VTT Technical Research Centre of Finland

Euro 6 Diesel Passenger Cars' Emissions Field Tests

Söderena, Petri; Laurikko, Juhani; Kuikka, Keijo; Tilli, Aki; Kousa, Anu; Väkevä, Outi; Venho, Antti ; Haaparanta, Suvi ; Nuottimäki, Jukka ; Lehto, Kalle ; Weber, Christian

Published: 28/10/2019

Document Version
Publisher's final version

RESEARCH REPORT

VTT-R-00636-19

Euro 6 Diesel Passenger Cars' Emissions Field Tests - Project Final Report

Authors: Petri Söderena and Juhani Laurikko, VTT
Keijo Kuikka and Aki Tilli, Finnish Transport and Communication Agency
Anu Kousa and Outi Väkevä, Helsinki Region Environmental Services Authority HSY
Antti Venho and Suvi Haaparanta, City of Helsinki
Jukka Nuottimäki and Kalle Lehto, Neste Oyj
Christian Weber, Institute of Transport Economics Norway

Confidentiality: Public

Report's title	
Euro 6 Diesel Passenger Cars Emissions Field Tests - Project Final Report	
Customer, contact person, address	
Joint project of Finnish Transport and Communication Agency, Helsinki Region Environmental Services Authority HSY, City of Helsinki, Neste Oyj, Institute of Transport Economics Norway and VTT Oy.	
Project name	**Pages**
Euro 6 diesel passenger cars emissions field tests	37/
Author(s)	
Petri Söderena and Juhani Laurikko, VTT, Keijo Kuikka and Aki Tilli, Finnish Transport and Communication Agency, Anu Kousa and Outi Väkevä, Helsinki Region Environmental Services Authority HSY, Antti Venho and Suvi Haaparanta, City of Helsinki, Jukka Nuottimäki and Kalle Lehto, Neste Oyj, Christian Weber, Institute of Transport Economics Norway	
Keywords	**Report identification code**
diesel passenger cars, Euro 6, on-road emissions, PEMS	VTT-R-00636-19

Summary

According to the measurements it can be stated with respect to NO_x emissions that there are large differences in NO_x emissions within the Euro 6b cars. One tested car showed high NO_x emissions on the chassis dynamometer and in the on-road tests with the conformity factor (CF) varying between 3.3…5.2. A second car was able to provide NO_x, CO and PN emissions fulfilling the Euro 6d-TEMP RDE requirements with a conformity factor around 1.8. A third Euro 6b car equipped with selective catalytic reduction system (SCR) was, after the update in engine control unit software, able to provide really low on-road NO_x emissions with a conformity factor varying between 0.2…0.9 depending on the test route. The only Euro 6d-TEMP car resulted low NO_x emissions on the chassis dynamometer independent of the test cycle. In on-road measurements, the conformity factor varied between 0.5…2.0 depending on the test route. Near-zero ambient temperature was not found to increase the NO_x, CO and PN emissions in tests on the RDE-route. Furthermore, one Euro 6b car showed a slight increase in CO_2 emissions, when tested close to zero ambient temperature compared to testing around 15 °C. Day-to-day NO_x concentration monitoring showed that Euro 6b cars equipped with a single lean NO_x trap (LNT) did emit relatively constant NO_x emissions and did not suffer from cold ambient conditions. On the other hand, a Euro 6b car with SCR showed 2…3 times higher NO_x emissions at below 0 °C compared to in summer conditions. A Euro 6d-TEMP car with dual LNT showed, on average, low NO_x concentration, but with high fluctuation and high peaks.
Two different diesel fuels were used in the Euro 6 RDE route. One fulfilling the EN590 diesel fuel standard and one using WWFC cat 5 diesel. None of the cars tested showed any observable difference between the emissions. There was no clear trend identified in respect of measurement accuracy in favor of either of the fuels.

Confidentiality	Public

Espoo 28.10.2019

Written by	**Reviewed and accepted by**
Petri Söderena, Senior Scientist	Jukka Lehtomäki, Research Team Leader

VTT's contact address
B.O. BOX 1000, FI-02044 VTT

Distribution (customer and VTT)
Customer, VTT, Euro 6 diesel passenger cars' field emissions tests project group

Abbreviations

CF	Conformity Factor
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EAT	Exhaust After-treatment
JRC	European Commission's Joint Research Centre
LHV	Lower Heating Value
LNT	Lean NO_x Trap
MY	Model Year
NEDC	New European Driving Cycle
OEM	Original Equipment Manufacturer
PEMS	Portable Emissions Measurement System
RDE	Real-Driving Emissions
SCR	Selective Catalytic Reduction
TDI	Turbocharged Direct-Injection
WLTC	World Harmonized Light-duty Vehicles Testing Cycle
WLTP	World Harmonized Light-duty Vehicles Testing Procedure

Preface

NO_x emissions of diesel passenger cars have been in the news on almost a daily basis since the so-called “Volkswagen scandal”, which took place in 2015. Early Euro 6 diesel passenger cars were reported as emitting multiple times higher NO_x emissions in normal on-road driving conditions than the legislation was aiming at. This contradiction raised high public opposition to diesel cars and has led cities in Europe to ban older diesel passenger cars entering city centers and has even raised the question do diesel passenger cars have a future? Since the introduction of Euro 6 the legislation has evolved through multiple amendments and the latest Euro 6 d-TEMP legislation requires all passenger cars complying with it to also fulfill the on-road testing requirements, which also secure low NO_x emissions in “real driving” conditions.

This project aimed to investigate the on-road NO_x emissions of typical Finnish diesel passenger cars in Finnish driving conditions and to provide information on Euro 6 diesel passenger cars on-road emissions to the wider public.

The project was carried out in cooperation with the Finnish Transport and Communication Agency, City of Helsinki, Helsinki Region Environmental Services Authority HSY, Neste Oyj, the Institute of Transport Economics Norway (TØI) with the financial support from Statens Vegvesen, Vegdirektoratet and VTT Technical Research Centre of Finland.

Espoo 28.10.2019

Authors

Contents

1. Introduction

Euro 6 legislation for passenger cars was made active in September 2014. Since then, the legislation has evolved with multiple amendments and steps. Two major changes in legislation were introduced in September 2017. The World Harmonized Light-Duty Vehicle test procedure (WLTP) replaced the New European Driving Cycle (NEDC) test procedure in new type approvals, and is in force from September 2018 onwards for all registrations of new cars. Furthermore, current Euro 6d-TEMP legislation, which introduced real-driving emissions (RDE) testing, also came into force in September 2017 for new type approvals, and for all new cars in September 2019.

In 2015, The ICCT (International Council on Clean Transportation) published a report, which revealed that diesel passenger cars emit many times more NO_x emissions relative to legislative limit values, and to those recorded in type approval testing. So-called cycle beating was being used when vehicles were tested on a chassis dynamometer, and during on-road driving NO_x emissions were allowed to rise to high levels that exceeded legislative limit values multiple times. Following the ICCT findings, large scale conformity testing was conducted by the type approval authorities. As a result, almost all OEMs were found to compromise the control of NO_x emissions in real-world driving. This was true especially for Euro 5 cars, but also to a lesser degree for the first generation of Euro 6 cars.

This ballyhooing, often referred to as “Dieselgate”, was exposed in September 2016, and brought the issue to the light of wide publicity and put pressure on the renewal of the type approval process to contain a “real-driving test” to end the OEMs practices, which had scaled from finding loopholes and bending the rules even to outright criminal acts. However, it is not so widely known that this work had actually already started as early as January 2011. The European Commission then set up a working group, involving all interested stakeholders, to develop a real driving emissions (RDE) test procedure that reflects the emissions measured on the road, using a new technical option in the form of a portable emission measurement systems (PEMS). The first “package” of the RDE test procedure was released in March 2016, long before the massive media publicity.

Subsequently, the 2nd, 3rd and 4th “packages of RDE legislation have now been implemented, forcing European diesel passenger cars to comply with lower NO_x emission levels in on-road driving and not just in laboratory testing.

This project was targeted to obtain an understanding of true on-road emissions performance of Euro 6 diesel passenger cars. To gain this information a comprehensive setup of measurements was conducted during a one-year monitoring period. Chassis dynamometer tests served as a repeatable and accurate method for observing the possible effects of ageing. On-road measurements exposed the “real-world” emissions of the tested cars. Lastly, the continuous on-board NO_x concentration monitoring provided information on the changes in the cars’ day-to-day NO_x emissions throughout the approximately one-year monitoring period.

2. Objective

Euro 6 diesel passenger cars had not brought the NO_x emissions to the level that the legislation was aiming for at the time of its introduction. The purpose of this project was to shed light on the on-road performance of Euro 6b and 6d-TEMP diesel passenger cars emissions performance, especially the NO_x emissions, in typical Finnish on-road driving routes and ambient conditions.

On-road measurements can be seen as a not-to-exceed type of testing. Typically, in on-road situations, there are many “disturbances” affecting the driving. This makes cycle-to-cycle variation high, and accurate comparison between different cycles is not feasible. Considering this, on-road measurement is not a suitable tool for direct vehicle-to-vehicle comparison purposes. Moreover, it should be considered as a tool for proving that the harmful emissions of the specific vehicle fulfill the targets of the legislation, and comply with the spirit of the legislation in different driving situations. Chassis dynamometer measurements, on the other hand, are by nature more accurate, repeatable and thus suitable for direct vehicle-to-vehicle comparisons, though they do not reflect the whole range of driving patterns that occur during real world driving.

In addition, day-to-day monitoring of NO_x concentration provides valuable information about the vehicles daily emissions and possible changes in those.

Due to the above-mentioned reasoning, three types of measurements were chosen to be performed: chassis dynamometer in the laboratory, on-road tests with a portable emission measurement system (PEMS) as well as continuous NO_x monitoring with a device installed in the vehicle. Chassis dynamometer tests provide a basis for direct vehicle-to-vehicle comparison and a base for defining the CO_2 emissions. They also provide a link to type approval test cycles, and thus to the emissions performance that should be achieved. On-road measurements on the other hand present a tool for assessing the real-world emissions performance of different Euro 6 vehicles selected for the project in different driving conditions.

The main focus of the project was on real-world NO_x emissions of Euro 6 passenger diesel cars, but the target was also to investigate CO, CO_2 and PN emissions in real-world conditions. The on-road measurement program was composed of both continuous (NO_x) and two PEMS measurement campaigns, in on-road conditions during a one-year period targeting approximately 30,000 km mileage for each car. Additionally, project start and end measurements on the chassis dynamometer were performed to monitor possible effects of ageing on cars' emissions performance. The target was to obtain NO_x concentration data from normal day-to-day driving and emissions from different on-road routes and from NEDC and WLTP cycles.

Also, the effect of WWFC cat 5 diesel fuel on emissions performance in on-road situations compared to EN590 diesel was studied.

3. Methods

3.1 Test Vehicles and Cycles

Four diesel vehicles were selected for the project. They represent medium size and common family-size cars in Finland. The main data can be found in Table 1. Cars A and B were of the same model, but different model year. Cars A to C had been type approved following the NEDC procedure, and fulfilled Euro 6b certification requirements. Car D was type approved for the Euro 6d-TEMP, and was thus tested according to the WLTP, as well as the RDE-procedure.

Cars A and B used a lean NO_x trap (LNT) for NO_x emissions reduction. Car C used selective catalytic reduction (SCR) and Car D was equipped with a dual LNT system in which two LNTs are placed in series. All cars were equipped with a diesel particulate filter (DPF). Cars A, B and D were also equipped with a diesel oxidation catalyst (DOC).

One objective of the project was to monitor possible effects of around 30,000 km mileage on vehicles' emissions performance. Thus, chassis dynamometer tests were performed at the project start and at the project end to see the possible effects of ageing on vehicles' emissions performance.

Chassis dynamometer tests for Car C were performed three times. At the start of the project it was tested with its original engine control unit (ECU) software. After the project started the manufacturer of Car C provided a possibility to update the ECU software for lower NO_x emissions as a part of their recall campaign. Therefore, some of the test cycles were repeated with the updated software. The Original Equipment Manufacturer (OEM) stated that the update in the ECU only had an effect on NO_x emissions, but not other emissions or fuel consumption. This claim had to be confirmed by measurements.

Table 1: Key data for the cars investigated in this project.

Id.	Description	Euro	Engine	Gear box	EAT	Mileage at start	CO_2 emission
Car A	Class C family car MY2015	Euro 6b	1.5-2.0 TDI	M6	DOC+DPF+LNT	73500 km	90 g/km @ NEDC
Car B	Class C family car MY2017	Euro 6b	1.5-2.0 TDI	M5	DOC+DPF+LNT	24800 km	106 g/km @ NEDC
Car C	Class C family car MY 2014	Euro 6b	1.5-2.0 TDI	M6	DPF+SCR (new software updated)	59100 km	109 g/km @ NEDC
Car D	Class C hatchback MY 2018	Euro 6d-temp	1.5-2.0 TDI	AT8	DOC+DPF+2xLNT	2000 km	112 g/km @ WLTP

On chassis dynamometer NEDC and WLTC test cycles were chosen to be performed. NEDC provides a link to type approval values of Cars A, B and C whereas WLTP applies for Car D. As WLTP reflects actual driving in a more realistic way than NEDC, it also provides a good base for assessing real-world emission performance of Cars A to C. For Car D, it provides a good comparison to on-road measurements.

The purpose of the emissions legislation should be that the vehicles produce emissions that comply with the emission legislation over the complete engine-operating map. However, on chassis dynamometer tests like NEDC and WLTC, not all parts of the engine map will be visited. Thus, it is important to also test the vehicles on-road, so that the whole engine operation map will be covered. Based on this reasoning, it was decided to perform on-road measurements on three different routes for estimation of the vehicles' emissions characteristics in different driving conditions, covering as far as possible the whole engine operation map. Of these three routes, one fulfilled the trip requirements of Euro 6 d-TEMP RDE measurements, one corresponded to normal driving in a city and one represented driving in rural and highway environments.

As on-road and chassis dynamometer tests provide information of vehicle performance for the specific event when measurement is conducted, it was decided to equip cars with continuous NO_x concentration monitoring devices. With continuous monitoring it is possible to generate a broader picture of cars NO_x tailpipe emissions under different ambient conditions throughout the year.

3.2 Chassis dynamometer test set-up

Vehicles were tested with their own summer tires. Prior to testing, rolling resistance tests on the chassis dynamometer were performed for each vehicle for defining the parasitic losses that must be deducted from the total road load. Due to lack of specific information, so-called "table values"[1], an accepted method for NEDC, were used to determine the road load coefficients on the dyno. Test inertia was calculated and set according to the NEDC and WLTP practices. Table 2 shows the dynamometer settings for NEDC and Table 3 for WLTC. It is important to be aware when evaluating the chassis dynamometer results that these pre-set table values often provide higher road load coefficients than those used by the manufacturers in type approval. This leads to higher emissions on a per kilometer basis than reported officially at type approval.

Table 2: Dynamometer settings for NEDC.

Car	Inertia [kg]	F0	F1	F2
Car A	1470	149.7	-0.476	0.0509
Car B	1470	154.0	-0.446	0.0510
Car C	1700	217.0	-1.389	0.0661
Car D	1470	152.8	-0.252	0.0479

Table 3: Dynamometer settings for WLTC.

Car	Inertia [kg]	F0	F1	F2
Car A	1549	149.7	-0.476	0.0509
Car B	1556	154.0	-0.446	0.0510
Car C	1983	217.0	-1.389	0.0661
Car D	1583	152.8	-0.252	0.0479

Before performing the chassis dynamometer tests engine oils were changed for each car to eliminate the effect of deviation in oil viscosity on the vehicles' performance. After the oil change, each car was driven approximately 50 km on a chassis dynamometer to guarantee similar aging for new oils. This procedure was performed in order to eliminate the effect on emission levels of the evaporative compounds originating from the fresh oil.

Table 5 shows the test program performed for each car in the measurements at project start and project end. In addition, a light version of the test matrix was conducted for Car C after the ECU software update to see the difference right after the update.

On the chassis dynamometer at project start and end, one cold-start WLTC run following three warm-start WLTC runs was performed. This was repeated twice on the following days, in order to monitor the possible deviation between each cycle. One cold-start NEDC following three warm start cycles was also performed. An average result was calculated from the two cold cycles and six warm cycles. Minimum and maximum value bars are added in the diagrams depicting the results. If the bars are missing, only one cycle was recorded. Test cell temperature was approximately 22 °C +- 1 °C and relative humidity varied from 33 % to 56 % during the chassis dynamometer tests.

[1] "Simulated inertia and dyno loading requirements", Table A4a/3 in ECE-R83/07.

VTT uses a standard full-flow dilution tunnel and bag sampling for emissions measurement on a light-duty chassis dynamometer. Figure 1 shows a schematic layout of VTT's light-duty vehicle emissions measurement system.

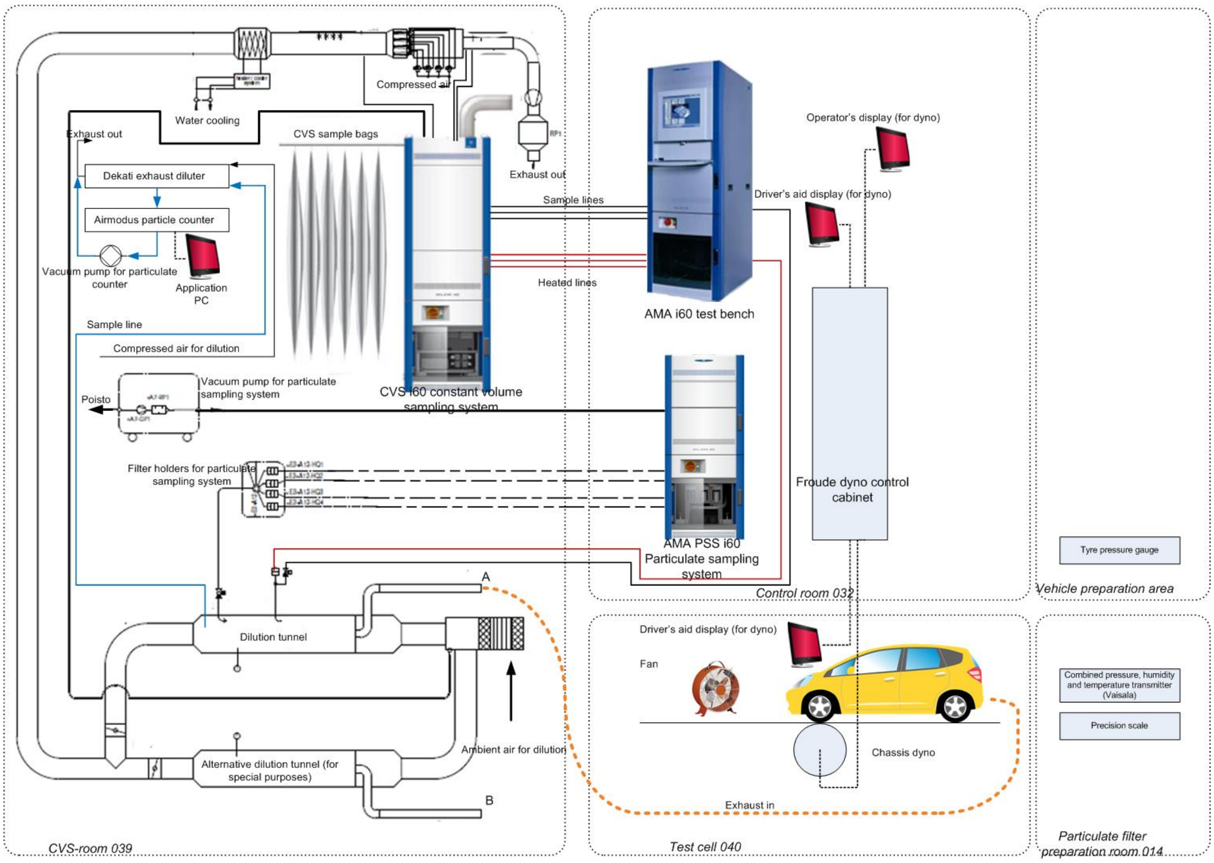

Figure 1: Schematic layout of VTT's light-duty vehicles chassis dynamometer measurement system.

Table 4 summarizes the instrumentation used for measurements on the light-duty chassis dynamometer.

Table 4: Summary of measurement devices used in chassis dynamometer tests.

Device	Specification / Emission component
Dynamometer	Froude Consine, 100 kW/ inertia 450-2750 kg
Exhaust Gas Dilution System	AVL CVS i60
Exhaust gas analyzer	AVL AMA i60, CLD (NO/NOx), IRD (CO), IRD (CO_2 high/low)
Particulate number counter	Airmodus A23
Temperature, pressure and humidity	Vaisala

Test fuel used in the chassis dynamometer tests fulfilled the EN590 standard. Specific properties of the fuels can be found in Table 7.

Table 5: Test program for chassis dynamometer tests.

Preconditioning	Test cycle	Dwell time btw tests
WLTC	cold start WLTC	soak over night
cold WLTC	warm start WLTC	approx. 20 min pause
warm start WLTC	warm start WLTC	approx. 20 min pause
warm start WLTC	warm start WLTC	approx. 20 min pause
warm start WLTC	cold start WLTC	soak over night
cold WLTC	warm start WLTC	approx. 20 min pause
warm start WLTC	warm start WLTC	approx. 20 min pause
warm start WLTC	warm start WLTC	approx. 20 min pause
warm start WLTC	cold start NEDC	soak over night
cold start NEDC	warm start NEDC	approx. 20 min pause
warm start NEDC	warm start NEDC	approx. 20 min pause
warm start NEDC	warm start NEDC	approx. 20 min pause

3.3 PEMS-measurements

On-road measurements were carried out in two different measurement campaigns: one representing driving in warm weather, with ambient temperature above 10 °C, and the other representing driving in winter conditions, with ambient temperature below 10 °C. The intention originally was to perform measurements in ambient temperature conditions under 0 °C, but unfortunately by the time of the winter measurement campaign, the ambient temperature was approximately 10 °C above normal temperature levels in southern Finland.

Cars A and B were tested in early autumn 2018 and in March 2019. Cars C and D were tested in March-April 2019 and in April-May 2019.

Measurements were performed on three on-road routes: one fulfilling the trip requirements of Euro 6d-TEMP RDE testing (VTT RDE), one representing normal city driving in Helsinki (VTT City) and one representing rural and motorway driving (VTT Highway). Figure 2 shows the example of speed profiles of each of the test routes during the winter speed limits. VTT RDE was performed as a cold start test, but the vehicle had soaked overnight inside at temperature of approximately 20 °C, whereas VTT City and VTT Highway were tested as warm-start tests. During each test cars were driven normally following the traffic stream. Table 6 shows the main information of the test routes.

The post processing of the measurement data was performed according to the RDE 3 package of Euro 6 legislation. A moving average window method was used for trip validity check and normalization.

The driving over the RDE and Highway routes was affected by the fact that in Finland, wintertime driving speed limits are in force between late October and early April. During that time the maximum speed on rural roads is 80 km/h (vs. 100 km/h during summer) and on the highway 100 km/h (vs. 120 km/h during summer). Thus, the highest speeds during the winter campaign were lower than in summer conditions.

Furthermore, summer and winter tires were used depending on whether the test was performed during “Summer conditions” or “Winter conditions”, as legislation in Finland mandates “M+S” (mud and snow) type of tires to be used from December to Easter. The tires used on Cars A and B were of a non-studded “friction” type and in Cars C and D a studded type was used.

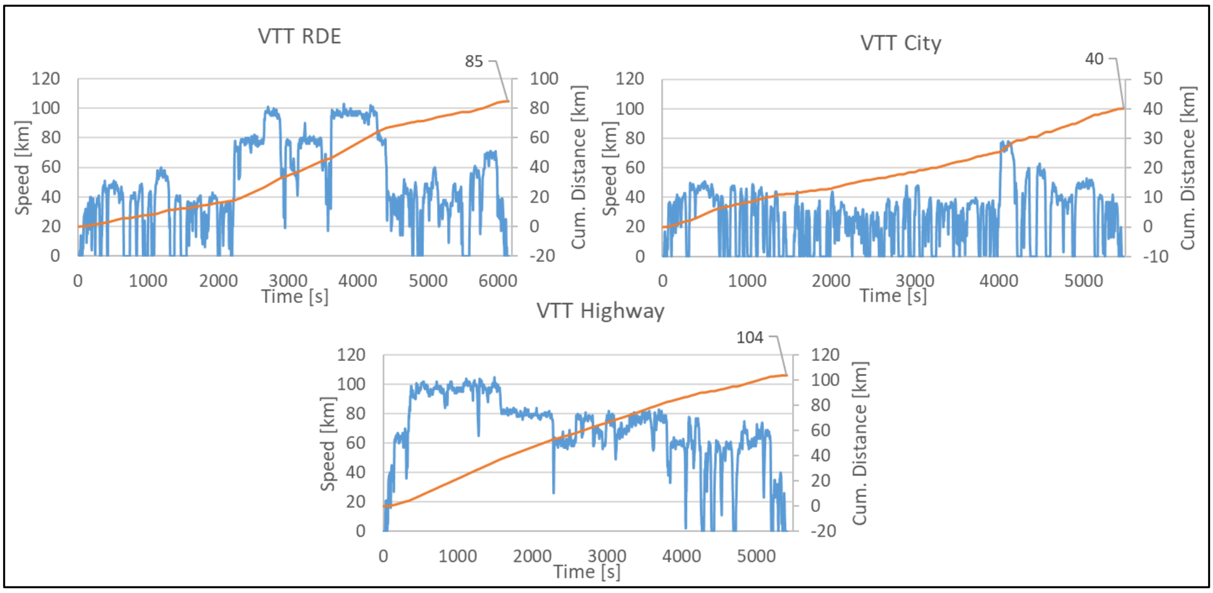

Figure 2: Example of test routes speed profiles and cumulative driving distance in winter conditions. Note during summer conditions maximum speed on the highway is 120 km/h.

Table 6: Information of on-road measurement routes.

Test route / variable	VTT RDE	VTT City	VTT Highway
Route mileage [km]	85	40	104
Trip share (urban/rural/highway) [%]	~42/~31/~27	~90/~10/~0	~17/~53/~30
Cold/warm start	cold start at app. 20 °C engine	warm start	warm start
Test fuel	VTT EN590 diesel & WWFC cat 5 diesel	VTT EN590 diesel	VTT EN590 diesel
Maximum speed	120 km/h during summer condition / 100 km/h during winter condition	80 km/h	120 km/h during summer condition / 100 km/h during winter condition

In addition, on the VTT RDE route PEMS measurements, two test fuels were used. The same EN590 diesel fuel batch as in the chassis dynamometer tests, and WWFC cat 5 diesel fuel (see Table 7). On the VTT RDE route, both fuels were tested, whereas on the VTT City and VTT Highway routes only the EN590 category fuel was used. Fuel consumption in on-road measurements was calculated from the measured CO_2 emission utilizing the JEC[2] well-to-tank CO_2 emission factor of 3.16 $kg_{,CO2}/kg_{,fuel}$.

[2] JRC technical report Well-to-tank Appendix 1 - Version 4a - Conversion factors and fuel properties https://ec.europa.eu/jrc/sites/jrcsh/files/wtt_appendix_1_v4a.pdf

Table 7: Properties of the fuels used in testing.

Fuel/ Property	EN590 diesel	WWFC cat 5 diesel
Density [kg/m^3]	834.3	825.6
Carbon content [w-%]	86.3	85.7
Hydrogen content [w-%]	13.7	14.3
AROM-DI+TRI [vol-%]	1.5	0.8
LVH [MJ/kg]	43.02	43.19
Cetane number [-]	55.7	59.1

A commercial AVL PEMS device was used in all tests. The PEMS device is attached to the towing hook with a special mounting bracket. In Table 8, the main information of the device and an example figure of installation are shown.

Table 8: Main information of the AVL PEMS device used for passenger cars measurements.

Device	Information
AVL MOVE Gas PEMS iS	CO, CO_2, NO, NO_2 emissions
AVL MOVE PN PEMS	PN emissions
AVL MOVE EFM 2.5”	Exhaust gas mass flow
GPS	Longitude, altitude, speed and acceleration
Weather station	Ambient temperature, pressure and relative humidity
OBD logger (integrated in PEMS device)	OBD information (engine speed, engine load, cooling water temp. etc.)

Comparison of the PEMS device and laboratory measurement devices was also performed during both of the chassis dynamometer measurements, at project start and project end. The test arrangement was conducted so that the PEMS device was placed first (i.e. right after the exhaust gas tailpipe) and then the exhaust gases were directed into the CVS dilution tunnel as in normal chassis dynamometer measurement.

3.4 Continuous NO_x monitoring

Each car was equipped with a tailpipe NO_x concentration monitoring device. Car C was also equipped with an engine-out NO_x concentration sensor. For other cars there was not enough free place to install a sensor in front of the exhaust after-treatment (EAT) device as the systems were coupled with a turbocharger. The installed monitoring system contains the following equipment:

- GPS for determination of location, speed and mileage
- NO_x sensor for determination of engine-out (possible only for Car C) and tailpipe NO_x concentration

- Temperature sensor for determination of exhaust gas temperature before (if possible) or after EAT

The NO_x sensor used is a commercial Continental sensor that is widely used in heavy-duty applications. The sensor light-off temperature is 200 °C, which means that NO_x concentration before the sensor reaches the light-off temperature are not seen, for example vehicle cold start concentrations and some short missions are not seen. This leads to the fact that some of the data is not stored.

4. Results

Results of comparison of the laboratory measurement devices against the PEMS device are presented in Section 4.1. A positive difference indicates that the PEMS device gave a higher result and a negative indicates a lower result for the PEMS device. Comparison was performed during project start measurements for Cars A-C and for Cars B-D during the project end measurements. Minimum and maximum difference bars are added in the diagrams.

The results of chassis dynamometer and on-road measurements are shown together in the same diagram for each of the cars.

NO_x concentration monitoring results are shown in two diagrams. The first diagram shows the daily average tailpipe NO_x concentrations for each car and the second shows the average tailpipe concentration throughout the project.

In Table 9 total mileage during the project for each test car is shown. Car A was the only one that fulfilled the original target of 30,000 km during the project. Car B reached 91 % of the target and Car C 88 %. Car D reached only 45 %. Car D was received late in the project, which explains the low mileage.

Table 9: Realized mileage for each test car.

Car	Odometer at start [km]	Odometer at end [km]	Total mileage [km]	%- of target [%]
Car A	73318	105164	31846	106
Car B	24882	52219	27337	91
Car C	59312	85846	26537	88
Car D	2010	15475	13465	45

4.1 Comparison of PEMS against laboratory measurement devices

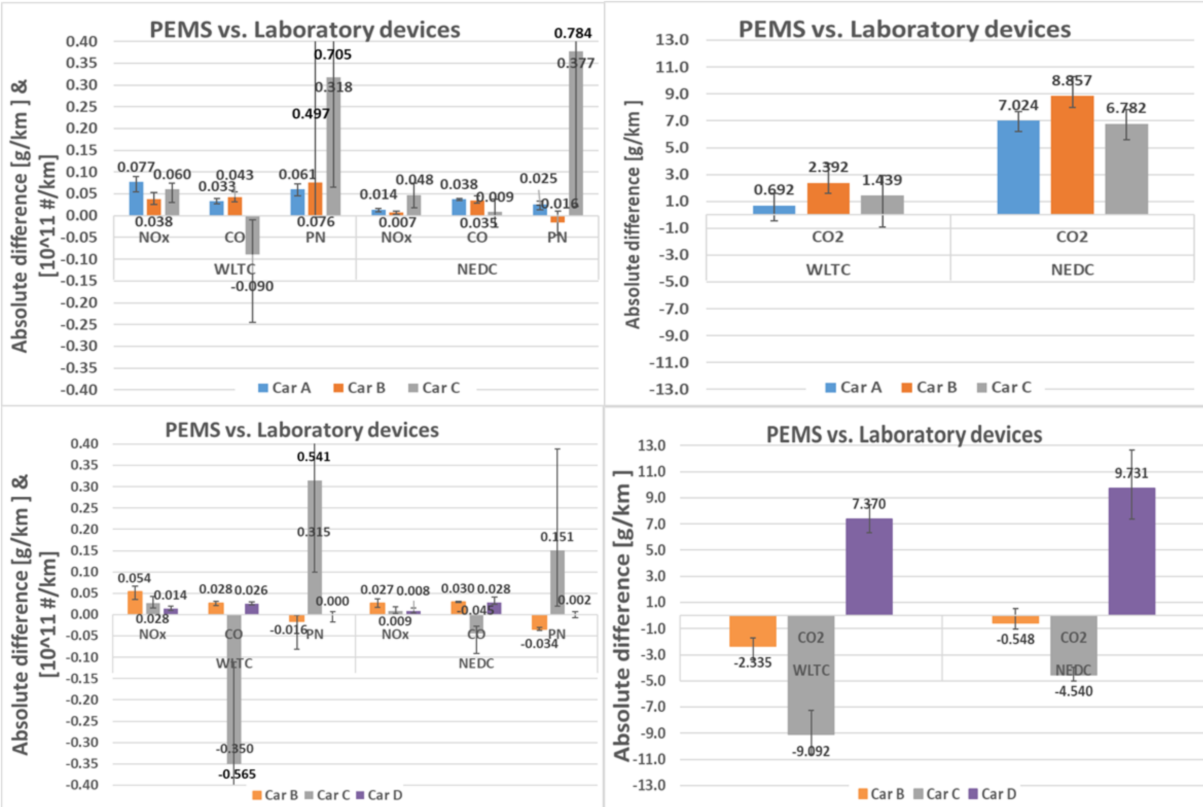

Figure 3: PEMS vs. laboratory measurement devices comparison in absolute difference (PEMS minus laboratory) on chassis dynamometer measurements.

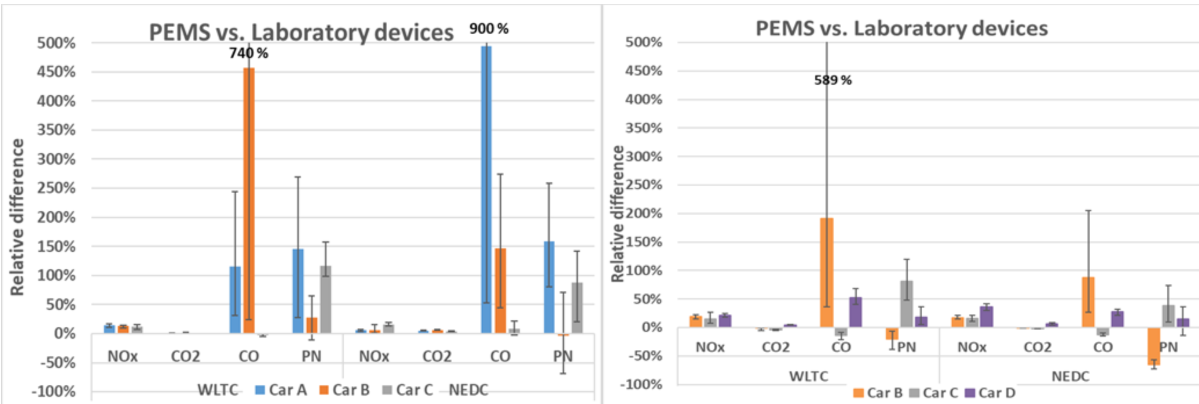

Figure 4: PEMS vs. laboratory measurement devices comparison (relative difference) at project start chassis dynamometer measurements.

4.2 NO_x emissions

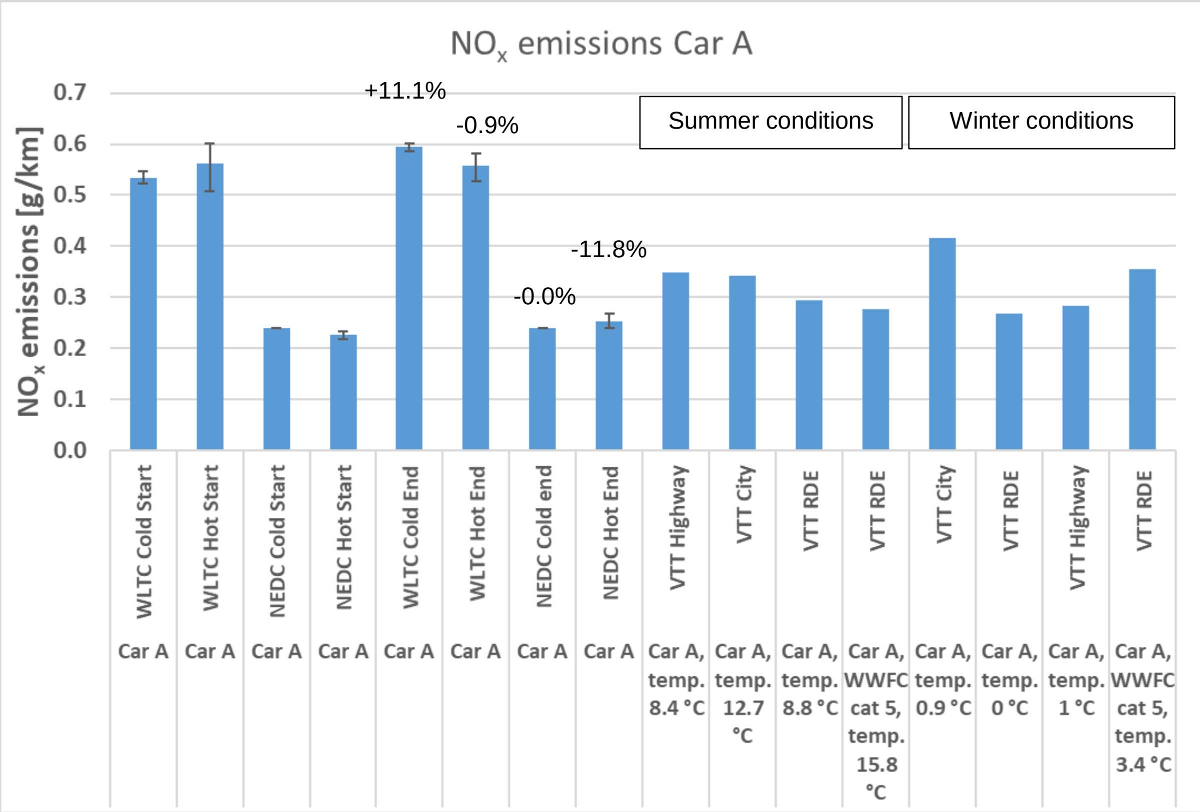

Figure 5: NO_x emissions of Car A on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

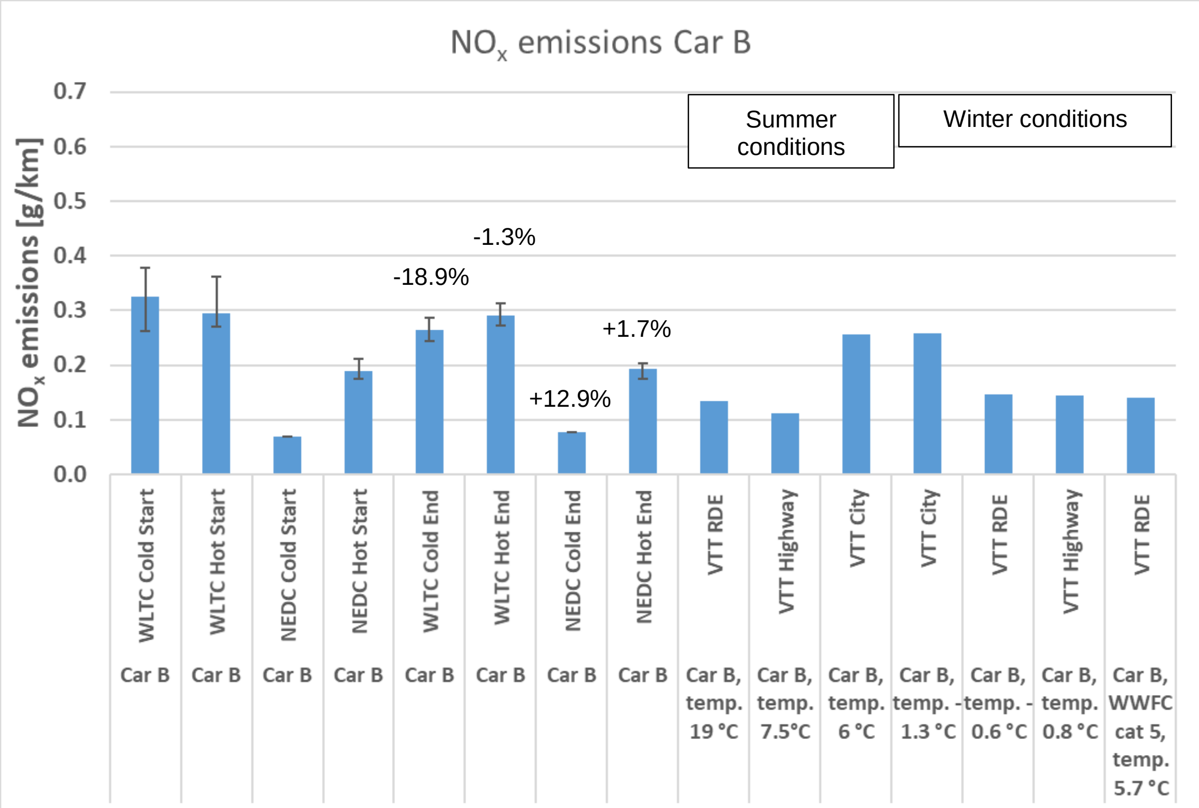

Figure 6: NO_x emissions of Car B on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

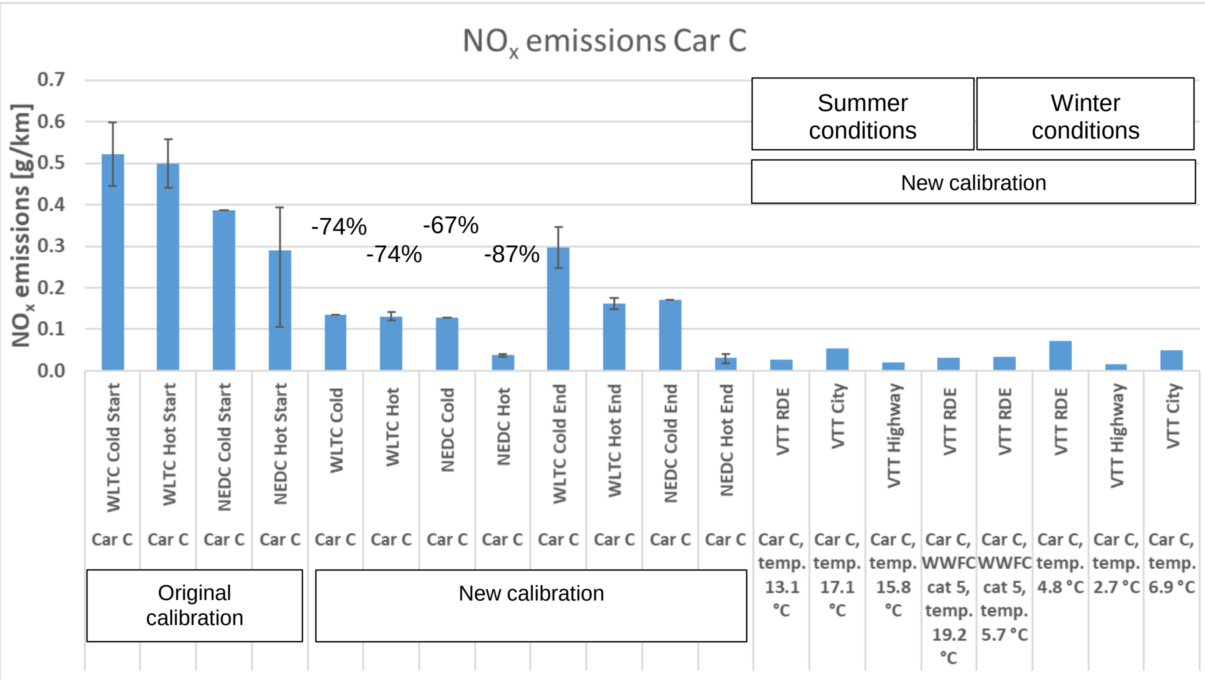

Figure 7: NO_x emissions of Car C on chassis dynamometer and on-road. Change between the new ECU software dynamometer and project end results are shown as percentages above the end results.

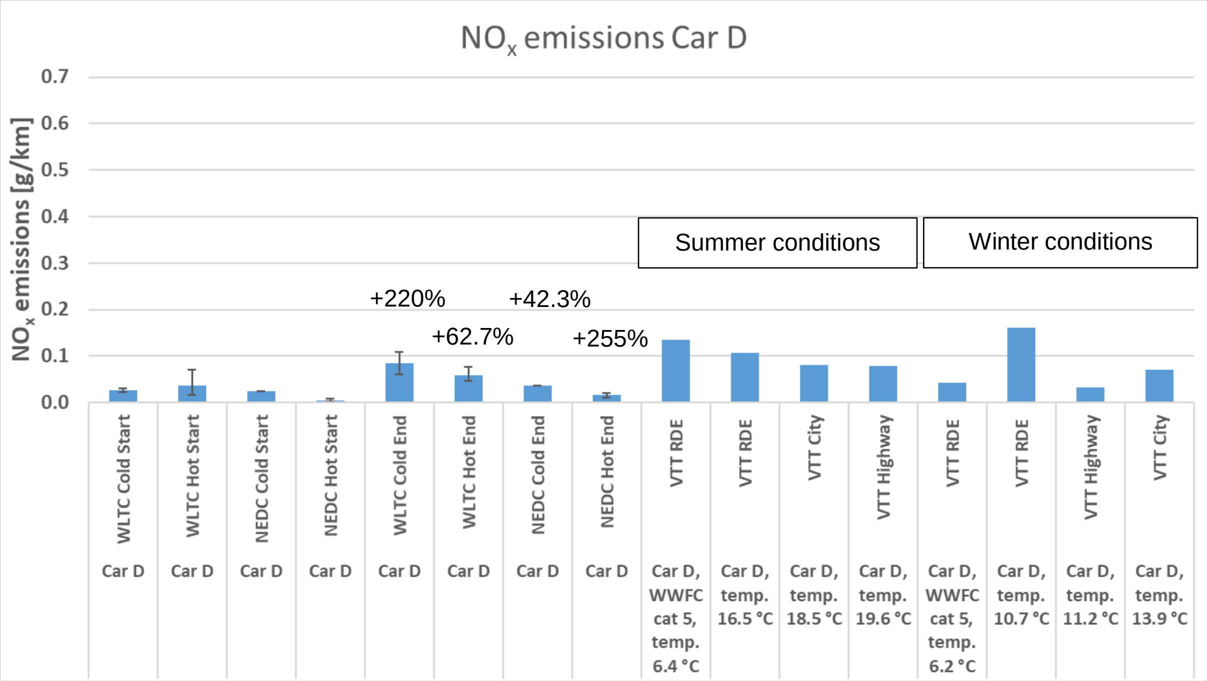

Figure 8: NO_x emissions of Car D on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

4.3 PN emissions

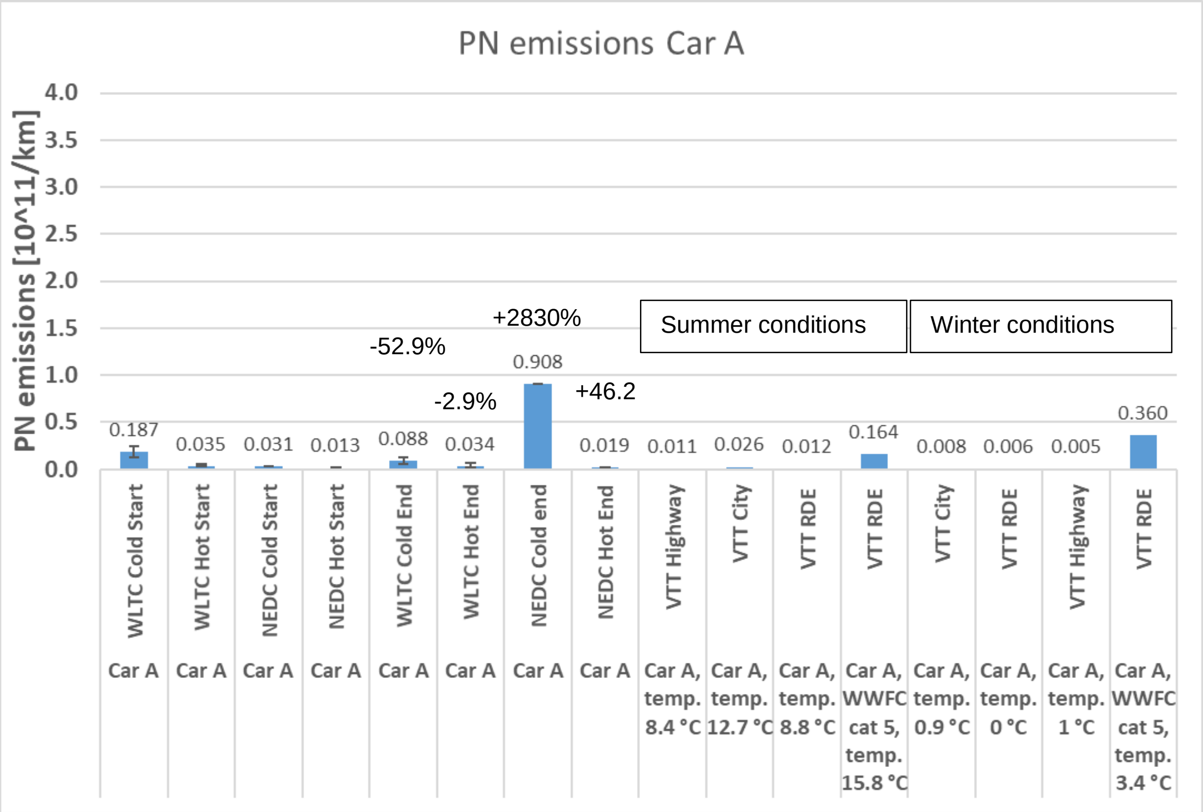

Figure 9: PN emissions of Car A on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

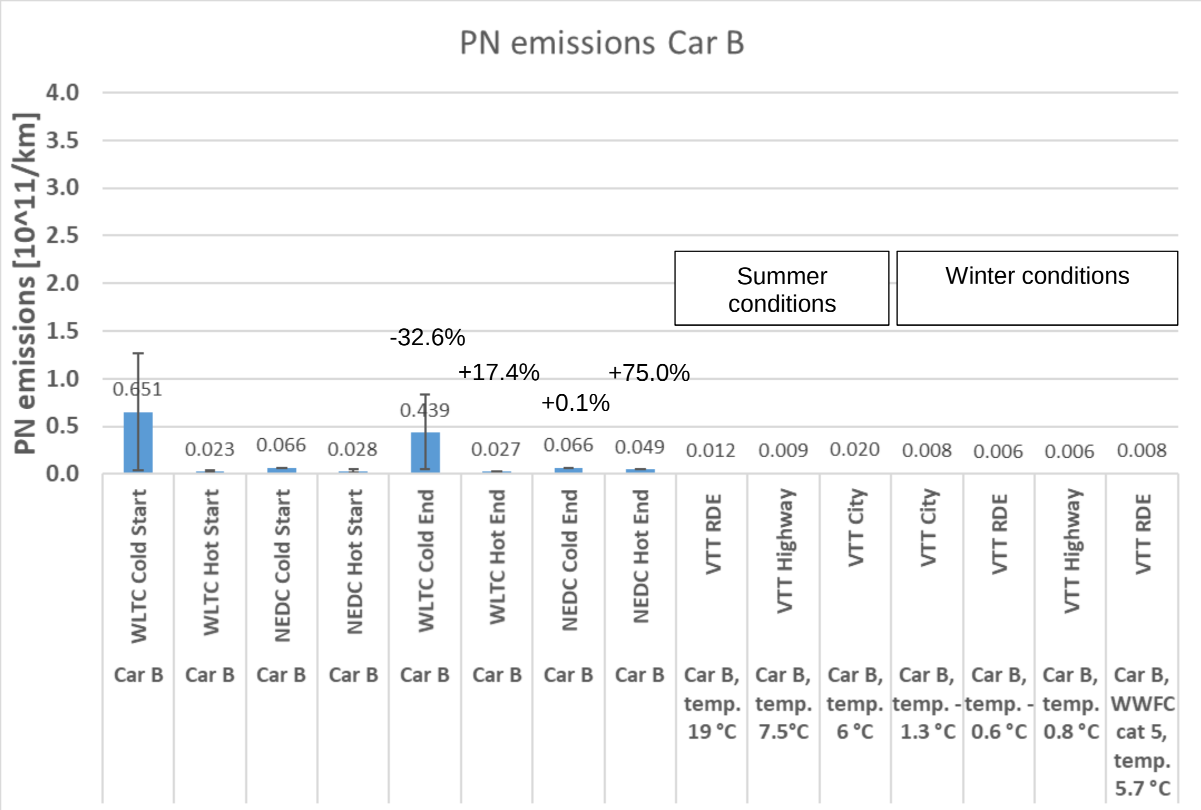

Figure 10: PN emissions of Car B on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

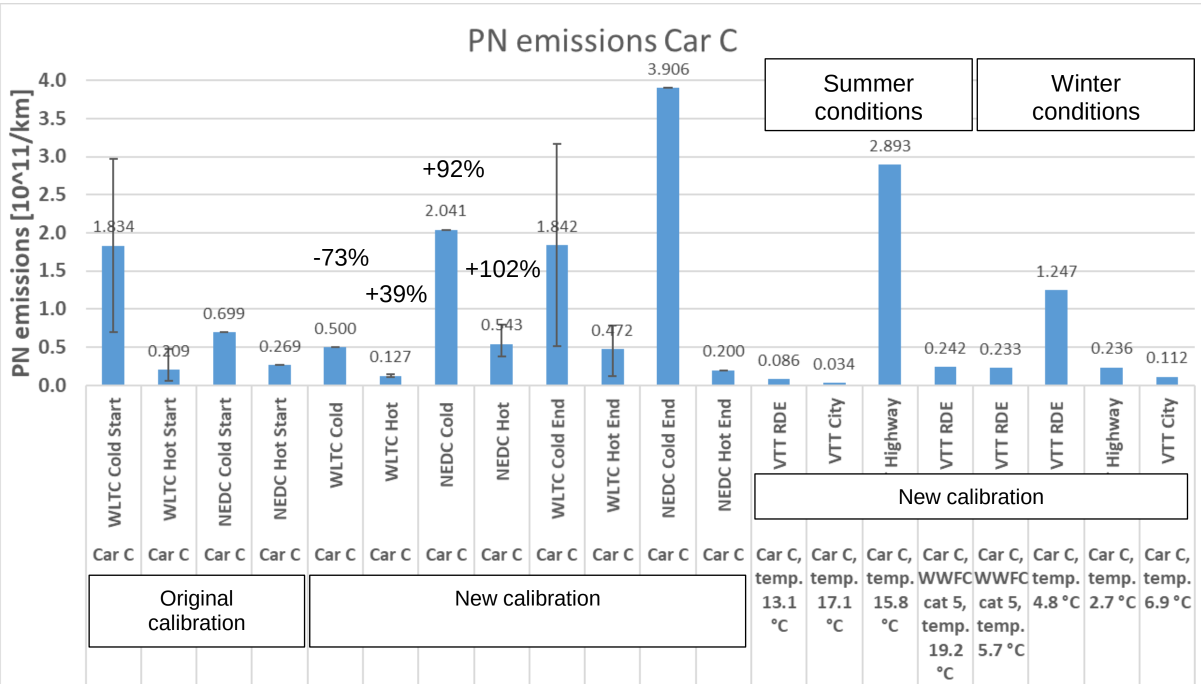

Figure 11: PN emissions of Car C on chassis dynamometer and on-road. Change between the new ECU software dynamometer and project end results are shown as percentages above the end results.

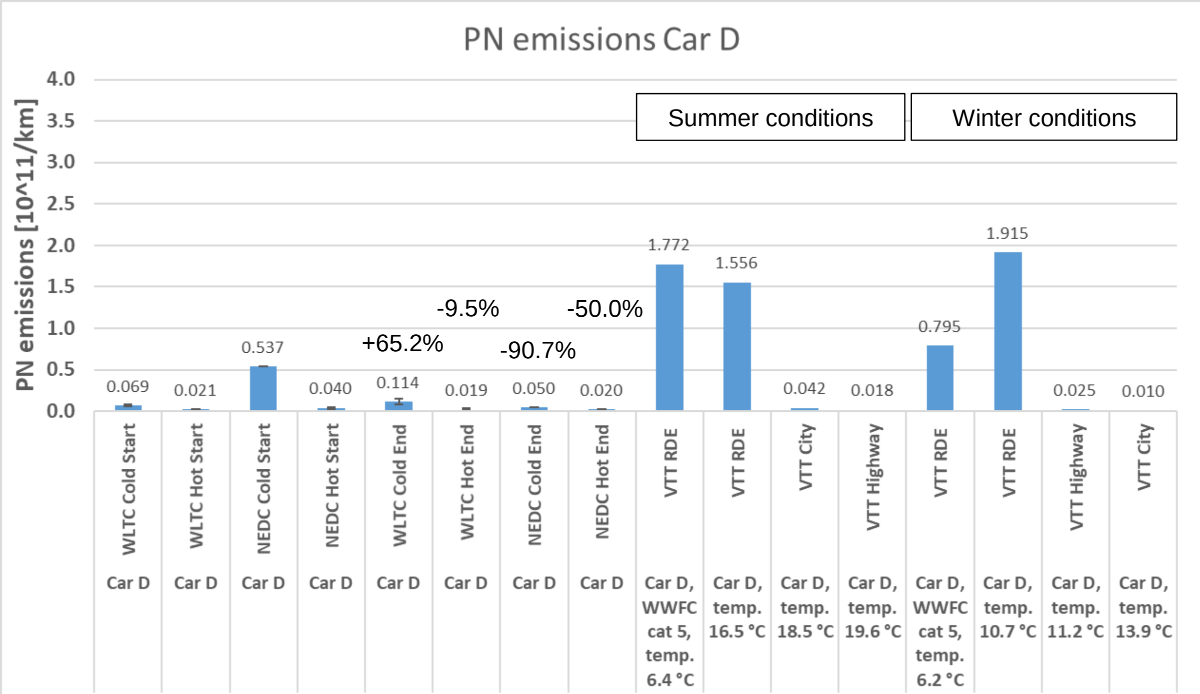

Figure 12: PN emissions of Car D on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

4.4 CO emissions

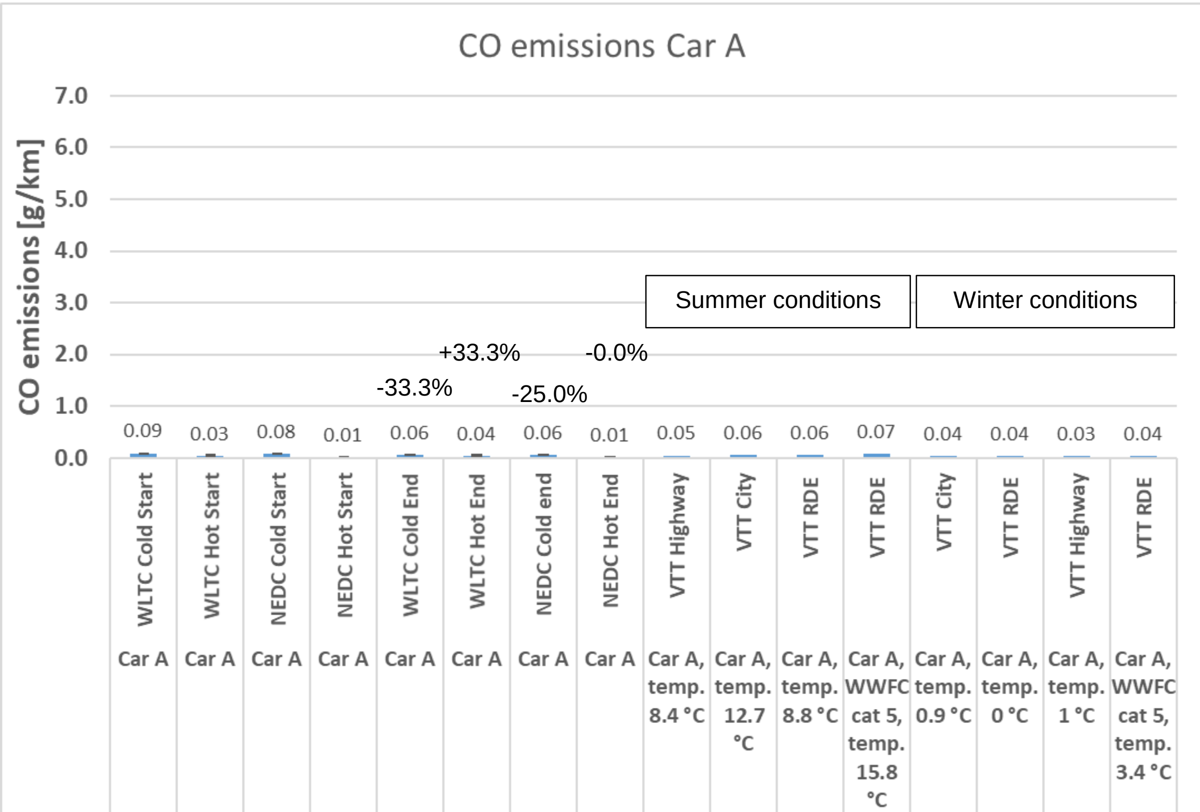

Figure 13: CO emissions of Car A on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

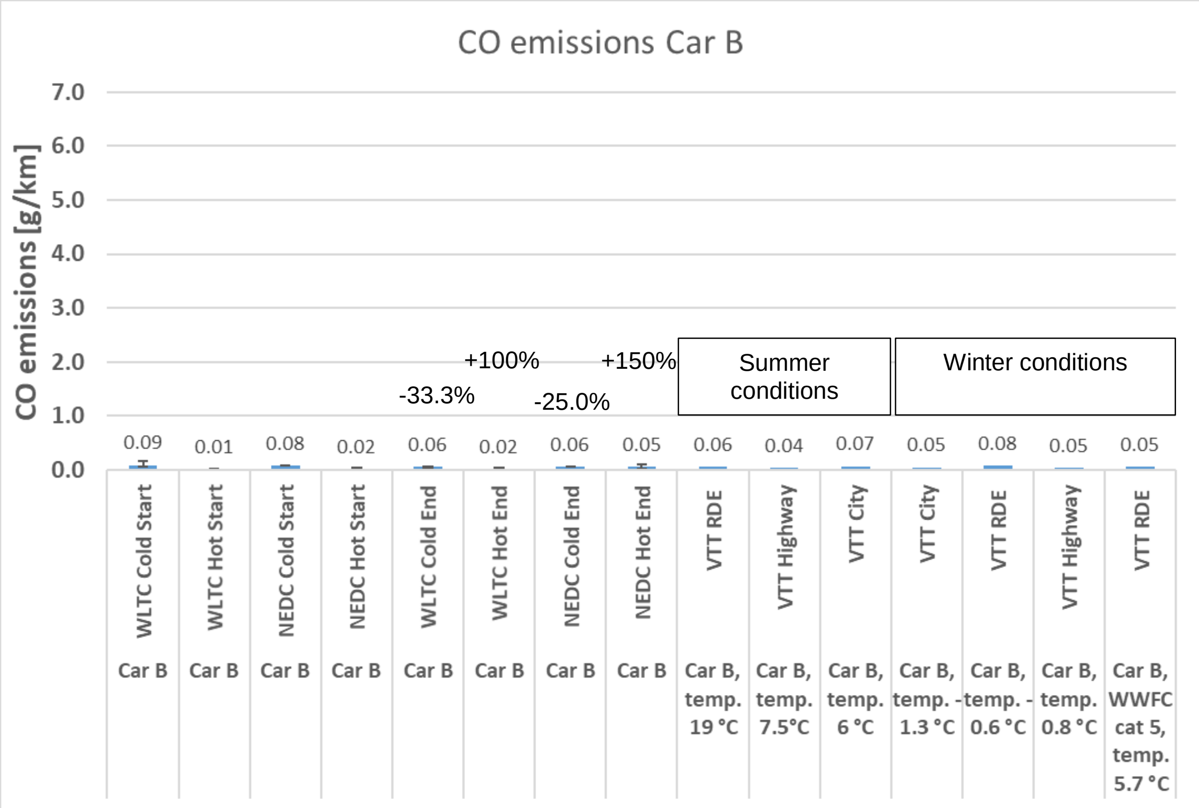

Figure 14: CO emissions of Car B on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

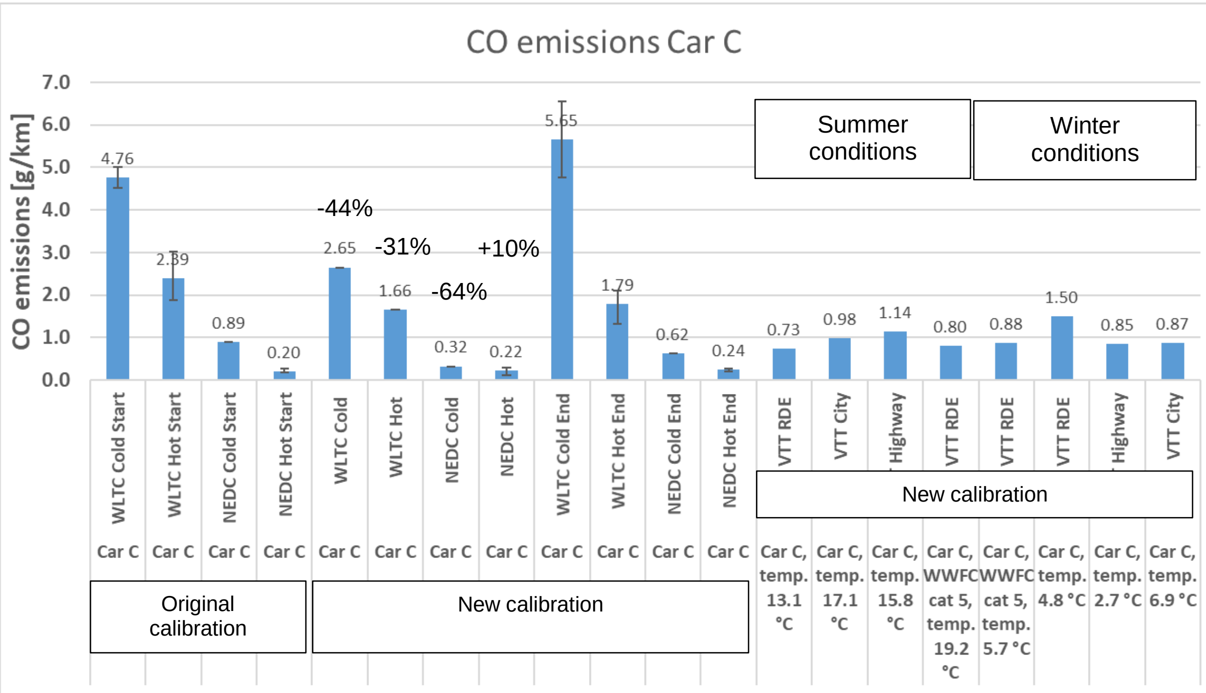

Figure 15: CO emissions of Car C on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

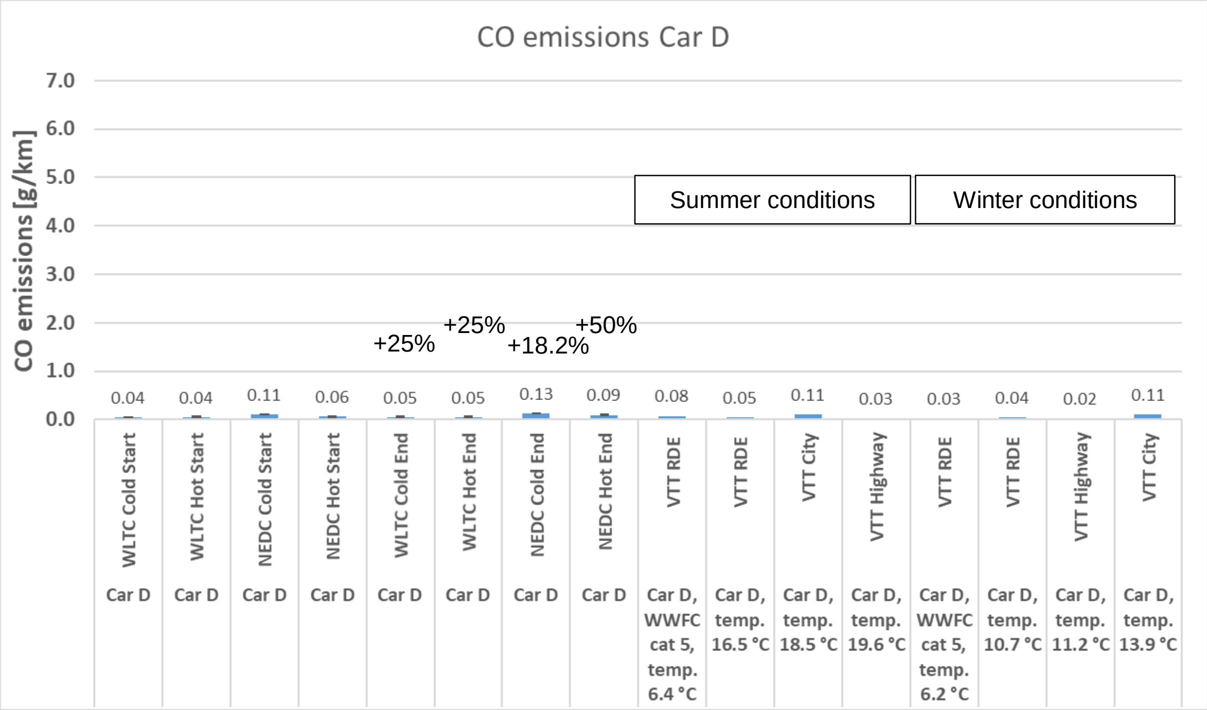

Figure 16: CO emissions of Car D on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

4.5 CO_2 emissions and fuel consumption

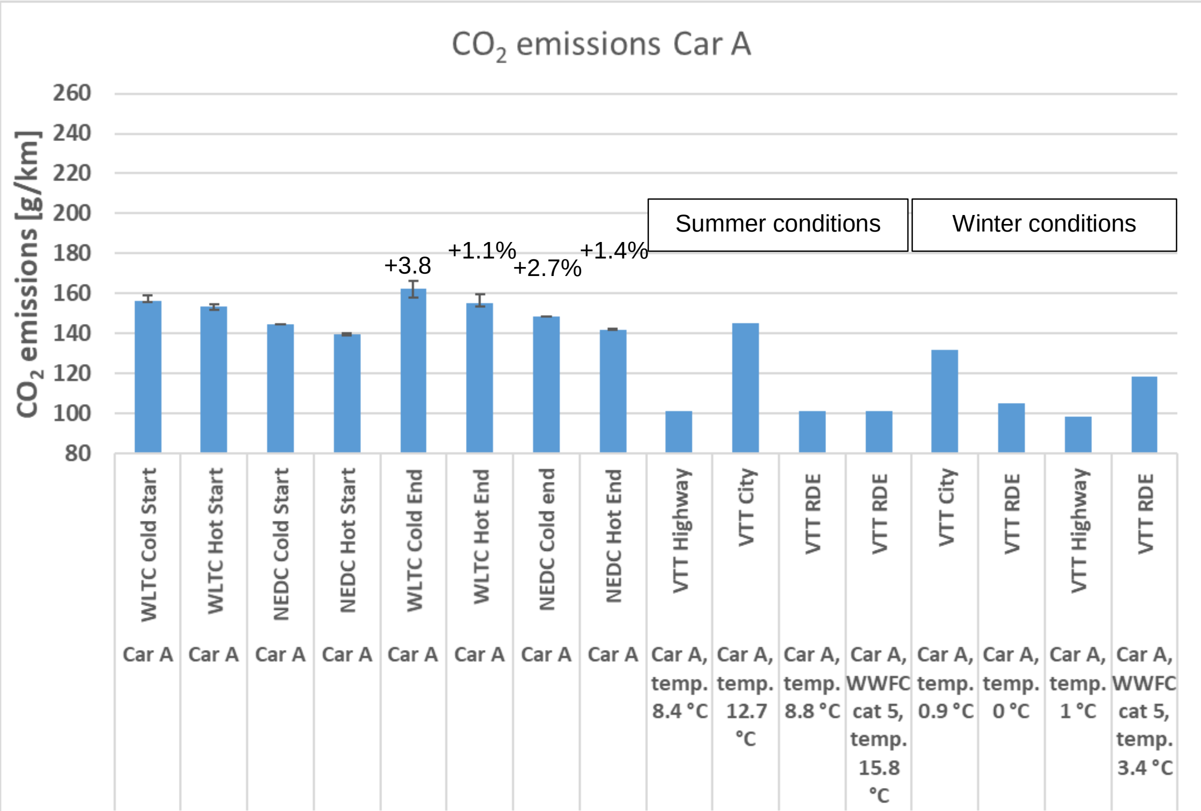

Figure 17: CO_2 emissions of Car A on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

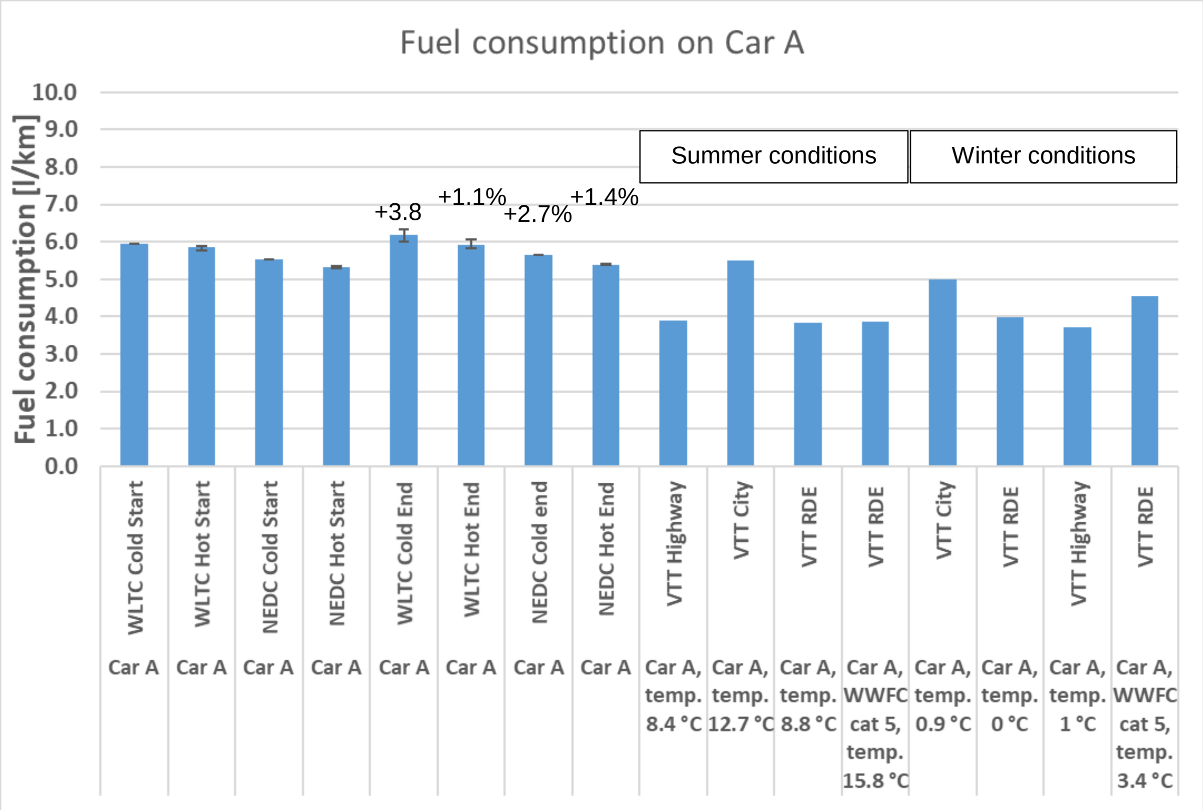

Figure 18: Fuel consumption of Car A on chassis dynamometer and on-road.

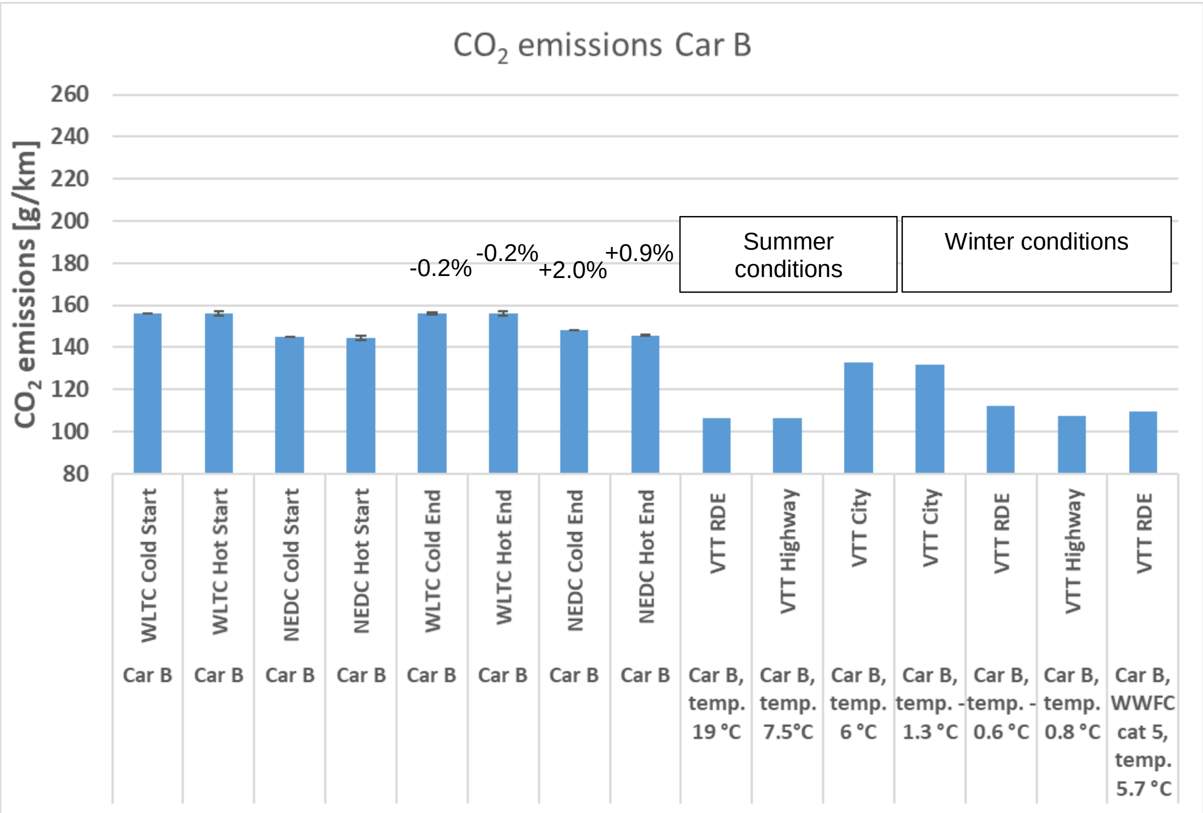

Figure 19: CO_2 emissions of Car B on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

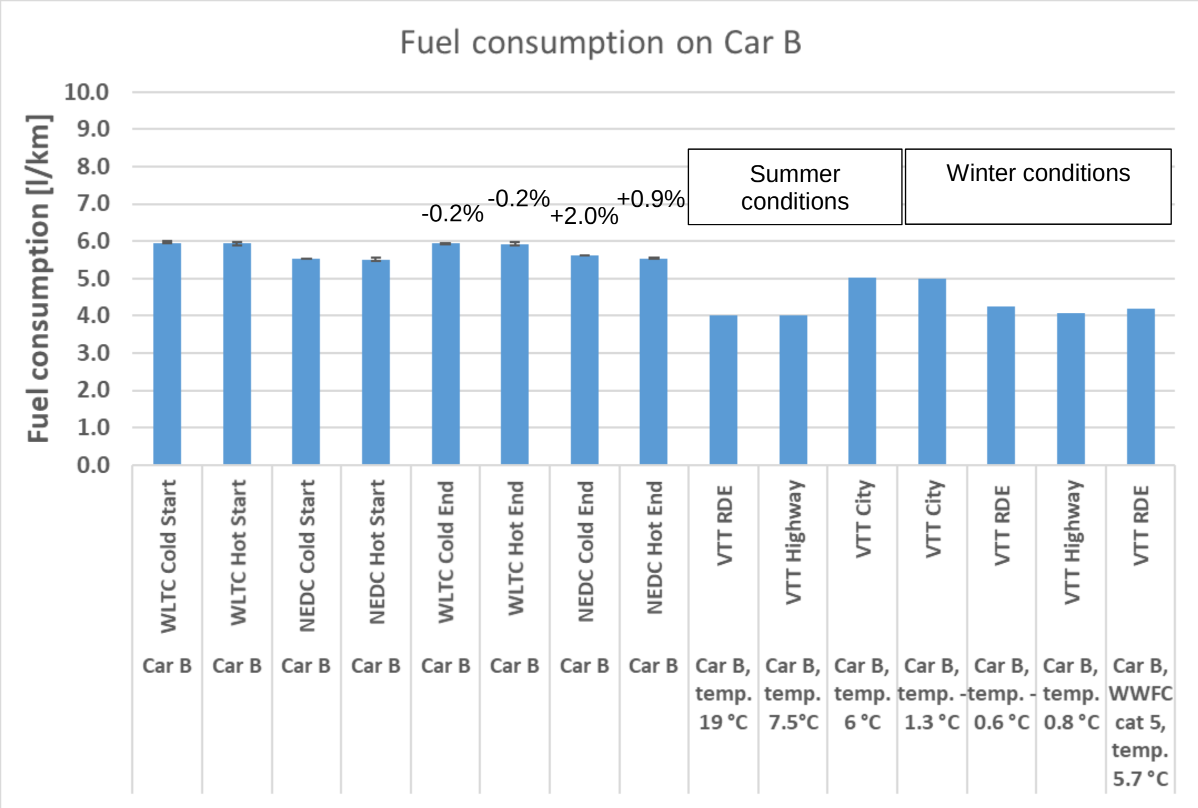

Figure 20: Fuel consumption of Car B on chassis dynamometer and on-road.

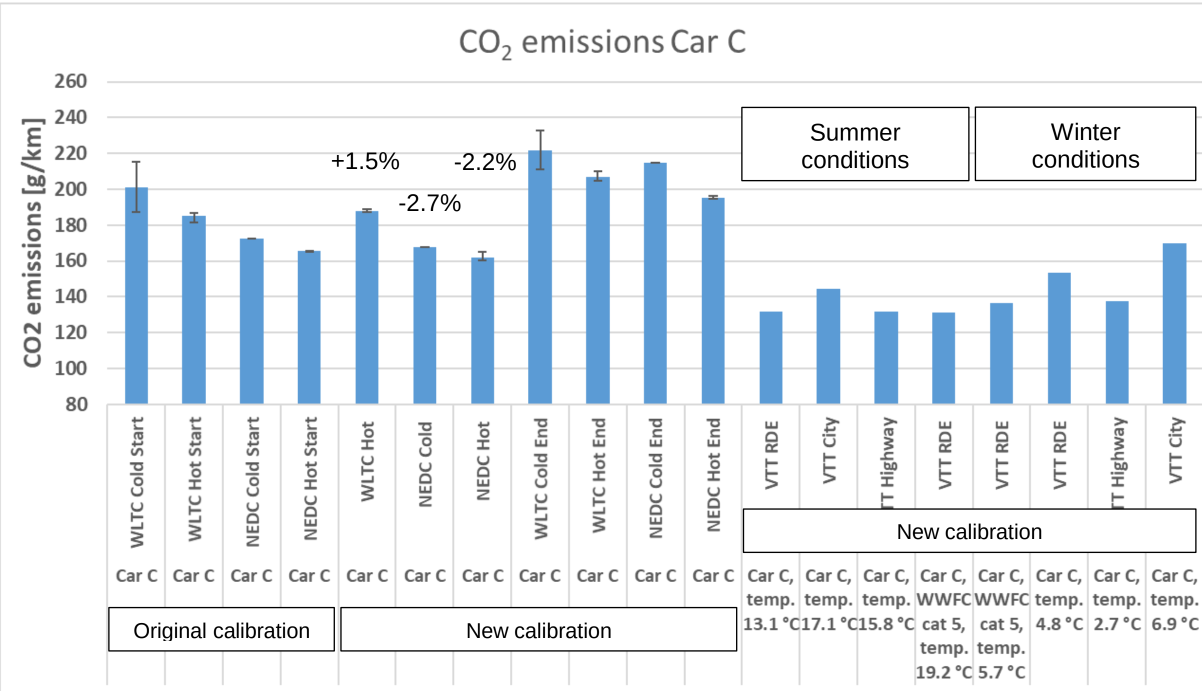

Figure 21: CO_2 emissions of Car C on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results

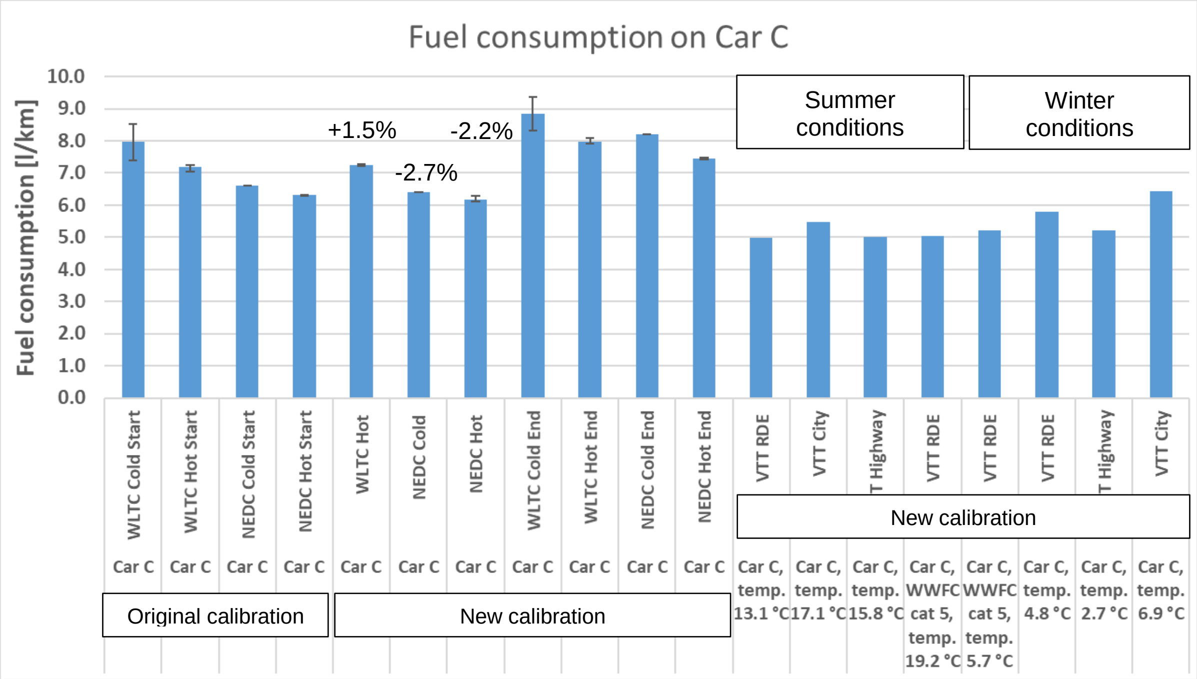

Figure 22: Fuel consumption of Car C on chassis dynamometer and on-road.

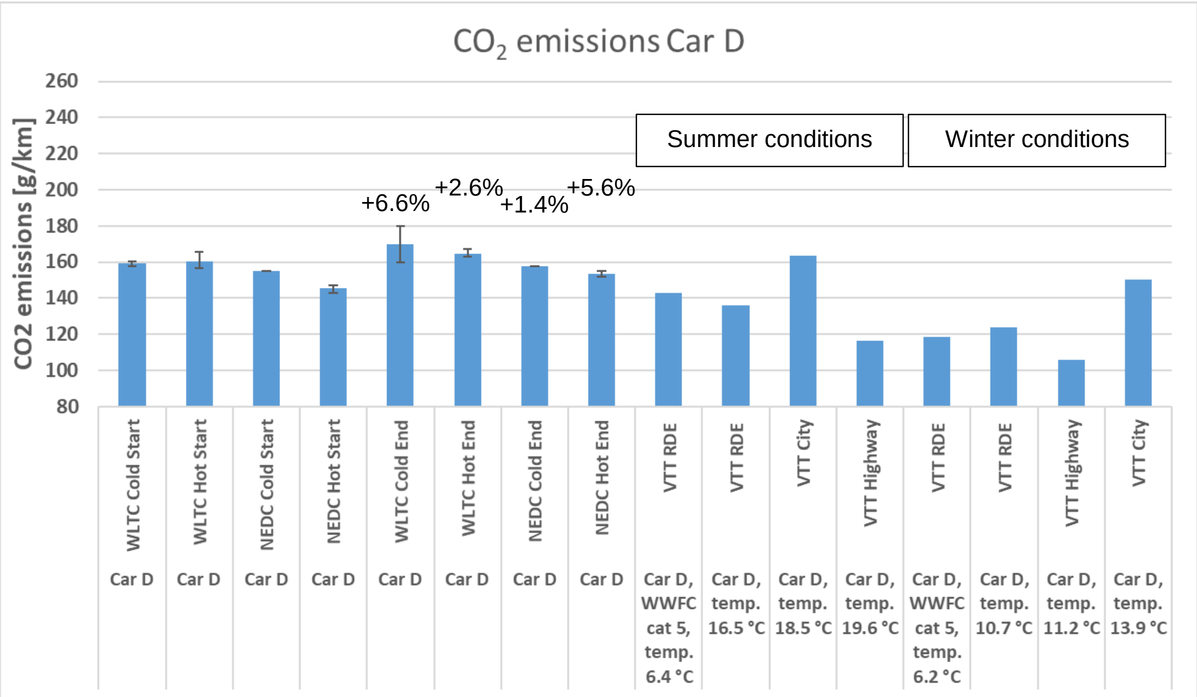

Figure 23: CO_2 emissions of Car D on chassis dynamometer and on-road. Change between the project end and start chassis dynamometer results are shown as percentages above the end results.

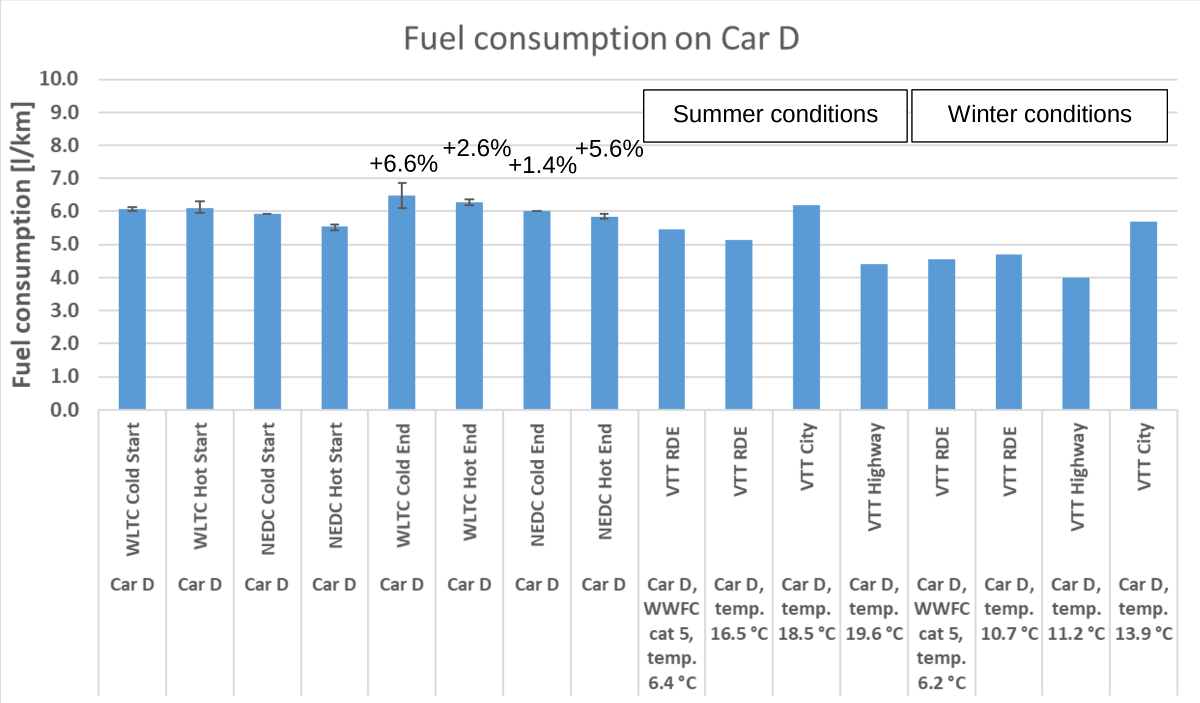

Figure 24: Fuel consumption of Car D on chassis dynamometer and on-road.

4.6 Conformity factor

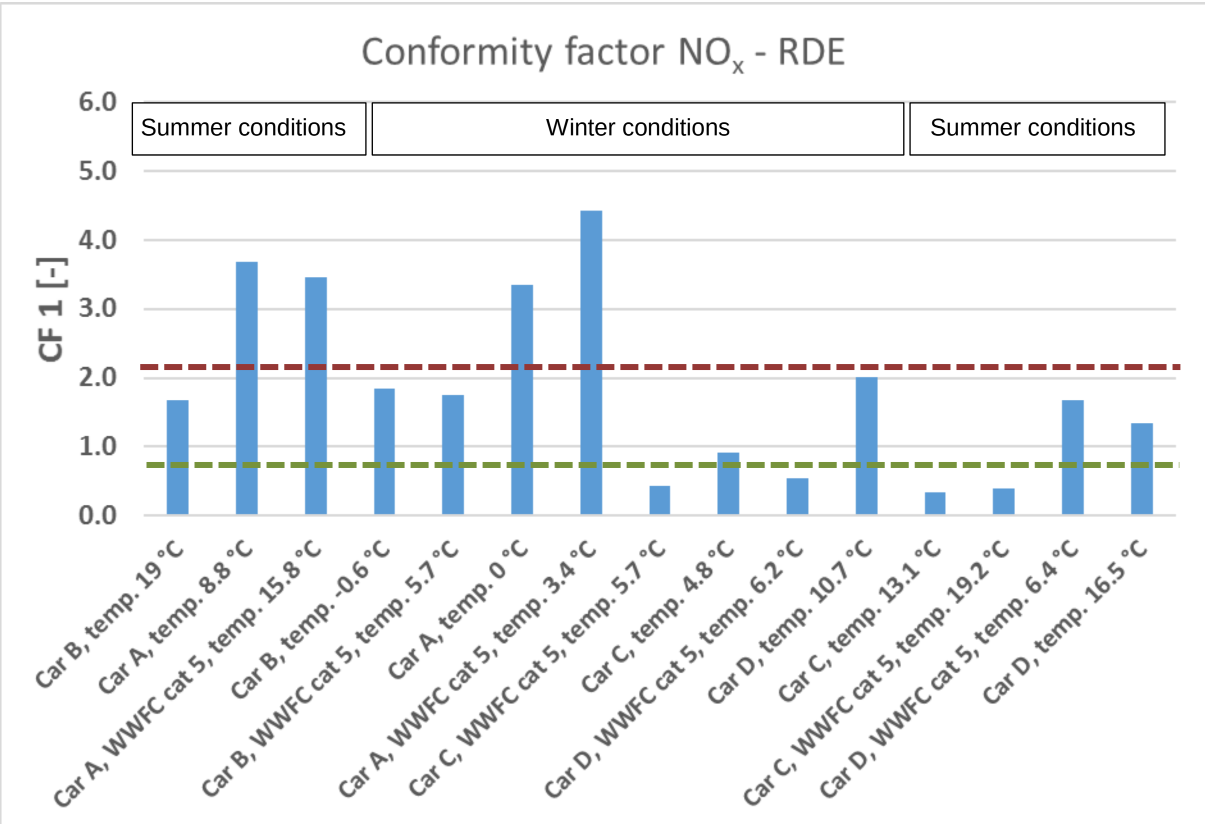

Figure 25: Conformity factor for NO_x on the VTT RDE route. Red bar illustrates the Euro 6 d-TEMP limit value for RDE (in effect only on RDE route) and green bar the Euro 6 limit value in type approval.

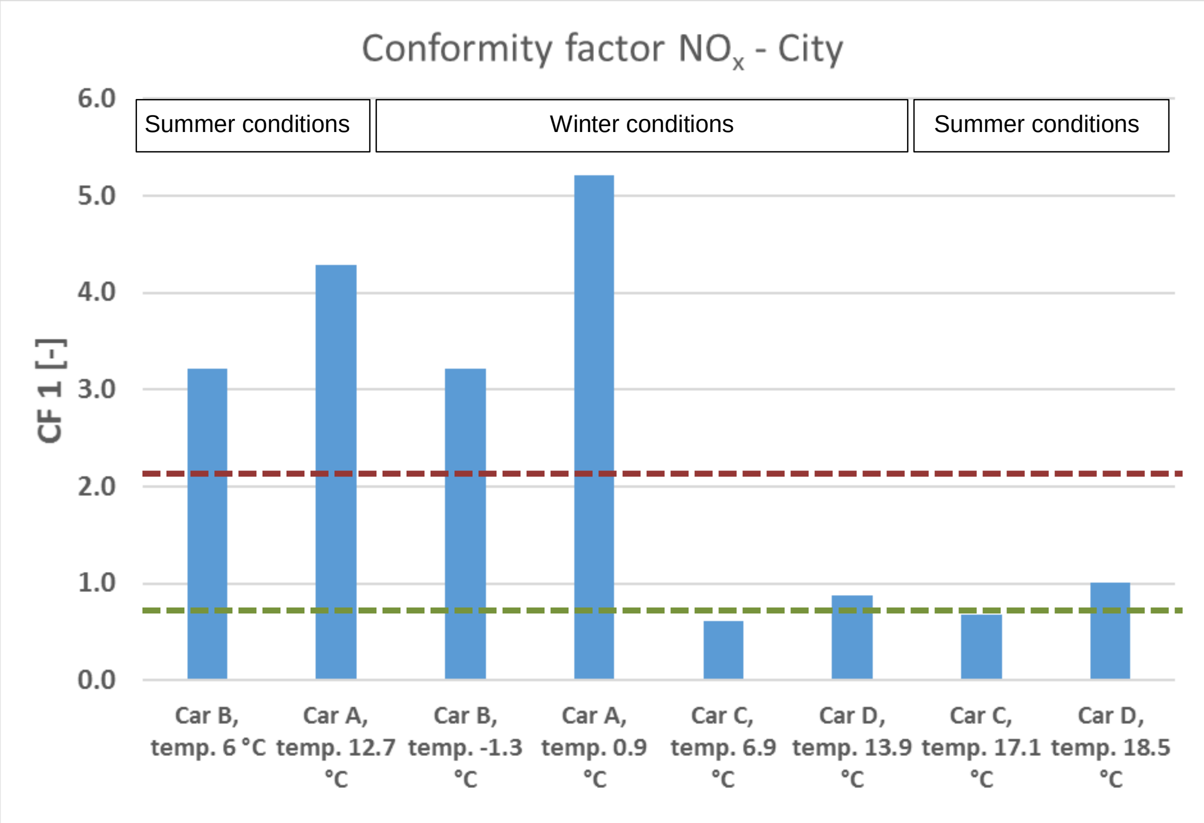

Figure 26: Conformity factor for NO_x on the VTT City route. Red bar illustrates the Euro 6 d-TEMP limit value for RDE (in effect only on RDE route) and green bar the Euro 6 limit value in type approval.

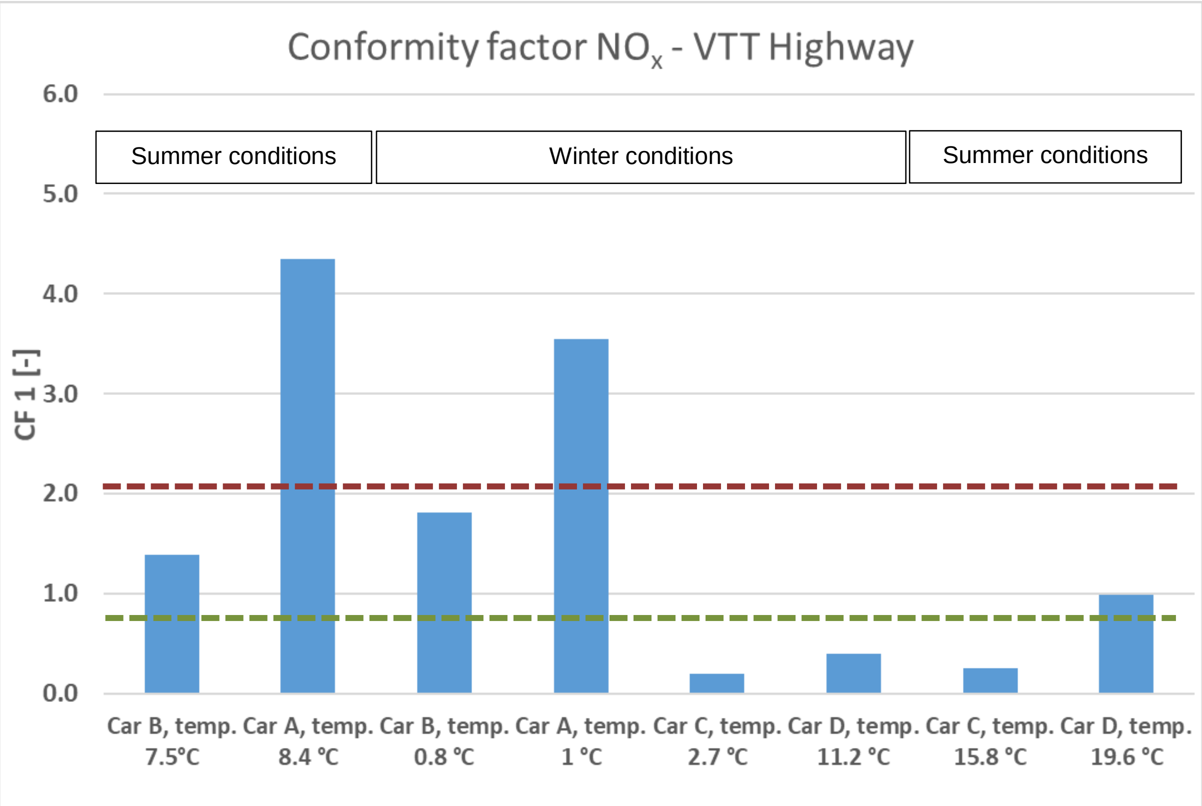

Figure 27: Conformity factor for NO_x on the VTT highway route. Red bar illustrates the Euro 6 d-TEMP limit value for RDE (in effect only on RDE route) and green bar the Euro 6 limit value in type approval.

4.7 Continuous NO_x monitoring

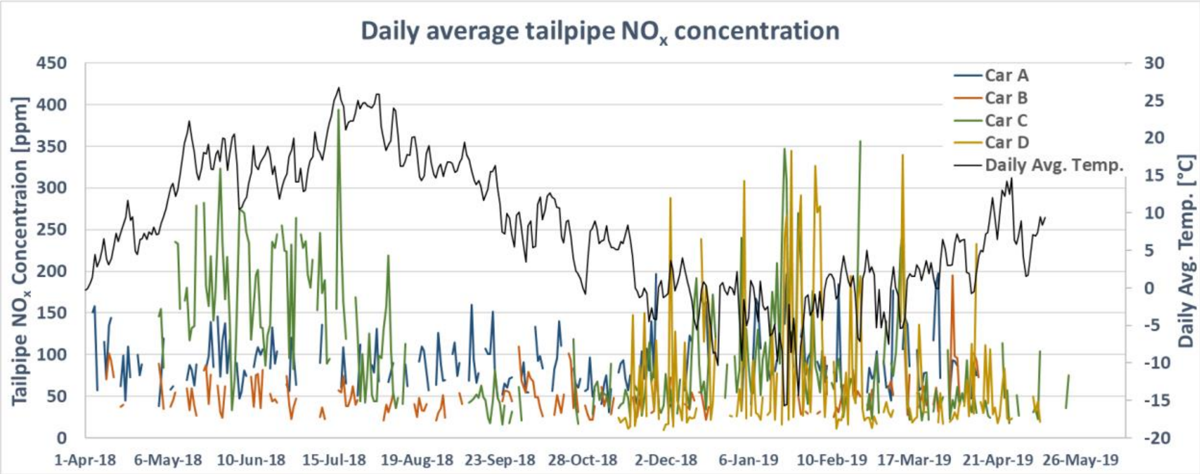

Figure 28: Daily average NO_x concentration during the project period.

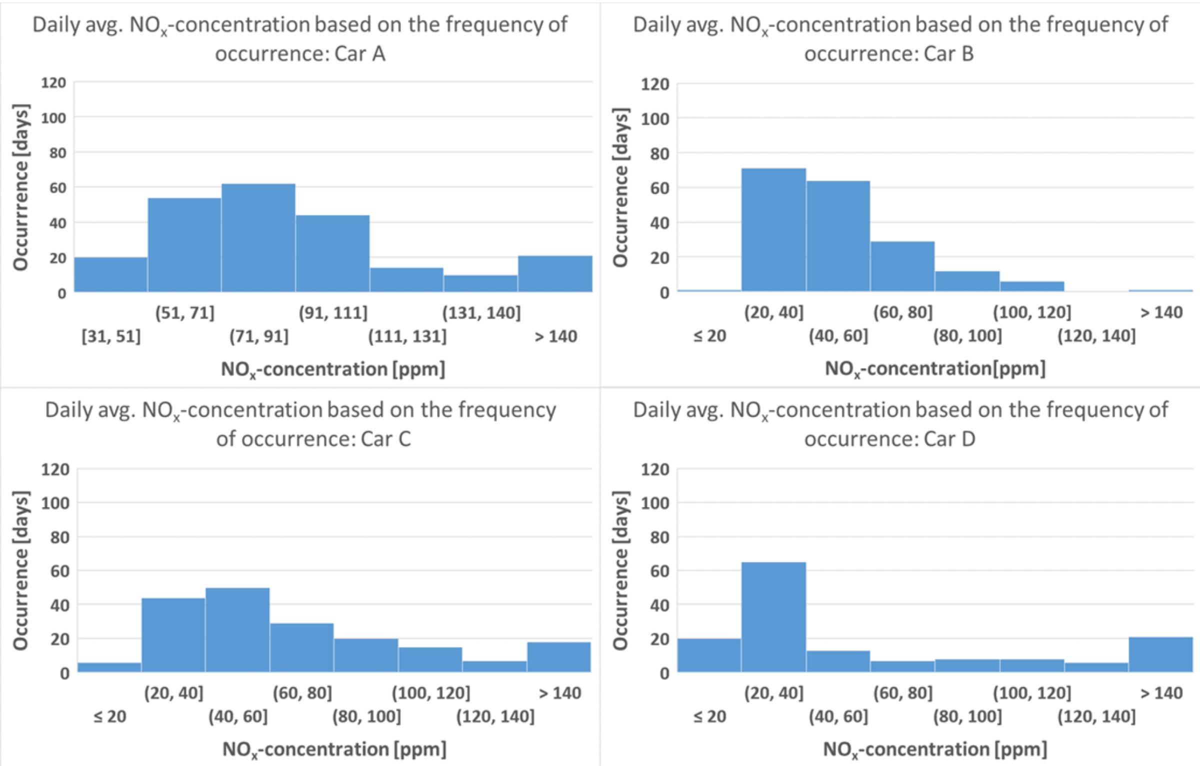

Figure 29: Daily average NO_x concentration based on the frequency of occurrence. Car C histogram covers data after the ECU update (August 2018 onwards).

5. Discussion of Results

The comparison of the PEMS device, in Table 8, to laboratory measurement device,s listed in Table 4, was performed for all the measurements at the project start measurement (i.e. 8 x WLTC and 4 x NEDC) for Cars A-C. During the project end measurement the comparison was also performed for Cars B-D on all test cycles. Minimum and maximum bars indicate the maximum and minimum difference. Overall as absolute emission levels are at a very low level the relative differences grow easily at a high level. This should be considered when interpreting the comparison results.

When evaluating the chassis dynamometer results, it should be kept in mind that the chassis dynamometer settings used during the chassis dynamometer tests were not the same as those used by the OEMs during the type approval. This has an effect on the results. Unfortunately, it is not known, how large the difference is in respect to each of the cars.

In the project end chassis dynamometer measurement, Car C showed anomalously high CO_2 emission values 10…25 % higher than during the project start measurement. The car's Start&Stop function was reported as not working during the "Summer" on-road measurements, which were performed just before the project end chassis dynamometer measurement, similarly to during the "Winter" on-road measurement. Any other abnormalities, like abnormal engine running or engine start or indicator lights, were not reported during the on-road and chassis dynamometer measurements. The most plausible reason for the abnormal high CO_2 emissions was the poor condition of the battery that was indicated afterwards. Higher fuel consumption also has an effect on other emissions too. Due to this uncertainty it was decided to compare project start and end measurements to each other after the ECU update and not to use project end measurement for the investigation of possible effects of vehicle ageing.

Day-to-day NO_x concentration monitoring results give a good guideline of the changes in average NO_x emissions throughout the monitoring period. However, it should be kept in mind that concentrations of different cars cannot be directly compared as the engines might operate with different exhaust gas mass flow levels. Cars A and B are based on the same base engine and they are operated rather similarly, thus they are the most comparable.

5.1 Comparison of PEMS against laboratory measurement devices

In Figure 3 and Figure 4 the comparison results of PEMS and laboratory measurement devices from the project start and end measurements on the chassis dynamometer are shown. During both measurement campaigns CO_2 emissions showed good agreement between the two devices. Average difference varied between -4.4 %…6.3 % depending of car and the test cycle. NO_x emissions showed also good agreement during both measurement campaigns, average difference varying between 6 %...36 %. Mostly the average difference varied between 6 %...21 %. These are somewhat similar results as previously reported in literature[3].

In the case of CO emissions, it should be noticed that the absolute values, especially with Cars A, B and D, are extremely low. This makes relative differences huge. The best agreement was identified with Car C, which also produced the highest CO emissions. The average difference varied between -14 %...8 %. The highest difference was identified with Cars A and B, varying between 87 %...494 %. Also the variation between the minimum and maximum difference was high. Cars A and B produced, on an absolute basis, the lowest CO emissions, on average

[3] Comparison of Portable Emissions Measurement
Systems (PEMS) with Laboratory Grade Equipment,
https://ec.europa.eu/jrc/en/publication/comparison-portable-emissions-measurement-systems-pems-laboratory-grade-equipment

approximately 48 mg/km. With Car D the average difference varied between 27 %...52 %. In literature the difference between -11.8 %...5 % was found[4,5].

In the case of PN emissions the emission levels on an absolute basis were also really low. This expanded the relative difference between the two measurement systems to a wide range. The best agreement was found with Car D. In which the average difference varied between 15 %...19 %. The highest difference was identified with Car A, where the difference varied between 146 %...159 %. In the case of Car B the average difference varied between -66 %...28 % and for Car C between 39 %...118 %. In the work performed by the Join Research Centre (JRC) of the European Commission, a difference between - 40 %...40 % was found in comparison of the PN-PEMS and laboratory measurement system[6].

Measured differences in PEMS device CO and PN emissions compared to laboratory devices were in some cases clearly outside the values indicated in previous studies. In the same cases a high variation in minimum and maximum difference was observed. During the project no clear reason was found to explain why the relative difference between CO and PN emissions measured by the PEMS and laboratory devices changed greatly depending on the car.

In summary, in the case of NO_x and CO_2 emissions rather good agreement with PEMS and laboratory device on an absolute and relative basis was found, which gives high confidence in the on-road results. In the case of CO and PN emissions, differences in absolute values were, in most of the cases, not high, but as emission levels were really low relative differences resulted in high differences.

5.2 Car A

In the chassis dynamometer tests, NO_x emissions of Car A were more than double in WLTC compared to NEDC. Absolute values in NEDC are over two times higher than the limit value of 0.08 g/km. In comparison of project start and end measurement, no clear difference is seen. The approximately 32,000 km that Car A was driven during the project seemed to have no effect on NO_x emissions.

Interestingly, the NO_x emissions in on-road measurements were lower over each of the on-road routes compared to WLTC. In on-road measurements, the VTT RDE route resulted in the lowest NO_x emissions, which were 2.3–2.7 times higher than the limit value 0.08 g/km in type approval. The overall conformity factor varied on-road between 3.3…5.2 depending on the test route. PN and CO emissions were low both on chassis dynamometer and on-road, and well below the type approval limits.

Car A is type approved according to NEDC with CO_2 emissions of 90 g/km. On the chassis dynamometer, the CO_2 emissions were approximately 145 g/km in cold start and 140 g/km in hot start NEDC, which are clearly higher than the official type approval value. In comparison of project start and end measurements, a slight increase in CO_2 emissions was identified. In project end measurements CO_2 emissions were 1.1 %...3.8 % higher depending on cycle. In on-road measurements, the VTT RDE and VTT Highway routes CO_2 emissions were surprisingly close to the type approval value, approximately 12.5 % higher. This could indicate

---

[4] A Comprehensive Evaluation of a Gaseous Portable Emissions
Measurement System with a Mobile Reference Laboratory, Cao, T., Durbin, T.D., Cocker, D.R. et al. Emiss. Control Sci. Technol. (2016) 2: 173. https://doi.org/10.1007/s40825-016-0040-4
[5] Inter-Laboratory Correlation Exercise with Portable Emissions Measurement Systems (PEMS) on Chassis Dynamometers, Appl. Sci. 2018, 8(11), 2275; https://doi.org/10.3390/app8112275
[6] Francesco Riccobono, Barouch Giechaskiel, Pablo Mendoza Villafuerte, Particle Number
PEMS Inter-Laboratory Comparison Exercise, EUR 28136 EN, doi: 10.2790/562,
https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/particle-number-pems-inter-laboratory-comparison-exercise

that Car A worked through the engine operation map used in normal on-road driving with similar fuel economy as in the type approval cycle NEDC.

Based on the measurements performed, it seems that ambient temperature difference of approximately 16 °C between the highest (approximately 16 °C) and lowest (0 °C) ambient temperature during the summer and winter measurement campaign did not have an observable effect on NO_x, PN and CO emissions, or on CO_2 emissions.

Day-to-day monitoring results (Figure 28) also support the conclusion that ambient temperature does not have an observable effect on NO_x emissions of Car A, as the daily average NO_x concentration is rather constant throughout the monitoring period. Maximum daily average concentrations are below 150 ppm. Overall the NO_x concentration is spread in a relatively large interval (Figure 29). The highest population of NO_x concentration is mostly between the 51…111 ppm. There is also a high cumulative population above 110 ppm.

5.3 Car B

Car B is a version of Car A that is two years newer with an updated engine. As expected, Car B had lower NO_x emissions than Car A on both chassis dynamometer cycles. Nevertheless, NO_x emissions were still more than double in warm NEDC and more than three times higher in WLTC compared to the legislative limit value of 0.08 g/km. Car B did gather 91 % of the target mileage of 30,000 km during the project. Ageing did not have an effect on NO_x emissions as no change was identified when project start and end measurements were compared.

On the VTT RDE and Highway routes, Car B resulted in a CF of 1.4…1.8 depending on route and measurement campaign, and only on the VTT City route was the CF was 3.2 compared to the limit value of 0.08 g/km. Car B produced rather constant NO_x emissions on each test route in both measurement campaigns.

Furthermore, PN and CO emissions were extremely low on both chassis dynamometer and on-road measurements independent of test type, route or time of testing. No effect of aging can be observed. Although the PN emissions in both cold start WLTC were clearly higher than on other cycles, they were still approximately a tenth of the limit value $6 x 10^{11}$ particulates/km.

Car B performed on the chassis dynamometer similarly to Car A with CO_2 emissions of approximately 156 g/km in WLTC and 145 g/km in NEDC. No change in CO_2 emissions between the project start and end measurements was observed. In on-road measurements during summer conditions, Car B produced CO_2 emissions of 106…109 g/km on the VTT RDE route, which is really close to the official type approval value. On one VTT RDE route during winter conditions emissions were 112 g/km.

Based on these results it seems for Car B that a temperature difference of some 18 °C (0.6 vs. 19 °C) has no effect on NO_x, PN and CO emissions, or on CO_2 emissions.

Car B clearly had lower day-to-day NO_x concentrations and thus emissions than Car A even though the base engine is the same and the operation of the cars was similar. Low ambient temperature in the winter period did not affect the NO_x concentrations. On average, the highest population of the concentration was concentrated between the interval of 20…60 ppm and there were only 7 days with concentrations above the 100 ppm level (Figure 29). This indicates that Car B's NO_x emissions reduction performance operates with rather constant performance.

5.4 Car C

On the chassis dynamometer, Car C was first measured with its original ECU software and afterwards with the updated software. The update was highly successful, as Car C had approximately 70 % lower NO_x emissions in WLTC and 70…90 % in NEDC after the ECU update. In warm start NEDC, NO_x emissions were less than half of the limit value of 0.08 g/km.

Because of the typical relationship, in diesel engines, between the NO_x emissions and fuel consumption it was of special interest whether the update had an effect on fuel consumption or other emissions. The difference in CO_2 emission between the measurements with new ECU software and project start measurements varied between -2.7 %...1.5 % depending on the cycle. Thus, it can be concluded that the ECU software did not have an observable effect on engine efficiency and fuel consumption. As engine efficiency was not changed in the ECU update it is most probable that SCR reduction efficiency was improved with the increased urea dosing. Nevertheless, it was not possible to measure urea consumption with good accuracy meaning that this assumption was not possible to demonstrate. NH_3 emissions were not measured for detection of possible slip.

Also with Car C, CO_2 emissions on the chassis dynamometer were much higher than in on-route measurements.

In on-road measurements, Car C performed extremely well. Car C had NO_x emissions with CF of 0.2…0.9 depending on the test route. An ambient temperature difference of 16.5 °C (2.7 vs. 19.2 °C) did not have an effect on NO_x emissions.

On the other hand, in on-road measurements PN emissions were clearly at a higher level than with Cars A and B, varying between 0.034×10^{11} and 2.9×10^{11} particulates/km.

Car C was not equipped with DOC, which resulted in surprisingly high CO emissions. CO emissions before the ECU update ranged from 2.89 g/km to 4.76 g/km in WLTC and from 0.2 g/km to 0.89 g/km in NEDC. After the ECU update, CO emissions declined to 2.65 g/km in cold-start WLTC and to 1.66 g/km in warm-start WLTC. In cold-start NEDC CO emissions declined to 0.32 g/km, but on warm-start NEDC the ECU update did not have an effect. In on-road measurements, CO emissions varied from 0.73 g/km to 1.5 g/km depending on the test route.

Car C had slightly higher CO_2 emissions (3.6…4.1 %) on the VTT RDE and VTT Highway routes during the winter measurement campaign compared to the summer campaign. On the VTT City route Car C had 13.5 % higher CO_2 emissions in the winter measurement campaign. However, it is difficult to differentiate, whether the differences originate from the difference in the vehicle's powertrain performance or from the driving conditions, including the different type of tires used and differences in speed limits during summer and winter campaigns.

The day-to-day results (Figure 28) also confirm that the ECU update really decreased NO_x emissions remarkably on normal daily operations. Before the ECU update NO_x concentration was on average well above 150 ppm and after the update it was under 50 ppm. Results also suggest that when daily ambient temperature drops below 0 °C, the NO_x concentration increases. During the coldest period (-5 °C…-15 °C) the concentration varied between 150…200 ppm and on some days was even up to 350 ppm. This is somewhat as expected as Car C is equipped with a SCR system that is sensitive to exhaust gas temperature. Most of the days Car C had NO_x concentrations between 20…60 ppm (Figure 29) and some (6 days) even below 20 ppm, but there was also a high population of days above 100 ppm, most probably due to the cold period as described above.

5.5 Car D

Car D was obtained latest into the project, roughly 6 months later than the others. Therefore, it gathered only 45 % of the target mileage of 30,000 km and was tested last in both test campaigns. During the winter measurement campaign the ambient temperature level was abnormally high compared to the typical ambient temperature at that time of year.

Car D is type approved for Euro 6d-TEMP legislation, and it performed well in NO_x emissions during the project start measurements. NO_x emissions were well under the legislation limit value of 0.08 g/km, ranging from 0.005 g/km in NEDC hot start to 0.036 g/km in WLTC hot start. In the project end measurements the NO_x emissions were clearly higher. Increase in NO_x emissions varied between 42.3 % in NEDC cold start to 255 % in NEDC hot start. In absolute values the highest emissions were measured in WLTC cold start, in which Car D resulted approximately 85 mg/km NO_x emissions. Based on these results it can be stated that the mileage of about 13,500 km during the project resulted in an increase in NO_x emissions. Based on these results no conclusion as to whether the NO_x emissions are still changing or not can be drawn.

In on-road measurements, NO_x emissions were slightly higher than on the chassis dynamometer, varying from 0.043 g/km to 0.16 g/km over the VTT RDE route and from 0.032 g/km to 0.081 g/km over the VTT City and VTT Highway routes. Ambient temperature between the measurement campaigns varied between 6.2…19.6 °C. Car D had conformity factor values between 0.4…2.0 depending on the test. The time and conditions of the testing did not have an effect that could be ascertained.

PN emissions on chassis dynamometer were well under the limit value of $6x10^{11}$ particulate/km. The NEDC cold start in the project start measurement clearly resulted in the highest PN emissions, but still less than a tenth of the limit value. No clear trend was observed in the change of PN emissions between the project end and start measurements. Absolute levels were extremely low during both measurement campaigns.

In on-route measurements Car D had quite variable PN emissions depending on the test route. Over the VTT RDE route, the emissions varied between $0.8…1.9x10^{11}$ particulate/km and on the VTT City and Highway routes between $0.01…0.042x10^{11}$ particulate/km.

CO emissions were at a very low level over every test cycle, route and condition. There was no difference between the emissions from the chassis dynamometer and on-route.

Car D had CO_2 emissions of approximately 160 g/km in WLTC and 155 g/km in cold-start NEDC and 145 g/km on warm-start NEDC during the project start measurement. During the project end measurement a slight increase was observed. The increase in CO_2 emissions varied between 1.4 %...6.6 %. However, some variation in cycle average results in WLTC hot start during the project start and WLTC cold start during the project end measurement was observed. Because of this no clear conclusion can be made as to whether the increase in CO_2 emissions was caused by ageing.

In on-road measurements, CO_2 emissions were clearly higher during the summer measurement campaign compared to winter conditions. However, similar results were not identified with other cars.

Car D had interesting day-to-day NO_x concentration figures (Figure 28). The concentration was mainly (approximately 66 %) on a low level (below 40 ppm) but high fluctuation was observed (Figure 29). The performance of Car D NO_x reduction is interesting since it seems to reduce NO_x emissions both well and not well, there is a low population between 60…140 ppm (app. 20 %). High concentration peaks seems to occur during the cold period more often. Nevertheless, due to the relative short monitoring period no clear statement on the effect of ambient temperature on NO_x concentration can be drawn. This mean that due to the relatively short monitoring period of Car D, which concentrated on the winter period, it is not possible draw a clear answer as to whether the high peaks are caused by the ambient temperature, due to LNT regeneration or if they are both causing high fluctuation in NO_x emissions.

5.6 Effect of fuel on emissions

On the VTT RDE route two fuels were tested: one fulfilling the EN590 diesel standard and one using WWFC cat 5 diesel. None of the cars tested showed any observable difference in emissions. There was no clear trend identified in respect to measurement accuracy in favor of either of the fuels. As the density, lower heating value (LHV) and C/H content of the fuels are really close to each other this result was anticipated. However, this result also shows that the diesel fulfilling WWFC cat 5 performs similarly to EN590 diesel in on-road conditions.

6. Summary

Within this project, four Euro 6 diesel passenger cars representing typical vehicles in Finland were tested on a chassis dynamometer and with on-road measurements. Three of the vehicles were Euro 6b class and one was Euro 6d-TEMP class. The project targeted mileage of 30,000 km for each of the cars in which only Car A succeeded, whereas Cars B and C gathered roughly 90 % of the target. Car D gathered only approximately 45 % of the target due to late entry to the project. On chassis dynamometer project start and end measurements were performed. Vehicles were tested on-road in two measurement campaigns, one in winter conditions and one in summer conditions.

WLTC and NEDC test cycles were used in the chassis dynamometer tests. Three different measurement routes was tested in on-road measurements, VTT RDE, VTT City and VTT Highway, representing different driving situations and thus different operation areas in the engine operating map. The VTT RDE route was run with two different fuels, one fulfilling EN590 diesel standard and one the WWFC cat 5 diesel standard.

Comparison of the PEMS device to a laboratory measurement device was also carried out. Based on the measurements a good agreement for CO_2 and NO_x (6 %...36 %) emissions was observed. In the case of CO_2 difference of -4.7 %…6.3 % was detected and for NO_x 6 %...36 %. On an absolute basis the CO and PN emissions were, in most cases, at a very low level making relative differences, also in most cases, huge. This caused high variation in relative basis depending on the car. Differences ranging from -5 % to 494 % were detected for CO emissions and from 2 % to 159 % for PN emissions.

On the chassis dynamometer, each car tested resulted in higher CO_2 emissions than the official type approval value. However, it must be borne in mind that the dynamometer settings were based on the table values allowed in the NEDC procedure. This method is widely known to overestimate the road load coefficients, thus leading to higher energy need and fuel consumption, as well as, correspondingly, CO_2 emissions.

Cars A and D had slightly higher CO_2 emissions during the project end than in the project start measurements. For Car B no change in CO_2 emissions was observed.

Overall for chassis dynamometer and on-road, each car had PN emissions that were well under the limit value of $6x10^{11}$ particulate/km. Cars A and B had on average the lowest PN emissions. Car C results from the chassis dynamometer measurements were clearly the highest PN emissions, especially on cold-start test cycles. In on-road measurements Car C performed better, but PN emissions varied quite a lot depending on the measurement. Car D had lower PN emissions in chassis dynamometer measurements than in on-road. Also Car D had variation in PN emissions on on-road.

Cars A and B had much higher NO_x emissions in WLTC compared to NEDC. Car B, which was a similar model to Car A but two years younger, had lower NO_x emissions than Car A. The NO_x emissions of Car A ranged between 0.24...0.59 g/km depending on the test cycle. Car B had NO_x emissions between 0.07…0.33 g/km depending on the test cycle. Mileage or ambient temperature was not observed to have an effect on NO_x emissions. On a day-to-day basis both of the cars performed rather consistently; Car B had roughly 50 % lower NO_x emissions.

Car C was first measured on the chassis dynamometer with its original ECU software and afterwards with the updated software. The update in ECU software was highly successful, and resulted in clearly lower NO_x emissions on both test cycles, ranging between 0.037…0.136 g/km depending on the test cycle and a reduction of 70…90 % compared to the original software. In addition, a modest decline in CO emissions was identified as a result of the software update. No change in CO_2 or PN emissions was identified. Day-to-day NO_x concentration also showed that the update decreased the NO_x levels on average below a third of the original. However, during the coldest period (-5 °C…-15 °C) the daily average NO_x concentration and emissions increased by an approximately 2…3 times higher level than in above 0 °C conditions.

In the project end measurements Car C had remarkably higher CO_2 emissions than in the previous two chassis dynamometer campaigns. During the measurements no clear reason was found. Afterwards it was found out that the battery was slightly damaged and thus might have been the reason for higher fuel consumption. Because of this uncertainty it was not possible to estimate the effect of mileage on Car C's emissions.

Car D had low NO_x emissions in the project start chassis dynamometer tests, ranging between 0.005 g/km and 0.036g/km. In the project end measurements an increase in NO_x emissions was observed. NO_x emissions varied between 0.017… 0.085 g/km. This gives an indication that the mileage might have had an effect on Car D's NO_x emissions reduction performance.

Cars C and D had low on-road NO_x emissions on each of the test routes. Varying from Car C's lowest result on the VTT Highway route with CF 0.2 to Car D's highest result on the VTT RDE route with CF of 2.0.

Car A had the highest NO_x emissions in the on-road measurements. The emissions were between 0.27 g/km on the VTT RDE route and 0.52 g/km on the VTT City route. Car B had lower NO_x emissions, ranging between 0.11 g/km on the VTT Highway route and 0.26 g/km on the VTT City route. Car B had NO_x emissions of 0.13…0.15 g/km (CF 1.7…1.8) on the VTT RDE route, which are under the CF value of 2.1 required in Euro 6d-TEMP.

Based on the test results, PN emissions are not a problem for Euro 6 diesel passenger cars. Euro 6 legislation forced OEM's to equip diesel vehicles with DPF, which seems to also work extremely well in on-road driving conditions. The highest PN emission measured in the on-road measurements was half of the limit value.

Cars A, B and D were equipped with DOC. Thus, the CO emissions of those cars were low, as expected, in the chassis dynamometer and on-road measurements. Car C was not equipped with DOC, and that was clearly reflected in the results, as in on-road tests, high CO emissions ranging from 0.73 g/km to 1.5 g/km were recorded.

The measurement program performed showed that there is a marked difference especially in NO_x emissions within the Euro 6 cars depending on the certification level and the after-treatment technology used. Euro 6b vehicles can emit either high NO_x emissions or NO_x emissions fulfilling the RDE-limits. Furthermore, a Euro 6b car equipped with SCR can emit low NO_x emissions with correctly designed exhaust after-treatment control software, which it is possible to update afterwards in the ECU. Moreover, a Euro 6d-TEMP car with dual-LNT is capable of fulfilling the emission limits in all driving conditions, quite as expected.

There was no clear difference identified in NO_x, CO or PN emissions reduction performance on-road when tested at near-zero ambient temperature compared to tests performed at approximately 13 °C…20 °C. Only Car C showed an observable difference in emissions on the RDE route NO_x between the summer and winter measurement campaigns. One aspect affecting this is the fact that during the winter measurement campaign ambient temperatures were approximately 10 °C higher than normal for that time of the year. This resulted in a relatively small difference in temperature during the summer and winter measurement campaigns. However, day-to-day monitoring results suggested that Car D's and especially Car C's NO_x emissions increased as the ambient temperature dropped below 0 °C. With Car C, NO_x concentration increased on average by a 2…3 times higher level, whereas Car D showed more fluctuation in day-to-day concentrations.

Two diesel fuels were used in tests on the VTT RDE route. One diesel fuel fulfilling the EN590 diesel standard and another using WWFC cat 5 diesel. None of the cars tested showed any observable difference in emissions. Thus, there was no clear trend identified in favor of either of the fuels. This result was as anticipated as the C/H ratio, LHV and density of the fuels are close to each other. The result also suggests that WWFC category 5 diesel fuel gives a similar emissions performance to EN590 diesel fuel in on-road usage.