COLD-START EMISSIONS AND EXCESS FUEL CONSUMPTION AT LOW AMBIENT TEMPERATURES – ASSESSMENT OF EU2, EU3 AND EU4 PASSENGER CAR PERFORMANCES

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ABSTRACT

Latest development of engines and emission control devices in passenger cars to bring them in compliance with the last amendments of European directives for exhaust emissions (EU3 and EU4) has apparently improved also their performance with regard to cold-start related emissions, even if the targeted test procedure to specifically measure and control these emissions was included in the type approval requirements of new types as late as year 2002. However, as the test results presented in this paper demonstrate, cold-start performance has been gradually improved, and emission rates measured at low ambient temperatures (-7 ºC) have declined. However, the negative effect of cold environment with regard to fuel consumption and CO_2 *emissions has not much diminished. According the results, elevated emission levels at cold-start are also mostly associated with petrol-fuelled cars, as much lower levels were recorded for those with diesel engines.*

Keywords: *Cold-start emissions, passenger cars, petrol, diesel.*

1. INTRODUCTION

Since the adoption of the original ECE Regulation No. 15 in 1970 as a European Directive 70/220/EEC, gradually more and more stringent exhaust emission control for passenger cars has been introduced in Europe at a regular pace. The coverage of legislation was increased by adding oxides of nitrogen (NOx) aside CO and total hydrocarbons (HC) in 1977, and standards for diesel-fuelled cars were introduced in 1983, with the inclusion of particulate matter (PM) standard in 1988.

Furthermore, employing catalytic converters was an inevitable outcome of the adoption of even lower standards during early years of the 1990's. The stringency and coverage of the legislation was simultaneously increased also via amendments to the test procedure that is used to assess the emissions. The original urban driving cycle (UDC) of ECE15 was complemented with extra-urban cycle (EUDC) in 91/441/EEC [1], where control of evaporative hydrocarbons was included, too.

The outcome of all this has been that new cars released less and less harmful emissions. However, ambient air quality around Member States has not been improving at the same pace. This was for the reason that especially since catalytic converters were introduced, emissions at cold-start and during the very first few minutes and kilometres of the driving were relatively high. Hence, their contribution was greatly increased, as they were not adequately subjected to the control, because the test procedure was not addressing these. Therefore, directive 98/69/EC was adopted in 1988, and in this amendment by the EU Commission features were included that were targeted to make manufacturers to enhance the performance of the emission control especially in the cold-start phase. One such feature was the modification of the test procedure to omit the 40 seconds idle that has been in the beginning of the test, and start collecting the exhaust sample immediately after the engine has fired-up. Therefore, the exhausts from the most-critical cold-start phase were not anymore by-passed, but included in the sample.

This modification was expected to make the manufacturers more careful in their programming of the cold-start enrichment, and force them to bring the catalytic converter closer to the engine for faster warm-up and subsequent light-off [2], [3]. Both of these features were expected to greatly improve the performance of the system right after the start-up. And they really succeeded, which could be demonstrated e.g. by testing these Euro 3 compliant vehicles using the old test procedure.

Furthermore, the revamped directive included a separate cold-start test at low operating temperatures, namely at –7 °C. This test consists of just the UDC phase of the revised European dynamometer driving schedule. As it is slightly over 4 km in length, it can be regarded as a fair representative of a short urban early-morning cold-start trip, as the vehicle subjected to the test needs to be soaked at that cold temperature at least 12 hours. Naturally, this test has its own set of standards. Limit values are given for CO (≤ 15 g/km) and total hydrocarbons (≤ 1.8 g/km), as NOx was not expected to increase markedly. Also, it deals only with petrol-fuelled cars, because diesel engines were considered to be less affected.

Although part of the package, this additional requirement was not, however, introduced at the same time as Euro 3 standards (1.1.2000 for new type approvals), but two years after in 2002. And even then, it was only for new types. Therefore, the implementation was rather slow. Even so, testing has shown that the modifications of the emission control system required due to this revised test procedure in the normal temperature have greatly improved the performance at low ambient temperature, as well.

2. OBJECTIVE

The objective of the original work at VTT on cold-start emissions [4], [5] was to show the weak points of the technology and underline the necessity to address this deficiency. Along with the similar research made in Sweden and the Netherlands, the evidence was clear enough for the legislators to implement the regulations with the inclusion of a low ambient temperature test, referred in the Directives as “type VI test”.

As part of that original mission, VTT has evaluated and reported cold-start performance of new cars since 1993, addressing also durability of the technology in Nordic conditions [6], [7], [8]. This work has been continued even after the legislation was passed and the initial objective was reached. Each year a batch of some 10 to 20 cars representing that particular model year has been tested. The objective of this work has been to make an assessment of the cold-start performance, and evaluate how it has been developing. Furthermore, the aim is to provide first-hand results for the motoring press of those cars for their annual evaluation tests. Therefore, measuring fuel consumption and CO_2 has been part of our test, even if it is not part of the legislative procedure.

3. TEST FLEET COMPOSITION

Even if the objective was to portray typical new car performance, the selection of each annual fleet has been rather random and not statistically composed, but the eventual choice of cars was made by the motor magazines that initiated the testing. However, they usually tried to favour cars of high sales volumes in Finland, but occasionally new, some marginal but interesting vehicles were included. Although cold-start excess emissions are primarily associated with petrol-fuelled cars, we have also tested diesel-fuelled cars, because emission inventories do need cold-start data also for diesel cars, and cold-start imposes also higher fuel consumption, which we wanted to assess. Most of the cars were fairly new, with odometer readings usually below 5,000 km.

Table 1 lists some characteristics for the different sub-fleets that in total comprise 203 vehicles, of which 161 were running on petrol, and 42 on diesel.

Table 1: Some main characteristics of annual sub-fleets tested by VTT

test fleet	# cars	average displ [dm^3]	average inertia [kg]	EU Std.	total # cars
EcoCar '98	9	1.254	1069	EU2	
TM Winter '99	16	1.536	1241	EU2	
EcoCar '99	9	1.413	1136	EU2	34
TM Winter '00	7	1.787	1327	EU3	
EcoCar '00	9	1.373	1134	EU3	
TM Winter '01	19	1.788	1354	EU3	
EcoCar '01	6	1.580	1247	EU3	
EcoCar '02	4	1.365	1050	EU3	
TM Winter '03	19	1.593	1289	EU3	
TM Winter '04	11	1.775	1400	EU3	75
TM Winter '05	20	1.738	1305	EU4	
TM Winter '06	12	1.629	1275	EU4	
TM Winter '07	20	1.626	1334	EU4	52
petrol, in total	161				
EcoCar '98	3	1.930	1247	EU2	3
EcoCar '00	3	1.837	1323	EU3	
TM Winter '00	7	2.074	1456	EU3	
EcoCar '01	7	1.776	1249	EU3	
EcoCar '02	7	1.951	1305	EU3	24
TM Winter '08	15	1.464	1473	EU4	15
diesel, in total	42				
all fleets, in total	203				

Because the two motor magazines that were contracting the tests had different views in their work, the fleets were somewhat different in terms of vehicle size and engine capacity. As the name already suggests, the “EcoCar” fleets were tested for the Finnish “Tuulilasi” (“Windscreen” in English) motor magazine mainly for their annual series “Search for the most ecological car” amongst the test group. Therefore, most of these sub-fleets were of smaller size and with less engine power, as sometimes, the initial selection was based on CO_2 emissions and the most low-emitting vehicles usually are small and low-powered. With petrol cars this was especially true, as on average all “EcoCar” fleets were some 15% lighter and with smaller displacement engines about the same amount compared to those sub-fleets tested for “Tekniikan Maailma” (“the World of Technology” in English), whose choices were more favouring cars with high sales volumes or technologically interesting types rather than low consumption or CO_2. However, in diesel-fuelled fleets this tendency was less visible.

4. TEST PROCEDURES AND EQUIPMENT

Tests were run at –7 ºC, and using ECE15 urban driving cycle (UDC). Thus, they conform with the type VI test specifications of the Directive 98/69/EU, and the results can be compared to the official limit values. Even those cars that were originally type approved according to Euro 2 (EU2) specification, i.e. using the NEDC test cycle, were tested with the new procedure to give comparative assessment of their performance. Furthermore, all cars were tested also over the same driving cycle, but now after a thorough warm-up (EUDC cycle). This second UDC cycle was initiated with a hot engine restart after a 1 minute pause. Such a procedure gave the opportunity of assessing the difference between the cold-start and hot-start results, and after deducting the hot restart value from the cold-start results, it gives a fair estimate of the cold-start/warm-up excess emissions.

Even if in principle, comparability with the legislative procedure was our target, the objective of this work was, however, neither to make an official check of the emissions output, nor to assess the conformity of production (COP). Therefore, for fair reasons of simplicity and cost-effectiveness, all tests were run using commercial fuel (RON 95) of good quality.

Vehicle preparation and preconditioning was also carried out along with to the definitions in the Directive. Accordingly, cars were soaked in the test cell for at least 12 hours, but not more than 24 hours, although the certification procedure allows cold-soak up to 36 hours. However, in stead of running the regulatory-defined preconditioning, three times EUDC, cars were usually run on road with at least a 20 km trip before garaging them into the test chamber for the cool down and overnight soak.

Dynamometer settings were based on the vehicles' reference mass and the corresponding factors were taken from the look-up table in the Directive.

A normal PDP-CVS system was used for all exhaust dilution and sampling, and an AMA2000 exhaust emission analysis system from Pierburg AG (FRG) was used for determining the concentrations of the regulated compounds as well as CO2.

5. RESULTS AND DISCUSSION

5.1. Petrol fuelled Euro 2, Euro 3 and Euro 4 cars

A good comparison between the performances of Euro 2, Euro 3 and Euro 4 cars can be made on the basis of results these sub-fleets of model year (MY) 1998 to 2007. As the aim was to assess performance of the newest cars, we were quite convinced that tested cars were at least in most cases type approved according to the certification standard applicable to their model year, i.e. Euro 2 for 1998 and 1999, Euro 3 for 2000 to 2004, and Euro 5 after 2005. As Table 1 lists, the number of cars belonging to each category was then 34, 75 and 52, respectively. However, on border years like 2000 and 2005, it is possible that a few cars of earlier standard also were included, as we have not made records of the original type approval standard of each individual car tested.

Figure 1 illustrates the test results for CO emissions, presented as a cold-start result, comparable to the cold-start type VI test described in Directive 96/69/EU, derived from a ECE15 driving cycle at –7 °C ambient. The results are shown as average values for each sub-fleet, and grouped separately for petrol and diesel fuelled cars, and sorted by year the sub-fleet has been measured. Error bars are also shown for the purpose of describing the spread of values between individual vehicles in each sub-fleet. We have also noted the number of cars that were exceeding the limit values imposed for new types after 2002. Furthermore, **Figure 2** is depicting HC emissions the same way.

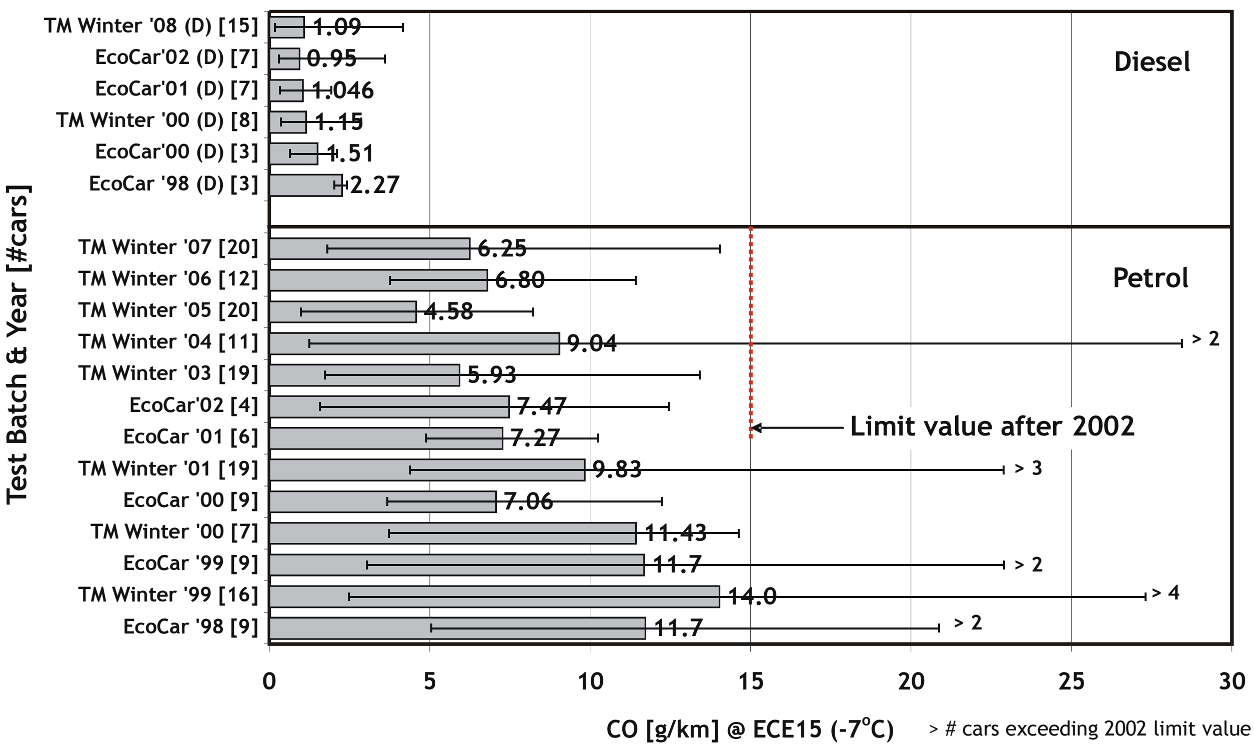

Figure 1: Average cold-start CO emissions of different annual fleet batches measured according to 98/69/EC cold-start (type VI test) procedure, as well as high and low values within each batch

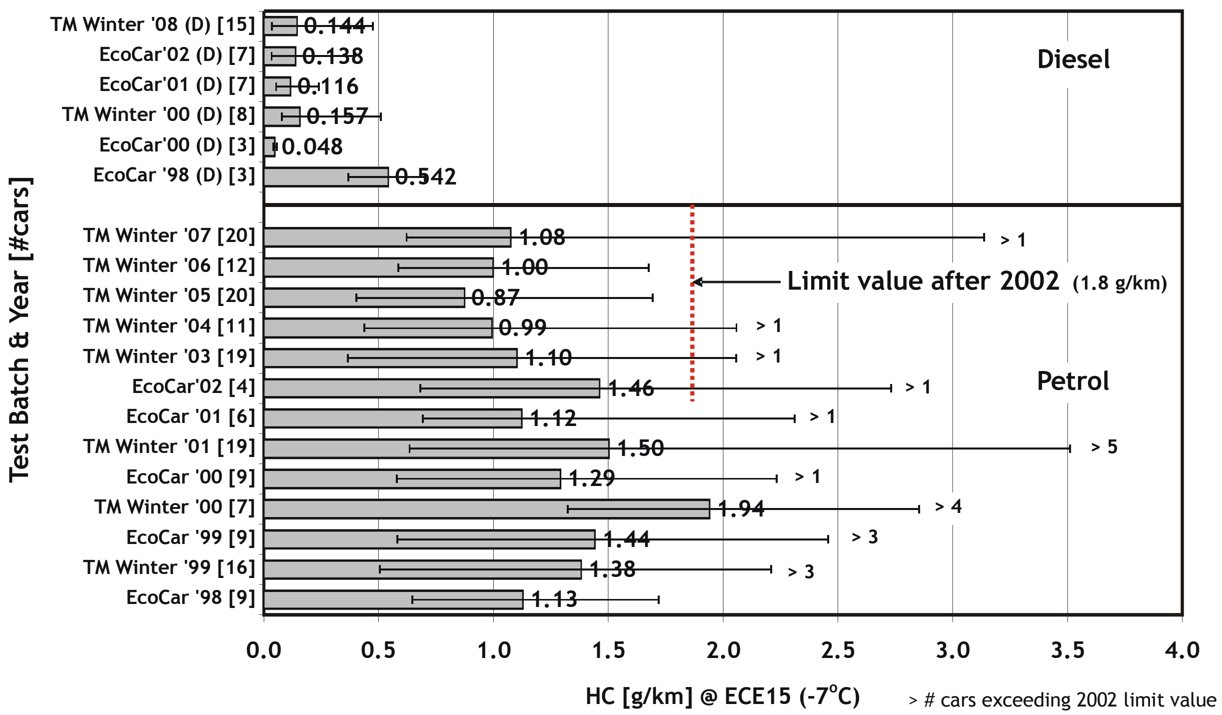

Figure 2: Average cold-start HC emissions of different annual fleet batches measured according to 98/69/EC cold-start (type VI test) procedure, as well as high and low values within each batch

As Figure 1 clearly shows, CO performance has been almost constantly improved over this period 1998 to present day. The differences between the sub-fleets within each type approval level category can probably be attributed to the somewhat random choice of cars when composing the batches. That is reflected in Table showing both average engine displacement and inertia weight differing from batch to batch, with apparent reflections to the emissions, as well.

If we calculate average values for each type approval category, Euro 3 fleet has an average CO emission level of 8.3 g/km, which is over 30 % lower cold-start CO than Euro 2 fleet, showing on average 12.5 g/km emissions. Furthermore, Euro 4 compliant cars have on average only 5.9 g/km CO emissions, more than 50 % below the level of emissions typical for Euro 2 cars.

Mostly the improvement has probably resulted from the various improvements that the manufacturers have made to the engines and the associated emissions control systems already, when they have sought compliance with Euro 3 level of standards. Because Euro 3 required testing with the revised European Test, without the 40 second idle, the emphasis was clearly in much faster warm-up performance of the catalyst, and using more sensible cold-start enrichment strategies than in Euro 2, when the first 40 seconds of idling was vented out of the sampling. Therefore, also low-ambient temperature performance is enhanced.

However, the story seems to be somewhat different for total hydrocarbons (HC), depicted in Figure 2. The recorded results do not show much improvement between the Euro 2 and Euro 3 fleets, and the highest average value recorded actually seem to be associated with one MY2000 fleet (TM Winter ’00) expected to contain already mostly Euro 3compliant cars. Furthermore, we have not been able to come up with any straightforward explanation to this kind of trend. Nevertheless, our experience suggest though, that low HC and low CO do not necessarily come together, as in many cases the cars with extremely low cold-start CO can show higher values of HC, than those with slightly higher CO output. This may be a result of a too lean air-fuel ratio setting during cold-start phase resulting in rough running and non-firing working cycles releasing unburned hydrocarbons in the exhaust. With a sensible enrichment, CO may be slightly higher, but with more stable combustion and less non-firing cycles, the HC output remains lower.

However, comparing the average performance of Euro 4 compliant sub-fleet to that of those Euro 2 fleets, we see a clear improvement as the latest technology has some 25 % lower average HC compared to Euro 2 level that is 0.98 g/km for Euro 4 vs. 1.3 g/km for Euro 2.

Even if it has been demonstrated by the present one as well others alike [9] that cold start is by far les influencing the emissions of NOx, and no specific limit values are imposed to their emissions in this type VI cold-start, low ambient temperature test, we have also measured NOx, and the results are depicted in **Figure 3** exactly the same way as previously with CO and HC results.

While looking at the bars in Figure 3, one cannot see much difference between the average levels of NOx in absolute figures, but relatively speaking, Euro 3 sub-fleets emit on average almost 50 % higher NOx than those Euro 2 sub-fleets on average, (0.15 g/km vs. 0.10 g/km), and actually MY2000 fleets show even higher levels of emissions at around 0.26 g/km level. However, while complying with the more stringent Euro 4 standards, OEM’s have managed to improve also low-temperature NOx performance, and those late-model sub-fleets again present some 30 % lower average emissions compared to the average Euro 2 levels (0.07 g/km vs. 0.10 g/km).

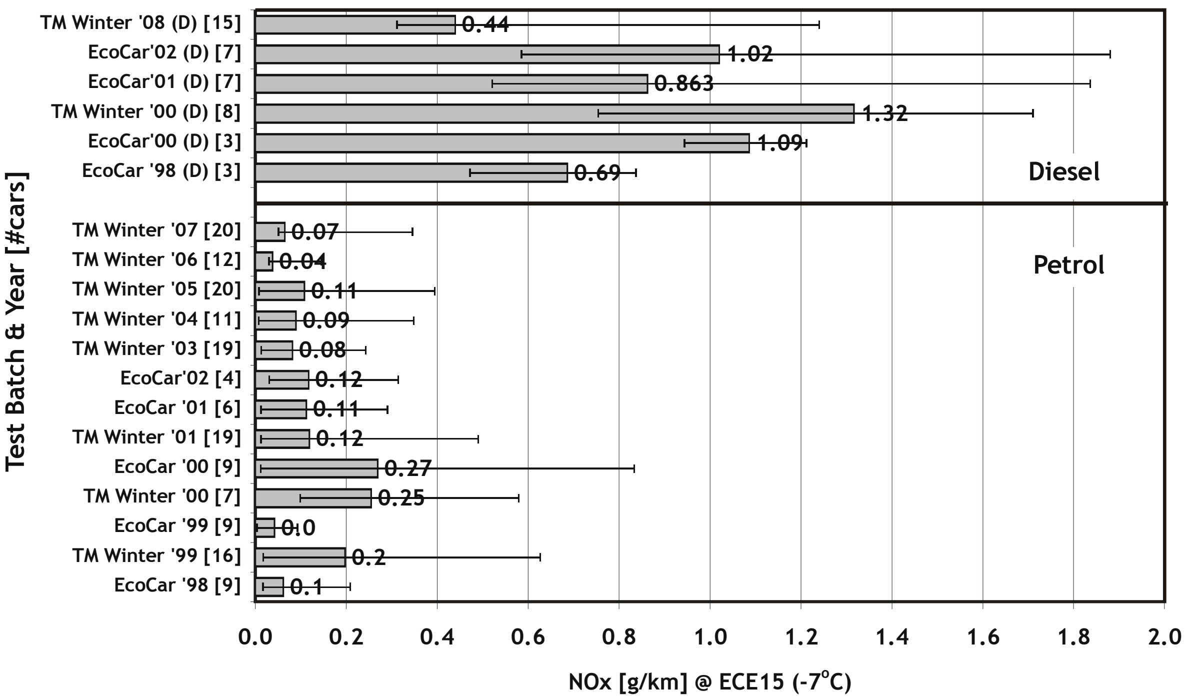

Figure 3: Average cold-start NOx emissions of different annual fleet batches measured according to 98/69/EC cold-start (type VI test) procedure, as well as high and low values within each batch

5.2. Diesel-fuelled cars

Although cold-start excess emissions are primarily associated with petrol-fuelled cars, we have also tested some diesel passenger cars, because emission inventories do need cold-start data also for diesel cars. Their results are depicted along with the results for petrol-fuelled sub-fleet in Figure 1 for CO, Figure 2 for HC and Figure 3 for NOx, respectively.

As we can see, when observing the CO and HC results, diesel-fuelled cars do emit much less CO and HC when started at a cold ambient temperature. Overall, the difference is almost of an order of magnitude, as typical average levels of both components are only some 10 to 20 % of the average emissions levels associated with their petrol-fuelled counterparts. However, when observing the high-low bars in the figures, we see that the results for worst-performing diesel cars are mixing with those of the best-performing petrol cars, as highest emissions for diesel cars are around 2.5 to 3 g/km for CO and 0.5 g/km for HC, and the best-performing late-model petrol-fuelled cars go even below 2 g/km for CO and are on par with HC at 0.5 g/km level.

Considering NOx emissions, the storyline is entirely different. When looking at Figure 3, one immediately notices how the levels of NOx emitted by the diesel-fuelled cars are on average 5 to 6 times higher than typical levels for their petrol-driven counterparts. However, in relative terms the evolution over the different Euro-levels seems to be much alike, because like with the petrol-fuelled sub-fleets the highest average emissions were recorded for those Euro 3-compliant sub-fleets, being at 1.1 g/km some 60 % higher than Euro 2 levels, but the Euro 4 compliant sub-fleet clearly showed almost a 40 % improvement over the Euro 2 level (0.44 g/km vs. 0.69 g/km).

The type approval standards for diesel-fuelled cars actually sum-up HC and NOx emissions, for the reason that when emitted together, both are important precursors for ozone formation.

Therefore, it is only fair to show that add-up also for the cold-start, cold temperature results, and this is depicted in **Figure 4**. While a clear difference between the different technologies in HC vs. NOx ratio is seen, the sums are quite close to each other in both groups, petrol vs. diesel, and from the point of view of inducing atmospheric reactions, their impact may not be far from the other at these ambient temperature conditions.

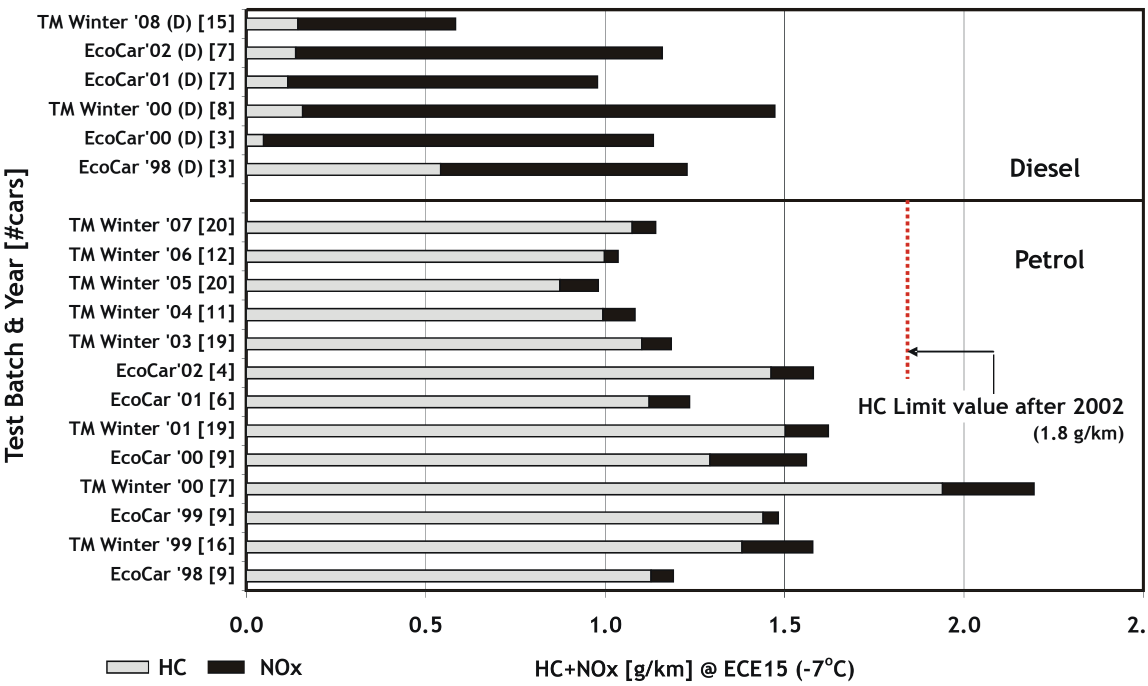

Figure 4: Average cold-start HC+NOx emissions of different annual fleet batches measured according to 98/69/EC cold-start (type VI test) procedure, as well as high and low values within each batch

5.3. Fuel consumption and CO_2 emissions

As already commented earlier, our aim in assessing the cold-start, low ambient temperature performance was also to address the impact of these conditions to fuel consumption and CO2 emissions, as their importance is in recent years risen enormously, especially the when effective emission control technology introduced to comply with Euro 4 standards has drastically reduced the regulated emissions.

Figure 5 depicts average CO_2 emissions measured in type VI cold start test for each sub-fleet tested. Already at a glance one sees that no apparent trend is present, if not a slight raise reflecting the slight increase in average weights of the later-model cars, as on average, the petrol-fuelled Euro 4 sub-fleets had 14 % higher weight than those of Euro 2 level, and Euro 3 fleets were falling in between. Furthermore, to compensate that added mass, the later-model fleets also had 15 to 20 % larger engines by displacement, and most probably power output was even more increased, as specific power (kW/dm^3) has definitely not decreased. Therefore, higher consumption was expected to newer vehicles, is spite of the fact that overall, the average CO_2 level of all newly sold cars in Europe has gone down at the same time from over 180 g/km level typical for Euro 2-era to below 170 g/km level associated with present-day petrol cars.

Interestingly, at the same time Finnish market has reacted quite differently, as typical average CO_2 for new Euro 2 cars was around 177 g/km in late 1990's, but petrol fuelled Euro 3 and

Euro 4 fleets now show typically 180 g/km CO_2 output or even higher. These are all so called "combined EU" emissions, where both the urban and extra-urban driving are contributing the result with their relative lengths of the driving cycle. As the extra-urban driving cycle is without any stops and much lower transients, the average fuel consumption is lower during this cycle, and the combined EU result usually lies between the figures for urban and extra-urban driving. Therefore, levels of CO_2 shown here should rather be compared with the fleet-average urban CO_2 values, but that information was not to be found with reasonable effort.

However, having noted the increase in both mass and engine displacement, the average CO_2 levels measured here for the Euro 3 and Euro 4 compliant sub-fleets were only some 10 % higher. So, improvements in engine efficiency are probably taken place.

We have also tried to assess the negative effect of the cold start by calculating the relative increase imposed by the cold-start using the difference recorded for fuel consumption during the cold-start and hot-restarted cycles. Those figures are also shown in Figure 5, and they are with some consistency around 40 % for the petrol-fuelled fleets, so no apparent improvement is observed, although Euro 4 sub-fleets are on the low side of the whole lot. Unfortunately, tests were conducted in somewhat different fashion for those Euro 2 fleets. Therefore, we are unable to calculate the same kind of relative cold-start effect for those.

This was the story for petrol-fuelled cars. Quite different trend is seen in diesel-driven cars, as the average cold-start increase in CO_2 was only around 10 to 20 % for Euro 3 sub-fleets, but in that single Euro 4 compliant diesel sub-fleet we have tested, the increase was on average 47 %, higher than any figure associated with those petrol-fuelled fleets. This certainly is an observation worth noting and follow-up in the future is both interesting and important.

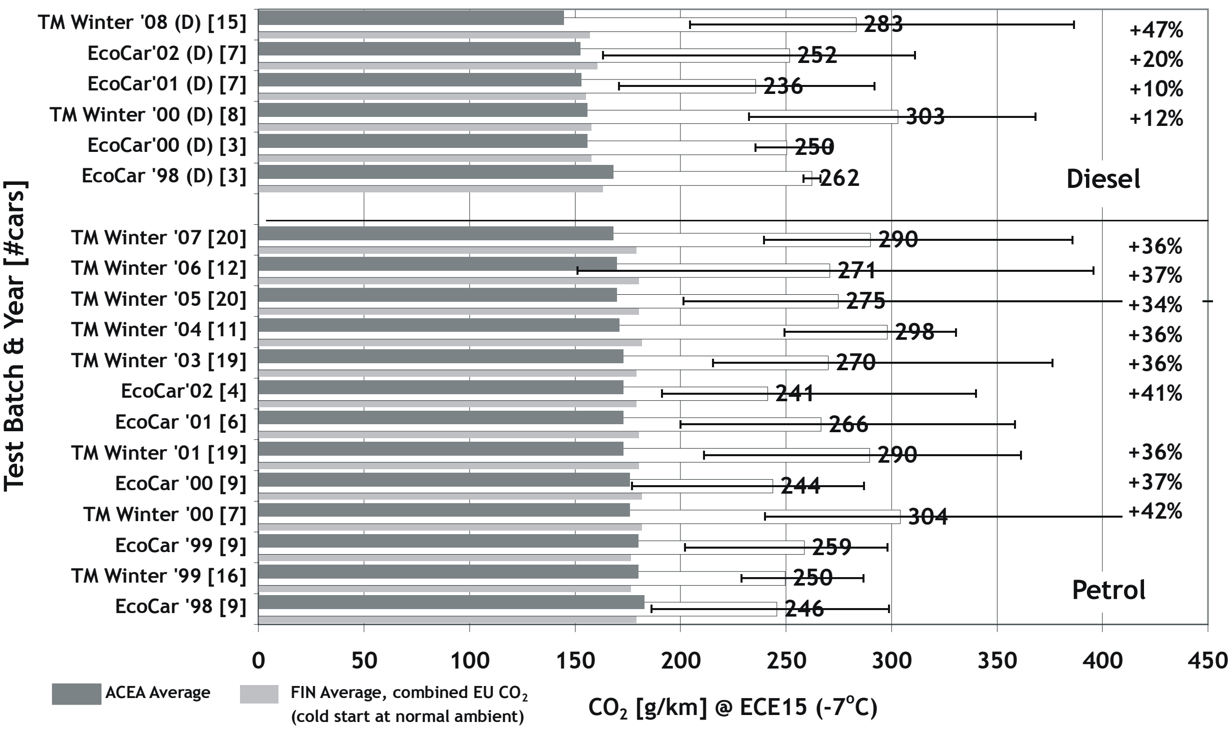

Figure 5: Average cold-start CO2 emissions of different annual fleet batches measured at -7 C, according to 98/69/EC cold-start (type VI test) procedure, as well as high and low values within each batch, and average cold-start increase over a hot-start cycle (in %), and as a reference, average new car CO2 (EU combined) for EU and Finnish markets

6. CONCLUSIONS

As the test results presented in this paper demonstrate, cold-start performance has been gradually improved, and emission rates measured at low ambient temperatures have declined. The average cold-start CO emission result has fallen over 50 % between the fleets of Euro 2 and Euro 4 cars. However, HC emissions have not improved with the same magnitude, as only some 25% improvement was observed. Extremely high values have been cut down, though, especially with the introduction of the latest Euro 4 cars.

According the results, elevated emission levels at cold-start are indeed mostly associated with petrol-fuelled cars, and much lower levels were recorded for those with diesel engines. Overall, the difference is almost of an order of magnitude. However, the worst performing diesel cars are close to the best-performing petrol cars.

Even if the emissions performance has been improved quite substantially, excess fuel consumption has not been lowered at all in practice. The test data shows that even in latest Euro 3 and Euro 4 compliant petrol cars, about 40 % extra fuel consumption was recorded between a cold-started ECE15 cycle and when running the same cycle with warm engine restart. As typical passenger car trips in most European countries are rather short, this excess cold-start consumption has a distinct impact of overall fuel economy of the passenger car fleet.

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