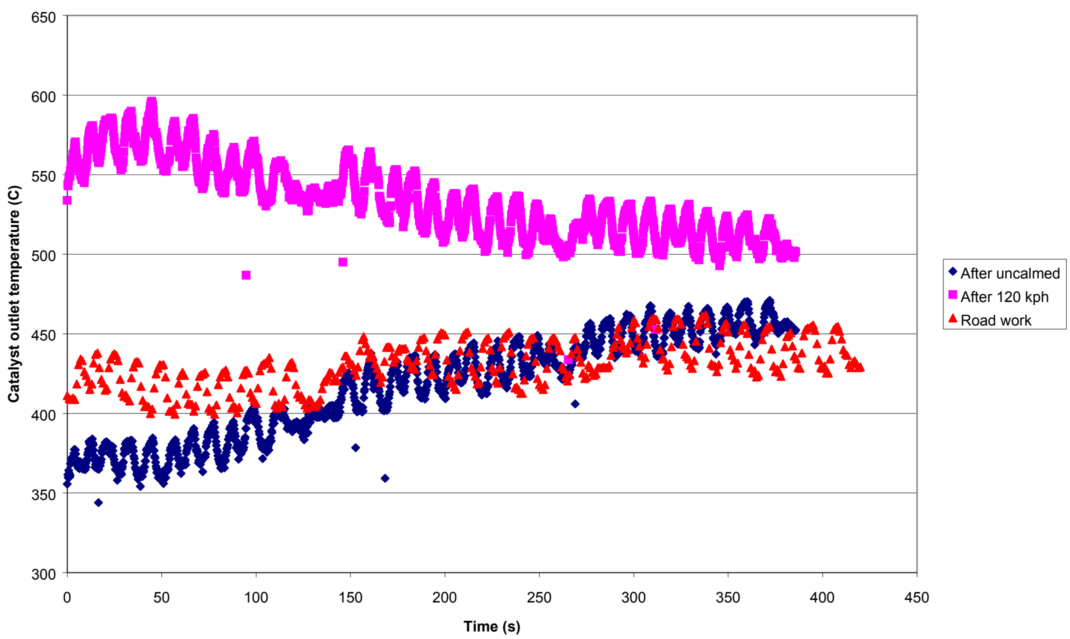


Figure 3.
Catalyst outlet temperatures for Sutton Courtenay calmed scheme
iv) On chassis dynamometer after conditioning with an uncalmed (low speed) cycle
v) On chassis dynamometer after conditioning with 2 min at 120 kph
vi) Real-world road-work



These results illustrated the importance of tailoring preconditioning sequences to the objectives of the test, which in this case were to achieve real world drive cycle emissions factor measurements that are both reproducible and representative of the real world behaviour of the vehicles. Similar considerations would also when defining test procedures and pass/fail criteria for short cycle based I/M tests.

Cold start studies

AEA Technology has recently completed a project, within the UK DETR's TRAMAQ Programme (Ref. 1), aimed at investigating vehicle cold start emissions so that their effects on actual parking control scenarios can be assessed. The experimental study provided a comprehensive map of the behaviour of key engine temperature indicators under cold to warm ambient conditions and variable engine start temperatures. In addition, these measurements along with emission measurements provided data on warm up and cool down characteristics for a range of 10 representative vehicles plus their excess emission generation when subjected to real world drive and parking scenarios. From this, a computer-based model was developed to predict cold and warm start emissions from vehicles in order to assess the effects of cold start emissions on actual vehicle parking control scenarios.

In the experimental programme, each vehicle was instrumented to allow second-by-second (modal) measurements of key temperature parameters (inlet air, oil, coolant, block, pre-catalyst exhaust gas and post-catalyst exhaust gas) which can be correlated with the modal gaseous emissions (THC, CO, CO_2 and NO_x). After overnight cold soaks, each vehicle had the above data logged over two consecutive ECE-15 cycles (thereby yielding eight identical components that can be treated/analysed separately). The temperature matrix used is shown below.

Ambient	Engine Temperature (°C)					
Temp (°C)	-7	0	10	20	40	60
-7	1	1	1	1	1	1
0		1	1	1	1	1
10			1	1	1	1
20				1	1	1

The first two vehicles tested were a VW Golf TDI (diesel) and a Vauxhall Vectra (gasoline). Ambient temperature appeared to play no significant role in the amount of excess emissions produced whereas engine temperature was the most influential parameter.

The following two tables give an insight into the relative speeds of warm up of engine and catalyst. In these tables the emissions were measured by integrating the modal data over the segment of the cycle. The duration of each segment is about 205 seconds.

Emissions from a GM Vectra over 2 ECE cycles (8 segments) after a cold start at 22°C.

	Emissions (g/segment)				Temperature at end of segment (°C)		
Segment	CO_2	CO	THC	NO_x	Oil	Catalyst inlet	Catalyst outlet
1	422	7.256	0.569	0.571	42	279	459
2	292	1.648	0.150	0.331	57	300	378
3	286	0.857	0.075	0.066	73	317	396
4	271	0.461	0.041	0.081	84	325	400
5	293	0.229	0.031	0.166	91	337	417
6	267	0.189	0.025	0.062	95	334	412
7	280	0.729	0.035	0.206	99	342	420
8	297	0.320	0.029	0.123	99	337	419

Emissions from a GM Vectra over 2 ECE cycles (8 segments) after a cold start at -7°C.

	Emissions (g/segment)				Temperature at end of segment (°C)		
Segment	CO_2	CO	THC	NO_x	Oil	Catalyst inlet	Catalyst outlet
1	354	34.003	6.987	2.558	19	230	192
2	324	7.716	1.920	1.001	39	283	322
3	295	1.332	0.508	0.583	54	305	370
4	277	0.796	0.265	0.493	67	315	387
5	269	0.818	0.187	0.479	78	323	392
6	261	0.483	0.131	0.467	84	327	399
7	253	0.884	0.113	0.427	88	328	402
8	254	0.475	0.082	0.313	91	326	388

In the case of the 22°C cold start experiments, the difference between catalyst inlet and outlet temperatures indicated that light-off had been achieved by the end of the first test cycle segment whereas it took longer for the engine temperature and emissions to stabilise. In the case the -7°C cold start experiments light-off was postponed until some time during the second segment but this was still before the engine temperature and emissions had stabilised. This is consistent with the general view that engine temperature is a more reliable indicator of readiness for a meaningful I/M test.

4 Discussion and recommendations for experimental work

4.1 DISCUSSION

The motivation for this work was to explore the technical options for minimising errors of commission in I/M tests resulting from inadequate control of catalyst system condition during the test.

The technical review has focussed on the scope for:
- measurements (particularly thermal) to verify catalyst condition at the time of test;
- vehicle preconditioning to minimise the possibility of sub-optimal operation of the emissions control system.

Whilst this has been a relatively superficial investigation the general view to emerge is that:
- there is little scope for additional measurements proving effective, particularly in view of the practical difficulties associated with intrusive measurements and of the complexities of the relationships between individual measurement parameters and the operation of specific emissions control systems;
- there may be scope for providing more prescriptive guidance on preconditioning to both the tester and the vehicle owner, although this would be difficult to specify on the basis of the limited experimental data currently available.

There is a paucity of information available on the nature and magnitude of the normal ageing behaviour of catalyst-based emissions control systems. This inadequacy of understanding is an obstacle to, for example, the reassessment of pass/fail thresholds.

4.2 PROPOSED EXPERIMENTAL PROGRAMME FOR WORK PACKAGE 420

An exploratory experimental work was proposed with a view to investigating some of the key relationships indicated by the above review under conditions representative of the I/M test arena. This work programme is set out in Annex A. Its aim was to generate some quantitative data on the effect of specific preconditioning sequences on measured emissions, thereby indicating the potential viability of reducing errors of commission in I/M testing by means of changes to the test procedure.

This proposition was discussed at the meeting in September 2001 of CITA Working Group 1. At that meeting it was decided that it would not be worth proceeding with this experimental programme, primarily because the results would be specific to the technology represented by the single vehicle tested and could therefore not be generalised to vehicle technologies representative of future national fleets within Europe.

5 Conclusions

- There is little scope for additional thermal measurements during I/M testing proving effective in reducing errors of commission.
- There may be scope for providing more prescriptive guidance on preconditioning to both the tester and the vehicle owner, although this would be difficult to specify on the basis of the limited experimental data currently available.
- There is a paucity of information available on the nature and magnitude of the normal ageing behaviour of catalyst-based emissions control systems and this may inhibit optimisation of pass/fail limits.
- A limited experimental programme, as envisaged at the outset of this study, would not be adequate to significantly address the identified shortcomings in available data.

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Annex A.

PROPOSED EXPERIMENTAL WORK FOR WORK PACKAGE 420

Phase 1. Generation of thermal and emissions data under typical idle I/M test scenarios

This work would be carried out on a chassis dynamometer using a conventional gasoline-engined passenger car with standard emissions control (lambda sensor and underfloor catalyst) with high mileage on the original catalyst. The car would be instrumented for logging the following temperatures: engine oil at dipstick; exhaust gas at catalyst inlet, catalyst outlet and tailpipe. The temperatures and regulatory emissions would be logged on a second-by-second basis.

The test sequence would be:
- take engine from cold to its high idle speed and maintain until temperatures and emissions stable (expected to take ~20 minutes) with I/M meter fast idle measurements made periodically;
- switch off engine and allow to cool from estimated ~100°C oil temperature to normal I/M test temperature (probably 80°C)and then repeat above emissions tests until emissions stable;
- switch off engine and allow to cool to 60°C and then repeat above emissions tests until emissions stable.

Phase 2. Generation of thermal and emissions data under typical steady state loaded I/M test scenarios

Repeat Phase 1 experimental matrix but with measurements made with running under steady state load rather than fast idle.

Phase 3. Generation of thermal and emissions data after laboratory preconditioning sequences simulating realistic customer preconditioning practice

Carry out I/M test after each of the following preconditioning sequences:
- 2xECE
- 2xECE followed by 5 minutes at idle
- 2xECE followed by 10 minutes at idle
- 2xEUDC
- 2xEUDC followed by 5 minutes at idle
- 2xEUDC followed by 10 minutes at idle.