

Study of Thermal Characteristics and Emissions during Cold Start using an on-board Measuring Method for Modern SI Car Real World Urban Driving

Hu Li, Gordon E Andrews, Dimitrios Savvidis and Basil Daham
Energy and Resources Research Institute

Karl Ropkins, Margaret Bell and James Tate
The University of Leeds

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ABSTRACT

Exhaust emissions were measured under real world urban driving conditions using a set of in-vehicle FTIR emission measurement system, which is able to measure 65 emission components simultaneously at a rate of 0.5 Hz. The test vehicle was a modern EURO4 emission compliant SI car equipped with temperature measurement along the exhaust pipe across the catalyst so as to match thermal characteristics to emission profiles. A free flow urban driving cycle was used for the test and four repeated journeys were conducted. The results were compared to EU emissions legislation.

The results show that the warm up of the lubricating oil needed 15 minutes. The TWC needed about 200 seconds to reach full conversion efficiency. CO, THC and NO_x emissions exceeded the EURO4 exhaust emission legislation. CO₂ emissions were well above the type approval value of this vehicle. Greenhouse gases methane and nitrous oxide and benzene as well as other hydrocarbons were predominantly emitted during cold start period before 200 seconds. The results had a reasonable repeatability for most of the emissions.

INTRODUCTION

In Europe, the USA and Japan passenger car emission regulations are for a cold start. However, this is defined at a summer's day temperature of 25°C and much lower temperatures are experienced in winter in many areas of the world. The impact of these lower cold start temperatures on air quality has led to the introduction of a -7°C cold start emissions test in Europe and the USA. In Europe all cities have to meet defined European air quality standards and must declare air quality management areas (AQMA) if they exceed these air quality standards. In an AQMA the city has to take action to determine the cause of the exceedence and has the power to introduce measures to reduce the emissions. In the UK nearly all cases where an AQMA has been declared have involved traffic pollution as the cause of the exceedence.

This study assessed the cold start emission characteristics of a EURO 4 emissions compliant SI car using a low traffic density city street drive cycle that is similar to the ECE15 Urban drive cycle. A Euro 4 vehicle was used as EURO 4 SI cars are the major proportion of the UK vehicle fleet and will continue to dominate the fleet composition in the UK for the near future. It takes about 16 years for 90% of vehicles sold in any one year to be no longer in use [1] and this period is becoming longer for modern vehicles. Figure 1 shows SI passenger car fleet composition in the UK from 1996 to 2025 published by NAEI [2]. The figure from 2003 onwards is projections. The fleet composition data are in terms of fractions of vehicle kilometres travelled, not just in terms of vehicle stock, by taking account of the fact

that newer vehicles travel more miles in a year than older vehicles. The data in figure 1 show that EURO 4 vehicles currently take up ~60% of SI passenger car fleet. Thus the work on Euro 4 vehicles has significance in terms of their current use in city driving and hence their impact on air quality.

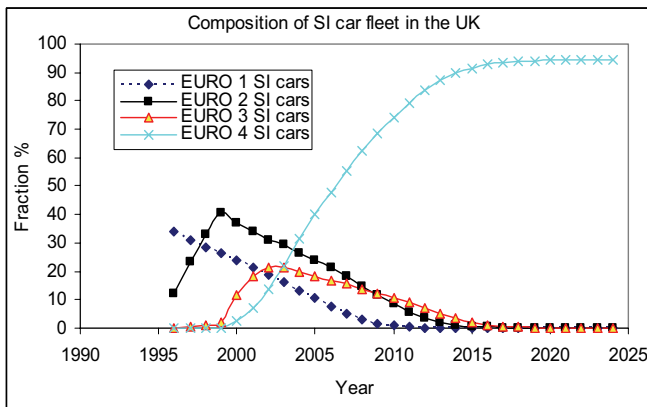


Figure 1 UK SI car fleet composition

It is well known that a SI engine in cold conditions has much higher exhaust emissions than one that is fully warmed up [3-9]. The new European passenger car emission regulation for EURO 3 and 4 has removed the first 40 seconds of non-sampling idle period and starts a short period of idle time exhaust sampling at engine start-up for the ECE driving cycle, in recognition of the importance of the cold start emissions. The new regulations also include -7°C tests for HC and CO emissions at cold start.

A cold start without producing a large amount of emissions is very difficult to achieve at sub-zero ambient temperature conditions, especially when the vehicle is cold soaked. The -7°C ECE test regulations do not allow the use of block heaters that are common in very cold climates. These are very effective and show that it is not the air temperature that is the main problem. The cold soak makes the oil, water, all metal surfaces and catalysts cold and it is the thermal energy required to heat these that is the main problem in cold starts [10-13].

The most convenient way to investigate the impact of the cold start and ambient temperature on exhaust emissions is to use an engine dynamometer test incorporating specialized cold enclosure facilities. However, there are some limits for this sort of test, as they cannot represent the whole vehicle response to cold start, e.g. gearbox and cold tyre effects. Although the legislated CVS test procedure can be conducted in a cold chamber, the cost of these is high and they are generally fully utilized for legislated test cycle work. Therefore, here on road testing has been used, as this is most cost effective, complementary to conventional

dynamometer and CVS cold start tests [14] and more directly representative of real-world conditions.

The significance of this real world test program lies in the fact that this test represented the whole vehicle response to cold start, including gearbox and cold tyre effects that can not be achieved by dynamometer tests. This research investigated engine thermal performance, legislative emission behaviors, fuel consumption and combustion inefficiency under different ambient temperatures, which can be used for a better understanding of the vehicle response under the real world driving conditions and provide valuable information to modelers for better prediction of emissions and air qualities in cities. This paper is the one of a series papers from this test program. A following paper from this test program will be published in the future which will focus on speciated hydrocarbon emissions, nitrous oxide, ammonia emissions and ozone formation potential assessment.

This work is part of a major research project RETEMM (REal-world Traffic Emissions Measurement and Modeling), which is part of the LANTERN research programme (Leeds health Air quality, Noise, Traffic, Emissions Research Network). One of the purposes of the RETEMM project is to investigate vehicle emissions characteristics under real world driving conditions, including the influence of ambient temperatures, driving cycles, traffic conditions, vehicle technologies etc.

EXPERIMENTAL

TEST CAR AND THERMAL MEASUREMENT

A EURO4 emission compliant Ford Mondeo manual transmission petrol car was used, which was fitted with a port fuel injected 1.8 litre 16V spark ignition engine with 4 cylinders and 16 valves. The odometer reading on the car was 4,400 miles prior to the tests. The vehicle was equipped with a Three Way Catalyst (TWC). The curb weight of the car is 1374 kg. The car was instrumented with 3 thermocouples, which measured the lubricating oil in sump temperature, upstream and downstream of the TWC exhaust gas temperatures. All temperatures were measured using grounded junction mineral insulated Type K thermocouples with a response time of ~ 0.25 ms.

EXHAUST FLOW, AIR/FUEL RATIO AND GPS MEASUREMENT

Exhaust flow measurement using OBS

The vehicle was instrumented with the Data Integration Unit (DIU) component of a Horiba On Board Emissions Measurement System (OBS 1300). This measures the exhaust mass flow rate together with λ and this enables the mass emissions to be computed from the volumetric

measurements. The DIU comprises a zirconia type NO_x and Air/Fuel ratio analyser (NO_x/A/F), Annubar (modified Pitot style) flow meter, additional in vehicle and ambient air monitoring, data logger (laptop) and software, global position system (GPS) and power supply unit.

All exhaust monitoring was conducted via a purpose built exhaust attachment fitted to the end of the vehicle exhaust pipe. NO_x concentrations and A/F were measured by NO_x A/F probe, exhaust flow rate was measured by Annubar, exhaust temperature monitored by thermocouple probe, all mounted on the exhaust attachment. Exhaust pressure was measured by open line connection and DIU mounted pressure sensor. Vehicle speed and engine revolutions were also logged from external (vehicle) inputs. In addition, ambient conditions (local temperature, pressure and humidity) were monitored using dedicated vehicle mounted sensors. For further details of this system, see development work of Nakamura et al [15]. In this paper the OBS 1300 was only used for exhaust mass flow rate and λ measurements. The other OBS1300 data is not reported within this study.

Air/fuel ratio

The air/fuel ratio was measured using a Horiba "Lambda Checker LD-700" in terms of lambda with a response time of 0.08 ~ 0.15 second. The LD-700 was connected to an NTK brand wide band oxygen sensor (ZrO₂ type), which was inserted into exhaust gas upstream of the TWC. The unit is calibrated for a fuel with a hydrogen/carbon ratio of 1.85 and an oxygen/carbon ratio of 0. The accuracy of the unit is $\pm 0.04\lambda$ for 0.91~1.19 λ and $\pm 0.08 \lambda$ outside this range. The LD-700 had a DC output of 0-5 volts, which was directly proportional to lambda. The DC voltage output was logged into a data logger and then into a laptop.

GPS system

A Racelogic VBOX II differential GPS system was used to provide geographical position, speed and acceleration data. The VBOX II is a GPS data logging system developed by Racelogic specifically for automotive applications. It is normally used for race track testing and other performance testing where accurate speed, position and acceleration data is required for driver performance evaluation. Data was logged at 1 Hz and stored on to a compact flash memory card, and subsequently transferred to a PC. The analogue output from the VBOX II was a 0-5V DC signal corresponding to road speed, and was fed to the data logger and then a laptop.

FTIR EMISSION MEASUREMENT SYSTEM

FTIR

A portable Fourier Transform Infrared (FTIR) spectrometer was used to measure on road real world emissions. The model used was the Temet Gasmet CR 2000 which was capable of measuring concentrations as low as 0.5~3 ppm, depending on the applications. It has been specifically calibrated by the manufacturer to an accuracy of 2% within the calibrated measurement range, which was 20,000 ppm for CO, 30% for CO₂ and 7000 ppm for NO_x respectively. THC emission measurement was the sum of 38 selected hydrocarbon species that was calibrated by the manufacturer from 0~500 ppm individually (methane was calibrated to 1000 ppm) [16]. The total hydrocarbon species measurable by this FTIR are 52 species, including extra 14 hydrocarbons using generic library that the calibration was carried out on the same type of the instrument but not particular for this instrument.

A FTIR emission measurement system was selected because of its ability to speciate VOC, NO/NO₂/N₂O and measure ammonia in addition to CO, NO_x, and THC emissions. The FTIR measurement for regulated emissions was calibrated against standard CVS measurement by authors using a chassis dynamometer facility and various driving cycles [17]. It was found that the FTIR measurement had excellent agreement with the CVS measurement for legislated emissions, though a correction factor of 1.1 for CO and 0.95 for NO_x and a correction of factor of 2.4 for THC have to be applied. The difference between the FTIR and CVS results was within 5%. All the regulated emissions data in this paper applies these corrections.

The Temet instrument comprised a FTIR analyser, a portable sample handling unit (filtering and controlling sample flow), heated sample lines and a laptop. The system weighed approximately 30 kg. The entire on-board measurement instrumentation including the FTIR system, the fuel consumption measurement system, two batteries and a DC-AC converter weighed approximately 150 kg.

The software of the FTIR system has the additional capability of accepting analog inputs, which can be logged together with the emissions spectra and analysis data. One of these analog inputs was employed to log one or two external analog signals for time alignment between the FTIR laptop and the second laptop. The throttle position was used as the external signal. Two laptops were used for data logging: One for the FTIR that logs emission spectra and external analog signals; the other one for OBS logging.

Power for instruments

The power needed for the on-board measuring system was around 1200 Watts and

necessitated drawing up to 100 A at 12V from the car's electrical system. This would have required an upgraded alternator and increased the load on the engine, therefore affecting the emissions characteristics. Another possibility was to use a small dedicated generator but this option is only feasible in large heavy duty vehicles. Therefore, a dedicated power supply, two 12V battery packs and an on-board DC-AC converter, were used to provide 240V AC necessary for instrument operation. The two batteries used weighed a total of 70 kg. They provided approximately 2-3 hours of operation before needing recharging.

Sample conditioning

In order to measure wet concentration, the raw undiluted sample gas extracted from the exhaust system had to be maintained at about 180°C otherwise low boiling point pollutants would drop out due to condensation. Furthermore, the extracted exhaust sample had to be hot filtered so that the sample cell remained free of particulates which would contaminate it and shorten its lifetime. A sample handling unit was acquired to perform these functions. The sample handling unit uses a pump to continuously extract sample from the vehicle's exhaust system at a constant flow rate (2~3 l/min) via a heated line. This is then filtered using a 0.2 µm filter and introduced via another heated line into the sample cell of the FTIR. Both heated lines were maintained to 180°C by the sample handling unit. The sample handling unit consumed the most power since it performed heating and pumping functions. It was installed in the boot of the car along with the FTIR. The gas sample was taken downstream of the catalyst and the heated sample line was passed through a small hole in the car's floorpan. There was no possibility of dilution of the sample by pressure pulsations from the tailpipe.

MASS EMISSION CALCULATION

For the EURO 4 car, the exhaust flow rate in l/min was measured by annubar flow meter as part of the OBS system. The mass emission rate was calculated by measured volumetric flow rate and the density calculated from the measured temperature and pressure, as in equation 1.

$$E_{\text{mass}} = Q_{\text{exh}} * D_{\text{exh}} * C * 10^{-6} / 60 \quad \text{g/s} \quad 1$$

where

- E_{mass} is the mass emission rate in g/s.
- Q_{exh} is measured exhaust flow rate in l/min.
- D_{exh} is the density of the exhaust gas in kg/m³.
- C is the concentration of the component in ppm. If this is measured in % then the equation has to be multiplied by 10⁴.

Then the accumulative emissions were calculated for any period and distance, as the sum of emissions per distance traveled (g/km).

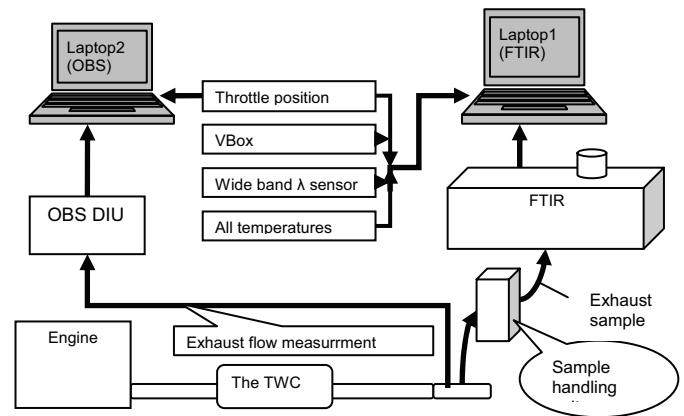


Figure 2 Schematic view of sampling and data logging system

TEST ROUTE AND CYCLE

An urban driving cycle was designed and referred as LU-BS – The Leeds University Business School driving cycle. This cycle was previously referred as LU-UDTC: Leeds University Urban Driving Test Cycle [18, 19]. Figure 3 shows the route of the test cycle. Leeds is a metropolitan district and has a high population density of around 1,300/km². There is a network of roads with many 90° turns. The car was started outside the University laboratories, which are close to a public road. The car was cold soaked for at least five hours prior to each test.

The cold start sampling was started before the ignition on. The vehicle was first driven about 70m to the public road, where it was then driven around the street test circuit shown in figure 3. This had a downhill and uphill portion on the top left part of the circuit in figure 3, the rest of the circuit was flat. There were seven 90° turns in the circuit, 5 of them left hand turns.

At the end of each lap of the 1.45 km test circuit the vehicle was stopped in a car park and then the circuit was repeated. The first cold-start circuit was thus slightly different to the other three circuits. The main road to the right of figure 3 was a very busy major road with one the highest traffic densities for an urban road in the UK. However, the traffic densities on the test circuit were much lower and the repeatability of each lap was not greatly influenced by differences in traffic loads.

The LU-BS is intended to simulate the ECE15 urban driving cycle. Figure 4 shows the typical speed profile of the test cycle driving mode in comparison with the ECE15 mode. This shows that the urban test circuit was very close to the ECE urban test cycle in terms of the duration of each lap and the peak speed. Each of the four laps of the LU-BS was regarded as one phase of

the test, similar to the four phases of the ECE test cycle. The first phase was under cold start conditions, as in the ECE urban test cycle.

The distance traveled for each lap was 1.45 km, giving a total distance for the four laps of 5.8 km. It involved 18~21 gear changes for each lap, depending on the traffic conditions. The speed limit on these urban streets was 48 km/hr (30 mph) and the peak speed never exceeded this, as shown in figure 4. Each section of the route involved acceleration from a 90° corner turn up to a peak speed close to the speed limit and then a deceleration to the next corner. Six or seven deceleration and acceleration modes were involved in each lap of the route. There were also short periods of idling between the laps due to traffic conditions.

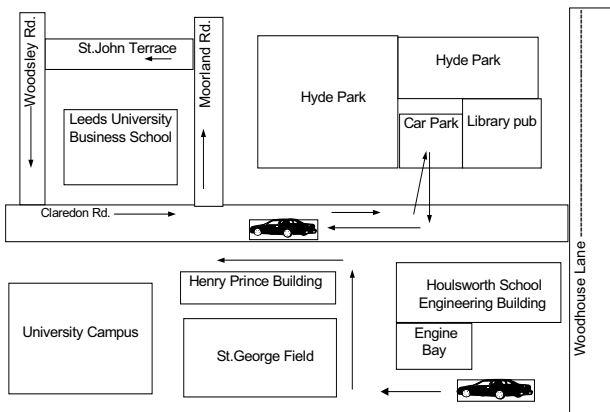


Figure 3 Driving route of test cycle

Figure 5 shows the accelerations and decelerations of LU-BS in comparison with ECE15 cycle. The LU-BS driving cycle has more frequent and sharper accelerations and decelerations than that in ECE15 cycle, indicating that the ECE15 cycle is less severe than real world driving cycle.

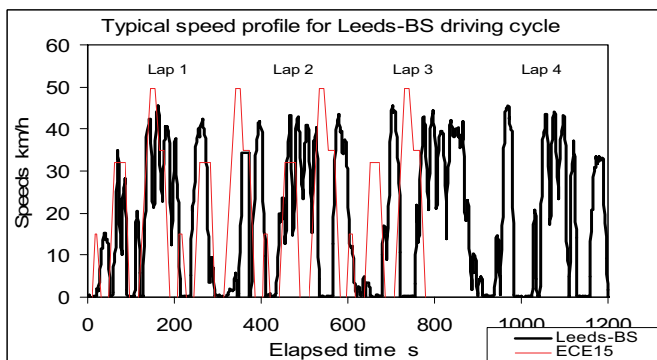


Figure 4 Typical road speed profile of LU-BS driving cycle and comparison with ECE 15 cycle

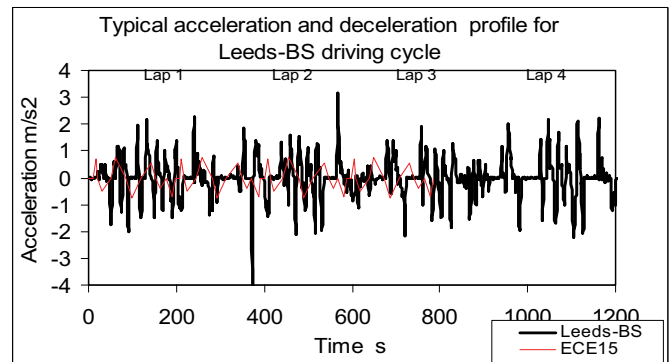


Figure 5 Comparison of acceleration and deceleration between LS-BS and ECE15 cycles

DRIVING PROFILE, WARM-UP OF THE ENGINE LUBRICANT AND THE TWC

DRIVING PROFILE

Four cold start runs were repeated by a single driver. The vehicle speed profile for four runs was shown in figure 6. The four runs had similar top speed. The run 2 and 3 had very similar features in terms of total journey time. The run1 had similar pattern but with shorter total journey time. The run4 had a long initial idle period (about 200s longer than the other 3 runs), though the rest of journey was similar to the others.

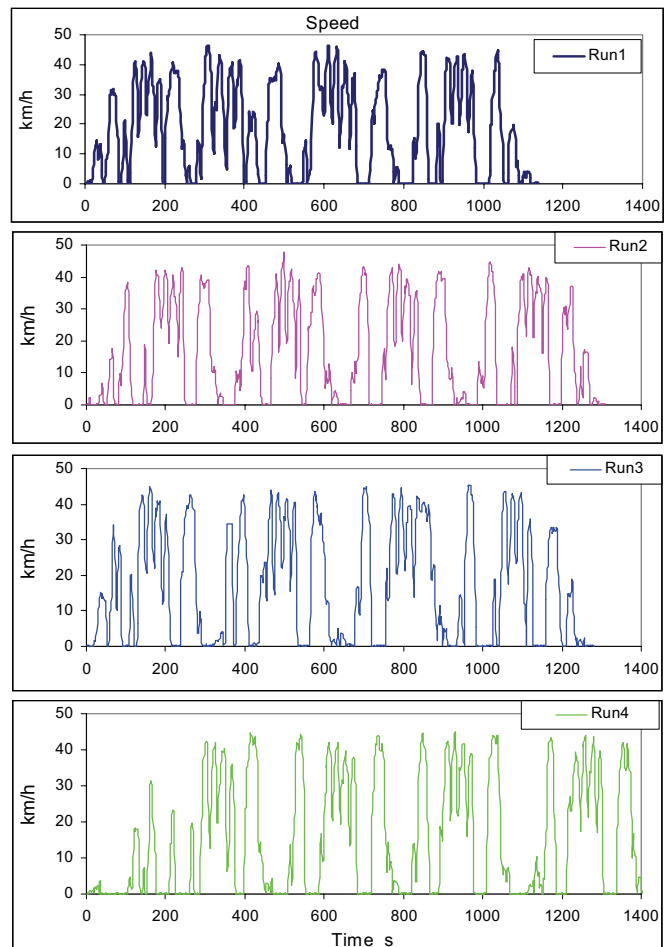


Figure 6 Vehicle speed profile for four runs