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Comparison of Gaseous Emissions for B100 and Diesel Fuels for Real World Urban and Extra Urban Driving

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ABSTRACT

A Euro 3 1.8 litre Diesel vehicle with an oxidation catalyst was used to investigate real world exhaust emissions over a real world driving cycle that included urban congested traffic and extra-urban driving conditions. Diesel fuel and B100 were compared. The B100 fuel was Fatty Acid Methyl Ester (FAME), derived from waste cooking oil, which was mainly RME. A multifunctional additive package was added at 800ppm to control fuel injector deposit formation. Gaseous emissions were monitored using an on-board heated Temet FTIR exhaust emission analyzer, which can measure 52 species at a rate of 0.5 Hz. A Horiba n board emissions measuring system was also used (OBS 1300), which measures the exhaust mass flow rate together with air/fuel ratio. The results show that CO, THC and NOx emissions exceeded the EURO 3 exhaust emission legislation in real world driving, due to the presence of higher acceleration and more stop/start actions than in the test cycles. 172g/km was the certified CO_2 value based on the standard test cycle, but in the real world driving the vehicle's CO_2 was slightly higher. B100 emissions were similar to those for diesel and both were higher than the legislated test cycle values. NOx was slightly higher for B100, but both fuels were much higher than the legislated value. This was due to the lack of catalytic control for NOx and the proportionality between NOx and acceleration rates. CO emissions were much lower than for the legislated cycle as most of this work was not carried out with a cold start and the catalyst was active for most of the journey. The catalyst front and rear temperatures were monitored to demonstrate that this did not drop below the light off temperature during the test journeys. There were no drivability issues detected by the driver with B100.

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INTRODUCTION

The transport sector is responsible for 21 percent of UK domestic greenhouse gas emission; travel by road accounts for 92 percent of this [1]. In order for the UK government to meet its GHG reduction targets the transport sector is going to have to play its part in reducing emissions and the use of larger proportions of biofuels is recognized as an important contributor to reducing CO_2 emissions from transport. The UK agreed to adopt the EU's New Car CO_2 regulations in April 2009, which puts in place a framework that effectively forces car manufacturers to develop vehicles with lower GHG emission. The average emission of CO_2 by new cars on UK roads fell from 190 g_{CO2}/km to 158 g_{CO2}/km between 1997 and 2008. The EU's new regulation targets an average for new cars of 130 g_{CO2}/km starting in 2012, with full compliance by 2015. This will then drop to 95 g_{CO2}/km by 2020 [1]. For light commercial vehicles such as that used here, new legislation from the European Commission targets a fleet average for all new light commercial vehicles of 175 g_{CO2}/km from 2014 phased-in to 2016 and a target of 135 g_{CO2}/km in 2020 [2].

In order to legislate and control the emissions from vehicles, the EU uses the NEDC (New European Driving Cycle) as shown in Fig.1. This uses a standardized cycle of

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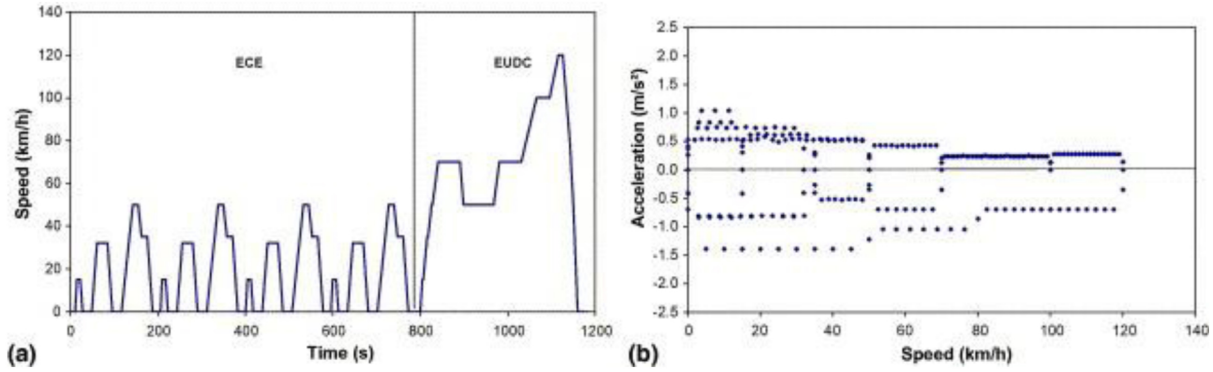


Fig.1. New European Driving Cycle

Table.1. EU Emission Standards Euro 1-6 Diesel light commercial vehicles (N1, Class II, 1350-1760kg) [5]

	EURO 1	EURO 2	**EURO 3**	EURO 4	EURO 5	EURO 6
Date	Oct 1994	Jan 1998	**Jan 2001**	Jan 2006	Sep 2010	Sep2015
CO g/km	5.17	1.25	**0.80**	0.63	0.63	0.63
NO_x g/km	-	-	**0.65**	0.33	0.235	0.105
HC+NO_x g/km	1.40	1.0	**0.72**	0.39	0.295	0.195
HC g/km			**0.07**	0.06	0.06	0.09
PM	0.19	0.14	**0.07**	0.04	0.005	0.005

acceleration, constant speed and deceleration. The aim of the test cycle is to generate repeatable emissions measurements [3] so that all manufacturers cars can be compared on the same basis. This cycle is made up of four identical phases of urban driving (using the ECE15 urban drive cycle) and a phase of Extra-Urban Driving (EUDC representing high speed driving). These phases of the test cycle and their time weightings were introduced to give a more realistic representation of real world driving and average passenger car usage than would be the case for steady state testing at constant speed and load. These cycles are usually measured on a chassis dynamometer with the Constant Volume Sampling (CVS) technique used to analyze each of the monitored exhaust emissions and the average emissions for the whole test cycle are divided by the total distance of the test cycle to give the legislated unit of g/km. If this cycle is used to estimate total pollution emissions from transport then the cycle must be representative of real world driving and there is ample evidence that this is not the case [4,5,6,7,8].

This work investigates real world emissions for a Euro 3 light duty diesel van. This work complements previous work by Li et al [6,7,8] for light duty SI engine vehicles of similar weight to the present diesel vehicle and uses the same in-vehicle emissions measurement equipment. A significant feature of the NEDC in Fig. 1b is the low acceleration and deceleration rates that were shown to underestimate by a factor of at least two the maximum acceleration and deceleration rates in real world driving [6,7,8]. For SI vehicles with TWC and lambda 1 control, the action of hard acceleration and deceleration is to create a deviation from lambda 1 control and this dominates the effects of real world driving on emissions. For lean burning diesel vehicles this strong effect of lambda should be absent and real world emissions might show less deviation from the test cycles. This work was carried out to determine if this was the case. The use of B100 methyl ester potentially makes fuel vaporization and atomization worse and this could create greater real world effects compared to diesel and the present work was undertaken to determine the deterioration in real world performance with B100 relative to diesel fuel.

The Euro 3 limits for diesel vehicles of over 1760 kg gross weight, as used in this work, are summarised in Table. 1. The purpose of this work was to investigate whether the regulated emissions are representative of the emissions in real-world driving conditions. The NEDC test cycle takes no account of how traffic flow is affected by street layout, or how people drive in congested or free flowing traffic.

The energy shortage and environmental issues have accelerated the research and development of renewable fuels for transport. Biodiesel such as rape methyl ester (RME) is a renewable fuel produced from renewable vegetable oils and the EU has legislated for all diesel sold in Europe to contain biofuels with the proportion starting at 2% in 2005, increasing to 5.75% in 2010. The EU has a target to achieve 15% biofuels by 2020. In many countries 20 and 30% are available and many manufacturers have agreed to B30 being a no harm limit for biofuels in new vehicles. However, where companies are registered for carbon trading then there are financial incentives to use higher proportions of biofuels and several fleets that return to a fuelling depot use B100 on a regular basis. The present work was carried out to investigate if there was a significant deterioration in real world exhaust

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emissions of a LDD vehicle using B100 in comparison with diesel.

Biodiesel is a processed biofuel made from transesterification of vegetable oils or animal fats. Biodiesel is defined as a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats [9]. Biodiesel can be produced from a variety of crops and plants such as soybean, rape, coconut, peanut, sunflower, karanja and palm. Soyabean oil derived biodiesel is predominant in the US market while the rapeseed oil is prevalent in Europe [10, 11].Biodiesel has similar physical properties with petroleum derived diesel and can be blended with diesel. It is a clean-burning, renewable, non-toxic, biodegradable and environmentally friendly transportation fuel that can be used in pure (B100) or blends with diesels in diesel engines [12]. One of the advantages of biodiesel is its low emission characteristics. Many researchers reported a significant reduction of CO, THC and PM with biodiesel, though NOx was increased slightly [13,14,15,16,17,18,19]. Most of the studies were concentrated on the legislated CO, THC, NOx and PM emissions as well as CO2 emissions. Li et al. [20] showed for a 6 litre 6 cylinder TCIC DI diesel that B100 RME significantly reduced engine out CO (13~24%) and THC (29~43%) emissions but increased NOx emissions slightly (2~4%) compared to diesel. Their FTIR measurements showed that B100 RME reduced most of the hydrocarbons, but formaldehyde emissions were increased compared to diesel during cold start. They also found that particulate mass emissions with B100 RME were reduced by between 13 - 37% compared to diesel. Consequently, it was expected in the present work that B100 RME would potentially reduce the gaseous emissions of HC and CO. The increase in NOx with B100 has been noted by several investigators and is usually ascribed to the shorter ignition delay of B100 RME compared to diesel with a consequent movement of the peak heat release closer to TDC with an associated increase in NOx.

EXPERIMENTAL METHODS

Test Vehicles and Thermal Measurement

A Euro 3 diesel Ford Connect TDCi, with a manual 1.8 litre in-line four cylinder, turbocharged, intercooled, 8-valve engine was used. The certified CO_2 emission was 172 g_{CO2}/km. The odometer reading on the Diesel light commercial vehicle was 6,400 miles prior to the tests. The vehicle was equipped with an oxidation catalyst for the control of particulate VOF, but this also controlled CO and HC. The curb weight of the vehicle was 1440 kg but its weight increased to around 1825 kg with two people on board and with the instrumentation with six batteries and inverter for instrumentation power. The temperature of the lubricating oil in the sump was measured so that the cold start warm-up of the lube oil could be monitored. The exhaust gas upstream and downstream of the oxidation catalyst was also measured together with the catalyst front and rear face temperatures. All temperatures were measured using grounded junction mineral insulated Type K thermocouples with a response time of ~0.25s. All the test runs were conducted by the same driver.

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 enabled the mass emissions to be computed from the volumetric measurements. The DIU comprises a zirconia type NOx and Air/Fuel ratio analyser, Annubar (modified Pitot style) exhaust pipe exit flow meter with exhaust pressure and temperature measurement, along with data logger (laptop) and software, global position system (GPS) and power supply unit. The NOx measurements reported in the present work were from the FTIR which measured NO and NO_2 separately. The OBS 1300 accuracy for exhaust mass flow measurement was validated by direct comparison with the legislated EU test cycle on a rolling road chassis dynamometer test cell [21]. All exhaust gas composition monitoring was conducted via a purpose built exhaust attachment fitted to the end of the vehicle exhaust pipe. In addition, the ambient temperatures was measured.

Air/Fuel RatiO

The air fuel ratio was measured by OBS zirconia sensor, which had an adequate range for diesel applications. The fuel elemental compositions were measured and this enabled the equivalence ratio to be determined from the stoichiometric A/F computed from the diesel H/C ratio and the B100 H, C and O elemental analysis. The exhaust mass flow was measured (air + fuel) using the Horiba OBS 1300.

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

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 species. It was calibrated by

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the manufacturer to an accuracy of 2% within the calibrated measurement range, which was 9960 ppm for CO, 16% for CO_2. The calibrated measurement range for NO and NO_2 was 2008 and 4885 respectively. THC emission measurement was the sum of 38 selected hydrocarbon species that was calibrated by the manufacturer from 0~500 ppm individually calibrated hydrocarbons (methane was calibrated to 1000 ppm) [4]. The total hydrocarbon species measured by this FTIR was 66 species, including 14 hydrocarbons using the generic library that the calibration was carried out on the same type of the instrument but not particular for this instrument. 52 species were directly calibrated on the instrument used in this work.

The FTIR emission measurement system was selected because of its ability to speciate VOC, $NO/NO_2/N_2O$ and measure ammonia in addition to CO, NOx, and THC emissions. The FTIR measurement for regulated emissions was calibrated against standard CVS measurements by the authors using a chassis dynamometer facility and various driving cycles [5]. 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 NOx 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 had these corrections applied.

The completed FTIR analysis system comprised the 180°C heated Temet FTIR analyzer with a 180°C heated 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. This brought the weight of the vehicle without passengers to 1924 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 vehicle speed 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 the OBS and exhaust temperature data logging. A schematic of the instrumentation and data acquisition system is shown in Fig. 1.

Power for Instruments

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, six 12V battery packs and an on-board DC-AC converter, were used to provide 240V AC necessary for instrument operation. The six batteries used weighed a total of 140 kg and this brought the vehicle weight to 2024kg (two already counted in the FTIR system). They provided approximately 2-3 hours of operation before needing recharging.

Sample Conditioning

In order to measure hot wet concentrations, the raw undiluted sample gas extracted from the exhaust system was maintained at 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. This then brought a clean hot exhaust sample into the heated FTIR test cell. A sample handling unit was acquired to perform these functions and this used 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 was then filtered using a 0.2 μm filter and the sample was then introduced via another heated line into the sample cell of the FTIR. Both heated lines were maintained at 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 van compartment along with the FTIR and battery system. The gas sample was taken at the tailpipe via the Horiba OBS 1300 exhaust sample system and the heated sample line was passed through a small hole in the car's floor-pan.

Mass Emissions Calculation

The FTIR emission measurements were on a volumetric basis. However, for the comparison with different experiments the data should be converted into a mass basis and Eq. 1 shows the conversion into emission index, EI, g/kg_{fuel} [Li et al., 2010].

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

• K is the conversion coefficient, which is the ratio of molecular weight of a specific pollutant to the molecular weight of the exhaust gas. The molecular weight of the exhaust gas is close to that of air and does not vary more than 1% for H/C ratios of about 2 (i.e. diesel), irrespective of the air/fuel ratio. For this reason, K is a constant for a particular pollutant.

• C is the concentration of the component. If this is measured in ppm or % then the equation has to be multiplied by10^{-6} or 10^{-2} respectively.

• A/F is the air/fuel ratio on a mass basis measured from the exhaust mass flow (air + fuel) and the fuel mass flow.

The emissions can be converted to g/s by multiplying the emission index by the fuel mass flow rate in kg/s. The

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cumulative emissions (g) were calculated for all experiments and then divided by the distance travelled from the GPS to give the average emissions per distance travelled (g/km), which can be compared with the legislated emissions.

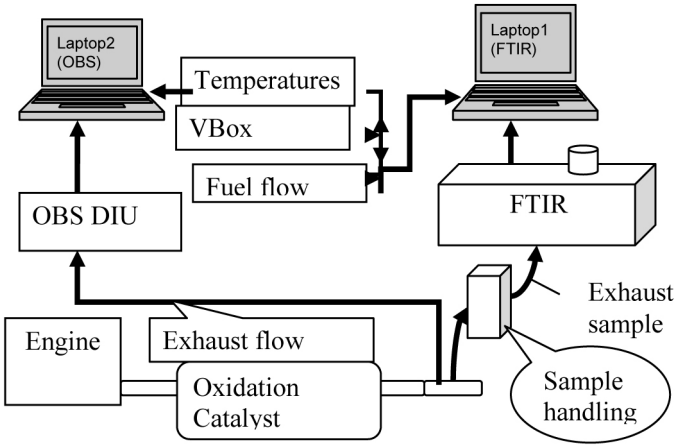


Fig. 2. Schematic view of sampling and data logging

TEST ROUTE AND CYCLE

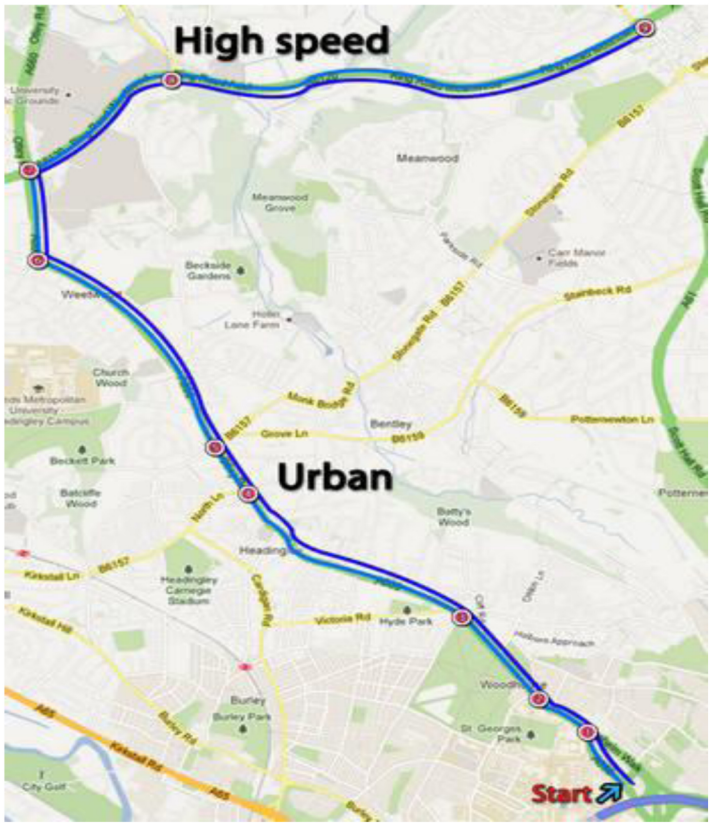


Fig.3. Headingly Ring Road 16.5 km Cycle with the major junctions numbered [23]

The test cycle selected for this emission test was the Leeds University Headingley Ring road cycle (LU-HR). This cycle consists of an urban driving section through Headingley and an extra-urban high speed section on the Leeds outer ring road. Fig. 3 shows the route of the test cycle. The distance of the cycle is approximately 16.5km and ranges in altitude above sea level is from 83m to 121m. The first section of the route is through Headingley, on typically congested urban commuter road, with several sets of traffic lights at major junctions and pedestrian crossings and is one of the most congested roads in the UK. The road is single lane in each direction for most of its length. The speed limit on this section of urban road is 48km/h (30mph). The outer ring road portion of the route is for a higher speed limit and it similar to the NEDC extra-urban drive cycle.

THE DRIVING CYCLE VELOCITY, ACCELERATION AND CONGESTION

This work did not include a cold start as the aim was to study the fully warmed up vehicle emissions. The vehicle was warmed up by prior operation on a different test cycle which concentrated on cold start issues with urban driving and these results are not included in this work. Three warm start runs were repeated by a single driver. The fuel for first three runs was 100% WME (Waste cooking oil Methyl Ester) derived from waste cooking oil. The comparison runs with diesel fuel were undertaken on a different day.

A typical vehicle speed plot with the two urban driving phases and the extra-urban in the middle is shown in Fig. 4. The route has several major junctions with traffic lights and this creates the stop/start part of the extra urban driving and associated high acceleration from the stationary position. This is a major difference from the NEDC in Fig. 1 were there are no stops in the EUDC phase.

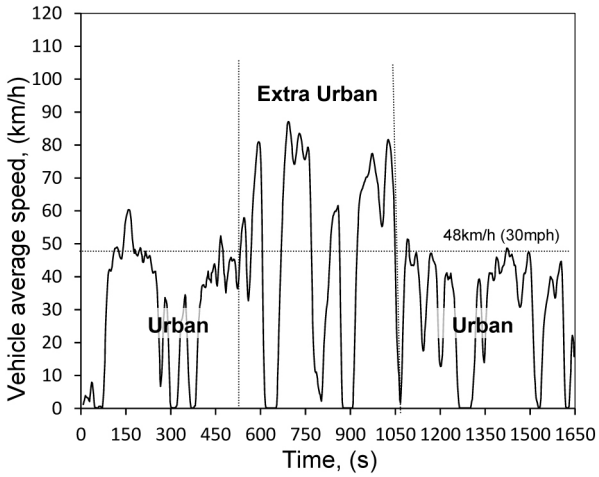


Fig.4. Typical vehicle speed in the three phases of the real world drive cycle, LU-HR.

The vehicle speed and acceleration profile for three repeat runs on B100 and one Diesel comparison run are shown in Fig. 5 and the mean parameters for the journey are shown in Table 1. The top speeds of all four runs were observed to be similar. Runs 2 and 3 had similar features with respect to the

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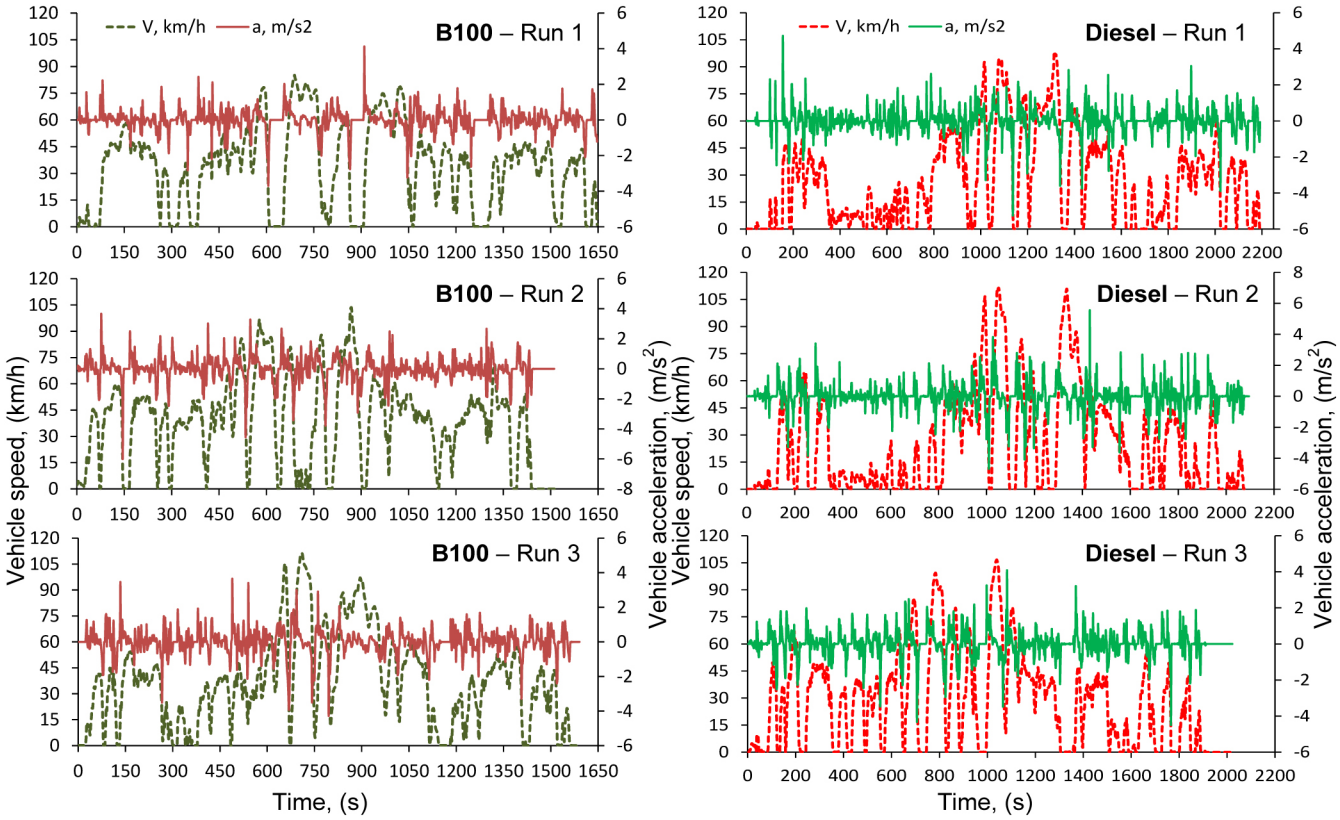


Fig.5. Vehicle speed and acceleratio profiles for three runs for B100 and Diesel

speed profiles, and runs 1-3 had similar average velocities. Run 3 and the diesel run also show similarities with periods around 500s in which congestion caused low speed events with lots of acceleration and deceleration. The traffic congestion, however, lasted longer on the diesel run affecting the overall time of the run having been stationary for 22% of the journey, this is also seen in the low average velocity. This will have affected the emissions observed and is one of the inherent difficulties when using real-world measurement techniques.

Table 1 shows that the percentage of the journey time for the three phases urban, extra-urban and return urban were 30, 43 and 26% respectively. This table also shows the mean acceleration, deceleration and vehicle speed for the three phases of the journey. A clear definition of what constitutes congestions is not simple to formulate. In the context of this study a convenient definition is when "a vehicle is forced to wait at more than one traffic junction" [24]. From this definition a coarse measure of congestion can be formulated as the difference in the average speed and the legal speed limit as a percentage of the legal limit. Thus a journey time of twice the free flow journey time, which gives an average speed of half the legal limit for the road is 50% congestion for that journey. This makes the assumption that the free-flow speed is equal to the legal speed limit, which it was in the present work. This measure of congestion is shown in Table 1 for the four journeys in Fig. 5. The four runs had a similar top speed. Runs 2 and 3 had very similar features in terms of the total journey time, which was higher than the others. Runs 1 and 4 had a similar pattern in term of speed, but the average speed was lower than runs 2and 3.

It can be seen from Fig. 5 for diesel that Runs 1 and 2 were quite different from the three runs for B100 as they had substantial periods in congested traffic at very low velocities. However, run 3 had similar traffic conditions to the three runs for B100. Comparison of the present real world vehicle movement parameters with those in the ECE urban test cycle is made in Table 1. This shows some key differences and the most important is that maximum accelerations and decelerations for all the journeys were much higher than those in the test cycle by a factor of 5. It is at the time of high accelerations and decelerations that the emissions results show the highest values and hence the principle cause of differences between test cycle emissions and real world emissions is the lack of realistic maximum acceleration and deceleration rates in the test cycle. Another key difference is that the urban test cycle has more congestion and longer period of stops than in real world driving.

WARM UP OF THE ENGINE LUBRICATING OIL

The tests were carried out with a pre-warmed vehicle. However, the slowest part of an engine warm-up is that of the lubricating oil [25] and the lubricating oil sump temperature

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Table 1. Parameters of the 16.5km LU-HR cycle

Mean value	**B 100** Run1	**B 100** Run2	**B 100** Run3	**Diesel** Run1	**Diesel** Run2	**Diesel** Run3	ECE urban test cycle
Ave. Acc, m/s^2	0.4	0.548	0.493	0.447	0.544	0.463	0.64
Max Acc m/s^2	4	3	3	4	6	4	0.74
Ave. Dec, m/s^2	-0.410	-0.568	-0.542	-0.445	-0.514	-0.527	-0.74
Max. Dec m/s^2	-4	-4	-4	-5	-3	-4	-0.74
Ave. V,km/h	35.96	40.44	37.29	26.785	25.178	29.178	-0.60
Stop, %	15.2%	9.6%	10.9%	22.0%	27.2%	23.6%	-0.74
Cong, %	30.0%	23.7%	32.0%	50.3%	56.3%	43.6%	18.7
Urban, %	43.7%	39.6%	40.9%	31.4%	26.5%	39.3%	32
High, %	26.2%	36.6%	27.0%	18.1%	17.2%	17.0%	61.0

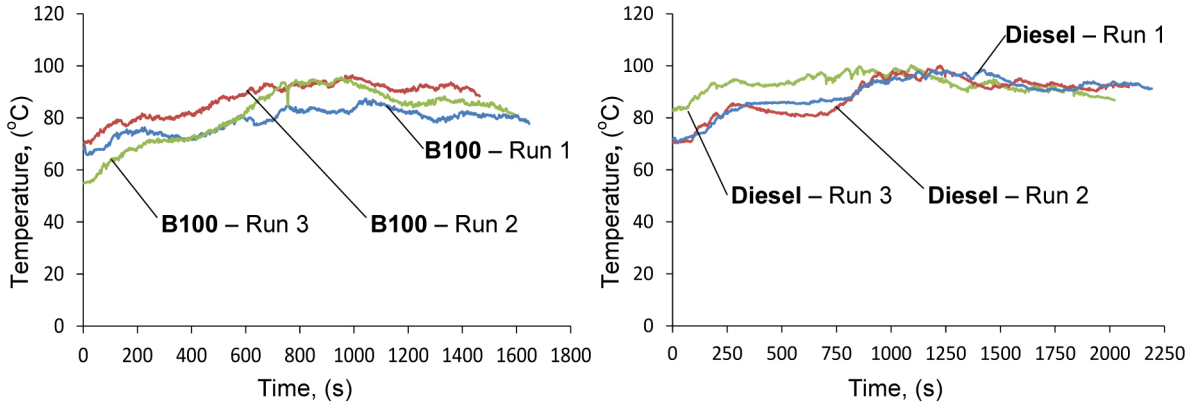


Figure 6. Lubricating oil warm up with time for three repeats on B100 and Diesel

was monitored in the present work to access how warm the lubricating oil was for each journey. The results are shown in Fig.6 which shows an initial lubricating oil temperature difference between the three B100 tests of 55 - 70°C. After about 1000s the lube oil temperature reached a roughly steady level that was well below the 100°C fully warmed up temperature. For the diesel journeys the initial lube oil temperatures varied from 70-83°C and it took about 1000s to reach an equilibrium termperature which was about 95°C for all three runs. The problem of lubricating oil warm-up was investigated in more detail in the related work of the authors on cold start emissions. For the present work it is considered that the differences in lube oil temperature were not a major cause of the differences in fuel consumption on the journeys.

OXIDATION CATALYST TEMPERATURES

Figure 7 shows the exhaust gas temperature upstream and downstream of the oxidation catalyst for three runs with B100 and a comparison diesel test. Oxidation catalysts efficiency at >90% occurs at about 200°C for HC with a slightly lower temperature for CO. The results in Fig. 7 show that in terms of the catalyst temperature there was a finite warm up time from about 100 to 200°C and this took about 100-150s. Thus, although the present work was not designed to include a cold start the time at the start of the test while instruments and data loggers were set up was sufficiently long for significant catalyst cooling to occur., as the catalysts was hot prior to the vehicle stop for system set up for the present journeys. The low oxidation catalyst temperatures at the start of the test could result in high CO and HC emissions

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