the effect of gasoline volatility on vehicle exhaust emissions at low ambient temperatures

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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ABSTRACT

Eight European vehicles, four of which were equipped with 3-way catalysts, have been tested on two gasolines with significantly different front-end/mid-range volatilities. The investigation was conducted over the new ECE+EUDC test cycle at various ambient temperatures.

It was found that emission levels varied widely between individual vehicles and that the effect of fuel volatility on emissions was much less than the effect of temperature.

Carbon Monoxide (CO) and Hydrocarbon (HC) emissions increased dramatically as test temperature was reduced. For catalyst cars, CO emissions increased by over 500 per cent and HC emissions by around 300 per cent as the temperature was reduced from 25 to -5°C. NO_x emissions were much less affected by test temperature.

KEYWORDS

Reformulated gasoline, front-end volatility, mid-range volatility, emissions, low temperature

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SUMMARY

CONCAWE has conducted a study to investigate the effect of front end and mid range volatility on exhaust emissions from eight European cars. Four current non-catalyst cars and four cars with 3-way catalysts were tested over the new ECE+EUDC test cycle on two fuels with significantly different volatilities. In view of the interest in emissions at low temperatures and, because it was felt that fuel volatility effects might vary with temperature, investigations were carried out over a range of ambient temperatures.

It was found that emission levels varied widely between individual vehicles and that the effect of fuel volatility on emissions was much less than the effect of temperature.

Carbon Monoxide (CO) and Hydrocarbon (HC) emissions increased dramatically as test temperature was reduced. For catalyst cars, CO emissions increased by over 500 per cent and HC emissions by around 300 per cent as the temperature was reduced from 25 to -5°C. NO_x emissions were much less affected by test temperature.

CO emissions increased with the high volatility fuel over the ECE test cycle but decreased over the EUDC cycle. The net effect over the whole cycle approximated to a 4 per cent increase in CO. The reasons for this effect are not clear and further work is needed. HC emissions decreased with the high volatility fuel in almost all cars by approximately of 5 per cent. Fuel volatility had little effect on NO_x emissions.

In general, fuel volatility did not have a greater effect at lower temperatures, although a few significant fuel/temperature interactions were found for individual cars.

1. INTRODUCTION

The effect of gasoline quality on exhaust emissions is a subject of intense debate at the present time. In the USA, legislation requiring the introduction of 'Reformulated Gasoline' has been introduced before the relative effects of changes to gasoline properties and composition are fully known. At the same time a major cooperative US Auto/Oil Industry Research programme has been set up to establish the magnitude of these effects and determine which are the most effective property changes. This Auto/Oil Air Quality Improvement Research Programme (AQIRP [1]), has determined the effects of a number of gasoline properties, specifically aromatic, olefin, oxygenate (ethers and alcohols) and sulphur contents and volatility as expressed by RVP and T90E ('heavy ends'). However, other work in the US has shown that front and mid-range volatility (ie T50E) have equally significant effects on exhaust emissions. [2,3]

In view of the growing interest in the effect of gasoline quality changes in Europe, and the pressure to reduce front-end volatility (to control evaporative emissions), CONCAWE decided to investigate the effect of front end/mid range volatility on exhaust emissions from a range of European cars. Four current non-catalyst cars and four cars with 3-way catalysts were tested over the new ECE+EUDC test cycle on two fuels with significantly different volatilities. In view of interest in emissions at low temperatures and because it was felt that fuel volatility effects might be more significant, tests were carried out at a range of temperatures between -15°C and +25°C.

2. TEST PROGRAMME

2.1 VEHICLES

Four non-catalyst cars were selected from vehicles available in the Research Laboratories of CONCAWE member companies. The group of vehicles finally tested included two carburettor cars and two models fitted with fuel injection.

Four cars equipped with three-way catalysts were also tested. These were all fuel injected, two with single-point injection, two with multipoint injection, and all had closed loop systems for the control of air/fuel ratio.

All test vehicles were subjected to a full diagnostic check before testing, and if necessary adjusted to be within manufacturers recommendations. Engines were drained and filled with a conventional 10W/40 non-synthetic lubricant. Full details of the test vehicles are given in Table 1.

2.2 FUELS

Two unleaded gasolines were blended from similar components to have high and low extremes of front end and mid range volatility, ie RVP, E70 and E100. However, other properties and, in particular, tail-end volatility were kept essentially constant. There was, however, a significant difference in density and H/C ratio. No oxygenates were used. **Table 2** gives full inspection properties of the two fuels, including calorific value and H/C ratio. These fuels are subsequently referred to as H (High-volatility) and L (Low-volatility).

2.3 TEST LOCATIONS AND PROCEDURES

The test programme was split between three laboratories as below:
BP Research - Sunbury, UK
Esso Research - Abingdon, UK
Mobil Research - Wedel, Germany

Tests were carried out at temperatures of -5, 5, 15 and 25°C, and also at -15°C for vehicles 1 and 5 tested at BP Sunbury. All tests were carried out using the latest ECE15 + EUDC test cycle as specified in EC Directive 91/441/EEC. Only regulated emissions were measured, ie CO, HC and NOx, but three separate CVS bags were used to determine emissions over ECE cycles 1+2, ECE cycles 3+4 and EUDC cycle. Duplicate tests were carried out for all vehicles except 2, 7 and 8. When changing from one fuel to the other, each vehicle was pre-conditioned as follows:

Drain and refill fuel tank to 40 per cent full.
Drive 3x EUDC test cycles to purge fuel system and canister*.
Soak overnight at test temperature.

(* Canister was disconnected for tests on vehicle 3).

3 RESULTS

Results from the three laboratories were pooled and statistical analysis carried out by Shell Research Thornton. Full results are tabulated in **Appendix 1**, which gives arithmetic means for the tests where duplicate measurements were made. **Figures A.1.1** to **A.1.8** in **Appendix 1** also show the CO, HC, and NOx emissions for each car/fuel/temperature combination for ECE cycles 1+2, ECE cycles 3+4, EUDC and total emissions. A separate programme using different fuels was carried out by Euron Milan, These results were not included in the statistical analysis but are attached as **Appendix 2**.

3.1 DATA SUMMARIES

Figures 1 to **7** show average emissions for the eight cars as a whole and also split into groups of four catalyst and four non-catalyst cars. Emissions are plotted on both a cycle-by-cycle basis (**Figures 1-4**) and an emissions basis (**Figures 5-7**). Emission measurements at -15°C are not included in **Figures 1** to **7** as they were only conducted on two cars at this temperature. **Figures 8** and **9** show emissions from these two cars.

In **Figures 1** to **7** which show average emissions over several cars, geometric means of the various subsets of the data have been taken. The geometric mean of n numbers $x_1, x_2, x_3, \ldots, x_n$, is the antilogarithm of the arithmetic mean of $\log(x_1)$, $\log(x_2) \ldots \log(x_n)$. A characteristic of the emissions data is an increase in variability as the actual level of emissions increases. This means that to be valid, statistical analyses and significance tests need to be conducted on the logarithms of measured emissions rather than the raw data. It is also more appropriate to use geometric and not arithmetic means to compare average emissions, over different cars or different temperatures, using the two fuels. Comparisons based on arithmetic means are dominated by results from cars with high emissions, whereas comparisons based on geometric means give all cars roughly equal influence.

3.2 STATISTICAL ANALYSIS

The prime objectives of the statistical analysis were to detect any differences in emissions between the two fuels and to investigate whether such differences varied with ambient temperature. **Table 3** gives the geometric mean emissions for each fuel in each car averaged over the temperature range -15 to +25°C (cars 1 and 5) or -5 to +25°C (other cars). These means are standardized so that each temperature makes an equal contribution (if the means were not standardized, temperatures where more repeat measurements were taken would have greater weight). **Table 3** also gives average differences in emissions between the two fuels, expressed as a percentage of the low volatility mean.

The asterisks in **Table 3** show where the two fuels gave statistically significant differences in emissions over a specific cycle in a particular car. Duplicate measurements were always taken from cars 1, 3, 4, 5 and 6 and therefore these cars show greater discrimination than cars 2, 7 and 8. In each row of **Table 3**, significant fuel differences in different cars were always in the same direction with one minor exception. Total HC emissions from car 8 were significantly higher using the high-volatility fuel, whereas they were significantly higher using the low-volatility fuel in cars 1, 3 and 5. No repeat measurements were made on car 8 so this reversal may be just a reflection of one unusual test.

The symbols §, §§, etc. in **Table 3** show where the fuel differences varied significantly between temperatures in a particular cycle for a particular car. The nature of these differences may be seen in **Figures A.1.1** to **A.1.8**. For example taking HC emissions over ECE cycles 1 and 2 for car 4 (**Figure A.1.1**) it can be seen that the high volatility fuel gives higher emissions at low temperatures whilst the low-volatility fuel gives higher emissions at high temperatures.

Table 4 and **Figure 10** give a global view of the effect of fuel volatility on emissions, showing average (geometric mean) emissions for the eight cars as a whole and for the two four-car groups of catalyst and non-catalyst cars. The means in **Table 4** are calculated over the restricted temperature range -5 to +25°C and are standardized so that all cars and the four temperatures are given the same weight, irrespective of whether single or duplicate measurements were made. Differences in average emissions between the two fuels are again expressed as percentages of the low volatility mean.

Formally 'correct' statistical analyses and significance tests could not be performed readily on data pooled together from the different cars, as Bartlett's homogeneity-of-variance test showed that the variability in log(emissions) was not constant over all cars. Nevertheless the geometric means in **Table 4** do form a valid data summary. The difficulty lies in estimating the precision of such means and in detecting 'significant' differences.

Table 3 shows very large differences in emissions from different cars as would be expected, and **Figures 1** to **7** show some very clear temperature effects. These effects were confirmed in multiple regression analyses with log(emissions) as the dependent variable. Car differences were always significant, at extremely high confidence levels in the vast majority of cases. Such confidence levels leave little doubt that car differences are indeed genuine, even though the assumptions underpinning the statistical analysis do not hold. Temperature effects were similarly significant except in a very few cases, these being the HC EUDC emissions from non-catalyst cars, NO_x ECE 3+4 and total emissions from non-catalyst cars and NO_x EUDC emissions from both catalyst and non-catalyst cars, and the two sets taken together.

It is more difficult to make global statements about fuel effects as differences between fuels were typically an order of magnitude lower than differences between cars. **Table 4** gives approximate 95 per cent confidence limits for the 'true' difference between the fuels (these limits being approximate because of the variance non-homogeneity problem discussed above). For example, the high-volatility fuel gave on average 5.1 per cent higher CO emissions in ECE cycles 1+2 than the low volatility fuel in this programme, and we can thus be (approximately) 95 per cent confident that the real difference between the fuels lies between +0.5 per cent and +9.9 per cent. As the 95 per cent confidence band excludes zero, the fuels have significantly different effects on ECE 1+2 emissions at the '95 per cent confidence level in an approximate test'.

Considering the 8-car fleet as a whole, significant fuel effects were found on CO emissions in all cycles, HC emissions in the EUDC and over the total cycle, and on NO_x emissions in ECE 1+2. Confidence limits for the 4-car catalyst and non-catalyst fleets were wider than those for the full fleet because fewer data are available, and fuel effects were not significant in most cases.

One of the main objectives of this study was to determine whether fuel effects are temperature dependent. A few significant fuel x temperature interactions were found for individual cars (**Table 3**) but the bar charts given in **Figures A.1.1** to **A.1.8** and **1** to **7** show little visual evidence to indicate that fuel differences do vary with temperature in a systematic manner. There are few clear, consistent and plausible patterns to be seen. Approximate significance tests were conducted but few significant interactions were found. There is perhaps some evidence to suggest that fuel effects on total CO emissions from non-catalyst cars may vary with temperature (**Figure 5**) but little else.

4 DISCUSSION OF RESULTS

For convenience of interpretation the percentage changes in emissions for the high-volatility fuel compared with the low-volatility fuel, as given in **Table 4** have been plotted in **Figure 10**. The results are reviewed by individual emission (HC, CO, NO_x) and effects of temperature and fuel volatility discussed.

4.1 HYDROCARBON EMISSIONS

HC emissions increased with decreasing temperature as can be clearly seen in **Figure 5**. The effect is most dramatic over the first two ECE cycles 1+2, and the difference between catalyst and non-catalyst cars is relatively small, especially at low temperatures. This is not surprising as the catalyst will not be fully operational over these cycles. Over ECE 3+4 cycles there is a small increase with decreasing temperature for the catalyst cars but not the non-catalyst, and over the EUDC only a small temperature effect for the catalyst cars can be seen. Emissions over the whole ECE+EUDC cycle increase from 0.28 g/km at 25°C to 1.17 g/km at -5°C for catalyst cars, i.e. by 314 per cent, and from 1.30 g/km to 2.34 g/km for non-catalyst cars, i.e. by 82 per cent. The increase appears to be roughly linear with decreasing temperature down to 5°C, but increases more steeply at -5°C.

Increasing fuel volatility reduced hydrocarbon emissions for almost all temperatures, test cycles and vehicle fleets, although individually car 8 and car 2 (over ECE 3+4 and EUDC) did show increased emissions (**Table 3**). The results, however, (**Table 4** and **Figure 10**) are only significant in a few cases. Total ECE+EUDC cycle emissions were reduced by 6.4 per cent for catalyst cars and 4.9 per cent for the total car fleet. The reduction of 3.3 per cent for non-catalyst cars was not significant. However, this was probably influenced by the ECE 1+2 cycle results which showed essentially no net effect but a very wide error band.

4.2 CARBON MONOXIDE EMISSIONS

CO emissions also increase significantly with decreasing temperature as can be seen in **Figures 1-4, 8-9** and most clearly in **Figure 6**. The most dramatic increases are over the first two ECE cycles, as might be expected due to increased mixture enrichment at lower temperatures. As shown in **Figure 1** and **Table 4** there is less relative difference for CO emissions than for HC emissions between catalyst and non-catalyst cars, again because the catalyst is not yet operational during these cycles.

Reducing temperature from 25 to -5°C increases CO cycle 1+2 emissions by 460 per cent for all cars (**Figure 1**). Over cycles 3+4 the effect of temperature is much less and a significant increase is only seen at -5°C (**Figure 2**), and there is no significant temperature effect over the EUDC cycle (**Figure 3**). The very high emissions over the first two cycles however dominate the total ECE+EUDC emissions, as seen in **Figure 6**, and at temperatures below 15°C emissions from catalyst and non-catalyst cars are essentially equal. This appears to be due to the very good emissions performance of the non-catalyst cars, especially cars 6 and 8, which at 25°C give CO emissions only slightly above the new EC 1993 limits (**Figure A.1.8**). Mean CO emissions at 25°C are 6.4 g/km for non-catalyst cars and 2.3 g/km for catalyst cars, increasing to 15 g/km for all cars at -5°C, i.e. by some 133 per cent and 545 per cent respectively. The temperature effects appear to be linear, or slightly exponential, even down to temperatures of -15°C as shown in **Figures 8** and **9**.

The effect of gasoline volatility is much less than the effect of temperature. As can be seen in **Table 4** and **Figure 10**, CO emissions INCREASE with increasing volatility over the ECE cycles 1+2 and 3+4, but DECREASE with volatility over the EUDC. The net effect is a statistically significant increase in CO of 4.3 per cent for the high volatility fuel in all cars over the total cycle. This increase is opposite to the effect for hydrocarbons described above, and was not expected as previous work [2,3] had shown a decrease in CO with increasing volatility.

It was felt that this effect might be due to fuel effects on the metered air/fuel ratio. Consequently the fuels H/C ratios were determined and stoichiometric air/fuel ratios calculated as shown in **Table 2**. The less volatile fuel (L) needs less air for complete combustion and thus shows a small natural leaning effect of 0.2 per cent equivalent to a lambda shift from 1.000 to 1.002. This, however, is based on mass and fuel is metered by volume, so there will be a further difference due to fuel density effects.

Assuming that fuel metering is affected by density directly for fuel injection and by the square root of density for carburettors, there is a further effect of 769/749 (1.027), ie the more volatile fuel will be 2.7 per cent leaner for fuel injected engines and 1.3 per cent for carburettors. Thus the overall effect expected is that the more volatile fuel (H) will run 2.5 per cent leaner in fuel injected engines and 1.2 per cent leaner in carburettor engines. This is borne out by the observed reductions in CO emissions over the EUDC test cycle when the engines will be warmed up and running at nearer steady state conditions. However, there is clearly some other factor at work during the cold transient ECE cycles.

One hypothesis is that the more volatile fuel causes less cylinder wall-wetting and hence a richer mixture inside the combustion chamber leading to increased CO emissions. The richer mixture would also increase hydrocarbon emissions slightly, but this would be more than offset by the reduction in unburned hydrocarbons from the cylinder wall films and quench layers.

To check the air/fuel ratio effect, some steady-state hot engine tests were run on the two fuels in a single cylinder fuel injected Ricardo Hydra engine. The engine was set up for stoichiometric operation on fuel L then switched to fuel H, and then the experiment was repeated the other way round. The results given in **Figure 11** show that in each case the more volatile fuel H ran richer by 0.5 to 1.3 per cent than fuel L. This is directionally in line with the H/C ratio effect but is not consistent with the density difference. It is interesting to note that other US work [4] has reported a similar CO effect. Further investigation is clearly needed to clarify the observed changes in CO emissions with fuel volatility.

4.3 NO_X EMISSIONS

Conflicting effects of temperature are seen on NOx over different parts of the test cycle, but the effects are much smaller than for HC and CO emissions. **Figures 7** and especially **8** show a distinct trend of REDUCING emissions over ECE 1+2 with reducing temperature for the catalyst cars, but less clear for the non-catalyst cars. Over ECE 3+4 the trend is reversed and there is a small but significant INCREASE in emissions with decreasing temperature for both catalyst and non-catalyst cars. There are no significant effects over the EUDC cycle. The overall effect for the total cycle therefore amounts to a 25 per cent DECREASE in emissions with decreasing temperature for the catalyst cars, but a 3 per cent INCREASE (non-significant) for the non-catalyst cars.

Fuel volatility changes appeared to have little significant effect on NO_x emissions. **Table 4** and **Figure 10** show that for the vehicle fleets the only statistically significant effect is a reduction for the high volatility fuel of 4.1 per cent over ECE 1+2 for all cars. This is most likely due to a larger (7.5 per cent) reduction for the non-catalyst fleet which is just non-significant. **Table 3** shows that this in turn is probably due to individual results of cars 7 and 8, which showed significant effects, reductions of 9-20 per cent in NO_x emissions with fuel H over all parts of the test cycle.

5 CONCLUSIONS

CO and HC emissions increase dramatically as test temperature is reduced. For catalyst cars CO emissions increased by over 500 per cent and HC emissions by around 300 per cent as temperature was reduced from 25 to -5°C. NO_x emissions were much less affected by temperature.

Emission levels vary widely between individual vehicles. In particular the two fuel-injected non-catalyst cars give remarkably low emissions.

As expected, exhaust emissions for all the cars tested decreased substantially as the engine/catalyst warms up, with the bulk of the emissions being collected in the first bag (ECE cycles 1+2).

The effect of fuel volatility on emissions is much less than the effect of temperature.

CO emissions INCREASE with the high volatility fuel over the ECE test cycle but DECREASE over the EUDC cycle. The net effect over the whole cycle is around a 4 per cent increase in CO. The reasons for this effect are not clear and further work is needed.

HC emissions DECREASE with the high volatility fuel in almost all cars by approximately 5 per cent.

NO_x emissions were much less affected by temperature. Over ECE cycles 1+2, emissions DECREASED at low temperatures, especially for catalyst cars. However, over ECE 3+4 there was a small but significant INCREASE. Over the total cycle, catalyst car emissions were reduced by 25 per cent, whereas there was no effect for the non-catalyst models. Fuel volatility also had little significant effect on NO_x emissions.

No overall evidence was found of a greater effect of fuel volatility at lower temperatures, although a few significant fuel/temperature interactions were found for individual cars.

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Table 1: Technical data for test vehicles

VEHICLE	1	2	3	4	5	6	7	8
Capacity cm^3	1781	1392	2298	1796	1597	1998	1389	1580
Cylinders	4	4	4	4	4	4	4	4
Valves/cylinder	2	2	2	2	2	2	2	2
Compression Ratio	10.0	8.5	9.0	9.2	9.8	9.2	9.4	9.8
Rated power (kW) at rpm	79 5250	54 5600	97 5100	66 5400	70 6000	85 5600	53 5600	83 6250
Rated Torque (Nm) at rpm	154 3250	103 -	198 3500	143 3000	135 4000	175 3000		131 4000
Fuel system 1)	MPI	SPI	MPI K-JET	SPI	CARB 2V	MPI	CARB 2V	MPI L-JET
Catalyst type 2)	3-way CL	Two CATS	3-way CL	3-way CL	-	-	-	-
Canister	yes	yes	yes	yes	-	-	-	-

Notes:

1) MPI = Multi-Point Injection
SPI = *Single-Point Injection*
K-JET = K-Jetronic
Carb 2V = Carburettor (2 Venturi)
L-JET = L-Jetronic

2) CL = Closed Loop
Two CATS = 3-Way Unit, incorporating small 'start-up' catalyst

Table 2: Test fuel properties

Property	Fuel H	Fuel L
RON	97.6	98.6
MON	86.0	86.9
Density kg/m³	749	769
Distillation °C (Recovered)		
IBP	30.1	34.9
2%	35.0	43.0
5%	38.0	47.9
10%	42.3	54.2
20%	50.5	64.6
30%	59.0	75.8
40%	70.3	90.6
50%	88.6	108.4
60%	114.4	122.2
70%	131.0	132.1
80%	141.5	142.4
90%	153.2	153.5
FBP	181.8	190.4
Residue % vol	1.4	0.5
Loss % vol	1.2	0.1
Evap @ 70°C	40.6	26.0
Evap @ 100°C	54.4	45.1
Evap @ 150°C	87.9	87.0
RVP kPa	96.4	61.4
FVI (RVP + 0.7E70)	124.8	79.6
FIA Analysis		
Aromatics % vol	47.9	46.2
Olefins % vol	5.1	4.8
Paraffins % vol	47.0	49.0
Sulphur ppm mass	9.0	8.0
Cal. Value J/g	45 060	44 680
C % mass	87.5	87.7
H % mass	12.4	12.25
H/C ratio	1.69	1.66
Stoich AFR	14.26	14.23

Table 3: Average Emissions (geometric means in g/km: catalyst cars)

EMISSION SPECIES AND TEST CYCLE	CATALYST CARS											
	CAR 1			CAR 2			CAR 3			CAR 4		
	HIGH	LOW	DIFF.(%)	HIGH	LOW	DIFF.(%)	HIGH	LOW	DIFF.(%)	HIGH	LOW	DIFF.(%)
CO												
ECE 1+2	41 2	38.5	+6 8**§	28 6	25 0	+18§	28 8	33 6	-11.3	26.4	26.9	-2.1§
ECE 3+4	0 98	0 78	+25.1*§§	6.54	3 63	+80 4	1.27	1.20	+6 2	2.29	2 21	+3.8
EUDC	0 37	0 41	-10.3*	1.54	1.10	+40 7	0.32	0.40	-19.1***	0.65	0 86	-24 5***
TOTAL	8 14	7 67	+6 2*§	8.13	6.13	+32 6*	6.10	6.73	-9 4	6 17	6 28	-1.8
HC												
ECE 1+2	3 11	3 31	-6.8**§	1 87	2 04	-8.2	2 63	2 98	-11.7**	3.20	3.21	-0.4§§
ECE 3+4	0 089	0 095	-6.4	0 51	0 46	+11 6	0 35	0 34	+1 0	0.36	0.41	-13 4**
EUDC	0 015	0 022	-33.6**	0 091	0 074	+23 0	0 066	0 066	-0 4	0 080	0 108	-25.3***
TOTAL	0 59	0 64	-8 0***§	0 50	0 52	-3 1	0.59	0.65	-9.6**	0 71	0.74	-3.7§§
NO_x												
ECE 1+2	0.32	0.31	+3.7§	0 65	0 66	-1.9	1.48	1 44	+2 8	0 99	1.12	-11.8**§
ECE 3+4	0.035	0.039	-11.4	0 38	0 34	+11 4	0.41	0 38	+7 8	0.065	0 067	-4.2
EUDC	0.010	0.012	-18.8*§	0 29	0 28	+2 5	0 124	0 083	+49.8	0.047	0 027	+71 1
TOTAL	0.073	0.071	+3 5§§	0 39	0.38	+3.0	0 39	0.40	-0.4	0 22	0 24	-8.7

Notes: Average emissions (geometric means: g/km) from each car using high and low volatility fuels over the temperature range -15° or -5° to +25°C

Differences are expressed as percentages of the low-volatility mean.

* superscripts indicate that fuel differences are significant at the * = 95%, ** = 99%, or *** = 99.9% confidence levels.

§ superscripts indicate that fuel x temperature interactions are significant at the § = 95%, §§ = 99%, or §§§ = 99.9% confidence levels, meaning that fuel differences vary significantly from temperature to temperature)

Table 3 (ctd.) Average emissions (geometric means in g/km: non-catalyst cars)

EMISSION SPECIES AND TEST CYCLE	NON-CATALYST CARS											
	CAR 5			CAR 6			CAR 7			CAR 8		
	HIGH	LOW	DIFF (%)	HIGH	LOW	DIFF (%)	HIGH	LOW	DIFF (%)	HIGH	LOW	DIFF (%)
CO												
ECE 1+2	80.5	73.7	+9.3***	22.7	19.9	+14.1**	40.7	38.4	+6.0	24.4	24.5	-0.3
ECE 3+4	12.3	11.3	+9.1§§	3.13	3.21	-2.5	13.3	12.1	+9.7	5.51	5.97	-7.7
EUDC	4.49	5.46	-17.8***	1.02	1.02	+0.1	4.22	5.55	-23.8	1.69	1.80	-5.8
TOTAL	20.7	20.1	+2.9§§	5.46	4.95	+10.3*	13.5	13.6	-0.5	6.64	6.79	-2.3
HC												
ECE 1+2	8.12	8.04	+1.0	2.28	2.49	-9.2	4.40	4.50	-2.0	3.33	3.11	+6.8
ECE 3+4	2.12	2.27	-6.5**	1.06	1.26	-16.3*	2.60	2.64	-1.9	1.84	1.64	+11.9
EUDC	1.15	1.37	-16.2	0.60	0.67	-12.0*	0.98	1.06	-7.3	0.67	0.82	+7.8
TOTAL	3.07	3.36	-8.5**	1.06	1.18	-10.2	1.96	2.01	-3.1	1.38	1.27	+8.7*
NO_x												
ECE 1+2	2.63	2.88	-9.0	2.62	2.64	-0.6	1.20	1.45	-17.3**	0.65	0.71	-8.6*
ECE 3+4	3.83	4.44	-13.8	2.00	1.96	+2.0	1.25	1.57	-20.2**	0.62	0.68	-9.4*
EUDC	5.58	5.33	+4.7	3.93	3.83	+2.7	2.48	2.77	-10.5**	1.45	1.59	-8.6*
TOTAL	4.85	4.72	+2.8	3.32	3.25	+2.1	2.03	2.32	-12.5**	1.15	1.26	-8.7*

Notes: Average emissions (geometric means: g/km) from each car using high and low volatility fuels over the temperature range -15° or -5° to +25°C

Differences are expressed as percentages of the low-volatility mean.

* superscripts indicate that fuel differences are significant at the * =95%, ** =99%, or *** =99.9% confidence levels.

§ superscripts indicate that fuel x temperature interactions are significant at the § =95%, §§ =99%, or §§§ =99.9% confidence levels, meaning that fuel differences vary significantly from temperature to temperature.

Table 4: Average emissions (geometric means in g/km)

EMISSION SPECIES AND TEST CYCLE	ALL CARS			CATALYST CARS			NON-CATALYST CARS		
	HIGH	LOW	DIFFERENCE(%)	HIGH	LOW	DIFFERENCE(%)	HIGH	LOW	DIFFERENCE(%)
CO									
ECE 1+2	32.3	30.8	+5 1 (+0 5, +9 9)	29.6	28 8	+2.6 (-4 6, +10.3)	35 4	32.9	+7 6 (+3.3, +11.9)
ECE 3+4	3.76	3.41	+10.3 (+3 3, +17.8)	1.90	1 62	+17 8 (+6 2, +30 6)	7.44	7 20	+3 3 (-3.3, +10 4)
EUDC	1.18	1.31	-9.2 (-14.1, -4 0)	0.58	0.62	-5.6 (-13.9, +3 5)	2.41	2 76	-12.7 (-15.9, -9 3)
Total	8 10	7 76	+4 3 (+0.2, + 8 5)	6.69	6.32	+5 9 (-0.7, +13 0)	9.79	9.54	+2.7 (-0.8, +6.3)
HC									
ECE 1+2	3.13	3.24	-3 4 (-8.7, +2.3)	2 52	2 7	-6 8 (-9 3, -4 3)	3.9	3 89	+0.2 (-12 8, +15.1)
ECE 3+4	0 67	0.7	-5 2 (-14 8, +5 5)	0 248	0 267	-7 1 (-22 4, +11.1)	1.79	1 85	-3.2 (-9.1, +3.
EUDC	0.182	0.214	-10.2 (-17.5, -2.2)	0 047	0 054	-12.6 (-23.0, -0 7)	0 76	0 85	-7.8 (-17.1, +2.5
Total	0.97	1 02	-4 9 (-7.7, -1 9)	0.56	0.6	-6 4 (-9.2, -3 6)	1 69	1 74	-3.3 (-9.3, +3.1)
NO_x									
ECE 1+2	1.1	1.15	-4.1 (-7.7, -0.4)	0 78	0.78	-0.6 (-4 3, +3.2)	1 57	1.7	-7.5 (-14.6, +0.2)
ECE 3+4	0.46	0.49	-5.0 (-18.3, +10 6)	0.139	0.135	+2 3 (-19.3, +29 6)	1 55	1 75	-11.7 (-24.7, +3.6)
EUDC	0.44	0.41	+7.8 (-8 7, +27.1)	0.064	0.054	+18 3 (-9.8, +57 8)	3 01	3 09	-2.7 (-10.0, +6.2
Total	0.76	0.77	-1.7 (-6.0, +2.8)	0.231	0.23	+0.5 (-4 9, +6 3)	2 5	2.6	-4.0 (-11.1, +3.8)

Notes: Average emissions (geometric means; g/km) using high and low volatility fuels over the temperature range -5°C to +25°C

(Differences are expressed as percentages of the low-volatility mean with figures in brackets denoting approximate 95% confidence intervals for the true population difference)

Figure 1: ECE Cycles 1 and 2 - Geometric Mean Emissions

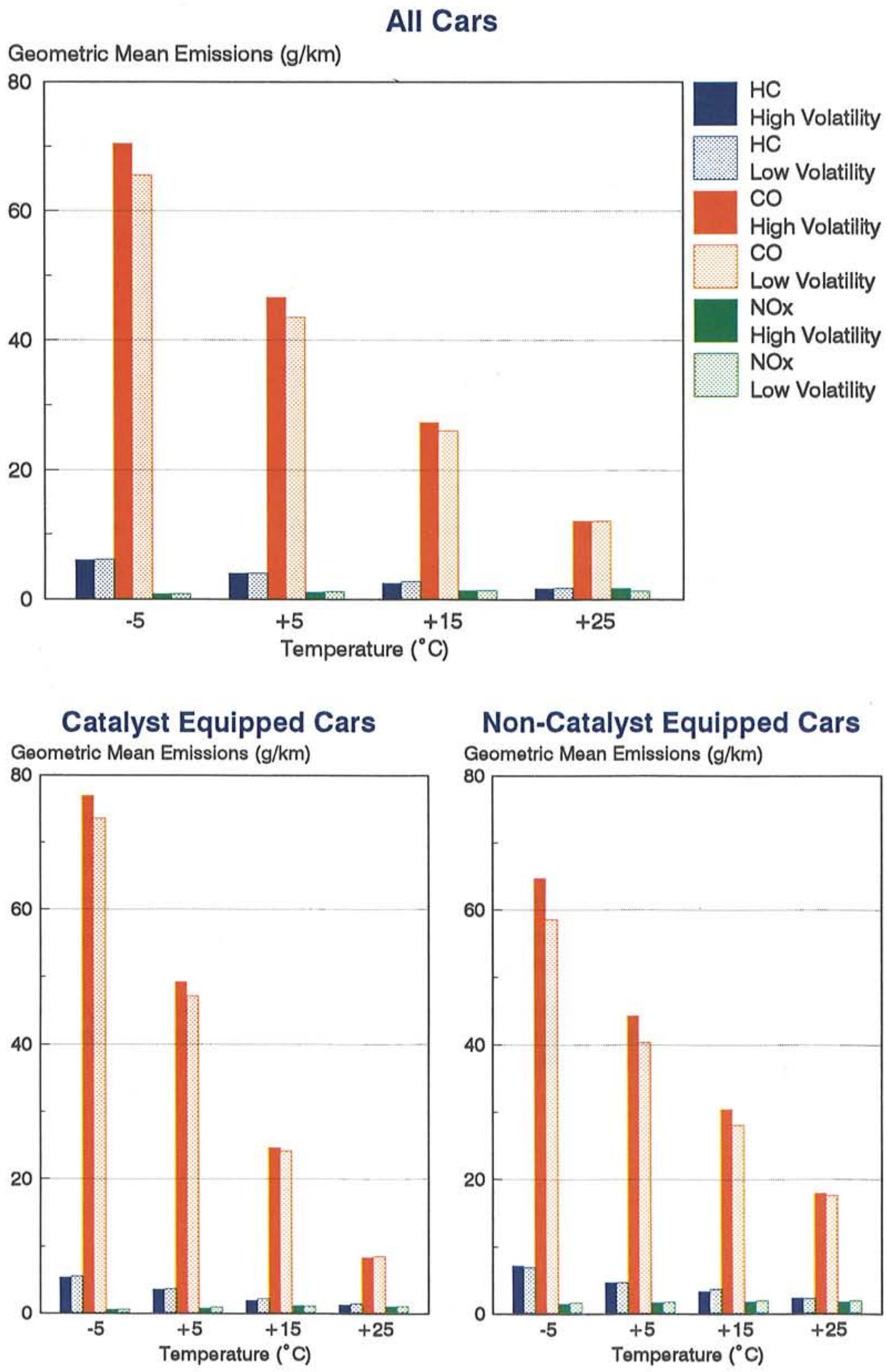


***Figure 2*:** ECE Cycles 3 and 4 - Geometric Mean Emissions

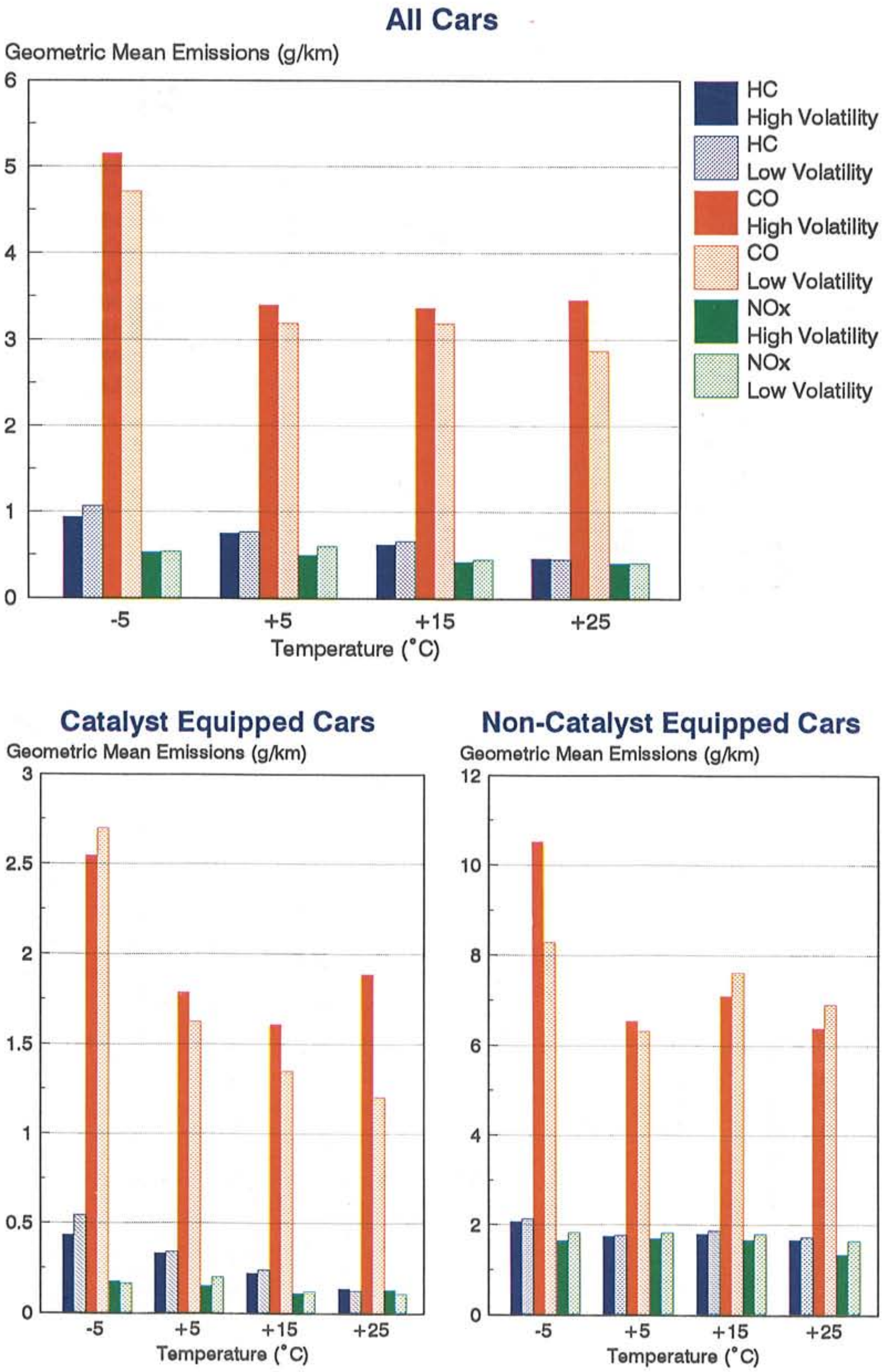


Figure 3: EUDC Cycle - Geometric Mean Emissions

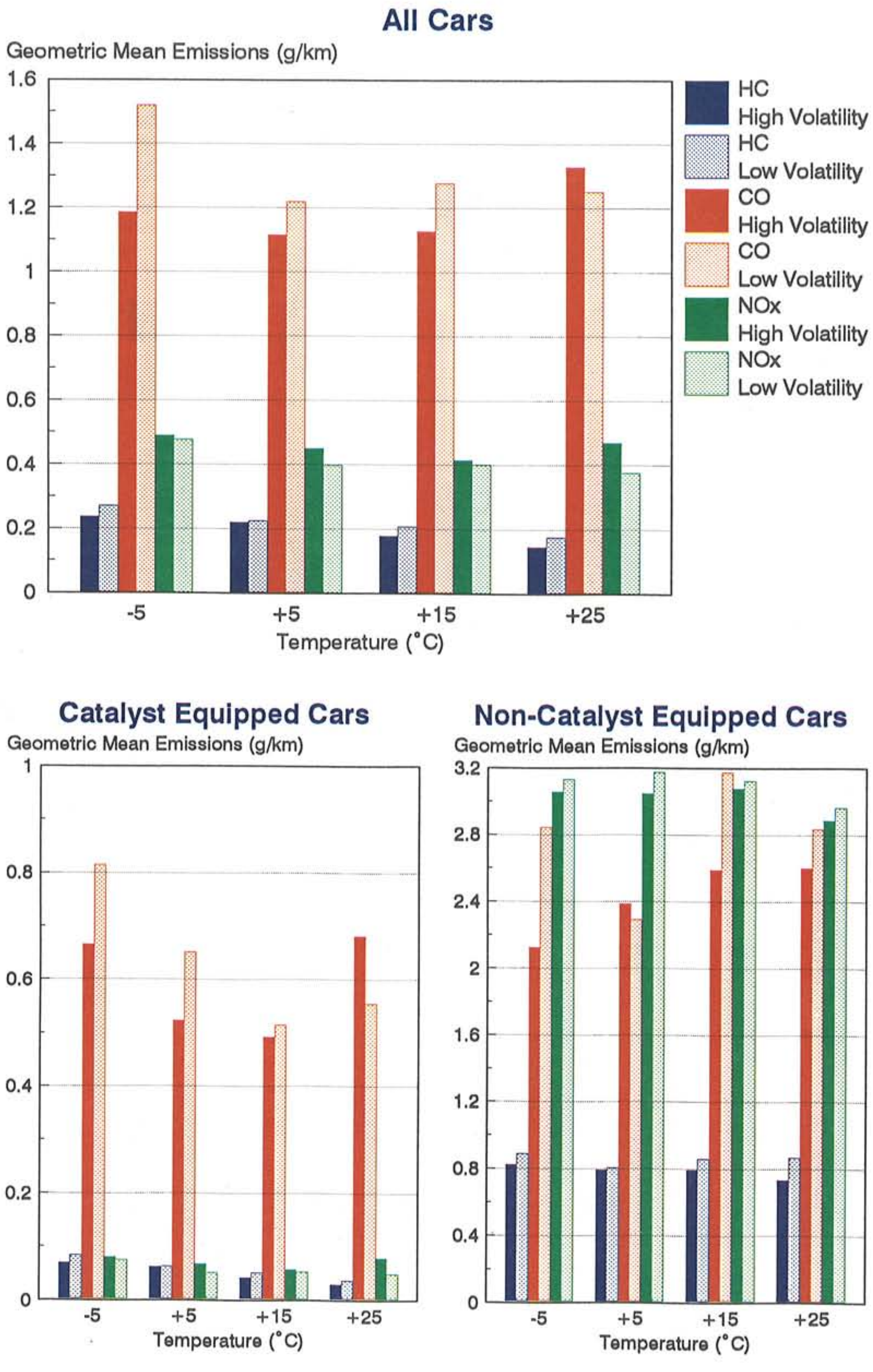


Figure 4: ECE+EUDC Cycles - Geometric Mean Emissions

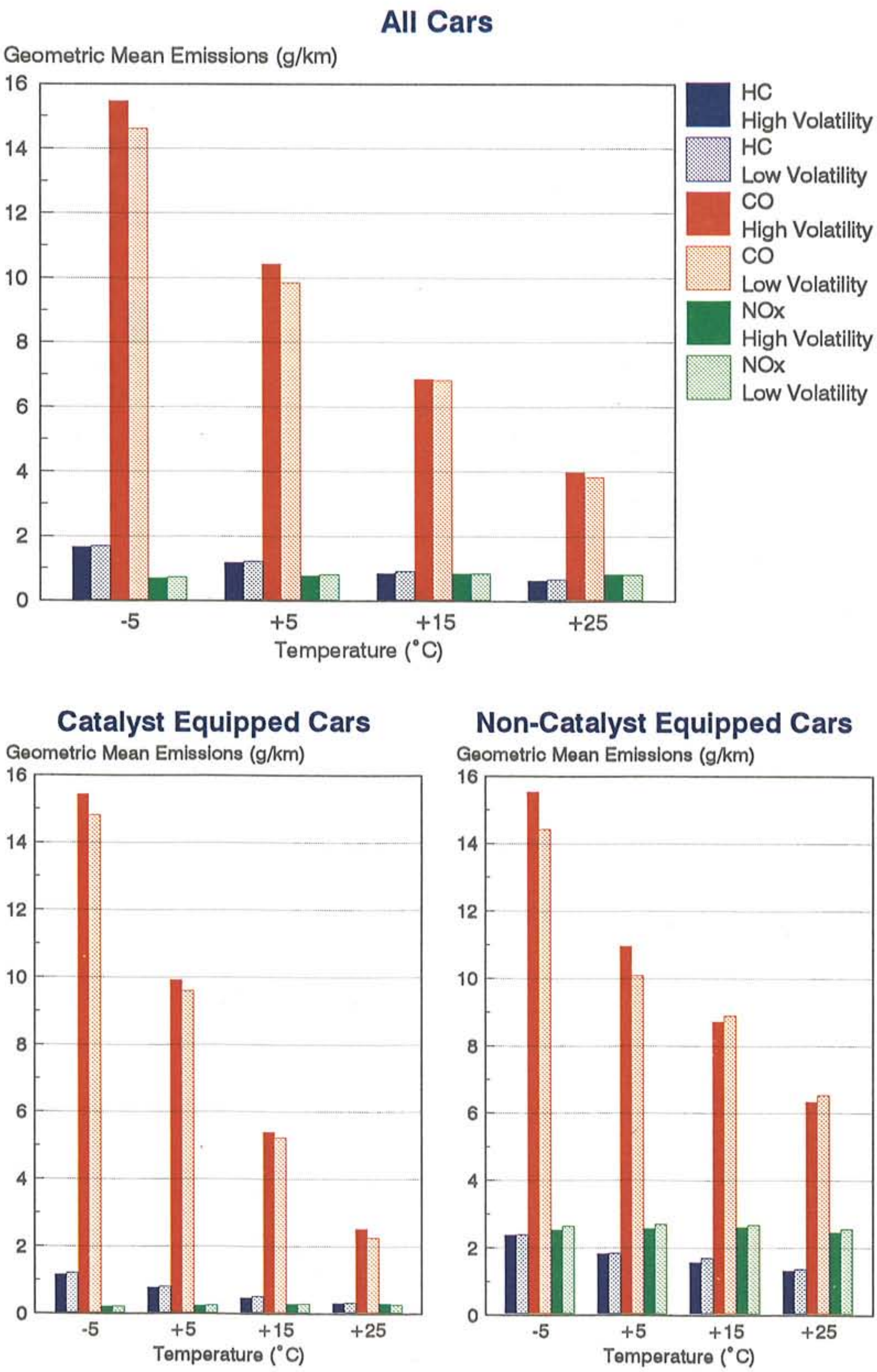


Figure 5: Geometric Mean HC Emissions

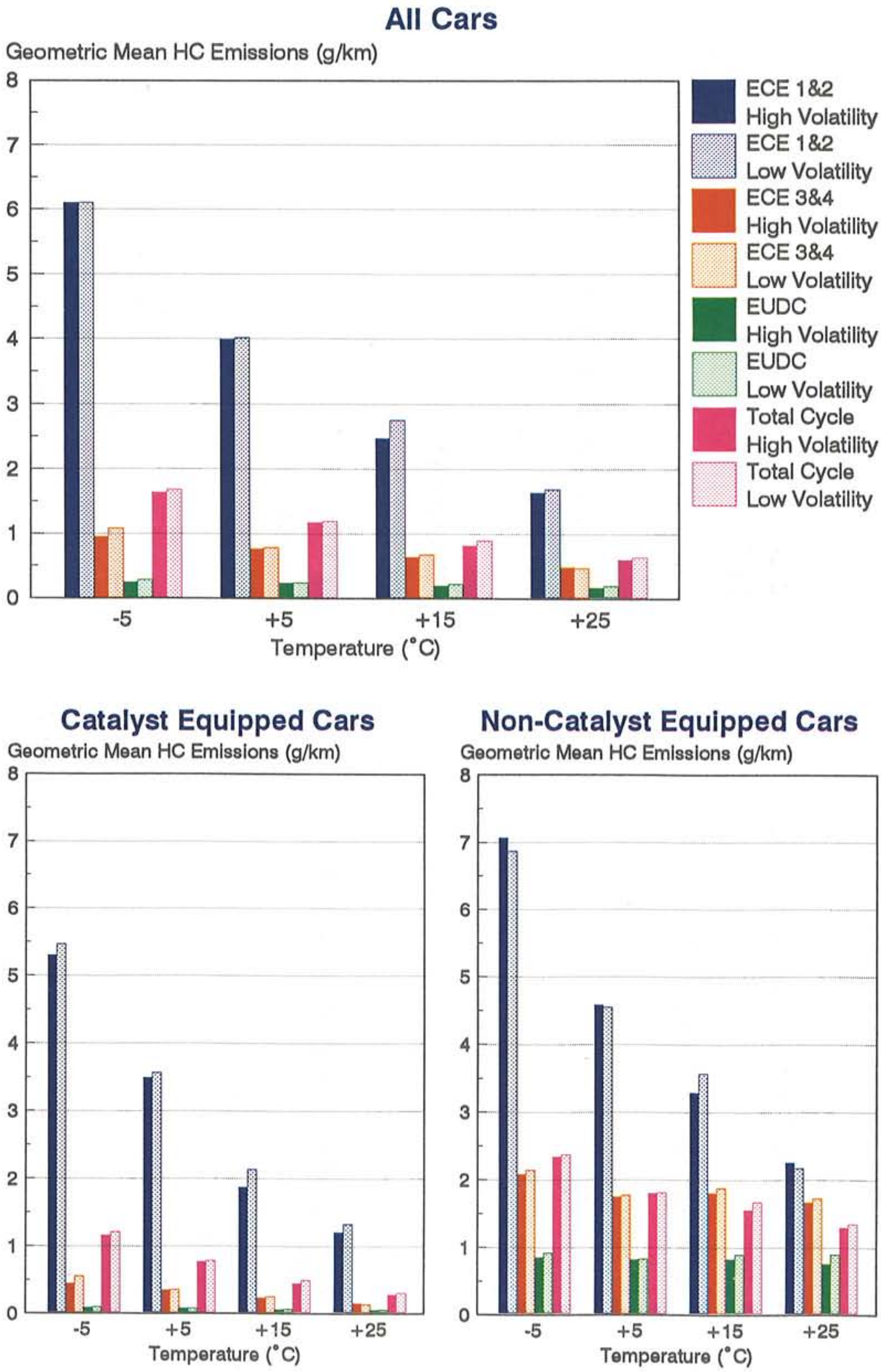


Figure 6: Geometric Mean CO Emissions

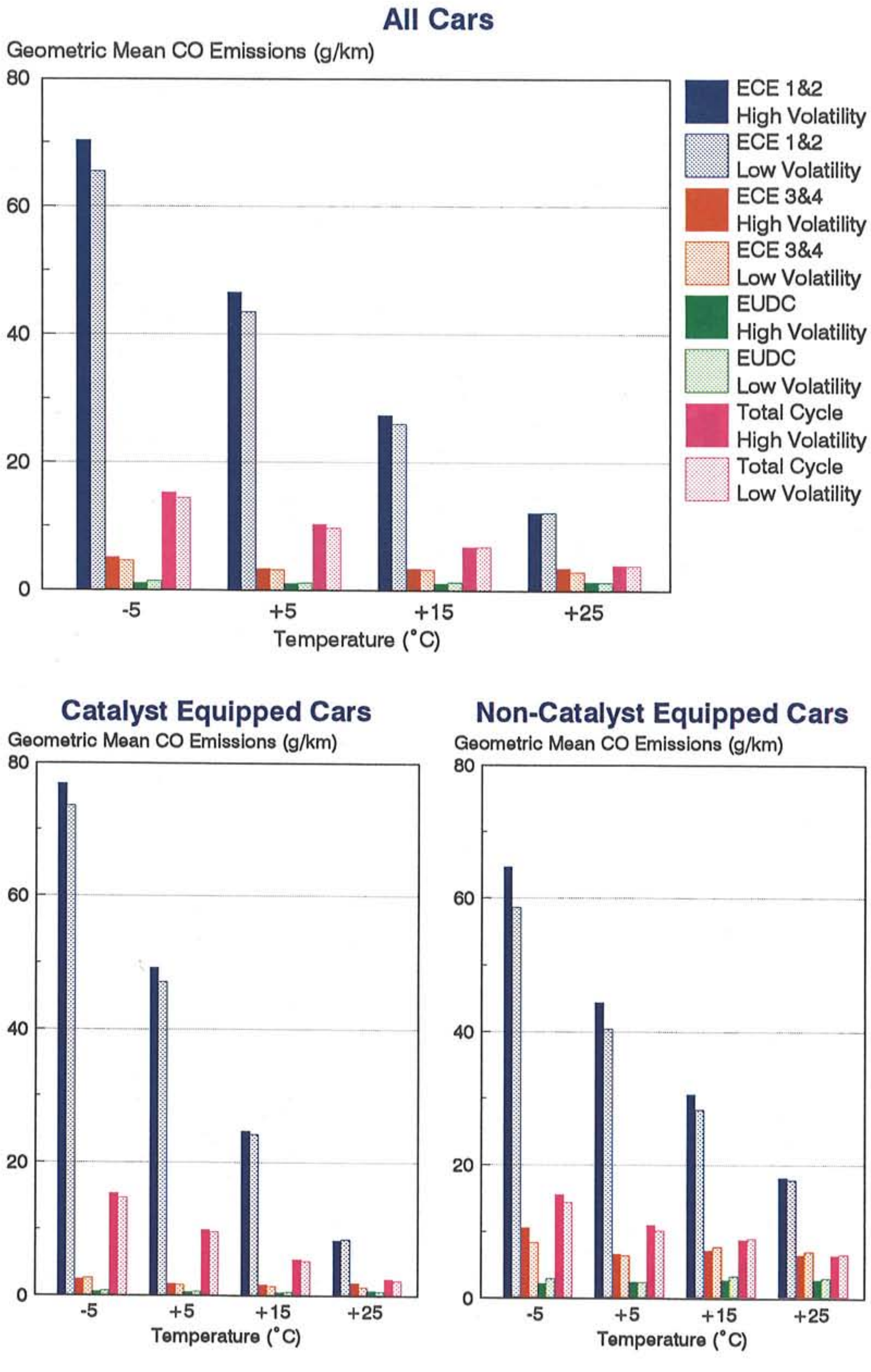


Figure 7: Geometric Mean NOx Emissions

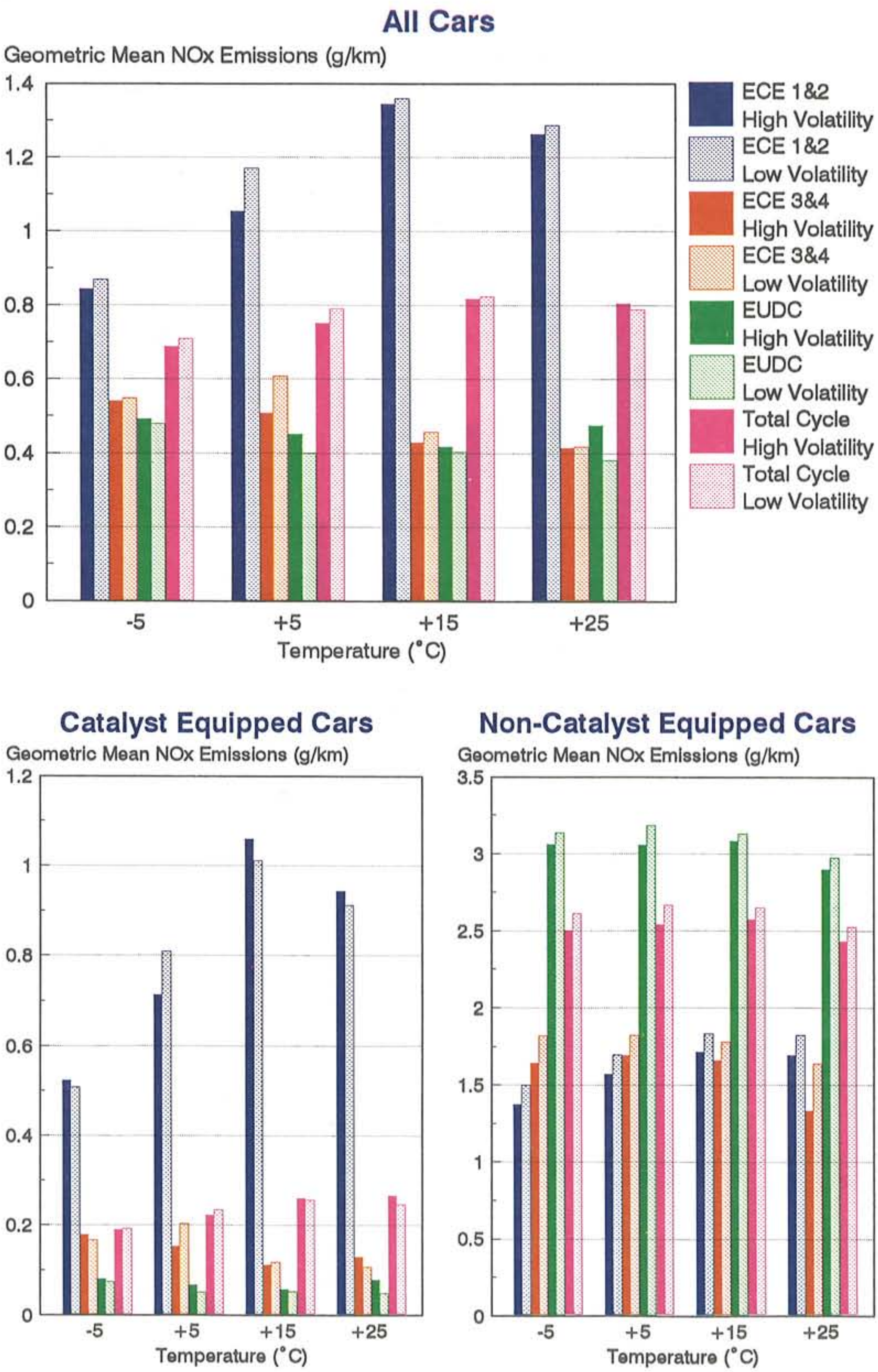


***Figure 8*:** Catalyst Car No 1 - Geometric Mean Emissions

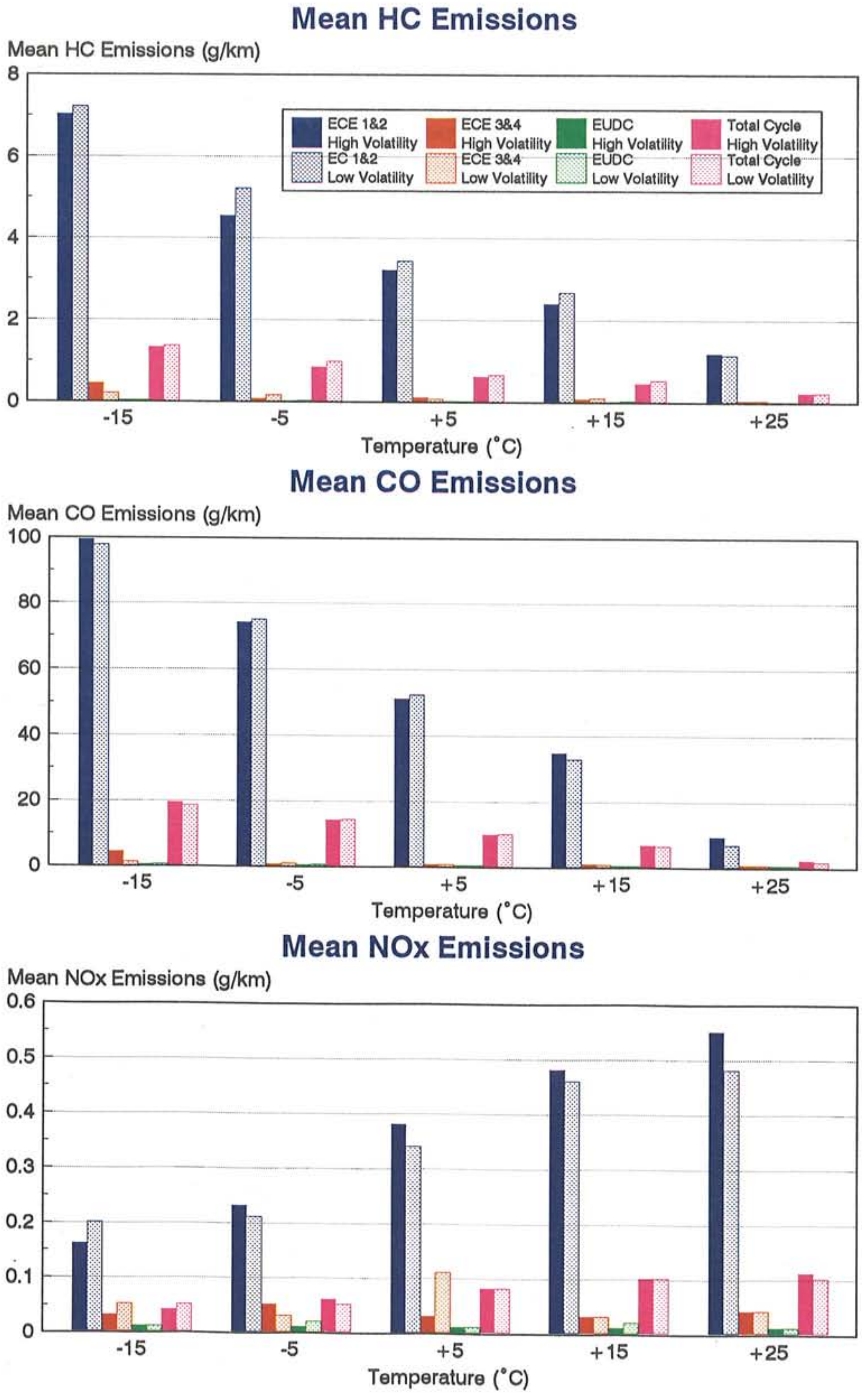


Figure 9: Non-Catalyst Car No 5 - Geometric Mean Emissions

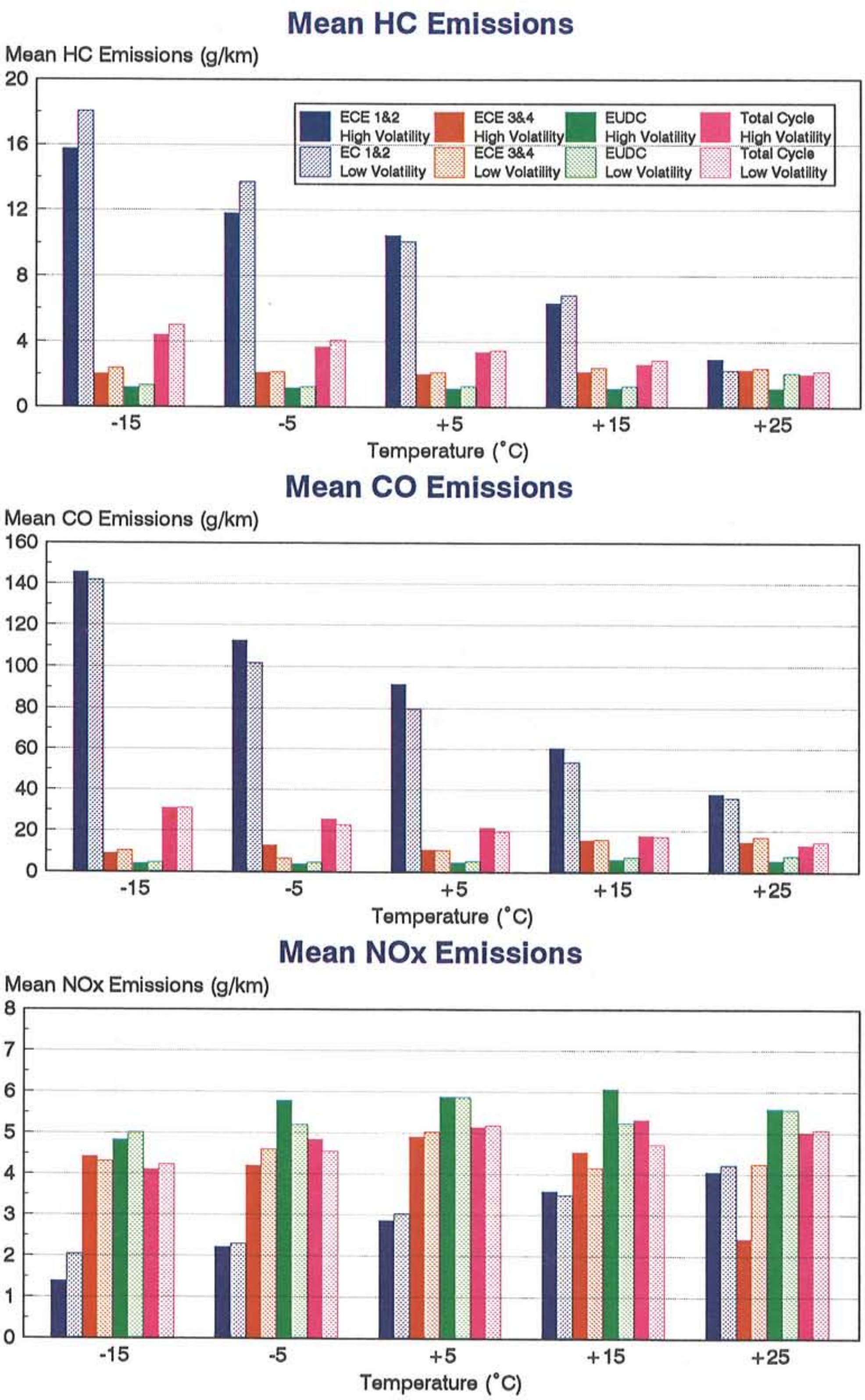


Figure 10: Difference in Emissions; Fuel H relative to Fuel L

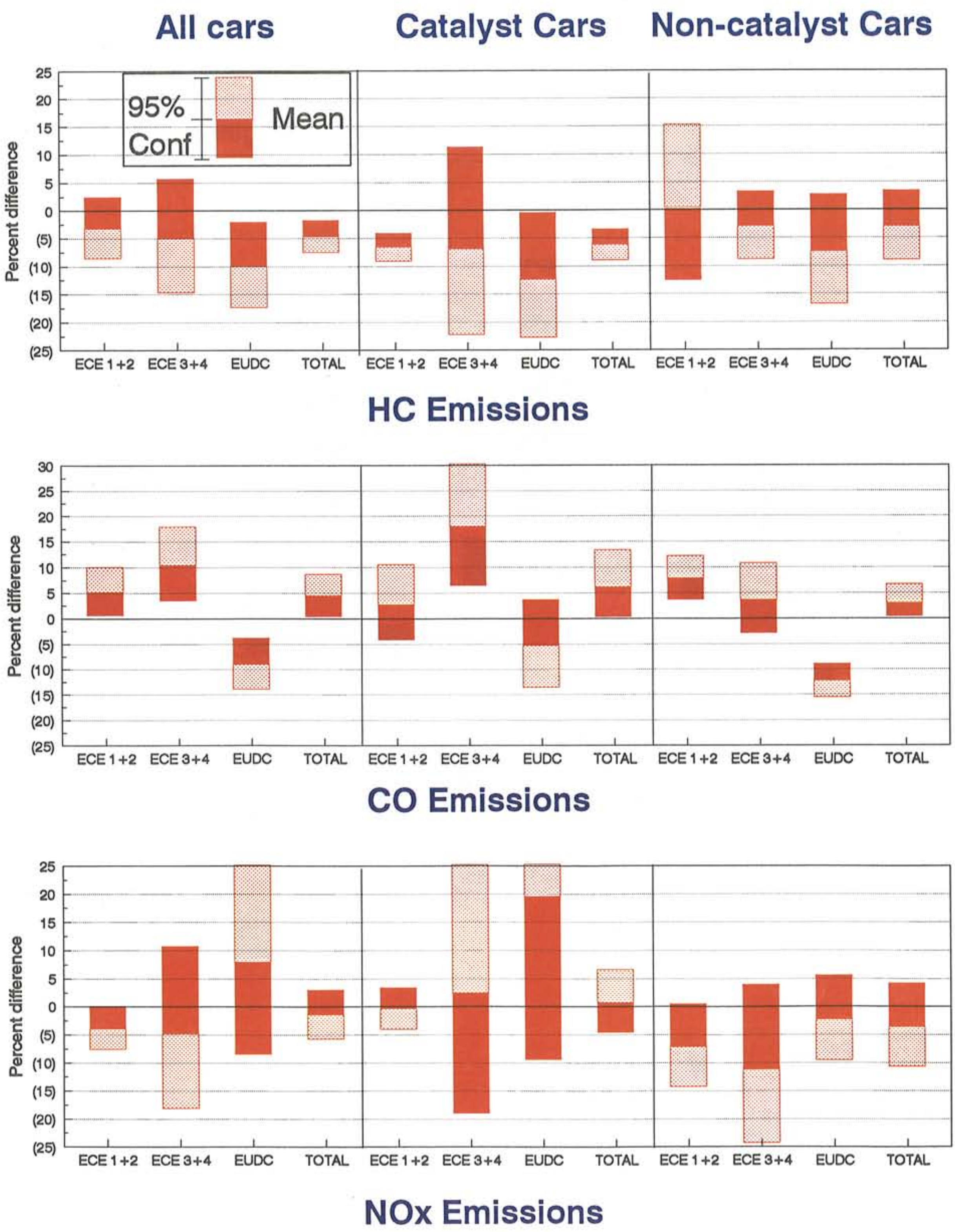
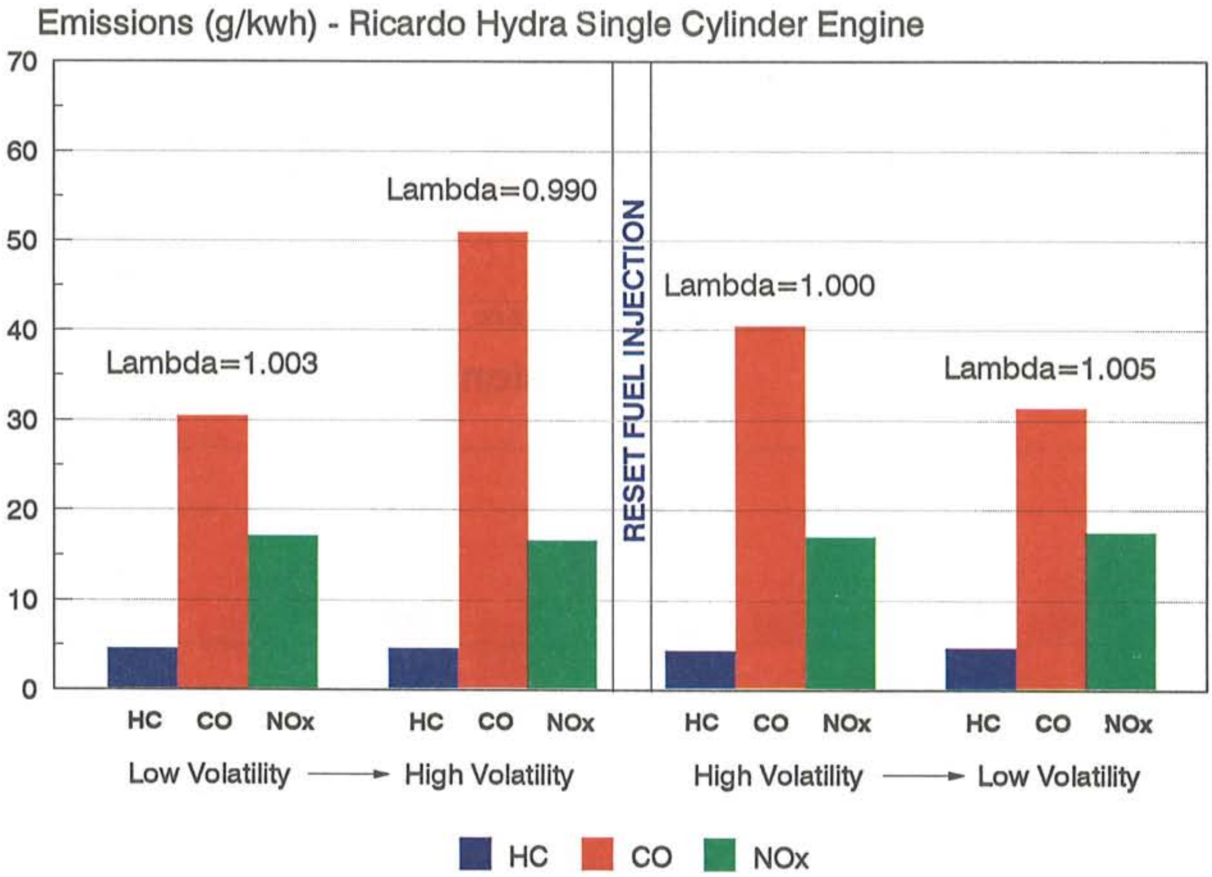


Figure 11: The Changes in Lambda and Emissions when Operating on Low and High Volatility Fuels



Appendix 1

Table A.1.1: HC emissions (g/km)

Temperature (°C)	-15		-5		5		15		25	
Fuel Volatility	High	Low	High	Low	High	Low	High	Low	High	Low
ECE cycles 1 and 2										
Car 1 (Cat)	7.03	7.21	4.54	5.21	3.23	3.44	2.40	2.68	1.18	1.14
Car 2 (Cat)	-	-	4.53	4.75	2.91	2.88	1.06	1.34	0.88	0.95
Car 3 (Cat)	-	-	5.01	5.64	3.11	3.79	2.07	2.20	1.49	1.69
Car 4 (Cat)	-	-	7.62	6.34	5.02	4.25	2.22	2.53	1.23	1.56
Car 5 (Non-cat)	15.77	18.07	11.84	13.77	10.47	10.10	6.32	6.80	2.90	2.20
Car 6 (Non-cat)	-	-	3.93	3.86	2.55	2.58	2.06	2.27	1.39	1.72
Car 7 (Non-cat)	-	-	10.88	9.80	5.15	5.25	2.85	3.42	2.36	2.32
Car 8 (Non-cat)	-	-	4.85	4.19	3.17	3.11	3.05	2.99	2.60	2.41
ECE cycles 3 and 4										
Car 1 (Cat)	0.45	0.21	0.08	0.17	0.11	0.08	0.08	0.10	0.03	0.03
Car 2 (Cat)	-	-	1.44	1.53	0.64	0.75	0.40	0.41	0.18	0.10
Car 3 (Cat)	-	-	0.41	0.43	0.35	0.35	0.32	0.31	0.31	0.30
Car 4 (Cat)	-	-	0.74	0.77	0.49	0.60	0.24	0.27	0.19	0.23
Car 5 (Non-cat)	2.05	2.37	2.12	2.13	2.02	2.11	2.15	2.38	2.25	2.35
Car 6 (Non-cat)	-	-	1.11	1.31	1.06	1.21	1.21	1.28	0.89	1.24
Car 7 (Non-cat)	-	-	3.97	3.98	2.20	2.19	2.20	2.33	2.03	2.06
Car 8 (Non-cat)	-	-	1.91	1.82	1.88	1.69	1.74	1.66	1.81	1.42
EUDC										
Car 1 (Cat)	0.03	0.04	0.02	0.03	0.02	0.02	0.01	0.03	0.01	0.01
Car 2 (Cat)	-	-	0.17	0.15	0.13	0.10	0.06	0.05	0.05	0.04
Car 3 (Cat)	-	-	0.07	0.06	0.05	0.06	0.05	0.05	0.05	0.05
Car 4 (Cat)	-	-	0.12	0.16	0.09	0.13	0.07	0.09	0.05	0.07
Car 5 (Non-cat)	1.19	1.32	1.16	1.22	1.12	1.25	1.12	1.25	1.13	2.04
Car 6 (Non-cat)	-	-	0.54	0.61	0.52	0.58	0.54	0.58	0.43	0.51
Car 7 (Non-cat)	-	-	1.04	1.20	0.96	0.95	0.98	1.15	0.95	0.97
Car 8 (Non-cat)	-	-	0.70	0.69	0.71	0.61	0.66	0.64	0.63	0.56
Total										
Car 1 (Cat)	1.33	1.38	0.86	1.00	0.62	0.66	0.46	0.53	0.23	0.23
Car 2 (Cat)	-	-	1.21	1.25	0.73	0.73	0.31	0.35	0.23	0.22
Car 3 (Cat)	-	-	1.04	1.16	0.67	0.80	0.47	0.49	0.36	0.40
Car 4 (Cat)	-	-	1.61	1.41	1.07	0.97	0.50	0.57	0.29	0.38
Car 5 (Non-cat)	4.41	5.01	3.65	4.07	3.34	3.45	2.58	2.83	1.96	2.13
Car 6 (Non-cat)	-	-	1.39	1.47	1.13	1.20	1.05	1.15	0.80	0.97
Car 7 (Non-cat)	-	-	3.39	3.29	1.96	1.97	1.55	1.78	1.41	1.42
Car 8 (Non-cat)	-	-	1.68	1.54	1.38	1.27	1.30	1.26	1.21	1.06

All the tabulated results for cars 1, 3, 4, 5, 6, plus the low volatility results for car 2 at -5° and +15°, are average emissions over duplicate tests (arithmetic means). The remaining results are emissions in single tests.

Appendix 1

Table A.1.2: CO emissions (g/km)

Temperature (°C)	-15		-5		5		15		25	
Fuel Volatility	High	Low	High	Low	High	Low	High	Low	High	Low
ECE cycles 1 and 2										
Car 1 (Cat)	99.48	97.88	74.28	75.12	51.05	52.27	34.71	32.76	9.09	6.76
Car 2 (Cat)	-	-	80.42	70.27	44.56	37.89	15.39	16.81	13.84	8.79
Car 3 (Cat)	-	-	73.98	75.06	48.36	51.85	27.65	24.83	8.05	14.33
Car 4 (Cat)	-	-	79.40	74.07	53.34	48.13	25.02	25.16	4.57	5.89
Car 5 (Non-cat)	145.98	142.13	112.59	101.78	91.20	79.17	60.08	53.16	37.54	35.71
Car 6 (Non-cat)	-	-	35.89	30.51	27.09	22.23	21.88	19.53	12.47	11.84
Car 7 (Non-cat)	-	-	97.57	91.29	53.59	53.24	29.15	28.70	18.01	15.56
Car 8 (Non-cat)	-	-	44.21	41.46	28.96	28.11	22.29	20.90	12.44	14.78
ECE cycles 3 and 4										
Car 1 (Cat)	4.25	1.16	0.61	0.94	0.75	0.76	0.81	0.64	0.62	0.57
Car 2 (Cat)	-	-	10.86	7.62	4.52	3.08	4.30	3.76	8.67	2.06
Car 3 (Cat)	-	-	1.62	2.20	1.16	1.12	1.13	0.87	1.30	0.96
Car 4 (Cat)	-	-	3.85	3.31	2.55	2.59	1.68	1.55	1.78	1.83
Car 5 (Non-cat)	9.00	10.33	12.89	6.60	10.84	10.43	15.41	15.67	14.69	16.88
Car 6 (Non-cat)	-	-	3.17	3.12	3.07	2.96	3.50	3.75	2.83	3.07
Car 7 (Non-cat)	-	-	36.90	29.66	9.24	8.16	9.35	9.89	9.84	9.05
Car 8 (Non-cat)	-	-	7.97	7.61	5.85	6.20	4.97	5.70	3.98	4.73
EUDC										
Car 1 (Cat)	0.40	0.50	0.42	0.49	0.32	0.33	0.36	0.42	0.35	0.35
Car 2 (Cat)	-	-	1.75	1.64	1.33	1.56	0.87	0.78	2.79	0.83
Car 3 (Cat)	-	-	0.40	0.53	0.28	0.42	0.32	0.31	0.30	0.37
Car 4 (Cat)	-	-	0.66	1.03	0.64	0.83	0.58	0.71	0.74	0.90
Car 5 (Non-cat)	3.93	4.51	3.58	4.40	4.35	4.88	5.70	6.82	5.23	7.34
Car 6 (Non-cat)	-	-	0.99	1.01	1.00	0.98	1.09	1.08	1.00	1.00
Car 7 (Non-cat)	-	-	2.69	6.93	4.37	3.15	4.52	7.94	5.99	5.46
Car 8 (Non-cat)	-	-	2.11	2.10	1.69	1.83	1.59	1.72	1.46	1.59
Total										
Car 1 (Cat)	19.34	18.59	14.06	14.33	9.75	9.96	6.77	6.39	2.01	1.56
Car 2 (Cat)	-	-	17.91	15.38	9.87	8.52	4.17	4.28	5.91	2.52
Car 3 (Cat)	-	-	14.17	14.56	9.29	10.01	5.50	4.92	1.91	3.04
Car 4 (Cat)	-	-	15.75	14.89	10.69	9.86	5.28	5.36	1.63	1.99
Car 5 (Non-cat)	31.00	30.93	25.41	22.69	21.51	19.58	17.57	16.93	12.90	14.29
Car 6 (Non-cat)	-	-	7.81	6.82	6.18	5.25	5.35	4.97	3.45	3.38
Car 7 (Non-cat)	-	-	26.45	26.64	14.32	13.29	9.94	12.12	8.91	7.98
Car 8 (Non-cat)	-	-	10.93	10.36	7.47	7.47	6.03	5.98	3.94	4.60

All the tabulated results for cars 1, 3, 4, 5, 6, plus the low volatility results for car 2 at -5°C and +15°C, are average emissions over duplicate tests (arithmetic means). The remaining results are emissions in single tests.

Appendix 1

Table A.1.3: NO_x emissions (g/km)

Temperature (°C)	-15		-5		5		15		25	
Fuel Volatility	High	Low	High	Low	High	Low	High	Low	High	Low
ECE cycles 1 and 2										
Car 1 (Cat)	0.16	0.20	0.23	0.21	0.38	0.34	0.48	0.46	0.55	0.48
Car 2 (Cat)	-	-	0.35	0.28	0.45	0.69	1.48	1.25	0.76	0.79
Car 3 (Cat)	-	-	1.12	1.02	1.39	1.34	1.69	1.71	1.83	1.84
Car 4 (Cat)	-	-	0.82	1.11	1.08	1.36	1.05	1.05	1.04	0.99
Car 5 (Non-cat)	1.38	2.04	2.21	2.29	2.85	3.01	3.57	3.47	4.03	4.20
Car 6 (Non-cat)	-	-	2.68	2.96	2.81	2.96	2.42	2.46	2.28	1.94
Car 7 (Non-cat)	-	-	0.84	1.05	1.16	1.29	1.45	1.80	1.46	1.81
Car 8 (Non-cat)	-	-	0.69	0.69	0.64	0.71	0.68	0.72	0.60	0.73
ECE cycles 3 and 4										
Car 1 (Cat)	0.03	0.05	0.05	0.03	0.03	0.11	0.03	0.03	0.04	0.04
Car 2 (Cat)	-	-	0.38	0.43	0.43	0.33	0.37	0.37	0.34	0.32
Car 3 (Cat)	-	-	0.49	0.49	0.42	0.41	0.38	0.34	0.39	0.32
Car 4 (Cat)	-	-	0.11	0.12	0.10	0.12	0.04	0.05	0.05	0.03
Car 5 (Non-cat)	4.41	4.30	4.20	4.59	4.89	5.02	4.52	4.14	2.41	4.24
Car 6 (Non-cat)	-	-	2.11	2.14	2.13	2.26	1.93	1.93	1.89	1.61
Car 7 (Non-cat)	-	-	1.19	1.62	1.26	1.45	1.38	1.78	1.18	1.43
Car 8 (Non-cat)	-	-	0.68	0.67	0.61	0.66	0.62	0.69	0.57	0.72
EUDC										
Car 1 (Cat)	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01
Car 2 (Cat)	-	-	0.26	0.27	0.28	0.27	0.24	0.29	0.40	0.31
Car 3 (Cat)	-	-	0.18	0.10	0.14	0.09	0.14	0.08	0.14	0.07
Car 4 (Cat)	-	-	0.08	0.06	0.05	0.03	0.03	0.02	0.06	0.03
Car 5 (Non-cat)	4.80	4.98	5.76	5.17	5.86	5.84	6.05	5.21	5.56	5.54
Car 6 (Non-cat)	-	-	3.82	4.01	4.23	4.37	3.96	3.92	3.83	3.18
Car 7 (Non-cat)	-	-	2.64	3.01	2.32	2.60	2.61	2.91	2.39	2.60
Car 8 (Non-cat)	-	-	1.50	1.53	1.50	1.53	1.43	1.59	1.37	1.69
Total										
Car 1 (Cat)	0.04	0.05	0.06	0.05	0.08	0.08	0.10	0.10	0.11	0.10
Car 2 (Cat)	-	-	0.30	0.30	0.34	0.36	0.49	0.48	0.46	0.40
Car 3 (Cat)	-	-	0.35	0.34	0.38	0.38	0.42	0.43	0.45	0.44
Car 4 (Cat)	-	-	0.21	0.27	0.24	0.29	0.22	0.22	0.22	0.21
Car 5 (Non-cat)	4.10	4.22	4.82	4.54	5.13	5.17	5.31	4.70	5.01	5.06
Car 6 (Non-cat)	-	-	3.29	3.48	3.59	3.72	3.31	3.28	3.18	2.67
Car 7 (Non-cat)	-	-	2.04	2.40	1.91	2.15	2.17	2.50	1.99	2.24
Car 8 (Non-cat)	-	-	1.20	1.22	1.18	1.22	1.14	1.27	1.08	1.33

All the tabulated results for cars 1, 3, 4, 5, 6, plus the low volatility results for car 2 at -5°C and +15°C, are average emissions over duplicate tests (arithmetic means). The remaining results are emissions in single tests.

Figure A.1.1: Catalyst Cars - Geometric Mean Emissions Over ECE Cycles 1 and 2

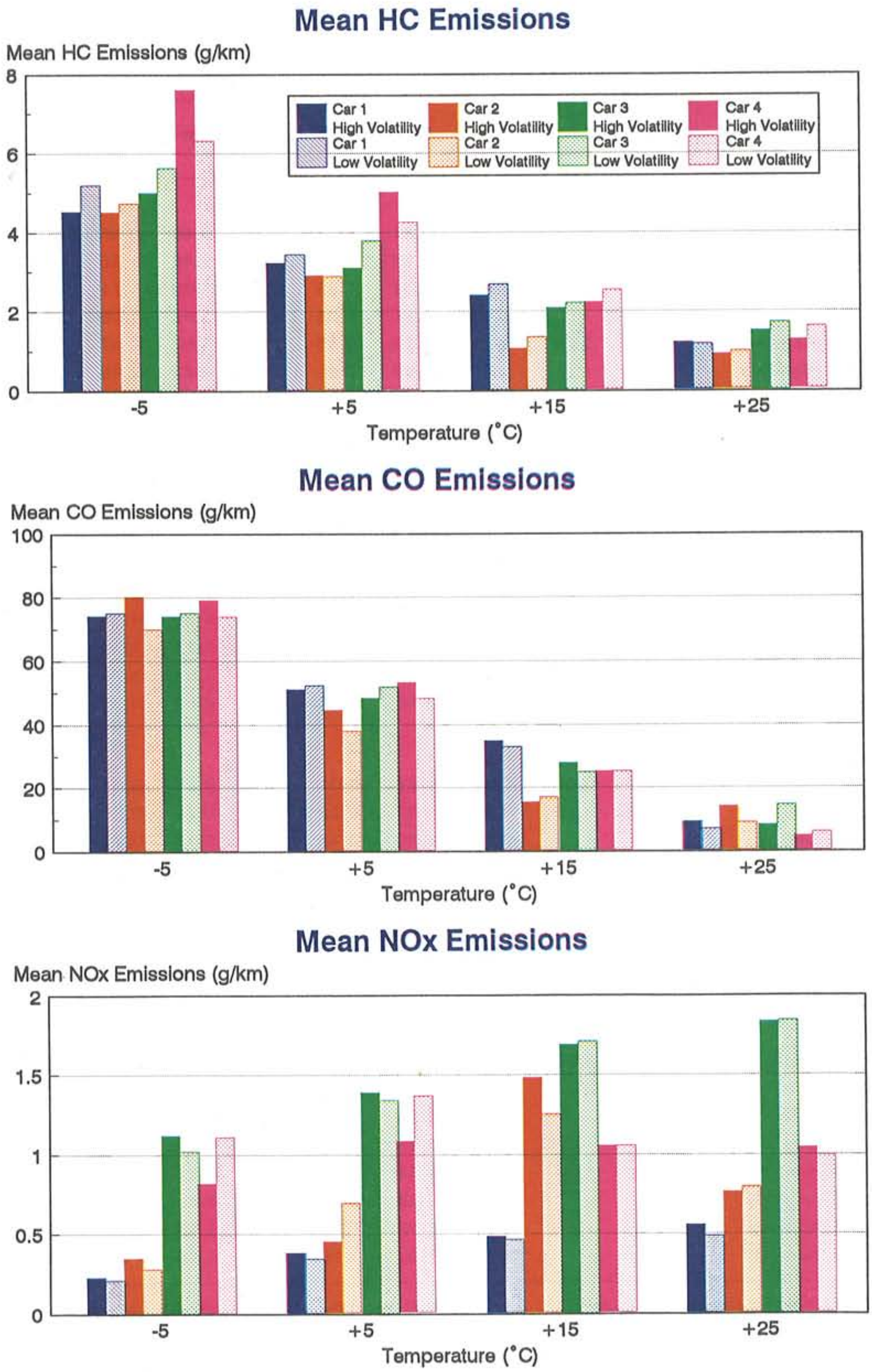


Figure A.1.2: Non-Catalyst Cars - Geometric Mean Emissions Over ECE Cycles 1 and 2

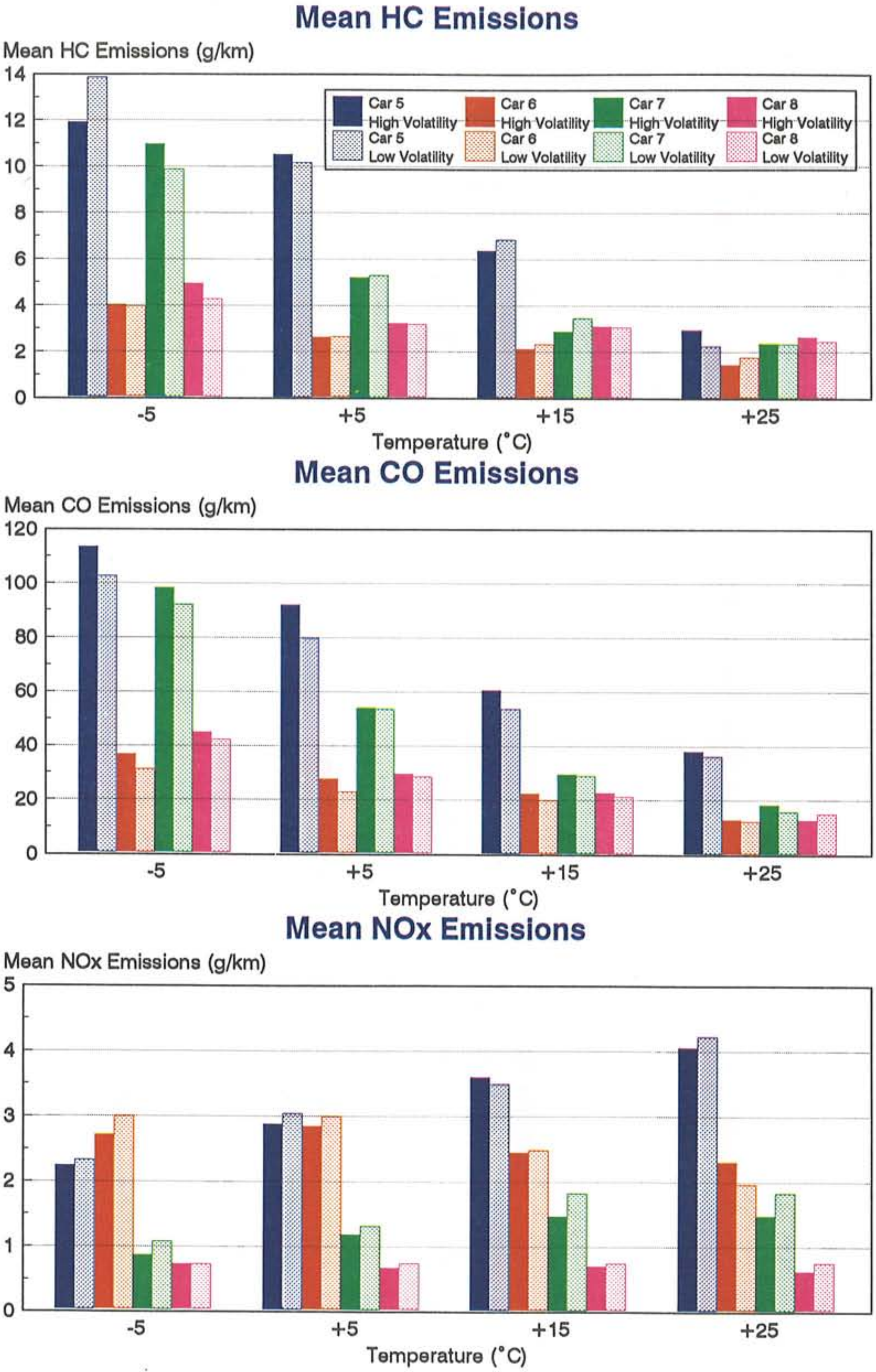
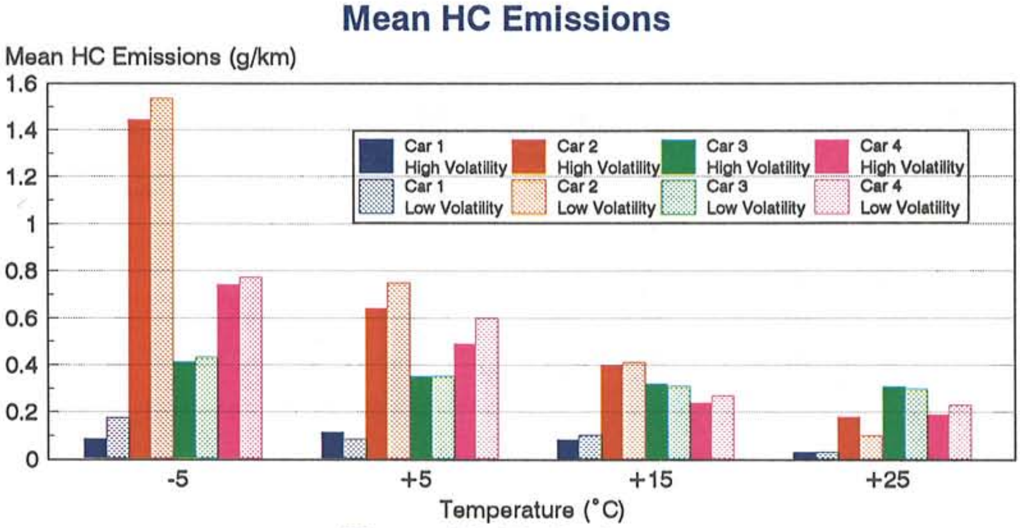
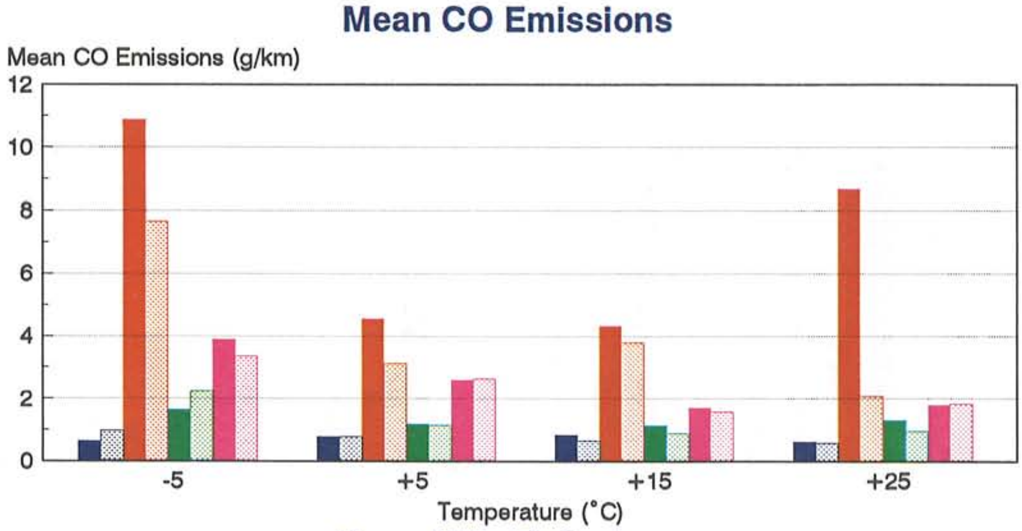


Figure A.1.3: Catalyst Cars - Geometric Mean Emissions Over ECE Cycles 3 and 4





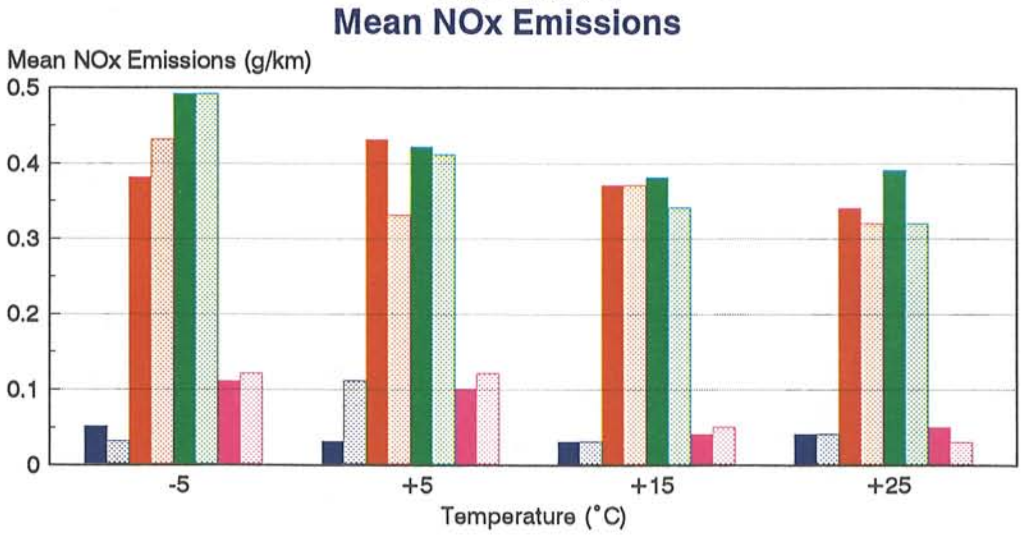
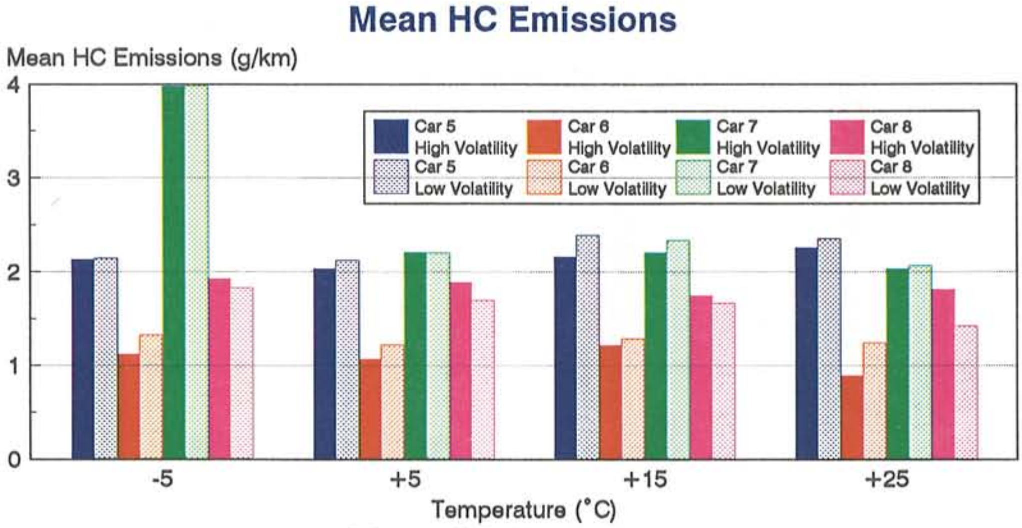
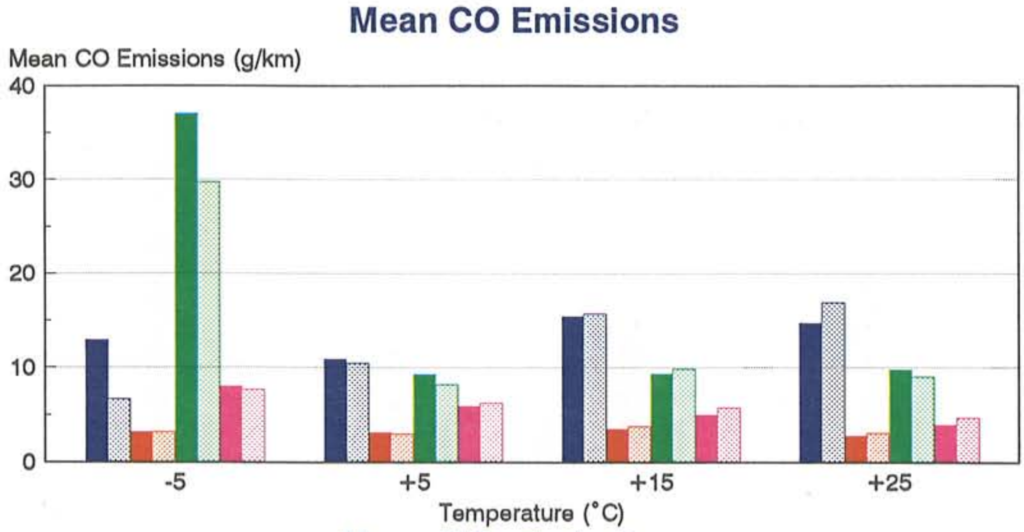


Figure A.1.4: Non-Catalyst Cars - Geometric Mean Emissions Over ECE Cycles 3 and 4





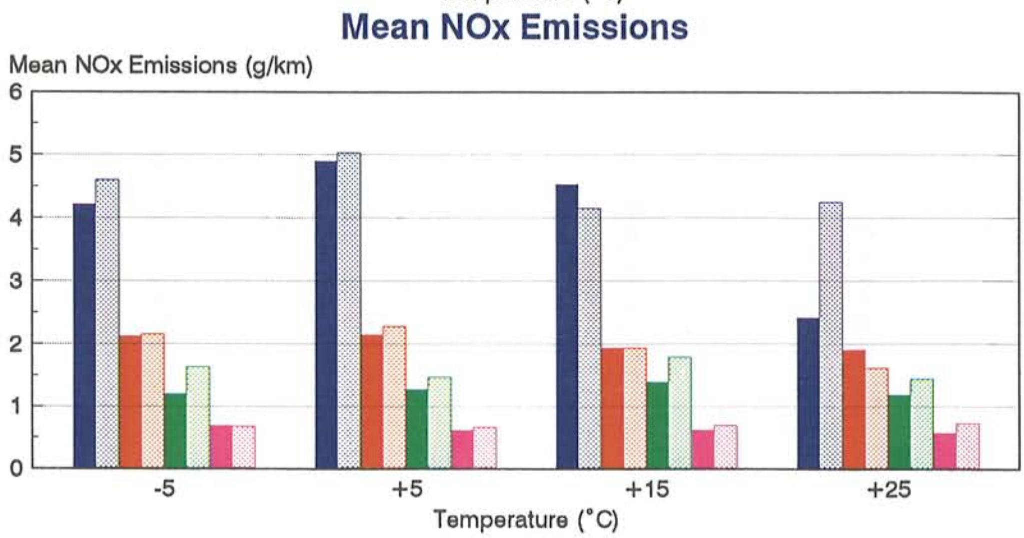


Figure A.1.5: Catalyst Cars - Geometric Mean Emissions Over the EUDC Cycle

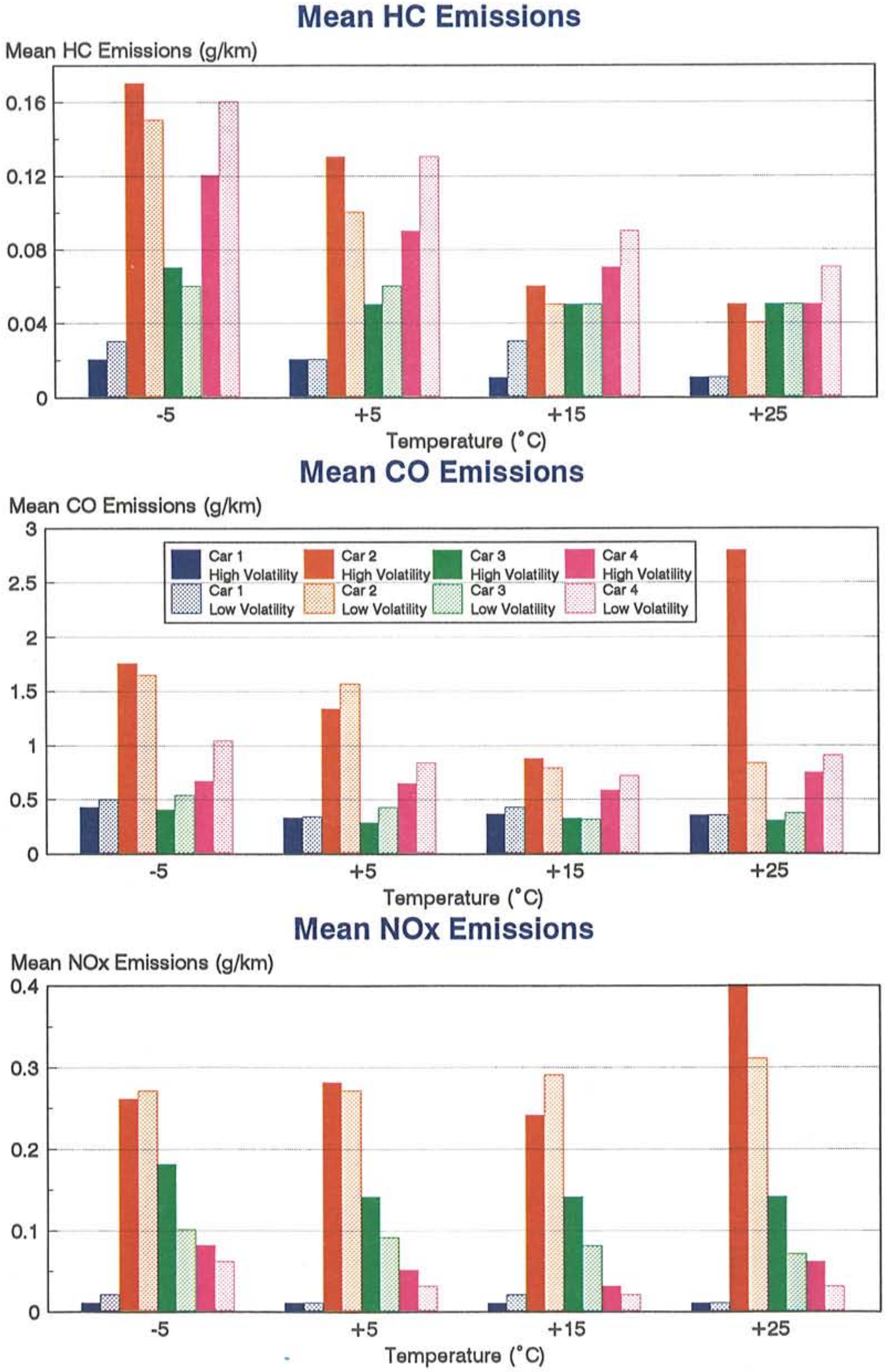


Figure A.1.6: Non-Catalyst Cars - Geometric Mean Emissions Over the EUDC Cycle

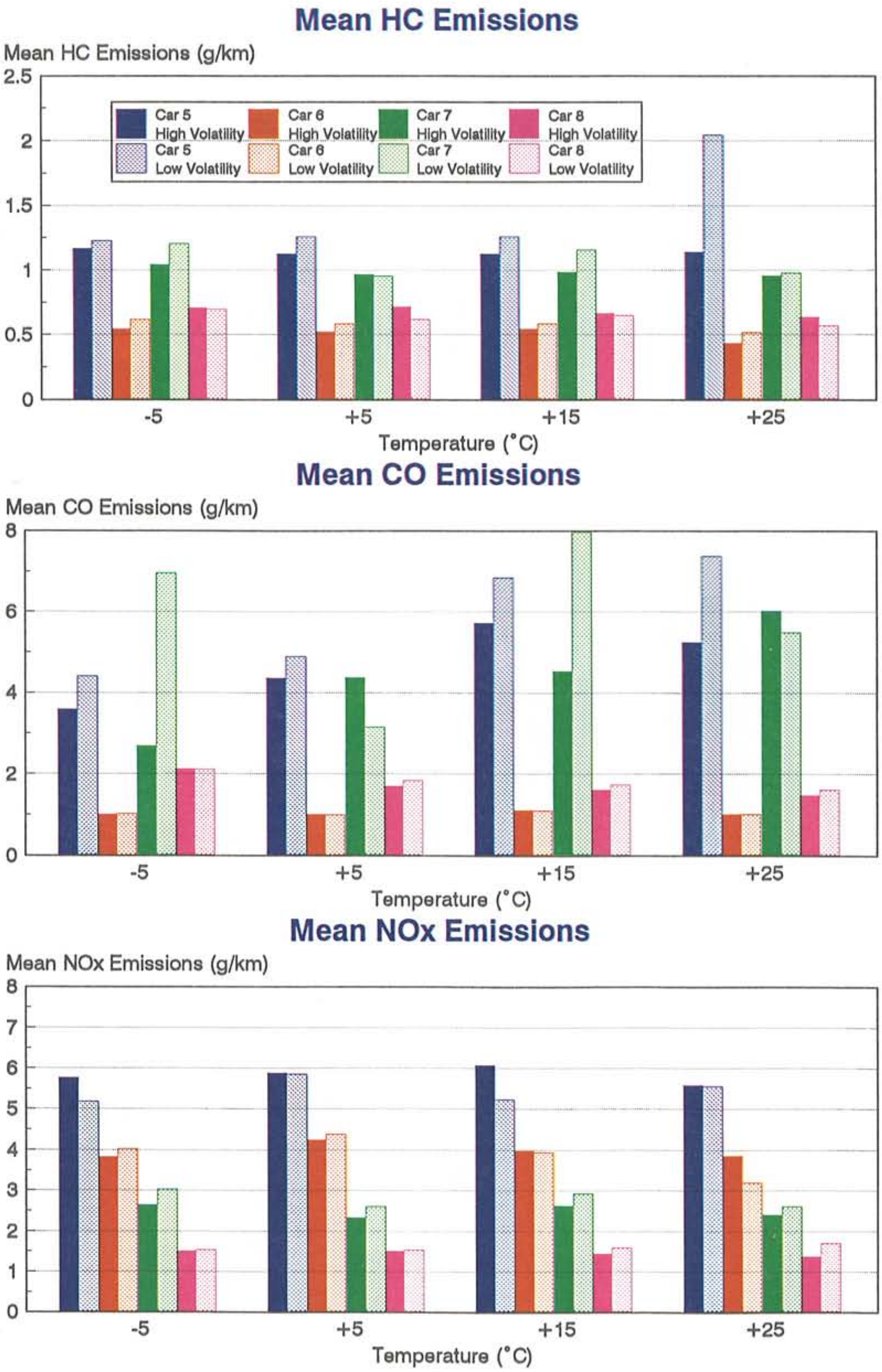


Figure A.1.7: Catalyst Cars - Geometric Mean Emissions Over the ECE + EUDC Cycles

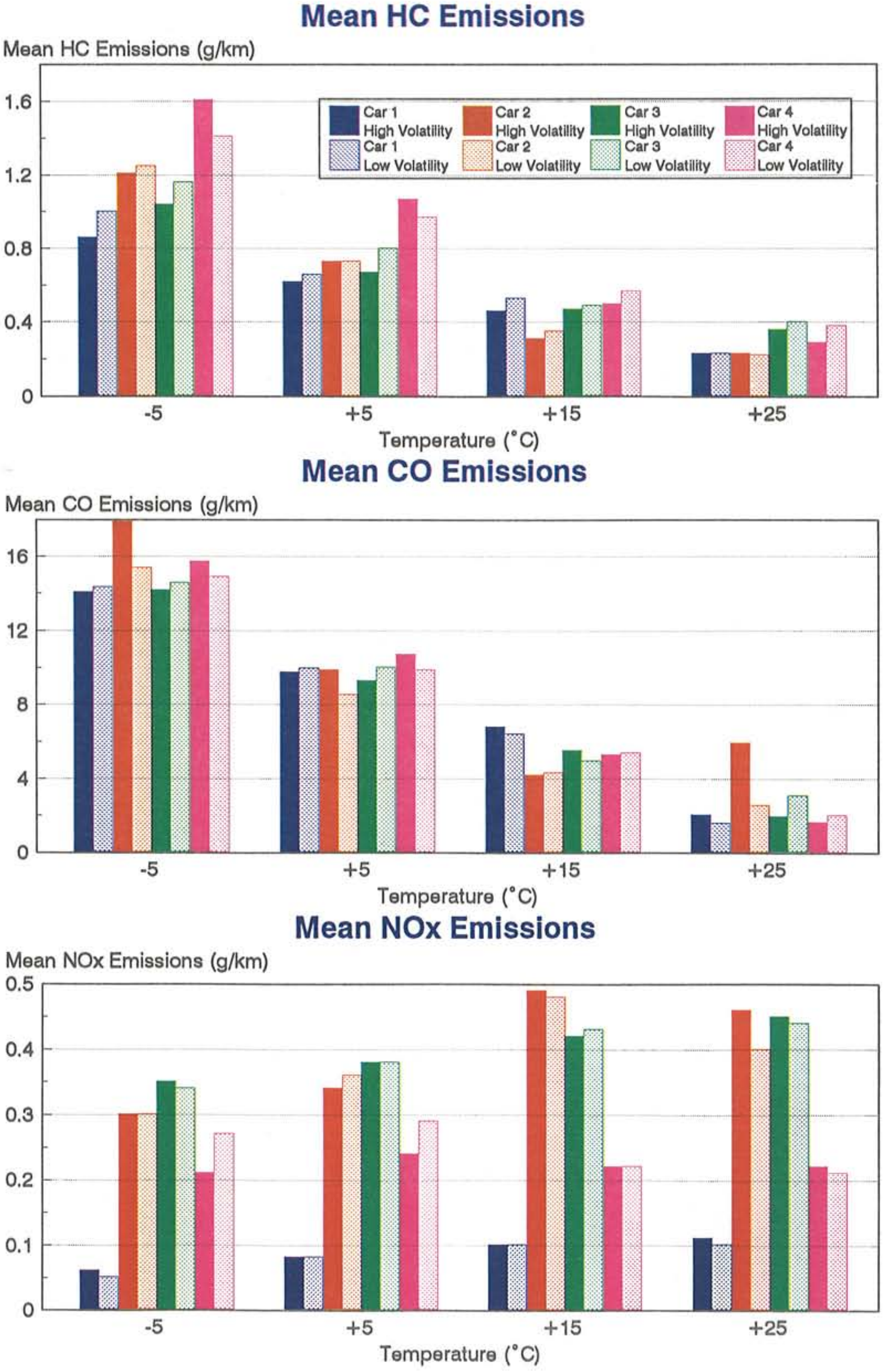
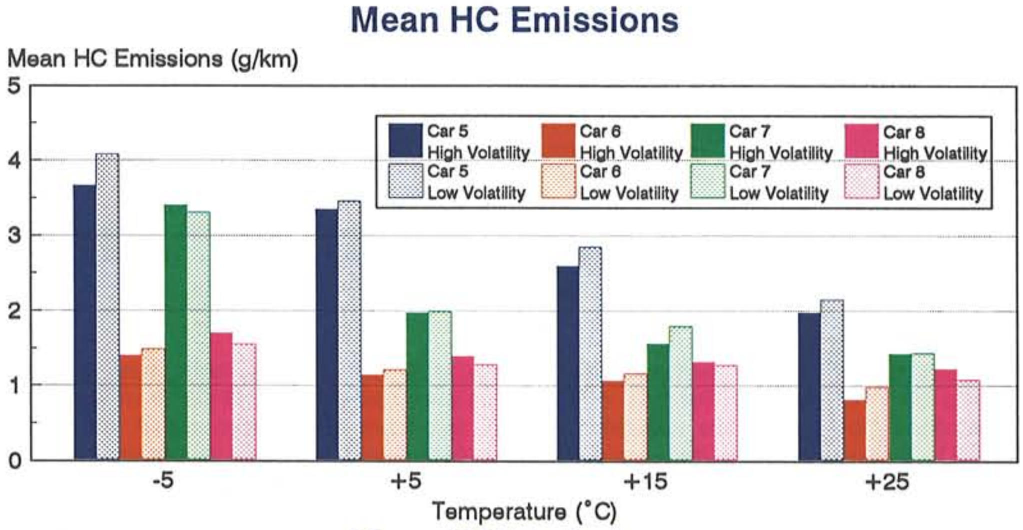
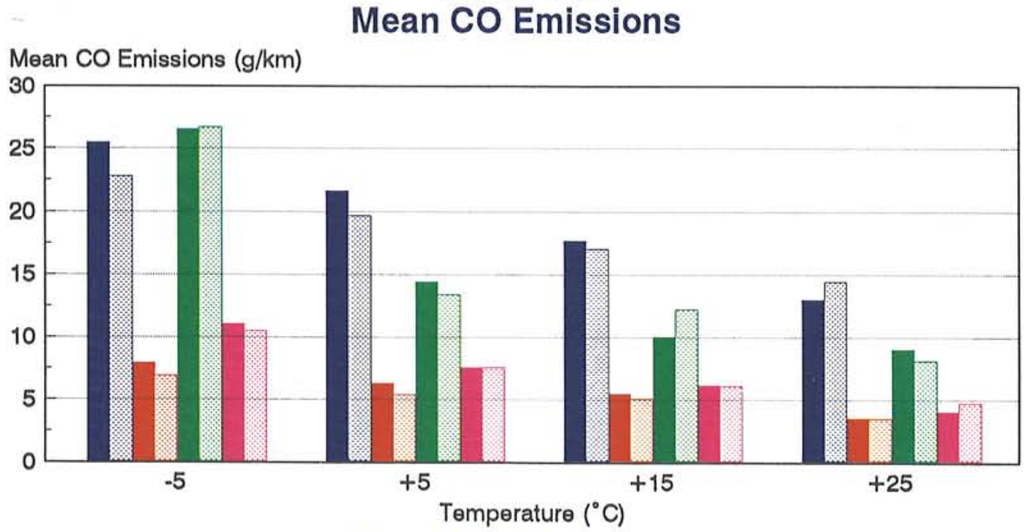
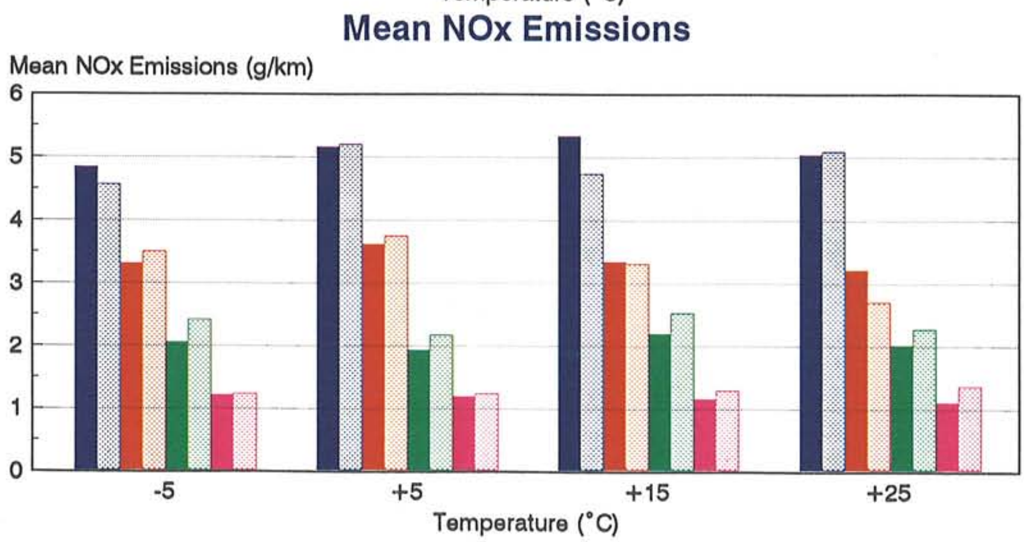


Figure A.1.8: Non-Catalyst Cars - Geometric Mean Emissions Over the ECE+EUDC Cycles







Appendix 2

Work by Euron

This work did not form part of the main CONCAWE programme but also looked at the effect of both fuel volatility and ambient temperature. Five vehicles were tested on three fuels as set out in **Table A.2.1**. Three cars (one with catalyst) were tested on three fuels of varying volatility and oxygenate content at 24°C (**Table A.2.2** and **Figure A.2.1**). The main variation was in mid-range volatility, and RVP was kept essentially constant. Results for this part of the programme are the mean of three tests. The other two cars (both catalyst) were tested at 0 and 24°C on one of the fuels (**Table A.2.3** and **Figure A.2.2**), where results are the mean of duplicate tests. Tests were carried out over the combined ECE plus EUDC cycle, but measurements were made in only two bags, for the ECE and EUDC cycles. No statistical analysis has been carried out on these data, so the results are discussed only on a quantitative basis.

The results on the three car/fuel matrix show that the more volatile fuel increased CO emissions by 7-12 per cent for two of the three cars tested over all parts of the test cycle. HC emissions however were reduced by 5-20 per cent apart from car A over the EUDC cycle. NO_x emissions were increased in some cases and reduced in others with no clear overall effect. These results are very much in line with those reported for the main programme. The fuel HO, which contained 15% MTBE and was also more volatile than either of the other two, reduced CO and HC emissions from all cars under almost all conditions. NO_x emissions were significantly increased for car A but showed little change for cars B and C.

The results for the two cars tested at 0 and 24°C show a major increase in CO emissions at low temperatures and a much smaller but still significant increase in HC emissions. NO_x emissions, however, are lower at low temperatures for both cars, apart from car E which shows an increase over the EUDC cycle. This again confirms the conclusions of the main programme.

Table A.2.1: Test fuel properties

	Fuel LE	Fuel HE	Fuel HO
Density kg/m^3	764	741	736
Evap @ 70°C	22.2	28.1	43.2
Evap @ 100°C	44.4	52.5	64.8
Evap @ 140°C	76.1	87.8	85.9
RVP kPa	63.6	68.5	68.5
FVI (RVP + 0.7E70)	79.1	88.2	98.7
FIA Analysis			
Aromatics % vol	43.0	26.0	28.0
Olefins % vol	1.0	12.0	1.0
Paraffins % vol	56.0	62.0	56.0
MTBE	0.0	0.0	15.0

Table A.2.2: Technical data for test vehicles

VEHICLE	A	B	C	D	E
Capacity cm3	1580	999	1990	1721	1581
Cylinders	4	4	4	4	4
Valves/Cylinder	2	2	2	2	2
Compression Ratio	8.9	9.0	9.8	10.0	9.2
Rated Power (kW) at rpm	65 6000	33 5000	95 6000	66 5800	57 5800
Rated Torque (Nm) at rpm	132 3600	80 2750	164 4300	142 3900	128 3500
Fuel System 1)	MPI	CARB	MPI	MPI	SPI
Catalyst Type 2)	3-way CL	- -	- -	3-way CL	3-way CL
Canister	-	-	-	-	-

Notes:

1) MPI = Multi-Point Injection
SPI = Single-Point Injection
Carb = Carburettor

2) 3-way = 3-way closed loop

Table A.2.3: Exhaust emissions - Euron work (g/km)

CAR	TEMP °C	FUEL	ECE 15 CO	ECE 15 HC	ECE 15 NO_x	EUDC CO	EUDC HC	EUDC NO_x	TOTAL CO	TOTAL HC	TOTAL NO_x
A	24	LE	5.56	0.43	0.21	0.07	0.08	0.25	2.07	0.21	0.23
		HE	4.89	0.40	0.24	0.07	0.11	0.31	1.82	0.21	0.28
		HO	4.70	0.36	0.35	0.07	0.09	0.28	1.75	0.18	0.31
B	24	LE	11.11	2.69	1.04	4.99	0.98	2.26	7.22	1.60	1.82
		HE	12.22	1.97	0.90	5.70	0.92	2.13	8.07	1.30	1.68
		HO	7.92	2.00	1.09	3.54	0.89	2.18	5.13	1.29	1.78
C	24	LE	16.36	2.80	1.76	2.51	0.99	3.00	7.54	1.65	2.58
		HE	17.70	2.70	1.76	2.51	0.99	2.75	8.04	1.61	2.39
		HO	13.39	2.55	1.69	1.97	0.91	2.92	6.12	1.50	2.47
D	24	LE	7.45	2.09	1.51	0.55	0.20	0.68	3.05	1.17	0.98
	0	LE	34.25	2.74	0.30	0.98	0.35	0.55	13.10	1.21	0.46
E	24	LE	2.67	0.44	0.42	0.02	0.03	0.70	0.98	0.18	0.60
	0	LE	23.58	1.25	0.31	0.21	0.05	0.79	8.70	0.48	0.61

Figure A.2.1: Effect of Fuel Volatility on Emissions

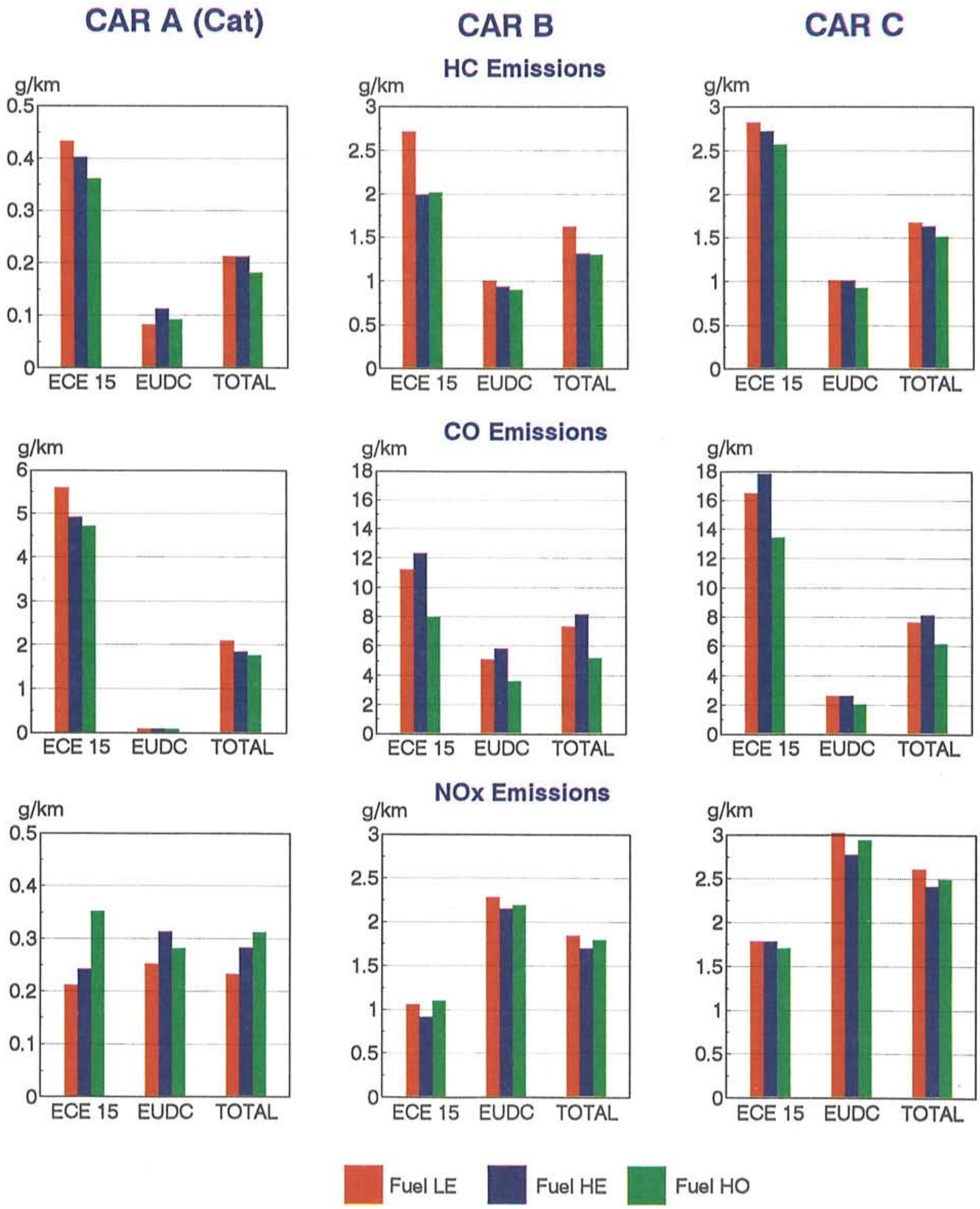
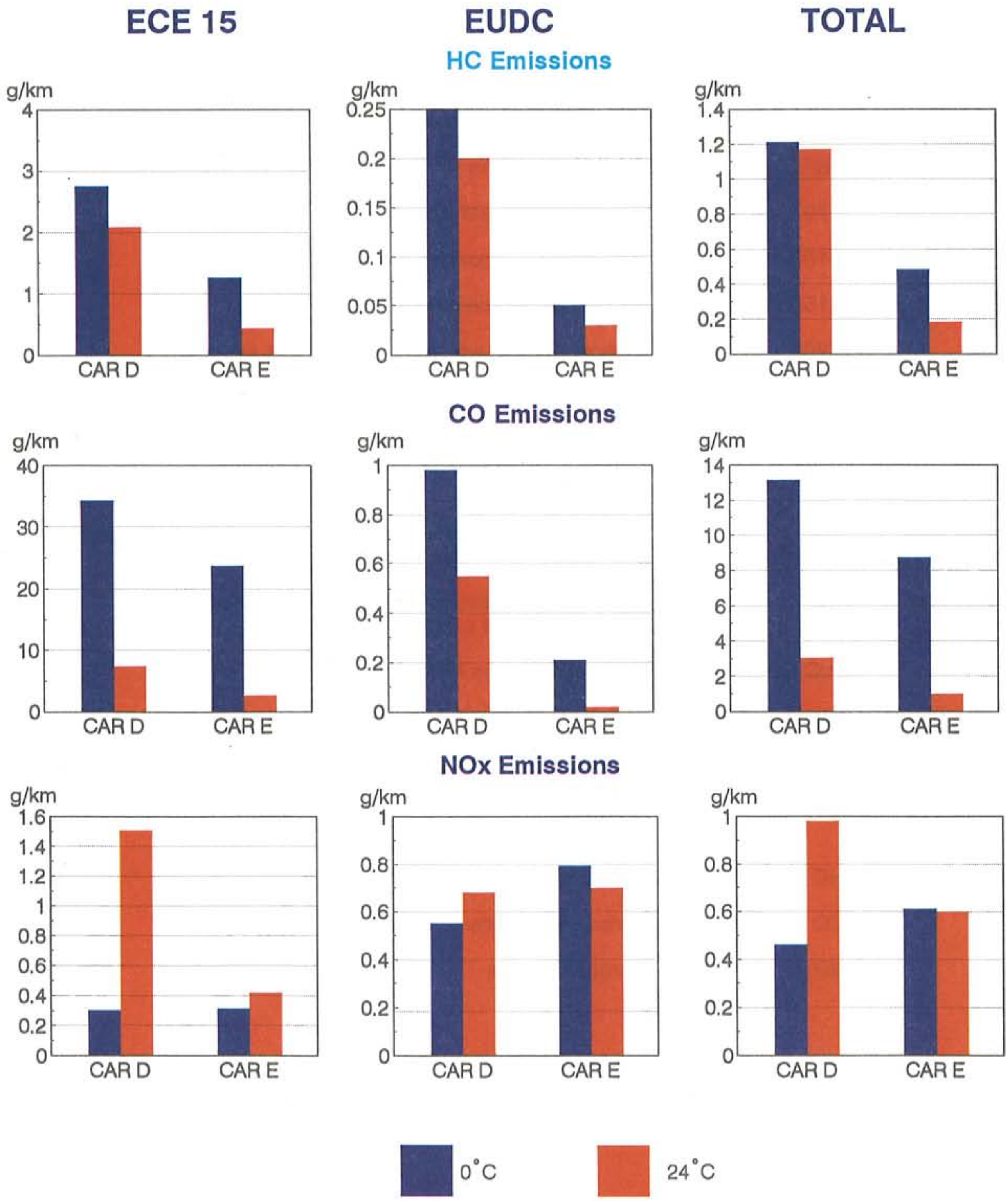


Figure A.2.2: Effect of Temperature on Emissions



Appendix 3 - Glossary of terms

RON	Research Octane Number
MON	Motor octane Number
IBP	Initial Boiling Point
FBP	Final Boiling Point
E70	Percentage evaporated at 70°C
E100	Percentage evaporated at 100°C
E150	Percentage evaporated at 150°C
T90E	Temperature at which 90% volume is evaporated
T50E	Temperature at which 50% volume is evaporated
RVP	Reid Vapour pressure - a standardized vapour pressure measurement, made at 38°C with a vapour/liquid ratio of 4:1
FVI	Flexible Volatility Index, for the flexible control of gasoline "front-end" volatility
FIA	Fluorescence Indicator Absorption method for the determination of gasoline composition
H/C Ratio	Hydrogen/Carbon Ratio
Stoich AFR	Stoichiometric air fuel ratio
ECE+EUDC cycle	Current (1993) EEC driving cycle, consisting of the ECE 15 urban driving cycle (a low speed cycle, repeated four times) and the EUDC (extra urban driving cycle) to simulate higher speed operation
HC	Hydrocarbons
CO	Carbon Monoxide
NO_x	Nitrogen Oxides