

Impact of Driving Cycles on Greenhouse Gas (GHG) Emissions, Global Warming Potential (GWP) and Fuel Economy for SI Car Real World Urban Driving

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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: CO₂, N₂O and CH₄ emissions as a function of engine warm up and driving cycles. Five different urban driving cycles were developed and used including free flow driving and congested driving. An in-vehicle FTIR (Fourier Transform Infrared) emission measurement system was installed on a EURO2 emission compliant SI (Spark Ignition) car for emissions measurement at a rate of 0.5 HZ under real world urban driving conditions. This emission measurement system was calibrated on a standard CVS (Constant Volume Sampling) measurement system and showed excellent agreement on CO₂ measurement with CVS results. The N₂O and CH₄ measurement was calibrated using calibration gas in lab. A MAX710 real time in-vehicle fuel consumption measurement system was installed in the test vehicle and real time fuel consumption was then obtained. The temperatures across the TWC (Three Way Catalyst) and engine out exhaust gas lambda were measured. The GHG (greenhouse gas) mass emissions and consequent GWP (Global Warming Potential) for different urban driving conditions were analyzed and presented. The results 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 and nitrous oxide. CO₂ is a dominant GHG and has been extensively investigated. Currently the CO₂ emissions from transport sector accounted for around 28% of total CO₂ emissions in the UK. The methane emissions mainly come from landfill sites and agriculture sector, which were 38% and 36% in the UK in year 2004. The transport sector only contributed a small fraction of total methane emissions. Transport sector is an important contributor to nitrous oxide emissions.

This project is part of a major study of real world emissions and the traffic control and road system impacts on real world vehicle emissions. In the present work the important influence of driving cycles on urban passenger SI car GHG emissions is investigated. Five different real world urban driving cycles were developed to simulate free flow, junctions, congested traffic and medium speed cruising etc.

A Euro 2 vehicle was used as they are one of the major proportions of the UK vehicle fleet and hence major contributors to air pollution in cities. The ongoing work is investigating Euro 3 and 4 vehicles. It takes about 16 years for 90% of vehicles sold in any one year to be no longer in use [1] and this period becomes longer for modern vehicles. Thus the work on EURO 2 vehicles has significance in terms of their current use in city driving and hence their impact on air quality. It will be at least 2010 before 90% of EURO 2 vehicles are not a significant proportion of city traffic [2]. This work on EURO 2 vehicles will also be the basis for future work on the influence of traffic

temperature and vehicles that meet subsequent lower emissions standards.

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 better prediction of emissions and air qualities in cities.

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 the emissions characteristics under real world driving conditions, including the influence of ambient temperatures, driving cycles, traffic conditions and vehicle technologies etc [3-8].

EXPERIMENTAL

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 odometer reading on the car was 85,000 miles. The vehicle was equipped with a Three Way Catalyst (TWC). The curb weight of the car is 1360 kg. The car was instrumented with 19 thermocouples, which measured the air inlet, engine coolant and lubricating oil temperatures. In addition the exhaust skin (metal), exhaust gas, catalyst and ambient temperatures were also measured. All temperatures were measured using grounded junction mineral insulated Type K thermocouples.

Table 1 identifies the thermocouples by 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 urban 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.

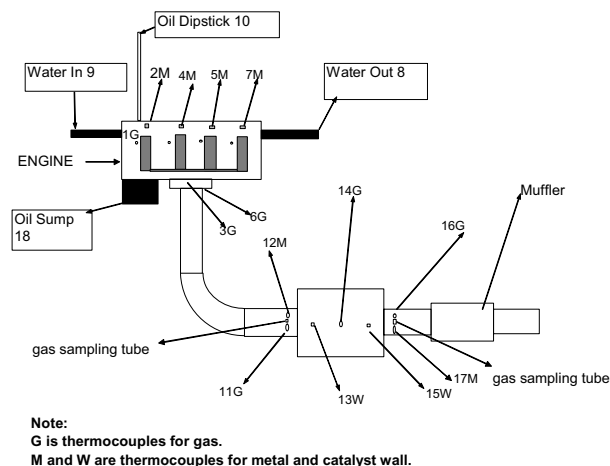


Figure 1: Schematic view of thermocouple locations

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 of 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

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 excellent agreement with the CVS measurement.

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 throttle position. Two laptops were used for data logging: One for FTIR that logs emission spectra and throttle position; the other one 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. Figure 2 shows the schematic view of the FTIR emissions measurement system, fuel consumption measurement system and data logging system.

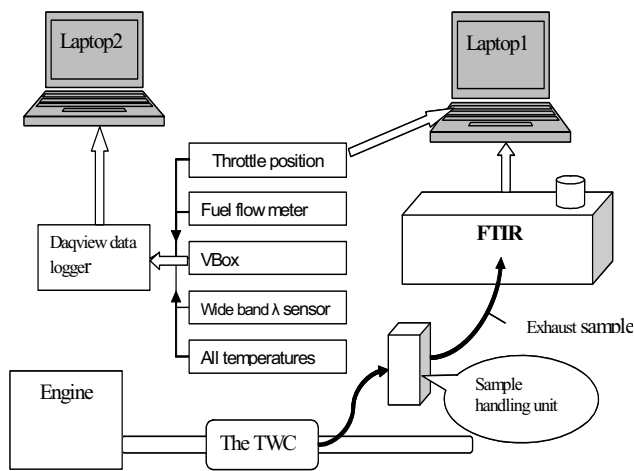


Figure 2: Schematic view of sampling and data logging system

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 that was logged onto the second laptop computer.

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. 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

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)

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

- K is 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 here treated as a constant.

- C is 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 lambda sensor.

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

DRIVING ROUTES AND CYCLES

Five driving cycles were selected for the emission tests. These five driving cycles are: LU-BS (Leeds University-Business School, hereafter referred as BS cycle), LU-Headingley (Leeds University-Headingley, hereafter referred as Headingley cycle), LU-HR-part1 (part 1 of the Leeds University-Headingley Ring road cycle, hereafter referred as HR-part1 cycle) and LU-HPL-A/B (Leeds University-Hyde Park Loop-A/B, hereafter referred as HPL-A/B; A is anticlockwise loop and B is clockwise loop).

The BS driving cycle is previously known as LU-UDTC (Leeds University-Urban Driving Test Cycle) [3]. Figure 3 shows the route of the test cycle. Leeds is a metropolitan district and has a high population density of around $1,300/\text{km}^2$. There is a network of roads with many 90° turns. The car was started from the authors' engine bay dynamometer laboratory, which was close to a public road. The car was parked outside the laboratory and 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. 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 of 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 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/h (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.

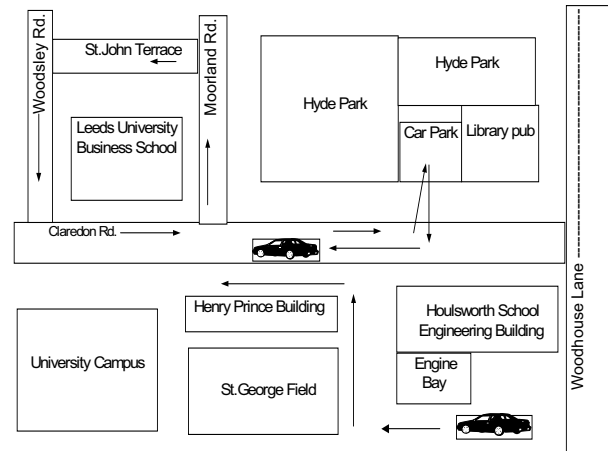


Figure 3: The route of BS driving cycle

The second driving cycle Headingley is one of the typical congested main urban commuter roads in Leeds. The journey started from the University (big star sign in the figure 4) and ended at West Park Roundabout (small star sign in figure 4). The distance traveled was 4.4 km. It passed 5 crossroads with traffic lights, 6 pedestrian lights and 9 give way junctions. The Headingley cycle does not involve any turns and all speed changes are caused by road traffic events.

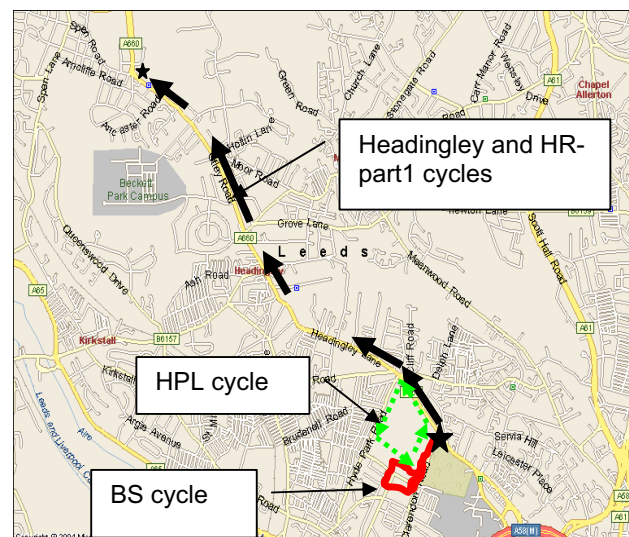


Figure 4: The route of Headingley driving cycle along with BS and HPL cycles.

The third driving cycle HR-part1 is the first part of a driving cycle HR. For the HR cycle, the vehicle was driving passing the west park roundabout (small star sign in figure 4) and continued to travel for approximately 400 m and then turned right into Leeds out ring road, where the national speed limit applies, i.e. the vehicle can drive up to 112 km/h (70mph). In

this study, only the first 1000 seconds of HR cycle was presented and referred as the HR-part1 as this was representing the cold start section of the HR cycle and comparable to other test cycles. The emission profile of whole HR cycle will be presented in a separated paper. The route of the HR-part1 in this study can be referred to figure 4. In fact, the journey used in this paper for HR-part1 driving cycle was a congested journey and the distance traveled was just over 4 km, which was shorter than Headingley cycle. So the Headingley journey and HR-part1 journey in this paper were driving on the same route but represented two different traffic situations: slightly congested Headingley journey and very congested HR-part1 journey.

The fourth and fifth driving cycles Leeds-HPL-A or B were a 1.96 km loop circuit, located in a busy residential area linked with major roads as shown in figure 5. The HPL-A cycle is driving in anticlockwise direction and HPL-B is driving in clockwise direction. Of the cycle, side AB was a dual carriage way on which the vehicle can travel up to ~60 km/h and have less traffic interferences. The other three sides were two-way single carriageways on which the vehicle can travel up to 48 km/h but with more traffic variation and interferences. The sides CD and DA have a set of pedestrian light on each road. Junction A, B and D are traffic light controlled. For HPL-A, the driving at junctions A, B and D will depend on traffic light status to stop or driving through and at junction C there will be not stop. For HPL-B, the driving at junctions will not only controlled by the traffic lights but also subject to oncoming straight traffic and therefore has longer stops.

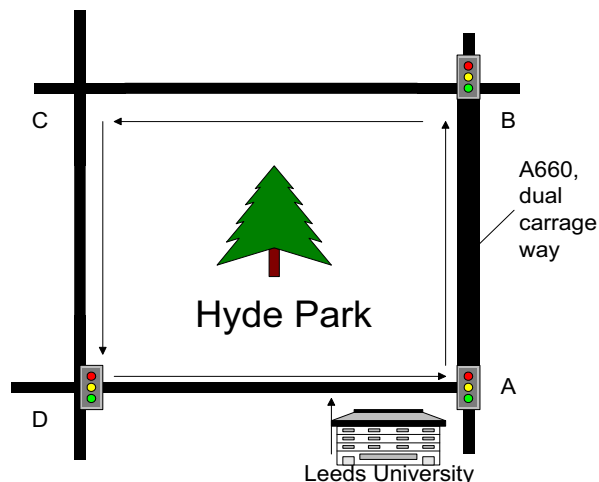


Figure 5: The route of HPL driving cycle

One example journey for each driving cycle was selected in this paper for the analysis of driving parameters and emissions. These examples may not be able to represent all features of the particular cycle but they represented most features of the traffic conditions of the particular cycle. Table 2 shows the summary of the five driving cycles for driving features and traveled distance.

Table 2: Summary of driving cycles

Name of Driving cycle	Represented driving condition	Distance km
LU-BS or BS	Urban short circuit loop free flow	5.8
Headingley	Urban free flow and slow/congested flow	4.4
HR-part1	Urban free flow and slow/congested flow	4.0
HPL-A	Urban large circuit loop, left turns at junctions	4.5
HPL-B	Urban large circuit loop, right turns at junctions	4.5

The ambient temperatures when these five tests were carried out were 11~20 °C. So there is little influence of ambient temperatures on engine warm up and emissions.

RESULTS

SPEED PROFILE

The vehicle travel speed was logged at 1Hz and plotted against time shown in figure 6 for all five journeys. The BS journey represented a free flow urban driving pattern with regular stops at traffic lights. The four loops had a good repeatability. The Headingley journey represented a mild congestion journey which started with normal free flow driving and stops and then experienced a short traffic queue from 300 to 430 seconds. The HR-part1 journey was a typical congested traffic scenario. The vehicle had an initial short period of cruising at around 150 second and then started stop-start congested driving period from 220 to 720 seconds. The HPL-A and HPL-B were driven on the same route but different direction: anticlockwise and clockwise. The different travel direction made a remarkable difference in speed profile of two journeys as the left or right turning at each junction was a significant factor that affects the driving and therefore emissions. The speed profile of HPL-A in figure 6 showed that the journey had typical stops at junctions controlled by traffic lights and cruising between stops. The HPL-B journey showed there were some stops at junctions similar to the HPL-A but some significantly long stops appeared due to the right turn which had to give way to the oncoming traffic.

Figure 7 shows the accumulated traveled distance and speed profile for five journeys. The BS journey had the longest distance of 5.8 km. The HR-part1 journey had shortest distance of just over 4 km.