# fuel effects on emissions from modern gasoline vehicles part 2 - aromatics, olefins and volatility effects

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## ABSTRACT

The influence of gasoline quality on exhaust emissions has been evaluated using four modern European gasoline cars with advanced engine technologies/after-treatment systems. Part 1 of this report described the short-term sensitivity of these four cars to gasoline sulphur content. This report describes the influence of other fuel effects: aromatics, olefins, volatility and final boiling point.

Emissions from the test vehicles were all very low, in compliance with the appropriate Euro-3 or Euro-4 emission limits. The measured effects of fuel changes on the regulated emissions: NOx, HC and CO, were small and often conflicting, with differing directional responses for different vehicles and emissions.

The three direct injection cars emitted higher levels of particulate mass (PM) than the advanced MPI car, although much lower than the Euro-4 diesel PM emission limit. Response to fuel effects was similar in the three direct injection cars. PM emissions from the advanced MPI car, which is more representative of the current fleet, were very low on all fuels tested and insensitive to fuel changes.

## KEYWORDS

Exhaust emissions, gasoline, aromatics, olefins, volatility, FBP, vehicle technology, engine technology, Euro-3, Euro-4, direct injection

## INTERNET

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## SUMMARY

The influence of gasoline quality on exhaust emissions has been evaluated using four modern European gasoline cars with advanced features designed to improve fuel economy and $CO_2$ emissions, including stoichiometric direct injection, lean direct injection and MPI with variable valve actuation. Part 1 of this report described the short-term sensitivity of these four cars to gasoline sulphur content. This report describes the influence of other fuel effects: aromatics, olefins, volatility and final boiling point (FBP).

Regulated emissions from the test vehicles were all very low, in compliance with the appropriate Euro-3 or Euro-4 emission limits. As expected, regulated emissions were particularly low when the after-treatment systems were fully operational in the EUDC part of the emissions test cycle. Reduction of $CO_2$ emissions is the greater challenge for future gasoline vehicles.

Fuel effects were evaluated over a wide range of aromatics content, olefins content, volatility and FBP, using a rigorous test protocol with multiple tests on each fuel/vehicle combination. The measured effects of these fuel changes on the regulated emissions: NOx, HC and CO, were small and often conflicting, with differing directional responses for different vehicles and emissions.

The three direct injection cars emitted higher levels of particulate mass (PM) than the advanced MPI car, although much lower than the Euro-4 diesel PM emission limit. Response to fuel effects was similar in the three direct injection cars: lower FBP and lower olefins gave lower PM emissions, while lower aromatics and volatility gave no overall benefits. PM emissions from the advanced MPI car, which is more representative of the current fleet, were very low on all fuels tested and insensitive to fuel changes.

# 1. INTRODUCTION/OBJECTIVES

Over the last two decades, gasoline vehicle technologies have evolved rapidly, with substantial improvements in emissions control. Exhaust catalysts were first required on European gasoline cars with the introduction of Euro-1 emissions limits in 1993. Today's vehicles have to meet the year 2000, Euro-3 limits, with continuing evolution to Euro-4 in 2005. European vehicle manufacturers are also working towards a voluntary agreement for a European passenger car fleet average $CO_2$ emissions of 140 g/km by 2008.

A range of advanced gasoline engine technologies and exhaust gas after-treatment technologies are being introduced to meet the more stringent emissions requirements together with $CO_2$ reduction. The introduction of sulphur-free fuels is also an important step, allowing regenerative devices such as NOx storage catalysts to be introduced.

New gasoline engine concepts, including lean direct injection, are entering the market and may respond differently to fuel properties than conventional MPI engines. Much of the European data used to establish the relationships between fuel effects, vehicle technologies and exhaust emissions is becoming rather dated, e.g. the EPEFE report [1] was based mainly on prototype Euro-2 vehicles. Given the evolution in vehicle and fuel technologies, there is a need to establish sound information on the influence of fuel quality on emissions from more advanced engines so that future debates on fuel quality are based on a firm foundation.

To update understanding, CONCAWE has performed this study to evaluate the impact of fuel quality on emissions from advanced gasoline vehicle technologies available in the market in 2002, covering three DI cars and one advanced MPI car. Two of these were certified to Euro-3 emissions limits and two to Euro-4. Part 1 of this study [2] evaluated the influence of gasoline sulphur content. In this Part 2, the effects of other fuel properties viz. volatility, FBP, aromatics and olefins were evaluated.

NOTE:
A glossary of terms is provided in **Section 8**.

## 2. TEST FUELS

The test fuel matrix was designed to evaluate the effects of aromatics, olefins, volatility and FBP on exhaust emissions. In order to maximize the chance to identify fuel effects, a wide range in the fuel parameters of interest, was investigated. On average this covered olefins from 14 to 5% v/v, aromatics from 38 to 26% v/v, E70 from 38 to 22% v/v and FBP from 197 to 176°C. To reduce the number of emissions tests required, a statistically designed half-factorial matrix of eight fuels was blended, based on high (H) and low (L) values of the design variables, treating volatility as the combined effects of E70 and E100 (See **Table 1** and **Appendix 1** for further details).

**Table 1** Test Fuel Matrix Design

| Fuel | E70/E100 | FBP | Aromatics | Olefins |
|---|---|---|---|---|
| **F1** | L | L | L | L |
| **F2** | H | L | H | L |
| **F3** | H | L | L | H |
| **F4** | L | L | H | H |
| **F5** | H | H | L | L |
| **F6** | L | H | H | L |
| **F7** | L | H | L | H |
| **F8** | H | H | H | H |

The sulphur content of all fuels was targeted in the 40-50 mg/kg range since at the time of testing, it was not practical to blend such a wide ranging fuel matrix at the 10 mg/kg sulphur level. In Part 1 of this report, it was shown that the effect of sulphur content on emissions from these vehicles was small, so the evaluation of other fuel effects is also considered valid at the 10 mg/kg sulphur level. Analysis of the test fuels was carried out in at least two laboratories. The mean analytical results for the fuels are shown in **Table 2**.

The correlation matrix for the average measured fuel properties is shown in **Table 3**. Although it is not feasible to produce a perfectly orthogonal fuel matrix, the correlation matrix demonstrates very good separation between the primary fuel variables. Correlation between vapour pressure, E70 and E100 was acceptable given the aim to investigate the overall impact of high/low volatility. Some correlations with other fuel properties could not be avoided, e.g. RON with aromatics, MON with E70, density with aromatics. The octane correlations were considered of secondary importance as the cars would not be expected to encounter knock under the test cycle driving conditions. The correlation of density and aromatics is a natural result of the fuel composition and would also be expected with market fuels.

## *Table 2* Test Gasoline Properties

| GASOLINE CODE | | | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 |
|---|---|---|---|---|---|---|---|---|---|---|
| | UNITS | TEST METHOD | | | | | | | | |
| Density @ 15 °C | $kg/m^3$ | EN ISO 3675 | 736.9 | 756.7 | 739.4 | 760.4 | 740.0 | 761.7 | 738.9 | 750.8 |
| Vapour Pressure (DVPE) | kPa | EN ISO 13016 | 63.1 | 69.7 | 67.1 | 54.0 | 64.4 | 56.0 | 49.3 | 68.5 |
| **DISTILLATION** | | EN ISO 3405 | | | | | | | | |
| IBP | °C | | 34 | 33 | 31 | 35 | 31 | 36 | 36 | 30 |
| 5 % v/v | °C | | 49 | 46 | 44 | 52 | 41 | 50 | 53 | 42 |
| 10 % v/v | °C | | 58 | 51 | 49 | 59 | 46 | 56 | 59 | 47 |
| 20 % v/v | °C | | 71 | 59 | 55 | 70 | 51 | 67 | 68 | 54 |
| 30 % v/v | °C | | 84 | 68 | 62 | 82 | 57 | 79 | 79 | 61 |
| 40 % v/v | °C | | 94 | 79 | 72 | 94 | 68 | 93 | 92 | 71 |
| 50 % v/v | °C | | 101 | 91 | 84 | 105 | 84 | 104 | 104 | 84 |
| 60 % v/v | °C | | 108 | 100 | 97 | 115 | 98 | 114 | 116 | 97 |
| 70 % v/v | °C | | 115 | 105 | 107 | 128 | 112 | 130 | 130 | 117 |
| 80 % v/v | °C | | 126 | 110 | 117 | 149 | 136 | 163 | 155 | 146 |
| 90 % v/v | °C | | 141 | 118 | 134 | 162 | 167 | 186 | 173 | 178 |
| 95 % v/v | °C | | 154 | 152 | 154 | 167 | 184 | 194 | 183 | 188 |
| FBP | °C | | 174 | 180 | 174 | 177 | 195 | 202 | 195 | 196 |
| Residue | % v/v | | 0.8 | 1.5 | 0.8 | 0.9 | 0.2 | 0.9 | 1.0 | 0.9 |
| E 70 °C | % v/v | | 19.1 | 33.4 | 39.2 | 20.5 | 41.2 | 24.5 | 22.8 | 39.0 |
| E 100 °C | % v/v | | 48.2 | 61.9 | 62.9 | 46.7 | 62.2 | 48.0 | 47.4 | 62.5 |
| E 150 °C | % v/v | | 94.4 | 96.4 | 94.9 | 80.6 | 84.9 | 78.5 | 78.1 | 81.0 |
| **COMPOSITION** | | | | | | | | | | |
| Saturates | % v/v | FIA - D1319 | 69.5 | 59.2 | 59.6 | 46.0 | 66.5 | 56.2 | 62.9 | 49.9 |
| Olefins | % v/v | FIA - D1319 | 5.5 | 3.0 | 12.7 | 14.1 | 4.9 | 5.3 | 13.0 | 14.2 |
| Aromatics | % v/v | FIA - D1319 | 25.0 | 37.8 | 27.7 | 39.9 | 28.6 | 38.5 | 24.1 | 35.9 |
| Benzene | % v/v | EN 12177:98 | 0.14 | 0.16 | 0.30 | 0.24 | 0.09 | 0.14 | 0.31 | 0.09 |
| **OCTANE** | | | | | | | | | | |
| RON | | ISO 25164 | 95.6 | 95.9 | 97.2 | 98.0 | 95.2 | 97.5 | 95.2 | 97.9 |
| MON | | ISO 25163 | 86.6 | 84.9 | 84.8 | 85.3 | 85.0 | 86.0 | 85.1 | 84.8 |
| Oxidation Stability | minutes | ISO 7536 | >360 | >360 | >360 | 285 | >360 | >360 | 210 | >360 |
| Existent Gum, washed | mg/100ml | ISO 6246 | <1 | 0.1 | <1 | 0.8 | <1 | 2 | 1.4 | 1 |
| Sulfur content | mg/kg | EN ISO 14596:98 | 48 | 50 | 44 | 46 | 52 | 48 | 45 | 46 |
| Lead content | mg/l | EN 237 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Copper Corrosion 3h, 50°C | | ISO 2160 | 1a | 1a | 1a | 1a | 1a | 1a | 1a | 1a |
| Oxygenates | % m/m | EN 1601:1997 | none | none | none | none | none | none | none | none |
| LHV | MJ/kg | GC (calc) | 43.62 | 42.97 | 43.60 | 42.95 | 43.36 | 43.03 | 43.69 | 43.25 |
| Carbon | % m/m | ASTM D5291 | 86.3 | 87.5 | 86.9 | 87.3 | 86.6 | 87.6 | 86.2 | 87.0 |
| Hydrogen | % m/m | ASTM D5291 | 13.7 | 12.5 | 13.1 | 12.7 | 13.4 | 12.4 | 13.8 | 13.0 |

| | |
|---|---|
| 🟦 | High values of design parameters |
| 🟨 | Low values of design parameters |

## *Table 3* Correlation Matrix for the fuel properties

| | E70 | E100 | E150 | FBP | AROMATICS | OLEFINS | RON | MON | DENSITY | RVP |
|---|---|---|---|---|---|---|---|---|---|---|
| **E70** | 1.00 | 0.96 | 0.23 | 0.17 | 0.00 | -0.01 | 0.03 | -0.72 | -0.18 | 0.72 |
| **E100** | 0.96 | 1.00 | 0.45 | -0.03 | 0.02 | -0.10 | 0.00 | -0.68 | -0.17 | 0.86 |
| **E150** | 0.23 | 0.45 | 1.00 | -0.75 | -0.23 | -0.42 | -0.28 | 0.05 | -0.32 | 0.70 |
| **FBP** | 0.17 | -0.03 | -0.75 | 1.00 | 0.14 | -0.05 | 0.00 | -0.13 | 0.20 | -0.28 |
| **AROMATICS** | 0.00 | 0.02 | -0.23 | 0.14 | 1.00 | -0.03 | 0.71 | -0.12 | 0.97 | 0.09 |
| **OLEFINS** | -0.01 | -0.10 | -0.42 | -0.05 | -0.03 | 1.00 | 0.50 | -0.40 | -0.06 | -0.30 |
| **RON** | 0.03 | 0.00 | -0.28 | 0.00 | 0.71 | 0.50 | 1.00 | -0.09 | 0.65 | 0.05 |
| **MON** | -0.72 | -0.68 | 0.05 | -0.13 | -0.12 | -0.40 | -0.09 | 1.00 | -0.01 | -0.27 |
| **DENSITY** | -0.18 | -0.17 | -0.32 | 0.20 | 0.97 | -0.06 | 0.65 | -0.01 | 1.00 | -0.10 |
| **DVPE** | 0.72 | 0.86 | 0.70 | -0.28 | 0.09 | -0.30 | 0.05 | -0.27 | -0.10 | 1.00 |

# 3. TEST VEHICLES

Four advanced gasoline vehicles were selected for evaluation in this programme. The technologies selected were those at the time judged likely to become significant in the near term future European car population. Three examples of direct injection technologies (one stoichiometric and two lean-burn) and one advanced MPI system were chosen. Further information on the vehicles tested is given in **Table 4**.

***Table 4*** Characteristics of Test Vehicles

| | **Car A** | **Car B** | **Car C** | **Car D** |
|---|---|---|---|---|
| Displacement (cm$^3$) | 1998 | 1796 | 1997 | 1598 |
| Max power (kW @ rpm) | 103@5500 | 85@5500 | 107@6000 | 81@5800 |
| Inertia class (kg) | 1250 | 1360 | 1470 | 1360 |
| No of cylinders | 4 | 4 | 4 | 4 |
| Valves per cylinder | 4 | 4 | 4 | 4 |
| Max torque (Nm @ rpm) | 200@4250 | 175@3750 | 193@4100 | 155@4400 |
| Compression ratio | 10.0:1 | 10.5:1 | 11.4:1 | 12.0:1 |
| Combustion / injection / control system | Stoichiometric DI | MPI Variable valve actuation | Lean DI | Lean DI |
| Catalyst system | TWC | TWC | TWC<br>+ NOx trap | TWC<br>+ NOx trap |
| Emissions Compliance | Euro-3 | Euro-4 | Euro-3 | Euro-4 |

# 4. TEST PROTOCOL AND DESIGN

## 4.1. TEST DESIGN

The objective of the test protocol was to define a sound and repeatable way of measuring the short-term effect of fuels on regulated emissions. The test procedures and protocols were based on the well-established EPEFE methods, but were modified where appropriate to the needs of this programme. These procedures assured sound test data and allowed statistically valid interpretation, so that the effects of fuel changes in the test vehicles could be accurately assessed.

The test programme was designed and analysed using rigorous statistical methods similar to those used in the recent CONCAWE diesel engine emission study [3]. The programme plan included testing of each fuel over the standard NEDC emissions test on three separate occasions in each vehicle. Based on the variability observed in earlier programmes, it was anticipated that this degree of replication would render differences in fleet-average emissions of approximately 7% between the two levels of each design variable (E70, FBP, aromatics, olefins) statistically significant at 95% confidence. Differences roughly twice this size would be needed for significance in individual vehicles. The variability levels and least significant effects actually achieved are tabulated in **Tables A.1.2** and **A.1.3** in **Appendix 1**.

The 24 tests on each car were conducted in three blocks with one block consisting of one single test on each fuel. This minimised the risk of fuel effects becoming compromised by any drift in vehicle performance or other time-related effects. Repeat tests on a fuel were not conducted back-to-back to ensure that the results were truly independent. The eight fuels were tested in a different randomised order in each block and different randomisations were used for each vehicle. A typical test order was thus as follows:

| | **Fuel Order** |
|---|---|
| **Block 1** | F2 F8 F5 F3 F1 F4 F7 F6 |
| **Block 2** | F4 F3 F2 F7 F5 F8 F1 F6 |
| **Block 3** | F7 F1 F5 F6 F3 F8 F2 F4 |

A fourth test was conducted whenever large variations were seen between the three tests on a particular fuel in a particular vehicle. The following thresholds were used (based on the variability levels seen in the EPEFE programme [1]):

| Emission | CO | HC | NOx |
|---|---|---|---|
| Ratio of highest to lowest emission on the same fuel | 1.40 | 1.45 | 1.49 |

When the differences exceeded these limits, additional tests were carried out at the completion of the test block. In the event, most fuels were tested four times in each vehicle. The complete data set was then examined for outliers and trends (**see Section 5**). For some vehicles, minor changes had to be made to the predetermined test order for logistical reasons.

## 4.2. VEHICLE PREPARATION AND MONITORING

All test vehicles were in good mechanical condition and had completed a minimum of 8000 km to ensure that their exhaust after-treatment systems were adequately aged and that engine combustion chamber deposits had stabilised. Each vehicle completed its mileage accumulation with 500 km on test fuel F8 and a common lubricant, prior to the start of the test programme, to ensure consistency between vehicles. The properties of test fuel F8 are given in **Table 2**.

Since the sulphur levels of the 8 test fuels were blended to be nominally constant at 40–50 mg/kg, it was decided that a sulphur purging protocol would only be implemented on the vehicles with NOx storage catalysts, as the deposition of sulphur in these catalyst technologies during test mileage would be cumulative. A sulphur purge was therefore carried out for cars C and D after every block of 8 emissions tests.

The principle of sulphur purging was to cause the vehicle to transiently run rich at a high catalyst temperature in order to remove accumulated sulphur. The sulphur purging procedure was tailored to each vehicle and followed manufacturers' guidelines where possible. In addition, NOx conversion efficiency was monitored within each testing block for signs of early catalyst deactivation due to the cumulative effect of sulphur.

## 4.3. VEHICLE TESTING

A specific fuel change protocol was followed to ensure consistency between tests and to ensure minimal crossover between test fuels. At fuel change, the fuel tank was drained, 10 litres of the new test fuel were added and the engine was idled for 5 minutes to allow the new test fuel to flush the fuel injection system thoroughly before the tank was drained again. A further 25 litres of the new test fuel was then added for the emissions test.

Prior to each NEDC emissions test, the test vehicle and fuel were conditioned by carrying out one ECE plus two consecutive EUDC test cycles but without emissions measurement. The vehicle was then soaked according to the NEDC test procedure ensuring that the soak period was restricted to 12 - 18 hours.

Vehicles were then tested according to the current legislated NEDC test procedure [4]. Exhaust gases were collected in two separate bags to measure emissions over the two different parts of the NEDC test. The first bag sampled over the ECE (cold start and city driving) and the second bag over the EUDC (warmed-up and higher speed driving) part of the NEDC test. The legislated exhaust emissions - CO, HC, NOx - plus $CO_2$ and PM were measured. In addition, continuous raw exhaust emissions were measured, at both engine-out and tailpipe, to allow the interpretation of both engine and catalyst performance.

# 5. STATISTICAL ANALYSIS METHODOLOGY

The test programme was constructed using the principles of statistical experimental design as described in **Section 4.1**. Each emission (CO, HC, NOx, $CO_2$, PM) was examined on a vehicle-by-vehicle basis. In the EPEFE gasoline project [1] and other previous emission studies [3,5,6,7], the variability in exhaust emissions measurements has typically been found to follow the lognormal distribution with the degree of scatter increasing as the emission level increases. Standard deviation vs. mean plots suggested that the present emissions data behaved similarly (see **Appendix 1**).

The data were examined for outliers by inspecting studentized residuals (residuals divided by their standard errors). Analysis of covariance techniques were then used to detect and adjust for systematic trends in the data. Whenever a consistent trend was found which was significant at $P < 1\%$[1], the means and standard errors were adjusted to eliminate any bias which might be caused by that trend. In practice however, the adjustments had relatively little effect on mean emissions owing to the robustness of the experimental design (**Appendix 2** gives both the uncorrected and corrected emissions data).

Some severe trends were observed in the emission measurements in car A. The tests in block 1 were rejected in their entirety due to the abnormally high CO and HC and abnormally low NOx emission measurements at the start of the test programme. Significant downwards trends were found in the remaining CO (NEDC and ECE) and PM (NEDC, ECE and EUDC) data in blocks 2-4 and consequently a linear trend correction was applied on the log(emissions) scale.

For car B, two complete tests were rejected from the analysis due to abnormally high HC measurements, relating to HC release from the catalyst, as described in **Figure 7 of Part 1** of this report [2]. Significant upwards trends were found in the remaining CO and NOx data (EUDC) and so linear trend corrections were applied on the original g/km scale.

For car C, one test was invalidated owing to a modal pipe split and another was rejected due to abnormally low CO and HC results. An outlying set of high PM (NEDC, ECE and EUDC) results was also rejected.

No results were rejected for car D. However substantial block-to-block variations were observed in the HC (NEDC and ECE), NOx (NEDC, ECE and EUDC) and PM (NEDC and EUDC) data. These variations were eliminated using blocked analysis of variance methods.

In the tables and graphs in this report, simple arithmetic means are used to summarise the emissions for each vehicle × fuel combination. As the final fuel matrix was slightly non-orthogonal (see **Appendix 1**), multiple regression techniques were used to relate emissions to the four design variables (E70, FBP, aromatics, olefins) on a vehicle-by-vehicle basis. Adjustments were made to the analysis to take into account the log-normality in the data using a similar methodology to that employed in the EPEFE programme [1].

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[1] $P < 1\%$ = the probability that such an event could be observed by chance when no real effect exists is less than 1%. In other words, we are 99% confident that the effect is real. Likewise $P < 5\%$ = 95% confidence and $P < 0.1\%$ = 99.9% confidence. NS = Not significant (< 95%).

**Appendix 4** gives the average emissions predicted from multiple regression analyses for the higher and lower levels of each of the design variables. The numerical levels in this table are based on the final fuel properties. In each case, the predictions are averaged over the two levels of the other three variables. Thus, for example, the predicted emissions at E70 = 22% are calculated at FBP = 186.5°C, 32% aromatics and 9.5% olefins using the appropriate multiple regression model.

The error bars in **Figures 1 to 4 in section 6 and Figures A.3.1 to A.3.8 in Appendix 3** are based on the:

mean value ± 1.4 × standard error of mean

These are constructed so that when two fuels are significantly different from one another at $P < 5\%$, their error bars will not overlap. We can be 84% confident that the true mean for each fuel lies within the limits shown.

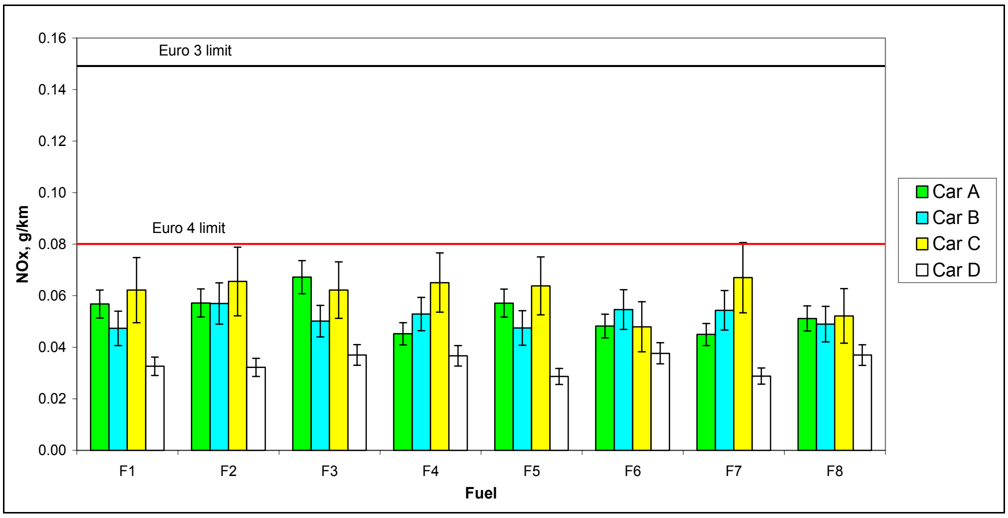
# 6. RESULTS AND DISCUSSION

## 6.1. EMISSIONS RESULTS BY FUEL AND VEHICLE

The mean emissions results for all cars over the ECE, EUDC and combined NEDC are given in **Appendix 2**. The first point of interest is the range of fuel effects on the regulated emissions, NOx, HC and CO, over the combined NEDC. Bar charts illustrating the mean emissions data for all four cars versus the emission limits (Euro-3 and Euro-4) are given in **Figures 1 to 3**. Comparable charts for the ECE and EUDC phases of the NEDC are given in **Appendix 3**.

For each mean value shown in the figures, a significant difference between fuels, at P<5% or stronger, would be indicated by non-overlapping error bars (see **Section 5**). Analysis of the individual fuel property effects is described in **Section 6.2**.

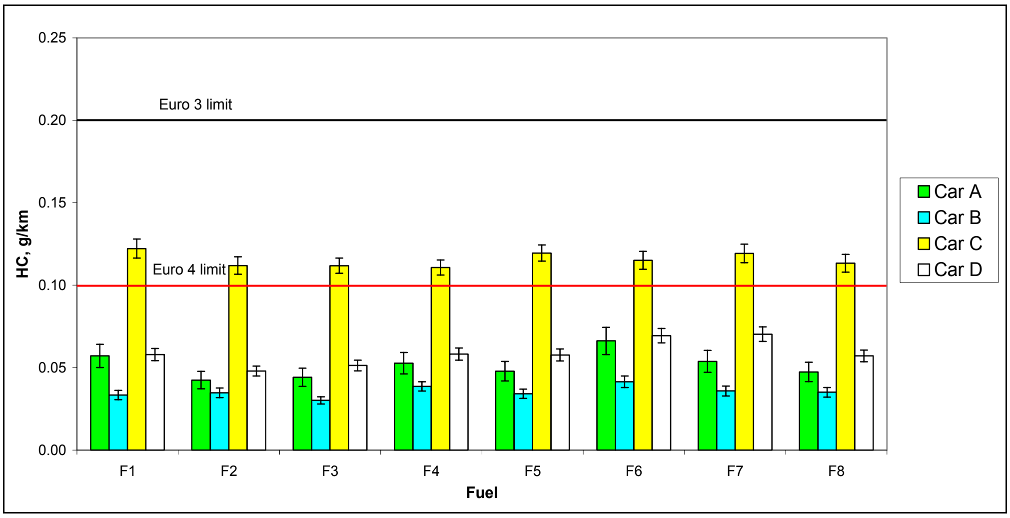
***Figure 1*** NEDC emissions data - NOx



The NOx emissions for all four vehicles were below the Euro-4 limit. No individual fuel gave consistently higher or lower NOx emissions across all four vehicles.

Car D gave consistently lower NOx emissions across all fuels. Its slightly smaller engine capacity compared to the other test vehicles may have been a factor, but this can also be explained by the good NOx emissions control displayed by this vehicle during the ECE phase of the cycle. The advanced MPI vehicle (car B) achieved the lowest NOx emissions in the EUDC phase.

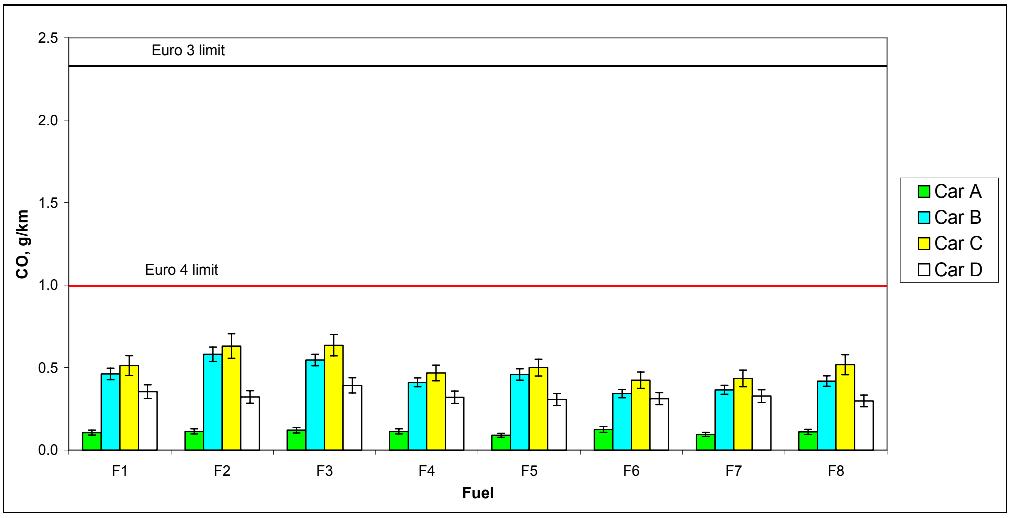
**_Figure 2_** NEDC emissions data - HC



HC emissions for three of the four vehicles were well below the Euro-4 limit, with car C operating well below the Euro-3 limit against which it was certified. The other Euro-3 vehicle (car A) had very low HC emissions, in line with the two Euro-4 vehicles. No individual fuel gave consistently higher or lower HC emissions across all four vehicles.

For all 4 vehicles, and car C in particular, the emissions from the ECE phase dominated the NEDC HC emissions. Car C produced the highest HC emissions in the ECE phase. Both of the lean-burn DI vehicles (cars C and D) gave relatively high HC emissions during the EUDC phase compared to cars A and B.

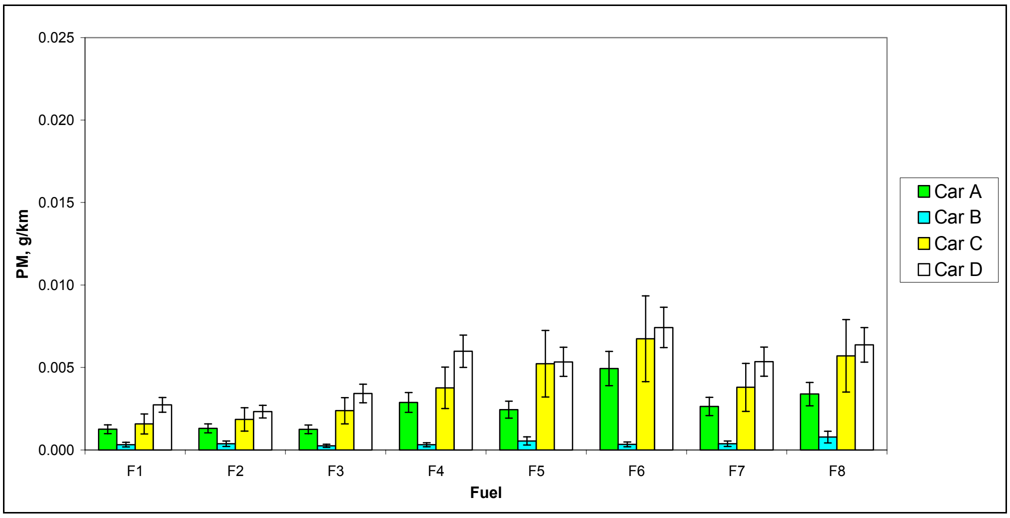
**_Figure 3_** NEDC emissions data - CO



CO emissions for all four vehicles were well below the Euro-4 limit. Some significant differences between fuels were apparent, which are evaluated in **Section 6.2**. Car A gave consistently lower CO emissions across all fuels.

For three of the four vehicles (cars B, C and D), the emissions from the ECE phase dominated the NEDC CO emissions. Car A gave extremely low emissions in the ECE phase. In the EUDC phase, there was less difference between the emissions from the four vehicles.

***Figure 4*** NEDC emissions data - PM



Particulate mass (PM) emissions were also measured using the standard diesel methodology but with a dedicated particulate tunnel. Despite low levels of particulate emissions, the repeatability of the PM measurements was sufficient to discriminate between technologies, given the multiple testing performed. The data are presented in **Figure 4** and show a clear ranking (high to low) of PM emissions according to vehicle technology, with:

lean burn DI > stoichiometric DI > advanced MPI

Even the lean burn DI vehicles gave PM emissions well below the Euro-4 light duty diesel limit of 0.025 g/km. Fuel properties showed an effect on PM emissions in the DI vehicles, which is discussed in **Section 6.2**.

The differences in PM emissions between the different combustion technologies were most evident in the ECE phase of the cycle. The ranking given above was still evident in the EUDC phase, although there was less discrimination between the lean-burn and stoichiometric DI vehicles.

## 6.2. ANALYSIS OF FUEL EFFECTS

The test fuel matrix was generated using a half-factorial design, as described in **Section 2 and Appendix 1**. This has the advantage that the effects of the four fuel variables volatility, FBP, aromatics and olefins can be evaluated in an efficient way, with an optimised number of tests. It also means, however, that the effects of the fuel variables cannot easily be seen by comparing individual fuels, and a statistical analysis is needed to identify these effects.

The half-factorial design is suitable, in principle, for an analysis of variance (ANOVA) approach. In practice, it was not possible to produce test fuels that exactly met all the targets of the design matrix. Nevertheless, good separation in the key variables was achieved (see **Section 2**). Analysis of fuel effects was therefore carried out using a pseudo ANOVA procedure, where multiple regression is used to derive model equations from which the individual fuel effects can be estimated. The detailed results of this analysis are given in **Appendix 4**.

In evaluating the emissions test results, it should be noted that the range of each fuel parameter studied represents a major change in fuel properties. The actual mean values of the fuel properties evaluated are shown in **Table 5**.

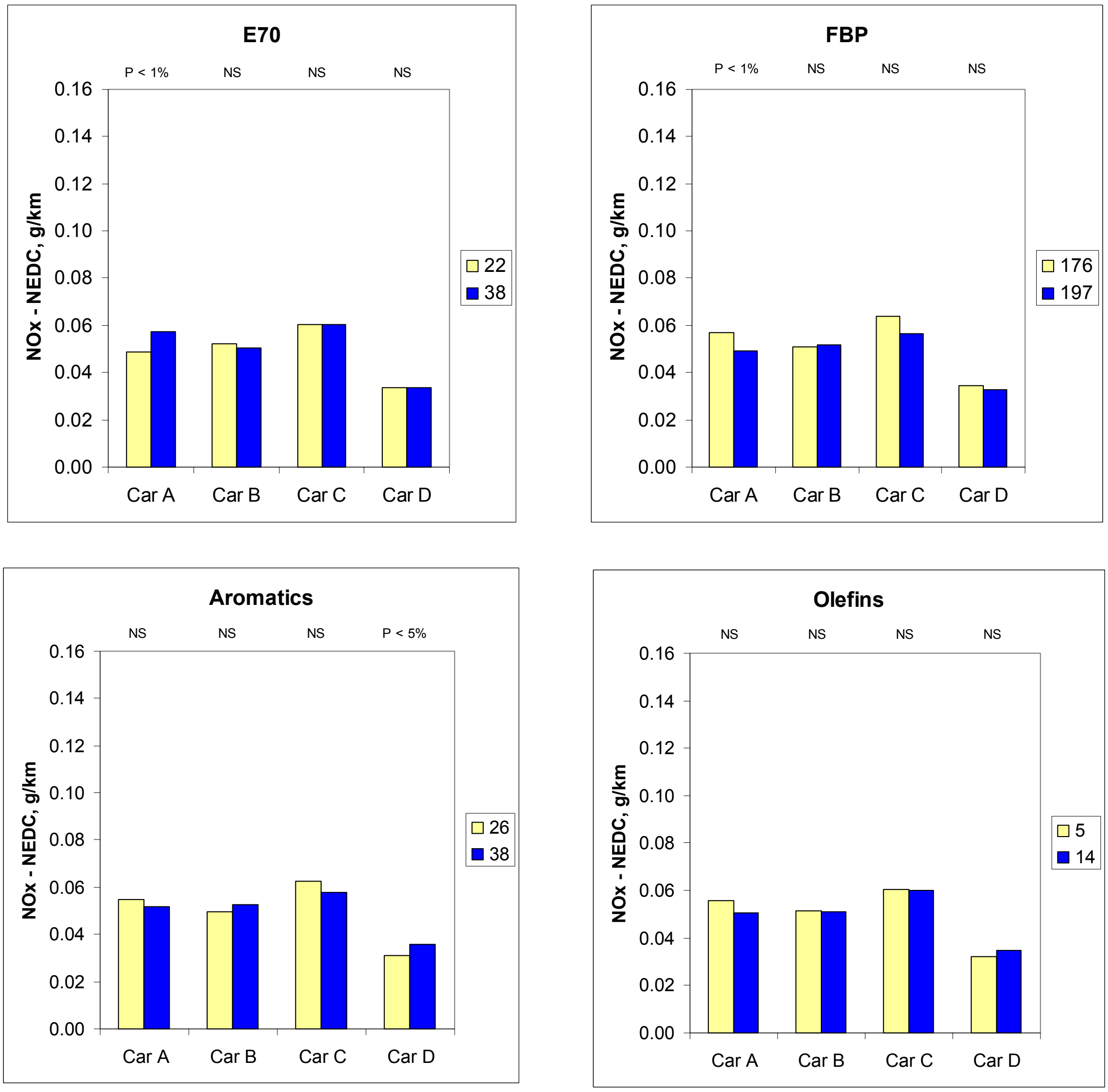
***Table 5*** Mean fuel property values studied

| Fuel property | High | Low |
|---|---|---|
| E70, % v/v | 38 | 22 |
| FBP, deg C | 197 | 176 |
| Aromatics, % v/v | 38 | 26 |
| Olefins, % v/v | 14 | 5 |

The results are shown graphically on the following pages, illustrating the fuel effects for each emission and car. Each plot shows the estimated emissions for the higher and lower values of the design variables (calculated at the average levels of the other three design variables as described in **Section 5**). Front/mid range volatility effects are represented by E70, however they could be equally described in terms of E100, since the two parameters were closely correlated in the fuel matrix. The statistical significance of differences between the high and low levels of the fuel parameters are given on the graphs (NS = Not Significant, P<5% = 95% confidence, P<1% = 99% confidence, P<0.1% = 99.9% confidence).

### 6.2.1. NOx emissions

*Figure 5* NEDC emissions analysis – NOx



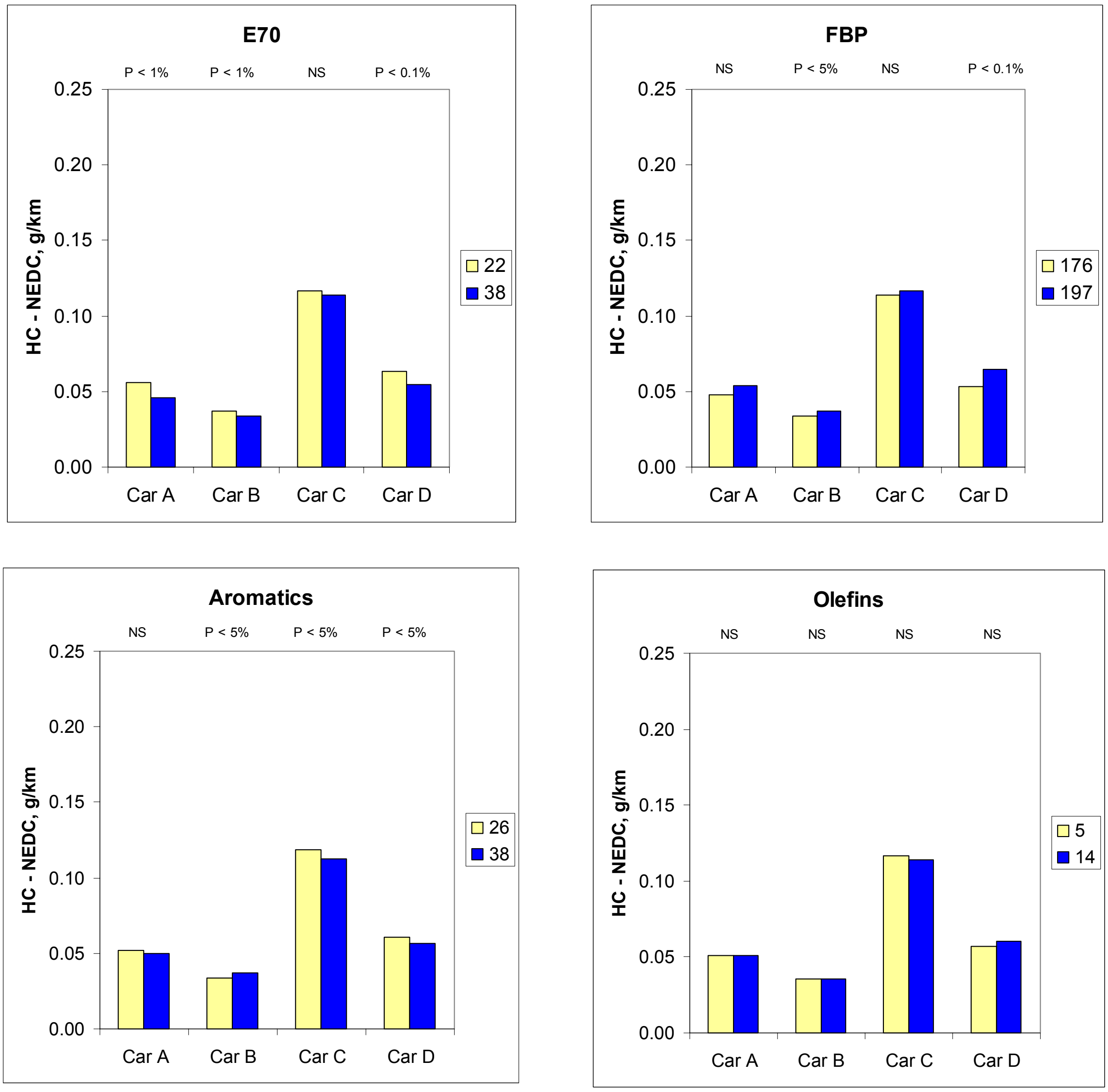
All four cars met the Euro-4 NOx emissions limit of 0.08g/km.

Three out of the four cars tested showed no impact of front/mid range volatility on NOx emissions. Only car A, the stoichiometric DI, showed a significant effect, with NOx increasing with higher volatility. Lowering FBP directionally increased NOx emissions in the 3 DI cars, although significant only in car A. There was no effect of FBP in the MPI car B.

Reducing aromatics yielded conflicting trends. The effects were not significant on NOx emissions in 3 cars. Car D, a lean DI, showed a small but significant decrease in NOx emissions with lower aromatics. Reducing olefins yielded no significant effect on NOx emissions in any car.

### 6.2.2. HC Emissions

***Figure 6*** NEDC emissions analysis – HC



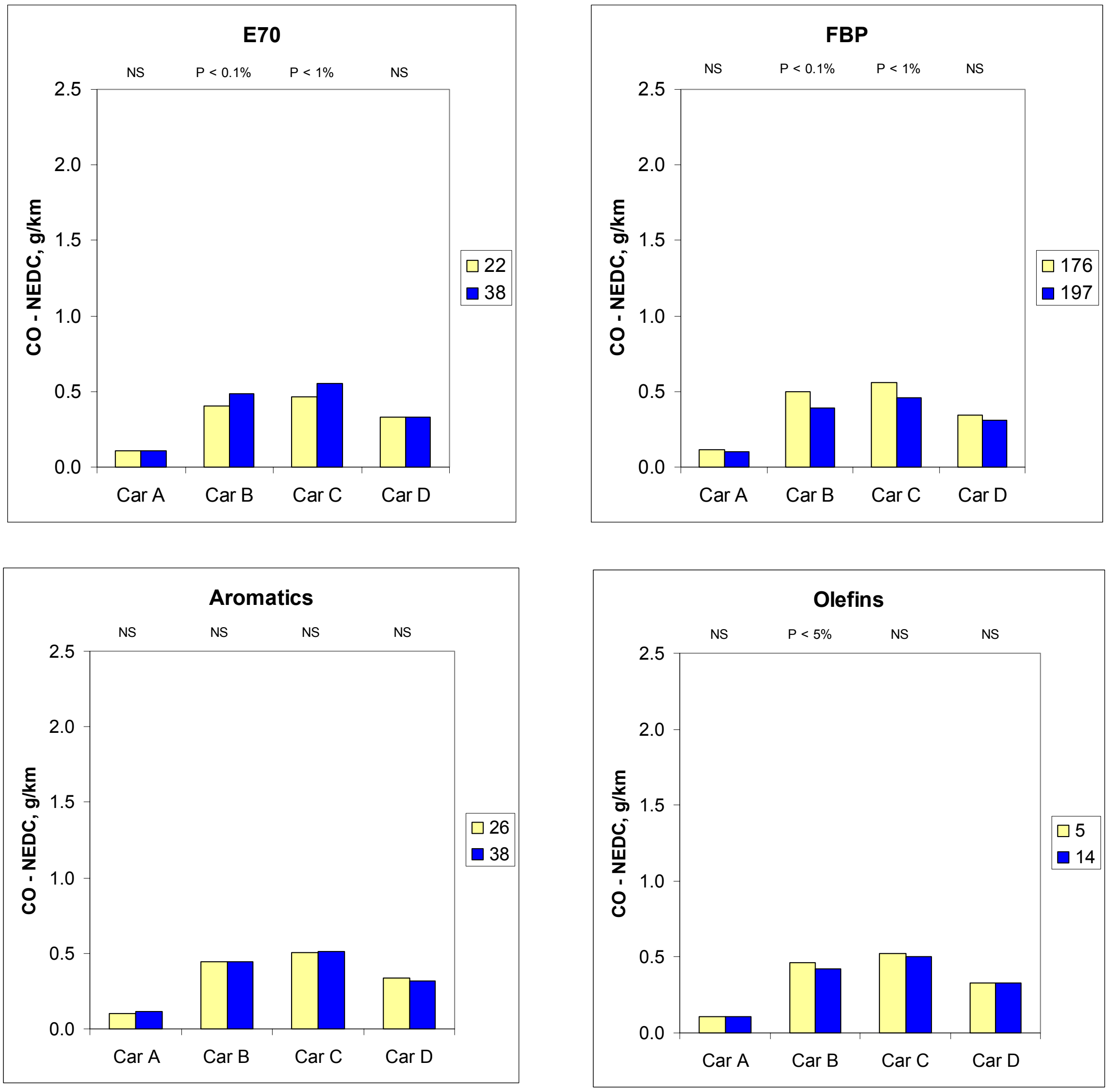
All of the cars met their HC emissions certification limits. Three of the cars met the Euro-4 limit for HC emissions of 0.10 g/km.

Decreasing front/mid range volatility (i.e. E70 decreasing from 38% to 22%) increased HC emissions in all four vehicles, and was significant in 3 cases. The overall average increase was 0.006 g/km (10%). Reducing FBP (from 197°C to 176°C) also reduced HC emissions in all four cars, and was significant in two cases. The overall average decrease was 0.006 g/km (9%).

Reducing aromatics (from 38% v/v to 26% v/v) increased HC emissions in all three DI cars, and was significant in two cases. The average increase in the DI cars was 0.004 g/km (5%). Car B, the advanced MPI car, showed a significant effect in the opposite direction. Reducing olefins had no significant effect on HC emissions in any of the four vehicles.

### 6.2.3. CO Emissions

***Figure 7*** NEDC emissions analysis – CO



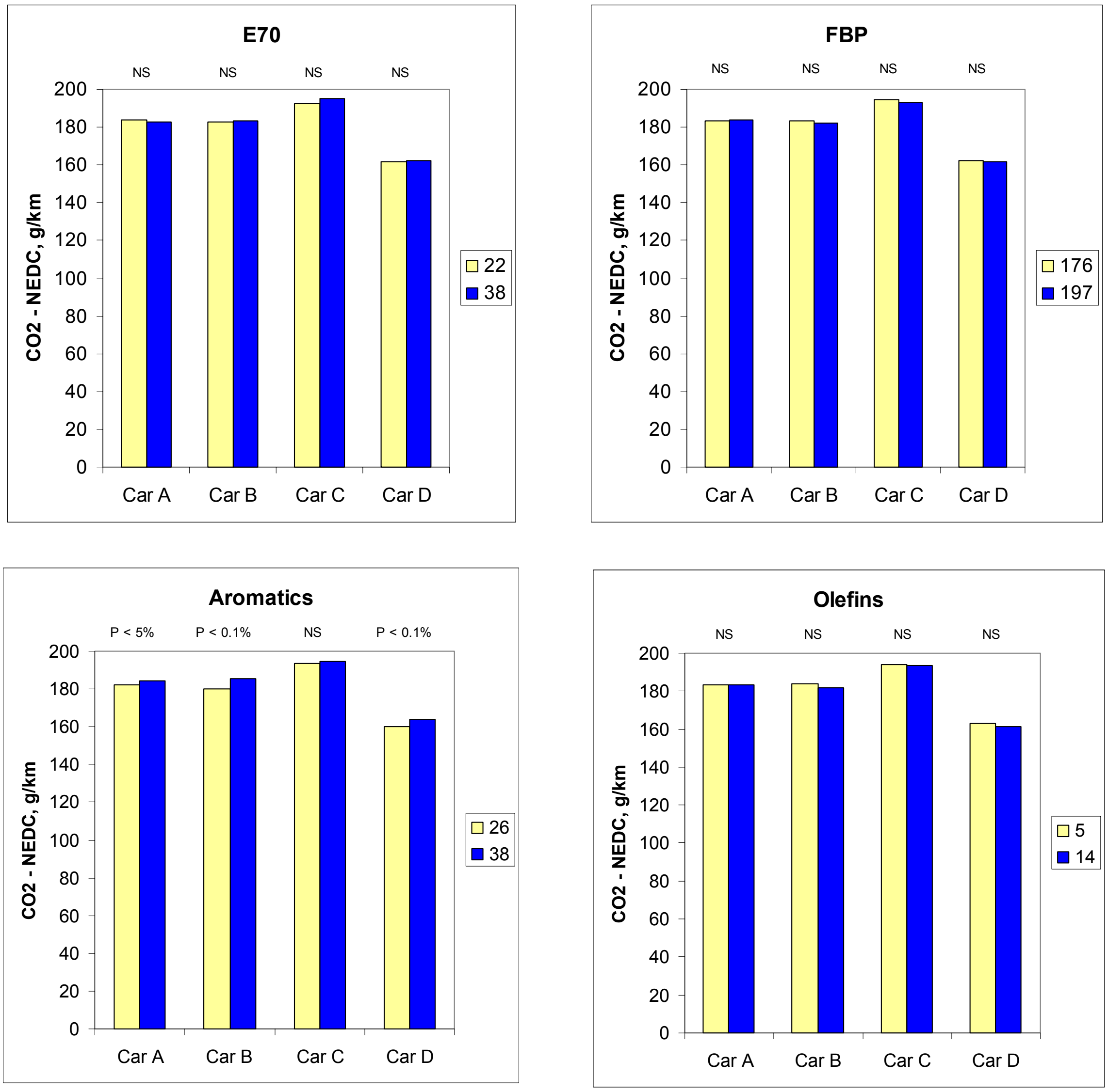
All the test vehicles met the Euro-4 CO limit of 1.0 g/km.

Decreasing front/mid range volatility gave a significant reduction in CO emissions in the lean DI car C and in the advanced MPI vehicle. It had no effect in the other two vehicles. Reducing FBP (from 197°C to 176°C) directionally increased CO emissions in all four vehicles but the effect was significant only in cars B and C. The overall average increase was 0.064 g/km (20%) and mainly arose from the ECE part of the test.

Changing aromatics content had no effect on CO emissions in any of the cars. Olefin effects on CO emissions were small. Only the advanced MPI vehicle showed a significant effect, with CO emissions increasing with lower olefins content.

### 6.2.4. $CO_2$ Emissions

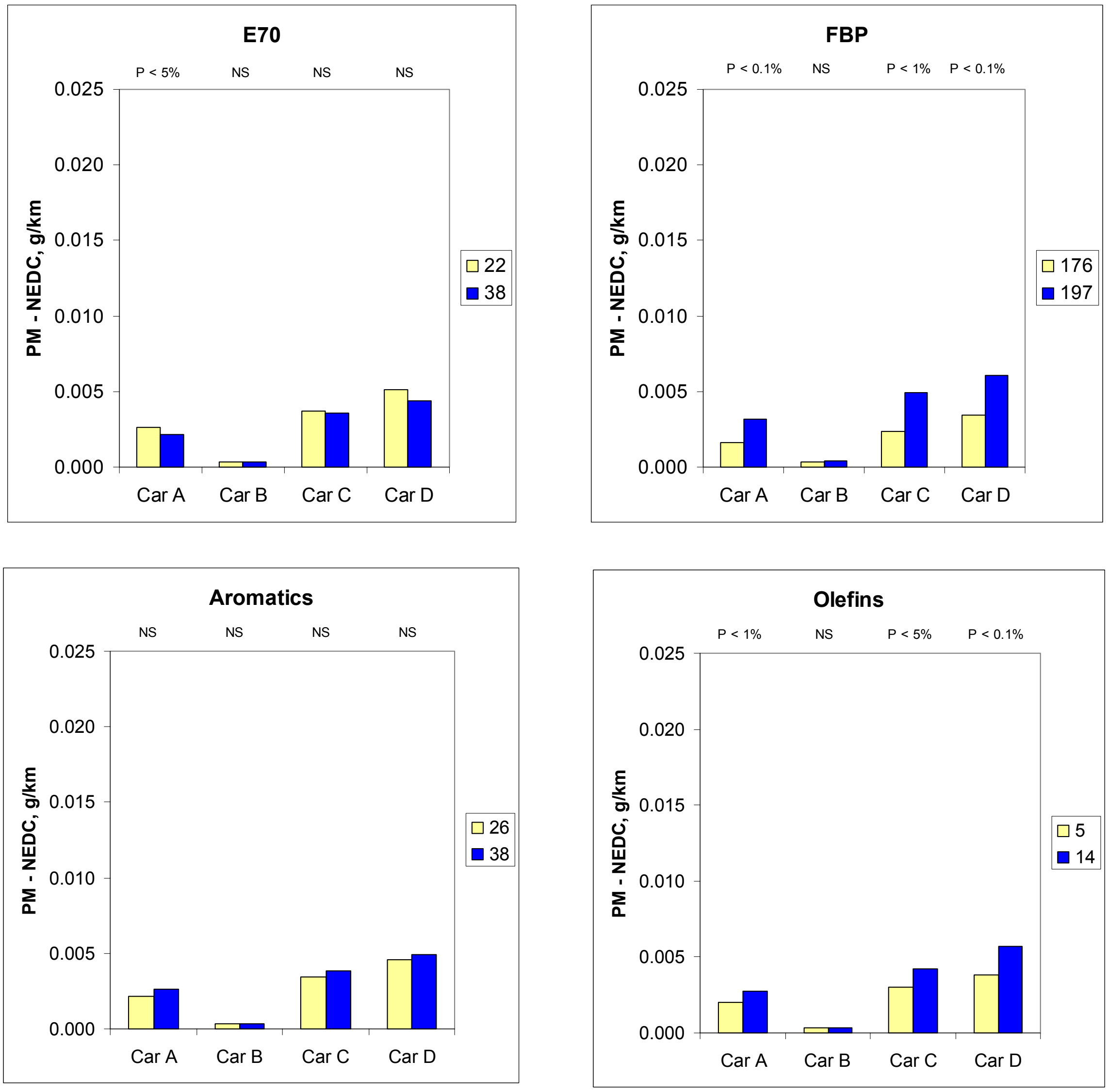
***Figure 8*** NEDC emissions data – $CO_2$



$CO_2$ emissions have been considered here although not currently a regulated emission. The only fuel property to have an influence on $CO_2$ emissions was aromatics. Reducing aromatics content reduced vehicle $CO_2$ emissions, as expected from the carbon content of the fuels. However, the overall $CO_2$ balance would need to be considered on a well-to-wheels basis.

### 6.2.5. PM Emissions

***Figure 9*** NEDC emissions analysis – PM



Although PM emissions are not currently regulated for spark ignition engines, it is known that DI gasoline vehicles can produce more emissions of particulates than MPI cars. However, emissions from all four test vehicles were substantially below the Euro-4 diesel car PM limit of 0.025 g/km.

For the advanced MPI vehicle, PM emissions were very low and there were no effects of changes in fuel properties over the NEDC. A small reduction was seen over the ECE cycle as FBP was reduced.

The stoichiometric and lean DI vehicles tested both produced higher PM emissions than the MPI car, although still well below the Euro-4 diesel limit. Emissions were reduced for fuels with lower FBP and lower olefins. Directional but not significant reductions were also seen with lower aromatics. Higher front/mid range volatility directionally reduced PM emissions in the three DI cars, significant only in car A.

The impact of changing fuel properties on PM emissions was similar over the ECE and EUDC parts of the NEDC, although the majority of the PM emissions occurred in the ECE, indicating the importance of the cold-start / warm-up phase.

As illustrated by the advanced MPI vehicle, PM emissions are very low when the fuel/air mixture is premixed. The fuel injection and mixing process in the DI cars will also be an important parameter in controlling PM emissions. DI gasoline vehicle technology is still at an early stage and PM emission control can be expected to improve as this new technology evolves.

# 7. CONCLUSIONS

- The four advanced technology, Euro-3 and Euro-4, vehicles tested all achieved their respective emissions certification limits and in most cases regulated emissions of CO, HC and NOx, were lower than the Euro-4 limits.
- A reduction in fuel volatility, representing the combined effects of vapour pressure, E70 (38% v/v to 22% v/v) and E100, had no consistent effect on NOx emissions, increased HC across all vehicle technologies (10%), but decreased CO emissions in two cars.
- A reduction in FBP from 197ºC to 176ºC increased NOx emissions in one car but had no significant effect in the others. HC emissions were directionally reduced (9%) and CO emissions directionally increased (20%), with significant effects in both cases in two cars.
- A reduction in aromatics content from 38% v/v to 26% v/v showed conflicting effects, increasing NOx emissions in two cars, decreasing in the others, but the effects were significant only in one vehicle. Reducing aromatics increased HC emissions in the two lean DI cars but showed the opposite effect in the MPI car.
- A reduction in olefins content from 14% v/v to 5% v/v gave no significant improvement in NOx, HC or CO emissions in any of the cars.
- The lean burn direct injection cars produced higher particulate mass (PM) emissions than the stoichiometric direct injection car which, in turn, produced higher PM emissions than the advanced MPI car. However, even the highest emitting lean direct injection car produced PM emissions which were much lower than the Euro 4 diesel PM emission limit.
- The stoichiometric and lean DI vehicles showed a similar response in PM emissions to changes in fuel quality. Lowering FBP and lowering olefins content gave a reduction in PM emissions whereas lowering aromatics and volatility showed no significant benefits. PM emissions from the advanced MPI car, which is more representative of the current fleet, were very low on all fuels tested and insensitive to fuel changes.

# 8. GLOSSARY

| | |
|---|---|
| AFR | Air Fuel Ratio |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| DI | Direct Injection |
| DVPE | Dry Vapour Pressure Equivalent |
| E70 | % v/v of gasoline evaporated at 70°C |
| E100 | % v/v of gasoline evaporated at 100°C |
| E150 | % v/v of gasoline evaporated at 150°C |
| ECE | Urban driving part of the NEDC |
| EPEFE | European Programme on Emissions, Fuels and Engine Technologies |
| EUDC | Extra Urban part of the NEDC |
| FC | Fuel consumption |
| FBP | Final Boiling Point |
| HC | Hydrocarbons |
| LHV | Lower Heating Value |
| MPI | Multi-point injection |
| NEDC | New European Drive Cycle (=ECE + EUDC) |
| NOx | Nitrogen Oxides |
| PM | Particulate Mass |
| RPM | Revolutions per minute |
| SD | Standard Deviation |
| TP | Tailpipe |
| TWC | Three-way catalyst |

# 9. REFERENCES

1. EPEFE (1995) European programme on emissions, fuels and engine technologies. EPEFE Report on behalf of ACEA and EUROPIA

2. CONCAWE (2003) Fuel effects on emissions from modern gasoline vehicles – part 1 – sulphur effects. Report No. 5/03. Brussels: CONCAWE

3. CONCAWE (2002) Evaluation of diesel fuel cetane and aromatics effects on emissions from euro-3 engines. Report No. 4/02. Brussels: CONCAWE

4. EU (1998) Directive 98/69/EC of the European Parliament and of the Council of 13 October 1998 relating to measures to be taken against air pollution by emissions from motor vehicles and amending Council Directive 70/220/EEC. Official Journal of the European Communities No. L350, 28.12.1998

5. Hochhauser, A.M. et al (1991) The effects of aromatics, MTBE, olefins and T90 on mass exhaust emissions from current and older vehicles - the auto/oil air quality improvement research program. SAE Paper No. 912322. Warrendale PA: Society of Automotive Engineers

6. Painter, L.J. and Rutherford, J.A. (1992) Statistical design and analysis methods for the auto/oil air quality research program. SAE Paper No. 920319. Warrendale PA: Society of Automotive Engineers

7. CONCAWE (1994) The influence of heavy gasoline components on the exhaust emissions of European vehicles. Part I - regulated emissions. Report No. 94/59. Brussels: CONCAWE

# APPENDIX 1 STATISTICAL DATA ANALYSIS

This appendix provides additional information on the statistical design and data analyses discussed in **Sections 2, 5 and 6**.

***Fuel matrix***

The target properties in the fuel matrix were generated using a half-replicate of a 2 × 2 × 2 × 2 factorial design testing lower and upper levels of E70, FBP, aromatics and olefins as shown in **Table A.1.1**:

***Table A.1.1*** Fuel matrix – Experimental design

| Fuel | E70 | FBP | Aromatics | Olefins |
|---|---|---|---|---|
| **F1** | L | L | L | L |
| **F2** | H | L | H | L |
| **F3** | H | L | L | H |
| **F4** | L | L | H | H |
| **F5** | H | H | L | L |
| **F6** | L | H | H | L |
| **F7** | L | H | L | H |
| **F8** | H | H | H | H |

E100 and RVP were varied in tandem with E70 and so the effects of these three factors cannot be disentangled in the subsequent data analysis. Variations in other factors such as sulphur content, E150, RON and MON were kept as small as possible.

The data generated by such a design would normally be analysed using analysis of variance techniques. The effect of each factor is determined by comparing the mean emission value for the 4 fuels at the higher level of that factor with the mean for the 4 lower level fuels. Thus the effect of FBP on CO would be measured by comparing the mean CO value over fuels F5-F8 with the mean over fuels F1-F4.

Unfortunately it is very difficult to blend fuel sets that meet target properties exactly. Properties are difficult to manipulate independently as some are compositional (aromatics, olefins), others are physical (E70, E100, E150, FBP) and yet others are performance related (RON, MON).

Multiple regression techniques can be used to perform analyses based on actual fuel properties rather than targets with models of the form

$$\text{emission} = a + b \times \text{E70} + c \times \text{FBP} + d \times \text{aromatics} + e \times \text{olefins}$$

being fitted to the data.

The half-replicate design allowed four factors to be tested with 8 fuels rather than three but places some limitations on the subsequent statistical analysis. As a consequence, it is not practicable to fit more complex models with cross-product (e.g. $f \times \text{E70} \times \text{aromatics}$) or quadratic (e.g. $g \times \text{FBP}^2$) terms.

### *Variability in test measurements*

The standard deviations in **Table A.1.2** quantify the levels of variability observed within sets of repeat results on the same fuel in the same vehicle in parts 1 (sulphur matrix) and 2 (main matrix) of the present programme. Variability levels observed in the earlier EPEFE programme [1] are also included for comparison.

***Table A.1.2*** Variability within sets of repeat results conducted on the same fuel in the same vehicle (NEDC)

| | **CO (g/km)** | | **HC (g/km)** | | **NOx (g/km)** | | **CO$_2$ (g/km)** | | **PM (g/km)** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **EPEFE**[2] | | | | | | | | | | |
| Typical vehicle | 1.417 | 10.1% | 0.173 | 11.2% | 0.172 | 12.0% | | | | |
| **Sulphur matrix (part 1)** | | | | | | | | | | |
| Vehicle A | 0.089 | 18.6% | 0.046 | 7.7% | 0.083 | 25.9% | 178.0 | 1.1% | 0.0015 | 18.7% |
| Vehicle B | 0.523 | 12.1% | 0.033 | 11.5% | 0.046 | 14.7% | 177.9 | 1.5% | 0.0004 | 33.2% |
| Vehicle C | 0.543 | 8.3% | 0.113 | 6.6% | 0.075 | 14.5% | 184.1 | 2.1% | 0.0028 | 35.7% |
| Vehicle D | 0.389 | 7.7% | 0.053 | 8.8% | 0.030 | 16.3% | 162.5 | 1.6% | 0.0026 | 16.0% |
| **Main matrix (part 2)** | | | | | | | | | | |
| Vehicle A | 0.109 | 17.4% | 0.051 | 14.8% | 0.053 | 11.7% | 183.4 | 1.5% | 0.0025 | 26.9% |
| Vehicle B | 0.448 | 9.3% | 0.035 | 10.7% | 0.052 | 17.7% | 183.0 | 1.3% | 0.0004 | 59.7% |
| Vehicle C | 0.515 | 13.8% | 0.115 | 5.9% | 0.061 | 24.0% | 194.3 | 3.7% | 0.0039 | 44.7% |
| Vehicle D | 0.329 | 17.6% | 0.059 | 9.2% | 0.034 | 16.1% | 162.2 | 1.3% | 0.0049 | 22.8% |

Variations in Part 2 of the present programme are similar to those seen in the sulphur study in Part 1. The variations in HC results in Part 2 are comparable with EPEFE in relative terms, despite the much lower levels of emissions. Variations in NOx and CO results, however, while lower in absolute terms than EPEFE are higher in relative terms. Variations in PM emissions were small on an absolute scale but large on a percentage basis.

**Table A.1.3** quantifies how large a measured fuel effect (i.e. E70, FBP, aromatics or olefins) needs to be in order to be declared statistically significant at $P < 5\%$[3] (where the measured fuel effect is the average difference in emissions between the 4 fuels coded “L” and the 4 fuels coded “H” in the corresponding column in **Table A.1.1**).

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[2] The EPEFE SDs quantify the variability observed between independent (i.e. not back-to-back) single tests on the same fuel in the same vehicle in the EPEFE programme [1].

[3] $P < 5\%$ = the probability that such an event could be observed by chance when no real effect exists is less than 5%. In other words, we are 95% confident that the effect is real.

***Table A.1.3*** Minimum measured fuel effects needed for statistical significance.

| | | **CO (g/km)** | **HC (g/km)** | **NOx (g/km)** | **$CO_2$ (g/km)** | **PM (g/km)** |
|---|---|---|---|---|---|---|
| Prior estimate | Vehicle A, B, C or D | 13.2% | 14.7% | 15.8% | | |
| Actual | Vehicle A | 23.7% | 19.9% | 15.4% | 1.8% | 39.0% |
| | Vehicle B | 12.1% | 14.0% | 24.2% | 1.6% | 107.7% |
| | Vehicle C | 18.5% | 7.4% | 34.2% | 4.7% | 72.8% |
| | Vehicle D | 24.0% | 11.9% | 21.8% | 1.6% | 32.2% |
| *Prior estimate* | *4-vehicle fleet* | *6.0%* | *6.7%* | *7.2%* | | |
| *Actual* | *4-vehicle fleet* | *9.0%* | *6.3%* | *10.9%* | *1.3%* | *26.9%* |
| This table gives the least significant difference (LSD) in emissions (on a percentage basis) at P < 5% (two-sided) between the higher and lower levels of each design variable (E70, FBP, aromatics, olefins) in a simple analysis of variance if three independent tests are conducted on each fuel in each vehicle. The LSDs for the 4-vehicle fleet relate to fuel effects averaged over the 4 chosen vehicles A to D and are not applicable to estimates of fuel effects over a more general vehicle population. | | | | | | |

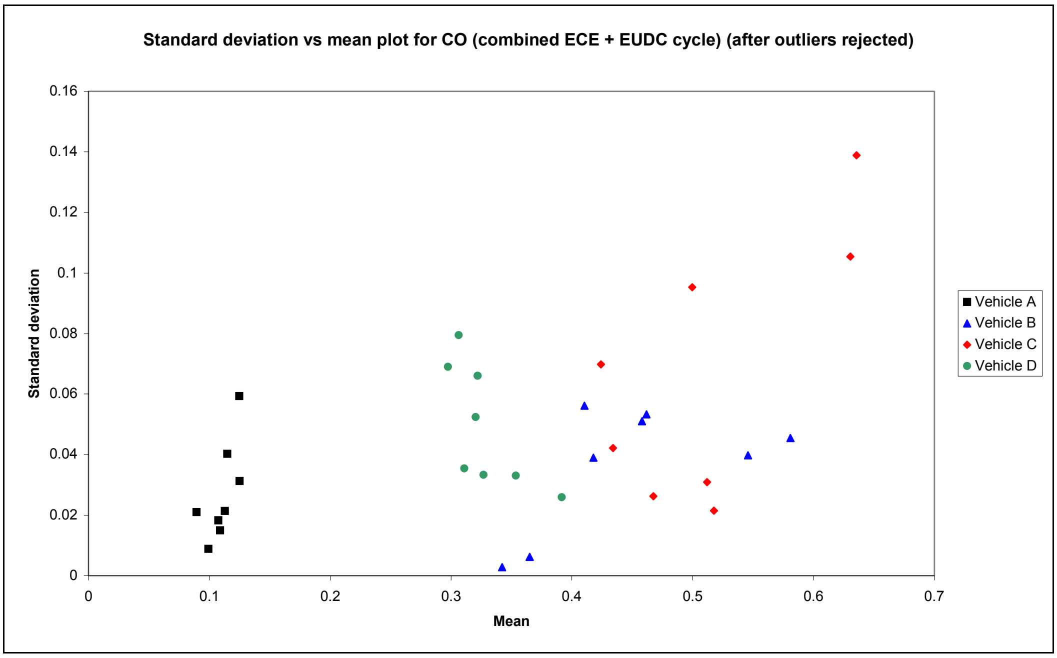
The "prior estimates" in **Table A.1.3** are the forecasts made at the experimental design stage assuming that variability levels would be similar to those seen in EPEFE (in percentage terms). In the event, CO and NOx effects needed to be larger than expected in relative terms. Nevertheless, the programme had sufficient replication for significant effects to be detected, even for PM.

***Standard deviation vs. mean plots***

The distributions of sets of repeat measurements of automotive emissions or atmospheric concentrations are typically asymmetric or "skewed" and bear little resemblance to the standard bell-shaped normal or "Gaussian" distribution. In the EPEFE gasoline project [1] and other previous emission studies [3,5,6,7], the variability in emissions measurements has been found to follow the lognormal distribution with the degree of scatter increasing as the emission level increases.

**Figure A1.1** is a typical standard deviation vs. mean graph plotting the S.D. of the three or four CO measurements for each of the 32 vehicle × fuel combinations in the present study against the mean. Looking at each vehicle in turn, the data supports the general hypothesis that the S.D. increases with the mean. Therefore it is assumed that the measurements in the present study do follow the lognormal distribution. The lognormal is the most plausible model for emissions data mechanistically.

***Figure A1.1*** Typical S.D. vs mean plot



### *Arithmetic means and regression analysis*

In this report, arithmetic means are used to summarise the average emissions using each fuel in each vehicle, in line with EPEFE [2]. Geometric means are sometimes used in emissions studies as they give excellent comparisons between fuels on a percentage basis. However, they have the disadvantage of underestimating total emissions to the atmosphere.

Weighted regression analysis was used to relate emissions to fuel properties as the emissions measurements were assumed to have lognormal distribution. When fitting models, each emission measurement was thus assigned a weight equal to

$$\text{weight} = 1 / (\text{mean emission for that fuel and vehicle})^2$$

See also Annex 05 of the EPEFE report [2].

In **Figures 1 to 4** and **Figures A.3.1 to A.3.8** in this report, "error bars" are shown around the average emissions for the various fuels. These have been constructed so that when two fuels are significantly different from one another at $P < 5\%$, their error bars will not overlap, as in EPEFE. We can be 84% confident that the true means lie within the limits shown.

# APPENDIX 2 EMISSIONS FOR EACH VEHICLE × FUEL COMBINATION (ARITHMETIC MEANS)

| Car | Fuel | CO (g/km) | | | | | | HC (g/km) | | | NOx (g/km) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | NEDC | | ECE | | EUDC | | NEDC | ECE | EUDC | NEDC | ECE | EUDC | |
| | | Uncorrected | Corrected | Uncorrected | Corrected | Uncorrected | Corrected | Uncorrected | Uncorrected | Uncorrected | Uncorrected | Uncorrected | Uncorrected | Corrected |
| **A** | **F1** | 0.107 | 0.106 | 0.204 | 0.201 | 0.051 | | 0.057 | 0.151 | 0.002 | 0.057 | 0.109 | 0.026 | |
| **A** | **F2** | 0.115 | 0.113 | 0.216 | 0.217 | 0.056 | | 0.042 | 0.111 | 0.002 | 0.057 | 0.106 | 0.029 | |
| **A** | **F3** | 0.125 | 0.120 | 0.229 | 0.226 | 0.064 | | 0.044 | 0.116 | 0.002 | 0.067 | 0.123 | 0.035 | |
| **A** | **F4** | 0.113 | 0.113 | 0.244 | 0.242 | 0.037 | | 0.053 | 0.140 | 0.002 | 0.045 | 0.090 | 0.019 | |
| **A** | **F5** | 0.089 | 0.090 | 0.196 | 0.195 | 0.027 | | 0.048 | 0.127 | 0.002 | 0.057 | 0.111 | 0.026 | |
| **A** | **F6** | 0.125 | 0.125 | 0.248 | 0.249 | 0.054 | | 0.066 | 0.176 | 0.002 | 0.048 | 0.087 | 0.026 | |
| **A** | **F7** | 0.099 | 0.095 | 0.227 | 0.217 | 0.025 | | 0.054 | 0.142 | 0.002 | 0.045 | 0.082 | 0.023 | |
| **A** | **F8** | 0.109 | 0.110 | 0.217 | 0.218 | 0.046 | | 0.047 | 0.125 | 0.002 | 0.051 | 0.098 | 0.024 | |
| **B** | **F1** | 0.462 | | 1.204 | | 0.028 | 0.033 | 0.033 | 0.083 | 0.004 | 0.047 | 0.112 | 0.010 | 0.011 |
| **B** | **F2** | 0.581 | | 1.496 | | 0.046 | 0.047 | 0.035 | 0.088 | 0.004 | 0.057 | 0.134 | 0.012 | 0.012 |
| **B** | **F3** | 0.546 | | 1.407 | | 0.042 | 0.044 | 0.030 | 0.074 | 0.004 | 0.050 | 0.121 | 0.009 | 0.009 |
| **B** | **F4** | 0.410 | | 1.036 | | 0.046 | 0.043 | 0.039 | 0.096 | 0.005 | 0.053 | 0.126 | 0.010 | 0.009 |
| **B** | **F5** | 0.458 | | 1.156 | | 0.051 | 0.050 | 0.034 | 0.084 | 0.005 | 0.048 | 0.113 | 0.010 | 0.009 |
| **B** | **F6** | 0.342 | | 0.851 | | 0.046 | 0.045 | 0.041 | 0.104 | 0.005 | 0.055 | 0.128 | 0.012 | 0.011 |
| **B** | **F7** | 0.365 | | 0.929 | | 0.037 | 0.035 | 0.036 | 0.088 | 0.005 | 0.054 | 0.128 | 0.011 | 0.011 |
| **B** | **F8** | 0.418 | | 1.077 | | 0.034 | 0.034 | 0.035 | 0.087 | 0.005 | 0.049 | 0.116 | 0.010 | 0.010 |
| **C** | **F1** | 0.512 | | 1.273 | | 0.067 | | 0.122 | 0.308 | 0.014 | 0.062 | 0.124 | 0.026 | |
| **C** | **F2** | 0.630 | | 1.490 | | 0.128 | | 0.112 | 0.290 | 0.008 | 0.066 | 0.133 | 0.026 | |
| **C** | **F3** | 0.636 | | 1.392 | | 0.193 | | 0.112 | 0.289 | 0.008 | 0.062 | 0.143 | 0.015 | |
| **C** | **F4** | 0.467 | | 1.191 | | 0.044 | | 0.111 | 0.282 | 0.011 | 0.065 | 0.086 | 0.053 | |
| **C** | **F5** | 0.500 | | 1.157 | | 0.114 | | 0.119 | 0.295 | 0.016 | 0.064 | 0.119 | 0.032 | |
| **C** | **F6** | 0.424 | | 1.003 | | 0.085 | | 0.115 | 0.284 | 0.016 | 0.048 | 0.073 | 0.033 | |
| **C** | **F7** | 0.434 | | 1.100 | | 0.044 | | 0.119 | 0.297 | 0.015 | 0.067 | 0.103 | 0.046 | |
| **C** | **F8** | 0.518 | | 1.236 | | 0.098 | | 0.113 | 0.287 | 0.012 | 0.052 | 0.090 | 0.030 | |
| **D** | **F1** | 0.354 | | 0.824 | | 0.079 | | 0.058 | 0.135 | 0.013 | 0.033 | 0.036 | 0.031 | |
| **D** | **F2** | 0.322 | | 0.748 | | 0.074 | | 0.048 | 0.117 | 0.008 | 0.032 | 0.047 | 0.023 | |
| **D** | **F3** | 0.392 | | 0.910 | | 0.089 | | 0.051 | 0.118 | 0.013 | 0.037 | 0.035 | 0.038 | |
| **D** | **F4** | 0.320 | | 0.670 | | 0.116 | | 0.058 | 0.138 | 0.011 | 0.037 | 0.042 | 0.033 | |
| **D** | **F5** | 0.306 | | 0.691 | | 0.082 | | 0.058 | 0.136 | 0.012 | 0.029 | 0.037 | 0.024 | |
| **D** | **F6** | 0.311 | | 0.669 | | 0.102 | | 0.069 | 0.168 | 0.012 | 0.038 | 0.040 | 0.036 | |
| **D** | **F7** | 0.327 | | 0.740 | | 0.086 | | 0.070 | 0.168 | 0.013 | 0.029 | 0.039 | 0.023 | |
| **D** | **F8** | 0.297 | | 0.700 | | 0.062 | | 0.057 | 0.138 | 0.010 | 0.037 | 0.043 | 0.033 | |

See Sections 5 and 6.1 for details on analysis and calculations of mean values.

| Car | Fuel | $CO_2$ (g/km) | | | PM (g/km) | | | | | | FC (l/100 km) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | NEDC | ECE | EUDC | NEDC | | ECE | | EUDC | | NEDC | ECE | EUDC |
| | | Uncorrected | Uncorrected | Uncorrected | Uncorrected | Corrected | Uncorrected | Corrected | Uncorrected | Corrected | Uncorrected | Uncorrected | Uncorrected |
| A | F1 | 183.2 | 232.6 | 154.4 | 0.0013 | 0.0013 | 0.0017 | 0.0017 | 0.0010 | 0.0010 | 7.877 | 10.018 | 6.632 |
| A | F2 | 183.2 | 233.2 | 154.0 | 0.0013 | 0.0013 | 0.0013 | 0.0014 | 0.0012 | 0.0013 | 7.551 | 9.627 | 6.341 |
| A | F3 | 181.4 | 229.5 | 153.3 | 0.0013 | 0.0012 | 0.0017 | 0.0016 | 0.0011 | 0.0010 | 7.710 | 9.769 | 6.510 |
| A | F4 | 185.4 | 235.0 | 156.5 | 0.0031 | 0.0029 | 0.0056 | 0.0052 | 0.0017 | 0.0015 | 7.630 | 9.687 | 6.433 |
| A | F5 | 182.2 | 230.6 | 154.1 | 0.0026 | 0.0024 | 0.0049 | 0.0045 | 0.0013 | 0.0012 | 7.758 | 9.833 | 6.552 |
| A | F6 | 185.7 | 236.4 | 156.3 | 0.0048 | 0.0049 | 0.0100 | 0.0103 | 0.0018 | 0.0018 | 7.584 | 9.669 | 6.373 |
| A | F7 | 182.2 | 231.1 | 153.8 | 0.0029 | 0.0026 | 0.0057 | 0.0053 | 0.0012 | 0.0011 | 7.818 | 9.934 | 6.589 |
| A | F8 | 184.4 | 234.0 | 155.6 | 0.0033 | 0.0034 | 0.0060 | 0.0061 | 0.0018 | 0.0018 | 7.724 | 9.815 | 6.507 |
| B | F1 | 180.5 | 257.6 | 135.5 | 0.0003 | | 0.0004 | | 0.0003 | | 7.785 | 11.148 | 5.820 |
| B | F2 | 187.8 | 269.8 | 139.9 | 0.0004 | | 0.0003 | | 0.0004 | | 7.770 | 11.210 | 5.761 |
| B | F3 | 181.5 | 258.9 | 136.3 | 0.0002 | | 0.0003 | | 0.0002 | | 7.742 | 11.088 | 5.786 |
| B | F4 | 184.9 | 263.9 | 138.9 | 0.0003 | | 0.0002 | | 0.0004 | | 7.627 | 10.922 | 5.709 |
| B | F5 | 181.1 | 257.9 | 136.4 | 0.0005 | | 0.0006 | | 0.0005 | | 7.736 | 11.051 | 5.804 |
| B | F6 | 186.1 | 267.0 | 138.9 | 0.0003 | | 0.0004 | | 0.0003 | | 7.610 | 10.946 | 5.664 |
| B | F7 | 178.5 | 254.7 | 134.1 | 0.0004 | | 0.0006 | | 0.0002 | | 7.676 | 10.985 | 5.748 |
| B | F8 | 183.7 | 262.4 | 137.8 | 0.0008 | | 0.0005 | | 0.0010 | | 7.712 | 11.054 | 5.765 |
| C | F1 | 193.7 | 244.0 | 164.2 | 0.0016 | | 0.0027 | | 0.0009 | | 8.364 | 10.602 | 7.056 |
| C | F2 | 200.1 | 252.0 | 169.8 | 0.0018 | | 0.0035 | | 0.0009 | | 8.292 | 10.504 | 6.999 |
| C | F3 | 195.4 | 249.5 | 163.8 | 0.0024 | | 0.0042 | | 0.0013 | | 8.350 | 10.720 | 6.964 |
| C | F4 | 190.9 | 251.4 | 155.4 | 0.0038 | | 0.0075 | | 0.0015 | | 7.887 | 10.444 | 6.390 |
| C | F5 | 191.8 | 242.3 | 162.2 | 0.0052 | | 0.0073 | | 0.0040 | | 8.205 | 10.419 | 6.907 |
| C | F6 | 191.3 | 246.7 | 158.9 | 0.0067 | | 0.0128 | | 0.0032 | | 7.839 | 10.152 | 6.484 |
| C | F7 | 193.1 | 237.9 | 166.8 | 0.0038 | | 0.0070 | | 0.0019 | | 8.316 | 10.305 | 7.151 |
| C | F8 | 198.1 | 249.9 | 167.9 | 0.0057 | | 0.0109 | | 0.0027 | | 8.333 | 10.567 | 7.028 |
| D | F1 | 160.0 | 213.6 | 128.7 | 0.0027 | | 0.0052 | | 0.0013 | | 6.901 | 9.243 | 5.534 |
| D | F2 | 165.8 | 221.6 | 133.3 | 0.0023 | | 0.0042 | | 0.0012 | | 6.851 | 9.181 | 5.492 |
| D | F3 | 160.2 | 214.1 | 128.8 | 0.0034 | | 0.0064 | | 0.0017 | | 6.831 | 9.161 | 5.471 |
| D | F4 | 163.7 | 218.7 | 131.6 | 0.0060 | | 0.0118 | | 0.0026 | | 6.754 | 9.047 | 5.415 |
| D | F5 | 162.4 | 217.2 | 130.4 | 0.0053 | | 0.0105 | | 0.0023 | | 6.931 | 9.299 | 5.550 |
| D | F6 | 163.2 | 218.0 | 131.3 | 0.0074 | | 0.0147 | | 0.0032 | | 6.679 | 8.946 | 5.358 |
| D | F7 | 159.6 | 213.1 | 128.4 | 0.0054 | | 0.0105 | | 0.0024 | | 6.869 | 9.200 | 5.508 |
| D | F8 | 162.2 | 216.8 | 130.4 | 0.0064 | | 0.0133 | | 0.0024 | | 6.811 | 9.131 | 5.457 |

# APPENDIX 3 EMISSION DATA PLOTS BY FUEL AND VEHICLE - ECE AND EUDC PHASES

The following figures allow the relative comparison of the emissions from the two phases (ECE and EUDC) of the test cycle. Comments relating to this breakdown are given in **Section 6.1.**

For each emission, different scaling has been used for the ECE and EUDC phases of the cycle. Since the ECE distance is about half that of the EUDC phase, the maximum y-axis value of the ECE plot is double that of the EUDC plot, so that their relative contributions to the NEDC are approximately correct.

***Figure A.3.1*** ECE emissions data - NOx

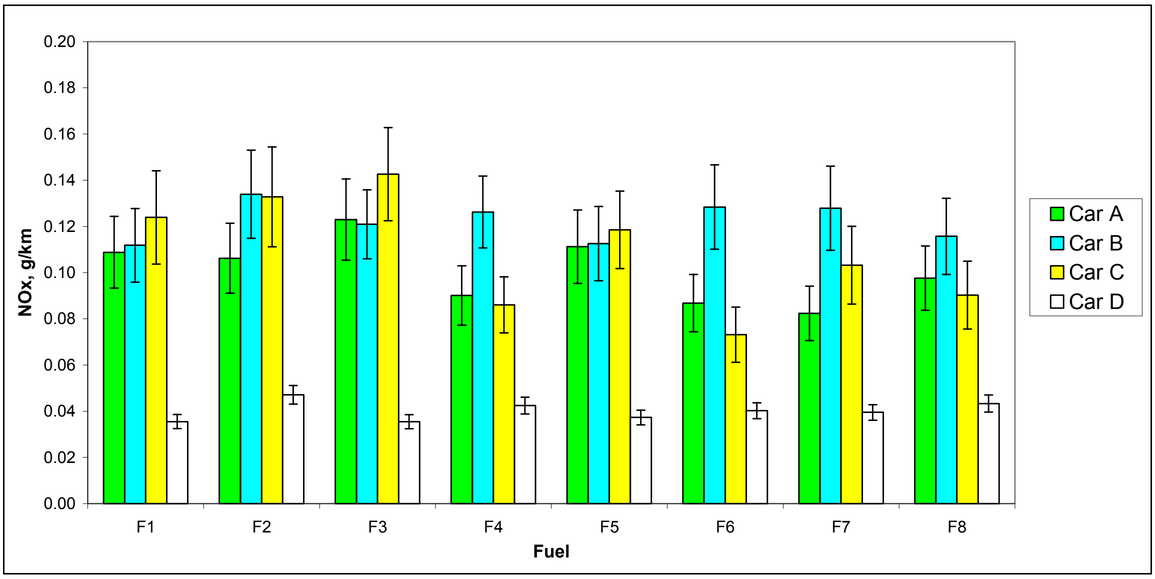


***Figure A.3.2*** EUDC emissions data - NOx

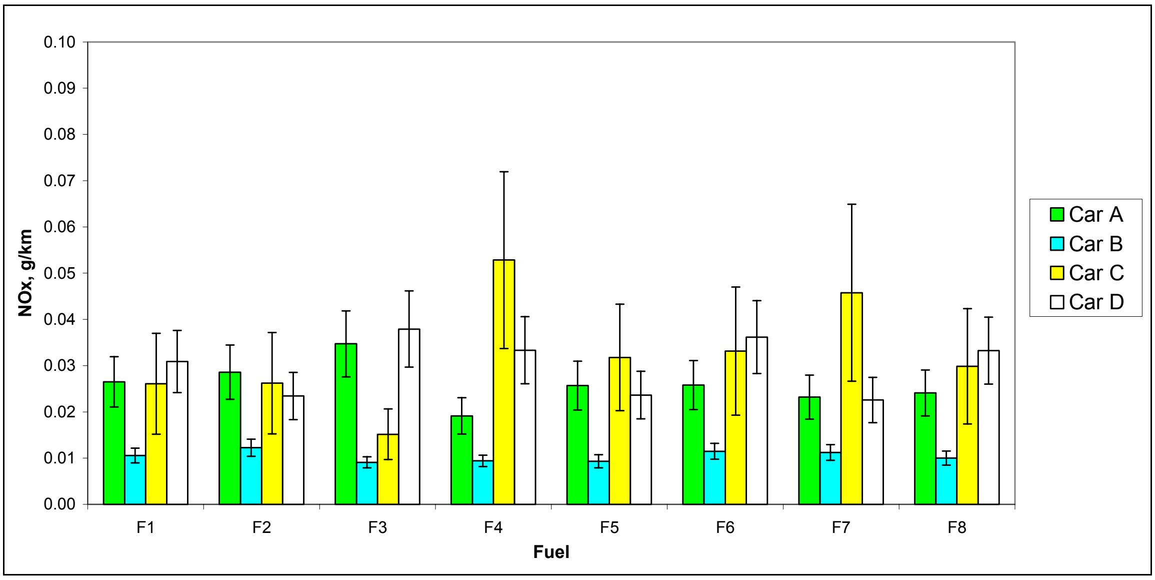


**Figure A.3.3** ECE emissions data - HC

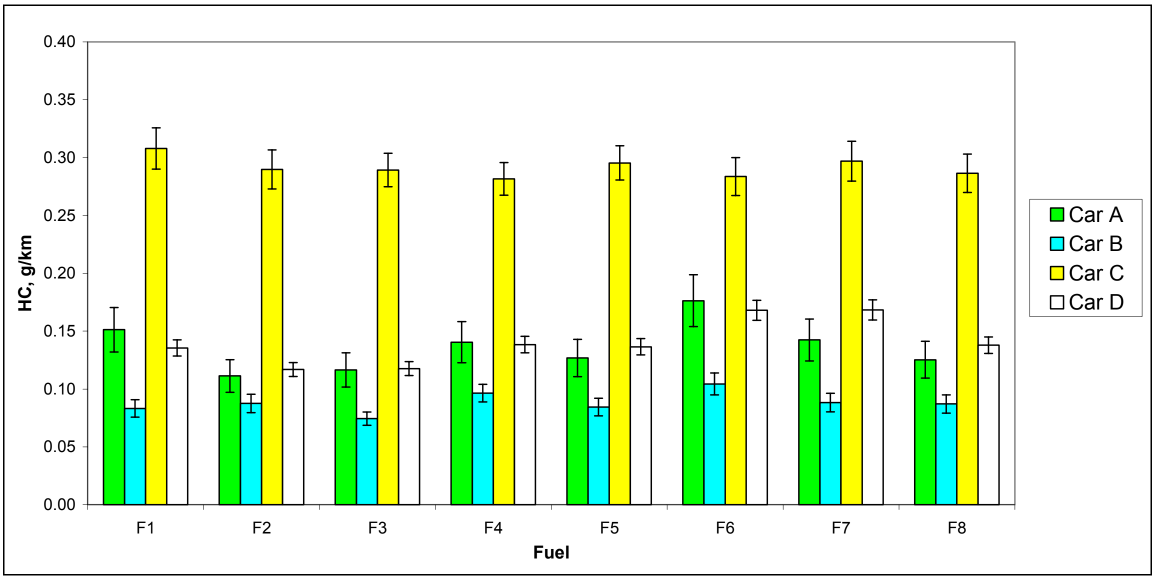


**Figure A.3.4** EUDC emissions data - HC

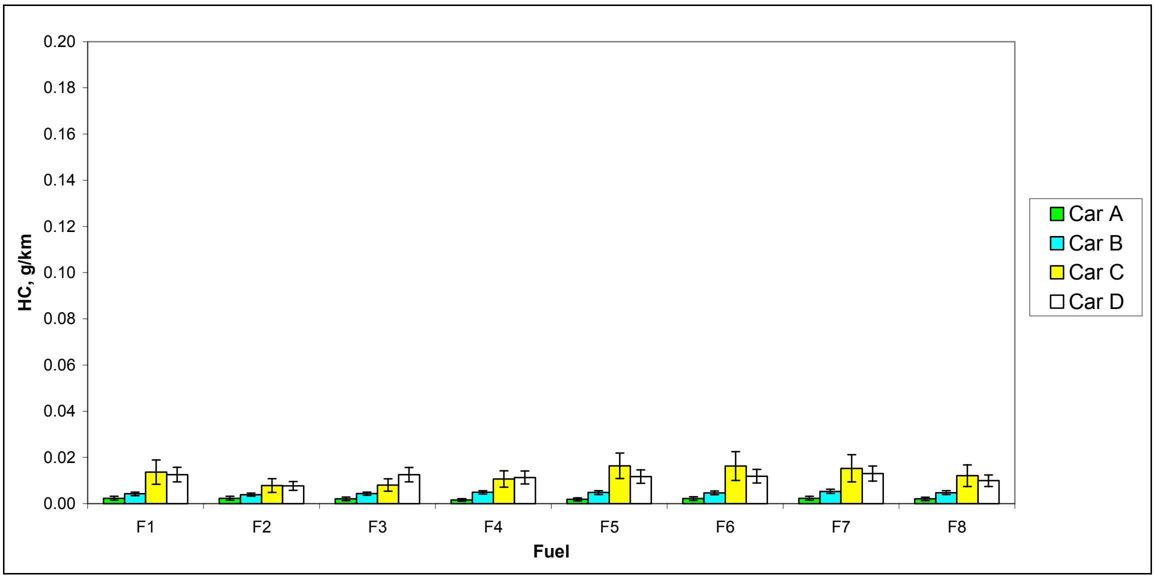


***Figure A.3.5*** ECE emissions data - CO

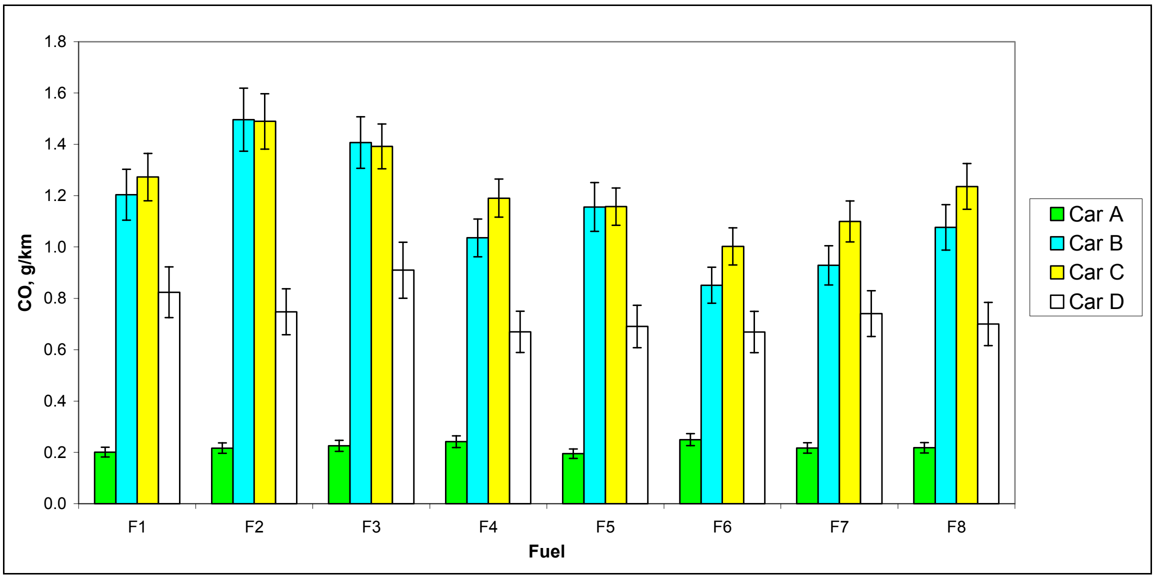


***Figure A.3.6*** EUDC emissions data - CO

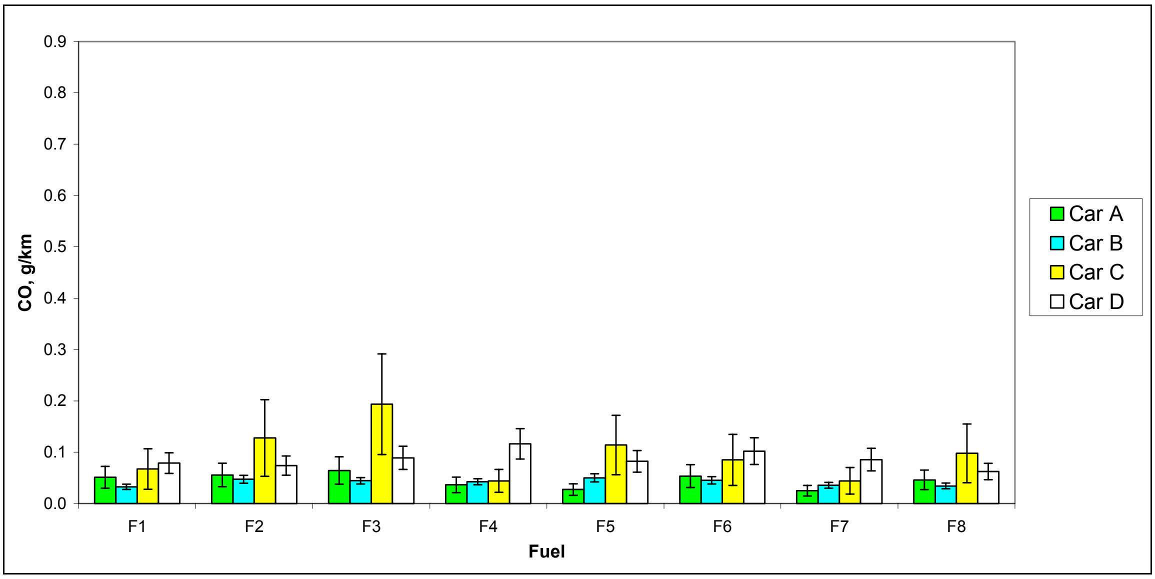


**Figure A.3.7** ECE emissions data - PM

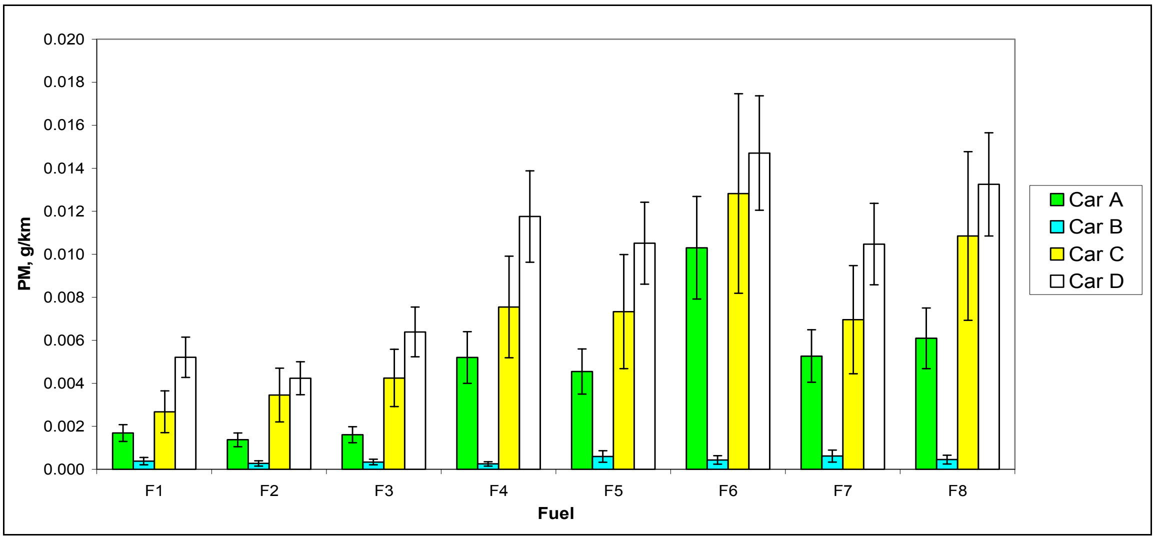
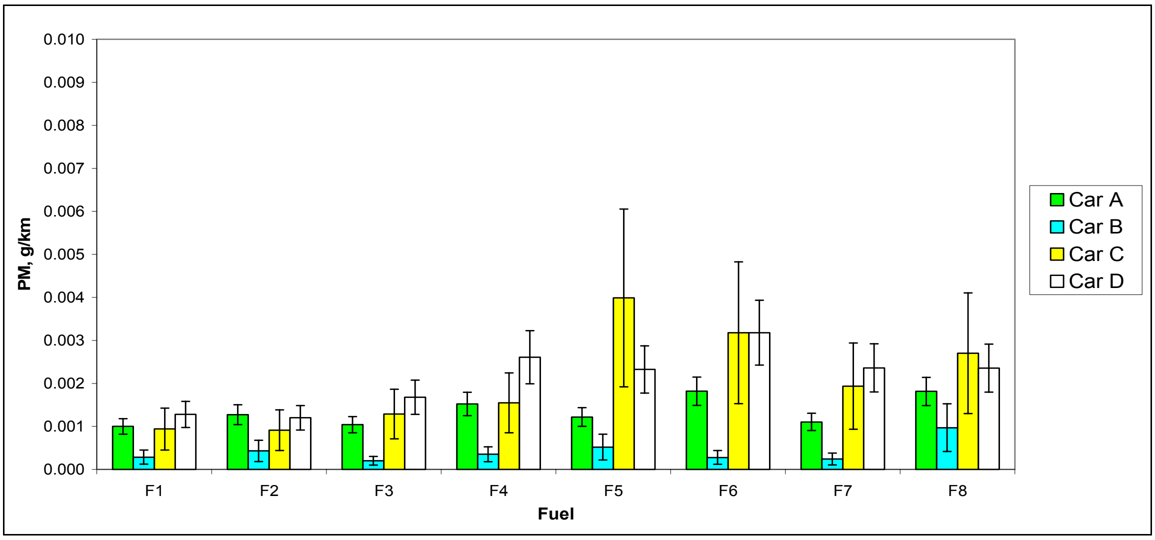


**Figure A.3.8** EUDC emissions data - PM



# APPENDIX 4 STATISTICAL ANALYSIS OF FUEL EFFECTS (PSEUDO ANOVA)

See also **Section 5** for details on the analysis methodology.

| CAR | Emission | Cycle | Fuel effects | E70 | | | | FBP | | | | Aromatics | | | | Olefins | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | overall sign. | 22 | 38 | Δ | sign. | 176 | 197 | Δ | sign. | 26 | 38 | Δ | sign. | 5 | 14 | Δ | sign. |
| | | | | | | | | | | | | | | | | | | | |
| A | CO (g/km) | ECE+EUDC (corr) | NS | 0.109 | 0.107 | -0.002 | NS | 0.111 | 0.104 | -0.007 | NS | 0.100 | 0.115 | 0.014 | NS | 0.106 | 0.109 | 0.002 | NS |
| A | | ECE (corr) | NS | 0.225 | 0.214 | -0.011 | NS | 0.219 | 0.221 | 0.003 | NS | 0.209 | 0.231 | 0.022 | P < 5% | 0.213 | 0.226 | 0.013 | NS |
| A | | EUDC | NS | 0.039 | 0.040 | 0.002 | NS | 0.046 | 0.033 | -0.013 | NS | 0.035 | 0.044 | 0.009 | NS | 0.042 | 0.037 | -0.005 | NS |
| A | HC (g/km) | ECE+EUDC | NS | 0.056 | 0.046 | -0.010 | P < 1% | 0.048 | 0.054 | 0.007 | NS | 0.052 | 0.050 | -0.001 | NS | 0.051 | 0.051 | 0.000 | NS |
| A | | ECE | NS | 0.148 | 0.121 | -0.027 | P < 1% | 0.126 | 0.144 | 0.018 | NS | 0.137 | 0.133 | -0.004 | NS | 0.135 | 0.135 | 0.000 | NS |
| A | | EUDC | NS | 0.002 | 0.002 | 0.000 | NS | 0.002 | 0.002 | 0.000 | NS | 0.002 | 0.002 | 0.000 | NS | 0.002 | 0.002 | 0.000 | NS |
| A | NOx (g/km) | ECE+EUDC | P < 5% | 0.049 | 0.058 | 0.009 | P < 1% | 0.057 | 0.049 | -0.008 | P < 1% | 0.055 | 0.052 | -0.003 | NS | 0.056 | 0.051 | -0.005 | NS |
| A | | ECE | NS | 0.092 | 0.109 | 0.017 | P < 5% | 0.109 | 0.092 | -0.017 | P < 5% | 0.103 | 0.098 | -0.005 | NS | 0.104 | 0.096 | -0.008 | NS |
| A | | EUDC | NS | 0.023 | 0.027 | 0.004 | NS | 0.026 | 0.024 | -0.002 | NS | 0.027 | 0.024 | -0.002 | NS | 0.027 | 0.024 | -0.003 | NS |
| A | $CO_2$ (g/km) | ECE+EUDC | NS | 184.1 | 182.8 | -1.3 | NS | 183.0 | 183.8 | 0.8 | NS | 182.3 | 184.5 | 2.2 | P < 5% | 183.3 | 183.5 | 0.2 | NS |
| A | | ECE | NS | 233.7 | 231.7 | -2.0 | NS | 232.1 | 233.3 | 1.1 | NS | 231.1 | 234.3 | 3.3 | P < 5% | 232.9 | 232.6 | -0.3 | NS |
| A | | EUDC | NS | 155.2 | 154.3 | -0.9 | NS | 154.4 | 155.0 | 0.6 | NS | 153.9 | 155.5 | 1.6 | NS | 154.5 | 155.0 | 0.4 | NS |
| A | PM (g/km) | ECE+EUDC (corr) | P < 0.1% | 0.0027 | 0.0021 | -0.0005 | P < 5% | 0.0016 | 0.0032 | 0.0016 | P < 0.1% | 0.0022 | 0.0026 | 0.0005 | NS | 0.0020 | 0.0028 | 0.0007 | P < 1% |
| A | | ECE (corr) | P < 0.1% | 0.0049 | 0.0035 | -0.0014 | P < 1% | 0.0022 | 0.0062 | 0.0039 | P < 0.1% | 0.0040 | 0.0044 | 0.0004 | NS | 0.0032 | 0.0052 | 0.0019 | P < 0.1% |
| A | | EUDC (corr) | P < 5% | 0.0013 | 0.0013 | 0.0000 | NS | 0.0012 | 0.0015 | 0.0002 | P < 5% | 0.0011 | 0.0015 | 0.0004 | P < 1% | 0.0013 | 0.0014 | 0.0001 | NS |
| A | FC (l/100 km) | ECE+EUDC | P < 5% | 7.725 | 7.696 | -0.029 | NS | 7.703 | 7.718 | 0.015 | NS | 7.802 | 7.618 | -0.184 | P < 0.1% | 7.692 | 7.729 | 0.037 | NS |
| A | | ECE | P < 5% | 9.825 | 9.770 | -0.056 | NS | 9.784 | 9.811 | 0.028 | NS | 9.906 | 9.689 | -0.216 | P < 1% | 9.785 | 9.810 | 0.025 | NS |
| A | | EUDC | NS | 6.504 | 6.488 | -0.016 | NS | 6.491 | 6.501 | 0.009 | NS | 6.579 | 6.413 | -0.166 | P < 1% | 6.474 | 6.518 | 0.044 | NS |
| | | | | | | | | | | | | | | | | | | | |
| B | CO (g/km) | ECE+EUDC | P < 0.1% | 0.401 | 0.487 | 0.086 | P < 0.1% | 0.501 | 0.388 | -0.113 | P < 0.1% | 0.447 | 0.442 | -0.005 | NS | 0.465 | 0.423 | -0.042 | P < 5% |
| B | | ECE | P < 0.1% | 1.021 | 1.247 | 0.226 | P < 0.1% | 1.287 | 0.981 | -0.306 | P < 0.1% | 1.147 | 1.121 | -0.026 | NS | 1.187 | 1.081 | -0.106 | P < 5% |
| B | | EUDC (corr) | NS | 0.038 | 0.043 | 0.004 | NS | 0.041 | 0.040 | -0.001 | NS | 0.038 | 0.043 | 0.005 | NS | 0.043 | 0.038 | -0.004 | NS |
| B | HC (g/km) | ECE+EUDC | P < 5% | 0.037 | 0.034 | -0.004 | P < 1% | 0.034 | 0.037 | 0.003 | P < 5% | 0.034 | 0.037 | 0.003 | P < 5% | 0.035 | 0.035 | 0.000 | NS |
| B | | ECE | P < 5% | 0.093 | 0.083 | -0.009 | P < 5% | 0.084 | 0.092 | 0.008 | P < 5% | 0.083 | 0.093 | 0.010 | P < 5% | 0.089 | 0.087 | -0.001 | NS |
| B | | EUDC | NS | 0.005 | 0.005 | 0.000 | NS | 0.004 | 0.005 | 0.001 | NS | 0.005 | 0.005 | 0.000 | NS | 0.004 | 0.005 | 0.001 | NS |
| B | NOx (g/km) | ECE+EUDC | NS | 0.052 | 0.050 | -0.002 | NS | 0.051 | 0.052 | 0.001 | NS | 0.050 | 0.053 | 0.003 | NS | 0.051 | 0.051 | 0.000 | NS |
| B | | ECE | NS | 0.123 | 0.120 | -0.003 | NS | 0.121 | 0.122 | 0.000 | NS | 0.118 | 0.125 | 0.007 | NS | 0.121 | 0.122 | 0.000 | NS |
| B | | EUDC (corr) | NS | 0.011 | 0.010 | -0.001 | NS | 0.010 | 0.011 | 0.001 | NS | 0.010 | 0.010 | 0.000 | NS | 0.011 | 0.010 | -0.001 | NS |
| B | $CO_2$ (g/km) | ECE+EUDC | P < 1% | 182.6 | 183.1 | 0.5 | NS | 183.3 | 182.4 | -0.9 | NS | 180.2 | 185.5 | 5.3 | P < 0.1% | 183.7 | 182.0 | -1.8 | NS |
| B | | ECE | P < 0.1% | 260.9 | 261.5 | 0.6 | NS | 261.8 | 260.6 | -1.1 | NS | 257.0 | 265.4 | 8.4 | P < 0.1% | 262.8 | 259.6 | -3.2 | P < 5% |
| B | | EUDC | P < 5% | 136.9 | 137.4 | 0.5 | NS | 137.4 | 136.8 | -0.6 | NS | 135.4 | 138.9 | 3.5 | P < 0.1% | 137.6 | 136.7 | -0.9 | NS |
| B | PM (g/km) | ECE+EUDC | NS | 0.0003 | 0.0004 | 0.0000 | NS | 0.0003 | 0.0004 | 0.0001 | NS | 0.0004 | 0.0004 | 0.0000 | NS | 0.0004 | 0.0003 | 0.0000 | NS |
| B | | ECE | NS | 0.0004 | 0.0004 | 0.0000 | NS | 0.0003 | 0.0005 | 0.0002 | P < 5% | 0.0005 | 0.0003 | -0.0001 | NS | 0.0004 | 0.0004 | 0.0000 | NS |
| B | | EUDC | NS | 0.0003 | 0.0003 | 0.0000 | NS | 0.0003 | 0.0003 | 0.0000 | NS | 0.0003 | 0.0003 | 0.0001 | NS | 0.0003 | 0.0003 | -0.0001 | NS |
| B | FC (l/100 km) | ECE+EUDC | NS | 7.679 | 7.730 | 0.051 | NS | 7.734 | 7.675 | -0.059 | NS | 7.730 | 7.679 | -0.051 | NS | 7.730 | 7.679 | -0.051 | NS |
| B | | ECE | NS | 11.008 | 11.080 | 0.072 | NS | 11.089 | 10.999 | -0.090 | NS | 11.063 | 11.025 | -0.038 | NS | 11.096 | 10.992 | -0.104 | NS |
| B | | EUDC | NS | 5.738 | 5.775 | 0.037 | NS | 5.775 | 5.737 | -0.038 | NS | 5.785 | 5.728 | -0.058 | NS | 5.765 | 5.748 | -0.018 | NS |
| | | | | | | | | | | | | | | | | | | | |

| CAR | Emission | Cycle | Fuel effects | E70 | | | | FBP | | | | Aromatics | | | | Olefins | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | overall sign. | 22 | 38 | Δ | sign. | 176 | 197 | Δ | sign. | 26 | 38 | Δ | sign. | 5 | 14 | Δ | sign. |
| | | | | | | | | | | | | | | | | | | | |
| C | CO<br>(g/km) | ECE+EUDC | P < 5% | 0.464 | 0.555 | 0.090 | P < 1% | 0.560 | 0.459 | -0.101 | P < 1% | 0.508 | 0.511 | 0.003 | NS | 0.520 | 0.499 | -0.020 | NS |
| C | | ECE | P < 0.1% | 1.154 | 1.281 | 0.127 | P < 1% | 1.331 | 1.104 | -0.228 | P < 0.1% | 1.211 | 1.224 | 0.013 | NS | 1.230 | 1.206 | -0.024 | NS |
| C | | EUDC | NS | 0.058 | 0.119 | 0.061 | P < 5% | 0.097 | 0.080 | -0.016 | NS | 0.088 | 0.089 | 0.000 | NS | 0.102 | 0.075 | -0.026 | NS |
| C | HC<br>(g/km) | ECE+EUDC | NS | 0.117 | 0.114 | -0.003 | NS | 0.114 | 0.117 | 0.003 | NS | 0.118 | 0.112 | -0.006 | P < 5% | 0.117 | 0.114 | -0.003 | NS |
| C | | ECE | NS | 0.292 | 0.290 | -0.003 | NS | 0.292 | 0.290 | -0.001 | NS | 0.297 | 0.285 | -0.013 | NS | 0.294 | 0.288 | -0.006 | NS |
| C | | EUDC | NS | 0.014 | 0.011 | -0.003 | NS | 0.010 | 0.015 | 0.006 | P < 5% | 0.014 | 0.011 | -0.003 | NS | 0.012 | 0.012 | 0.000 | NS |
| C | NOx<br>(g/km) | ECE+EUDC | NS | 0.060 | 0.060 | 0.000 | NS | 0.064 | 0.057 | -0.007 | NS | 0.063 | 0.058 | -0.005 | NS | 0.060 | 0.060 | 0.000 | NS |
| C | | ECE | P < 1% | 0.098 | 0.118 | 0.020 | P < 5% | 0.123 | 0.093 | -0.029 | P < 1% | 0.119 | 0.097 | -0.022 | P < 1% | 0.115 | 0.101 | -0.013 | NS |
| C | | EUDC | NS | 0.036 | 0.025 | -0.012 | NS | 0.025 | 0.036 | 0.011 | NS | 0.028 | 0.033 | 0.004 | NS | 0.029 | 0.032 | 0.003 | NS |
| C | $CO_2$<br>(g/km) | ECE+EUDC | NS | 192.5 | 195.3 | 2.8 | NS | 194.8 | 193.0 | -1.8 | NS | 193.5 | 194.4 | 0.9 | NS | 194.2 | 193.7 | -0.6 | NS |
| C | | ECE | NS | 245.2 | 248.0 | 2.8 | NS | 249.2 | 243.9 | -5.3 | P < 5% | 242.7 | 250.4 | 7.7 | P < 1% | 246.2 | 246.9 | 0.7 | NS |
| C | | EUDC | NS | 161.6 | 164.5 | 2.9 | NS | 163.0 | 163.2 | 0.2 | NS | 164.6 | 161.5 | -3.1 | NS | 163.7 | 162.4 | -1.4 | NS |
| C | PM<br>(g/km) | ECE+EUDC | P < 5% | 0.0037 | 0.0036 | -0.0001 | NS | 0.0024 | 0.0049 | 0.0025 | P < 1% | 0.0035 | 0.0038 | 0.0004 | NS | 0.0030 | 0.0042 | 0.0012 | P < 5% |
| C | | ECE | P < 1% | 0.0069 | 0.0064 | -0.0006 | NS | 0.0045 | 0.0089 | 0.0044 | P < 1% | 0.0060 | 0.0073 | 0.0013 | NS | 0.0054 | 0.0079 | 0.0025 | P < 5% |
| C | | EUDC | NS | 0.0018 | 0.0018 | 0.0000 | NS | 0.0012 | 0.0025 | 0.0013 | P < 5% | 0.0019 | 0.0018 | -0.0001 | NS | 0.0016 | 0.0021 | 0.0005 | NS |
| C | FC<br>(l/100 km) | ECE+EUDC | NS | 8.112 | 8.264 | 0.152 | NS | 8.237 | 8.138 | -0.099 | NS | 8.315 | 8.061 | -0.254 | P < 5% | 8.187 | 8.188 | 0.001 | NS |
| C | | ECE | NS | 10.384 | 10.545 | 0.161 | NS | 10.594 | 10.336 | -0.258 | P < 5% | 10.490 | 10.440 | -0.050 | NS | 10.435 | 10.495 | 0.060 | NS |
| C | | EUDC | NS | 6.777 | 6.928 | 0.150 | NS | 6.857 | 6.848 | -0.009 | NS | 7.040 | 6.665 | -0.375 | P < 5% | 6.871 | 6.834 | -0.036 | NS |
| | | | | | | | | | | | | | | | | | | | |
| D | CO<br>(g/km) | ECE+EUDC | NS | 0.328 | 0.328 | 0.000 | NS | 0.345 | 0.311 | -0.034 | NS | 0.339 | 0.317 | -0.021 | NS | 0.327 | 0.329 | 0.002 | NS |
| D | | ECE | NS | 0.727 | 0.755 | 0.029 | NS | 0.784 | 0.698 | -0.086 | NS | 0.779 | 0.704 | -0.075 | NS | 0.743 | 0.739 | -0.004 | NS |
| D | | EUDC | NS | 0.090 | 0.075 | -0.014 | NS | 0.084 | 0.081 | -0.002 | NS | 0.080 | 0.084 | 0.004 | NS | 0.082 | 0.083 | 0.001 | NS |
| D | HC<br>(g/km) | ECE+EUDC | P < 0.1% | 0.063 | 0.054 | -0.009 | P < 0.1% | 0.053 | 0.064 | 0.011 | P < 0.1% | 0.061 | 0.057 | -0.004 | P < 5% | 0.057 | 0.060 | 0.003 | NS |
| D | | ECE | P < 0.1% | 0.151 | 0.129 | -0.021 | P < 0.1% | 0.125 | 0.155 | 0.030 | P < 0.1% | 0.144 | 0.136 | -0.007 | NS | 0.137 | 0.143 | 0.006 | NS |
| D | | EUDC | NS | 0.012 | 0.011 | -0.001 | NS | 0.011 | 0.012 | 0.001 | NS | 0.013 | 0.010 | -0.003 | NS | 0.011 | 0.012 | 0.001 | NS |
| D | NOx<br>(g/km) | ECE+EUDC | NS | 0.034 | 0.034 | 0.000 | NS | 0.034 | 0.033 | -0.002 | NS | 0.031 | 0.036 | 0.005 | P < 5% | 0.032 | 0.035 | 0.003 | NS |
| D | | ECE | P < 5% | 0.040 | 0.040 | 0.000 | NS | 0.039 | 0.040 | 0.001 | NS | 0.037 | 0.042 | 0.005 | P < 5% | 0.040 | 0.040 | 0.000 | NS |
| D | | EUDC | NS | 0.029 | 0.029 | 0.000 | NS | 0.030 | 0.027 | -0.003 | NS | 0.027 | 0.031 | 0.004 | NS | 0.026 | 0.031 | 0.005 | NS |
| D | $CO_2$<br>(g/km) | ECE+EUDC | P < 1% | 161.8 | 162.3 | 0.5 | NS | 162.2 | 161.9 | -0.4 | NS | 160.3 | 163.7 | 3.4 | P < 0.1% | 162.8 | 161.3 | -1.5 | NS |
| D | | ECE | P < 5% | 216.0 | 216.9 | 0.9 | NS | 216.7 | 216.2 | -0.5 | NS | 214.2 | 218.8 | 4.6 | P < 0.1% | 217.5 | 215.5 | -2.0 | NS |
| D | | EUDC | P < 1% | 130.1 | 130.4 | 0.3 | NS | 130.4 | 130.1 | -0.3 | NS | 128.9 | 131.6 | 2.7 | P < 0.1% | 130.9 | 129.7 | -1.2 | P < 5% |
| D | PM<br>(g/km) | ECE+EUDC | P < 0.1% | 0.0051 | 0.0044 | -0.0007 | NS | 0.0034 | 0.0061 | 0.0026 | P < 0.1% | 0.0046 | 0.0049 | 0.0003 | NS | 0.0038 | 0.0057 | 0.0019 | P < 0.1% |
| D | | ECE | P < 0.1% | 0.0100 | 0.0086 | -0.0015 | NS | 0.0065 | 0.0121 | 0.0056 | P < 0.1% | 0.0090 | 0.0096 | 0.0006 | NS | 0.0074 | 0.0113 | 0.0039 | P < 0.1% |
| D | | EUDC | P < 1% | 0.0022 | 0.0019 | -0.0002 | NS | 0.0016 | 0.0025 | 0.0009 | P < 1% | 0.0020 | 0.0021 | 0.0002 | NS | 0.0017 | 0.0024 | 0.0006 | P < 5% |
| D | FC<br>(l/100 km) | ECE+EUDC | P < 5% | 6.805 | 6.852 | 0.047 | NS | 6.846 | 6.811 | -0.035 | NS | 6.881 | 6.776 | -0.106 | P < 1% | 6.846 | 6.811 | -0.035 | NS |
| D | | ECE | NS | 9.115 | 9.188 | 0.073 | NS | 9.175 | 9.127 | -0.047 | NS | 9.223 | 9.080 | -0.143 | P < 5% | 9.174 | 9.128 | -0.047 | NS |
| D | | EUDC | P < 1% | 5.457 | 5.489 | 0.032 | NS | 5.486 | 5.460 | -0.026 | NS | 5.515 | 5.431 | -0.084 | P < 1% | 5.487 | 5.458 | -0.029 | NS |
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