

Influence of Cold Start and Ambient Temperatures on Greenhouse Gas (GHG) Emissions, Global Warming Potential (GWP) and Fuel Economy for SI Car Real World Driving

2010-01-0477

Published
04/12/2010

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ABSTRACT

The transport sector is one of the major contributors to greenhouse gas emissions. This study investigated three greenhouse gases emitted from road transport using a probe vehicle: CO₂, N₂O and CH₄ emissions as a function of cold start and ambient temperatures. A real world driving cycle has been developed at Leeds and referred as LU-BS, which has an urban free flow driving pattern. The test vehicle was driven on the same route by the same driver on different days with different ambient temperatures. All the journeys were started from cold. An in-vehicle FTIR emission measurement system was installed on an EURO2 emission compliance SI car for emissions measurement at a rate of 0.5 Hz. This emission measurement system was calibrated on a standard CVS measurement system and showed an excellent agreement on the CO₂ measurement with the CVS results. The N₂O and CH₄ were calibrated by calibration gas bottles. A MAX710 real time in-vehicle fuel consumption measurement system was installed in the test vehicle and the real time fuel consumption was then obtained. The Global Warming Potential (GWP) was evaluated using IPCC data for all three measured GHGs. The results show that N₂O and CH₄ can contribute to approximately 6~10% of GWP during cold start due to high GWP index, though their emissions were in a much lower magnitude. The influence of ambient temperatures on GHG emissions and GWP were assessed. The research provided a better understanding of traffic related greenhouse gas emission profile in urban area and will contribute to the control of climate change.

INTRODUCTION

As a part of global effort to control the climate change, the UK government has agreed to reduce emissions of a basket of six greenhouse gases (CO₂, CH₄, N₂O, HFCs, PFCs and SF₆) by 12.5% from base year by 2008~2012. The base year is 1990 for CO₂, CH₄ and N₂O and 1995 for HFCs, PFCs and SF₆.

The Greenhouse gases produced by transport sectors include CO₂, methane (CH₄) and nitrous oxide (N₂O). The CO₂ is a dominant GHG and has been extensively investigated. Currently the CO₂ emissions from transport sector accounted for around 28% of the total CO₂ emissions in the UK. The methane emissions mainly come from landfill sites and the agriculture sector, which were 38% and 36% in the UK in the year 2004. The transport sector only contributed a small fraction of total methane emissions. The transport sector is an important contributor to nitrous oxide emissions.

It is well known that a SI (Spark Ignition) engine in cold atmospheric conditions has much higher exhaust emissions than one that is fully warmed up [1,2,3,4,5,6,7,8]. The new European passenger car emissions regulations has removed the first 40 seconds of idle period 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 (Hydrocarbon) and CO (Carbon monoxide) emissions at cold start. Extensive research had been undertaken in the past to investigate the influence of ambient temperature on the exhaust emissions [2,3,4,5,6,7], normally using legislated test cycles and CVS (Constant Volume Sampling) test

procedures. It was found that the exhaust emissions could be drastically increased, relative to 25°C, at cold ambient conditions. For instance, the hydrocarbon emissions were found to increase by 650% at -20°C and carbon monoxide emissions by 800% [6].

The significance of this real world test program lies in 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, fuel consumption, GHG emission behaviors and GWP under different urban driving conditions, which can be used for a better understanding of the vehicle response in the real world driving conditions and provide valuable information to modelers for a better prediction of the emissions and air qualities in cities.

EXPERIMENTAL SETUP

TEST CAR AND THERMAL MEASUREMENT

A Ford Mondeo manual transmission petrol car was used, which was fitted with a port fuel injected 2.0 litre 16V Zetec spark ignition engine with 4 cylinders and 16 valves. The car was manufactured in 1998. The odometer reading on the car was 136,000 km when the test was conducted, which gave an average annual travel mileage of 17,000 km per year, a typical mileage for the UK passenger cars. The vehicle was equipped with a Three Way Catalyst (TWC). The curb weight of the car was 1360 kg. The car was instrumented with 19 thermocouples, which measured the ambient air, engine coolant and lubricating oil temperatures. In addition the temperatures of exhaust skin (the metal temperatures of the exhaust manifold and the TWC), exhaust gases and catalyst bricks were also measured. The ambient temperatures were measured on the roof of the vehicle by a thermocouple. The metal temperatures were measured by attaching the thermocouples to the metal surface. The exhaust gas and catalyst temperatures were measured by inserting thermocouples into the gas streams and catalyst bricks respectively. All the temperature measurements used grounded junction mineral insulated Type K thermocouples.

Table 1 identifies the thermocouples by the number, location and function. These references are used in the schematic view of the thermocouple locations on the test car (figure 1) and the later graphical presentation of the warm-up temperature results in real world driving. Figure 2 presents the outline of the measurement system and data logging system that was used. A differential GPS system was used to measure the vehicle's travel speed and distance, and this was connected to an analog Daqview data logger along with all 19 thermocouples, fuel consumption and lambda data. The data logger was then connected to a second laptop PC. The

thermal measurements were logged at 1Hz and the FTIR emission measurements at 0.5 Hz.

Table 1. Thermocouple locations and functions

The number of thermocouple	The measuring target
1G	Engine out gas temperature from cylinder 1
3G, 6G	Top and bottom side of manifold gas temperature
2M, 4M, 5M 7M	Metal temperature at four different locations on the manifold to monitor overall thermal profile on manifold
8, 9	Coolant water out and in temperature from the engine
11G,14G,16G	Gas temperature at the upstream (11), between the two catalyst bricks (14) and downstream of the TWC (16).
12M,17M	Upstream and downstream of TWC face temperature
13W, 15W	TWC brick temperature
10, 18	Engine oil temperature in dipstick top layer (10) and sump bottom (18)
19 (not shown in graph)	Ambient temperature

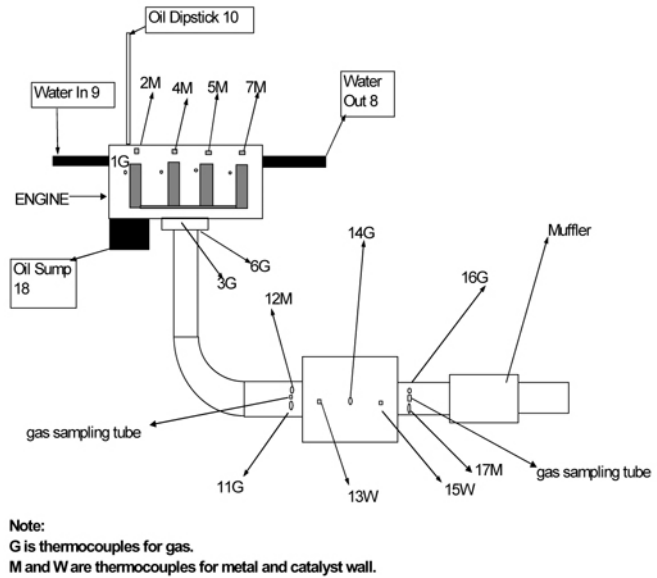


Figure 1. Schematic view of thermocouple locations

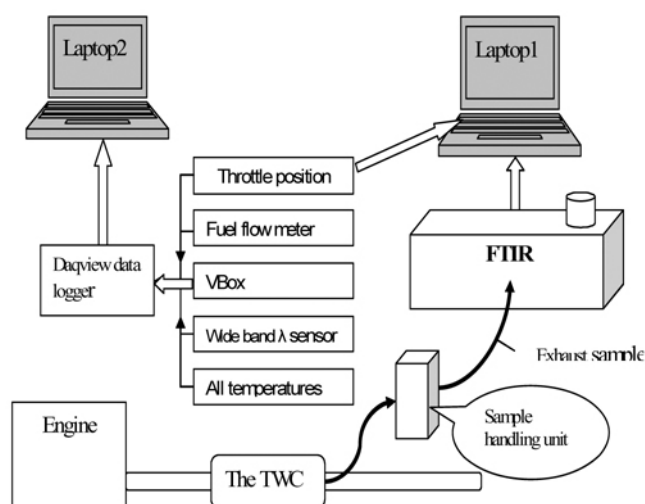


Figure 2. Schematic view of sampling and data logging system

ON BOARD EMISSION MEASUREMENT

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 an accuracy of 2% within the calibrated measurement range, which was 30% for CO₂, 1000 ppm for CH₄ and 500 ppm for N₂O respectively. This FTIR measurement was calibrated against standard CVS measurement by authors using a chassis dynamometer facility and various driving cycles [9]. It was found that the FTIR measurement had an excellent agreement with the CVS measurement.

The Temet instrument comprised a FTIR analyzer, a portable sampling unit (filtering and controlling sample flow), heated sample lines (180°C) and a laptop. The cell temperature of the FTIR was 180°C. The exhaust gas sample was taken every two seconds.

The FTIR system weighed about 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 about 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 throttle position. Two laptops were used for data logging. One was for FTIR that logs emission spectra and throttle position. The other one was for thermal and driving parameters that logs GPS road speed, fuel mass flow, throttle position, air/fuel ratio and ambient

temperature. The two laptops were time aligned using the throttle position measurement that was logged by both.

FUEL CONSUMPTION MEASUREMENT

A MAX710 fuel flow measurement system was used to measure real world fuel consumptions. This measured the fuel mass flow rate using a level controlled recirculation tank, transfer pump and a high-resolution flow meter. The pump maintained a constant pressure to the recirculation tank that fed fuel to the engine. This recirculation tank collected return fuel from the engine and recirculated this fuel back to the engine instead of returning it to the fuel tank. This recirculation loop allowed the use of a single meter to measure make-up fuel as it replaced the fuel consumed by the engine. Total fuel consumption was determined to better than 1% accuracy. The rate of fuel consumption was determined at a 1-second resolution. The device had an analog output, which was logged onto the second laptop computer.

The commercially available standard ultra low sulfur RON95 petrol fuel was used throughout the tests.

SOURCE OF POWER

The power needed for the on-board measuring system was around 1200 Watts and this would have 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. The best solution was to use two battery packs providing a total of 24V which was then converted to 240V AC using an on-board DC-AC converter. The two batteries used weighed a total of 70kg. 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 micron filter and introduced via another heated line into the sample cell of the FTIR. Both heated lines were controlled 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

The FTIR emission measurements were on a volumetric basis. These were converted into a mass basis using the conventional method for the computation of emissions index (EI: g/kg fuel)

$$EI = 1000K * C * (1 + A/F) \quad \text{g/kg fuel}$$

Equation 1

- K is the conversion coefficient, which is the ratio of molecular weight of a certain emission component to the molecular weight of the whole sample gas. The molecular weight of the exhaust sample gas is close to that of air and does not vary more than 1% for H/C ratios of about 2 (i.e. gasoline), irrespective of the air/fuel ratio. For this reason, K is a constant.
- C is the concentration of the component. If this is measured in ppm or % then the equation has to be multiplied by 10^{-6} or 10^{-2} respectively.
- A/F is the air/fuel ratio on a mass basis measured by the lambda sensor.

The EI was then converted into mass emission rate g/s using the fuel consumption measured during the sampling period. Then the distance based emissions can be calculated for any distance traveled.

TEST ROUTE AND CYCLE

An urban driving cycle was designed and referred as LU-BS: Leeds University Business School driving cycle. This cycle was previously referred as LU-UDTC: Leeds University Urban Driving Test Cycle[7, 9]. [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 testing.

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](#). There was 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 lap was thus slightly different to the other three laps. 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 the differences in traffic loads.

The LU-BS driving cycle was aimed at the simulation of 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 LU-BS driving cycle was 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 circuit 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.

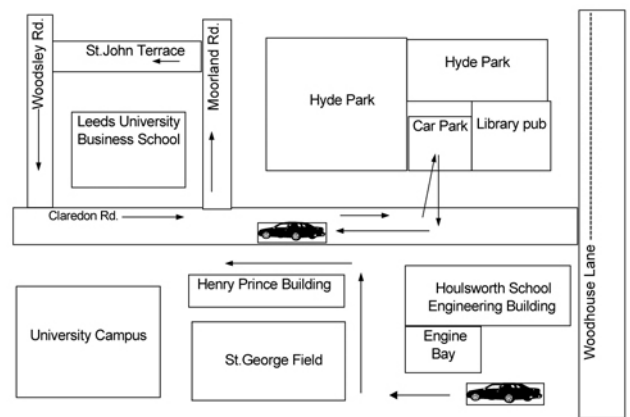


Figure 3. Driving route of the test cycle

RESULTS

DRIVING PARAMETERS ANALYSIS

Five journeys were driven over the LU-BS driving cycle by a single driver. These five runs were operated under different ambient temperature conditions ranging from 7 to 30°C and started from cold. The vehicle speed profile for five runs shown in [figure 4](#) clearly indicated four laps for each run. All five runs had the similar peak speed of ~40 km/h and the

comparable journey duration. The run 1 had the longest journey time due to longer stoppage periods between laps and at a couple of junctions. The run 2 to 4 were relatively consistent. The run 5 encountered interferences at the turnaround between laps due to a blockage at the entrance of the car park (see [figure 3](#)) by a delivery vehicle, which caused delays at the turnaround.

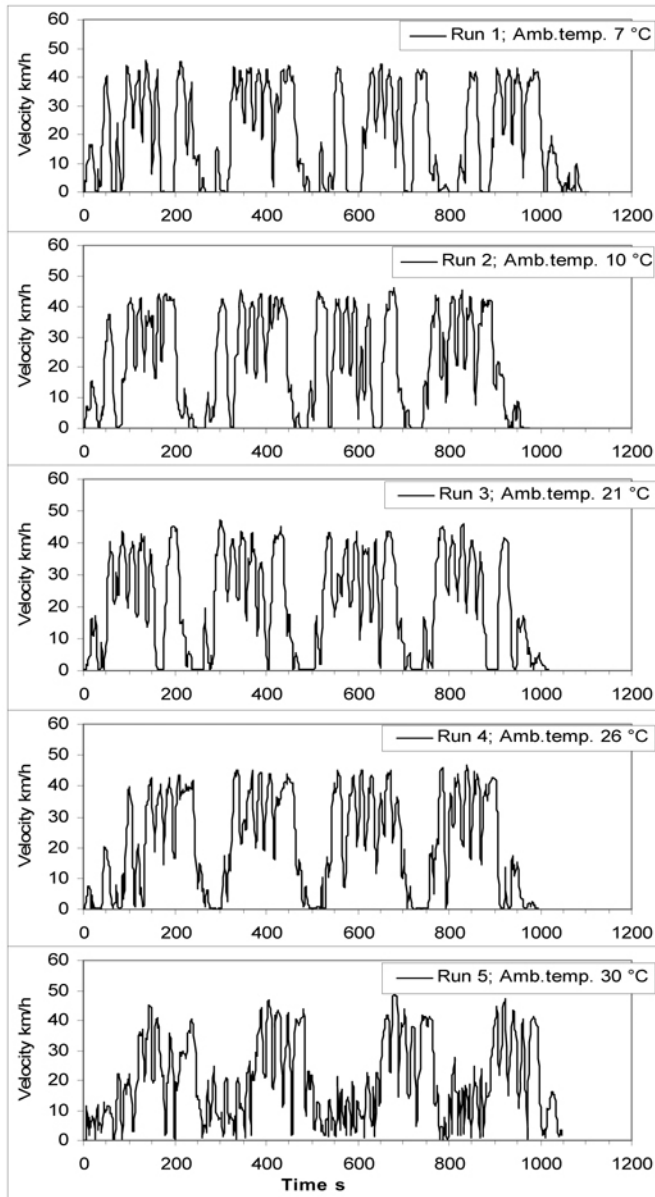


Figure 4. Speed profile for five runs

LAMBDA

The deviation of air/fuel ratio from stoichiometric is one of the most influential factors affecting emission behavior as it was strongly linked to the performance and efficiency of the TWC. [Figure 5](#) shows the variation of lambda values for five runs. The rich and lean spikes were clearly shown as a result of sudden accelerations and decelerations. The initial lambda values at engine start were ~ 0.7 at 7°C and 10°C ambient temperatures and increased to 0.9 at 21°C and 0.95 at 30°C . It is also observed that the time to reach lambda one operation was longer at lower ambient temperatures, which was approximately 100 seconds for the runs 1 and 2 and 50 seconds for the runs 3 to 5. The richer fuel air mixture during engine start and the longer duration to reach lambda one at lower ambient temperatures resulted in higher emissions shown later. It is observed that there was a large increase in the initial lambda values and significant shorter duration of rich fuel air mixture (the lambda was lower than 0.9) when the ambient temperatures increased from 10°C to 21°C . The differences in the initial lambda values and duration of rich mixture become much smaller from 21°C to 30°C , which led to a similar emission level for the runs 3 to 5 shown later.