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Cold Start SI Passenger Car Emissions from Real World Urban Congested Traffic

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Abstract

The tailpipe exhaust emissions were measured under real world urban driving conditions by using a EURO4 emissions compliant SI car equipped with an on-board heated FTIR for speciated gaseous emission measurements, a differential GPS for travel profiles, thermocouples for temperatures, and a MAX fuel meter for transient fuel consumption. Emissions species were measured at 0.5 Hz. The tests were designed to enable cold start to occur into congested traffic, typical of the situation of people living alongside congested roads into a large city. The cold start was monitored through temperature measurements of the TWC front and rear face temperatures and lubricating oil temperatures. The emissions are presented to the end of the cold start, defined when the downstream TWC face temperature is hotter than the front face which occurred at ~350-400°C. Journeys at various times of the day were conducted to investigate traffic flow impacts on the cold start. The test route had traffic and pedestrian crossing lights, several major road junctions and a busy shopping area. The time aligned vehicle moving parameters with pollutant emission data and fuel consumption enabled the micro-analysis of correlations between these parameters. The average cold start emissions, fuel consumption and temperature data are presented for the journeys into different levels of congestion (based on the mean speed of the cold start journey). The mean complete journey speed during was shown to reasonably correlate the emissions, which increased as mean speed reduced. The cold start congested traffic portion was separately analysed to show the much higher emissions for equivalence mean speeds. Engine vehicle specific power (VSP) output was calculated and used together with the fuel flow to determine the instantaneous and average thermal efficiency. Three way catalysts (TWC) light off was approximately 200 seconds, much longer than for the NEDC test cycle. Currently urban air quality monitoring does not include cold start into congested traffic from vehicles at houses along the road, but does have procedures where cold start occur at large car parks.

Introduction

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 exceedance and has the power to introduce measures to reduce the emissions. In the UK nearly all cases where an AQMA had been declared involved traffic pollution as the cause of the exceedance [1]. The road on which this research was undertaken was the subject of a City of Leeds traffic and congestion study[2]**.**The air quality in the same area was monitored and compared with traffic emission modelling results. It has been found that the modelled NO_2 concentrations were 47% lower than actually measured results in the area and 28% lower for the city. The NO_2 measurements showed 14 sites in Leeds above the EU limit where the model only predicted 4 sites in exceedance. The high NO_2 in the area was attributed to traffic congestions as there are no other pollution sources.

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 [3-10]. The cold start also has cold oil, water, all metal surfaces as well as the cold catalysts cold and it is the thermal energy required to heat these that is the main thermal efficiency and CO_2 problem in cold starts[11-14]. The warm up of the lubricating oil takes about 15 minutes. Greenhouse gases methane and nitrous oxide and benzene as well as other hydrocarbons are predominantly emitted during cold start period before 200 seconds[15].

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 the road geometry strongly influence real world emissions[1, 16-24] .

In the present work with cold start into congested traffic after leaving a car park next to the road, stop start velocities of 10 kmph occur and it is often >100s before the first significant acceleration to 40 kmph and 200s before the TWC is fully active. The cold start emissions dominate the whole journey emissions, though as the journey length extends, the proportion of cold start emissions is reduced. The net result is that emissions are higher in cold start into congested traffic and this is part of the reason that air quality in cities has not responded in proportion to emissions reduction on the test cycle. The stop-start frequency of movements is also greater in real world driving than on the test cycles and this gives higher NOx emissions after the TWC has lit off. This is now recognized as a problem and the continuing air quality problems have resulted in the adoption of a new World Light-duty Test Cycle (WLTC), which is more real world based and this might be more representative of congested traffic. However, the proposed cycle has a time to first acceleration much shorter than occurs in congested traffic.

Lenaers[25] investigated fuel consumption and tailpipe CO2 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_2 emissions are highest on urban roads. Fonseca[26] measured CO_2 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_2 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[27] investigated the impacts of traffic congestions on CO_2 emissions in Southern California and found that the CO_2 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 acceleration and declaration events which are associated with the stop start events during congested traffic. Figliozzi[28] analyzed the CO_2 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_2 emissions and fuel economy. The paper suggested that if the speed is set at optimal, CO_2 emissions can be reduced without compromise in fleet sizes and distances travelled.

Nitrogen compound from vehicle tailpipe such as NO, NO_2, N_2O, NH_3 and HCN are toxic air pollutants (TAPs). NO is a product of combustion inside the engine. NO_2 is mainly a secondary pollutant from the exhaust catalytic systems where extra oxygen is available to oxidize NO into NO_2. NO and NO_2 are involved in the formation of ozone (O_3) in the atmosphere and able to oxidize unburned hydrocarbons to form oxygenated irritants such as formaldehyde, peroxyacetyl nitrate Finlayson[29]. NO_2 itself is an irritant air pollutant regulated by EU air quality legislation. NH_3 is not a product of combustion and instead is formed across the TWC. NH_3 is not directly regulated by vehicle emission legislation but is required to be monitored for the sake of the air quality, soil and surface water concerns[30]. The United Nations Economic Commission for Europe (UN ECE) has set the limits for NH_3 for different European countries. However, there is no legislative requirement for NH_3 released from vehicle tailpipe. NH_3 can form NH_4NO_3 and/or $(NH_4)_2SO_4$and contribute to the formation of the secondary aerosols and is an important constituent of particulate matter (PM).NH_3 has a potential to be transported over a long distance in the atmosphere and thus could potentially have adverse impacts on soil and water because of the deposition of ammonium salts which lead to acidification and eutrophication of soils and surface waters.

Heeb [31-33] investigated NH_3 emissions and their correlation with NO emissions and concluded that catalyst temperatures and air/fuel ratios are key parameters affecting the formation of NH_3in EURO 3 and 4 gasoline passenger cars. They also reported a conversion ratio of 2% to 45% for NO converting to NH_3 when operating a Pd/Rh-based TWC vehicle under transient driving conditions. There is a kind of trade-off between NOx and NH_3. As the NOx emission legislation is getting more stringent, more effective and efficient NOx reduction across the TWC is demanding. This may cause the rising of NH_3 emissions. The authors [34, 35] have also shown the significant emissions of NH_3 from TWC under real world driving with associated Hydrogen cyanide (HCN) emissions. HCN is a toxic air pollutant and a by-product formed during the NOx reduction reactions across the catalyst [36, 37]. There are very limited data on the HCN emissions from vehicle tailpipe being reported [36].

Nitrous oxide (N_2O) is a powerful GHG (~300 stronger than CO_2) and has a long life span (>170 years). The transport sector is a minor contributor to the total N_2O flux in the atmosphere. However, its GWP (Global Warming Potential) could account for a notable contribution to the total GWP from vehicle tailpipe emissions. Li et al [1] investigated GWP of CO_2, N_2O and CH_4 tailpipe emissions for five urban driving cycles and reported ~10% of the total GWP coming from N_2O.

The limit values for each EU exhaust emission standard represented in table 1. Prior to EURO 3 THC and NOx were summated. They have been listed as separate targets here on the basis of their ratio in the EURO 3 legislation[38].

Table 1 EU exhaust legislation of EURO SI passenger cars

	EURO1	EURO2	EURO3	EURO4
CO g/km	2.7	2.2	2.3	1.0
THC+NOx g/km	0.97	0.50	-	-
THC g/km	0.55*	0.29*	0.2	0.1
NOx g/km	0.42*	0.21*	0.15	0.08

*: EURO 3 THC/NOx ratios were used to calculate EURO1 and 2 THC and NOx limit values, the cold start procedure was altered for EURO 3

The objective of this work is to investigate the fuel consumption, brake thermal efficiency, legislated emissions, GHG (Green House Gas) and five nitrogen compounds (NO, NO_2, NH_3, HCN, N_2O) emissions during cold start under real world urban driving conditions, specifically looking at the impact of traffic congestion on emissions. Multiple journeys were taken at different times of days. The routes used represented typical urban busy circuits including arterial and minor roads, turnings, pedestrian crossings and traffic lights. The impact of cold start and traffic on emissions was investigated.

A Euro 4 vehicle was used as EURO 4 SI cars are still a significant proportion of the UK vehicle fleet. It takes about 16 years for 90% of vehicles sold in any one year to be no longer in use [15]

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, exhaust gas temperatures upstream and downstream of the TWC. All temperatures were measured using grounded junction mineral insulated Type K thermocouples with a response time of ~0.25 ms.

Measurements of Fuel Flow, Air/Fuel Ratio and GPS

Fuel Consumption Measurement

A MAX710 fuel flow measurement system was used to measure real world fuel consumptions which intercepted the vehicle fuel system and was connected between the fuel tank and engine. 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_2 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 ± 0.04λ for 0.91~1.19 λ and ± 0.08 λ 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.

Emissions 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 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_2 and 7000 ppm for NOx respectively.

A 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 measurement by authors using a chassis dynamometer facility and various driving cycles. It was found that the FTIR measurement had excellent agreement (2% deviation) with the CVS measurement for CO_2 emissions. The N_2O and CH_4 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. The throttle position and VBox Voltage output were used for time alignment between two laptops as both signals were sent to two laptops.

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℃ 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℃ 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.

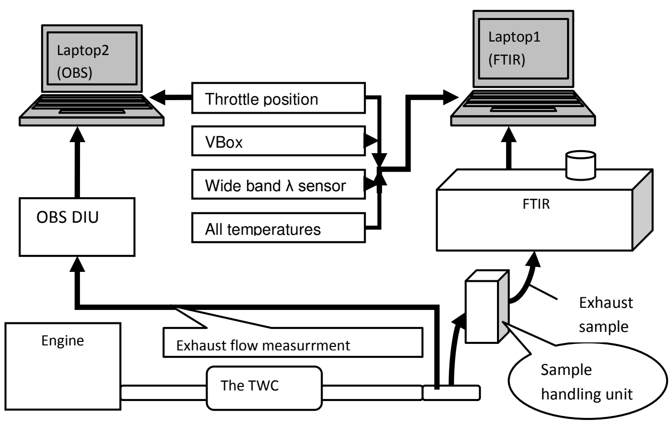

Figure 1: Schematic view of sampling and data logging system

Mass Emission and VSP Calculations

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*K*C*(1+A/F) 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

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

VSP= v*(1.1*a+9.81*sin(atan(grade)) +0.132)+ 0.000302*$(v)^3$ (2)

Where:

- v is vehicle speed (m/s)
- a is vehicle acceleration (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

An urban road network located in Headingley of Leeds city was designed to carry out emission tests as shown in figure 2. 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. Four different cycles were conducted: CSR1, CSR2, CSR3 and CSR3s. All trips started from point 1, travelling uphill towards point 2 where the road became relatively flat. The trips continued towards point 3 with some uphill and downhill sections and from point 3, the trips were divided into different route as shown in table 2.

Table 2: Directions of different driving routes

Driving cycle (route)	Direction
CSR1	1-2-3-5-6
CSR2	1-2-3-4-5-6
CSR3	1-2-3-4-3-5
CSR3s	1-2-3-4-3

There are eight pedestrian crossings and seven 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 experienced. 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)

Table 3 listed the file names and starting and ending time of the eight testing trips. The file names are based on the estimated trip starting time but the actual starting time was slightly late than the planned time. Vehicle's travel profiles, fuel consumption, VSP and emissions for all these eight journeys were analyzed for journey average and presented in Appendix A. Two journeys were selected for detailed analysis (Day 2_EURO4_1150_CSR2 and Day 5_EURO4_1624_CSR2) and presented in figures 3 to 14. One was a congested journey which had the longer journey time and the other one was much less congested having much shorter journey time. Both had the same route.

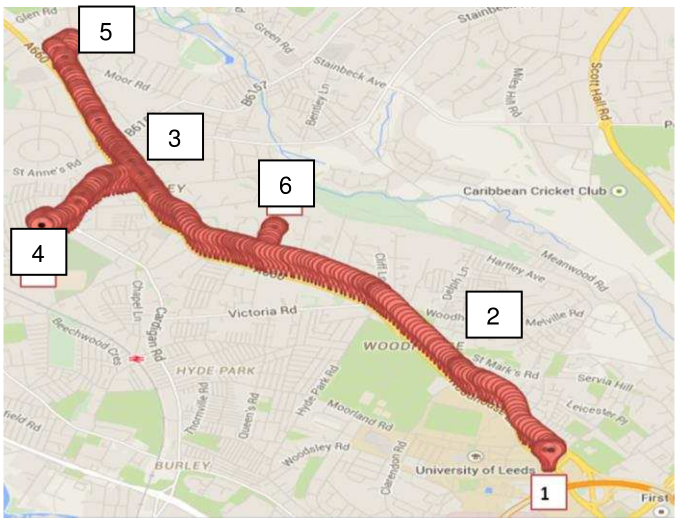

Figure 2: Map and notations of driving route.

Table 3: Start and end time of all the testing trips

Trip name	Start time	End time
Day 1_EURO4_1850_CSR1	18:51:42	19:04:26
Day 2_EURO4_1150_CSR2	11:52:09	12:09:49
Day 3_EURO4_0722_CSR2	07:24:31	07:43:30
Day 3_EURO4_1153_CSR2	11:53:38	12:12:47
Day 5_EURO4_1157_CSR2	11:58:47	12:19:06
Day 5_EURO4_1624_CSR2	16:25:22	16:59:03
Day 2_EURO4_1620_CSR3	16:20:51	16:52:49
Day 4_EURO4_1620_CR3s	16:21:21	16:42:39

Results and discussions

Driving Parameter Analysis – Velocity, Acceleration and TWC Light Off

From Appendix A, it can be seen that the average velocity was from 8.8 to 25.5 km/h. The slowest trips were those ones during evening rush hours. The evening trip was in fact a free flow trip (Day 1_EURO4_1850_CSR1). It can be seen that the maximum acceleration was from 2.39 to 2.68 m/s^2. The Maximum acceleration was in fact a free flow trip in the morning (Day 3_EURO4_0722_CSR2). The average acceleration was from -0.0076 to 0.0083 m/s^2.The average was negative value (deceleration) in all trips in the morning. It can be seen that the average VSP^+ was from1.43 to 3.24 kw/tonne. The lowest one was in fact a congested trip in the evening (Day 2_EURO4_1620_CSR3). It can be seen that the stoppage time was from 160 to 952 s. The highest stoppage time was in fact a congested trip in the evening (Day 2_EURO4_1620_CSR3). Also number of stops was from 10 to 54 stop. The highest stoppage time was in fact a congested trip in the evening (Day 5_EURO4_1624_CSR2). Appendix A shows that the cruise percentage was from 9.7 to 52.62 %. Minimum value was in fact a congested trip in the evening (Day 2_EURO4_1620_CSR3).

Figures 3 to 14 show the profiles of the trips (Day 2_EURO4_1150_CSR2 and Day 5_EURO4_1624_CSR2) representing free flow and congested respectively, including vehicle's velocity, acceleration, transient and cumulative fuel consumption, Transient VSP and cumulative work done, elevation of road, distance travelled, lambda and GHG emissions Vs time. Figures 3 and 4 compared GHG emissions Vs time and figures 5 and 6 compared GHG emissions Vs distance for two journeys. Figures 7 and 8 compared nitrogen species emissions Vs time and figures 9 and 10 compared nitrogen species emissions Vs distance for two journeys.

Figures 11 and 12 compared legislated emissions Vs time and figures 13 and 14 compared legislated emissions Vs distance for two journeys.

The trips started from the garage in Lodge Street (point 1 in figure 2) and were divided into two directions: outwards and inwards towards the city center. The distance from point 1 to 2 was 0.4 km, 2.2 km from point 2 to 3, 0.6 km from point 3 to 4, 1.5 km from point 4 to 5 and 1.9 km from point 5 to 6. The inwards trip was 3.2 km from point 4 to 6. It can be found in the figures 3, 5, 7, 9,11and 13 that the journey took 1060 seconds indicating free flow trip whereas the figures 4,6,8,10,12 and 14 took 2021 second, indicating congested traffic trip. The velocity and acceleration profiles show that outbound journeys were less congested than that of inbound journeys for free flow trip and opposite in congested trip. There were eleven stops for free flow trip with duration of 212 seconds as total stoppage time whereas there were fifty four stops for congested journey with duration of 905 seconds as total stoppage time. The free trips in general there was a chunk of time when the vehicle was in cruise mode. However, were much more congested, indicated by more stops and longer idling times. This was particularly obvious for congested trips as they were in rush hours.

The catalyst temperatures measured at upstream and downstream of TWC were used for determination of the catalyst light off, which is defined as when the downstream temperature is equal or higher than the upstream temperature. Appendix A shows that the light off time was 196-349 seconds, which was related to the severity of congestions.

Fuel Consumption and VSP

Vehicle speed and acceleration is related directly to fuel consumption. The results shows the spikes for fuel consumption were with every speed and acceleration spikes followed by a decrease in fuel consumption during deceleration and when vehicle was travelling at a constant speed. Vehicle fuel consumption is increased during uphill travels, which required more fuel supply. The traffic and pedestrian lights major reason for frequent stop start events in a congested traffic, which caused lot of increase in fuel consumption in congested trips. The fuel economy for congested trip is only 18.3 mile/UKG whereas for the free flow trip in the off peak time this could be increased to 34.9 mile/UKG as shown in appendix A. The fuel consumption for this type of vehicle measured on the NEDC urban part is 28 mile/UKG including cold start. It can be seen that the congested trips had much higher fuel consumption than the certified values by NEDC.

VSP represents the power required from the engine to move a vehicle to overcome the aerodynamic drag, rolling resistance and the road grade effect. The value of VSP is mainly determined by acceleration and road grade. If the vehicle is travelling on a flat or downhill road at a constant speed, the value of VSP would be small as the power demand will be low. This can be illustrated with examples in the figures 3, 5,7,9,11 and 13 with low VSP less spikes whereas high VSP more spikes in the figures 4, 6, 8,10,12 and 14. The most dominant factor for VSP is acceleration, evidenced by that most of negative VSP spikes are linked with deceleration peaks and number of stops.

The average of overall VSP and positive VSP for all trips presented in appendix A in general shows that the free flow trips had the higher values as results of more free flow driving. The congested trips had lower values. This means that the average VSP could be used an indication for congestion. From this study, an initial suggest is that average VSP 1.41 or average positive VSP 3.24 could be used as indication for a non-congested trip.

Brake Thermal Efficiency

The brake thermal efficiency, as a measure for the conversion efficiency of fuel energy to useful work output, is used here to assess overall thermal efficiency and is defined as follow:

η_b=(brake work output)/(fuel energy)= (VSP*mass of vehicle*3600)/(fuel consumption*Cv of fuel)

When the vehicle is at stoppage or deceleration, the VSP values become zero or negative. This means that the energy from fuel was wasted as there was no effective work output for driving the vehicle. Therefore the brake thermal efficiency of the engine was compromised.

The positive VSP values were multiplied by the vehicle weight and then integrated. This gives rise to the trip total brake power output from the engine as shown in c of all diagrams and appendix A. The power output was then divided by the fuel energy and thus the brake thermal efficiency of the trip was obtained. The brake thermal efficiency for all trips in appendix A was in a range of 14~19%. This is low compared to the typical SI engine thermal efficiency of ~30%. The reason for this is the stop start driving pattern that seriously compromised the SI engine's thermal efficiency.

Greenhouse Gases Emissions

Figures 3 to 4 show the mass emission rate (g/s) and cumulated mass emissions for greenhouse gases emissions (GHG) as a function of time along with some driving parameters. Figure 4 shows more GHG spikes than figure 3, which is a free flow trip. Also figure 4 show more spikes for lambda, VSP, fuel consumption, velocity and acceleration as it is a congested trip.

Figures 5 and 6 show the cumulative mass emission (g) as a function of the distance travelled for GHG. Figure 5 shows the mass of CH_4, N_2O and CO_2 were 0.09, 0.05 and 1500 g respectively. Total fuel was 450 g and cumulative work done was 0.95 kWh. Whereas a higher value shows in figure 6, which is a congested trip, the mass of CH_4, N_2O and CO_2 were 0.23, 0.11 and 2100 g respectively. Total fuel was 680 g and cumulative work done was 1.3 kWh.

The vehicle started from cold. This has resulted in a spike in CH_4 and N_2O emissions during the initial 250 seconds. These spike in N_2O emissions indicated that the catalyst is not lit off.

The three way catalyst took longer time to light off in congested traffic compared to free flow traffic.

The CO_2 emissions are directly responded to fuel consumptions in all figures and also a good reflection of VSP spikes. CH_4 and N_2O emissions were very low after the engine was fully warmed up (after 300s) and only had occasional spikes, which were linked to sharp accelerations, spikes of fuel consumption and VSP, and lean spike in lambda values. Interestingly, not all of these spikes produce high CH_4 and N_2O emissions. It seems that the spikes of CH_4 and N_2O only occurred when the fuel consumption had a sharp rise with a peak value of 2 g/s and above.

By examination of all these trips it can be found that most of the CO_2 peaks are linked to pedestrian crossings, traffic lights and turnings where the vehicle was forced to stop (red light or queue). There were a few CO_2 peaks are related to uphill movements.

Nitrogen Compound Emissions

Figures 7 and 8 show the mass emission rate (g/s) and cumulated mass emissions for five nitrogen compounds as a function of time, along with some driving parameters.

Figure 8 shows more nitrogen species spikes than figure 7, which is a free flow trip. Also figure 8 show more spikes for lambda, VSP, fuel consumption, velocity and acceleration as it is a congested trip.

Figures 9 and 10 show the cumulative mass emission (g) as a function of the distance travelled for five nitrogen compounds.

Figure 9 shows the mass of N_2O, NO, NO_2, $NH_3$and HCN were 0.05, 0.5, 0.01, 0.4 and 0.008 g respectively. Total fuel was 450 g and cumulative work done was 0.95 kWh. Whereas a higher value except HCN were similar shows in figure 10, which is a congested trip, the mass of N_2O, NO, NO_2, $NH_3$and HCN were 0.11, 0.9, 0.03, 0.7 and 0.008 g respectively. Total fuel was 680 g and cumulative work done was 1.3 kWh.

One of the main purposes for these diagrams is to illustrate the effect of pollutant accumulation on the congested traffic. The longer the vehicle stands still, the higher the accumulated emissions. All the major step rises in any emissions are linked to stoppages of the vehicle. As the traffic lights, pedestrian crossing lights, left or U turns are marked in the diagrams, the accumulation of pollution can then be determined.

NH3 is abundant nitrogen compound emitted from the exhaust gases and has a value of 0.05~0.11 g/km (see appendix A). Bielaczyc etc [39] investigated NH3 emissions from EURO5, 4 and 3 emission compliance SI passenger cars using the NEDC test cycle. They reported much lower NH3 emissions from all three vehicles. Table 2 compared NH3emissions from Bielaczyc work with this research. The make and model of the EURO4 passenger car in Bielaczyc's paper is unknown and therefore direction comparison may be difficult as the tailpipe NH3 emissions may be related to type of the TWC. However, the gap between their results from NEDC and the real world driving cycle in this research is too large to be attributed to the possible difference in catalyst technology and type. The frequent stop and start, much harsher acceleration and deceleration, greater and more transient power demands for engine under real world driving conditions presented in this paper are important parameters causing high tailpipe NH3 emissions. Karlsson [37]compared NH3 emissions from NEDC and UDC (Urban Driving Cycle) of FTP-75 and observed a much higher NH3 emissions from UDC than NEDC due to harsher accelerations in the UDC. This is in a good agreement with this paper's finding, i.e. rapid and harsh accelerations are the main causes of NH3 emissions.

The peak NH3 emission rate (g/s) from eight trips in figures 7 and 8 are generally in the range of 2~4 mg/s, well aligned with the reported data from Heeb [33]. Using the German highway cycle (BAB).

Table 4: Comparison of NH_3 emission (mg/km) from reference [39] and this research

Cycle	EURO 5	EURO4	EURO3	EURO4
NEDC	5.27	2.91	16.52	
UDC	6.7	4.13	19.21	
EUDC	4.46	2.2	14.99	
LHC (this work)				60~108

The peak mass emission rate of HCN was generally around 1 mg/s. These values are significantly higher than those using Euro 1 and 2 SI cars and close to the values of a high mileage pre-Euro SI car reported by Karlsson[37]. The high HCN emissions from the Euro4 SI car may be related to the high NH3 emissions as both are by-products of de-NOx reduction reactions across the TWC. However, the detailed mechanism on the formation of HCN through the TWC is not clear.

The NO_2 emissions are generally low for all the trips but the fraction of NO_2 in NOx is higher than those generally recognized values[33], which were <1%. The possible reasons for this are that the journeys presented in this paper were mostly congested and thus have more decelerations (lean spikes), which resulted in further oxidation of NO.

N_2O is usually formed when the TWC temperature is at certain ranges (250~450 C). The downstream of TWC gas temperature was measured in this research. The N_2O emissions had an initial spike first 250 seconds for all the journeys after the engine started. However, there were hardly any obviously detectable N_2O emissions during the rest of the trips. This indicated that when the catalyst temperature was hotter than 450 C, N_2O formation across the TWC was trivial.

All the nitrogen compound emissions are related to the accelerations and positive VSP, even when there was no lambda deviation from 1.But not all the accelerations produce emission spikes.

Legislated Emissions

Figures 11 and 12 shows the mass emission rate (g/s) and cumulated mass emissions for legislated emissions as a function of time along with some driving parameters.

Figure 12 shows more legislated emissions spikes than figure 11, which was free flow trip. Also figure 12 show more spikes for lambda, VSP, fuel consumption, velocity and acceleration as it was a congested trip.

Figures13 and 14 shows the cumulative mass emission (g) as a function of the distance travelled for legislated emissions. Figure 13 shows the mass of CO, NOx and THC were 9.5, 0.8 and 2 g respectively. Total fuel was 450 g and cumulative work done was 0.95 kWh. Whereas a higher value shows in figure 14, which was a congested trip, the mass of CH_4, N_2O and CO_2 were 17, 1.4 and 3.2 g respectively. Total fuel consumption was 680 g and cumulative work done was 1.3 kWh.

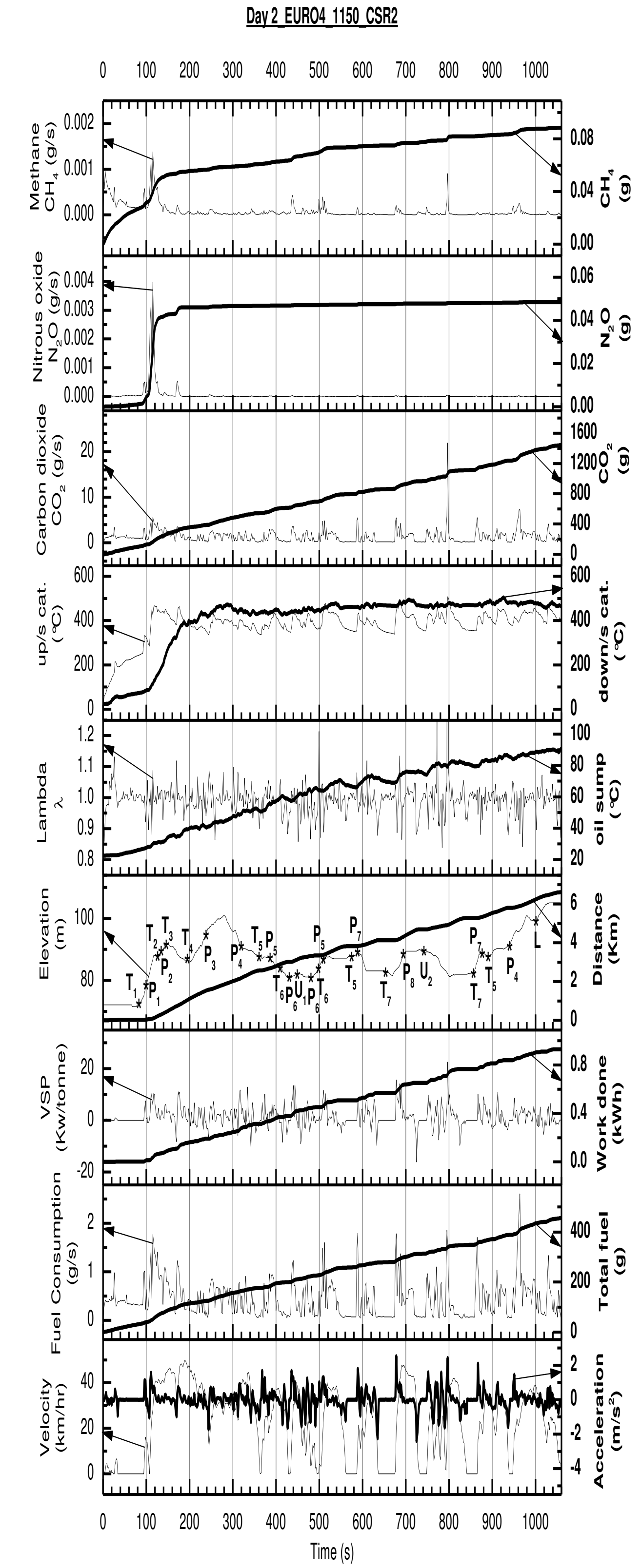

Figure 3: GHG Vs time profiles for the free flow trip 11:50

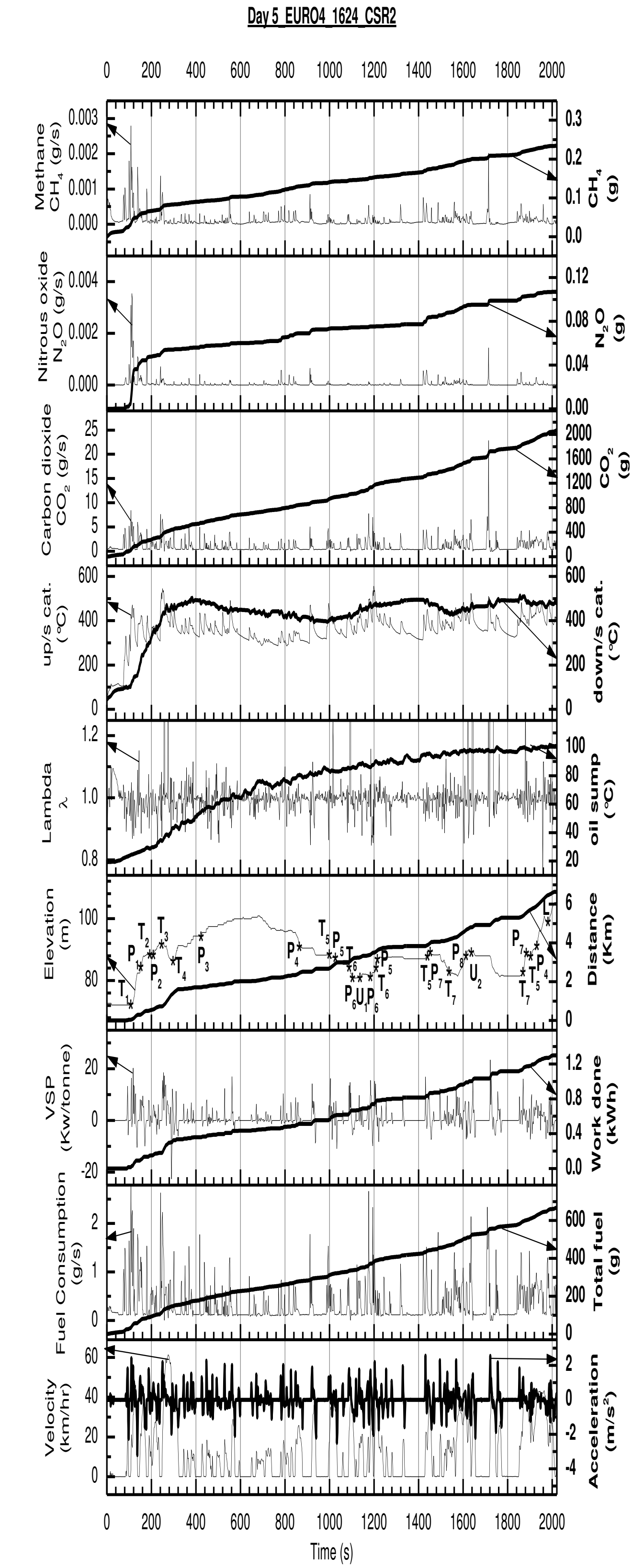

Figure 4: GHG Vs time profiles for the congested trip 16:24

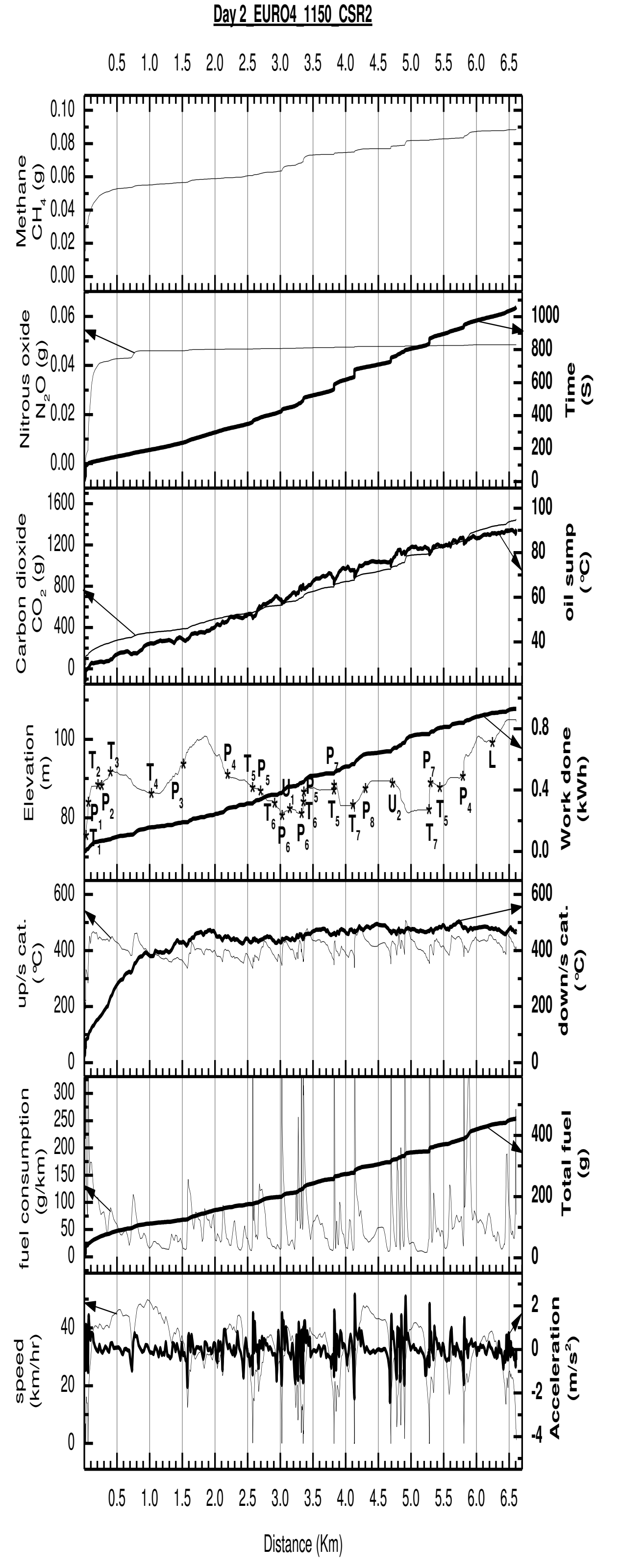

Figure 5: GHG Vs distance profiles for the free flow trip 11:50

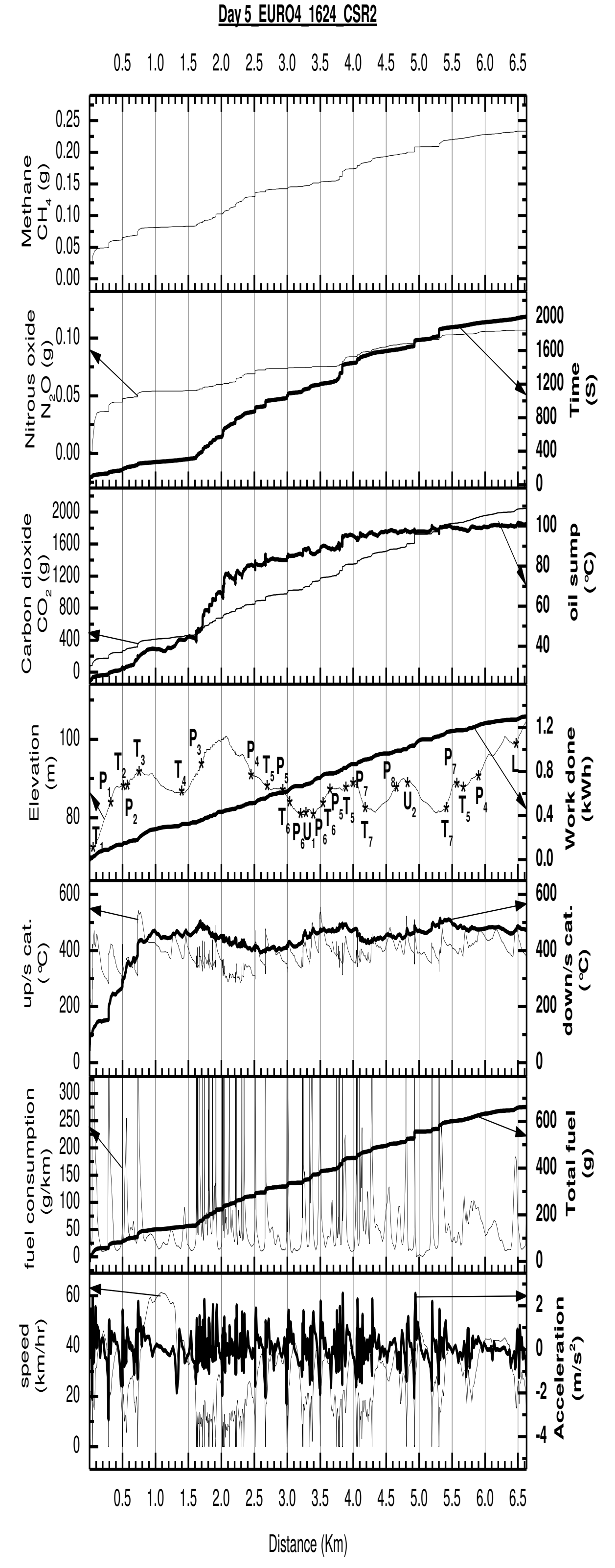

Figure 6: GHG Vs distance profiles for the congested trip 16:24

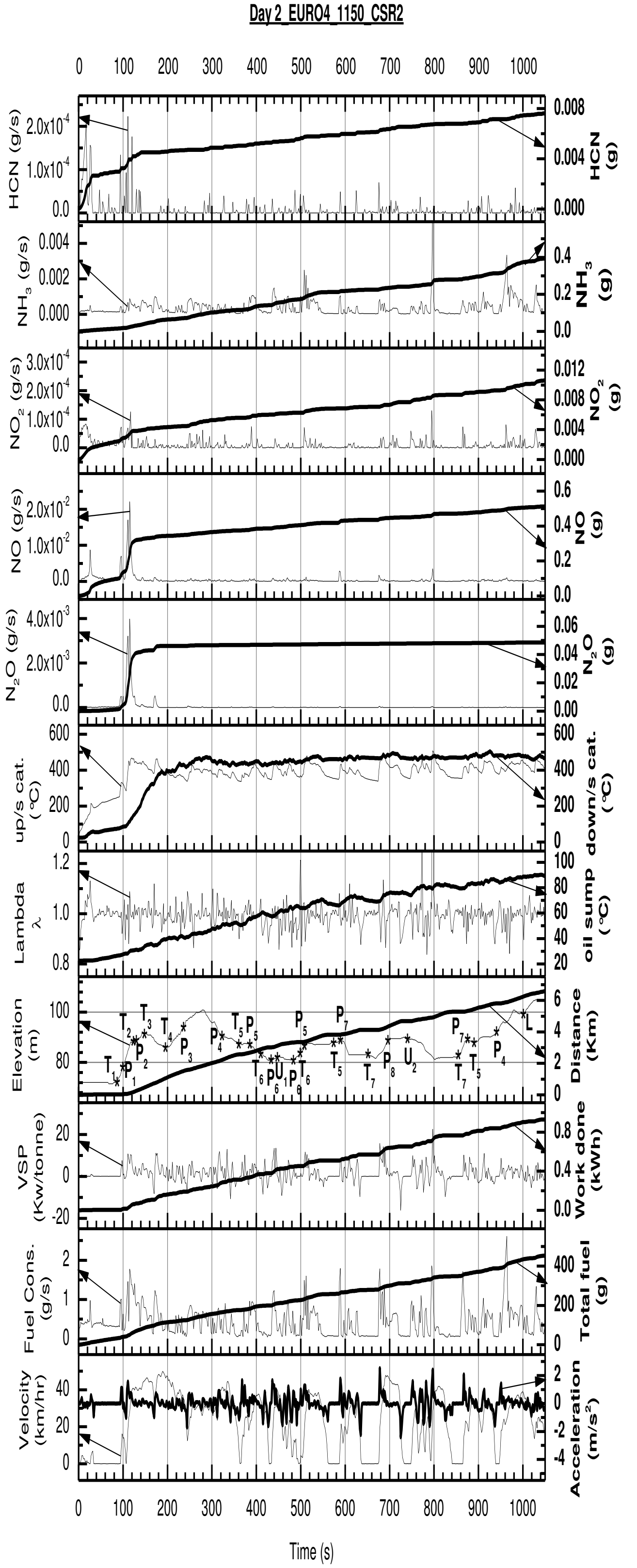

Figure 7: Nitrogen species Vs time profiles for the free flow trip 11:50

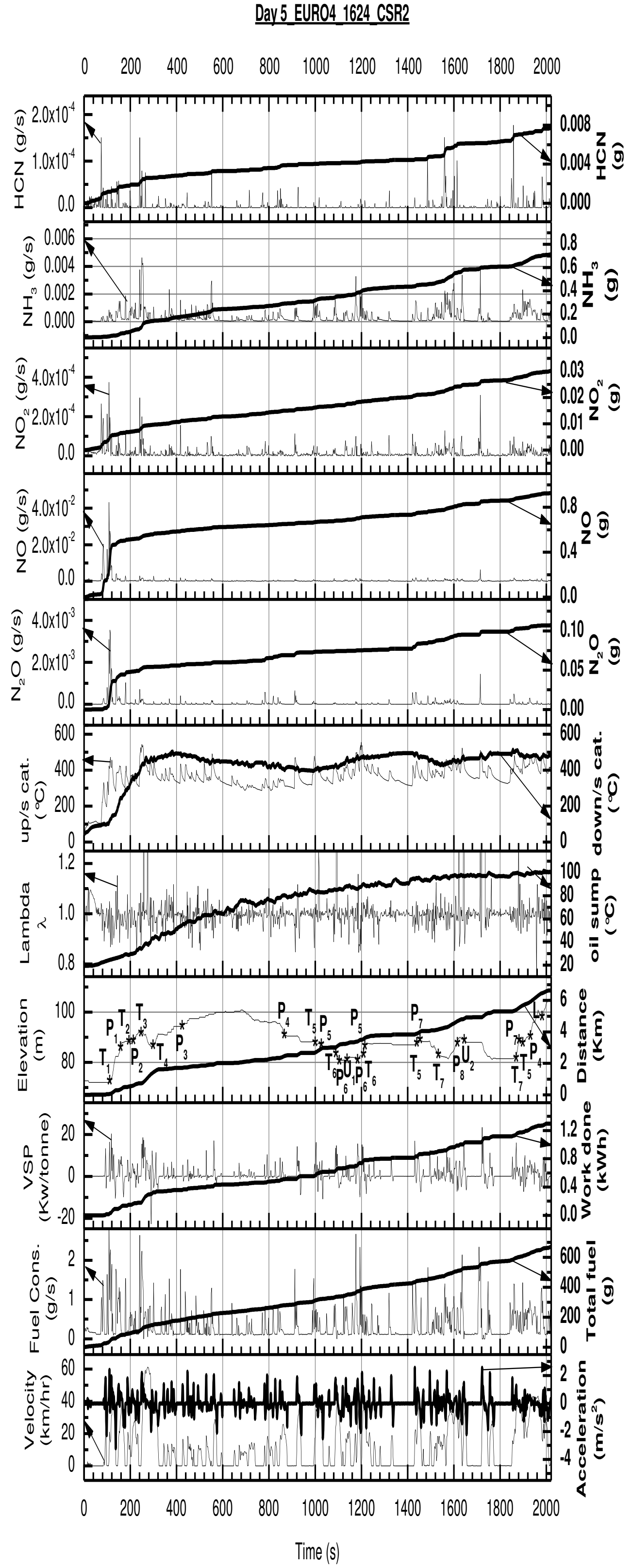

Figure 8: Nitrogen species Vs time profiles for the congested trip 16:24

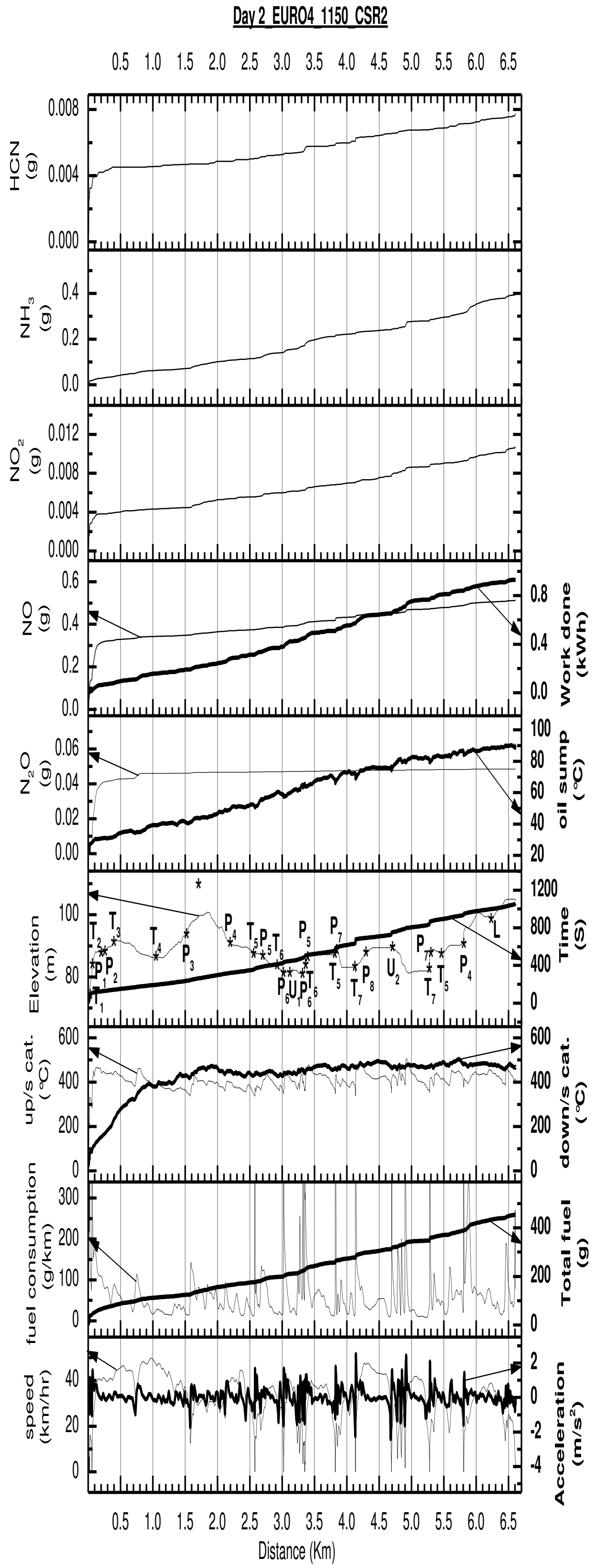

Figure 9: Nitrogen species Vs distance profiles for the free flow trip 11:50

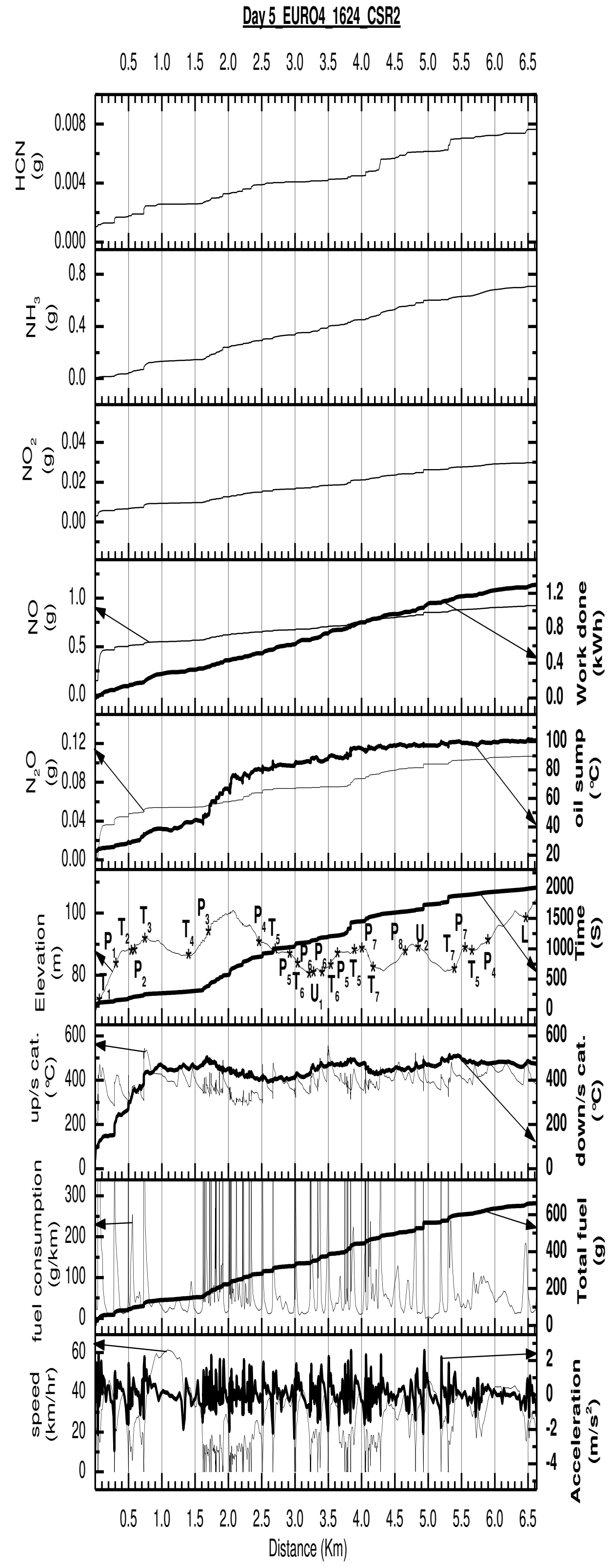

Figure 10: Nitrogen species Vs distance profiles for the congested trip 16:24

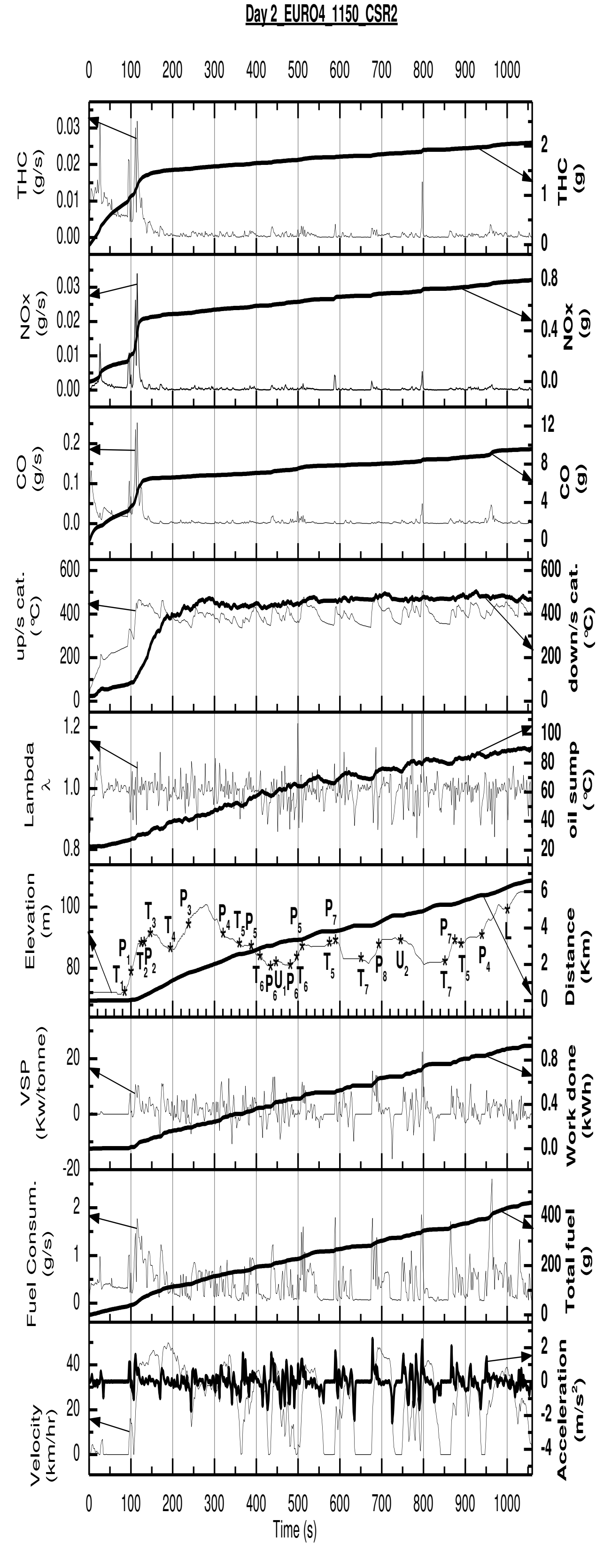

Figure 11: Legislated species Vs time profiles for the free flow trip 11:50

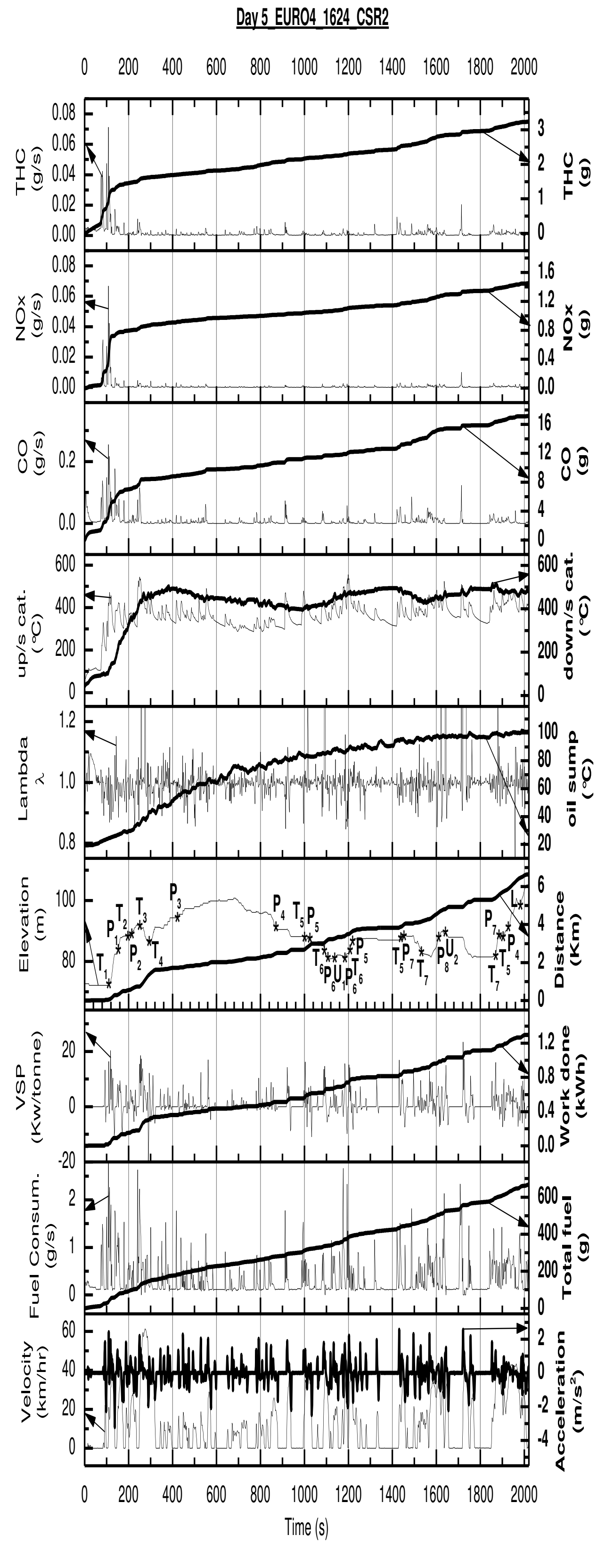

Figure 12: Legislated species Vs time profiles for the congested trip 16:24

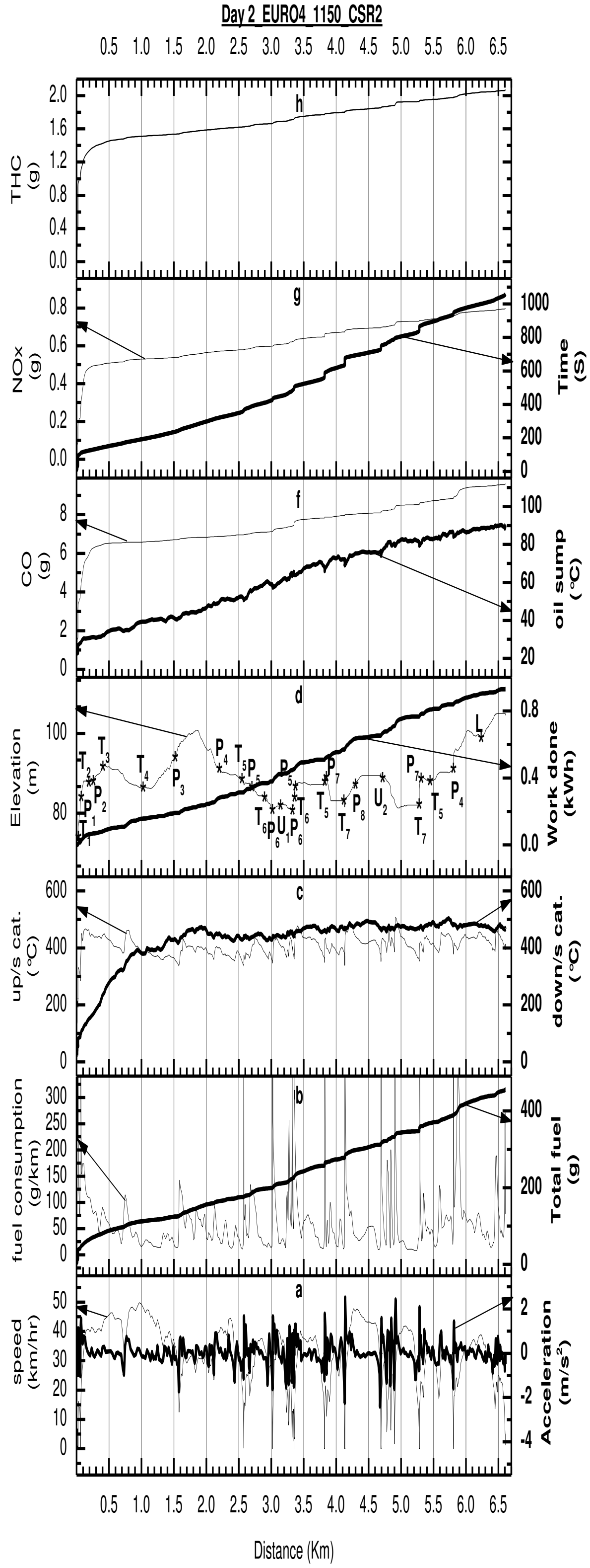

Figure 13: Legislated species Vs Dist. profiles for the free flow trip 11:50

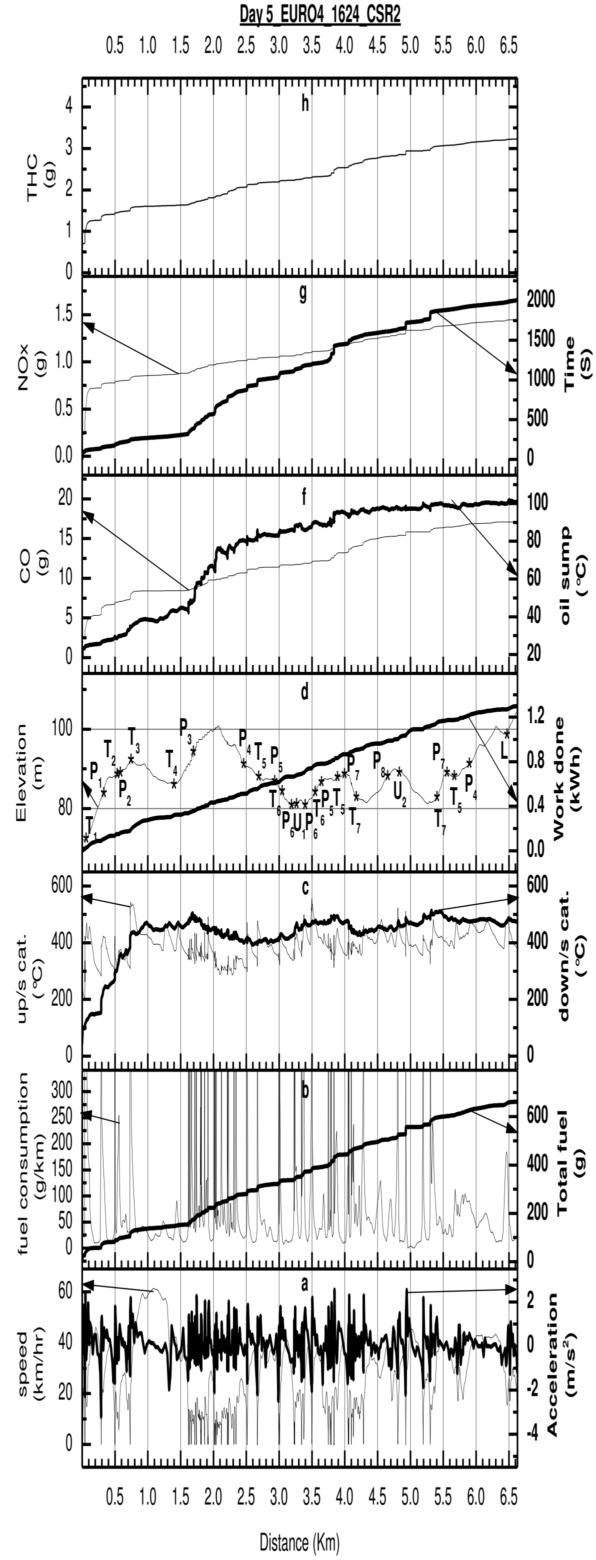

Figure 14: Legislated species Vs Dist. profiles for the congested trip 16:24

Correlations between Emissions and Driving Parameters

Figure 15 presents the correlation between trip NH_3 emissions in terms of g/km Vs average speed for eight trips. A good linear correlation is observed. Similarly a good linear correlation between THC emissions Vs average speed is observed as shown in Figure 17. Also a good linear correlation between CO_2 emissions is observed as shown in Figure 18. As well as a good linear correlation between CH_4 emissions Vs average speed is observed as shown in Figure 19, whereas a moderate linear correlation between N_2O emissions Vs average speed is observed as shown in Figure 16.

The type approval CO_2 emission data for this make and model is 179 g/km based on NEDC driving cycle [40] but the driving cycles in this paper were urban cycles so to be fair, the results from this paper can be only compared to NEDC urban part. Based on the ratio between the combined and urban part fuel consumption from NEDC which was 1.36, it is estimated that the NEDC urban part CO2 for this model of vehicle is 244 g/km. The CO2 emissions from this study have a range of 178-374 g/km. It indicated the real world CO_2 emissions in the densely populated areas could be much higher than legislated cycle results, which will depend on the severity of congestion. It can be seen in the appendix (A) that only four of those very congested journeys, these are (0722_CSR2), (1624_CSR2), (1620_CSR3) and (1620_CR3s) produced higher than NEDC urban part certified CO2 emissions values. Figure 18 shows the correlation of journey average velocity with journey average CO2 emissions. It shows that CO2 (g/km) was higher than 244 g/km when the journey average velocity was slower than 20 km/h.

N_2O and CH_4 have a much higher global warming potential (GWP) compared to CO_2 and their GWP index is about 300 and 35 relative to CO_2 respectively. However, due to the very low mass emissions their contributions to GWP are only 0.1-0.4% and thus negligible.

The reductions in NH_3, N_2O, THC, CO_2 and CH4, with increased average velocity might be due to reduced congestions and more free flow driving and thus less rich spikes in lambda. The reduction in N_2O with increased average velocity is probably due to that the catalyst temperatures exceeded the N_2O formation window.

Figures 20, 22 and 23 present the relationship between emissions of NH_3, CO_2 and CH_4 Vs average vehicle specific power (VSP) for eight trips respectively. A moderate linear correlation is observed in these figures.

Figure 21 presents the correlation between trip THC emissions in terms of g/km Vs average vehicle specific power (VSP) for eight trips. A good linear correlation is observed. The values of VSP are determined by travel velocity.

The results in figures 4, 6, 8, 10, 12 and 14 are warm start not truly cold start tests as the car was stopped for approximately 2.5 hours from previous tests and oil sump temperature was around 50-60 ^{o}C at the start of the tests. If the tests were conducted with the vehicle soaked long enough, the emissions and fuel consumption would be even higher than the presented.

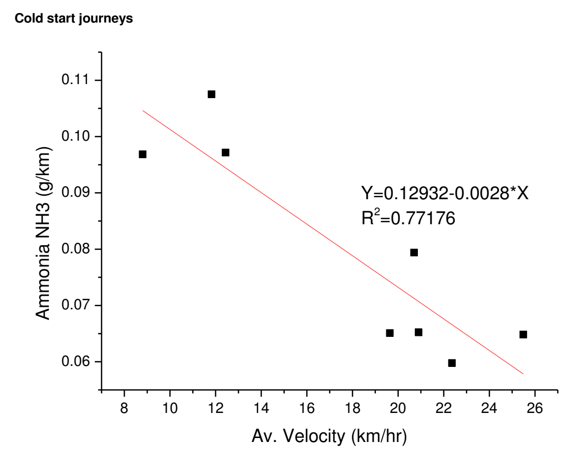

Figure 15: Trip mean NH_3 emissions Vs vehicle's average trip velocity

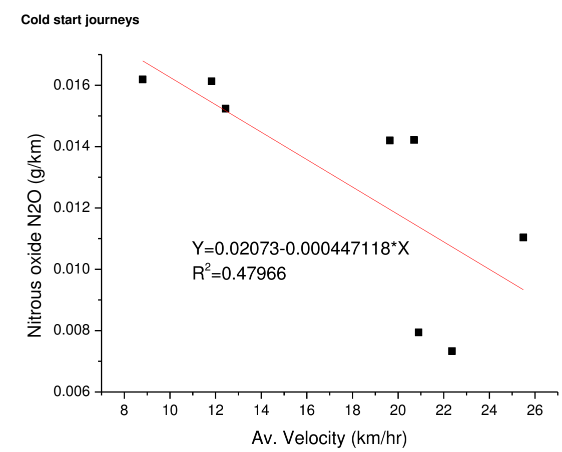

Figure 16: Trip mean N_2O emissions Vs vehicle's average trip velocity

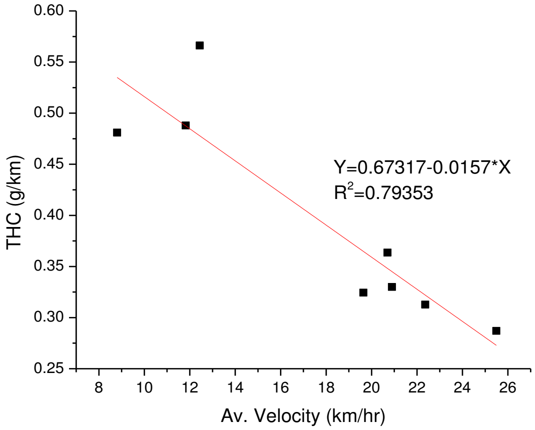

Figure 17: Trip mean THC emissions Vs vehicle's average trip velocity

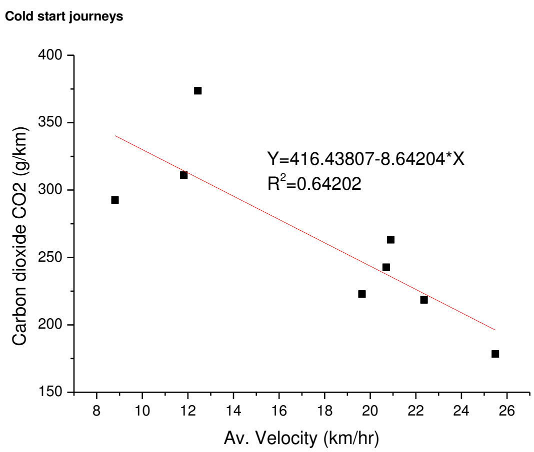

Figure 18: Trip mean CO_2 emissions Vs vehicle's average trip velocity

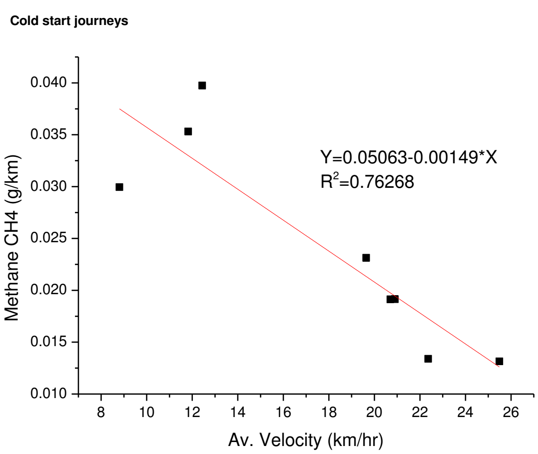

Figure 19: Trip mean CH_4 emissions Vs vehicle's average trip velocity

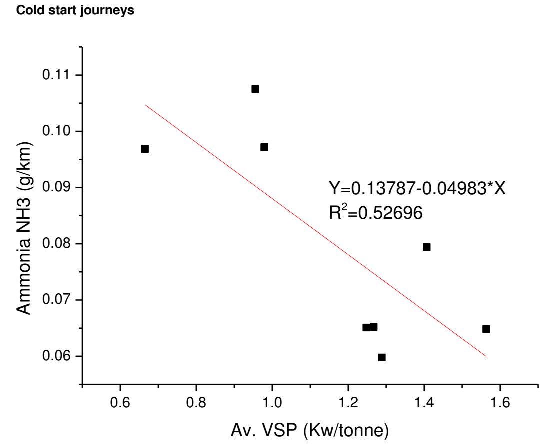

Figure 20: Trip mean NH_3 emissions Vs vehicle's average trip vehicle specific power

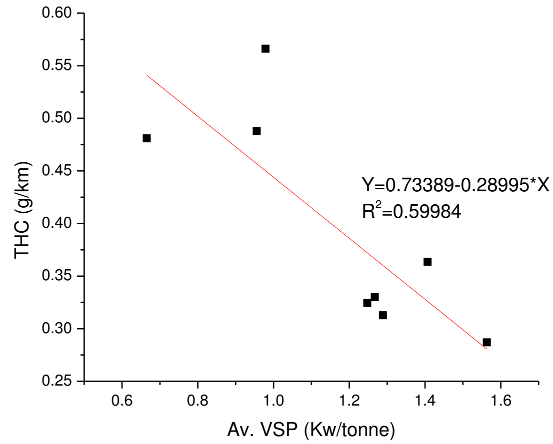

Figure 21: Trip mean THC emissions Vs vehicle's average trip vehicle specific power

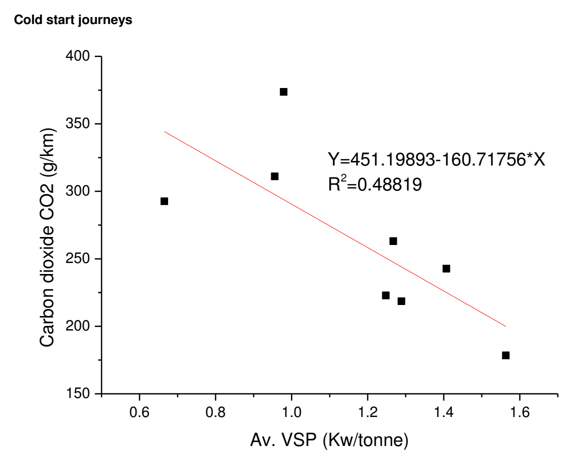

Figure 22: Trip mean CO_2 emissions Vs vehicle's average trip vehicle specific power

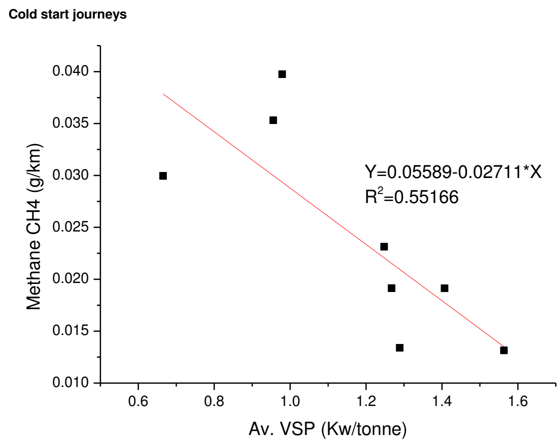

Figure 23: Trip mean CH_4 emissions Vs vehicle's average trip vehicle specific power

Conclusions

Greenhouse gases (GHG), nitrogen compound emissions (HCN, NO, NO_2, N_2O and NH_3) and legislated emissions from a EURO4 SI passenger car were measured using a portable FTIR system. The vehicle was driven on real world driving cycles (route CSR1, CSR2, CSR3 and CSR3s) using the routes located in a dense populated area of Leeds representing typical urban road network. Eight real world emission tests were conducted at different times of rush hours in days such as the morning, lunch time, evening, and off-peak time. The emissions were presented in ppm, g/s and g/km. The correlations between emissions and trip average velocity, acceleration and VSP were analyzed.

The results have shown that:

1. The light off time for the TWC was approximately 200 seconds for the free flow trips and 350 seconds for congested trips. Congested trip shows more emissions and driving parameters spikes (lambda, VSP, fuel consumption, velocity and acceleration) than free flow trip.
2. Fuel consumption in congested traffic is much deteriorated. Fuel economy can hardly achieve the certified values in urban congested traffic. The idling fuel consumption accounted for 7~28% of total fuel consumption, which will give rise to 7~28% of increase in CO_2 emissions as well. The total fuel consumption for congested traffic could be doubled compared to the free flow trip. CO_2 showed good correlation with the average velocity and a moderate linear correlation with average VSP. The long stoppage time (idle) in a traffic queue can seriously deteriorate the engine thermal efficiency. In this study, the thermal efficiency of the engine was 14-20%, significantly lower than theoretical values.CO_2 emissions were 178-373 g/km from this study. The type approval CO_2 for this make and model of the vehicle is 179 g/km based on NEDC cycle (the NEDC urban part CO2 is estimated at 244 g/km based on fuel consumption ratio). This would result in an underestimation of CO_2 emissions for emission inventories.
3. VSP representing the power demand to move a vehicle is dominantly affected by the accelerations in urban driving conditions. The value of average VSP and average VSP^+ can be used as indicators for traffic congestions. The minimum values for free flow VSP could be 1.3 for average VSP and 3 for average VSP^+ whereas the minimum values for congested flow VSP could be 1 for average VSP and 2.1 for average VSP^+.
4. The journey average CH_4 was 0.013 g/km for free flow traffic and 0.035 g/km for congested traffic from this study.
5. CH_4 emissions can be very low when the engine is hot in congested traffic. CH_4 showed good correlation with the average velocity and a moderate linear correlation with average VSP.
6. The N_2O emissions had an initial spike first 250 seconds for all the journeys after the engine is started then was trivial, when TWC get hot even in very congested traffic. N_2O showed a moderate correlation with the average velocity.
7. THC showed good correlation with the average velocity and a moderate linear correlation with average VSP. THC emissions were 0.29-0.57 g/km from this study, about 60% more in congested traffic.
8. NO and NH_3 emissions are the most abundant nitrogen species in the tailpipe and can be detected from all the trips. HCN in general was very low below detection limit during most of the journeys and only had occasional detectable spikes at harsh accelerations and during the beginning of the trips.
9. NH_3 emissions is one of the most abundant nitrogen species in the tailpipe and can be detected from all the trips NH_3 emissions from this research were significantly higher than some reported data from other Euro 4 SI cars using NEDC due to lots of traffic and pedestrian leads to frequent stop and start and more harsh accelerations. NH_3 showed good correlation with the average velocity and a moderate linear correlation with average VSP.
10. The results of mass emissions as a function of distance travelled showed clear evidences of the accumulation of emissions during vehicle's stoppage periods at traffic lights and in the queues.
11. CO emissions were 1.45-2.66 g/km from this study.

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Definitions/Abbreviations

AQMA: Air Quality Management Areas.
A/F: Air Fuel ratio
CVS: Constant Volume Sampling.
ECE: Economic Commission for Europe.
EI: Emissions Index
FTIR: Fourier Transform Infrared.
FTP: Federal Test Procedure.
GHG: Green House Gas.
GPS: Global Positioning System.
GWP: Global Warming Potential
LHC: Leeds Headingley Cycle
NEDC: New European Driving Cycle.
OBS: On Board Emissions Measurement System.
SI: Spark Ignition.
TAPs: toxic air pollutants.
TWC: Three Way Catalyst.
UDC: Urban Driving Cycle.
UN: United Nations.
EUDC: Extra Urban Driving Cycle
WLTC: World Light-duty Test Cycle.

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Appendix A: Summary of driving parameters and emissions species for all journeys

Journeys	1850_CSR1	1150_CSR2	0722_CSR2	1153_CSR2	1157_CSR2	1624_CSR2	1620_CSR3	1620_CSR3s
Av. Velocity (km/hr)	25.490	22.36	20.90	20.70	19.64	11.82	8.80	12.44
Max Velocity (km/hr)	49.180	49.85	61.20	54.63	66.76	61.35	52.80	55.43
Min Velocity (km/hr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Av.Acceleration (m/s2)	0.0083	-0.0076	-0.0010	-0.0016	-0.0029	0.0029	0.0051	-0.0012
Max Acceleration (m/s2)	2.493	2.52	2.68	2.67	2.60	2.57	2.46	2.39
Max Deceleration (m/s2)	-1.954	-2.41	-1.88	-2.60	-2.46	-3.21	-1.83	-2.69
Av. VSP (Kw/tonne)	1.563	1.29	1.27	1.41	1.25	0.96	0.67	0.98
Max VSP (Kw/tonne)	17.292	22.51	26.34	23.43	23.86	23.39	17.83	20.63
Min VSP (Kw/tonne)	-11.215	-16.17	-14.70	-18.55	-11.12	-22.67	-8.30	-14.88
Av. VSP+ (Kw/tonne)	3.06	2.97	2.75	3.24	2.73	2.09	1.43	1.99
Av. VSP- (Kw/tonne)	-2.34	-2.23	-2.58	-2.60	-2.39	-2.00	-1.30	-2.35
Power output+ (kWh)	0.73	0.93	0.96	1.10	1.04	1.30	0.81	0.83
Power output- (kWh)	-0.22	-0.31	-0.33	-0.38	-0.36	-0.46	-0.27	-0.29
Total stoppage time (s)	160.00	212.00	313.00	290.00	356.00	905.00	952.00	594.00
Stoppage time (%)	20.94	20.00	27.64	25.24	29.20	44.78	49.64	46.48
Cruise%	52.62	47.45	42.32	43.60	39.79	19.69	9.70	18.70
Total fuel consumption (g)	317.00	456.09	544.68	514.63	461.97	668.26	441.71	488.33
Av. fuel consumption (g/s)	0.42	0.43	0.48	0.45	0.38	0.33	0.23	0.38
Idle fuel consumption (g)	30.85	43.22	42.12	63.30	39.88	157.30	122.13	94.37
Idle fuel consumption (%)	9.73	9.48	7.73	12.30	8.63	23.54	27.65	19.33
Journey Av. fuel consumption (g/km)	58.40	69.00	82.25	77.57	69.49	100.65	94.85	111.39
Fuel economy (mile/UKG)	34.91	29.55	24.79	26.28	29.34	20.26	21.50	18.30
Overall thermal efficiency (%)	0.19	0.17	0.14	0.17	0.18	0.16	0.15	0.14
Total Distance (Km)	5.43	6.61	6.62	6.63	6.65	6.64	4.66	4.38
Carbon dioxide CO2 (g/km)	178.375	218.61	263.13	242.73	222.80	311.09	292.61	373.64
Nitrous oxide N2O (g/km)	0.0110	0.0073	0.0079	0.0142	0.0142	0.0161	0.0162	0.0152
Methane CH4 (g/km)	0.013	0.013	0.019	0.019	0.023	0.035	0.030	0.040
Nitrogen monoxide NO (g/km)	0.085	0.078	0.066	0.161	0.070	0.140	0.126	0.100
Nitrogen dioxide NO2 (g/km)	0.001	0.002	0.008	0.003	0.008	0.005	0.004	0.006
Ammonia NH3 (g/km)	0.065	0.060	0.065	0.079	0.065	0.108	0.097	0.097
Hydrogen cyanide HCN (g/km)	0.0008	0.0012	0.0022	0.0008	0.0010	0.0012	0.0010	0.0018
NOx (g/km)	0.13	0.12	0.11	0.25	0.12	0.22	0.20	0.16
Total HydrocarbonTHC (g/km)	0.29	0.31	0.33	0.36	0.32	0.49	0.48	0.57
Carbon monoxide CO (g/km)	1.57	1.45	1.85	1.94	2.25	2.58	1.88	2.66
Number of stops	10	11	17	17	15	54	50	39
Journey duration (s)	764.00	1060.00	1139.00	1149.00	1219.00	2021.00	1918.00	1278.00
Light off time (s)	227.0	196.0	295.0	257.0	231.0	262.0	263.0	349.0
Light off distance (km)	1.18	1.06	0.97	1.11	1.08	0.87	1.11	0.93
Oil temperatrue when TWC lit off (°C)	56.3	39.2	43.4	67.0	36.0	38.1	69.0	52.8