

# Determination of GHG Emissions, Fuel Consumption and Thermal Efficiency for Real World Urban Driving using a SI Probe Car

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## ABSTRACT

A SI probe car, defined here as a normal commercial car equipped with GPS, in-vehicle FTIR tailpipe emission measurement and real time fuel consumption measurement systems, and temperature measurements, was used for measuring greenhouse gas emissions including CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> under real world urban driving conditions. The vehicle used was a EURO4 emission compliant SI car. Two real world driving cycles/routes were designed and employed for the tests, which were located in a densely populated area and a busy major road representing a typical urban road network. Eight trips were conducted at morning rush hours, day time non-peak traffic periods and evening off peak time respectively. The aim is to investigate the impacts of traffic conditions such as road congestion, grade and turnings on fuel consumption, engine thermal efficiency and emissions. The time aligned vehicle moving parameters with fuel consumption and emission data enabled the micro-analysis of the correlations between these parameters. The trip average data for fuel consumption, thermal efficiency and emissions etc were calculated. The impact of vehicle's transient movements and traffic events on emissions were studied. VSP (Vehicle Specific Power) has been used for the determination of engine power output. The results show that the transient emissions were dominated by sharp accelerations occurred at traffic light and pedestrian crossing. The trip average CO<sub>2</sub> and CH<sub>4</sub> emissions had a good linear correlation with vehicle's average speed which is directly related to vehicle idle periods but no clear correlation between vehicle's speed and N<sub>2</sub>O emissions.

**CITATION:** Li, H., Khalfan, A., and Andrews, G., "Determination of GHG emissions, fuel consumption and thermal efficiency for real world urban driving using a SI probe car," *SAE Int. J. Engines* 7(3):2014, doi:10.4271/2014-01-1615.

## INTRODUCTION

Current methods for evaluating exhaust emissions from road transport are mainly based on measurements from rolling road constant volume sampling facilities using standard drive cycles. Emissions are typically described as a function of average speed or distance for the complete cycle. The average values are subsequently used to estimate transport emissions. However, studies have demonstrated that many other parameters such as vehicle operating conditions, traffic conditions (free-flow, congested), ambient temperatures, fuel compositions, topography and road geometry strongly influence real world emissions [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

Lenaers [11] investigated fuel consumption and tailpipe CO<sub>2</sub> emissions from four family cars including gasoline, diesel and hybrid cars driving on various roads such as urban, rural and motorway routes. The results found that fuel consumption and CO<sub>2</sub> emissions are highest on urban roads. Fonseca [12] measured CO<sub>2</sub> emissions using two diesel vehicles in two urban driving circuits with one of the vehicles equipped with a fuel cut off system at stoppage. Their results showed up to 20% reductions in CO<sub>2</sub> for the vehicle with the fuel cut off

system compared to the one without the fuel cut off system due to zero idling emissions. This is agreed with the results in this paper which has shown that idle fuel consumption could account of 12~24% of total fuel consumption. Barth [13] investigated the impacts of traffic congestions on CO<sub>2</sub> emissions in Southern California and found that the CO<sub>2</sub> can be reduced up to ~20% via three strategies: Congestion mitigation that reduce severe congestion allowing free flow traffic, speed management techniques to reduce excessively high free flow speeds to more moderate conditions, and shock wave suppression techniques to eliminate and acceleration and deceleration events which are associated with the stop start events during congested traffic. Figliozzi [14] analyzed the CO<sub>2</sub> emissions from commercial freight vehicles for different levels of congestion and showed significant impacts of congestion or speed limits on commercial vehicle emissions but admitted that it is difficult to predict. The research concluded that the public agencies and highway operators must carefully consider the implications of transport policies such as travel speed limits on CO<sub>2</sub> emissions and fuel economy. The paper suggested that if the speed is set at optimal, CO<sub>2</sub> emissions can be reduced without compromise in fleet sizes and distances travelled.

This paper investigated the fuel consumption, brake thermal efficiency and GHG (Green House Gas) emissions generated under real world urban driving conditions during the different time of a day. The routes used represented typical urban busy circuits including arterial and minor roads, turnings, pedestrian crossings and traffic lights. The impact of traffic conditions, road grade and vehicle's movements was investigated.

## 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.

### *Fuel Flow, Air/Fuel Ratio, and GPS Measurements*

#### **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.

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

#### **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 (ZrO<sub>2</sub> 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  $\lambda$  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 Gasmeter CR 2000 which was capable of measuring concentrations as low as 0.5~3 ppm, depending on the species and 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 CO<sub>2</sub> and 7000 ppm for NO<sub>x</sub> respectively.

A FTIR emission measurement system was selected because of its ability to speciate VOC, NO/NO<sub>2</sub>/N<sub>2</sub>O and measure ammonia in addition to CO, NO<sub>x</sub>, 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 [15]. It was found that the FTIR measurement had excellent agreement (2% deviation) with the CVS measurement for CO<sub>2</sub> emissions. The N<sub>2</sub>O and CH<sub>4</sub> were checked in laboratory using bottled gases and found good agreements as well.

The Temet instrument comprised a FTIR analyzer, 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 input channels was employed to log one or two external analog signals for time alignment between the FTIR laptop and the second laptop. The voltage output from the VBox was used as the external signal and exported to two laptops: One for the FTIR that logs emission spectra and external analog signals; the other one for temperature measurement and fuel meter logging.

### 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, 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 floor pan. There was no possibility of dilution of the sample by pressure pulsations from the tailpipe.

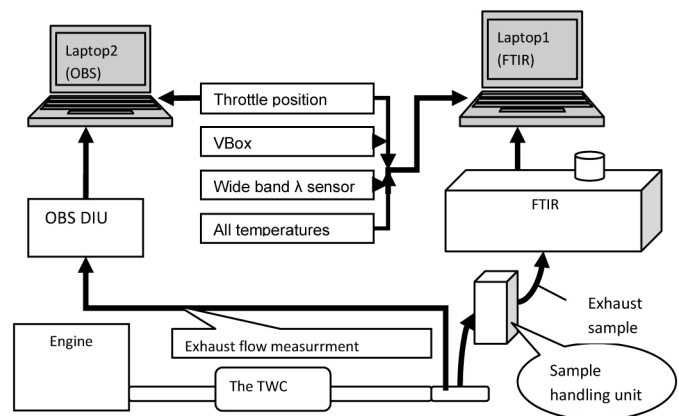


Figure 1. Schematic view of sampling and data logging system

## Mass Emission and VSP Calculation

### 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)

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

(1)

Where

- 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.

### Vehicle Specific Power (VSP)

The generic VSP estimation equation was used with the typical coefficient values for a light-duty vehicle [16].

$$VSP = v \cdot (1.1 \cdot a + 9.81 \cdot \sin(\text{atan}(\text{grade})) + 0.132) + 0.000302 \cdot (v)^3$$

(2)

Where:

- $v$  is vehicle speed (m/s)
- $a$  is vehicle acceleration ( $\text{m/s}^2$ )
- grade is road grade, = vertical rise/horizontal distance (dimensionless)

VSP is defined as the instantaneous power per unit mass of the vehicle, with units of kilowatts per tonne (kW/tonne).

### Test Route and Procedure

Two urban driving cycles were designed to carry out emission tests: Headingley route A and route B, referred as route A and B hereafter. Figure 2 shows the map of the routes. Headingley is a dense residential area in Leeds and has a feature of typical urban road network, i.e. carrying numerous city social-economy activities and being one of the main transportation carriers.

The test trips started from point 1 in figure 2, a side road, enabling preparation of instruments and then turned right to join one of the city's major roads A660. The probe vehicle passed a pedestrian crossing and travelled towards point 2, where the route A and route B differed. Figure 3 shows the different movement at point 2 for two routes. For the route A, the vehicle went straight through the junction and travelled to point 3 and then took a U-turn moving back towards point 2. At the junction the vehicle took a right turn and moved towards point 4 and then took the second U turn travelling back to point 2. The vehicle turned right at point 2 back to A660 and travelled back to point 1. For route B, the vehicle coming from point 1 took a left turn at point 2 and travelled up to point 4 and then had a U turn moving back to point 2. The vehicle turned left at point 2 and continued to travel to point 3, where a U turn is taken and the vehicle was back to point 2 along A660. The vehicle was then straight travelling through the junction at point 2 and moved back to point 1.

There are 4 pedestrian crossings and three sets of junction traffic lights in this urban road network. Though the testing routes were a return trip but did not pass all these crossing and traffic lights. The topography of the road is not flat and thus uphill and downhill travels are experience. The real time elevations of the probe vehicle were logged by on-board GPS system and were validated by the ordnance map and the final corrected elevation data was plotted in all diagrams.

The distance traveled for each trip is ~5 km The speed limit on these urban streets is 48 km/h (30 mph)

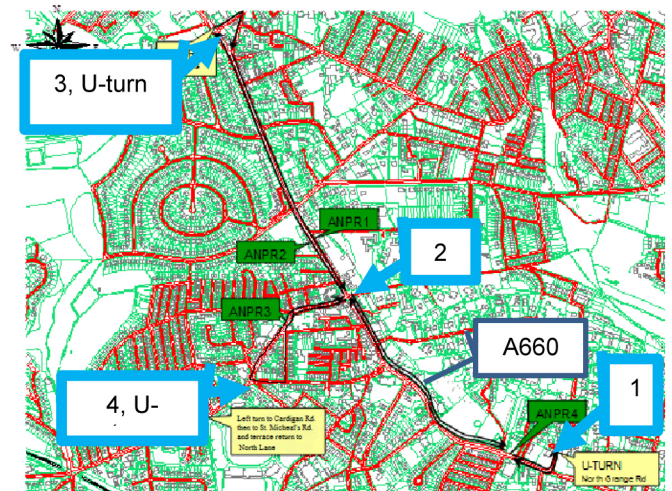


Figure 2. Map and notations of driving route.



Figure 3. Different maneuver at point 2 for Route A (left) and B (right)

## RESULTS AND DISCUSSIONS

### Driving Parameter Analysis

#### Velocity and Acceleration

Figures 4, 5, 6, 7 shows profiles for four A trips, including vehicle's velocity, acceleration, transient and cumulative fuel consumption, Transient VSP and cumulative power output, elevation of road, distance travelled, lambda, transient and cumulative  $\text{CO}_2$ ,  $\text{N}_2\text{O}$  and  $\text{CH}_4$  mass emission rates. The important milestones for the trip are marked on the elevation diagrams of figures 4, 5, 6, 7, 8, 9, 10, 11. The notes are R for right turn, L for left turn, P for pedestrian crossing and T for traffic light.

The trip A can be divided into two directions: outwards and inwards section towards city center. The first 2.0 km was the outward trip. The inwards trip towards city center is about 2.5 km except figure 5 where the logging of instruments finished earlier due to technical problems. It can be found in the figures 4a, 5, 6, 7a that the outbound journeys for two morning ones and lunch time one took approximately 300 seconds whereas the one in evening (figure 7) took ~250 second, indicating less traffic in the evening. The velocity and acceleration profiles