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## Comparison of Real World Emissions in Urban Driving for Euro 1-4 Vehicles Using a PEMS

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### ABSTRACT

An on-board emission measurement system (PEMS), the Horiba OBS 1300, was installed in Euro 1-4 SI cars of the same model to investigate the impact of vehicle technology on exhaust emissions, under urban driving conditions with a fully warmed-up catalyst. A typical urban driving loop cycle was used with no traffic loading so that driver behavior without the influence of other traffic could be investigated. The results showed that under real world driving conditions the NO<sub>x</sub> emissions exceeded the legislated values and only at cruise was the NO<sub>x</sub> emissions below the legislated value. The higher NO<sub>x</sub> emissions during real-world driving have implications for higher urban Ozone formation. With the exception of the old EURO1 vehicle, HC and CO emissions were under control for all the vehicles, as these are dominated by cold start issues, which were not included in this investigation. The CO and HC emissions for hot catalysts were low and modeling of real world emissions for the parts of journeys where the catalysts was hot, using legislated emissions per km, would over predict the real world CO and HC emissions. Cold start emissions should be treated as a separate

emissions quantity that occurs with all cold start journeys at the start of the journey and should not be spread out over the 11km of the NEDC or 18km of the US FTP75 test cycles as at present. The fuel consumption and CO<sub>2</sub> emissions were of the order of double the legislated NEDC values for real world emissions for Euro 1-4 vehicles. The higher acceleration rates after junctions were the principle cause of the higher fuel consumption and NO<sub>x</sub> emissions.

### INTRODUCTION

Urban air quality of the legislated emissions of CO, HC and NO<sub>x</sub> are not falling as fast as might be expected from the percentage reduction in legislated vehicle emissions. Part of this problem is the growth of the number of vehicles and of the distances driven. However, part of the problem also lies in the inappropriate legislated test cycles, particularly for urban driving. 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. The legislated emissions are expressed as the total mass

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divided by the total distance for the complete cycle with units of g/km. Current urban air quality models use this data together with knowledge of the number of Euro 1-4 vehicles registered in a city and on road traffic density measurements to produce total mass emissions data per km for each road in a city. This traffic emissions data is then combined with point emissions data from factories and houses to yield the total city emissions sources.

A dispersion model computes the city wide pollution concentrations from the above input data and is calibrated against a very few local point pollution measurement locations. If these predictions exceed, at any location, the European air quality standards then the city must declare an air quality management zone for that local area or for the whole city. They must then produce an action plan to bring the air quality within standards. In every case where cities have exceeded the air quality standards the main source has been identified as traffic pollution on congested roads. The pollution source is then not local and the traffic comes from all over the city, this results in the entire city being declared an air quality management zone. The only tools available to city transport planners to control this is to control traffic loads directly over all the city, as in the London congestion charge, or indirectly through traffic light sequence control. However, the effects of this control is modeled by assuming every car emits the same emissions as on the legislated test cycle and hence controlling traffic flow controls emissions.

The problem is that emissions on test cycles are not uniform with time and are dominated by cold start emissions (1-14) for any vehicle that relies on a catalyst to control exhaust emissions. The vast majority of SI gasoline vehicles operate under lambda 1 ( $\lambda=1$ ) control with a three way catalyst (TWC) that is not efficient at the 90%+ level until it reaches 400°C. Once the catalyst is hot the removal of pollutants is >90% and often reaches 99%. The legislated procedure averages the total mass emissions of the whole legislated cycle over the complete distance of the legislated journey (11km for NEDC and 18 km for the USFTP cycles). For many urban journeys the distance travelled is 2 km or less in European cities. The effect of this is to underestimate urban transport emissions from gasoline vehicles and to overestimate them on journeys longer than the legislated test cycles. The lack of specific accounting for cold starts in cities leads to an under prediction of air quality in cities.

The air quality predictions can be improved by using urban driving cycles measured in real city driving and then reproducing these on the legislated CVS emissions measurement system. This approach is preferable to the use of the legislated data as the drive cycles are more

realistic. However, it still has the same problem that the cold start emissions are averaged over the total distance driven. In real world driving cold start emissions are greater than in the test cycles in many cases (1-14) and hence there is a greater error in averaging the emissions over the distance driven. In the present work the differences in Euro 1 – 4 vehicle emissions for hot catalyst conditions were investigated. Separate investigations of the real world cold start emissions have been undertaken (1, 2).

A further problem with the current approach to modeling of traffic emissions in urban air quality models is that there is no input for the actual street layout of a particular city and no impact of how people drive vehicles in real world congested traffic. The authors are involved in a major programme of real world vehicle emissions measurement using Euro 1-4 vehicles, where the aim is to determine emissions for micro scale driving actions such as left and right turns, stops and start at traffic lights and so on. Some work on this has been published for Euro 1 and 2 Ford Mondeo cars [3, 4]. In traffic management models the movement of traffic in a given city street layout can be predicted on a second by second basis and the micro vehicle movement emissions are to be used to add micro emission modeling to traffic management models.

EURO 1, 2, 3 and 4 standards were introduced in year 1993, 1996, 2000 and 2005 respectively and further emissions reductions are planned. Table 1 shows the limit values for each EU exhaust emission standard. 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.

Table 1 EU exhaust legislation for EURO 1-4 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 ratio was used to calculate EURO1 and 2 THC and NOx limit values. The cold start procedure was altered for Euro 3.

Euro 1>2 was mainly a ~ 50% reduction in HC and NOx  
Euro 2>3 was mainly a ~ 30% reduction in HC and NOx  
Euro 3>4 was mainly a ~ 50% HC, CO and NOx reduction.

For all petrol vehicles the regulatory test cycle involves starting the engine when cold followed by driving a cycle simulating urban and sub-urban driving (ECE 15 + EUDC). From EURO 3 onwards the cold start procedures were altered to remove the 40s idle during which the emissions were not measured and replace it with 11s idle, with the emissions measured from start of ignition (NEDC). The emissions are monitored for the whole cycle and, after dividing by the cycle's length (11km), the emission standards are expressed in grams of pollutant per kilometer.

The reductions of exhaust emissions for the EURO 2, 3 and 4 vehicles were achieved predominantly by reducing the cold start emissions[1-14]. In January 2002, a low temperature emissions test (-7°C) for gasoline vehicles was introduced. This is measured at -7°C test temperature over 4 repeats of the urban drive cycle (ECE15 or UDC). The limit values for SI passenger cars are 15 g/km for CO and 1.8 g/km for THC. The authors have previously shown [15,16] that this is not particularly arduous and can be met by Euro 1 vehicles in free flowing urban traffic or in congested traffic jam test conditions. However, this specific cold start legislation indicates the importance that legislators place on the cold start emissions problem.

The difference between Euro 1-4 emissions control technologies are in the cold start and only to a much smaller extent in the subsequent hot catalyst performance. Modeling of urban air quality should take this into account, as it results in lower CO and THC emissions for most of the distance driven, but higher NOx. The cold start emissions should be treated as dispersed point sources, concentrated in the morning at every house and in the evening at the major city car parks. Such transport source modeling is likely to give better urban air quality modeling. This paper is aimed at investigating the hot catalyst performance of Euro 1-4 vehicles under real world driving.

The aim is to determine the influence of the road layout and driver behavior on emissions. This influence is expected to be due to the sensitivity of a TWC vehicle to the control of  $\lambda$ . Deviations on the rich side occur during acceleration and on the lean side during deceleration. The catalyst continues to act on CO and HC during rich excursions due to the use of ceria as an oxygen storage medium in the TWC formulation. The oxidation catalyst remains effective for CO and HC removal for lean excursions. However, NOx control is adversely affected by lean excursions, but NOx is under control for rich excursions as NOx removal is a reducing action (15, 16). The difference between Euro 1-4 vehicles for hot catalysts is then due to differences in the accuracy of TWC  $\lambda=1$  control. The reason that this may be sensitive to real world driving effects is that accelerations and

decelerations are greater in the real world than in test cycles. They are also very driver and road layout dependent. Thus the effect of vehicle engine technology could still be significant in Euro 1-4 vehicles and these differences could be greater than on the legislated test cycles due to the higher acceleration rates. It was the objective of this paper to determine the significance of these hot catalyst performance differences in real world urban driving.

## **PORTABLE EMISSIONS MONITORING SYSTEM (PEMS) AND ITS VALIDATION FOR USE WITH GASOLINE VEHICLES**

The Horiba OBS-1300 (19, 20) was developed as a dedicated in-vehicle emission monitoring system for diesel vehicle applications. It had a specific design requirement that no on-board gas bottles would be required to operate it, for safety reasons. This precluded the use of a FID for total hydrocarbon analysis and chemiluminescence analysers for NOx measurement. Many operators of in-vehicle emissions analysis systems have internal health and safety procedures that would make approval difficult for the use on a public highway of equipment with pressurized gas bottles. This was one of the reasons for the use of this equipment in the present work. For organizations that do not have safety concerns over pressurized gas bottles in vehicles, there is an updated version of this equipment that uses a heated FID for total hydrocarbons and chemiluminescence analysis for NOx (21). This equipment was not available at the time this work was carried out.

The Horiba OBS-1300 comprises a Data Integration Unit (DIU), heated Non-Dispersive Infra Red analyzer (HNDIR), zirconia type NOx and Air/Fuel ratio sensor (NOx-AFR) manufactured by NGK, Annubar (area averaging pitot-static) flow meter, global positioning system (GPS), exhaust temperature and pressure, vehicle and engine speed, ambient air temperature, pressure and humidity sensors, data logger (laptop) and software, power supply unit and dedicated batteries.

All exhaust sampling was conducted via the OBS 1300 exhaust attachment fitted to the end of the vehicle exhaust pipe. The sample line and analyzer cells operated at  $120 \pm 2^\circ\text{C}$  and  $87 \pm 2^\circ\text{C}$ , respectively. The OBS 1300 volumetric concentration measurements were converted into mass using the equation

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

- K is conversion coefficient, which is the ratio of molecular weight of the 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 the concentration of the component. If this is measured in ppm or % then the equation has to be multiplied by 10<sup>-6</sup> or 10<sup>-2</sup> respectively.
- A/F is the air/fuel ratio on a mass basis measured by the lambda sensor.

The EI was then converted into mass emission rate g/s using the exhaust mass flow rate and A/F from the  $\lambda$  probe, as given by Eq. 2.

$$E_{\text{mass}} = EI * \text{fuel (kg/s)} \text{ g/s} \quad 2$$

Where the fuel mass flow rate is give by the exhaust mass flow divided by  $(1 + A/F)$  as the measured exhaust mass flow rate is  $(A + F)$  and the lambda probe measures the A/F.

In addition to the Horiba OBS 1300 the authors also have used a Temet portable FTIR (Gaset) (1, 2, 17, and 18). This is used where speciation of the exhaust emissions is required for specific hydrocarbon toxics and for NO, NO<sub>2</sub>, HCN and NH<sub>3</sub> direct measurements. This instrument does not measure the total hydrocarbons, but it measures 38 hydrocarbon species out of typically 200 that are present in engine exhausts. The instrument accuracy of this FTIR instrument has been reported previously (22, 23) and was evaluated against legislated instruments on a CVS system for various drive cycles for a Euro 1 Ford Mondeo (23). This was carried out at the same time as the calibration work on the Horiba OBS 1300 (24) that is summarized here. Thus measurements of NH<sub>3</sub> were available for investigating the sensitivity to NH<sub>3</sub> of the NGK zirconia NOx sensor that is used in the OBS 1300.

The FTIR calibration (23) showed that the total hydrocarbons measured by the FTIR had to be multiplied by 2.4 to give agreement with FID measurements. The correction equation that resulted from CVS comparisons over several test cycles was:

$$\text{Corrected THC (ppm)} = 2.4 \times \text{FTIR raw THC (ppm)} - 42$$

In the development of the OBS-1300 it was evaluated against CVS tests with a FID analyzer (19) and the hot NDIR analysis was lower than the FID. A correction factor of 1.66 was applied for diesel exhaust sampling to the heated NDIR reading for HC to give agreement with

the FID results (19). This is a smaller correction than that required for the FTIR and potentially the heated NDIR analyzer gives more reliable measurements on vehicle total hydrocarbon emissions. The authors have shown (23) for a Euro 1 gasoline engine that the 1.66 correction factor for the HNDIR analyser did not give a good agreement with the FID results on the CVS test facility for gasoline  $\lambda=1$  vehicles. A further correction factor of 1.39 was required, giving an overall correction factor of 2.31. This is very similar to the 2.4 correction factor found for the FTIR measurements to have agreement with the FID. The resultant corrected total hydrocarbon mass measurements were in good agreement with the FID results over a transient cycle as shown in Fig. 1. This includes the error for exhaust mass flow using the pitot and the agreement of the area average pitot (annubar) exhaust flow measurement system with the CVS is shown in Fig. 2 to be very good. The only problem was at idle, where pulsating flow in the tailpipe induced flow reversal at the pitot position. The areas where this was significant is shown in Fig. 2.

The effect of the flow reversal at idle was to read a slightly higher flow than using the CVS gas tracer measurement. The effect could be corrected by adding a longer pipe downstream of the exhaust attachment (22).

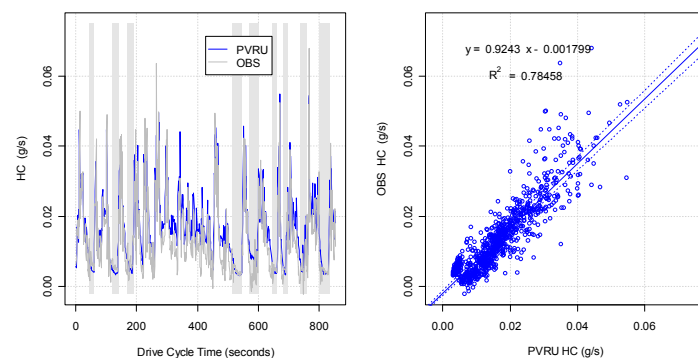


Figure 1 OBS-1300 agreement with the MEXA 7400 and MEXA 710 exhaust flow meter for HC mass emissions during US FTP-75 Phase 2, with regions associated with idle 'pulse effect' highlighted. The MEXA calibration was carried out at the University of Bath Powertrain and Vehicle Research Centre, PVRU. (24)

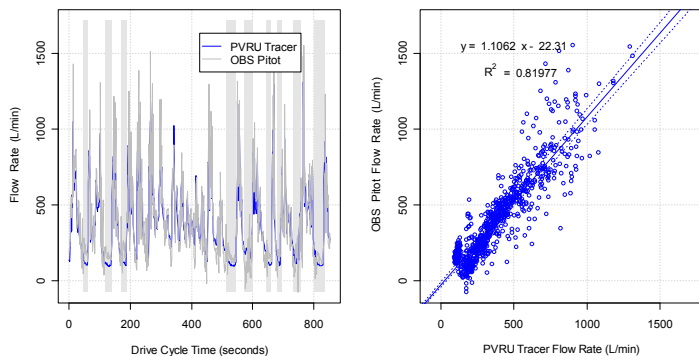


Figure 2 OBS-1300 agreement for with the MEXA 710 exhaust flow during US FTP-75 Phase 2, with regions associated with idle 'pulse effect' highlighted.

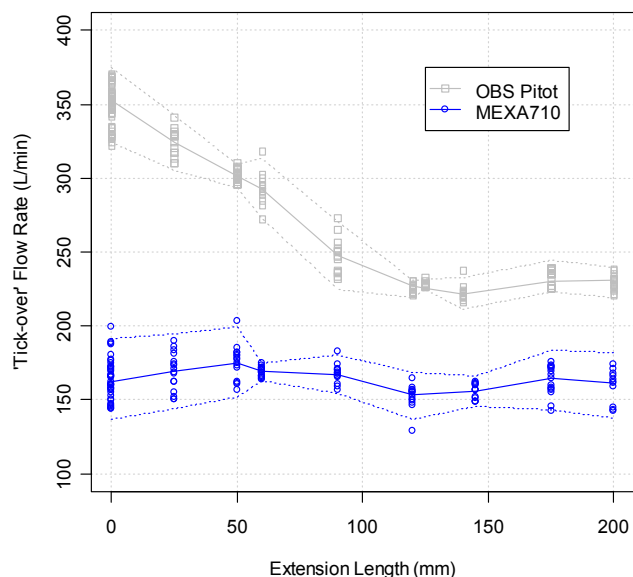


Figure 3 Effect of OBS-1300 Exhaust Attachment Extension Length on idle 'pulse effect'

The effect of the length of this on the flow measurement is shown in Fig. 3. This shows that even with an extension on the exhaust the idle flow was overestimated by about 40% and there was no length of exhaust extension that reduced this. The significance of this obviously depends on the proportion of idle flow in the total cycle. Normally the total idle flow is a small proportion of the total flow in the test cycle and hence the overall error is small. This resulted in good agreement between the OBS 1300 summated cycle results and the CVS bag sample analysis and comparable with equivalent transient measurements using a Horiba MEXA 7400 in the same calibration tests. For CO the OBS 1300 was on average, over several transient test cycles, 7% lower than the bag analysis, which was the same as found for the MEXA 7400. For CO<sub>2</sub> the OBS 1300 was 4% high and the MEXA 7400 was 3% low. For HC a bag analysis was not made, but

the corrected OBS 1300 was 8% lower than the MEXA 7400 FID transient measurements (24).

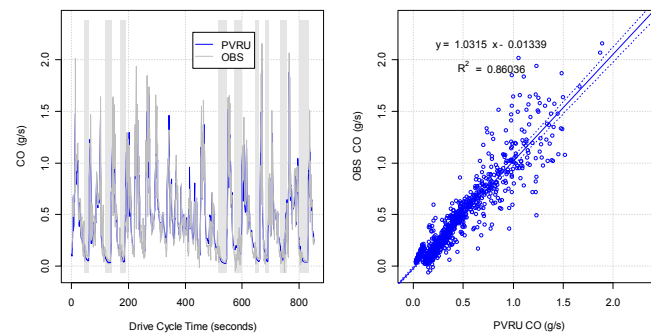


Figure 4 OBS-1300 agreement with the MEXA 7400 and MEXA 710 for CO mass emissions during the US FTP-75 Phase 2, with regions associated with idle 'pulse effect' highlighted.

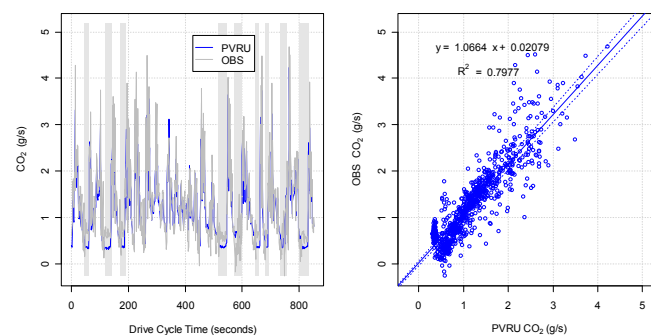


Figure 5 OBS-1300 agreement with MEXA 7400 and MEXA 710 for CO<sub>2</sub> mass emissions during the US FTP-75 Phase 2, with regions associated with the idle 'pulse effect' highlighted

The agreement of the OBS 1300 with CVS systems is shown in Figs. 4 and 5 for CO and CO<sub>2</sub> for part of the FTP75 test cycle. The agreement was good. The Horiba 1300 NO<sub>x</sub> measurements were shown for diesel engines to have very good agreement with chemiluminescence measurements and no correction was required (19, 20). However, for SI engines with TWC there was a problem relating to the sensitivity of the NGK zirconia NO<sub>x</sub> sensor to NH<sub>3</sub>. This is not a problem in diesels without SCR after treatment as the engine does not produce NH<sub>3</sub>. However, a feature of a TWC is that it produces NH<sub>3</sub> during rich excursions and the NGK NO<sub>x</sub> sensor measures them as NO. This problem is illustrated for a Euro 4 Ford Mondeo in Figs. 6 and 7 for NH<sub>3</sub> and NO<sub>x</sub> respectively. These measurements were made by the Temet FTIR on a cold start cycle (25). The accumulated ammonia emissions were twice those of the accumulated NO<sub>x</sub> emissions. If the cold start period was ignored, where NO<sub>x</sub> emissions were significant and ammonia was absent, then the ammonia for the hot catalyst was much higher than the NO<sub>x</sub> by at least at factor of 5. The problem occurs through the high temperature catalytic conversion of

NH<sub>3</sub> into NO in the zirconia probe when there is oxygen still present from a lean excursion followed by a rich excursion. The ammonia problem was shown by the authors to be significantly worse for the Euro 4 Mondeo than the Euro 1-3 Mondeo, even though the NO<sub>x</sub>

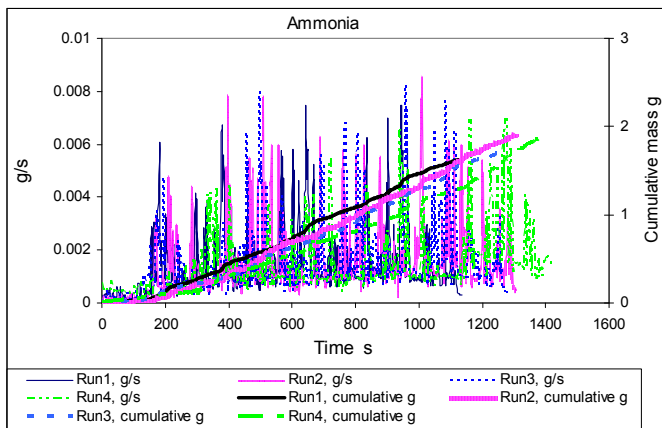


Fig. 6 Ammonia emissions during cold start real-world driving for a Euro 4 Ford Mondeo. Three repeat runs for instantaneous mass emissions rate and accumulated mass emissions (25).

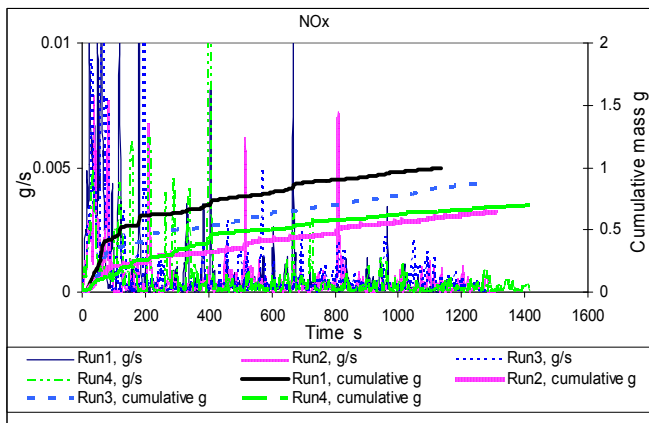


Fig. 7 NO<sub>x</sub> emissions during cold start real-world driving for a Euro 4 Ford Mondeo. Three repeat runs for instantaneous mass emissions rate and accumulated mass emissions (25).

Emissions were much lower in real world driving (1). Ammonia generation is worse in real world driving than in test cycles due to the higher acceleration rates than produce more rich excursions. In the NEDC ammonia is normally only generated in the EUDC portion, where the greatest accelerations occur.

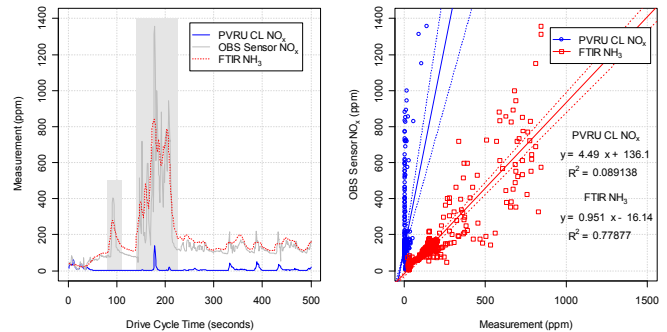


Fig. 8 OBS-1300 NO<sub>x</sub>-AFR sensor NO<sub>x</sub> compared with chemiluminescence measurements during US FTP-75 Phase 1, under rich engine operating conditions. Comparison with FTIR NH<sub>3</sub> measurements.

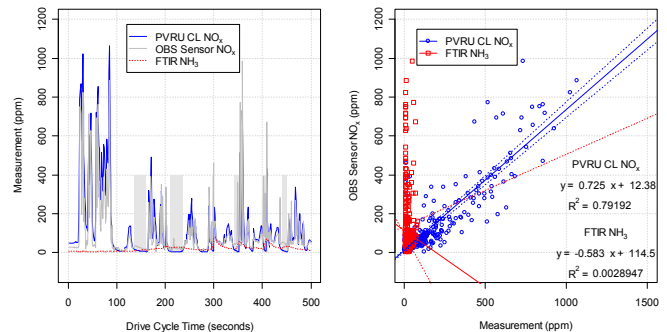


Fig. 9 OBS-1300 NO<sub>x</sub>-AFR sensor compared with NO<sub>x</sub> Chemiluminescence Measurements during US FTP-75 Phase 1, under lean and  $\lambda=1$  engine operating conditions. Comparison with FTIR NH<sub>3</sub> measurements.

In the calibration of the OBS 1300 (24) the agreement of the OBS 1300 with the MEXA equipment on the CVS system was good for lean or  $\lambda=1$  mixtures but read high for rich mixtures, due to the formation of ammonia and sensitivity of the NGK zirconia sensor to ammonia. The problem is shown in Figs.8 and 9. For rich operation Fig. 8 shows that the NGK zirconia sensor correlates well with the FTIR NH<sub>3</sub> reading and has a very poor correlation with the chemiluminescence NO<sub>x</sub> results. However, for lean or  $\lambda=1$  mixtures the NGK zirconia NO<sub>x</sub> sensor has a very good correlation with chemiluminescence NO<sub>x</sub> and very poor with FTIR NH<sub>3</sub>. Thus in a real world test cycle the correlation with legislated emissions will depend on the proportion of time that the vehicle is under rich conditions and this will depend on the test cycle. Also different generations of engines have a different tendency to form NH<sub>3</sub>. This is a

particular problem for the Euro 4 Mondeo as the calibration is slightly rich to ensure the maximum NO<sub>x</sub> reduction at the TWC, as required by the Euro 4 legislation with a near 50% NO<sub>x</sub> reduction. All these factors were present in this work comparing Euro 1-4 vehicles and an attempt has been made to correct for the NH<sub>3</sub> interference for rich mixtures using comparison with previous work using the FTIR on cold start real world cycles. These corrected values are shown in the Tables of results, but their basis will be justified later.

## URBAN DRIVING ROUTE

The urban driving route that was used in this work has been used in previous work and is a route with very little other traffic (26). This allows the driving mode to be set by the road layout and the driver, without any influence of other drivers. The route is shown in Fig. 10 and was about 5km from the point of cold start of the vehicles and hence the vehicles were warm with catalyst above their light off temperature and the water and lube oil were hot. Emission variations were then due to the driving mode and were not influenced by the catalyst temperature. The route was a simple circuit with four left hand turns and the total circuit length was 0.6 km. The road circuit was in an area of Leeds called West Park and hence is referred to as the Leeds-WP circuit.

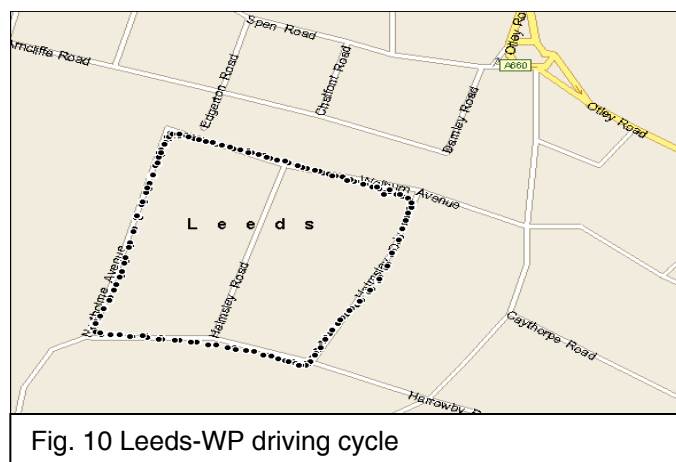


Fig. 10 Leeds-WP driving cycle

The circuit was level with no gradients of any significance.

The driving mode influences the acceleration and deceleration rates and the average speed. For a TWC car the emissions performance would largely be governed by the accuracy with which  $\lambda=1$  control was maintained. Data on this has been reported previously (1, 26) and need not be repeated here. The key difference was the use of fuel cut offs in Euro 1-3 vehicles, which resulted in poor  $\lambda$  control. This was omitted in the Euro 4 vehicle and  $\lambda$  control was much better in the Euro 4 compared to the Euro 3 vehicle. The Euro 3 had less fuel cut off than for Euro 1 and 2.

The test program was divided into four runs/journeys: left turn (anticlockwise) with and without stop at intersections; right turn (clockwise) with and without stop at intersections. Each run/journey consisted of four loops. Runs were also carried out where the loop was driven without used the brake, simply changing the gears and using no throttle to approach the junctions. It should be noted that when the vehicle is conducting left turns (anticlockwise direction) circuits, it will travel a shorter distance than when completing right turns (clockwise). When the vehicle was completing the right turn experiments, higher accelerations at the intersection were observed. This can be attributed to the larger turn radii allowing higher desired rates of acceleration. Typical speed and acceleration events for two different driving modes on the loop are shown in Figs. 11 and 12. Acceleration levels were much higher than for the NEDC or the FTP 75 and are greater for loops with a stop prior to a junction. This is due to the greater acceleration rates following a start from stationary. All the four vehicles were compared with the same driver.

## The Test Vehicles

Five Ford Mondeo manual transmission SI gasoline cars with EURO1 to 4 emissions compliance were used and are detailed in Table 2. The 1992 vehicle was a Ford Orion and was a first generation TWC vehicle, this has been termed Euro 0 in this work, although strictly it is a first generation Euro 1. All the other vehicles were Ford

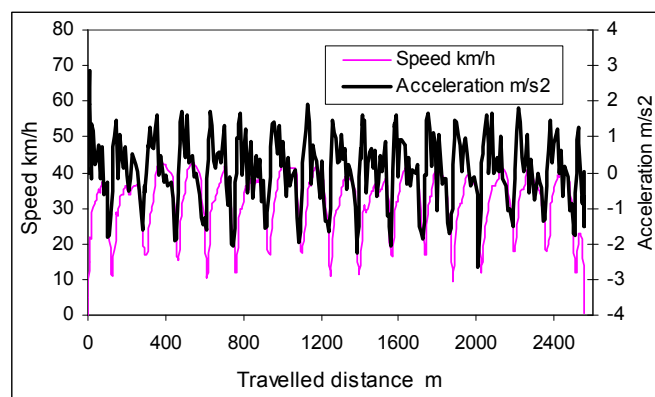


Figure 11 Vehicle speed and accelerations profile of a journey without stop turning (right turn, no stop)

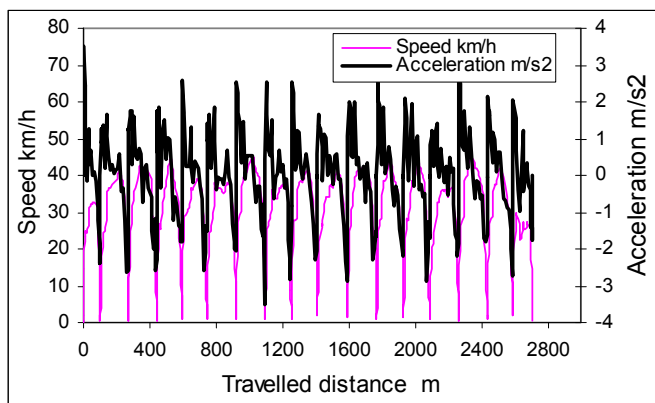


Figure 12 Speed and acceleration profile of a journey with stop turning (right turn, stop)

Mondeos. All the cars were fitted with port fuel injection, 4 cylinder, 16V spark ignition engines with a Three Way Catalyst (TWC) and  $\lambda=1$  control. The TWC was fitted underbody in all five vehicles. There was no close coupled catalyst in the Euro 3 or 4 vehicles. The higher weight of the Euro 2-4 vehicles will tend to increase their fuel consumption and CO<sub>2</sub> emissions relative to those for Euro 0 and Euro 1. However, design advances in the engine powertrain resulted in no increase in CO<sub>2</sub> emissions.

Table 2 Vehicles used for comparison

	EURO 0	EURO 1	EURO 2	EURO 3	EURO 4
Year produced	1992	1995	1998	2003	2005
Mileage miles	30000	74000	85000	11000	4000
Curb Wt.kg	1160	1260	1360	1388	1374
Engine capacity Litres	1.8	1.8	1.8	2.0	2.0
CO <sub>2</sub> g/km	190	194	194	191	189

## EXPERIMENTAL RESULTS

The results are presented as a set of tables with the average emissions in g/km and the highest emissions for any individual lap (Max) and the standard deviation (SD) for the repeat laps. The CO results for the Euro 2 vehicle had a data fault that could not be corrected.

## Urban loop driving with no stops but with the use of the brake at junctions

The emissions data for loops with no stops at the junctions, but with the use of the brake at junctions are summarized in Table 4. This includes the CO<sub>2</sub> data, which can be converted into fuel consumption data by using the relationship of 3.16 kg CO<sub>2</sub> for every kg of fuel, for gasoline with a H/C of 1.9. The certified CO<sub>2</sub> emissions for Ford Mondeos are around 190 g/km and hence a simple urban loop with several junctions nearly doubles the fuel consumption from that in the test cycle. This has important consequences for estimation of the contribution of passenger car transport to total CO<sub>2</sub> emissions. The use of the brake at junctions but no stop involved a driving mode with harsher decelerations and accelerations than if no brake was used and the speed was only controlled by the gear box and throttle.

Table 3 Emissions data in g/km for no-stop runs with engine braking

Gas		Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub>	Ave	350	323	388	375	310
	Max	426	388	456	468	385
	SD	50	36	42	47	38
CO	Ave	2.12	0.31	NA	0.39	0.74
	Max	3.27	0.77	NA	1.84	1.71
	SD	0.61	0.21	NA	0.56	0.45
NOx	Ave	1.06 (0.88)*	0.44 (0.37)*	0.67 (0.56)*	0.32 (0.27)*	0.37 (0.065)*
	Max	1.87	0.71	0.95	0.81	0.74
	SD	0.31	0.12	0.17	0.19	0.12
HC	Ave	0.251	0.077	0.064	0.089	0.031
	Max	0.316	0.118	0.099	0.201	0.113
	SD	0.033	0.022	0.016	0.049	0.024

The average emissions data in Table 3 is normalized to the Euro regulation values in Table 2 and listed in Table 4. The Euro limits include cold start and hence it would be expected that all the ratios would be well below unity for operation of passenger cars with hot catalysts. However, Table 4 shows that only for hydrocarbons and CO are the emissions with a hot catalyst lower in real world urban driving than in the NEDC. The HC emissions were on average 31% of the legislation HC for Euro 1-4 vehicles. This is higher than expected as the catalyst light off normally accounts for 80%+ of NEDC cycle emissions. The rich excursions during accelerations after junctions are the main cause of the

hydrocarbon emissions. The CO emission limits were easily met with a hot catalyst in Euro 1 and 3, but the lower limit for Euro 4 was much more difficult to meet with a hot catalyst and this was due to the rich excursions being higher than on test cycles. For NOx the emission regulations were never met for any vehicle with a hot catalyst. Part of the problem here may be the measurement problem of the presence of ammonia and the corrected NOx results with the ammonia interference corrected for, as discussed later, are also shown in Tables 3 and 4. The NOx emissions are still well above legislated levels for Euro 0, 2 and 3, but are just below the legislation for Euro 1 and 4. However, the corrections are large and hence the use of the NGK NOx sensor for  $\lambda=1$  SI vehicles is a problem.

Table 4 Ratio of average emissions to the Euro limit for the urban loop driving with no stops at junctions but with the use of the brake

	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub>	1.84	1.66	2.00	1.96	1.64
CO	0.79	0.14	NA	0.17	0.74
NOx	2.51 (2.09)*	1.05 (0.87)*	3.20 2.66)*	2.10 (1.75)*	4.60 (0.81)*
HC	0.46	0.27	0.22	0.44	0.31

\* Corrected for NH<sub>3</sub> interference – see below

#### Urban loop driving with no stops at junctions and no use of the brake

In this driving mode the vehicle speed was controlled solely by the throttle and use of the gears, this produced slower deceleration rates coming into junctions. The average, maximum and standard deviations of repeat loops are summarized in Table 5 and these values normalized to the Euro limit values are shown in Table 6. Comparison with the loop driving with braking before the junctions in Table 3 shows very little difference in CO<sub>2</sub> emissions or fuel consumption, in spite of the gentler driving mode. The main reason for this was that the lack of the use of a brake only decreased the deceleration rates before the junction and this mode of driving used little fuel. Mean cycle speeds and acceleration rates were similar. Comparison of Tables 4 and 6 shows that there was also no major effect on the relative emissions. The most significant effect was higher hydrocarbons when braking was used and generally less CO but similar NOx. Braking with the throttle closed essentially increases the load at idle, which increases the fuelling and hence the HC.

Table 5 Urban loop driving emissions for no stops and no use of the brake

Gas		Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub>	Ave	370	330	346	366	313
	Max	447	396	422	445	377
	SD	43	36	36	47	34
CO	Ave	1.95	0.48	NA	0.28	0.95
	Max	4.89	1.45	NA	1.35	1.58
	SD	0.93	0.32	NA	0.37	0.30
NOx	Ave	1.47 (1.22)*	0.46 (0.38)*	0.40 (0.33)*	0.31 (0.26)*	0.42 (0.074)*
	Max	2.15	0.60	0.61	0.64	0.64
	SD	0.39	0.10	0.10	0.16	0.07
HC	Ave	0.12	0.048	0.067	0.056	0.076
	Max	0.224	0.078	0.086	0.131	0.139
	SD	0.037	0.012	0.012	0.027	0.039

Table 6 Urban loop driving emissions as a ratio to the Euro limit for no stops and no use of the brake

Gas	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub>	1.95	1.70	1.78	1.92	1.74
CO	0.72	0.22	NA	0.98	0.95
NOx	3.5 (2.91) *	1.10 (0.92) *	1.90 (1.58)	2.07 (1.72) *	5.25 (0.92) *
HC	0.22	0.087	0.23	0.28	0.76

\* Corrected for NH<sub>3</sub> interference – see below.

#### Urban loop driving emissions (g/km) with a 10s stop at each junction, which requires the use of the brake.

Table 7 Urban loop with 10s stop emissions g/km

Gas		Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub>	Ave	369	444	511	546	409
	Max	430	478	590	642	457
	SD	34	27	37	42	31
CO	Ave	0.98	1.75	NA	0.98	1.46
	Max	1.14	3.59	NA	1.52	2.33
	SD	0.12	0.77	NA	0.46	0.48
NOx	Ave	1.20 (1.00)*	0.89 (0.74)*	0.53 (0.44)*	0.47 (0.39)*	0.65 (0.11)*
	Max	1.95	1.13	0.95	1.03	0.89
	SD	0.34	0.13	0.15	0.23	0.11
HC	Ave	0.22	0.17	0.086	0.085	0.068
	Max	0.26	0.36	0.108	0.238	0.168
	SD	0.02	0.08	0.014	0.051	0.044

\* Corrected for NH<sub>3</sub> interference – see below.

Table 8 Urban loop with 10s stop emissions relative to the Euro standards

	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub>	1.94	2.29	2.63	2.86	2.16
CO	0.36	0.65	NA	0.43	1.46
NOx	2.85 (2.34)*	2.11 (1.76)*	2.53 (2.10)*	3.14 (2.61)*	8.1 (1.42)*
HC	0.40	0.31	0.30	0.43	0.68

\* Corrected for NH<sub>3</sub> interference – see below.

Table 7 compared with Table 4 shows that the CO<sub>2</sub> emissions and hence the fuel consumption was significantly higher for Euro 1-4 vehicles when there was a stop at each junction. The levels are of the order of 2.5 times the CO<sub>2</sub> emissions for the NEDC. This is the extra fuel used to accelerate the vehicle from stationary, at the same time as turning the corner. Table 8 compared with Table 5 shows that for Euro 1-4 CO and HC emissions increased substantially. For NOx only the Euro 4 vehicle had a substantial increase in NOx but there was a lower increase for Euro 1 and 3. This is caused by the acceleration from stationary, which causes a rich excursion and the power demand increases NOx and the rich excursion increases CO and HC.

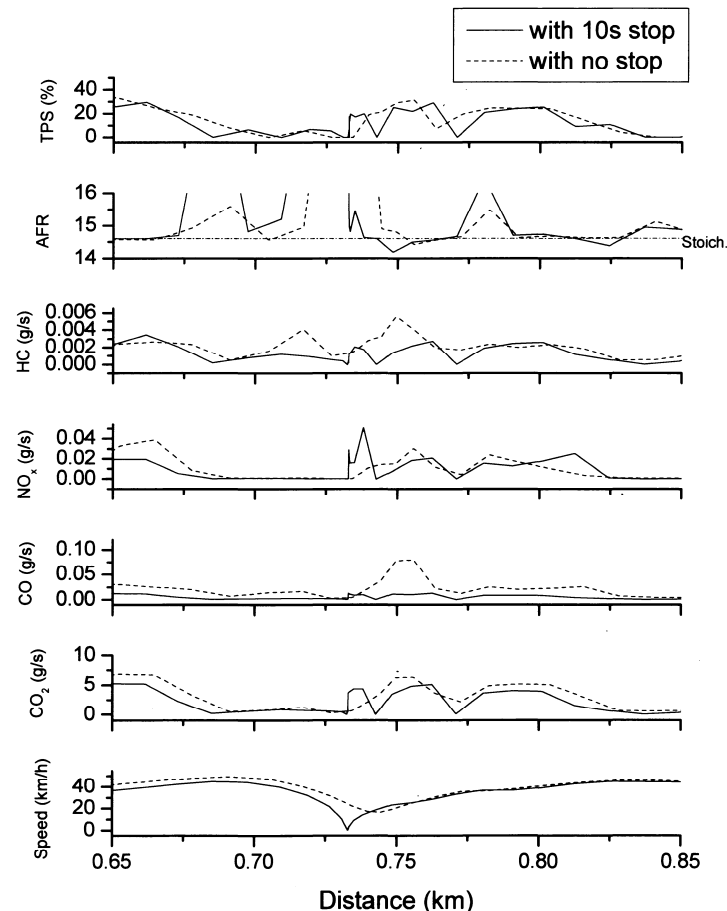


Fig. 13 Euro 1 vehicle micro emissions at a left hand junction with and without a 10s stop.

Fig.13 shows the micro emissions, speed and throttle movements and A/F for the Euro 1 vehicle undertaking an approach to a junction, left and turn and acceleration back to the same speed as the approach to the junction. These results were chosen as the nearest equivalent driving modes in terms of the speeds entering and leaving the junction. The increase in fuel consumption in the acceleration from the bend and the increase in NOx is shown, but the CO is not increased. However, the average emissions over 4 loops with 16 junction events are listed in the above tables and hence it may be concluded that the two events compared here were not representative of the 16 junction average. Fig. 13 demonstrates that deviation from  $\lambda=1$  (A/F=14.6) is a significant feature of the junction events. Lean deviations occur during deceleration and after the 10s stop there is a rich excursion during the acceleration that is not there when there is no stop. However, examination of the throttle trace shows that on these two circuits the junction turn with no stop had a greater throttle opening after the bend than for the stop loop. This was probably the cause of the higher CO on the no stop loop in Fig. 13.

#### Urban loop emissions for 10s with aggressive driving mode

Aggressive driving was simulated acceleration from the junction to 3000 rpm before a gear change, which entailed greater throttle angles. In the normal non-aggressive driving the gear change was made at 2500 rpm. This was similar to the definition of aggressive driving used by Samuel et al. (27), they used passive gear changes at about 2000rpm, intermediate at 2500 rpm and aggressive at about 3,500 rpm. A comparison for one junction between aggressive and non-aggressive driving is made for the Euro 1 vehicle in Fig. 14. The aggressive driver approaches the junction faster and accelerates out of the junction after the stop faster. There is a rich excursion during the hard acceleration and this gives a high CO and NOx peak as well as higher CO<sub>2</sub> emissions, resulting in higher fuel consumption for aggressive driving. The magnitude of the increase in emissions and fuel consumption is shown in Fig. 15, which compares the two junction events with the emissions under steady 48 km/hr (30mph) driving on a level road with no traffic. This shows the very significant effect of a junction on emissions and fuel consumptions (CO<sub>2</sub>) for aggressive and non-aggressive driving. This is further summarized in Table 9, which ratios the total emissions for the junction event, from 48 km/hr before the junction to back to the same speed after the junction.

Table 9 Overall influence of a junction. Emissions ratio relative to a steady 48 km/hr (30 mph)

	Non-Aggressive	Aggressive
Duration s	27s	22s
CO <sub>2</sub>	2.1	3.3
CO	2.2	7.5
NOx	2.6	8.7
HC	3.0	2.5

Fig. 15 and Table 9 show the major impact of aggressive driving on fuel consumption and emissions. They also show the major impact of a junction event with a stop, which more than doubles all the emissions. For aggressive driving the main impact is on CO and NOx emissions, which increase by over a factor of 3 relative to non-aggressive driving.

The loop emissions for all five vehicles for aggressive driving are shown in Table 10 and the average values normalized to the Euro limits are shown in Table 11. Table 10 shows very high CO<sub>2</sub> emissions for aggressive driving for all vehicles and on average 2.5 times the certified values for the NEDC. Aggressive driving is also bad for NOx emissions, but these effects are lower for Euro 3 vehicles. CO and HC are reasonably well controlled relative to the regulated values. Thus aggressive driving has its main impact on fuel consumption or CO<sub>2</sub> emissions and NOx emissions.

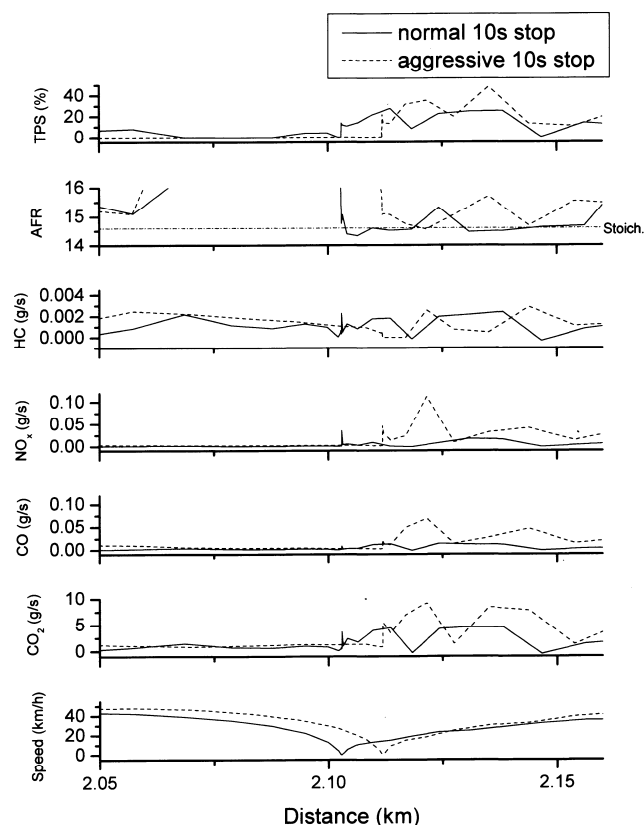


Fig. 14 Comparison of aggressive (3000 rpm) and non-aggressive driving (2500rpm) after a junction with a stop, for the Euro 1 vehicle.

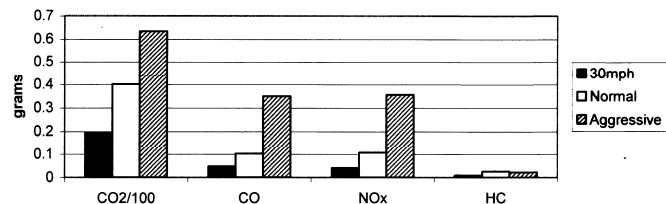


Fig. 15 Comparison of steady 48 km/hr (30 mph) driving with that at a junction with normal (2500 rpm) and aggressive (3000 rpm) driving, for the Euro 1 vehicle.

Table 15 Emissions data for aggressive driving with a 10s stop at a junction and a left turn.

Gas		Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub>	Ave	518	464	579	478	
	Max	582	524	677	568	
	SD	48	36	54	44	
CO	Ave	3.52	1.68	NA	0.095	
	Max	4.79	3.69	NA	1.20	
	SD	0.72	0.76	NA	0.31	
NOx	Ave	2.67	1.09	1.08	0.47	
	Max	3.81	1.42	1.55	2.41	
	SD	0.53	0.22	0.24	0.58	
HC	Ave	0.184	0.12	0.11	0.053	
	Max	0.290	0.32	0.16	0.096	
	SD	0.048	0.07	0.02	0.015	

Table 16 Normalised aggressive driving emissions with a 10s stop at a junction.

	Euro 0	Euro 1	Euro 2	Euro 3	
CO <sub>2</sub>	2.73	2.39	2.98	2.50	
CO	1.30	0.62	NA	0.04	
NOx	6.35	5.20	5.17	3.12	
HC	0.33	0.22	0.37	0.27	

### Cruising at 48 km/hr (30 mph)

The emissions at 48 km/hr cruise are shown in Tables 17 and 18 for cruise in third and fourth gear respectively. The emissions as a ratio to the Euro limits are shown for fourth gear cruise in Table 19. These results show that the emissions at a steady 48 km/hour were a very low proportion of the Euro limit for CO and HC. The HC emissions are essentially negligible for Euro 1, 3 and 4 vehicles once the catalyst was hot. The CO emissions were a little higher relative to the Euro standard and this was due to the extra CO that occurs for any rich deviation from  $\lambda=1$  control. These occur because the driver was not perfectly steady on the throttle for a near constant speed. The NOx emissions relative to the Euro standard were the highest, especially for the Euro 4 vehicle. This may have been influenced by the ammonia problem and the NGK zirconia NOx detector sensitivity to this. However, at steady speed the rich excursions that give rise to the ammonia generation are minimized under steady vehicle speed.

The CO<sub>2</sub> emissions were lower than the certified values on the NEDC for all except the Euro 0 vehicle. This is the well known effect of low fuel consumption at steady speed and is the reason for the more realistic NEDC being used as the measurement basis for certified CO<sub>2</sub> and fuel consumption evaluation. However, the NEDC is well removed from the real world simple urban loop driving that is the basis of the present work, as shown the previous sections.

Table 17 Emissions data, g/km, for 48 km/hr cruise on a level traffic free road in 3<sup>rd</sup> Gear

Gas		Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub>	Ave	211	166	187	173	
	Max	251	196	234	225	
	SD	54	27	45	41	
CO	Ave	0.49	0.055	NA	0.085	
	Max	0.60	0.126	NA	0.155	
	SD	0.13	0.041	NA	0.049	
NOx	Ave	0.472	0.068	0.054	0.020	
	Max	0.748	0.110	0.084	0.050	
	SD	0.30	0.032	0.018	0.016	
HC	Ave	0.088	0.002	0.053	0.001	
	Max	0.091	0.007	0.059	0.002	
	SD	0.004	0.002	0.006	0.001	

Table 18 Emissions data, g/km, for 48 km/hr cruise on a level traffic free road in 4<sup>th</sup> gear

Gas		Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub>	Ave	213	134	121	139	121
	Max	268	163			175
	SD	42	24			36
CO	Ave	0.351	0.110	NA	0.057	0.117
	Max	0.782	0.247	NA		0.176
	SD	0.207	0.089	NA		0.033
NOx	Ave	0.825	0.075	0.027	0.042	0.102 (0.018)*
	Max	1.376	0.175	0.046	0.072	0.144
	SD	0.33	0.065	0.020	0.024	0.029
HC	Ave	0.091	0.003	0.044	0.002	0.001
	Max	0.111	0.007	0.069	0.006	0.006
	SD	0.012	0.002	0.031	0.002	0.002

\* Corrected for NH<sub>3</sub> interference – see below.

Table 19 Emissions data normalized to the Euro limit for the NEDC for 48 km/hr cruise on a level traffic free road in 4<sup>th</sup> gear

Gas	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub>	1.12	0.69	0.62	0.91	0.64
CO	0.13	0.04	NA	0.025	0.117
NOx	0.34 (0.28)*	0.17 (0.14)*	0.13 (0.11)*	0.28 (0.23)*	1.275 (0.223)*
HC	0.17	0.005	0.152	0.01	0.01

\* Corrected for NH<sub>3</sub> interference – see below.

### Comparison with the FTIR Measurements and Assessment of the Ammonia Interference Problem with the Zirconia NOx Analyzer in the OBS 1300 Results

The FTIR results for the same vehicles as used in the present work (1) were for a cold start and an urban loop that was close to the University laboratories where the vehicle for cold start was cold soaked outside overnight. This urban loop was 1.45km compared with the one used in the present work of 0.6 km. However, the cold start urban loop had 7 junctions so that the average distance between junctions was 207m in the cold start loop and 150m in the urban loop. Thus the cold start loop would have more 48km/hr cruise than in the present work and this would reduce the average fuel consumption and CO<sub>2</sub> emissions as well as reduce the other loop averaged emissions. The other difference was that the present work was traffic free and the cold start route had normal urban traffic, but not high density traffic. The present results for urban loop driving with no stops and with the use of the brake (Tables 3 and 4) were used, as the nearest equivalent to the work on cold start urban loop driving.

The first lap of the cold start route was dominated by the catalyst light off. However, the last two laps were with fully warmed up catalyst and hence should be comparable to the present work, but with only two repeat laps. The remaining difference was the lube oil temperature which was not completely warmed up during the last two laps and was in the present work. Higher engine and transmission friction losses would occur. The warm up time for the cooling water was complete during the first two laps (29).

Table 20 Mean FTIR measurements (g/km) for the last two laps of the Leeds Cold Start Urban Route (1) including ammonia measurements. Comparison with the present OBS 1300 results, but for different urban loop circuits

Gas	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub> FTIR	359	305	263	142
CO <sub>2</sub> OBS 1300	323	388	375	310
CO FTIR	3.645	1.825	0.235	1.21
CO OBS 1300	0.305	NA	0.387	0.738
HC FTIR	0.33	0.16	0.055	0.040
HC OBS 1300	0.077	0.064	0.089	0.031
NO <sub>x</sub> FTIR	0.600	0.335	0.305	0.040
NO <sub>x</sub> OBS 1300	0.441 (0.367)*	0.673 (0.560)*	0.316 (0.263)*	0.368 (0.064)*
NH <sub>3</sub> FTIR	0.110	0.070	0.060	0.185
NO <sub>x</sub> /(NH <sub>3</sub> +NO <sub>x</sub> )	84.5%	82.7%	83.6%	17.8%

\* Corrected for NH<sub>3</sub> interference – see below

The cold start loop and the present loop cannot be directly compared as the distances and number of junctions are different. However, the four junctions in the present loop make up the complete loop and there is minimal 48 km/hr cruise. The average distance per junction is then 150m for the deceleration and acceleration induced by a junction. The cold start loop has 7 junctions plus an average cruise distance between junctions of 208 -150m or 58m and Table 18 may be used to determine the cruise emissions. The two driving loops can then be made equivalent by deducting the 58m cruise per bend at 48 km/hr emissions and taking the remaining emissions for the junction as spread over 150m. This then allows the route used with the FTIR to be directly compared with the route used in the present work. These corrected results are compared in Table 21.

Table 21 Comparison of the FTIR (1) and OBS 1300 emissions for the same equivalent drive loop - WP

Gas	Euro 1	Euro 2	Euro 3	Euro 4
CO <sub>2</sub> FTIR	449	381	317	156
CO <sub>2</sub> OBS 1300	323	388	375	310
CO FTIR	5.00	2.50	0.305	1.63
CO OBS 1300	0.305	NA	0.387	0.738
HC FTIR	0.455	0.206	0.075	0.055
HC OBS 1300	0.077	0.064	0.089	0.031
NO <sub>x</sub> FTIR	0.803	0.453	0.407	0.054
NO <sub>x</sub> OBS 1300	0.441 (0.367)*	0.673 (0.560)*	0.316 (0.263)*	0.368 (0.064)*
NH <sub>3</sub> FTIR	0.152	0.097	0.083	0.255
NO <sub>x</sub> /(NH <sub>3</sub> +NO <sub>x</sub> )	84.1%	82.4%	83.1%	17.5%

\* Corrected for NH<sub>3</sub> interference – see below.

These corrected results show some agreements in the two measurement method and some disagreements. The Euro 4 CO<sub>2</sub> emissions were substantially lower for the runs with the FTIR, but similar for the Euro 2 and 3 vehicles. The CO emissions were similar for Euro 3 but higher for Euro 1 and 4 for the FTIR measurements. The hydrocarbon measurements were similar for Euro 3 and 4 but higher for Euro 1 and 2 using the FTIR.

The NO<sub>x</sub> emissions were very much higher for the Euro 4 using the OBS 1300 and this was probably due to the NH<sub>3</sub> interference. The FTIR results show that NO<sub>x</sub> was 17.5%% of the combined NO<sub>x</sub> plus NH<sub>3</sub>. If the interference is linear with NH<sub>3</sub> then the true NO<sub>x</sub> would be 0.064 g/km for the OBS1300 and this is in reasonable agreement with the FTIR results. The ammonia levels were much lower for Euro 1-3 and hence the correction would be smaller. If the proportion of NH<sub>3</sub> to NO<sub>x</sub> remains the same then the true NO<sub>x</sub> reading for the OBS 1300 is 17.5% of the actual NO<sub>x</sub> reading for the Euro 4 vehicle. For the Euro 1-3 vehicles the proportion of NH<sub>3</sub> was very similar at a mean of 83.2%. These two factors (0.175 OBS NO<sub>x</sub> for Euro 4 and 0.832 OBS NO<sub>x</sub> for Euro 1-3) were applied to all the results to get the OBS 1300 readings corrected for NO<sub>x</sub> interference. The reason for the higher correction for the Euro 4 vehicle was the higher generation of NH<sub>3</sub> due to the richer overall mixture for better TWC NO<sub>x</sub> conversion. Comparison between the two instruments would be better in the same vehicle and this has been done for the Euro 1 vehicle and good agreement obtained.

## CONCLUSIONS

1. The Horiba OBS 1300 PEMS was used to compare Euro 0-4 Ford Mondeo vehicle emissions. The OBS 1300 was calibrated on a CVS facility against legislation quality emissions equipment. This equipment was shown to have very good agreement with exhaust mass flow measurements, apart from a small problem with the idle flow. The CO and CO<sub>2</sub> mass emissions were in very good agreement with the CVS emissions results.
2. The NGK zirconia NO<sub>x</sub> sensor gave good agreement with the chemiluminescence NO<sub>x</sub> analyzer for lean and λ=1 mixtures. However, it read high for rich mixtures and this was shown to be due to the generation of ammonia by TWC in rich excursions. This was a particular problem in the Euro 4 vehicle and less so in the Euro 0-3 vehicles. The FTIR results for the Euro 4 vehicle were used to derive a correction for this problem for urban driving conditions with significant rich excursions.

3. For an urban journey with four close junctions in a 0.6 km loop the results for no stops and braking before junctions showed double the CO<sub>2</sub> emissions than on the NEDC for Euro 2 and 3 vehicles. The Euro 4 vehicle only had 61% higher CO<sub>2</sub>. The HC emissions were very significant at 31% for the NEDC legislation for Euro 1-4 and this was high for a hot catalyst due to the frequent rich excursions in the accelerations after the junctions. For CO the Euro 1 and 3 vehicles had low emissions at 15% of the NEDC legislated levels for Euro 1 and 3 but this increased to 75% for Euro 0 and 4. For Euro 4 this was caused by the slightly rich calibration, which maximized the NO<sub>x</sub> reduction but gave a greater sensitivity to rich excursions for CO emissions.
4. The repeat of the urban loop, without the use of braking before the junctions, had little influence on the emissions compared to those for faster driving with braking. All emissions were slightly higher due to lower overall speeds and the presence of the acceleration mode after the junctions.
5. The addition of a 10s stop at each of the four junctions in the urban driving loop greatly increased all the emissions and the fuel consumption, due to the greater accelerations after the junction and the loss of all momentum in the stop sequence. CO<sub>2</sub> emissions were about 2.5 times the certified values. CO and NO<sub>x</sub> exceeded the legislated NEDC cycle emissions, even though the catalyst was hot. Even HC emissions were only just under the legislation. The Euro 4 vehicle has the worst performance relative to its legislation.
6. The use of more aggressive driving, with higher engine speeds before gear changes, resulted in increases in all the emissions and fuel consumption.
7. Under steady cruise at 48 km/hr the hot TWC worked well and all the emissions were well inside the NEDC Euro limits, but they were not negligible apart from for HC for the Euro 3 and 4 vehicles. The CO<sub>2</sub> emissions were also significantly less than the NEDC certified values.

## NOTE

The authors would like to thank Horiba staff, particularly Rick Spurgeon and Hiroshi Nakamura for comments and advice with regards to this study and would like to emphasize the following:

- The exhaust flow meter incorporated in the 'next generation' OBS-2000 includes features for correction of drift and idle 'pulse effect', and
- Horiba have never endorsed the use of the NO<sub>x</sub>-AFR sensor with petrol vehicles and that

likewise sensor evaluations presented here demonstrate the practicability/limitations of using the sensor with a petrol vehicle.

## ACKNOWLEDGMENTS

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