

VOC Emissions and OFP Assessment for Two Real World Urban Driving Cycles using a EURO 2 SI Car

Hu Li, Gordon E. Andrews and Adnan A. Khan
The University of Leeds, UK

Copyright © 2008 SAE International

ABSTRACT

A FTIR in-vehicle on-road emission measurement system was installed in a EURO2 emissions compliant SI (Spark Ignition) car to investigate exhaust Volatile Organic Compounds (VOC) emissions and Ozone Formation Potential (OFP) under different urban traffic conditions. The real time fuel consumption and vehicle traveling speed were measured and logged. The temperatures were measured along the exhaust pipe so as to monitor the thermal characteristics and efficiency of the catalyst. Two real world driving cycles were developed with different traffic conditions. One (West Park Loop cycle) was located in a quiet area with few traffic interference and the other one (Hyde Park Loop cycle) was in a busy area with more traffic variations. The test car was pre-warmed before each test to eliminate cold start effect.

The driving parameters were analyzed for two real world cycles. The WPL cycle had higher acceleration rate, longer acceleration mode and less steady speed driving mode and thus harsher than the HPL cycle. The 52 volatile organic compounds (VOCs), including benzene, toluene and 1,3butadiene VOC emissions were measured. OFP was evaluated using Maximum Incremental Reactivity (MIR). The results showed higher VOC emissions and OFP for the WPL cycle, indicating that an isolated driving cycle produced greater emissions because of free accelerations and more change on driving mode. The research helped to understand traffic emission profiles in urban areas. The data of this research can be used for prediction of VOC emissions and OFP in cities.

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, research 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 [1-5].

This research forms a component of a major project investigating the relationship between urban traffic control and real world emissions. In this paper the emissions from two driving cycles: an isolated four-side circuit and an open four-side circuit were investigated using a EURO 2 emissions compliant SI car and compared with EU legislation. The variability in driving profiles for two cycles was analyzed. The objective was to develop understanding and provide more realistic data on traffic emissions so that authorities could more accurately model the generation of emissions and hence air quality consequences of particular traffic management schemes.

EURO 2 emission legislation came into effect in 1996 and set limits for petrol passenger cars as 0.5 g/km for HC+NO_x emissions and 2.2 g/km for CO emissions. These legislated emissions are based on the standard NEDC driving cycle with the first 40 seconds cold start not sampled. The authors have studied the cold start emissions and found that for a urban driving cycle similar to ECE15, the TWC (Three Way Catalyst) needed 150~200 seconds to be lit off when the catalytic conversion efficiency reached at least 50%. Thus EU

emission legislation for EURO 2 contained at least 110 seconds cold start emissions. However the relatively simplistic NEDC cycle has been shown[4-10] to underestimate emissions when compared to the real world cold start driving conditions that was involved more transient speed profiles. It is therefore one of aims in this study to investigate if a EURO2 SI car can meet the EU legislation when the engine was hot.

This study assessed the emission characteristics of a EURO 2 emissions compliant SI car at urban intersection. The key point is to investigate the impact of real world driving cycles on emissions. A Euro 2 vehicle was used as EURO 2 SI cars are one of the major proportions of the UK vehicle fleet and hence major contributors to air pollution in cities. The ongoing work is investigating Euro 3 and 4 vehicles. It takes about 16 years for 90% of vehicles sold in any one year to be no longer in use [5] and this period is becoming longer for modern vehicles. Figure 1 shows SI passenger car fleet composition in the UK from 1996 to 2025 published by NAEI [11]. The fleet composition data are in terms of fractions of vehicle kilometers traveled, not just in terms of vehicle stock, by taking account of the fact that newer vehicles travel more miles in a year than older vehicles. The data in figure 1 show that EURO 2 vehicles currently take up ~23% of SI passenger car fleet. Thus the work on Euro 2 vehicles has significance in terms of their current use in city driving and hence their impact on air quality. It will be at least 2010 before 90% of Euro 2 vehicles become an insignificant portion of city traffic. Future work under-way is investigating variability in driver behaviour and real-world emissions from EURO 3 and 4 vehicles at a variety of junction types (priority, signalised, roundabout, multi-level).

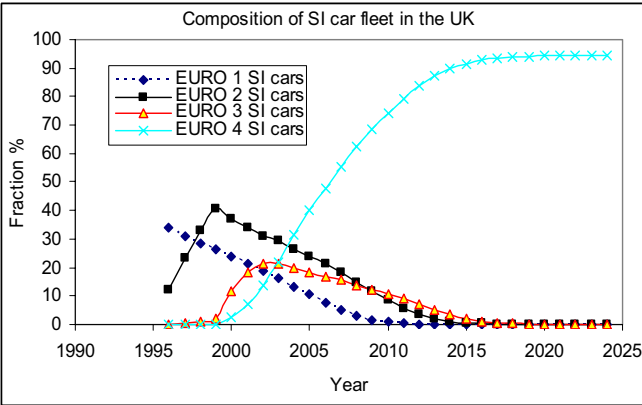


Figure 1: UK SI car fleet composition

Transport related hydrocarbon emissions have three main health and environmental impacts: ozone forming potential, toxicity and greenhouse effect (methane). Ozone is an irritant gas that affects eyes, nose, lungs and reduces the lung function and triggers asthma attacks. This paper presents a pilot phase experiments studying real world VOC emissions and OFP assessment using a FTIR measurement system.

EXPERIMENTAL

TEST CAR AND THERMAL MEASUREMENT - A Ford Mondeo manual transmission petrol car was used, which was fitted with a port fuel injected 2.0 litre 16V Zetec spark ignition engine with 4 cylinders and 16 valves. The odometer reading on the car was 136,000 km, which had annual travel mileage of 16,000 to 19,000 km per year, a typical mileage for UK passenger cars. The vehicle was equipped with a Three Way Catalyst (TWC). The curb weight of the car was 1360 kg. The car was instrumented with 19 thermocouples, which measured the air inlet, engine coolant and lubricating oil temperatures. In addition the exhaust skin (metal), exhaust gas, catalyst and ambient temperatures were also measured. All temperature measurements used grounded junction mineral insulated Type K thermocouples.

Table 1 identifies the thermocouples by number, location and function. These references are used in the schematic view of the thermocouple locations on the test car (figure 2) and the later graphical presentation of the warm-up temperature results in real world driving. Figure 3 presents the outline of the measurement system and data logging system that was used. A differential GPS system was used to measure the vehicle's travel speed and distance, and this was connected to an analog Daqview data logger along with all 19 thermocouples, fuel consumption and lambda data. The data logger was then connected to a second laptop PC. The thermal measurements were logged at 1Hz and the FTIR emission measurements at 0.5 Hz.

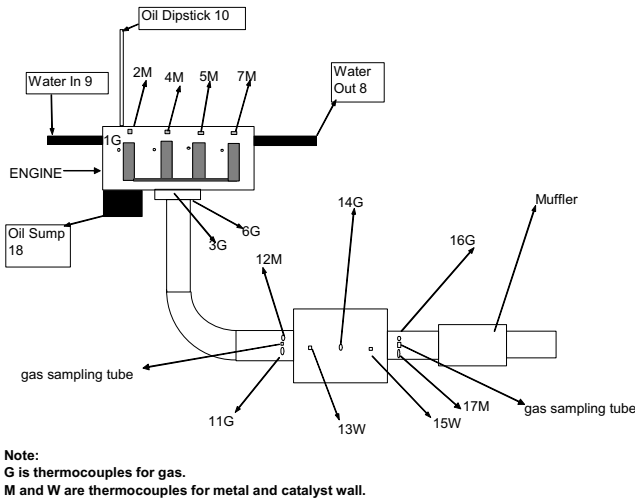


Figure 2: Schematic view of thermocouple locations

Table 1: Thermocouple locations and functions

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

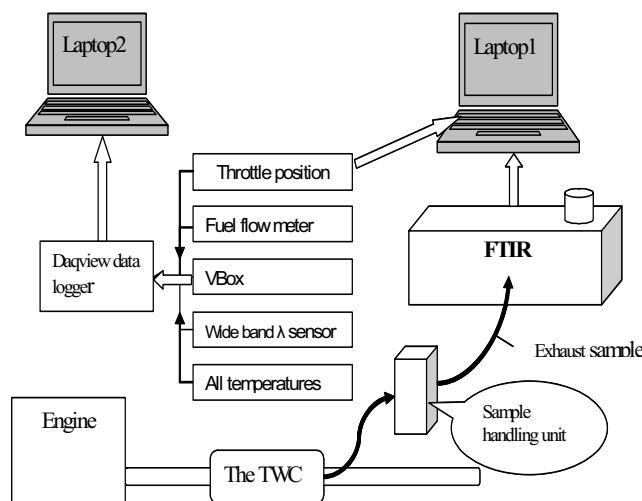


Figure 3: Schematic view of sampling and data logging system

ON BOARD EMISSION MEASUREMENT –A portable Fourier Transform Infrared (FTIR) spectrometer was used to measure on road real world emissions. The model used was the Temet Gasmet CR 2000 which was capable of measuring concentrations as low as 0.5~3 ppm, depending on the applications. It has been specifically calibrated for this instrument by the manufacturer for 38 hydrocarbons species to an accuracy of 2% within the calibrated measurement range that was from 0~500 ppm individually (methane was calibrated to 1000 ppm). Another 14 hydrocarbons

were added to the calibration library by using the calibration files done for the same make and type of the instrument. These 14 hydrocarbons are reported here as indications only marked with a symbol “ * ”. The calibration for this instrument is needed for precise quantitative analysis for these 14 species. The total VOCs emissions in this paper are the sum of 38 precisely calibrated hydrocarbon emissions.

The Temet instrument comprised a FTIR analyzer, a portable sampling unit (filtering and controlling sample flow), heated sample lines (180°C) and a laptop. The cell temperature of the FTIR was 180°C. The exhaust gas sample was taken every two seconds. The sampling period was about 1 second period. Therefore there was a leap between each sampling process.

The FTIR system weighed about 30 kg. The entire on-board measurement instrumentation including the FTIR system, the fuel consumption measurement system, two batteries and a DC-AC converter weighed about 150 kg.

The software of the FTIR system has the additional capability of accepting analog inputs, which can be logged together with the emissions spectra and analysis data. One of these analog inputs was employed to log throttle position. Two laptops were used for data logging. One was for FTIR that logs emission spectra and throttle position. The other one was for thermal and driving parameters that logs GPS road speed, fuel mass flow, throttle position, air/fuel ratio and ambient temperature. The two laptops were time aligned using the throttle position measurement that was logged by both.

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

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

SOURCE OF POWER - The power needed for the on-board measuring system was around 1200 Watts and this would have necessitated drawing up to 100 A at 12V from the car's electrical system. This would have required an upgraded alternator and increased the load on the engine, therefore affecting the emissions.

characteristics. Another possibility was to use a small dedicated generator but this option is only feasible in large heavy duty vehicles. The best solution was to use two battery packs providing a total of 24V which was then converted to 240V AC using an on-board DC-AC converter. The two batteries used weighed a total of 70kg. They provided approximately 2-3 hours of operation before needing recharging.

SAMPLE CONDITIONING - In order to measure wet concentration, the raw undiluted sample gas extracted from the exhaust system had to be maintained at about 180°C otherwise low boiling point pollutants would drop out due to condensation. Furthermore, the extracted exhaust sample had to be hot filtered so that the sample cell remained free of particulates which would contaminate it and shorten its lifetime. A sample handling unit was acquired to perform these functions. The sample handling unit uses a pump to continuously extract sample from the vehicle's exhaust system at a constant flow rate (2~3 l/min) via a heated line. This is then filtered using a 0.2 µm filter and introduced via another heated line into the sample cell of the FTIR. Both heated lines were controlled to 180°C by the sample handling unit. The sample handling unit consumed the most power since it performed heating and pumping functions. It was installed in the boot of the car along with the FTIR. The gas sample was taken downstream of the catalyst and the heated sample line was passed through a small hole in the car's floorpan. There was no possibility of dilution of the sample by pressure pulsations from the tailpipe.

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

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

- K is conversion coefficient, which is the ratio of molecular weight of a certain emission component to the molecular weight of the whole sample gas. The molecular weight of the exhaust sample gas is close to that of air and does not vary more than 1% for H/C ratios of about 2 (i.e. gasoline), irrespective of the air/fuel ratio. For this reason, K is 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 during the sampling

period. Then the distance based emissions can be calculated for any distance traveled.

TEST ROUTE AND PROCEDURES – Two driving cycles were selected for urban intersection research, Leeds-WPL and Leeds-HPL. Leeds-WPL cycle (Leeds West Park Loop, hereafter referred as WPL cycle) was a 0.63km loop circuit, located in a quiet area with minimum interferences from traffic and pedestrians. There were no traffic lights in this circuit. This cycle was situated on a flat area and thus not affected by road gradient factors. A single driver was used to eliminate driver variability. Figure 4 shows a map of the Leeds-WPL test route.



Figure 4: The map of West Park Loop (WPL) driving cycle

The vehicle was driven anticlockwise without stop at intersections for five loops for the WPL cycle. This was to simulate the situation when a vehicle was accessing a junction with green traffic light on and the vehicle was decelerating, turning and accelerating. The previous studies by authors demonstrated that this scenario produced lower emissions when compared to the turning with stop which was to simulate the situation when a vehicle was accessing a junction with red light on.

The second driving cycle Leeds-HPL (Leeds-Hyde Park Loop, hereafter referred as HPL cycle) was a 1.96 km loop circuit, located in a busy residential area linked with major roads as shown in figure 5. Of the cycle, side AB was a dual carriage way on which the vehicle can travel up to ~60 km/h and have less traffic interferences. The other three sides were two-way single carriageways on which the vehicle can travel up to 48 km/h but with more traffic variation and interferences. The sides CD and DA have a set of pedestrian light on each road.

The WPL cycle has a shorter distance of straight driving than that of HPL. This made WPL cycle contain more acceleration and deceleration mode and less steady speed cruising mode, compared to HPL.

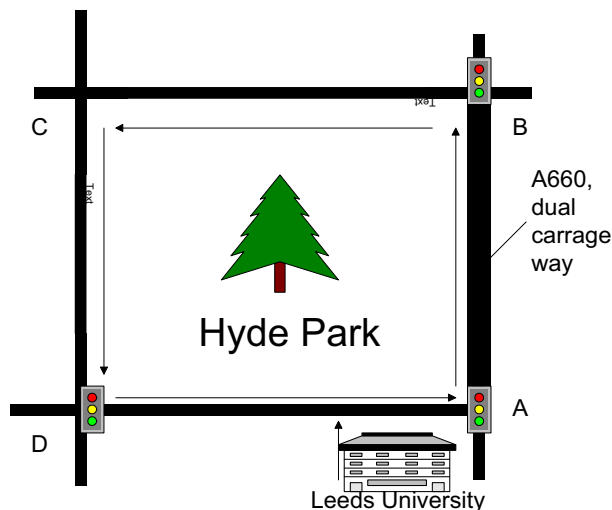


Figure 5: The schematic of Hyde Park Loop (HPL) driving cycle

ESTIMATION OF OFP

The ozone control strategy requires some quantitative methods to determine the tendency of ozone formation for a particular substance. The use of incremental reactivity is an appropriate reactivity ranking scheme. The incremental reactivity (IR) of an organic compound is defined as the amount of ozone produced per unit mass of VOC added to an organic mixture, or:

$$IR_i = \Delta O_3 / \Delta VOC_i \quad gO_3/gVOC_i \quad \text{Equation 2}$$

The maximum incremental reactivity (MIR) is the primary reactivity scale used in VOC control regulations for gasoline vehicles and aerosol coating in California [14] and is developed using a box model. For the MIR box model calculation, NO_x level is adjusted to result in the highest incremental reactivity. MIR conditions are likely to occur in VOC-limited urban air masses, where the mixture is most sensitive to organic compounds because of low VOC-to-NO_x ratios. MIR represented the maximum possible ozone formation tendency under the optimum condition. Table 2 listed the MIRs for the VOCs measured by this study.

The OFP for a particular VOC is calculated by the following equation:

$$OFP_i = MIR_i \cdot MASS_{VOC_i} \quad gO_3/s \quad \text{Equation 3}$$

Where $MASS_{VOC_i}$ is the mass emission rate of VOC_i by g/s.

MIR conditions are of high practical significance because they represent areas of dense human population.

Table 2: MIR factors

VOCs	MIR	VOCs	MIR
Methane CH ₄	0.0139	Ethanol	1.69
Ethane C ₂ H ₆	0.31	Propanol	2.73
Propane C ₃ H ₈	0.56	Butanol	3.33
Butane C ₄ H ₁₀	1.32	MTBE	0.78
Pentane C ₅ H ₁₂	1.53	Dimethyl ether	0.93
iso-Pentane C ₅ H ₁₂	1.67	Formaldehyde	8.96
Hexane C ₆ H ₁₄	1.43	Acetaldehyde	6.83
Heptane C ₇ H ₁₆	1.26	Formic Acid	0.076
Octane C ₈ H ₁₈	1.09	Acetic acid	0.50
Iso-Octane C ₈ H ₁₈	1.18	Acrolein	7.55
Cetane C ₁₆ H ₃₄	0.50	Naphtalene	3.26
Acetylene C ₂ H ₂	1.24	i-Butane*	1.34
Ethylene C ₂ H ₄	9.07	1-Butene*	10.22
Propene C ₃ H ₆	11.57	Trans-2-Butene*	13.90
1,3-Butadiene C ₄ H ₆	13.47	Cis-2-Butene*	13.22
Benzene	0.81	i-Butene C ₄ H ₈ *	6.31
Toluene	3.97	Pentene C ₅ H ₁₀ *	7.73
m-Xylene	10.61	Hexene C ₆ H ₁₂ *	6.12
o-Xylene	7.48	Heptene C ₇ H ₁₄ *	4.20
p-Xylene	4.24	Octene C ₈ H ₁₆ *	3.42
1,2,3-Trimethylbenzene	11.25	Nonene C ₉ H ₁₈ *	2.73
1,2,4-Trimethylbenzene	7.18	Cyclopropane C ₃ H ₆ *	0.103
1,3,5-Trimethylbenzene	11.22	Cyclohexane C ₆ H ₁₂ *	1.44
Ethylbenzene	2.79	Alpha-Pinene C ₁₀ H ₁₆ *	4.29
Indene	3.21	Beta-pinene* C ₁₀ H ₁₆	3.28
Methanol	0.69		

Another box model reactivity scale, maximum ozone incremental reactivity (MOIR), is calculated by adjusting to the NO_x levels that result in maximum ozone concentration for a given VOC mixture. MOIR conditions occur at higher VOC-to-NO_x ratios than MIR, more typical of aged urban air masses. Historically, reactivity scales were derived from instantaneous values, but they can also be averaged over time. In light of the proposed

8-h ozone standard, 8-h reactivity scales have been developed [15].

Reactivities by definition are the sensitivity of ozone concentrations to the mass of individual organic compounds added to the system, and therefore, different sensitivity analysis techniques can be applied for their assessment.

One of the objectives of this research was to provide urban air quality modellers with speciated hydrocarbons information for real world driving. This will assist in local air quality management now that ozone precursors have to be monitored and ozone standard met [12]. The new European environmental law that requires ozone precursor substances to be measured includes 31 individual hydrocarbon species and total NMHC as shown in table 3 (m-xylene and p-xylene are listed as one in the table). The FTIR in this study measured 28 out of 31.

Table 3: Volatile organic compounds recommended for measurement by EU environmental law

1	Ethane	17	n-Hexane
2	Ethylene	18	i-Hexane
3	Acetylene	19	n-Heptane
4	Propane	20	n-Octane
5	Propene	21	i-Octane
6	n-Butane	22	Benzene
7	i-Butane	23	Toluene
8	1-Butene	24	Ethyl benzene
9	trans-2-butene	25	m+p-Xylene
10	Cis-2-Butene	26	o-Xylene
11	1,3-Butadiene	27	1,2,4-trimethylbenzene
12	n-Pentane	28	1,2,3-trimethylbenzene
13	i-Pentane	29	1,2,5-trimethylbenzene
14	1-Pentene	30	Formaldehyde
15	2-Pentene	31	Total NMHC
16	Isoprene		

N.B. 1. NMHC: non-methane hydrocarbons.
2. Bold font means the species measured by the FTIR.

RESULTS

DRIVING CYCLE ANALYSIS-SPEED AND ACCELERATIONS

The test vehicle was driven for five loops for WPL cycle and three loops for HPL cycle. Figures 6 and 7 show the typical profile of vehicle speed and acceleration for WPL and HPL driving cycles respectively. The peak speed for WPL cycle was 40 km/h (25 mph). The turning speed at intersections was about 10-15 km/h. The accelerations and decelerations were between -2 to 2 m/s².

For HPL cycle, the peak speed reached 60 km/h (37 mph). The turning speed at intersections was 0~15 km/h. The accelerations and decelerations were between -1.8 to 1.8 m/s².

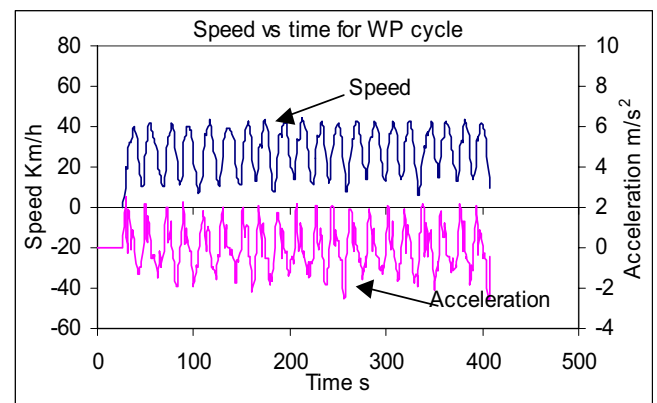


Figure 6: Speed and acceleration profile of a WPL journey

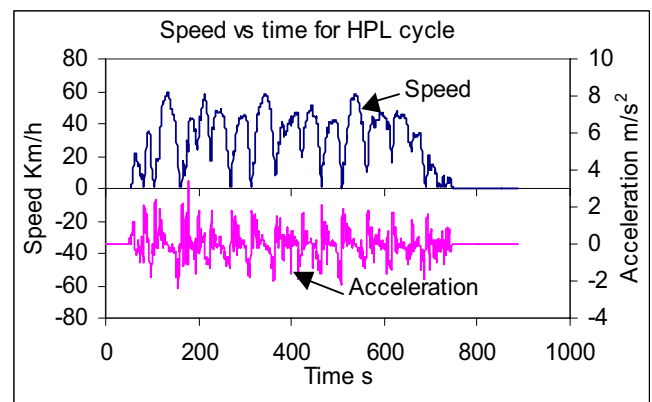


Figure 7: Speed and acceleration profile of a HPL journey

The driving parameters for WPL and HPL cycles were statistically analyzed and compared to ECE15 urban driving cycle as shown in table 4. It shows that the WPL cycle had greatest acceleration and deceleration rate and also largest acceleration and deceleration percentages of the cycle. The HPL had highest maximum speed and longest steady speed driving mode. The ECE15 cycle had lowest average and maximum acceleration rate, longest idle mode and least acceleration period. Obviously, the two real world driving

cycles WPL and HPL were more stringent than ECE15 cycle.

Table 4: Comparison of driving parameter between WPL and HPL cycle

	WPL	HPL	ECE15
Av speed km/h	28	36	17.22
Max. speed	40	60	49.6
Av acc m/s ²	1.16	0.73	0.64
Max acc.	2.08	1.98	0.74
Av dec m/s ²	-1.00	-0.54	-0.6
Max dec.	-2.35	-1.96	-0.74
Av λ	1.54	1.33	
Idle time %	0	2.9	28.6
Cruise time %	32.5	42.7	26.6
Acc. time &	32.5	26.6	22.4
Dec. time %	35	27.8	22.4

MICRO-ANALYSIS OF DRIVING PARAMETERS

To investigate the repeatability of the driving patterns of each loop for two driving cycles, the driving parameters were further analyzed for each loop of cycles. Table 5 lists the results for the WPL cycle and table 6 presents the results for the HPL cycle. It clearly shows good repeatability for each loop of the journeys. The standard deviation indicated that the WPL cycle had better repeatability than that of the HPL cycle. This was expected as the WPL cycle was located in a quiet area whereas the HPL cycle was in a busy area. The high maximum air fuel ratio indicated the fuel cut-off events.

Table 5: Micro-analysis of driving parameters for WPL driving cycle

Loop Av.	Lp1	Lp2	Lp3	Lp4	Lp5	Mean	SD
Av. Speed km/h	25.81	27.26	28.61	27.65	28.48	27.56	1.13
Av. Cruising Speed km/h	37.56	38.87	39.63	39.68	39.34	39.02	0.88
Av. Junc Acc m/s ²	1.07	1.28	1.19	1.05	1.19	1.16	0.10
Av. Junc Dec m/s ²	-1.00	-0.98	-1.08	-1.01	-0.93	-1.00	0.05
Max. Junc Acc m/s ²	2.08	1.88	2.05	1.90	2.03	1.99	0.09
Max. Junc Dec m/s ²	-1.91	-1.70	-2.35	-1.75	-2.07	-1.95	0.26
Av. λ	1.49	1.48	1.51	1.52	1.69	1.54	0.09
Max. λ	5.00	5.00	5.00	5.00	5.00	5.00	0.00

N.B. (1) Max. Junc. Acc. is the Maximum Junction Acceleration.

(2) Av. Junc. Acc. is the Average Junction Acceleration.

(3) SD is the Standard Deviation.

Table 6: Micro-analysis of driving parameters for HPL cycle

Loop Av.	Lp1	Lp2	Lp3	Mean	SD
Av. Speed km/h	35.02	37.44	36.38	36.28	1.21
Av. Cruising Speed km/h	47.03	45.29	44.18	45.50	1.44
Av. Junc Acc m/s ²	0.75	0.70	0.76	0.74	0.03
Av. Junc Dec m/s ²	-0.62	-0.54	-0.45	-0.54	0.09
Max. Junc Acc m/s ²	1.98	1.58	1.71	1.76	0.20
Max. Junc Dec m/s ²	-1.96	-1.93	-1.30	-1.73	0.38
Av. λ	1.58	1.16	1.35	1.36	0.21
Max. λ	5.00	5.00	5.00	5.00	0.00
Number of stops	3	2	2		

AIR/FUEL RATIO

The deviation of air/fuel ratio was one of the most influential factors affecting emission behavior as it was strongly linked to the performance and efficiency of the TWC. Figures 8 and 9 show the variation of lambda values for two cycles. It shows that the WPL cycle had greater deviation of lambda from stoichiometric value due to more frequent accelerations and decelerations. The fuel cut-off during decelerations when reaching a turning produced spikes of air/fuel ratio. The HPL had relatively large percentage of steady speed driving mode and thus less deviation of lambda values. The deviation of air/fuel ratio from lambda one was a major factor that caused high emissions for a journey when the engine was hot.

In comparison, the air/fuel ratio for a journey traveled in the steady speed 30 mph was shown in figure 10. This journey was taken on a 1.1 km flat straight dual