the influence of heavy gasoline components on the exhaust emissions of european vehicles part 1 - regulated emissions

Prepared for the CONCAWE Automotive Emissions Management Group, based on work carried out by the Special Task Force on emissions from gasoline powered vehicles (AE/STF-1):

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Brussels
December 1994

ABSTRACT

Ten European vehicles, meeting the requirements of the EU 'Consolidated Emissions Directive', have been tested on a matrix of seven gasolines over the current ECE+EUDC test cycle. The programme was designed to investigate the effects of heavy gasoline components in terms of both distillation and composition on the emissions performance of a fleet of modern fuel injected catalyst cars.

Gasoline back end volatility and composition both had some effect on regulated emissions performance. For HC and CO emissions, back end volatility overall had a larger effect than composition. However, The back end effects were discontinuous, with no measurable effect between the 160°C and 180°C T90 fuels. The fuel effects on NOx emissions were in the opposite direction to those for HC and CO, and compositional influences in this instance were greater than those due to back end volatility.

The back end volatilities of all the test fuels differed to an increasing extent from mid range (T50) to final boiling point (FBP). It was not possible to ascribe the fuel effects to any one distillation point within this range; neither to distillation temperatures at percent volumes recovered (T values), nor to percent evaporated volumes at certain temperatures (E values). Throughout all the tests, it was evident that emissions performance differences between the cars were substantially higher than differences observed across the fuel matrix.

KEYWORDS

Reformulated gasoline, back end volatility, composition, emissions, 'Fuel Volumetric Air Demand'

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SUMMARY

CONCAWE has conducted a study to investigate the effects of heavy gasoline components in terms of both distillation and composition on exhaust emissions from a fleet of modern fuel injected catalyst cars. The US Auto/Oil AQIRP [1,2] has reported that back end gasoline volatility can have a major impact on vehicle exhaust emissions. However, it was not known whether these effects would be reproduced in European cars and fuels, particularly as European gasolines contain less heavy components than their US counterparts.

Seven experimental fuels designed with widely varying back end distillation properties and composition were tested in a chassis dynamometer study on ten vehicles meeting the requirements of the 'Consolidated Emissions Directive'. The investigation was conducted over the current ECE+EUDC test cycle. The careful statistical design of this programme has allowed small effects to be detected. Some effects, although statistically significant, are of little practical importance, being very small compared with car to car variability.

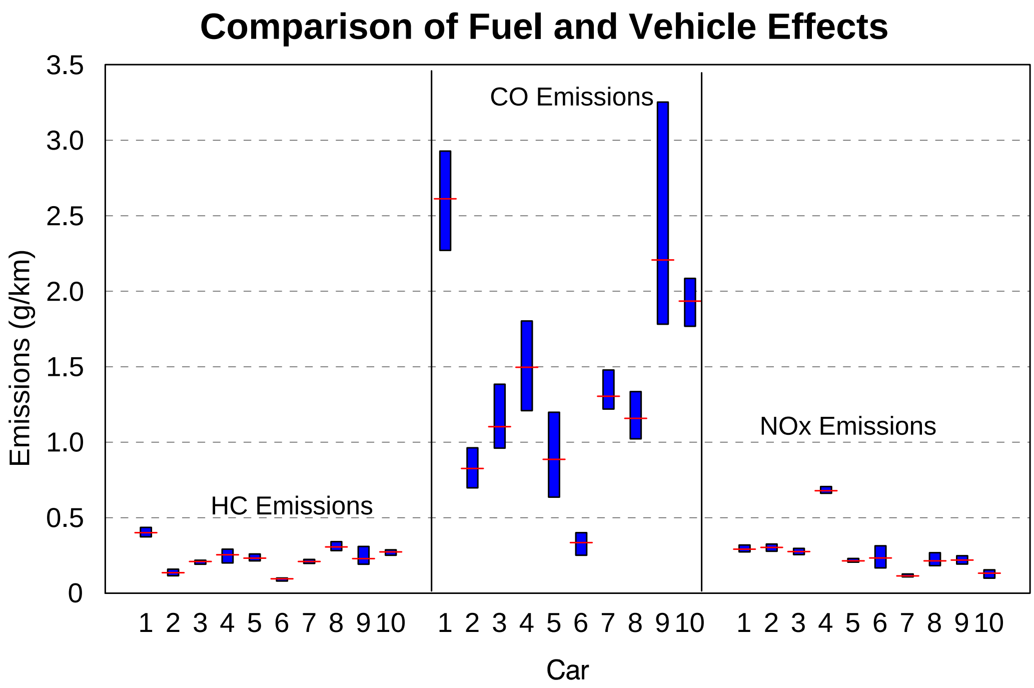
A wide variation in regulated emissions performance was observed between individual vehicles, the differences between cars being substantially greater than the differences observed across the fuel matrix. However, the majority of vehicles met the 1996 emissions limits for CO and (HC+NOx). Within the ten car fleet, some cars were more sensitive to differences in fuel characteristics than others, but there was no clear evidence to suggest that high emitting cars were any more (or less) sensitive than low emitting models.

Gasoline back end volatility and composition both had some effect on regulated emissions performance. For HC and CO emissions, back end volatility overall had a larger effect than composition. However, the back end effects were discontinuous, with no measurable effect between the 160 and 180°C T90 fuels. The fuel effects on NOx emissions were in the opposite direction to those for HC and CO and compositional influences in this instance were greater than those due to back end volatility.

The back end volatilities of all the test fuels differed to an increasing extent from mid range (T50) to final boiling point (FBP). It was not possible to ascribe the fuel effects to any one distillation point within this range; neither to distillation temperatures at percent volumes recovered (T values), nor to percent evaporated volumes at certain temperatures (E values).

Fuel effects on NOx emissions were in the opposite direction to those for HC and CO. This suggests that there could be changes in metered air/fuel ratio (AFR), perhaps caused by variation in stoichiometric AFR of the test fuels. All the vehicles were equipped with lambda sensors to control AFR. However, these sensors do not operate effectively before the engine and catalyst have warmed up. They may also fail to be completely effective during transient operations because of their finite response time. Thus small changes in the stoichiometric AFR of the fuel could affect the engine air/fuel ratio under these conditions, influencing catalyst efficiency and hence emissions.

If it is assumed that, during transients, a constant volume of fuel is injected for a given speed/load combination, then it is the stoichiometric air demand for that constant volume of fuel that will affect the AFR at which the engine operates. This can be described by the 'fuel volumetric air demand' term [$AFR_{(stoich)}$ x Density], which gave a good ranking of the emission results. Further evidence of changes in AFR with fuel composition can be seen, for certain vehicles, from traces of transient AFR response over the current European cycle.



The variation across the fuels for each car is represented by the vertical bars. The horizontal line indicates the mean emissions for each car averaged over the seven fuels. The ten cars are represented for each emissions species across the horizontal axis

1. INTRODUCTION

The US Auto/Oil AQIRP [1,2] has reported that back end gasoline volatility can have a major impact on vehicle exhaust emissions, especially in modern fuel injected catalyst equipped vehicles. One explanation proposed [3] is that the lower manifold temperatures and shorter residence times of fuel in the inlet manifolds of such cars may not allow full vaporisation of the heavier gasoline components, resulting in incomplete combustion and hence higher exhaust emissions. Phase 1 of the AQIRP [1] reported a 21% reduction in HC emissions and reductions of 10 to 30% in the so-called 'air-toxic' emissions from newer US cars when T90 was reduced from 182°C to 138°C.

A more specific study in Phase 2 of AQIRP [2] has examined this in more detail and also reported significant reductions in HC emissions with increasing mid range to back end volatility. Their analysis showed that these decreases in HC emissions were probably due to changes in distillation characteristics rather than compositional effects, although some intercorrelations between mid range to back end distillation and compositional parameters were present in the fuel set. The programme studied heavy aromatics from reformate and cat-cracked components, and heavy paraffins from alkylate. HC emissions were reported to be best expressed by an equation containing non-linear terms in both E149 and E93, although for the fuels tested, these parameters were highly correlated. The reported direction of non-linearity was such that reducing back end volatility below a T90 of approximately 150°C gave no further significant benefits in HC emissions. No clear relationships were seen between tail-pipe or engine-out CO emissions and fuel composition or distillation. Tail-pipe NOx appeared to decrease as the fuel became less volatile.

It was not known whether these effects would be reproduced in European cars and fuels, particularly as European gasolines have lower T90 than US fuels (typically 155°C v 165-170°C). A test programme has therefore been planned and carried out by CONCAWE task force AE/STF-1, at the request of the CONCAWE Automotive Emissions Management Group. The objective was to investigate the effects of heavy gasoline components on exhaust emissions from European catalyst-equipped vehicles.

Note: Throughout this report the term ‘increasing volatility’ (i.e. lighter fuels) refers to higher percentage evaporated at fixed temperature (E numbers), but lower temperatures for a fixed percentage of evaporated fuel (T numbers).

2. OUTLINE OF PROGRAMME

The programme was designed to investigate the effects of heavy gasoline components in terms of both distillation (e.g. T90) and composition on exhaust emissions from a fleet of modern fuel injected catalyst cars.

Seven fuels designed with widely varying back end distillation properties and composition were tested in a chassis dynamometer study on ten vehicles meeting the requirements of the EU 'Consolidated Emissions Directive' (91/441/EEC). The investigation was carried out over the current ECE+EUDC test cycle. Emissions were collected for the three phases ECE 1 + 2, ECE 3 + 4, EUDC, and results are reported by phase and are also summed to give total emission data over the complete test.

The compositional interest was reinforced by the analysis of speciated HC and aldehyde/ketone exhaust products, as well as the regulated pollutants (HC, CO, NOx). CO_2 and fuel economy were also measured. Results for NMHC (non-methane HC) were also measured but are not discussed, as the observations were similar to the total HC emissions.

Speciated emissions measurements were confined to ECE 1 + 2, (the first two urban driving cycles), and EUDC phases, and limited tests were duplicated. These results on speciated emissions, which give insight into the way in which detailed fuel composition affects exhaust composition, will be treated in a separate report. Emission tests for regulated exhaust components were conducted in triplicate, except for the tests on base fuel which were quadruplicated. This approach was taken on statistical advice so as to optimize the discriminating power of the experiment in relation to the available resources. Time resolved modal analysis of HC, CO and NOx emissions, pre- and post-catalyst, were also carried out.

3. FUEL DESIGN AND BLENDING

A base fuel was blended from typical refinery components, but with a low content of heavy hydrocarbons. This gave a light gasoline, containing virtually no olefins which is not representative of European quality. This fuel was then blended with distillate fractions from selected heavy aromatic, paraffinic and olefinic refinery components to produce a test fuel matrix to separate physical and compositional effects. It should be emphasized this fundamental separation of physical and compositional parameters could not be achieved with 'typical' fuels and it is therefore not possible to make comparisons between the test fuel blends and commercial products. The test fuel matrix is as follows:

	Base (B)	**Intermediate (I)**	**Heavy (H)**
Target T90 (°C)	140	160	180
Base Fuel	B140 (145)		
Base Fuel + Aromatics		A160 (161)	A180 (173)
Base Fuel + Paraffins		P160 (165)	P180 (176)
Base Fuel + Olefins		O160 (156)	O180 (170)

The test fuels were blended to two nominal T90 levels, 160 and 180°C. The T90 values actually achieved are shown in parentheses in the above table.

Reducing the back end volatility (e.g. increasing T90) of the test fuels also reduced the mid range volatility (e.g. increased T50) which may also have a measurable impact on vehicle emissions. Therefore to ensure a true comparison of base and test fuels, the front-end/mid range distillation characteristics of the base fuel were carefully adjusted with light paraffinic components to provide a modified base fuel which matched the front-end/mid range (up to T50) of the test fuels (**Table 4**).

It should be recognised that it is impossible to change only one aspect of a fuel distillation characteristic without changing other distillation points. Therefore, it will be seen from **Figure 1** that although the designed changes of T90 have been achieved, other distillation points above T50 have also been affected. However, within this fuels matrix the Task Force was confident that only mid range to back end distillation effects were being measured.

All test fuels were blended to a minimum 85 MON specification. Inspection data are provided in **Table 1** and composition details are shown in **Table 2**. Fuel distillation curves are shown in **Figure 1**. The test fuels do not exactly match the T90 target values, as it was agreed that the volume of each of the heavy components (i.e. aromatic, olefinic, paraffinic) added to the common base fuel should be the same to ensure that the compositional variation was consistent across all fuels. The addition of heavy components can of course affect fuel density and C/H ratio (and hence stoichiometric air/fuel ratio), particularly in the aromatic fuel series. The RVP and T50 of all the test fuels were similar and sulphur levels were kept to a minimum (9-16 ppm) to eliminate any possible exhaust catalyst deactivation effects.

4. TEST EQUIPMENT

All emissions test work was carried out at BP Oil Technology Centre, Sunbury-on-Thames, UK. This facility was equipped with an Horiba VETS 9000 system, linked to three MEXA 9000 emissions analyser trains (one dilute gas, two raw gas). For the European drive cycle, this allowed analysis of HC, CO, NOx, NMHC and carbon dioxide in three separate bags (ECE 1 + 2, ECE 3 + 4, EUDC). In addition raw gas was sampled on-line to give second-by-second and modal results of engine-out and tailpipe emissions, together with catalyst efficiencies and air fuel ratio.

5. TEST PROCEDURE AND TEST VEHICLES

Prior to the start of the emissions test programme all vehicles were subject to a full engine service check and the crankcase lubricant was replaced using a commercial multi-grade lubricant. The carbon canisters for evaporative emission control of all the vehicles were sealed-off prior to the start of the test work, thus minimizing the need for lengthy soak/purge vehicle preconditioning prior to test commencement. Evaporative emissions were not measured in this programme. A 10 km constant speed preconditioning was carried out, followed by an overnight soak of not less than 15 hours, at a temperature in the range of 25-30°C. One test vehicle was equipped with an 'adaptive learning' engine management system and was therefore driven a full European drive cycle prior to the test work after each fuel change, to enable the electronic adaptive learning system to adjust to the new test fuel.

Technical details of the 10 test cars (which were all 3-way catalyst equipped with closed loop lambda feed-back control) are provided in **Table 3**. The light base fuel was tested on at least four occasions in each car and each of the six less volatile fuels on at least three occasions. The emissions testing was carried out over the current European emissions test cycle (ECE+EUDC).

Dilute exhaust gas samples were taken from the ECE 1 + 2 and EUDC (representing cold start and fully warmed up conditions) into Tedlar bags for hydrocarbon speciation (C1 to C9) using a gas chromatographic separation technique (a capillary PLOT column, temperature programmed from 32°C - 195°C at 15°C/min for 5 minutes followed by 5°C/min up to 195°C). Aldehyde and ketone analysis was also carried out using an HPLC (high performance liquid chromatography) separation technique of the DNPH (dinitrophenylhydrazine) derivatives of the carbonyl compounds. Speciation was carried out over the ECE 1 + 2 cycle for each car/fuel combination. However, for the EUDC cycle, HC emissions were extremely low and only four cars were tested.

6. RESULTS

The results were subjected to a full statistical analysis, which was a critical element in the study. Except where indicated (i.e. **Figures 2-5)**, the data are presented as geometric means (GM), or offset geometric means (OGM) rather than arithmetic means. Geometric means give better comparisons between fuels over a car population but tend to underestimate the absolute emission levels. All differences quoted in **Sections 6.1** to **6.5** are significant at the 95% confidence level in either a t-test or F-test. Full details of the statistical approach, including rejection of outliers, are given in **Appendix 1**.

All geometric and offset geometric mean results for regulated exhaust emissions (HC, CO and NOx), NMHC, CO_2 emissions and fuel consumption over ECE 1 + 2, ECE 3 + 4, EUDC and the total cycle for all test vehicles and fuels are given in **Appendix 2**. For each emission, the following GM or OGM are given:

1. Mean emission data for each fuel averaged over the 10 cars.
2. Mean emission data for the base, paraffinic, aromatic and olefinic fuels averaged over the 10 cars.
3. Mean emission data for the three back end volatility levels: base, intermediate and heavy (designated by B140, I160, H180, respectively) averaged over the 10 cars.
4. Mean emission data for each car averaged over the 7 fuels.
5. Mean emission data for each car/fuel combination.

Graphs showing regulated emissions by car on each fuel are presented in **Figures 2-5**.

6.1. HC EMISSIONS

Total ECE+EUDC cycle

Considering the back end volatility effect, the geometric 10 car mean is shown for each fuel in **Figures 6** and **7**, plotted against T90 and E150 respectively. The base fuel (B140) was lower in HC emissions than the other 6 'heavier' fuels. Raising the back end contribution from B140 to the intermediate level (I160) increased HC emissions by an average of 8.7%. There was no effect on HC emission upon raising from the intermediate level (I160) to the heavy level (H180).

For each back end volatility level, (I160 and H180), there were some small but statistically significant compositional effects. For the intermediate set of fuels, the aromatic fuel gave 4.1% higher emissions than either the olefinic or paraffinic fuels which were similar. There was greater separation of compositional effects for the heavier set of fuels. Here the aromatic fuel was 4.5% higher than the paraffinic one which in turn was 3.9% higher than the olefinic fuel.

Within the ten car fleet some cars were more sensitive to differences in fuel characteristics than others, as highlighted in **Figure 2**. Car 9 appeared to be the most sensitive whilst Car 6 was the least sensitive to changes in fuel characteristics.

It was readily apparent that for the total HC emissions, car differences were much greater than fuel differences. Car means, averaged over the 7 fuels varied from 0.090 to 0.399 g/km whilst fuel means, averaged over the 10 cars, only varied from 0.202 to 0.229 g/km.

Separate ECE 1 + 2, ECE 3 + 4 and EUDC cycles

HC emissions over the ECE 1 + 2 cycle followed a broadly similar pattern to the total HC emissions. Emissions for the three intermediate I160 fuels were, on average, 8.1% higher than the base (B140) fuel. Increasing the back end contribution from I160 to H180 had no effect on HC emissions, indeed there was a small reduction. Some compositional effects were again apparent over the I160 and H180 levels. The effects were similar for each level, and on average, aromatic fuels gave a 4.2% increase in HC emissions compared with the paraffinic and olefinic fuels which performed similarly.

As expected, HC emissions in ECE 3 + 4 cycles were an order of magnitude lower than for ECE 1 + 2 cycles. HC emissions increased by an average 17.8% when comparing the intermediate I160 fuels to the base fuel. There was a slight decrease when the back end contribution was raised from the intermediate to the heavy H180 fuels, primarily due to the O180 fuel, which gave much lower emissions than the other two fuels, being only 3.6% higher than the base fuel. Compositional effects were less evident for this cycle, apart from the aforementioned O180 result.

EUDC HC emissions were lower than both ECE 1 + 2 and ECE 3 + 4 but tended to show a more marked back end volatility effect. HC emissions increased, on average, 10.7% from the base to the intermediate I160 fuels. There was a further increase in emissions from I160 to the heavy H180 fuels, by an average of 7.8%. There was little evidence to suggest a compositional effect for the intermediate I160 range of fuels. However, there was a strong compositional effect observed for the heavy H180 fuels. The emissions from the aromatic fuel were 22.5% higher than the paraffinic fuel which was 9.6% higher than the olefinic fuel.

There were some appreciable differences in the vehicle emissions performance on various fuels within the test fleet. By far the most noticeable feature was the very high emission using fuel O180 in Car 9 for ECE 1 + 2 cycles. However, it should be noted that some driveability problems were experienced with this vehicle on this particular fuel which may have contributed to the high emissions. Subsequently, these high ECE 1 + 2 emissions were reflected strongly in the high total HC emission values. Also noticeable were high ECE 1 + 2 and total HC emissions using fuel O160 in Car 2. Differences in performance were not limited solely to ECE 1 + 2 cycles. Car 4 gave surprisingly high emissions in cycle ECE 3 + 4 for fuels P180, O160 and P160, but low emissions for the base and O180 fuel. Relatively high ECE 3 + 4 emissions were also observed for Car 1 using the base fuel.

6.2. CO EMISSIONS

The CO emission results, both for the total and separate cycles, were similar in many respects to the HC results reported above. The same wide range of vehicle sensitivity to differences in fuel characteristics was evident for CO emissions within the test fleet as shown in **Figure 3**.

Total ECE+EUDC cycle

The back end volatility effect is shown in **Figures 8** and **9**, where the 10 car geometric mean is plotted against T90 and E150 respectively. The CO emissions behaved in a similar manner to that seen for the HC emissions. The base fuel (B140) clearly gave lower CO emissions than the other 6 'heavier' fuels. Raising the heavy-end contribution from B140 to the intermediate level I160 fuels, increased CO emissions by an average of 14.2%. There was no effect on CO emissions on reducing back end volatility from the intermediate I160 fuels to the heavy H180 fuels.

Again, similar to the HC emissions, there were some significant compositional effects for the intermediate and heavy series of fuels. For the intermediate fuels, the aromatic fuel gave 3.8% higher emissions than the paraffinic fuel which in turn gave 5.3% higher emissions than the olefinic fuel. Slightly greater differences were observed for the heavier fuels. The aromatic fuel gave 8.4% higher CO emissions than the paraffinic fuel, which gave 4.4% higher emissions than the olefinic fuel.

Car differences were again much greater than fuel differences for CO emissions. Car means varied from 0.33 to 2.59 g/km whilst fuel means only varied from 1.07 to 1.30 g/km. Car 9 appeared to be most sensitive whilst once again Car 6 was the least sensitive to changes in fuel characteristics (**Figure 3**).

Separate ECE 1 + 2, ECE 3 + 4 and EUDC cycles

CO emissions in ECE 1 + 2 showed broadly similar patterns to total CO emissions. The three intermediate I160 fuels gave, on average, 16.4% higher CO emissions compared with the base fuel. Reducing back end volatility further, from the intermediate to the heavy fuels had no effect on CO emissions, indeed there was a small overall reduction. Some compositional effects were again noticeable for the I160 and H180 fuels. The effects were similar for each level and on average aromatic fuels gave 3.8% increase in CO emissions compared with paraffinic fuels which in turn were 4.2% higher than olefinic ones.

As anticipated, CO emissions in ECE 3 + 4 were an order of magnitude less compared with ECE 1 + 2 cycles. CO emissions were increased by an average of 7.7% when raising the back end contribution from the base fuel to the intermediate level fuels. There was a smaller increase of 4.7% in CO emissions upon reducing volatility from the I160 to the H180 level. There was little evidence to suggest a compositional effect for the intermediate level of fuels. However, there was a compositional effect for the heavy set of fuels. The aromatic fuel was 24.2% higher in CO emission compared with the paraffinic and olefinic H180 fuels which performed similarly.

CO emissions in the EUDC were also low and tended to show a larger back end volatility effect, again very similar to that reported for HC emissions. CO emissions increased on average 15.2% in going from the base to the intermediate set of fuels. There was a further increase of 8.1% in emissions in going from the intermediate to the heavy fuels. There were again some compositional effects, particularly for the two aromatic fuels. For the intermediate fuels, the aromatic fuel gave on average 16.3% higher emissions than the paraffinic and olefinic fuels. There was a larger effect for the heavy fuels. The aromatic fuel gave 28.1% higher emissions than the paraffinic fuel which, in turn, yielded a rise of 18.0% over the olefinic fuel.

Again there were some appreciable differences in the performances of the various fuels in the different cars. By far the most noticeable feature was the very high emissions using the O180 fuel in Car 9 in ECE 1 + 2 cycles; these high ECE 1 + 2 emissions were reflected strongly in the total emission figures. This fuel x car combination also gave very high HC emissions in ECE 1 + 2 cycles. These mean emissions are based on only two tests, but the high emissions were seen in both. Also noticeable were the very high emissions from Car 5 using the A180 fuel in ECE 3 + 4 cycles.

6.3. NOx EMISSIONS

A very different picture was observed for fuel effects on NOx emissions compared with those already reported for HC and CO emissions, mainly because NOx trends were in the opposite direction. In this instance, compositional effects on NOx emissions were far more important than the influence of back end volatility.

Total ECE+EUDC cycle

The 10 car geometric mean for each fuel is shown in **Figures 10** and **11** plotted against T90 and E150 respectively. On average, NOx emissions for the 6 heavier fuels were 4.8% lower than those for the base fuel. The compositional effects were similar for the intermediate and heavy fuel series. The two aromatic fuels gave the lowest NOx emissions followed by the two paraffinic fuels, whilst the two olefinic fuels slightly increased NOx emissions compared with the base fuel. On average, the aromatic fuels were 7.0% lower in NOx emissions than the paraffinic fuels, which were in turn 7.5% lower than the olefinic fuels.

A wide range of vehicle sensitivity to differences in fuel characteristics was evident for NOx emissions for the 10 cars, as shown in **Figure 4**. However, the cars were now reacting in a different way to the fuels. Car 6 was the most sensitive and Car 7 appeared to be the least sensitive.

Total NOx emissions, like total HC and CO emissions, varied more from car to car than from fuel to fuel. Car means varied from 0.115 to 0.678 g/km whilst fuel means varied from 0.217 to 0.257 g/km.

Separate ECE 1 + 2, ECE 3 + 4 and EUDC cycles

For the ECE 1 + 2 cycles, fuel differences were slightly smaller in relative terms than those seen for the total emissions . The base fuel gave 3.8% higher NOx emissions than the intermediate I160 fuels, which in turn, yielded 2.9% higher emissions than the heavy H180 fuels. The compositional effects for this cycle were not so clear cut. For the intermediate fuels, the olefinic fuel gave 4.5% higher emissions than the aromatic fuel which gave 2.2% higher emission than the paraffinic fuels. However, for the heavy H180 fuels, the performance of the fuels was different. The aromatic fuel now yielded the lowest NOx emission, being 4.0% lower than the paraffinic and olefinic fuels which performed similarly.

In the ECE 3 + 4 cycles the direction of NOx emissions was actually reversed upon increasing the back end contribution. On average, NOx emissions for the six heavier fuels were 9.6% higher than emissions from the light base fuel. Whilst there was no difference in average emissions between the intermediate and heavy fuels, a compositional effect was seen for the I160 fuels but not for the H180 blends. At a T90 of 160°C, the aromatic fuel gave 12.1% lower emissions than the paraffinic and olefinic blends which performed similarly.

In the EUDC cycle, NOx emissions were dominated by compositional effects and followed a similar pattern to that observed for the total ECE+EUDC cycle. The two aromatic fuels again gave the lowest NOx emissions, being 17.4% lower than the paraffinic fuels, which in turn were 14.5% lower in emissions than the olefinic fuels. Both olefinic fuels were higher in NOx emissions compared with the base fuel. There were some variations in the performances of the different fuels in the different cars. In the EUDC, Car 8 gave high emissions with fuel O180 and low emissions on the aromatic fuels. Car 6 gave some unusual results in the ECE 3 + 4 and the EUDC leading to high total emissions with the base fuel and fuel O160 and low total emissions with fuel A180. In the ECE 1 + 2 cycles, Car 9 gave low emissions with fuel O180, whilst in ECE 3 + 4, base fuel emissions were low in Car 1.

6.4. CO_2 EMISSIONS

As would be expected, there was a wide variation in total CO_2 emissions from different cars, with means ranging from 144.4 to 227.2 g/km. The best and worst fuels only differed by some 2.5%. Although statistically significant, fuel effects on total CO_2 emissions were of minor importance in practical terms.

6.5. FUEL CONSUMPTION

As for CO_2 emissions, total fuel consumption varied widely between cars, with car means varying from 6.16 to 9.82 l/100km. Fuel differences had a much smaller effect, fuel means varying from 7.56 to 7.74 l/100km. The dominant feature in the results totalled over all cycles was the high volumetric consumption of fuel P160. This was 1.53% higher than the consumption of O160 which, in turn was 0.65% higher than that of A160. For the heavy H180 fuel series, the paraffinic fuel gave 0.62% higher consumption than the aromatic and olefinic fuels which exhibited similar performance. Average consumption for the three I160 fuels was 0.73% higher than for the three heavier fuels. The intermediate fuels also gave 0.41% higher consumption than the base fuel.

7. DISCUSSION

The programme was conducted to test the effects of heavy back end gasoline components on exhaust emissions, and results reported here refer to regulated emissions only. The major aim of this study was to examine the extent to which physical fuel effects may be separated from chemical effects on regulated emissions. The physical interest focused on mid range to back end volatility, whilst the chemistry concentrated on the relative effects of aromatic, paraffinic and olefinic components.

A high degree of replication was achieved in these experiments with three or four independent measurements being made on each fuel in each car. This enabled the programme to detect relatively small effects. For example, total emissions, averaged over the 10 cars, only needed to differ by 2.3% (HC), 4.0% (CO) or 2.7% (NOx) to show a significant 160°C to 180°C T90 effect (at 95% confidence).

This work showed that back end volatility and composition contribute in different ways to HC, CO and NOx emissions. As far as HC and CO were concerned, the largest difference was between the six heavier fuels and the base fuel. The back end effect occurred between the base and intermediate fuels, with no overall difference being observed between the intermediate and heavy fuels. However, T90 was not the only difference between the base and the heavier fuels; while distillation up to T50 was effectively constant, there were differences in distillation from T50 to the FBP. Hence, the observed differences in HC and CO behaviour could be ascribed to a general rather than a specific difference in back end volatility characteristics between the base fuel and the other six blends. Differences in emissions within the six heavier fuels were dominated by compositional effects with aromatic fuels giving greater HC and CO emissions than paraffinic fuels which, in turn, produced greater emissions than olefinic ones.

The NOx results moved in the opposite direction to HC and CO emissions as regards both volatility and composition. Composition had a greater effect on NOx emissions than back end volatility with olefinic fuels giving greater emissions than paraffinic ones which, in turn, tended towards greater emissions than aromatic fuels.

Figures 2 to **5** show HC, CO, NOx and HC+NOx emissions for individual vehicles, with the 1993 (Conformity of Production) and 1996 EU limits superimposed on the CO and HC+NOx figures. Wide emission performance differences were observed between vehicles. Arithmetic mean HC emissions varied from 0.09 to 0.40 g/km, CO from 0.33 to 2.61 g/km, and NOx from 0.11 to 0.68 g/km. There were also considerable differences in vehicle sensitivity to changes in fuel characteristics. Car 6 was least sensitive for HC and CO emissions, but the most sensitive for NOx. Car 9, by contrast, was most sensitive to fuel changes for HC and CO emissions, but average for NOx. There was no clear relationship between absolute emission level and vehicle sensitivity to fuel changes.

During this programme the full analysis of the US Auto/Oil AQIRP Phase 2 Heavy Hydrocarbon Study became available.[2] This programme aimed to determine whether an apparent effect of T90 on emissions (found in the Phase 1 work) was due to fuel composition or distillation effects and also to determine if such effects were linear or non-linear. In contrast to the CONCAWE programme, the AQIRP study used two factorially designed fuel matrices with the independent variables consisting of a range of catalytically cracked, reformate and alkylate streams. The distillation characteristics, T50 and T90, plus the aromatic, olefinic and paraffinic composition of the fuels were not, in fact, 'design variables, but rather dependent variables'.[2] Within the programme, therefore, a number of fuel composition and distillation parameter intercorrelations were observed. For example, T90, T50 and aromatics (in addition to a number of other distillation parameters between T90 and T50) were intercorrelated to varying degrees. The study reported a regression equation containing non-linear terms in both E149 and E93, as describing the HC emission results best (**Figure 12**), although these parameters were highly intercorrelated:

$$\ln(HC) = -1.576+\{0.00236[(E149-E93)-41]+0.04634\}\exp[0.1716(100-E149-12)]+0.0255M$$

Where M = Constant

However, due to the parameter intercorrelations mentioned above, a number of similar equations could be derived in these and other distillation variables which would also describe the data satisfactorily. No clear fuel effects were observed on CO emissions, although NOx emissions were influenced in a similar fashion to that found in the CONCAWE programme. That is, NOx tended to vary in the <u>opposite</u> direction to HC emissions, <u>increasing</u> as the fuel became more volatile.

The CONCAWE test fuels matrix was not designed to unambiguously determine which distillation parameter(s) was the most important factor in determining emissions. However, an important difference from the US programme was that the fuels were blended to differ only in their back end volatilities and to be similar in mid range volatility. Thus there was a very narrow spread in the T50 values which progressively increased to a wide spread in T90 values up the distillation curve. However, notwithstanding these reservations, regression analysis was carried out to try and establish which parameters gave the best correlation.

Plots of HC, CO and NOx emissions against T50 to FBP and E100 to E150 are given in **Appendix 3** (**Figures A** to **F**). In simple linear regression analyses, T60 emerged as the best single 'T' predictor of HC and CO emissions and T50 as the best predictor of NOx emissions. The best 'E' predictors of HC, CO and NOx emissions were E110, E120 and E130 respectively. Such analyses could be over-simplistic, however, and might be misleading. They do not prove or disprove that such mid range factors were the true determinants of differences in emissions between fuels, as there were intercorrelations between adjacent distillation parameters. For a fuel property to correlate strongly with HC, CO and NOx emissions, it merely needs to rank fuels in the following order:

BASE< OLEFINIC< PARAFFINIC< AROMATIC (or vice-versa)

In the case of HC and CO emissions, a clear separation between the light base fuel and the other six blends would be adequate to demonstrate a good correlation. T60 (and to a lesser extent T70) were the only first order fuel parameters examined which achieved the desired ranking. The parameter E120 was highly correlated with HC and CO emissions because it gave a large ‘base to test fuel’ separation. However, the spread of these values in the fuel matrix made it impossible to prove (or disprove) the existence of any genuine causal link. Moreover, it was clear from the data analysis discussed in **Section 6** that composition was the more important fuel factor influencing the emissions performance of the six less volatile fuels.

The fact that the effects of fuel composition changes on NOx emissions were generally in opposite directions to those for HC and CO, suggests that the effects could be influenced by small changes in metered air/fuel ratio (AFR). All the engines have lambda sensors to enable AFR to be controlled; however, these sensors do not operate over the first part of the test cycle before the engine and catalyst have warmed up and may not be fully effective during transients due to their finite response time. Thus small changes in the stoichiometric AFR of the fuel could affect the engine air/fuel ratio under these conditions and could have a major effect on catalyst efficiency and hence emissions. If we assume, that during transients, a constant volume of fuel will be injected for a given speed/load combination (and hence air flow), then it is the stoichiometric air demand for a constant volume of fuel that will affect the AFR at which the engine operates. This can be described by [$AFR_{(stoich)}$ x Density], i.e. of kg air per litre of fuel for stoichiometric combustion. **Figures 13** to **15** thus show HC, CO, and NOx emissions plotted against [$AFR_{(stoich)}$ x Density], which ranks fuels generally in the desired order.

Further evidence for possible effects of fuel properties on engine AFR can be obtained from the continuous analysis of AFR. This was conducted for a number of different fuel/vehicle combinations. Analysis of the AFR perturbations over each phase of the European cycle clearly showed that certain vehicles when operating on fuel A180 had a pronounced tendency for greater rich excursions during transient operation than for the base fuel (B140), especially during warm-up, i.e. ECE 1 + 2.

The AFR traces (**Figure 16**) over ECE 1 + 2 for Car 9, which exhibited the largest HC and CO fuel effects, show a much greater incidence of rich excursions on fuel A180. This was still evident when the sensor and catalyst were fully operational. These excursions away from optimum AFR will influence emissions performance. Continuous analysis of catalyst HC and CO conversion efficiency for ECE 1 + 2 is plotted for the same car and fuels in **Figures 17** and **18**. This clearly shows the reduced efficiency when operating on A180 over the ECE 1 + 2. Exhaust emission results (**Appendix 2**) for Car 9 demonstrated that HC and CO emissions increased by 37% and 33% respectively over the total ECE+EUDC cycle on fuel A180 compared with the base fuel.

Analysis of AFR excursions for another vehicle (Car 7) with different AFR control technology and fuel cut-off on throttle closure is shown in **Figure 19**. It is clear that this vehicle frequently operated lean, particularly during the deceleration phases of the drive cycle. There were fewer rich perturbations and the difference between the base fuel and fuel A180 was much less than that observed for Car 9. HC and CO catalyst conversion efficiencies for this vehicle are shown in **Figures 20** and **21**, which show similar efficiencies for both fuels (i.e. the fuel effects on catalyst efficiency were less pronounced than those observed for Car 9). The exhaust emission results (**Appendix 2**) for Car 7 also demonstrated little fuel effect on emissions, i.e. total cycle geometric mean results for the base and A180 fuels were 0.223 & 0.220 g/km respectively for HC emissions and 1.341 & 1.323 g/km respectively for CO.

Car 6 gave the lowest HC emissions (**Figure 2**) of all the vehicles tested. Continuous analysis of the AFR, HC and CO catalyst efficiency for this vehicle are plotted for the base and A180 fuels in **Figures 22** to **24**. It is clear from this analysis that rich AFR excursions were extremely limited and that catalyst conversion efficiency for HC was very good (i.e. after ~190 seconds from engine start HC catalyst efficiency was >95%). Furthermore, after the initial catalyst warm-up period high catalyst conversion efficiency was observed throughout the drive cycle. The AFR control and catalyst technology for Car 6 was the most effective of the whole test fleet and resulted in the lowest HC emissions on any of the fuels tested. This car also showed the smallest fuel effect for HC and CO emissions.

8. CONCLUSIONS

1. The careful statistical design of this programme has allowed small fuel influences to be detected. Some effects, although statistically significant, are of little practical importance being very small compared with car to car variability.

2. A wide variation in regulated emissions performance was observed between individual vehicles, the differences between cars being substantially greater than the differences observed across the fuel matrix. However, the majority of vehicles met the 1996 emissions limits for CO and (HC+NOx). Within the ten car fleet some cars were far more sensitive to differences in fuel characteristics than others but there was no clear evidence to suggest that higher emitting vehicles were any more (or less) sensitive than low emitting models.

3. Both gasoline back end volatility and composition had some effect on regulated emissions performance. For HC and CO emissions, back end volatility had a larger effect than composition. For NOx emissions, compositional effects were greater than those due to back end volatility.

4. Back end volatility effects were non-linear. Reducing back end volatility by moving from the light base fuel to the intermediate (I160) fuels increased fleet average total HC emissions from 0.202 g/km to 0.220 g/km (9%) and total CO emissions from 1.066 g/km to 1.217 g/km (14%). Further reducing back end volatility to the heavy (H180) fuels had no effect on HC or CO emissions.

   Note: All the averages quoted above and in the following paragraphs are geometric means.

5. The back end volatility of all the test fuels differed to an increasing extent from mid range (T50) to final boiling point (FBP). Within this range it was not possible to ascribe the fuel effects to any one distillation point, either T or E values.

6. Aromatic fuels gave a fleet average of 0.227 g/km HC emissions, approximately 5% greater than paraffinic fuels at 0.218 g/km and olefinic fuels at 0.214 g/km. Similarly, the aromatic fuels gave 1.286 g/km CO emissions, some 6% higher than the 1.213 g/km from the paraffinic fuels which were, in turn, about 5% higher than the 1.156 g/km CO emissions associated with the olefinic fuels.

7. Fuel effects on NOx emissions were in the opposite direction to those for HC and CO. Aromatic fuels gave a fleet average of 0.218 g/km NOx emissions, 7% lower than the paraffinic fuels at 0.234 g/km which, in turn, gave 8% lower NOx emissions than the olefinic fuels at 0.254 g/km. This confirmed the apparent beneficial effect of aromatics on NOx control in catalyst cars. Changing from the base fuel to the intermediate and heavy fuel series gave reductions in NOx emissions from 0.247 g/km to 0.218 g/km for aromatics (12%) and 0.234 g/km for paraffins (5%). The olefinic fuels at 0.254 g/km gave no reduction in NOx emissions.

8. Fuel effects on NOx emissions were in the opposite direction to those for HC and CO. This suggests that there could be changes in metered air/fuel ratio (AFR), perhaps caused by variation in stoichiometric AFR of the test fuels. The 'Fuel Volumetric Air Demand' term [$AFR_{(stoich)}$ x Density] gave a good ranking of the emissions results. Further evidence of changes in AFR with fuel composition can be seen, for certain vehicles, from traces of transient AFR response over the current European cycle.

9. Total CO_2 emissions varied by less than 3%, and fuel consumption by just over 2% for the seven fuels tested.

9. REFERENCES

1. AQIRP (1993) Auto/Oil Air Quality Improvement Research Program Phase 1 Final Report

2. SAE (1993) US Auto/Oil Air Quality Improvement Research Program. Volume 2 SAE Publication SP 1000. Warrendale, PA: Society of Automotive Engineers

3. Quader, A et al (1991) Why gasoline 90% distillation temperature affects emissions with port fuel injection and pre-mixed charge. SAE paper 912430. Warrendale, PA: Society of Automotive Engineers

4. Atkinson, A.C.(1985) Plots, transformations and regression. An introduction to graphical methods of diagnostic regression analysis. Oxford: Clarendon Press

DETAILED RESULTS

Table 1 Test Fuel Inspection Data

FUEL	B140	P160	P180	A160	A180	O160	O180
Distillation (T numbers)							
IBP °C	21.2	33.5	32.7	33.2	34.1	34.6	33.9
5% Evaporated at°C	43.2	44.7	44.0	44.9	44.8	47.2	46.1
10% Evaporated at°C	51.7	52.7	52.0	52.8	52.4	55.9	53.5
20% Evaporated at°C	65.0	64.3	63.8	64.7	63.9	68.6	64.2
30% Evaporated at°C	78.6	76.9	75.6	77.5	76.7	82.0	75.5
40% Evaporated at°C	93.4	91.9	90.9	93.2	91.8	95.9	90.2
50% Evaporated at°C	104.2	108.2	107.0	109.1	108.2	107.1	105.3
60% Evaporated at°C	111.0	120.7	120.2	122.5	121.5	115.1	117.6
70% Evaporated at°C	117.2	132.5	133.1	134.5	135.4	123.5	129.4
80% Evaporated at°C	126.9	147.8	152.0	149.0	154.2	136.2	146.5
90% Evaporated at°C	144.9	164.8	175.6	160.7	172.8	156.1	169.5
FBP °C	179.5	189.6	200.9	182.4	199.9	193.8	203.7
Residue %vol	1.0	1.2	1.2	0.9	1.0	0.8	1.1
Loss %vol	2.3	2.5	2.5	2.5	2.1	2.3	2.3
Distillation (E numbers)							
% Evaporated at 70°C	23.8	24.8	25.6	25.0	25.0	21.0	25.1
% Evaporated at 80°C	30.9	35.7	33.0	32.8	32.2	28.6	33.2
% Evaporated at 90°C	37.7	41.9	39.5	38.0	38.8	35.6	39.9
% Evaporated at 100°C	45.4	48.0	45.6	44.4	44.9	43.1	46.3
% Evaporated at 110°C	58.0	55.0	52.2	50.7	51.3	53.3	53.7
% Evaporated at 120°C	73.2	64.0	59.9	58.0	59.0	65.6	62.1
% Evaporated at 130°C	82.1	71.7	66.7	66.3	66.3	75.9	70.3
% Evaporated at 140°C	87.7	78.2	74.0	73.9	72.7	81.9	76.4
% Evaporated at 150°C	92.0	84.0	79.0	80.8	78.0	86.8	81.9
% Evaporated at 160°C	95.7	90.0	83.3	89.3	83.3	91.1	86.5
% Evaporated at 170°C	97.9	95.5	87.6	96.2	88.7	94.0	90.1
% Evaporated at 180°C	100.0	98.5	92.5	99.4	93.7	96.7	93.6
Vapour Pressure kPa	65	61	62	62	62	55	61
RON	97.9	94.4	94.2	98.1	98.1	97.5	95.8
MON	89.1	86.9	86.9	87.5	87.5	87.1	86.3
Density kg/l	0.7475	0.7456	0.7451	0.7630	0.7650	0.7510	0.7480

Table 2 Test Fuel Compositional Data

			B140	P160	P180	A160	A180	O160	O180
PIONA	(% w/w)								
	iso		44.4	42.4	36.2	33.5	32.1	34.0	34.0
Paraffins	normal		6.8	7.7	7.9	7.4	7.3	6.6	8.2
	naphthenic		1.6	3.5	3.6	3.4	3.5	2.5	3.3
		Total	52.8	53.6	47.7	44.3	42.9	43.1	45.5
	iso		0.2	0.2	0.2	0.2	0.1	8.6	3.9
Olefins	normal		0.1	0.1	-	0.1	0.1	0.4	0.1
	naphthenic		-	-	-	-	-	0.4	0.3
		Total	0.3	0.3	0.2	0.3	0.2	9.4	4.3
Aromatics			45.5	38.2	38.1	51.8	55.0	41.7	42.3
> C11			1.4	* 7.9	* 14.0	Δ 3.7	Δ 1.9	# 5.8	# 7.7
GLC	(% w/w)								
Paraffins + naphthenes			53.9	63.0	60.8	44.9	45.5	** 57.8	** 59.2
Olefins			0.3	0.2	0.2	0.3	0.2	-	-
Aromatics			45.8	36.8	39.0	54.8	54.3	42.2	40.8
Sulphur	ppm		14	11	11	9	12	16	11
Benzene	% w/w		1.3	1.1	1.1	1.0	1.1	1.3	1.1
Calorific value	MJ/kg		43.3	43.9	43.6	43.1	43.1	43.5	43.5
% mass Carbon			86.9	86.8	86.5	87.5	87.5	87.0	86.9
% mass Hydrogen			13.1	13.4	13.5	12.5	12.5	13.0	13.1
Carbon:Hydrogen ratio			1:1.80	1:1.84	1:1.86	1:1.70	1:1.70	1:1.78	1:1.80
Stoichiometric air/fuel ratio (SAFR)			14.42	14.48	14.51	14.28	14.28	14.40	14.42
SAFR x Density			10.779	10.796	10.811	10.896	10.924	10.814	10.78

Notes:
- * iso paraffins
- Δ Aromatics
- \# iso olefins
- ** includes olefins

Table 3 Technical Data for Test Vehicles

VEHICLE	1	2	3	4	5	6	7	8	9	10
Capacity cm^3	1998	1392	1598	1598	1997	998	1361	1043	1597	999
Cylinders	4	4	4	4	4	4	4	4	4	4
Valves/cylinder	4	2	2	4	2	4	2	2	2	2
Compression Ratio	10.5	8.5	9.2	9.1	9.1	9.5	8.8	10.1	9.0	9.0
Rated power (kW) at rpm	110	52	55	66	87	43	55	33	59	33
Rated torque (Nm) at rpm	196/ 4600	103/ 4000	125/ 3200	135/ 4000	172/ 3500	79/ 4000	109/ 4000	76/ 2800	121/ 3500	76/ 3250
Fuel system (1)	MPI L-JET	SPI	SPI	MPI	MPI K-JET	MPI	SPI	SPI	SPI	SPI
Catalyst type (2)	3-way CL ADL	3-way CL	3-way CL	3-way CL	3-way CL	3-way CL	3-way CL	3-way CL	3-way CL	3-way CL
Canister	ALL CANISTERS DISCONNECTED									

Notes: (1) MPI = MultiPoint Injection
SPI = Single-Point Injection
K-JET = K-Jetronic
L-JET = L-Jetronic
(2) CL = Closed Loop
ADL = Adaptive Learning Ignition

Figure 1 Test Fuel Distillation Curves

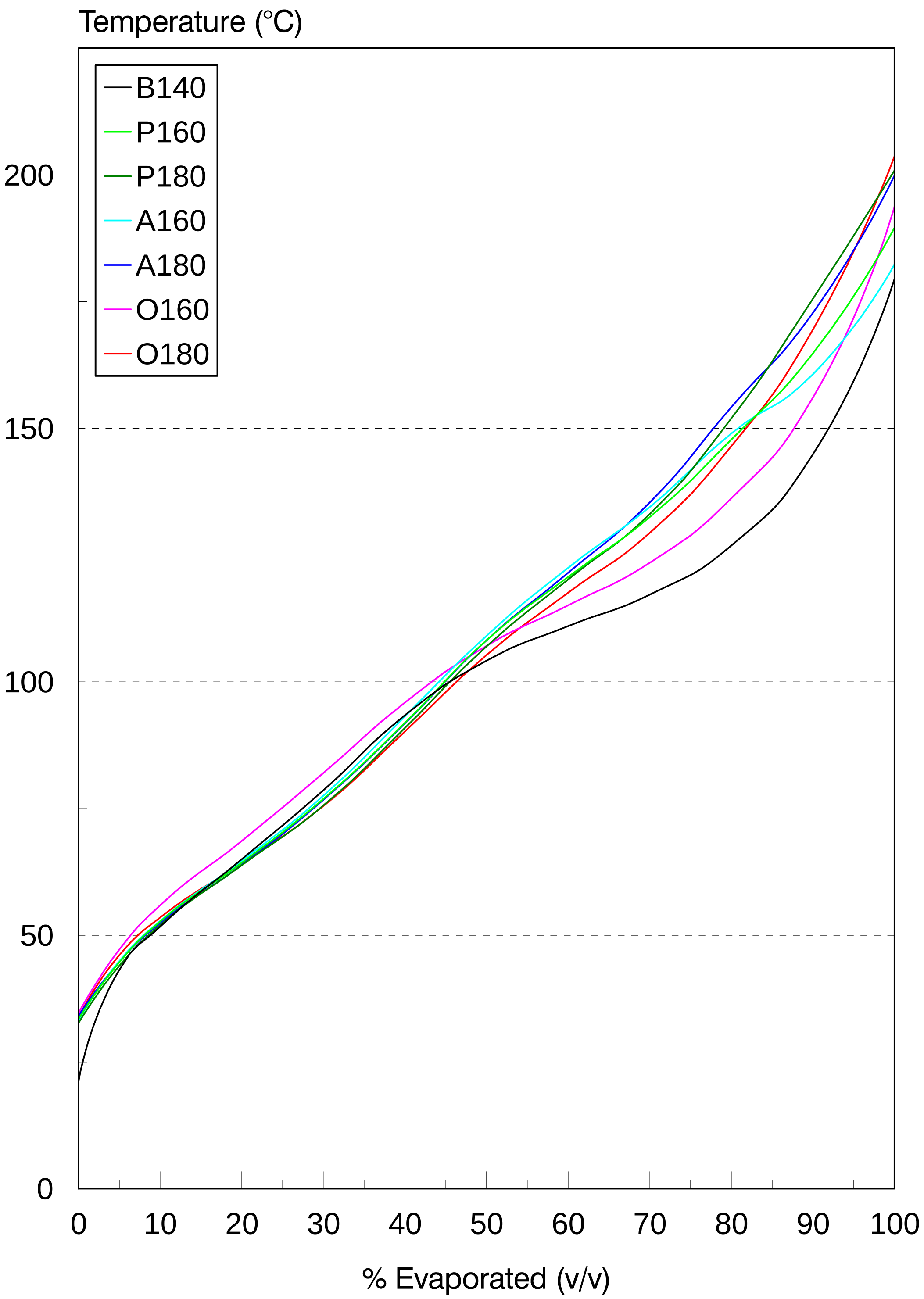
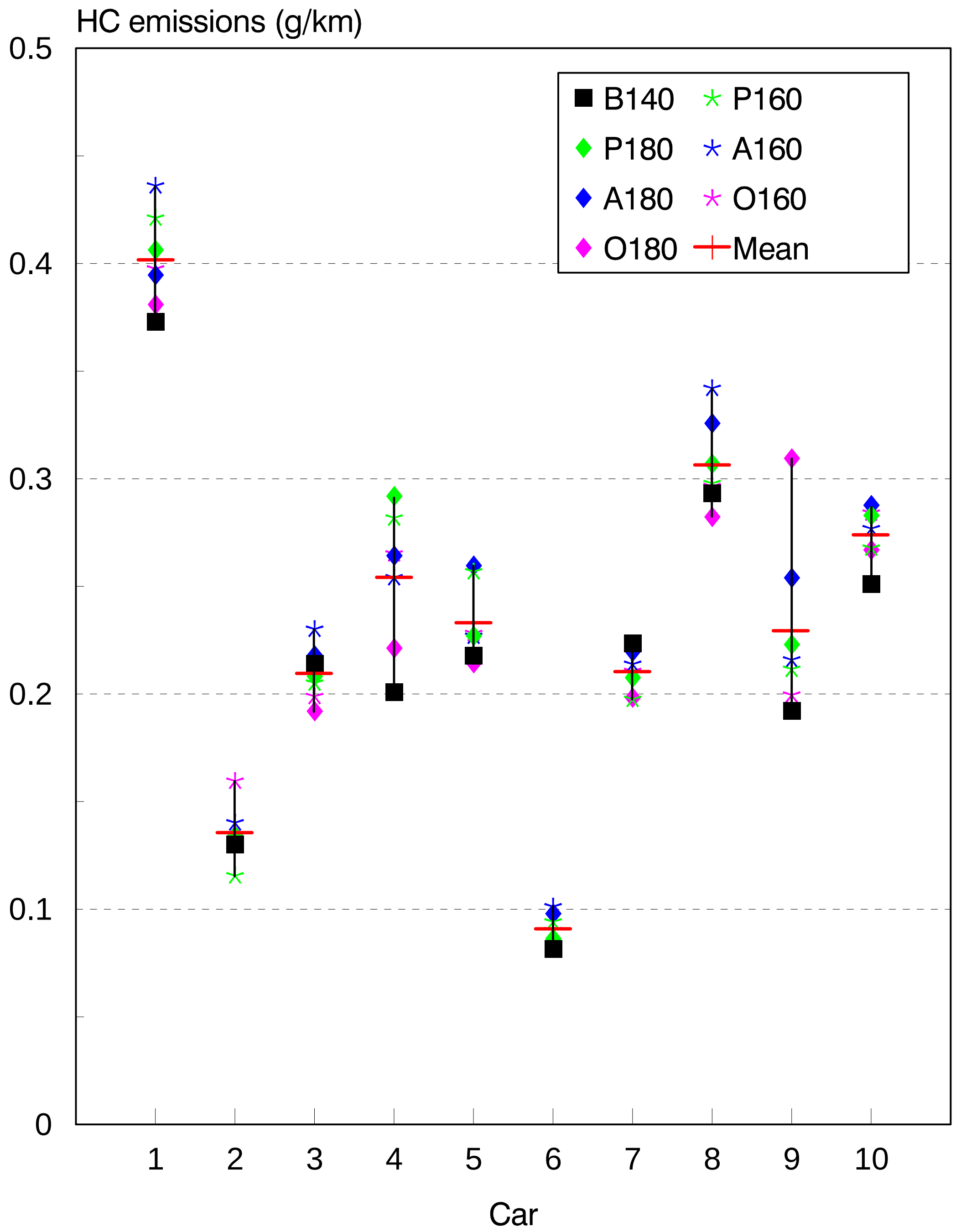
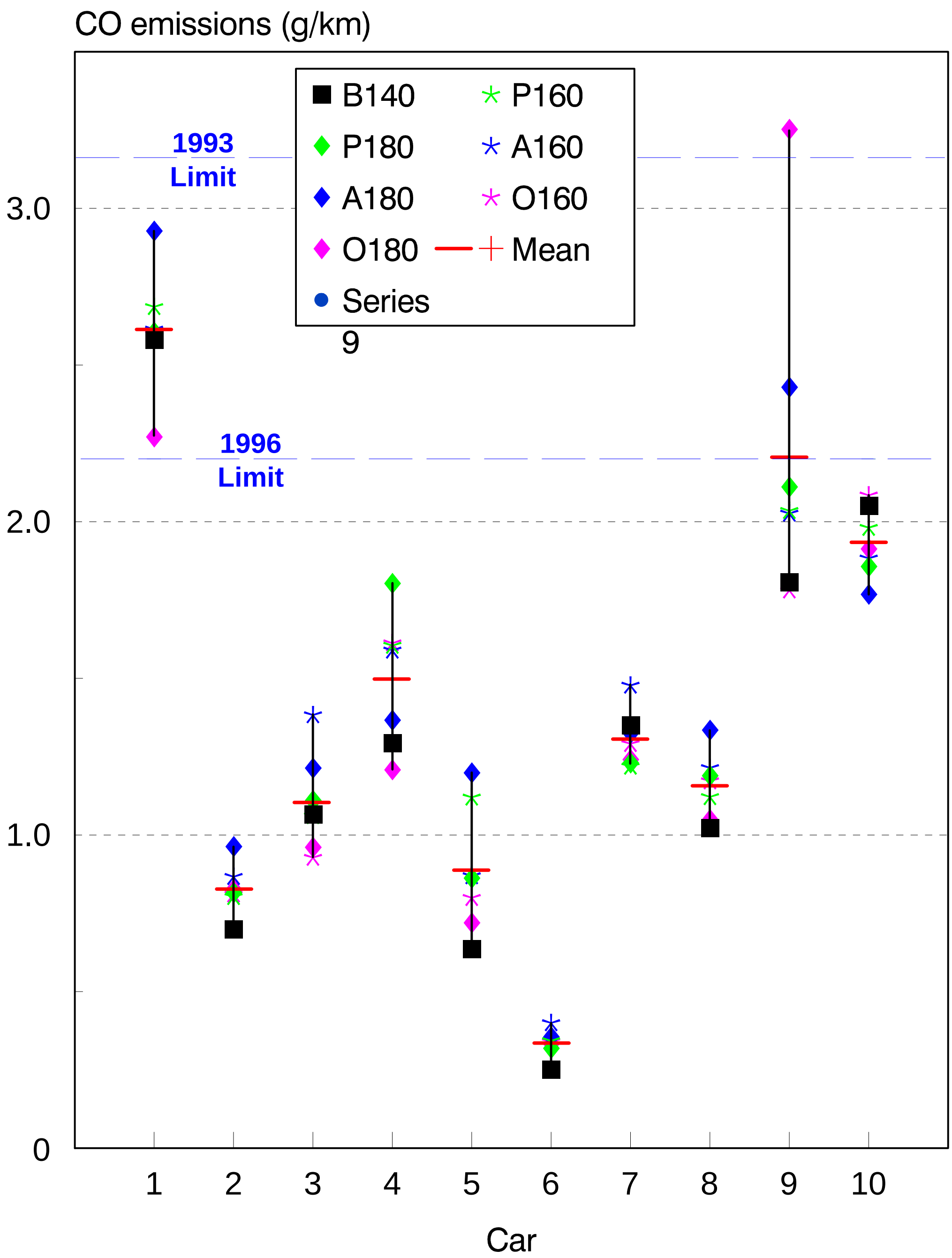


Figure 2 Total cycle HC Emissions by Fuel and by Car (Arithmetic Means)



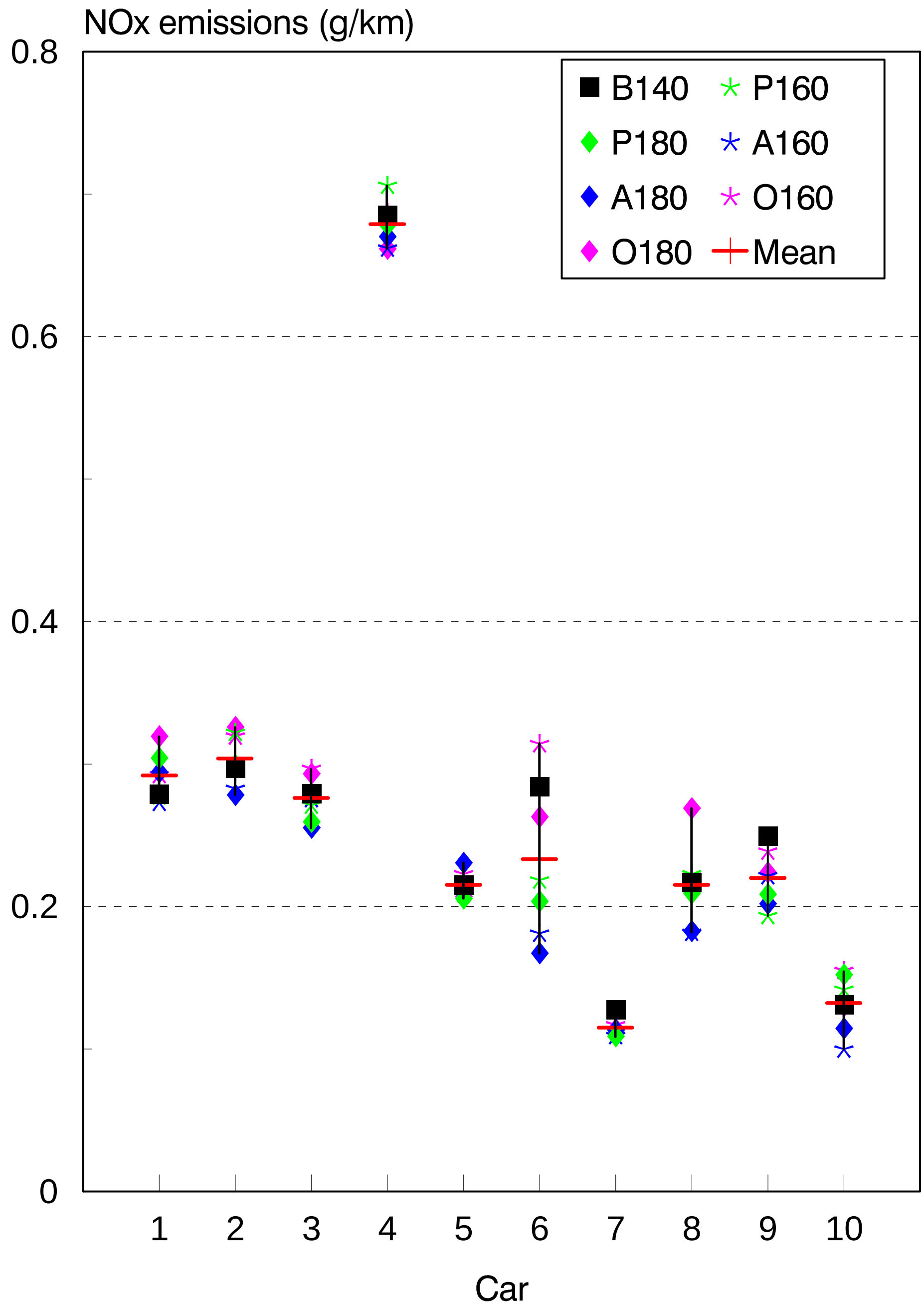
The asterisks and crosses show the emissions for each of the seven fuels in each car. The red **+** shows the mean emissions for each car over the seven fuels.

Figure 3 Total cycle CO Emissions by Fuel and by Car
Arithmetic Means)



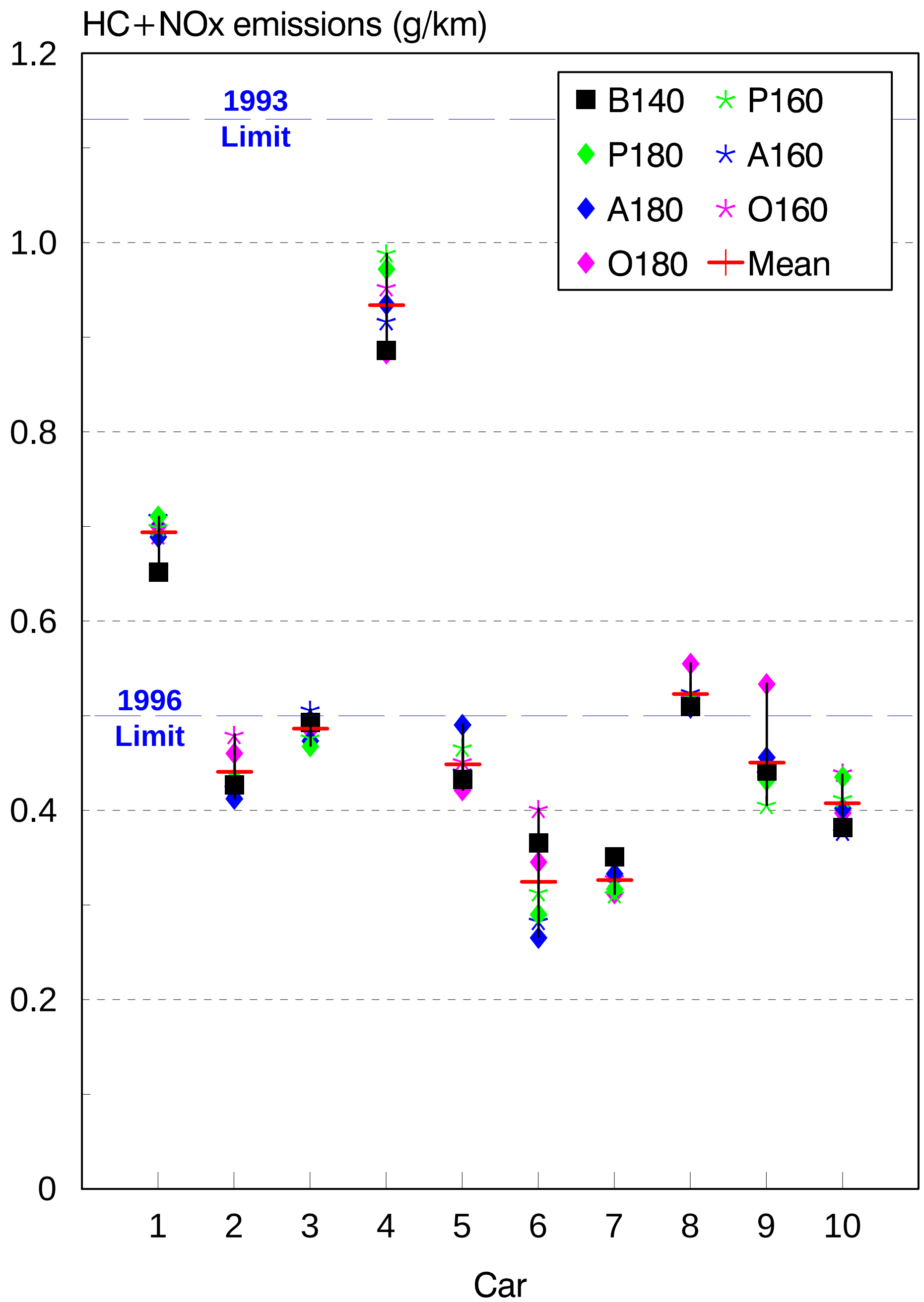
The asterisks and crosses show the emissions for each of the seven fuels in each car. The red **+** shows the mean emissions for each car over the seven fuels.

Figure 4 Total cycle NOx Emissions by Fuel and by Car
(Arithmetic Means)



The asterisks and crosses show the emissions for each of the seven fuels in each car. The red + shows the mean emissions for each car over the seven fuels.

Figure 5 Total cycle HC+NOx Emissions by Fuel and by Car (Arithmetic Means)



The asterisks and crosses show the emissions for each of the seven fuels in each car. The red + shows the mean emissions for each car over the seven fuels.

Figure 6 Total cycle HC Emissions (Ten-car Geometric Mean)

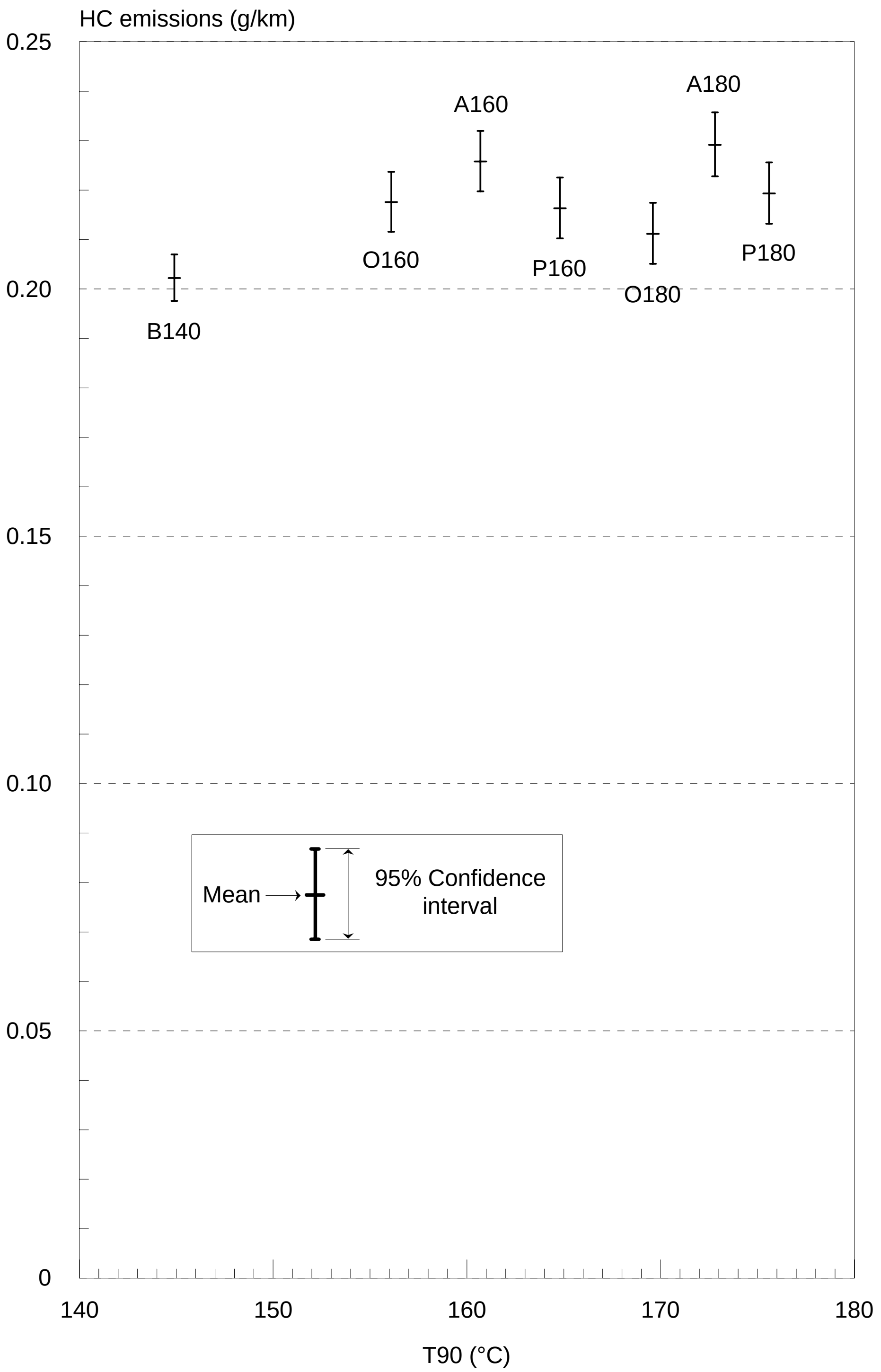


Figure 7 Total cycle HC Emissions (Ten-car Geometric Mean)

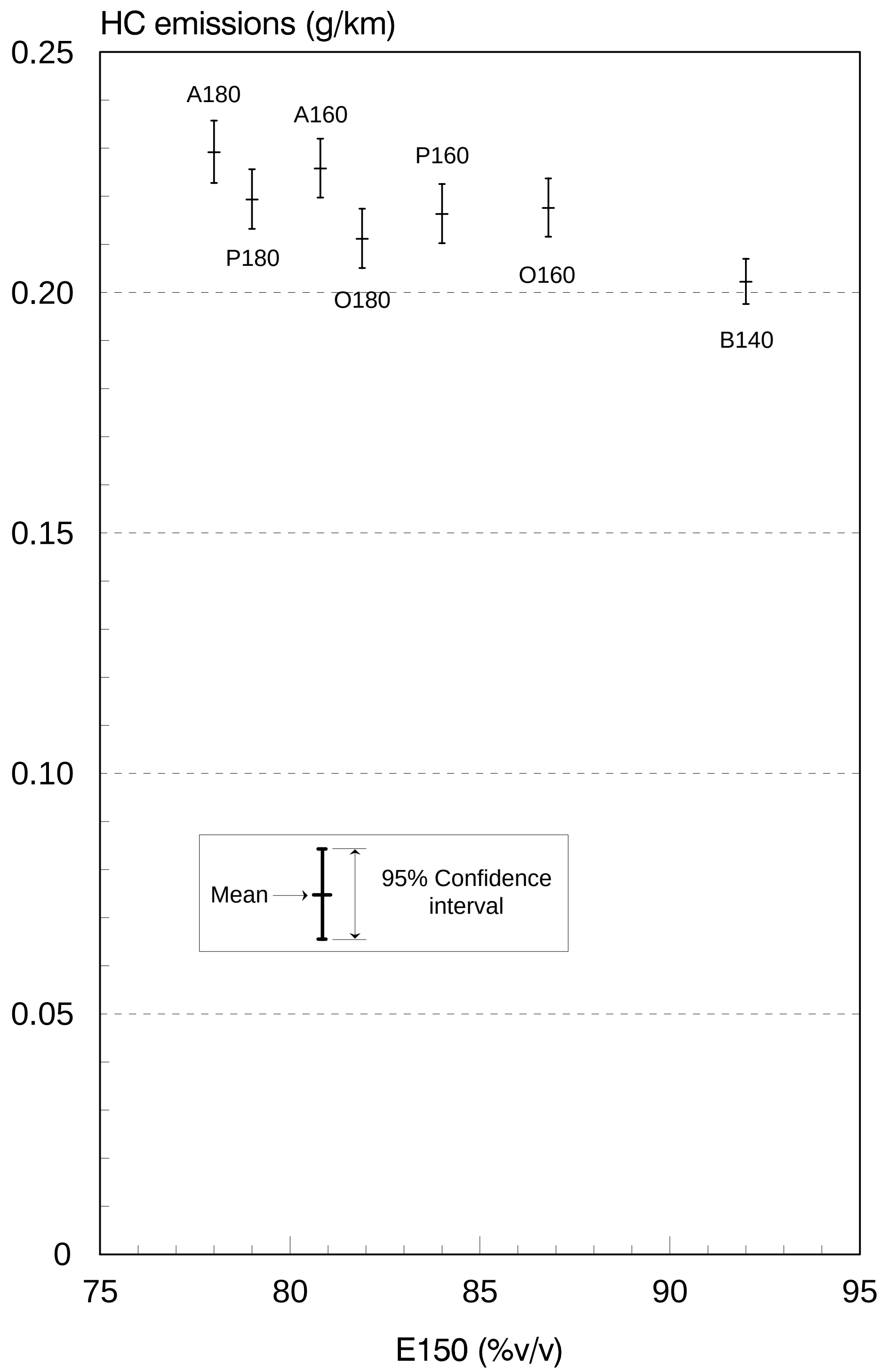


Figure 8 Total cycle CO Emissions (Ten-car Geometric Mean)

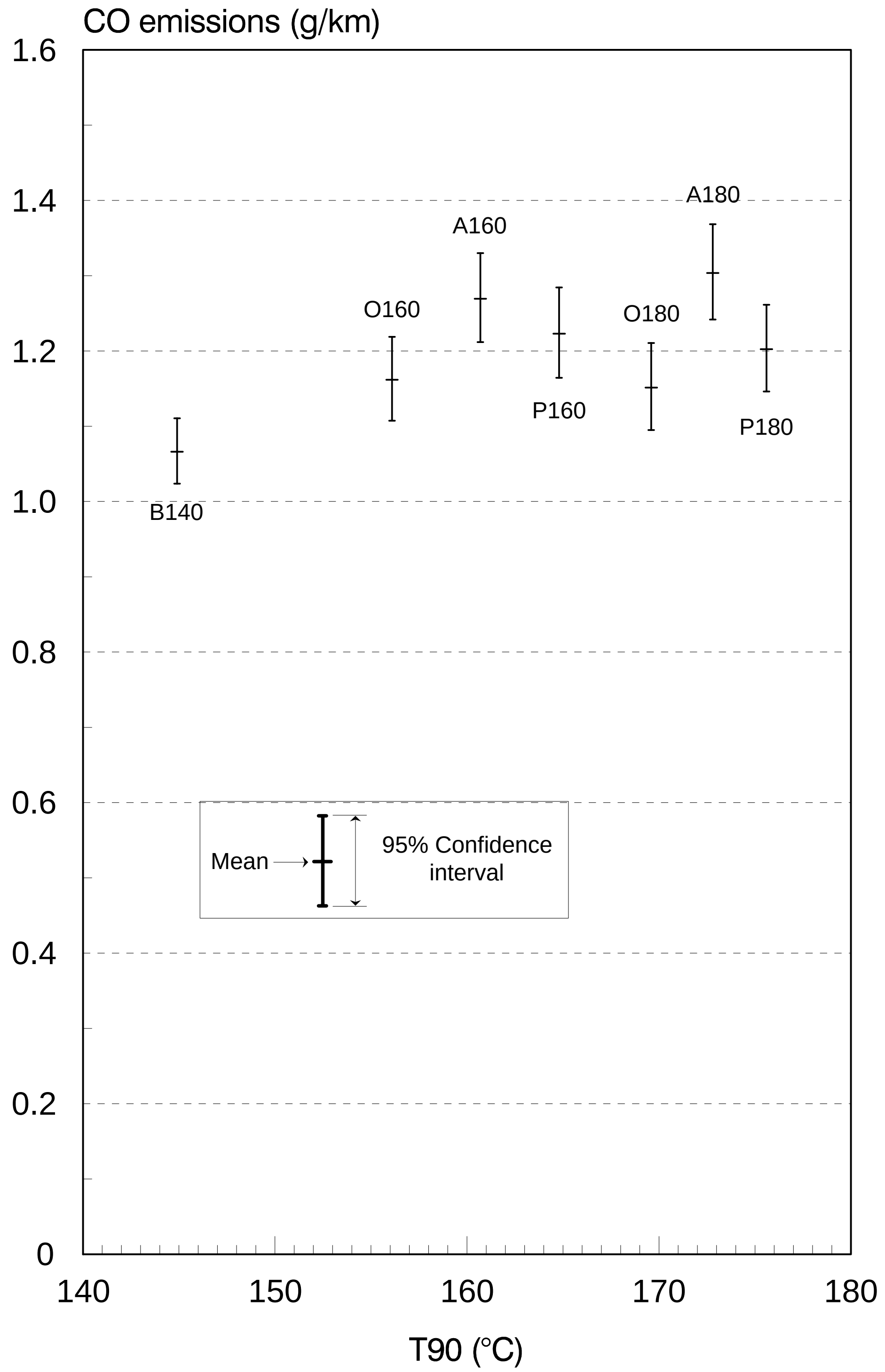


Figure 9 Total cycle CO Emissions (Ten-car Geometric Mean)

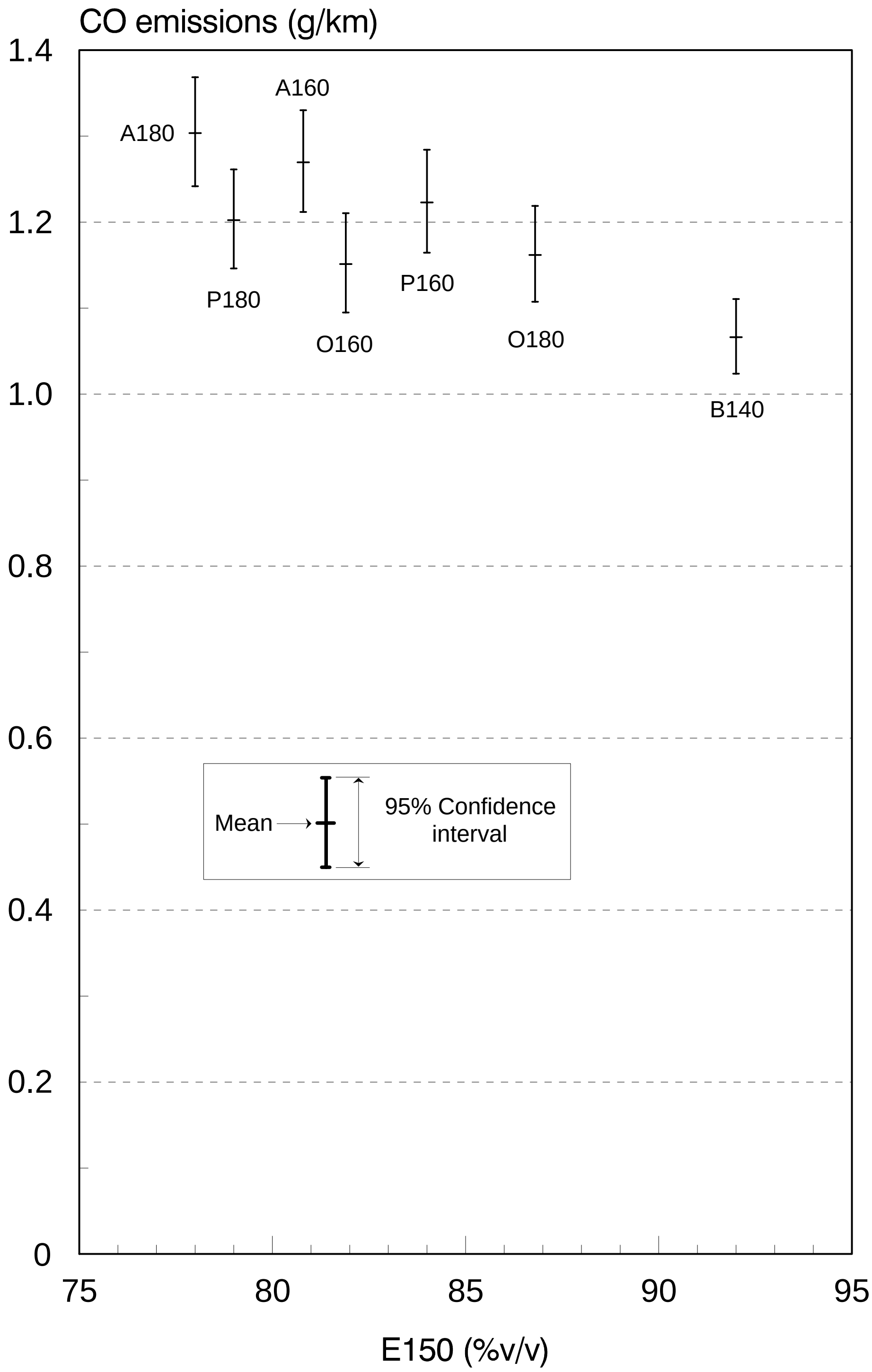


Figure 10 Total cycle NOx Emissions (Ten-car Geometric Mean)

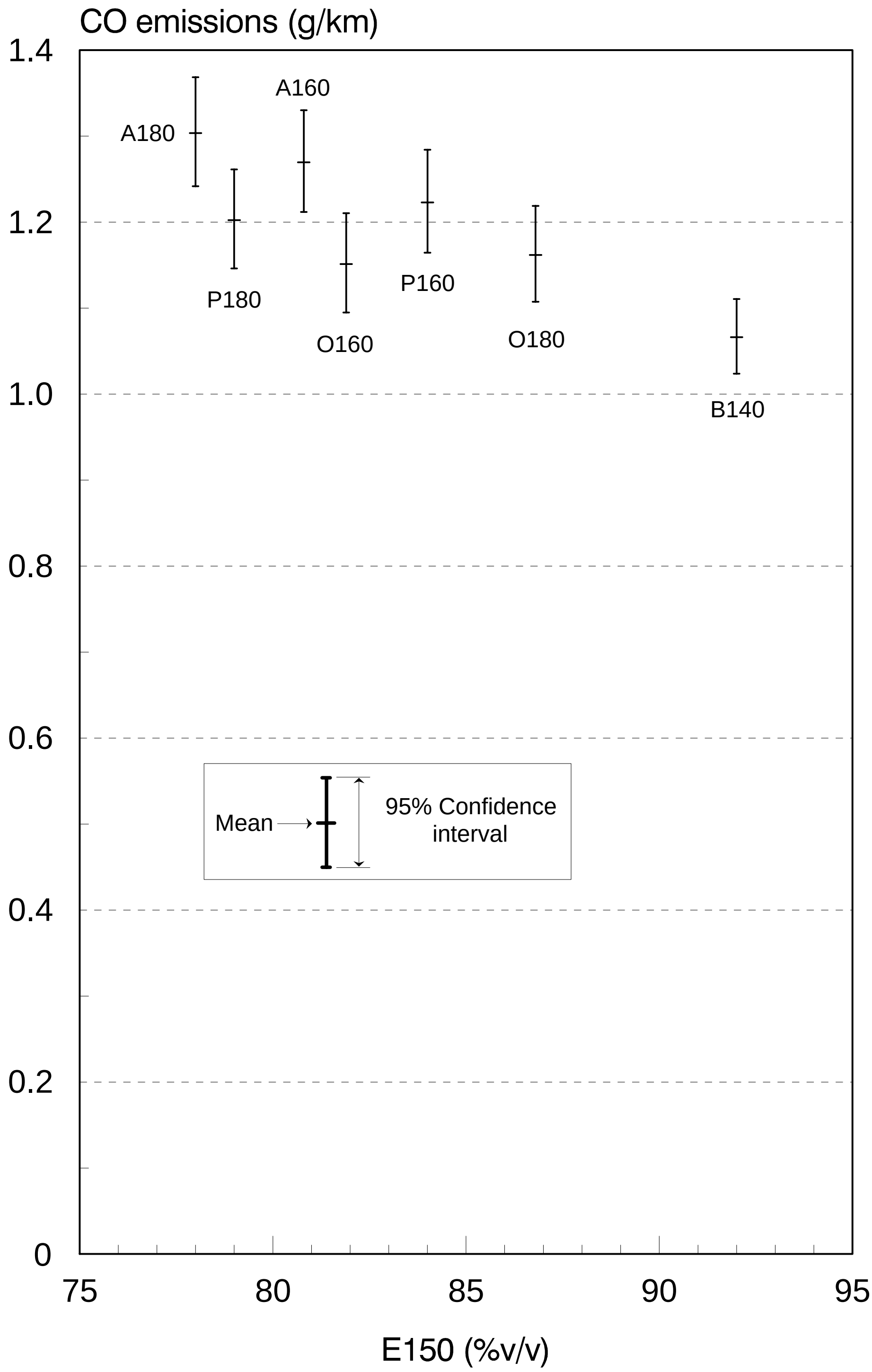


Figure 11 Total cycle NOx Emissions (Ten-car Geometric Mean)

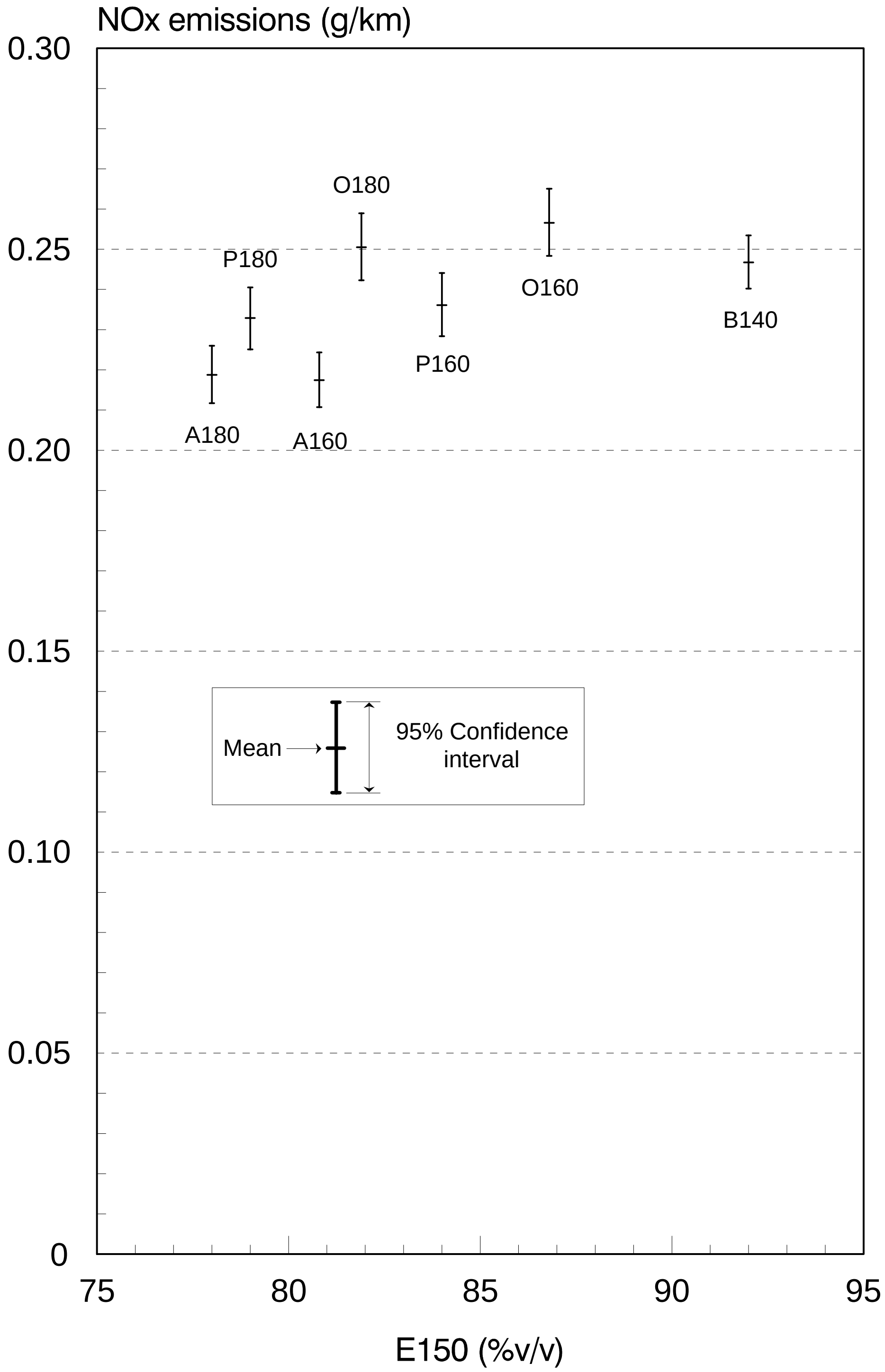
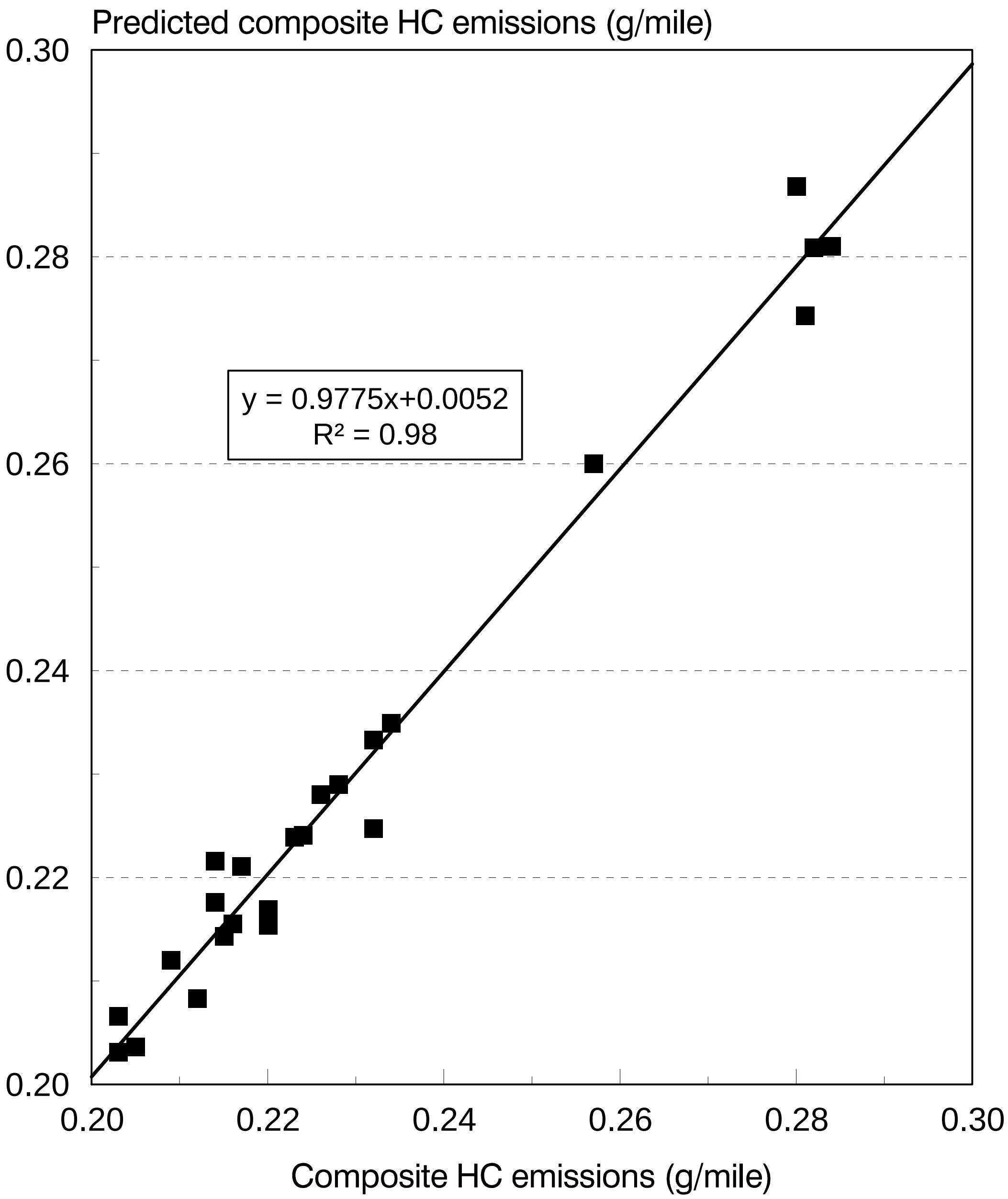


Figure 12 US Auto/oil AQIRP Phase 2 Heavy Hydrocarbon Study



AQIRP reported a regression equation for Matrices A and B:

ln(HC) = -1.576+{0.00236[(E149-E93)-41]+0.04634}exp[0.1716(100-E149-12)]+0.0255M

Baseline emissions are corrected for shift between Matrices A and B:
(M = +1 Matrix A, -1 Matrix B)

Figure 13 Total cycle HC Emissions vs. Fuel Volumetric Air Demand (Ten Car Geometric Mean)

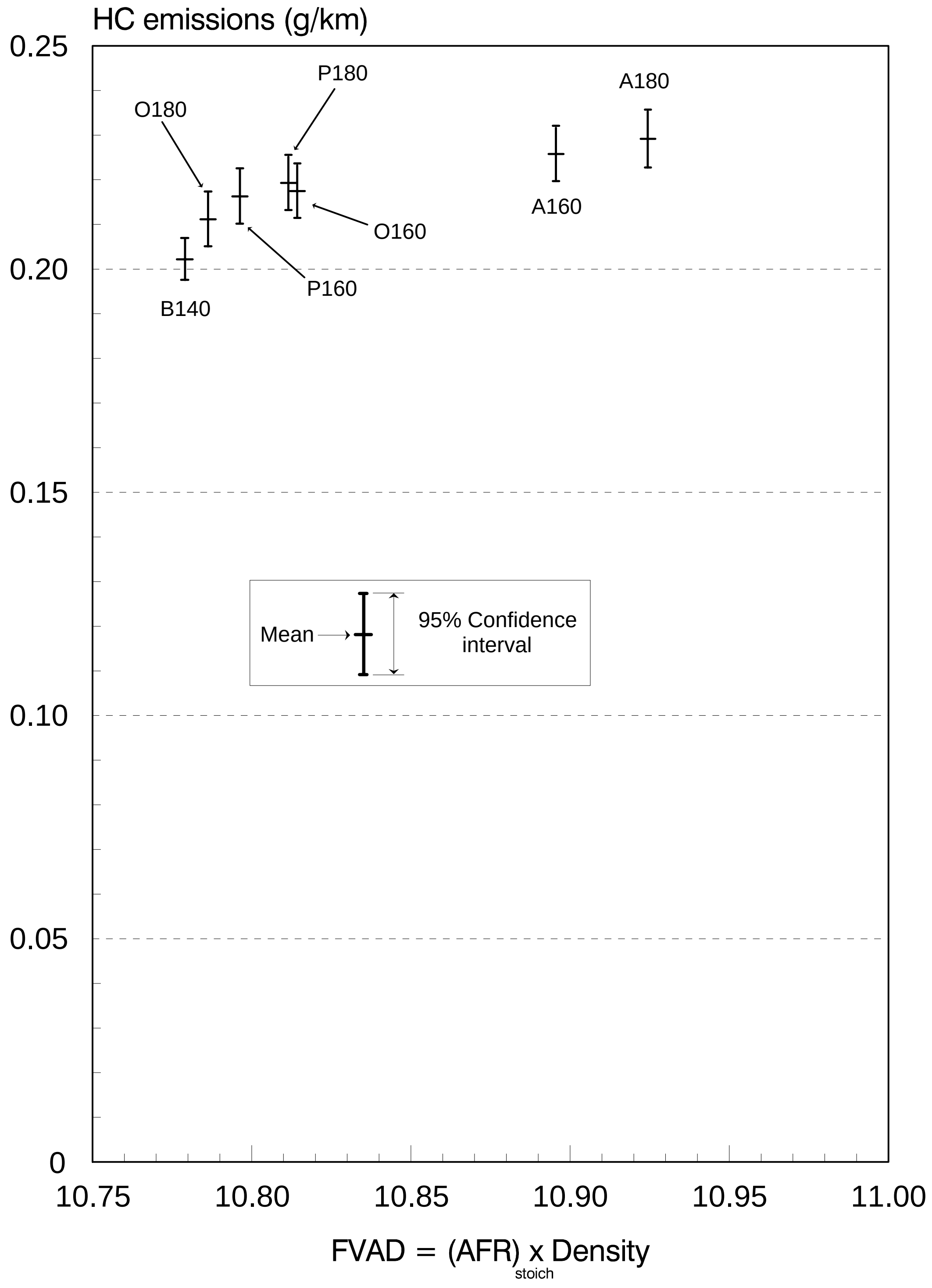


Figure 14 Total cycle CO Emissions vs. Fuel Volumetric Air Demand (Ten Car Geometric Mean)

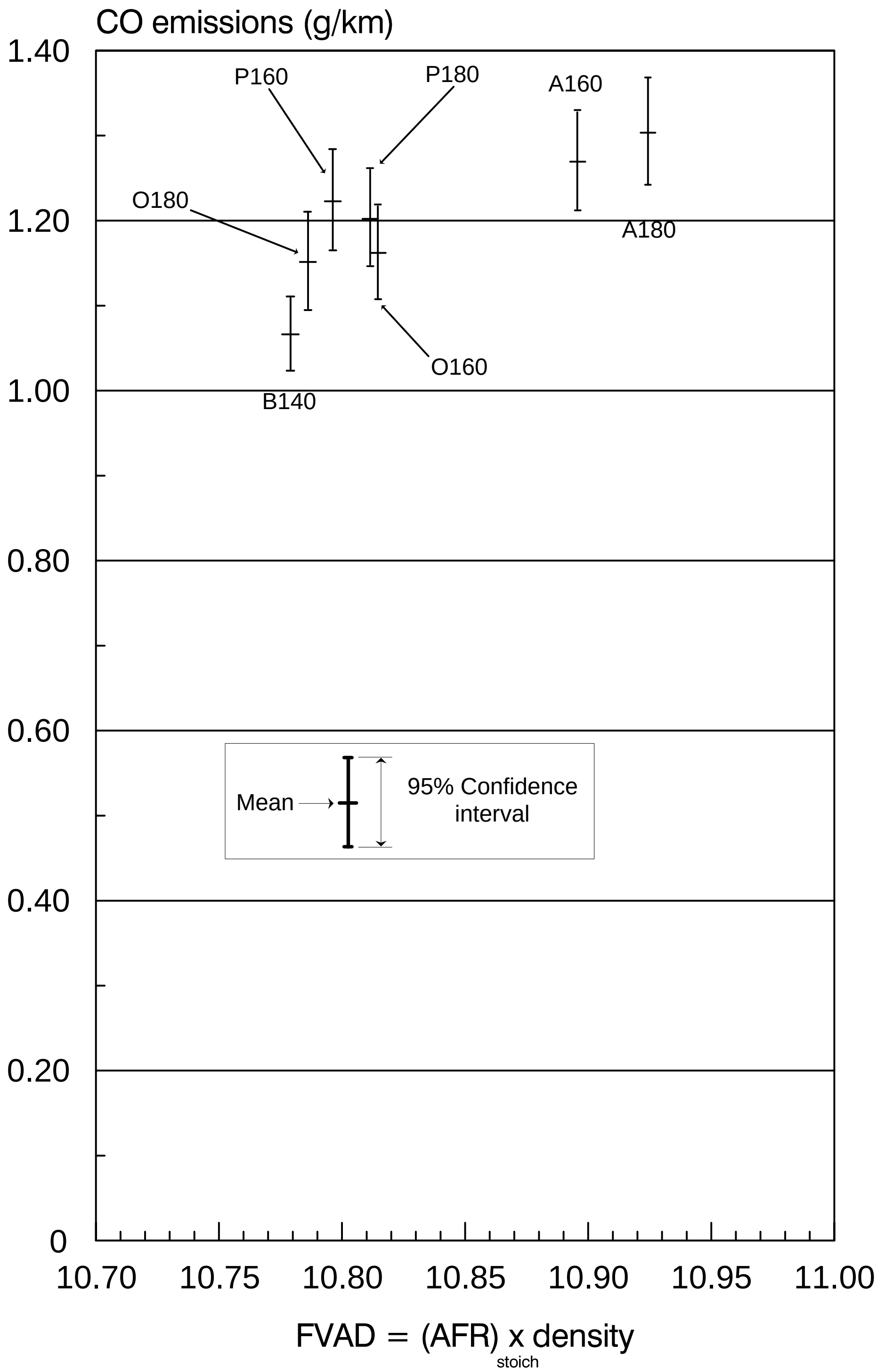


Figure 15 Total cycle NOx Emissions vs. Fuel Volumetric Air Demand (Ten Car Geometric Mean)

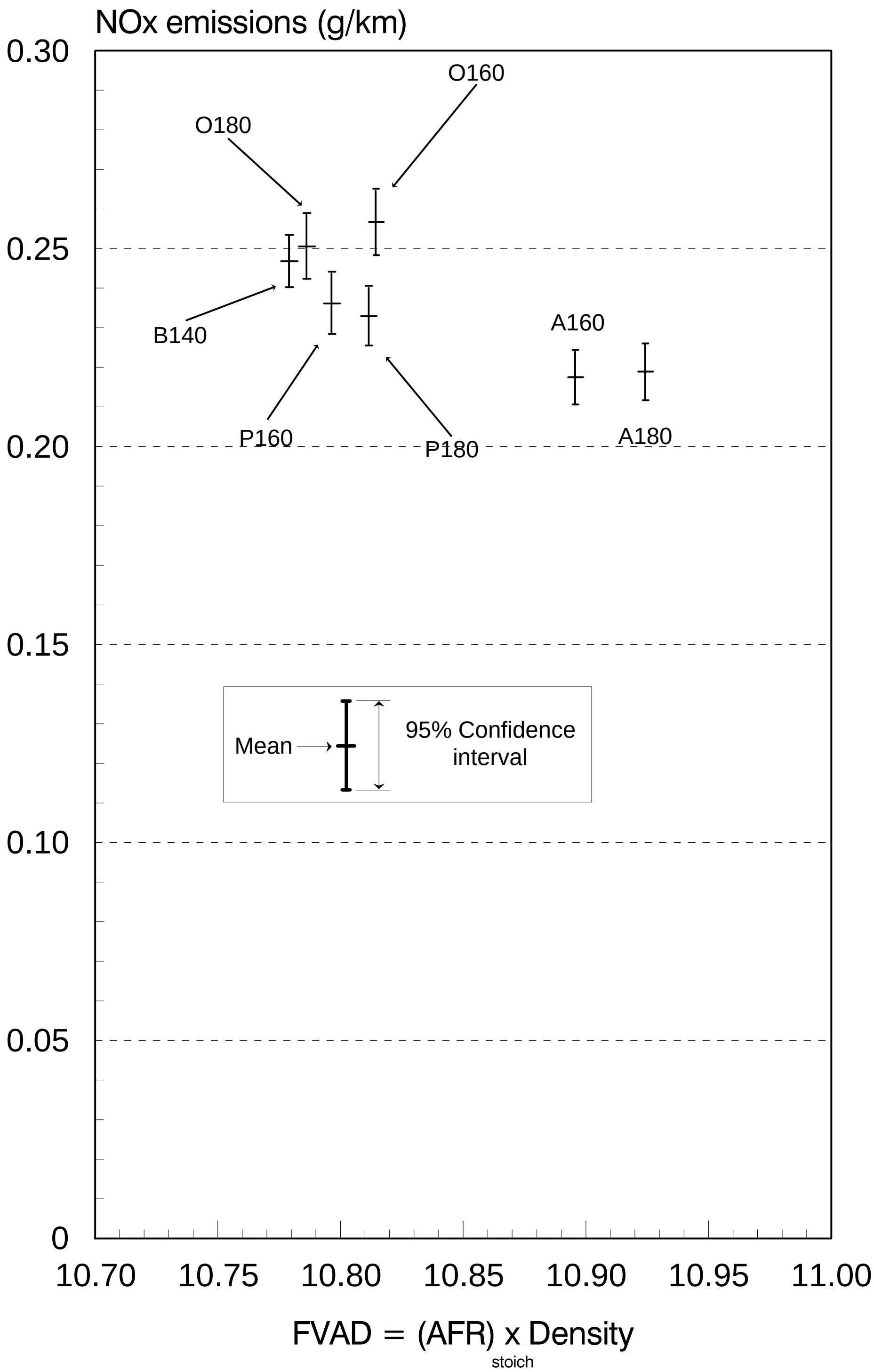
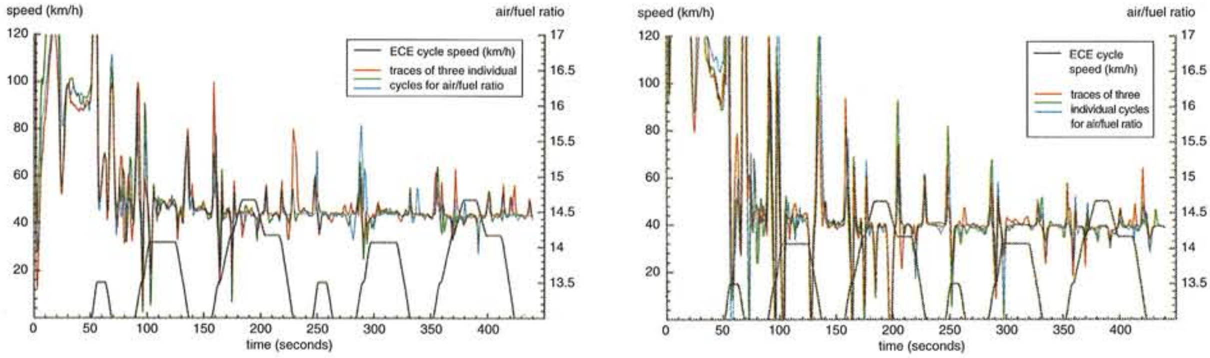
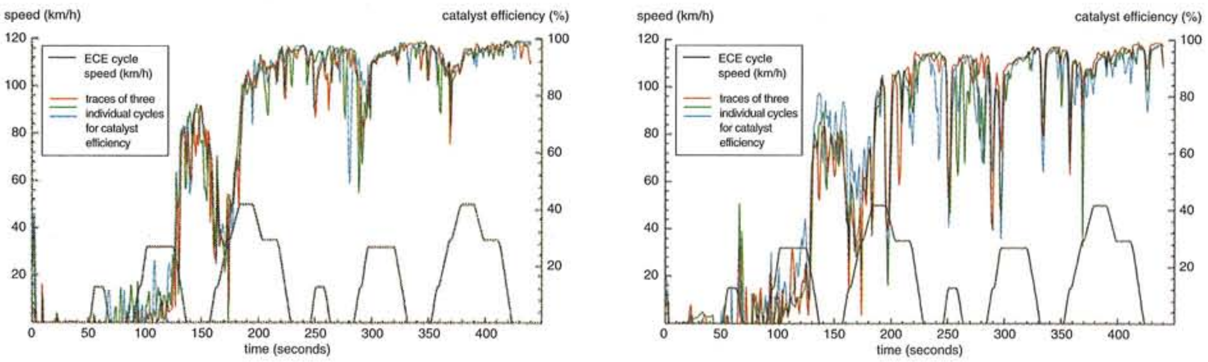


Figure 16 Air/Fuel Ratio Traces - Car 9 over ECE 1 + 2



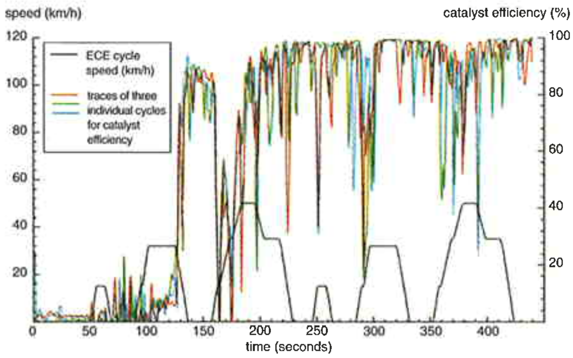
Fuel B140 **Fuel A180**

Figure 17 Catalyst HC Efficiency - Car 9 over ECE 1 + 2

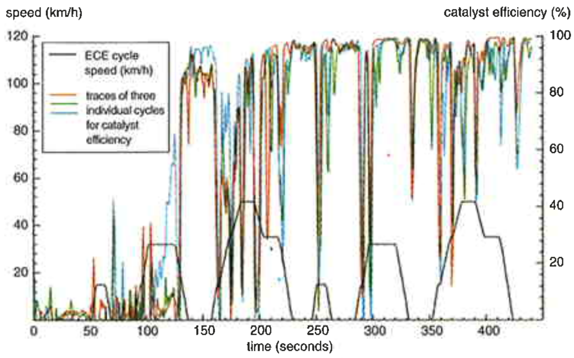


Fuel B140 **Fuel A180**

Figure 18 Catalyst CO Efficiency - Car 9 over ECE 1 + 2

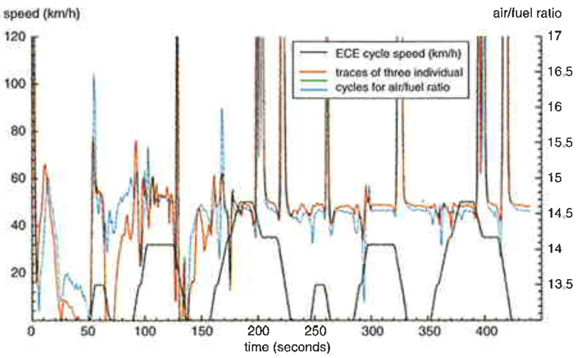


Fuel B140

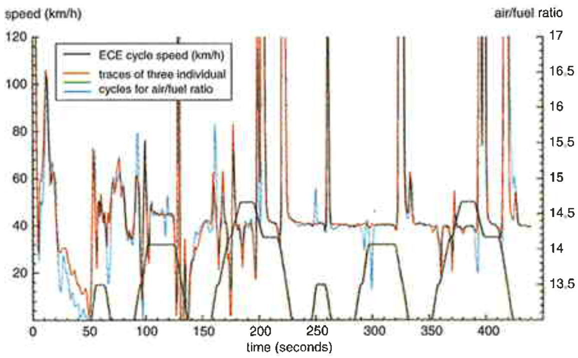


Fuel A180

Figure 19 Air/Fuel Ratio Traces - Car 7 over ECE 1 + 2

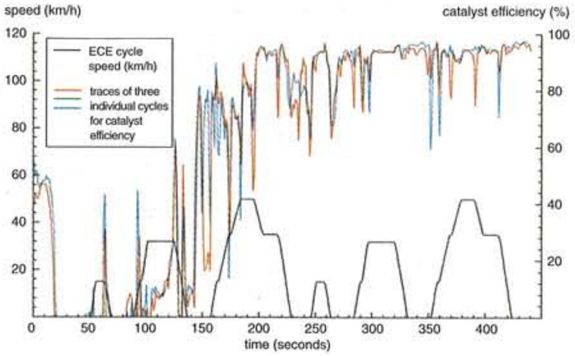


Fuel B140

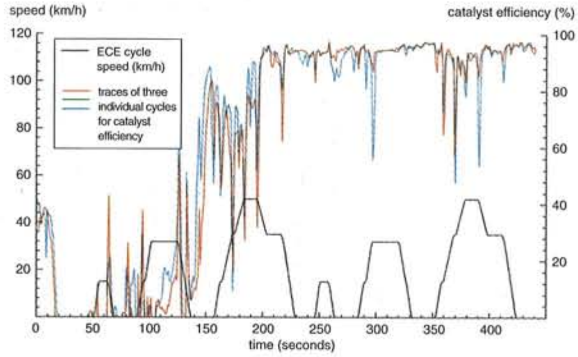


Fuel A180

Figure 20 Catalyst HC Efficiency - Car 7 over ECE 1 + 2

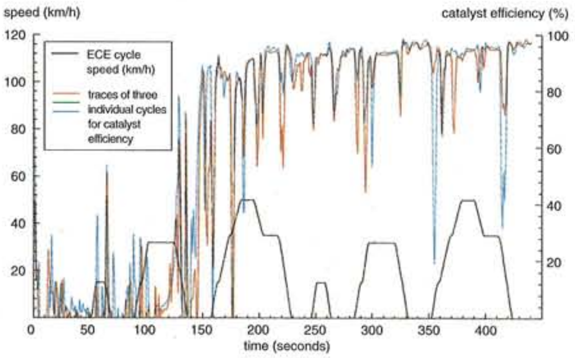


Fuel B140

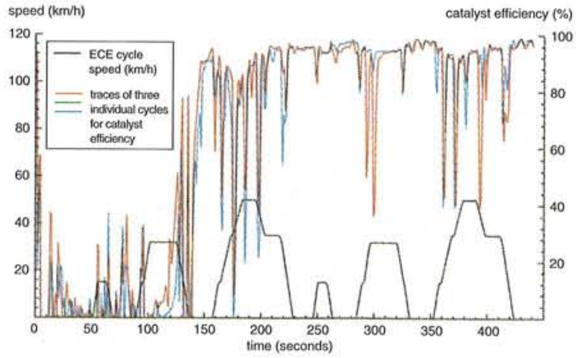


Fuel A180

Figure 21 Catalyst CO Efficiency - Car 7 over ECE 1 + 2

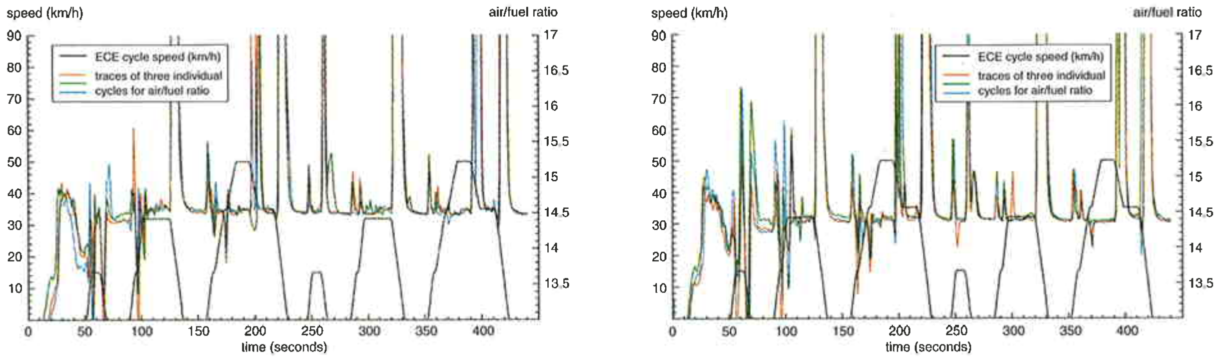


Fuel B140



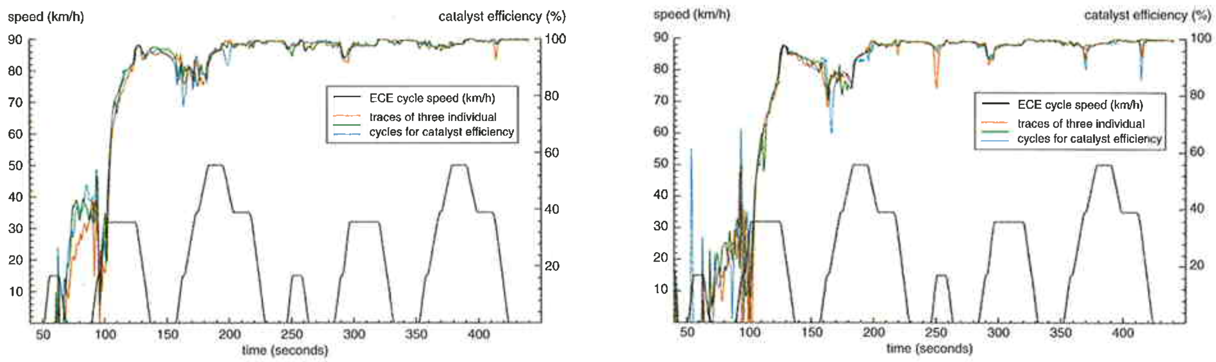
Fuel A180

Figure 22 Air/Fuel Ratio Traces - Car 6 over ECE 1 + 2



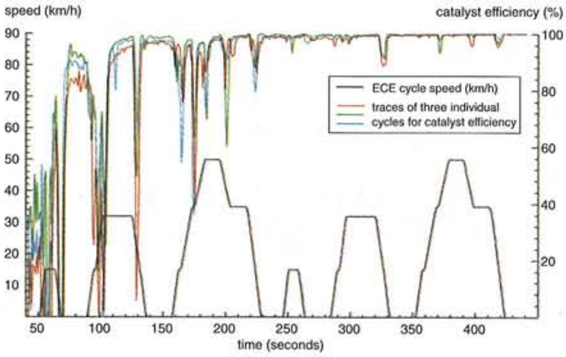
Fuel B140 **Fuel A180**

Figure 23 Catalyst HC Efficiency - Car 6 over ECE 1 + 2

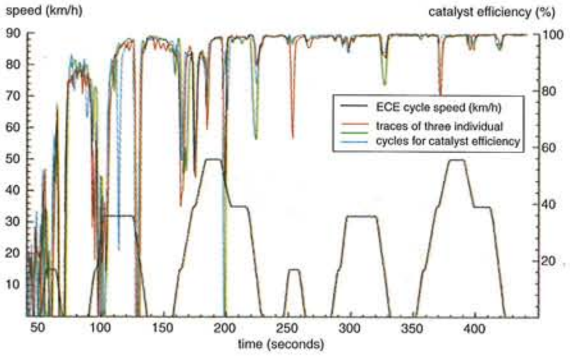


Fuel B140 **Fuel A180**

Figure 24 Catalyst CO Efficiency - Car 6 over ECE 1 + 2



Fuel B140



Fuel A180

APPENDIX 1

DESCRIPTION OF THE STATISTICAL ANALYSIS

DATA TRANSFORMS AND GEOMETRIC MEANS

The statistical 'multiple regression' technique needed to analyse the results requires all the results in a data set to be subject to the same level of random variation or 'noise'. In the present context, this means that for any particular test cycle and type of emission, similar levels of variation are required within each set of repeat measurements, there being one such set for each car x fuel combination. Raw emissions data do not meet this requirement. Measurements from high-emitting car x fuel combinations are likely to vary far more in absolute terms than measurements from low high-emitting combinations. In order to make multiple regression valid in such circumstances, it is necessary first to transform the data to stabilize the variance.

In many emissions programmes, it is sufficient to perform the analysis using log (emissions) as the response variable instead of simply emissions. As a consequence, results are more appropriately presented as tables of geometric means rather than arithmetic means.

The geometric mean of n numbers x_1, x_2,..., x_n ($x_i > 0$) is $(x_1 x_2 ... x_n)^{1/n}$ or, equivalently, the antilogarithm of the mean of $\log(x_1)$, $\log(x_2)$,..., $\log(x_n)$. In the present analysis, geometric means will give better comparisons between emissions using different fuels over a car population as emissions from each car will have equal weight in the comparison. Were arithmetic means to be used, then the conclusions would be dominated by the results from high-emitting cars. When comparing geometric mean emissions, fuel differences should be expressed in percentage terms; when comparing arithmetic mean emissions, fuel differences should be expressed in absolute terms.

Geometric means do, unfortunately have one disadvantage and that is they are 'biased'. Geometric means underestimate the absolute emission levels from a car or car population. Geometric means thus form a poor basis for estimating total emissions to the atmosphere from a car or car population and so the geometric mean emissions in the tables and bar charts associated with this report must not be used in atmospheric modelling work; arithmetic means should be used instead.

Geometric means are quoted in this report and its appendages because they provide the soundest basis for comparing fuels, which is the objective of this particular study.

For some emissions in certain cycles, it was found that the simple log transform did not give a satisfactory variance stabilisation, primarily because variations between near-zero results were grossly inflated when logarithms were taken. To overcome this problem, it was found necessary to add a small offset before taking logarithms. With the assistance of standard deviation vs. mean plots, the following transformations were finally decided upon:

	ECE 1 + 2	ECE 3 + 4	EUDC	TOTAL
HC	log (HC)	log (HC)	log (HC)	log (HC)
CO	log (CO)	log (CO + 0.05)	log (CO + 0.05)	log (CO
NOx	log (NOx)	log (NOx + 0.1)	log (NOx + 0.1)	log (NOx)
CO_2	log (CO_2)	log (CO_2)	log (CO_2)	log (CO_2)
NMHC	log (NMHC)	log (NMHC)	log (NMHC + 0.01)	log (NMHC)
FC	log (FC)	log (FC)	log (FC)	log (FC)

When an offset d is added before taking logarithms, results are presented as offset geometric means (OGMs). The offset geometric mean of *n* numbers x_1, x_2,..., x_n (x_i > -d) is computed by taking the antilog of the mean of log(x_1+d), log(x_2+d),..., log(x_n+d) and then subtracting d.

REJECTION OF OUTLIERS

Outliers are values which are so different from the remainder that it can only be concluded that they have arisen from some fault in the application of the test method or from an equipment malfunction. Limited repeat tests were carried out when the test laboratory had doubts about a particular result. All data were then submitted for statistical analysis. A list of suspicious points was identified from normal plots of residuals (see, for example, Atkinson [4]) and these were queried with the test laboratory. Those deemed to be outliers were rejected and the test repeated where possible.

CALCULATION OF TABLES OF MEANS

For each emission in each cycle, the (offset) geometric mean was calculated for each fuel over the 10 cars. These means are adjusted so that each car has equal weight irrespective of the actual number of valid measurements available on that fuel in that car. The (offset) geometric mean emissions for each car are calculated similarly with each fuel having equal weight. Also calculated are the mean emissions for paraffinic, aromatic and olefinic fuels (type P, A and O) - and the mean emissions for fuels with target T90s of 160°C and 180°C.

In this report the words '(offset) geometric mean' will be omitted for brevity and we shall refer simply to 'means' or just 'emissions'. Percentage differences between fuels will not be quoted in this report for those emissions and cycles where offset geometric means are used as the use of OGMs implies that percentage differences vary from car to car; actual OGMs will be quoted instead.

APPENDIX 2

GEOMETRIC MEAN AND OFFSET GEOMETRIC MEAN RESULTS

Table 3.1 Geometric Means - ECE 1+2 HC Emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.922	0.978	0.986	1.025	1.017	0.988	0.970

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.922	0.982	1.021	0.979

T90	140	160	180
10 CAR MEAN	0.922	0.997	0.991

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	2.010	0.601	0.928	1.142	1.049	0.428	0.838	1.382	0.981	1.294

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	1.835	2.117	2.037	2.179	1.991	2.020	1.908
CAR 2	0.580	0.521	0.581	0.634	0.574	0.738	0.597
CAR 3	0.941	0.914	0.928	1.018	0.953	0.890	0.859
CAR 4	0.971	1.238	1.207	1.169	1.227	1.144	1.065
CAR 5	0.994	1.170	1.045	1.023	1.115	1.038	0.973
CAR 6	0.390	0.443	0.415	0.474	0.463	0.426	0.393
CAR 7	0.894	0.794	0.843	0.857	0.833	0.840	0.811
CAR 8	1.368	1.349	1.388	1.527	1.440	1.336	1.280
CAR 9	0.804	0.910	0.956	0.944	1.073	0.873	1.413
CAR 10	1.200	1.270	1.352	1.304	1.337	1.341	1.260

Table 3.2 Geometric Means - ECE 1+2 CO Emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	4.505	5.323	5.138	5.418	5.440	5.004	5.032

FUEL TYPE	B	P	A	O
10 CAR MEAN	4.505	5.230	5.429	5.018

T90	140	160	180
10 CAR MEAN	4.505	5.245	5.201

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	11.941	3.233	4.098	6.527	3.920	1.445	5.495	4.853	8.101	9.673

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	11.523	12.492	12.067	12.002	13.365	12.354	10.055
CAR 2	2.532	3.385	3.111	3.443	3.654	3.324	3.314
CAR 3	3.795	3.990	4.222	5.267	4.705	3.408	3.597
CAR 4	6.004	6.814	7.486	7.025	6.072	6.765	5.708
CAR 5	2.841	5.264	4.086	3.736	5.033	3.700	3.347
CAR 6	1.170	1.525	1.417	1.683	1.460	1.433	1.480
CAR 7	5.529	5.274	5.321	6.374	5.289	5.492	5.265
CAR 8	4.484	4.784	4.966	5.094	5.574	4.917	4.261
CAR 9	6.067	7.808	7.498	7.300	8.879	6.898	14.418
CAR 10	10.353	10.042	9.431	9.561	8.455	10.533	9.492

Table 3.3 Geometric Means - ECE 1+2 NOx Emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.680	0.637	0.645	0.651	0.620	0.680	0.646

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.680	0.641	0.635	0.663

T90	140	160	180
10 CAR MEAN	0.680	0.656	0.637

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.915	0.561	1.104	1.131	0.886	0.436	0.307	0.751	0.525	0.458

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.934	0.900	0.898	0.916	0.903	0.901	0.955
CAR 2	0.556	0.570	0.554	0.571	0.481	0.657	0.550
CAR 3	1.142	1.103	1.040	1.146	1.017	1.150	1.143
CAR 4	1.058	1.177	1.133	1.126	1.108	1.186	1.131
CAR 5	0.898	0.878	0.842	0.876	0.917	0.931	0.861
CAR 6	0.487	0.430	0.449	0.384	0.370	0.481	0.465
CAR 7	0.351	0.309	0.288	0.287	0.301	0.306	0.311
CAR 8	0.776	0.708	0.718	0.781	0.735	0.766	0.778
CAR 9	0.630	0.453	0.580	0.601	0.519	0.511	0.414
CAR 10	0.451	0.443	0.472	0.446	0.442	0.488	0.467

Table 3.4 Geometric Means - ECE 1+2 CO_2 Emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	249.6	250.9	246.3	252.4	253.2	250.0	246.6

FUEL TYPE	B	P	A	O
10 CAR MEAN	249.6	248.6	252.8	248.3

T90	140	160
10 CAR MEAN	249.6	251.1

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	289.0	270.3	236.2	260.8	333.5	190.6	232.3	210.6	319.8	198.1

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	285.3	293.3	281.8	293.4	293.9	291.2	284.4
CAR 2	270.0	274.1	268.8	270.4	275.6	267.7	265.6
CAR 3	235.4	233.7	232.1	238.8	240.2	237.9	235.5
CAR 4	261.0	259.4	261.2	264.2	262.9	257.9	258.9
CAR 5	337.6	331.7	327.0	338.9	341.7	334.5	323.5
CAR 6	190.3	190.3	188.2	194.0	191.9	190.6	188.6
CAR 7	231.6	237.3	227.6	234.5	232.4	232.4	230.3
CAR 8	209.8	211.7	208.7	212.3	212.9	210.0	208.8
CAR 9	323.0	323.5	315.5	317.1	324.0	321.7	314.1
CAR 10	196.5	197.9	193.9	202.1	201.3	199.1	196.0

Table 3.5 Geometric Means - ECE 1+2 NMHC Emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.881	0.928	0.938	0.982	0.975	0.935	0.921

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.881	0.933	0.978	0.928

T90	140	160	180
10 CAR MEAN	0.881	0.948	0.944

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	1.933	0.556	0.894	1.091	0.987	0.408	0.798	1.347	0.921	1.244

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	1.767	2.027	1.959	2.101	1.918	1.938	1.838
CAR 2	0.538	0.478	0.534	0.593	0.531	0.691	0.549
CAR 3	0.907	0.880	0.891	0.983	0.922	0.857	0.826
CAR 4	0.927	1.181	1.149	1.123	1.181	1.088	1.013
CAR 5	0.947	1.108	0.987	0.973	1.060	0.927	0.921
CAR 6	0.373	0.420	0.396	0.454	0.446	0.406	0.373
CAR 7	0.854	0.752	0.802	0.815	0.797	0.798	0.771
CAR 8	1.334	1.312	1.352	1.494	1.407	1.299	1.243
CAR 9	0.756	0.851	0.899	0.894	1.016	0.818	1.309
CAR 10	1.155	1.205	1.298	1.262	1.295	1.288	1.210

Table 3.6 Geometric Means - ECE 1+2 Fuel Consumption (l/100 km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	11.098	11.345	11.115	11.086	11.103	11.152	11.053

FUEL TYPE	B	P	A	O
10 CAR MEAN	11.098	11.230	11.095	11.103

T90	140	160	180
10 CAR MEAN	11.098	11.194	11.091

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	13.334	11.763	10.429	11.653	14.538	8.237	10.335	9.462	14.259	9.213

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	13.149	13.759	13.185	13.341	13.397	13.467	13.050
CAR 2	11.724	12.085	11.824	11.592	11.805	11.695	11.625
CAR 3	10.400	10.451	10.386	10.462	10.459	10.454	10.394
CAR 4	11.624	11.785	11.884	11.638	11.519	11.559	11.566
CAR 5	14.675	14.781	14.453	14.525	14.722	14.593	14.029
CAR 6	8.221	8.347	8.230	8.266	8.156	8.251	8.191
CAR 7	10.337	10.671	10.242	10.321	10.146	10.354	10.281
CAR 8	9.401	9.611	9.472	9.404	9.435	9.431	9.478
CAR 9	14.242	14.563	14.178	13.836	14.230	14.239	14.538
CAR 10	9.103	9.364	9.143	9.234	9.138	9.342	9.169

Table 3.7 Geometric Means - ECE 3+4 HC emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.0720	0.0854	0.0835	0.0854	0.0871	0.0836	0.0746

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.0720	0.0844	0.0862	0.0790

T90	140	160	180
10 CAR MEAN	0.0720	0.0848	0.0815

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.1016	0.0660	0.0768	0.1395	0.0754	0.0243	0.1319	0.1466	0.0800	0.0632

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.1318	0.1061	0.1027	0.0981	0.0925	0.0856	0.1002
CAR 2	0.0660	0.0543	0.0729	0.0649	0.0787	0.0620	0.0656
CAR 3	0.0828	0.0790	0.0747	0.0918	0.0733	0.0704	0.0683
CAR 4	0.0643	0.2072	0.2615	0.1378	0.1247	0.2176	0.0791
CAR 5	0.0633	0.0748	0.0722	0.0733	0.1114	0.0653	0.0759
CAR 6	0.0212	0.0325	0.0203	0.0339	0.0222	0.0246	0.0193
CAR 7	0.1358	0.1293	0.1226	0.1300	0.1365	0.1479	0.1226
CAR 8	0.1175	0.1427	0.1440	0.1646	0.1713	0.1523	0.1402
CAR 9	0.0665	0.0760	0.0793	0.0802	0.0967	0.0773	0.0870
CAR 10	0.0565	0.0638	0.0551	0.0598	0.0674	0.0734	0.0681

Table 3.8 Offset Geometric Means - ECE 3+4 CO emissions (g/km)
Note: Offset = 0.05

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.407	0.415	0.424	0.464	0.529	0.436	0.428

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.407	0.419	0.496	0.432

T90	140	160	180
10 CAR MEAN	0.407	0.438	0.458

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	1.301	0.581	0.517	0.937	0.109	0.034	0.681	0.828	0.772	0.197

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	1.896	1.376	1.168	1.148	1.373	0.982	1.333
CAR 2	0.633	0.360	0.592	0.655	0.774	0.563	0.574
CAR 3	0.554	0.549	0.468	0.735	0.541	0.388	0.442
CAR 4	0.579	1.141	1.444	1.040	0.867	1.361	0.527
CAR 5	0.072	0.081	0.101	0.098	0.386	0.066	0.097
CAR 6	0.012	0.043	0.019	0.064	0.028	0.063	0.022
CAR 7	0.840	0.611	0.569	0.621	0.640	0.767	0.760
CAR 8	0.659	0.785	0.839	0.809	1.004	0.849	0.891
CAR 9	0.714	0.665	0.764	0.828	0.836	0.675	0.958
CAR 10	0.163	0.183	0.154	0.158	0.255	0.223	0.267

Table 3.9 Offset Geometric Means - ECE 3+4 NOx emissions (g/km)
Note: Offset = 0.1

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.157	0.179	0.172	0.157	0.169	0.179	0.175

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.157	0.175	0.163	0.177

T90	140	160	180
10 CAR MEAN	0.157	0.172	0.172

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.131	0.275	0.219	0.444	0.137	0.385	0.070	0.091	0.163	0.038

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.070	0.141	0.135	0.128	0.187	0.131	0.140
CAR 2	0.267	0.306	0.266	0.286	0.258	0.254	0.294
CAR 3	0.205	0.203	0.196	0.191	0.210	0.269	0.274
CAR 4	0.406	0.482	0.460	0.432	0.454	0.462	0.414
CAR 5	0.108	0.133	0.141	0.153	0.170	0.141	0.119
CAR 6	0.447	0.401	0.395	0.282	0.300	0.475	0.429
CAR 7	0.079	0.068	0.068	0.067	0.061	0.072	0.073
CAR 8	0.081	0.096	0.104	0.069	0.100	0.084	0.108
CAR 9	0.156	0.183	0.135	0.177	0.142	0.191	0.161
CAR 10	0.038	0.052	0.063	0.025	0.035	0.033	0.027

Table 3.10 Geometric Means - ECE 3+4 CO_2 emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	218.5	219.3	215.9	221.4	221.3	218.5	216.5

FUEL TYPE	B	P	A	O
10 CAR MEAN	218.5	217.6	221.3	217.5

T90	140	160	180
10 CAR MEAN	218.5	219.8	217.9

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	267.0	223.2	208.1	231.3	286.5	167.9	191.1	184.7	280.1	184.0

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	263.8	268.2	261.4	270.1	273.1	268.6	264.3
CAR 2	222.7	226.0	218.9	225.5	225.0	224.0	220.0
CAR 3	207.1	206.1	205.2	211.1	211.7	208.3	207.4
CAR 4	230.9	230.0	232.3	235.1	232.7	227.4	230.7
CAR 5	288.2	287.3	283.1	289.6	291.1	286.9	279.4
CAR 6	167.9	167.5	165.8	170.8	169.1	167.7	166.7
CAR 7	192.0	193.6	188.0	192.3	192.8	190.1	188.8
CAR 8	184.7	185.2	182.5	186.3	186.8	183.7	183.7
CAR 9	281.7	282.7	276.2	281.6	282.6	281.3	274.7
CAR 10	182.2	183.9	181.6	187.4	185.8	184.5	183.1

Table 3.11 Geometric Means - ECE 3+4 NMHC emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.0496	0.0604	0.0592	0.0634	0.0655	0.0584	0.0509

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.0496	0.0598	0.0645	0.0545

T90	140	160	180
10 CAR MEAN	0.0496	0.0607	0.0582

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.0771	0.0387	0.0599	0.1081	0.0515	0.0137	0.1132	0.1256	0.0471	0.0468

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.1051	0.0807	0.0769	0.0751	0.0718	0.0619	0.0742
CAR 2	0.0385	0.0290	0.0443	0.0395	0.0523	0.0353	0.0364
CAR 3	0.0663	0.0625	0.0584	0.0750	0.0575	0.0527	0.0503
CAR 4	0.0411	0.1732	0.2239	0.1102	0.1005	0.1805	0.0541
CAR 5	0.0426	0.0506	0.0471	0.0523	0.0849	0.0423	0.0506
CAR 6	0.0111	0.0201	0.0107	0.0223	0.0130	0.0140	0.0093
CAR 7	0.1161	0.1107	0.1050	0.1124	0.1179	0.1274	0.1046
CAR 8	0.0992	0.1214	0.1215	0.1445	0.1505	0.1301	0.1190
CAR 9	0.0369	0.0412	0.0472	0.0505	0.0649	0.0410	0.0529
CAR 10	0.0405	0.0456	0.0395	0.0451	0.0525	0.0554	0.0514

Table 3.12 Geometric Means - ECE 3+4 Fuel Consumption (l/100 km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	9.336	9.494	9.324	9.289	9.280	9.333	9.272

FUEL TYPE	B	P	A	O
10 CAR MEAN	9.336	9.409	9.285	9.302

T90	140	160	180
10 CAR MEAN	9.336	9.372	9.292

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	11.451	9.514	8.874	9.897	12.152	7.129	8.168	7.912	11.947	7.829

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	11.359	11.768	11.315	11.359	11.485	11.484	11.391
CAR 2	9.519	9.753	9.447	9.462	9.439	9.558	9.424
CAR 3	8.852	8.912	8.852	8.869	8.870	8.882	8.880
CAR 4	9.864	9.994	10.104	9.894	9.772	9.779	9.879
CAR 5	12.263	12.371	12.168	12.097	12.174	12.197	11.804
CAR 6	7.140	7.211	7.121	7.135	7.053	7.130	7.112
CAR 7	8.236	8.383	8.124	8.082	8.095	8.147	8.115
CAR 8	7.912	8.036	7.930	7.856	7.877	7.867	7.910
CAR 9	12.029	12.212	11.916	11.815	11.846	12.001	11.815
CAR 10	7.764	7.928	7.813	7.835	7.770	7.861	7.831

Table 3.13 Geometric Means - EUDC HC emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.0203	0.0222	0.0233	0.0234	0.0286	0.0218	0.0213

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.0203	0.0227	0.0258	0.0215

T90	140	160	180
10 CAR MEAN	0.0203	0.0224	0.0242

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.0126	0.0168	0.0360	0.0203	0.0363	0.0065	0.0480	0.0209	0.0464	0.0229

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.0118	0.0116	0.0147	0.0115	0.0133	0.0123	0.0134
CAR 2	0.0148	0.0149	0.0192	0.0162	0.0196	0.0157	0.0176
CAR 3	0.0374	0.0334	0.0340	0.0379	0.0439	0.0335	0.0333
CAR 4	0.0151	0.0232	0.0253	0.0195	0.0233	0.0223	0.0156
CAR 5	0.0339	0.0407	0.0300	0.0371	0.0487	0.0359	0.0306
CAR 6	0.0054	0.0063	0.0056	0.0072	0.0087	0.0067	0.0059
CAR 7	0.0509	0.0431	0.0469	0.0488	0.0646	0.0442	0.0409
CAR 8	0.0159	0.0199	0.0213	0.0248	0.0283	0.0196	0.0191
CAR 9	0.0487	0.0452	0.0488	0.0412	0.0592	0.0370	0.0480
CAR 10	0.0166	0.0212	0.0236	0.0265	0.0297	0.0220	0.0228

Table 3.14 Offset Geometric Means - EUDC CO emissions (g/km)
Note: Offset = 0.05

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.152	0.170	0.184	0.194	0.236	0.163	0.156

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.152	0.177	0.214	0.160

T90	140	160	180
10 CAR MEAN	0.152	0.176	0.190

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.190	0.174	0.332	0.148	0.176	0.078	0.239	0.090	0.777	0.047

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.117	0.149	0.228	0.195	0.274	0.199	0.200
CAR 2	0.164	0.173	0.203	0.167	0.221	0.138	0.163
CAR 3	0.340	0.316	0.311	0.348	0.339	0.335	0.336
CAR 4	0.115	0.210	0.196	0.155	0.131	0.174	0.084
CAR 5	0.143	0.202	0.129	0.233	0.294	0.153	0.123
CAR 6	0.042	0.071	0.073	0.110	0.115	0.075	0.076
CAR 7	0.250	0.201	0.224	0.281	0.361	0.193	0.196
CAR 8	0.064	0.087	0.091	0.091	0.125	0.091	0.087
CAR 9	0.864	0.725	0.911	0.828	0.991	0.597	0.609
CAR 10	0.041	0.029	0.047	0.042	0.089	0.037	0.053

Table 3.15 Offset Geometric Means - EUDC NOx emissions (g/km)
Note: Offset = 0.1

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.132	0.125	0.120	0.099	0.103	0.142	0.144

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.132	0.122	0.101	0.143

T90	140	160	180
10 CAR MEAN	0.132	0.121	0.122

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.152	0.234	0.047	0.613	0.039	0.114	0.071	0.081	0.142	0.053

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.144	0.133	0.177	0.127	0.146	0.158	0.184
CAR 2	0.229	0.255	0.233	0.197	0.222	0.236	0.268
CAR 3	0.047	0.047	0.045	0.042	0.045	0.053	0.051
CAR 4	0.654	0.634	0.609	0.592	0.602	0.606	0.596
CAR 5	0.043	0.034	0.036	0.035	0.046	0.039	0.038
CAR 6	0.166	0.098	0.067	0.087	0.063	0.212	0.149
CAR 7	0.075	0.069	0.068	0.069	0.074	0.074	0.069
CAR 8	0.083	0.113	0.081	0.031	0.038	0.090	0.161
CAR 9	0.162	0.119	0.120	0.124	0.124	0.171	0.186
CAR 10	0.057	0.077	0.081	0.016	0.015	0.087	0.058

Table 3.16 Geometric Means - EUDC CO_2 emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	142.2	142.4	140.9	143.7	144.1	142.3	140.7

FUEL TYPE	B	P	A	O
10 CAR MEAN	**142.2**	141.7	143.9	141.5

T90	140	160	180
10 CAR MEAN	142.2	142.8	141.9

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	158.6	145.4	127.2	155.9	174.5	123.1	127.8	126.6	184.3	116.2

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	158.4	159.7	156.0	160.0	161.1	159.2	156.2
CAR 2	145.3	147.1	143.0	147.0	146.7	145.4	143.7
CAR 3	126.2	127.3	125.3	128.5	129.3	128.0	126.0
CAR 4	155.3	154.2	156.7	157.9	158.0	153.7	155.8
CAR 5	175.5	175.3	172.4	176.2	175.7	174.9	171.9
CAR 6	123.5	122.0	122.4	124.9	124.3	122.8	121.7
CAR 7	127.2	128.5	126.7	127.6	130.7	128.5	125.8
CAR 8	127.5	125.1	125.5	128.0	128.4	126.0	125.9
CAR 9	184.6	186.5	182.0	185.0	186.1	184.4	181.7
CAR 10	115.2	116.2	115.2	118.0	117.5	116.7	114.5

Table 3.17 Offset Geometric Means - EUDC NMHC emissions (g/km)
Note: Offset = 0.01

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.0156	0.0171	0.0181	0.0187	0.0229	0.0160	0.0158

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.0156	0.0176	0.0207	0.0159

T90	140	160	180
10 CAR MEAN	0.0156	0.0172	0.0188

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.0064	0.0109	0.0283	0.0120	0.0257	0.0037	0.0430	0.0156	0.0362	0.0191

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.0062	0.0060	0.0073	0.0064	0.0073	0.0057	0.0062
CAR 2	0.0091	0.0096	0.0134	0.0102	0.0140	0.0097	0.0111
CAR 3	0.0297	0.0257	0.0263	0.0304	0.0366	0.0255	0.0253
CAR 4	0.0073	0.0139	0.0164	0.0118	0.0160	0.0126	0.0079
CAR 5	0.0241	0.0275	0.0212	0.0274	0.0368	0.0236	0.0216
CAR 6	0.0030	0.0043	0.0033	0.0050	0.0034	0.0037	0.0030
CAR 7	0.0456	0.0386	0.0423	0.0436	0.0573	0.0396	0.0366
CAR 8	0.0109	0.0151	0.0152	0.0198	0.0227	0.0141	0.0132
CAR 9	0.0382	0.0342	0.0393	0.0319	0.0486	0.0268	0.0374
CAR 10	0.0124	0.0174	0.0197	0.0239	0.0263	0.0180	0.0183

Table 3.18 Geometric Means - EUDC Fuel Consumption (l/100 km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	6.059	6.142	6.068	6.012	6.030	6.059	6.006

FUEL TYPE	B	P	A	O
10 CAR MEAN	6.059	6.105	6.021	6.033

T90	140	160	180
10 CAR MEAN	6.059	6.071	6.035

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	6.743	6.183	5.422	6.627	7.406	5.227	5.445	5.384	7.881	4.933

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	6.742	6.879	6.714	6.689	6.733	6.777	6.673
CAR 2	6.188	6.339	6.152	6.148	6.132	6.184	6.138
CAR 3	5.390	5.500	5.404	5.387	5.417	5.461	5.396
CAR 4	6.612	6.647	6.740	6.602	6.599	6.540	6.648
CAR 5	7.472	7.555	7.415	7.370	7.349	7.444	7.246
CAR 6	5.254	5.252	5.259	5.219	5.189	5.223	5.194
CAR 7	5.431	5.547	5.460	5.347	5.479	5.474	5.380
CAR 8	5.426	5.390	5.423	5.349	5.363	5.361	5.374
CAR 9	7.912	8.075	7.878	7.780	7.831	7.874	7.818
CAR 10	4.901	5.001	4.949	4.928	4.906	4.962	4.887

Table 3.19 Geometric Means - Total Cycle HC emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.202	0.216	0.219	0.226	0.229	0.218	0.211

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.202	0.218	0.227	0.214

T90	140	160	180
10 CAR MEAN	0.202	0.220	0.220

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.399	0.134	0.209	0.252	0.232	0.090	0.210	0.305	0.226	0.273

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.372	0.417	0.406	0.429	0.395	0.397	0.381
CAR 2	0.129	0.116	0.134	0.140	0.134	0.157	0.134
CAR 3	0.213	0.205	0.207	0.229	0.218	0.198	0.192
CAR 4	0.200	0.282	0.292	0.254	0.264	0.265	0.221
CAR 5	0.218	0.257	0.226	0.227	0.258	0.228	0.214
CAR 6	0.081	0.094	0.086	0.101	0.098	0.090	0.082
CAR 7	0.223	0.197	0.208	0.213	0.220	0.211	0.198
CAR 8	0.293	0.297	0.306	0.338	0.325	0.296	0.282
CAR 9	0.192	0.211	0.223	0.216	0.254	0.199	0.309
CAR 10	0.251	0.268	0.283	0.277	0.287	0.284	0.267

Table 3.20 Geometric Means - Total Cycle CO emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	1.066	1.223	1.202	1.270	1.304	1.162	1.151

FUEL TYPE	B	P	A	O
10 CAR MEAN	1.066	1.213	1.286	1.156

T90	140	160	180
10 CAR MEAN	1.066	1.217	1.217

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	2.586	0.821	1.074	1.479	0.863	0.330	1.297	1.144	2.161	1.916

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	2.567	2.659	2.604	2.567	2.911	2.599	2.240
CAR 2	0.694	0.803	0.816	0.865	0.962	0.806	0.826
CAR 3	1.039	1.043	1.082	1.341	1.191	0.916	0.961
CAR 4	1.289	1.604	1.779	1.589	1.366	1.611	1.206
CAR 5	0.632	1.120	0.860	0.863	1.193	0.795	0.717
CAR 6	0.250	0.343	0.319	0.400	0.355	0.332	0.333
CAR 7	1.341	1.213	1.229	1.470	1.323	1.280	1.240
CAR 8	1.020	1.121	1.171	1.187	1.331	1.160	1.048
CAR 9	1.804	2.036	2.106	2.027	2.426	1.781	3.251
CAR 10	2.041	1.970	1.856	1.882	1.719	2.078	1.893

Table 3.21 Geometric Means - Total Cycle NOx emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.247	0.236	0.233	0.217	0.219	0.257	0.250

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.247	0.234	0.218	0.254

T90	140	160	180
10 CAR MEAN	0.247	0.236	0.234

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.291	0.303	0.274	0.678	0.214	0.227	0.115	0.212	0.219	0.130

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.278	0.276	0.304	0.273	0.294	0.292	0.319
CAR 2	0.297	0.322	0.299	0.283	0.278	0.319	0.326
CAR 3	0.279	0.271	0.256	0.274	0.255	0.295	0.293
CAR 4	0.683	0.706	0.678	0.662	0.669	0.686	0.662
CAR 5	0.214	0.209	0.205	0.213	0.230	0.223	0.206
CAR 6	0.282	0.219	0.204	0.180	0.167	0.313	0.262
CAR 7	0.127	0.113	0.109	0.109	0.113	0.117	0.114
CAR 8	0.215	0.223	0.207	0.181	0.183	0.219	0.268
CAR 9	0.248	0.193	0.208	0.222	0.202	0.239	0.224
CAR 10	0.129	0.142	0.152	0.100	0.112	0.154	0.130

Table 3.22 Geometric Means - Total Cycle CO_2 emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	176.5	177.1	174.6	178.5	179.0	176.7	174.7

FUEL TYPE	B	P	A	O
10 CAR MEAN	176.5	175.9	178.7	175.7

T90	140	160	180
10 CAR MEAN	176.5	177.4	176.1

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	203.0	183.0	162.3	189.2	224.8	144.4	158.8	153.7	227.2	144.7

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	201.5	204.9	199.0	205.0	206.5	203.9	200.0
CAR 2	182.8	185.1	180.4	184.5	185.2	182.5	180.5
CAR 3	161.3	161.5	159.8	164.1	165.0	163.1	161.2
CAR 4	188.8	187.6	189.9	191.8	191.2	186.5	188.6
CAR 5	226.4	225.1	221.6	227.4	227.9	225.3	220.0
CAR 6	144.7	143.6	143.2	146.7	145.7	144.3	143.0
CAR 7	158.4	160.6	156.6	159.2	160.9	159.0	156.7
CAR 8	154.1	153.1	152.2	155.1	155.6	152.9	152.6
CAR 9	228.2	229.8	224.1	227.4	229.5	227.7	223.5
CAR 10	143.5	144.7	142.8	147.3	146.5	145.4	143.1

Table 3.23 Geometric Means - Total Cycle NMHC emissions (g/km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	0.187	0.198	0.202	0.210	0.213	0.199	0.193

FUEL TYPE	B	P	A	O
10 CAR MEAN	0.187	0.200	0.211	0.196

T90	140	160	180
10 CAR MEAN	0.187	0.202	0.202

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	0.377	0.118	0.194	0.232	0.209	0.083	0.196	0.291	0.203	0.258

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	0.351	0.393	0.383	0.406	0.374	0.374	0.359
CAR 2	0.114	0.100	0.116	0.124	0.117	0.140	0.116
CAR 3	0.199	0.190	0.190	0.215	0.204	0.184	0.178
CAR 4	0.183	0.259	0.268	0.235	0.247	0.242	0.202
CAR 5	0.199	0.233	0.205	0.208	0.236	0.195	0.194
CAR 6	0.075	0.086	0.080	0.094	0.090	0.082	0.074
CAR 7	0.208	0.183	0.194	0.198	0.205	0.196	0.185
CAR 8	0.280	0.283	0.291	0.325	0.311	0.281	0.268
CAR 9	0.173	0.187	0.202	0.195	0.231	0.176	0.276
CAR 10	0.236	0.250	0.267	0.264	0.274	0.265	0.248

Table 3.24 Geometric Means - Total Fuel Consumption (l/100 km)

FUEL	B140	P160	P180	A160	A180	O160	O180
10 CAR MEAN	7.614	7.740	7.621	7.573	7.587	7.623	7.561

FUEL TYPE	B	P	A	O
10 CAR MEAN	7.614	7.680	7.580	7.592

T90	140	160	180
10 CAR MEAN	7.614	7.645	7.590

CAR	1	2	3	4	5	6	7	8	9	10
FUEL MEAN	8.836	7.835	6.985	8.159	9.610	6.161	6.850	6.642	9.816	6.301

Individual Car Results

FUEL	B140	P160	P180	A160	A180	O160	O180
CAR 1	8.787	9.050	8.770	8.785	8.852	8.886	8.728
CAR 2	7.834	8.030	7.817	7.771	7.801	7.824	7.768
CAR 3	6.955	7.044	6.961	6.968	6.988	7.017	6.963
CAR 4	8.137	8.215	8.312	8.140	8.093	8.064	8.152
CAR 5	9.696	9.789	9.602	9.573	9.611	9.651	9.353
CAR 6	6.176	6.211	6.177	6.162	6.108	6.162	6.128
CAR 7	6.853	7.015	6.834	6.769	6.823	6.867	6.790
CAR 8	6.656	6.698	6.673	6.599	6.617	6.613	6.636
CAR 9	9.847	10.047	9.792	9.648	9.758	9.818	9.807
CAR 10	6.249	6.391	6.293	6.305	6.259	6.351	6.263

APPENDIX 3

PLOTS OF EMISSIONS AGAINST VARIOUS VOLATILITY DESCRIPTORS

The bars in Figures A to F of this appendix follow the convention of earlier illustrations, namely:

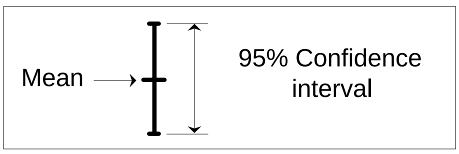


Figure A Total Cycle HC Emissions

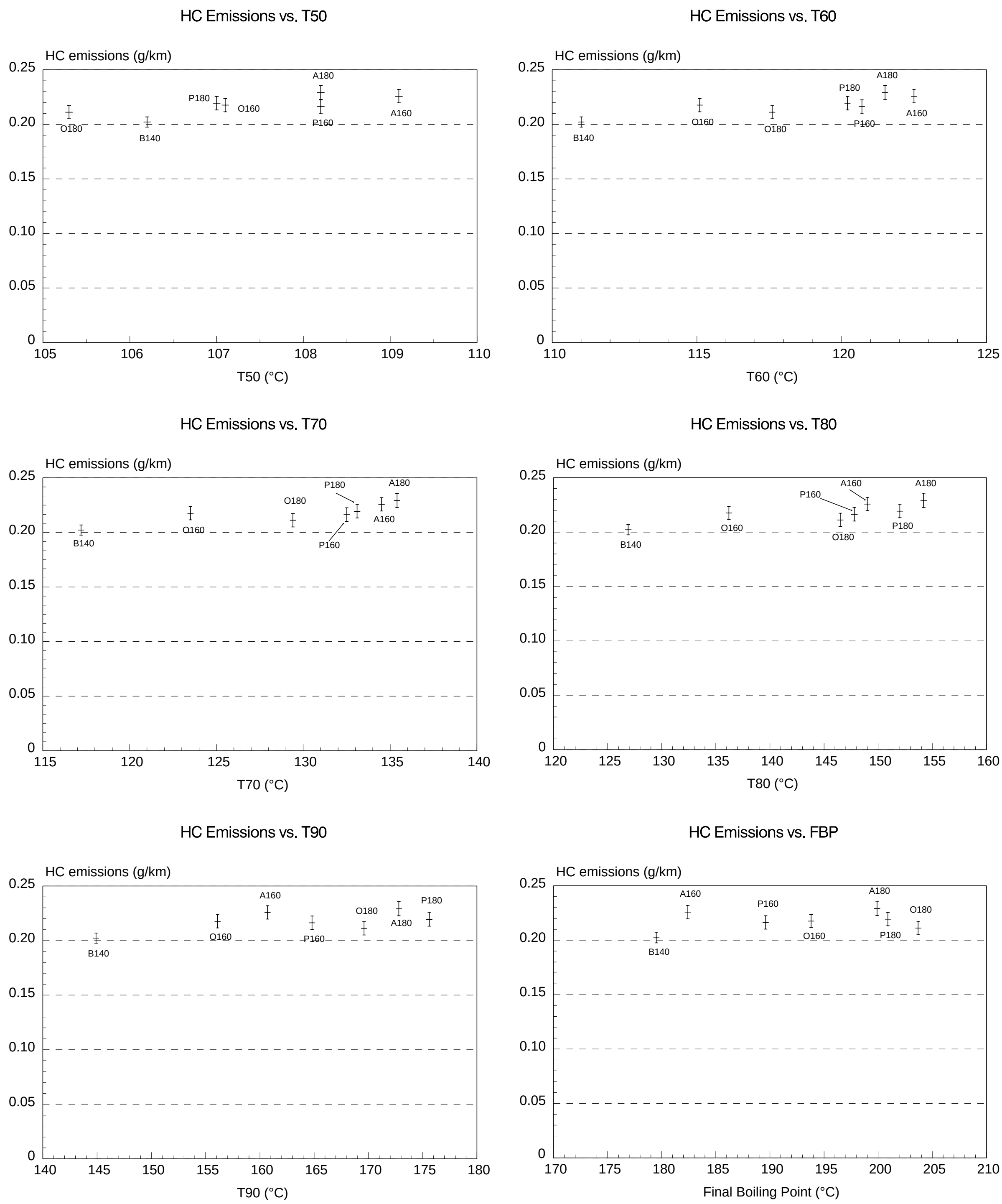


Figure B Total Cycle HC Emissions

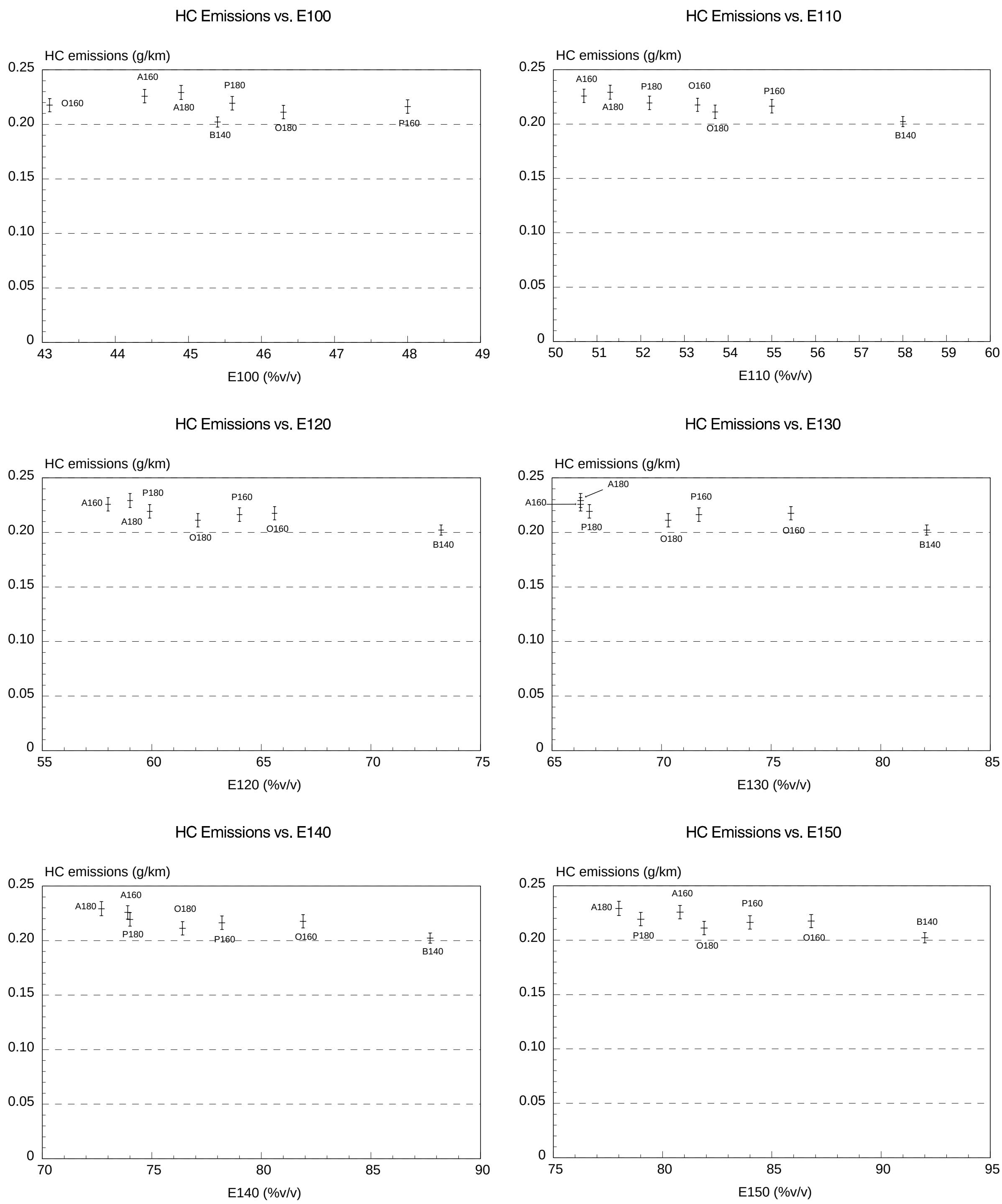


Figure C Total Cycle CO Emissions

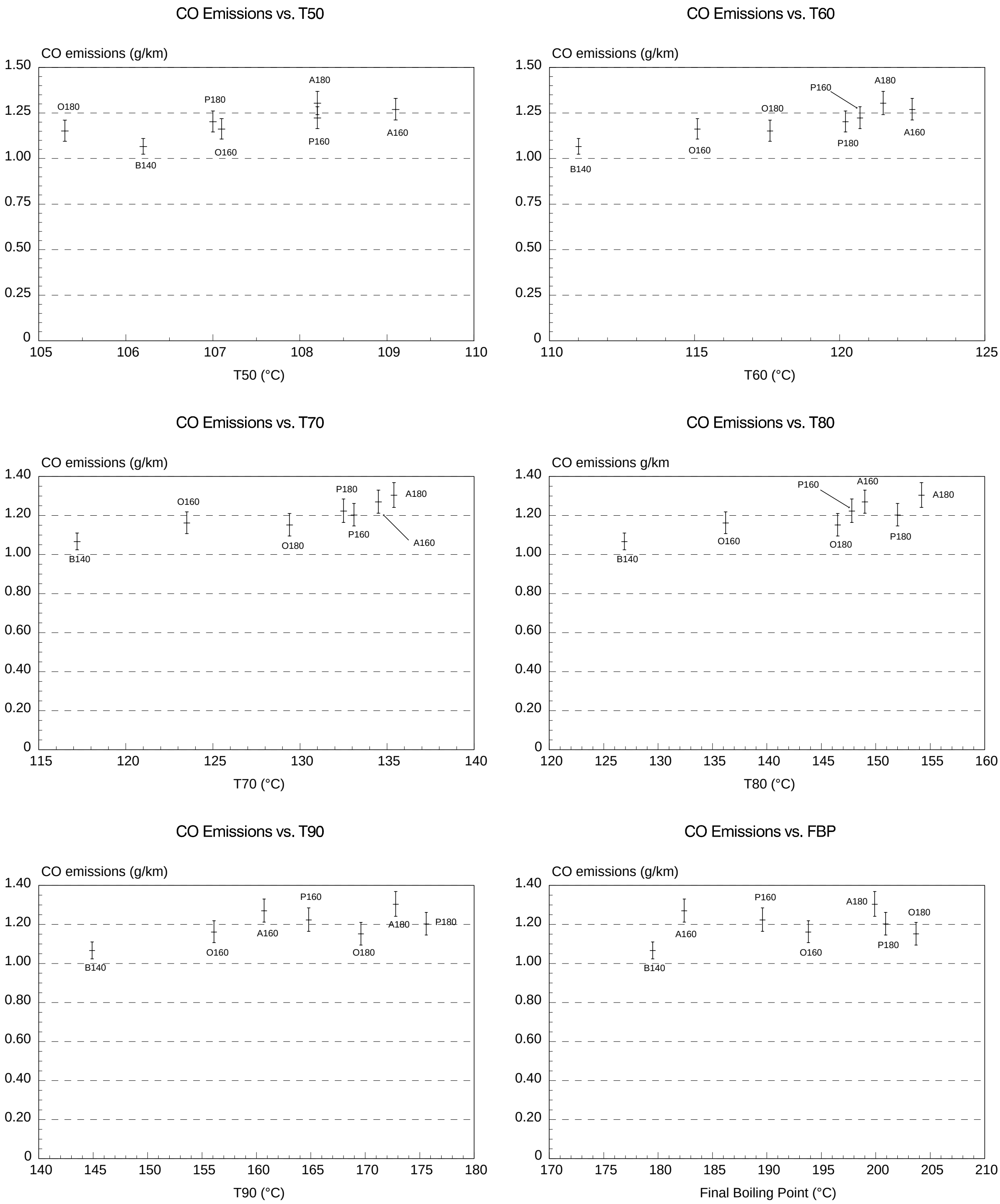


Figure D Total Cycle CO Emissions

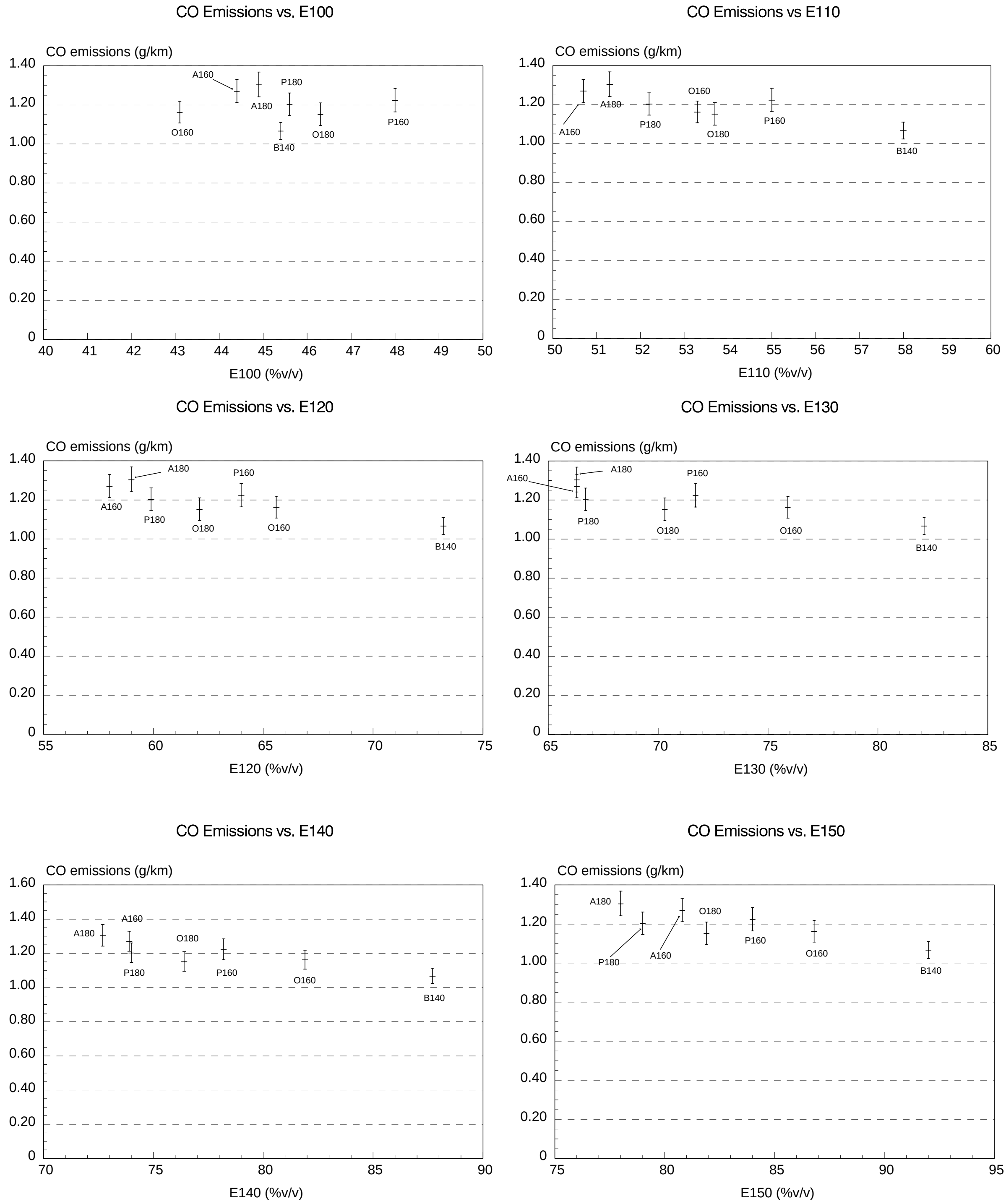


Figure E Total Cycle NOx Emissions

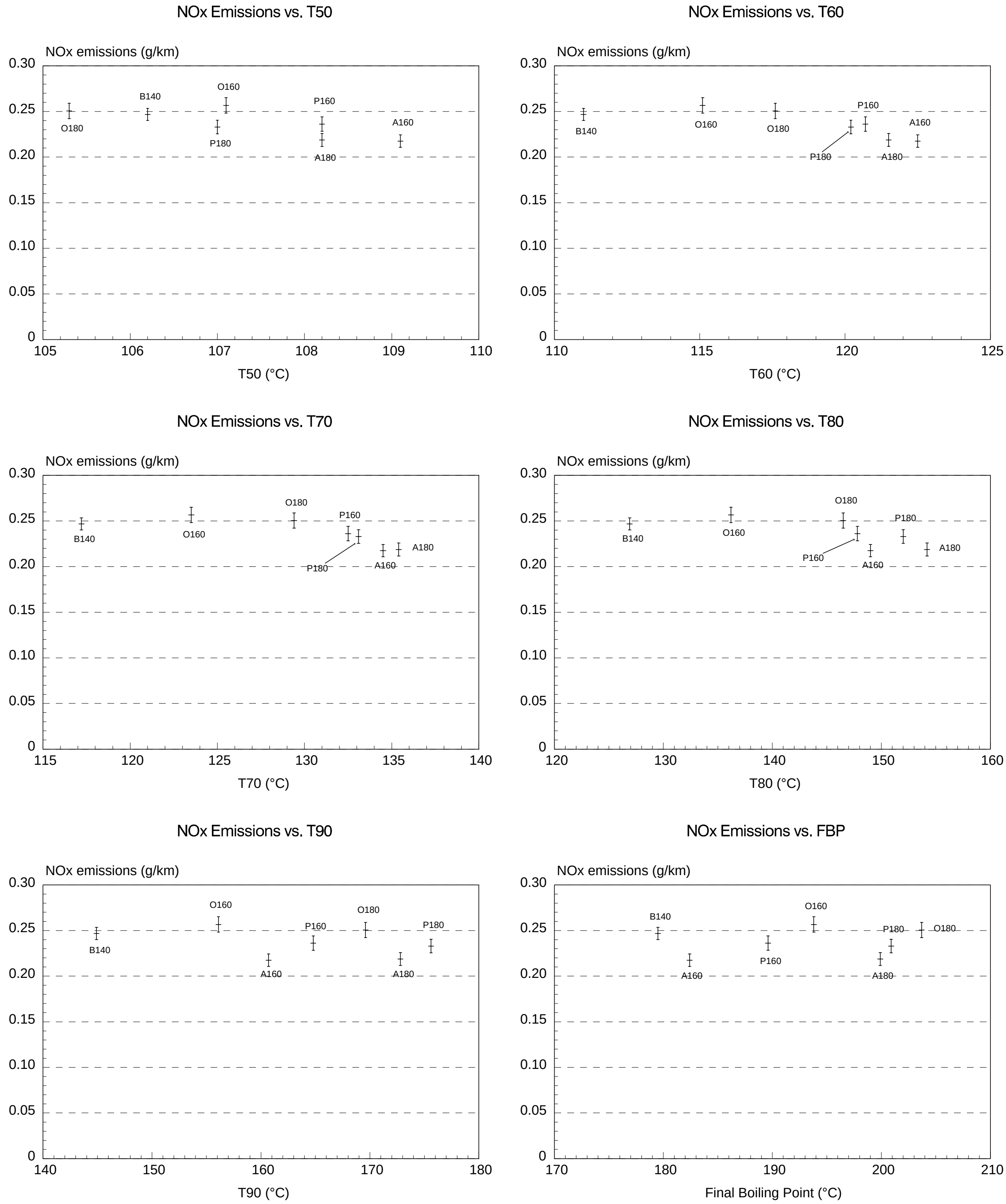


Figure F Total Cycle NOx Emissions