RESEARCH REPORT

VTT-R-01080-22

Euro 6 d-TEMP PHEV and diesel passenger cars on-road research

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beyond the obvious

Report's title

Euro 6 d-TEMP PHEV and diesel passenger cars on-road research - EPSILON

Project partners

City of Helsinki, HSY, Traficom, TØI The Institute of Transport Economics and VTT

Project name	**Project number/Short name**
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Summary

Based on the results obtained in the project it can be stated that PHEVs could provide an effective additional measure for reducing CO_2 emissions in typical Finnish daily trips where 93% of daily mileage is less than 50 km. Results showed that PHEVs are capable of covering the typical Finnish daily mileage fully electrically in different driving conditions. However, results also showed that the electric range drops greatly when the ambient temperature decreases below roughly 5 °C. If a PHEV is used with an empty battery, CO_2 emissions are well above the officially declared values. On the commuter test route where the test started with an empty battery, PHEVs produced 5% to 66% higher CO_2 emissions depending on the PHEV compared to a diesel car. However, on the city test route, two of the PHEVs were in best case capable of diesel car-like CO_2 emissions when the test was started with an empty battery. The NO_x emissions of the tested PHEVs, diesel car and van were at a low level, even well below the regulatory limit values. Overall, PHEVs performed the best, producing NO_x emissions mostly below 0.01 g/km, corresponding to a conformity factor (CF) value of 0.17 and below. There was no observed significant increase in NO_x emissions during the change of propulsion from electric drive to ICE drive, even in sub-zero Celsius temperatures. The NO_x emissions of the diesel car were also well below the legislative limit value. Emissions varied between 0.005 g/km to 0.092 g/km depending on test route and ambient conditions; these correspond to CF values of between 0.063 to 1.15. The ambient temperature had a clear effect on NO_x emissions, as an increasing trend was observed as a function of decreasing ambient temperatures. A van was tested on a test route replicating a typical delivery journey in a suburban area. NO_x emissions were 0.05 g/km when start-stop functionality was deactivated, and 0.065 g/km when it was activated. These figures correspond to CF values of 0.40 and 0.52. NO_x emission performance was also tested against the proposed limit values of Euro 7 regulation. PHEVs were capable of meeting the limit values with clear margins. The diesel car greatly exceeded the proposed limit values on cold start routes. However, it did meet the limit values in warm start tests. NO_x emissions from the van were close to the limit value and in some tests, they were below the limit. In general, PN emissions were well below the regulatory limit values in every test condition with all tested vehicles.

In summary, it can be stated that the tested vehicles are capable of low NO_x and PN emissions in different driving and ambient conditions. In addition, PHEVs with renewable fuels like high ethanol fuels (E85) could provide effective additional measures for reducing CO_2 emissions among BEVs. Especially on short trips, regularly charged PHEVs provide close to BEV energy consumption and thus CO_2 emissions. For longer distances, renewable fuels would ensure a low carbon footprint. To achieve regular charging all incentives that discourage the user to charge the battery regularly should be removed.

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Abbreviations

BEV	Battery Electric Vehicle
CF	Conformity Factor
CoC	Certificate of Conformity
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EAT	Exhaust After-treatment
ICE	Internal Combustion Engine
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
PHEV	Plug-in Hybrid Electric Vehicle
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
TTW	Tank-To-Wheel
WTT	Well-To-Tank
WTW	Well-To-Wheel

Preface

Carbon dioxide (CO_2) and pollutant emissions from plug-in hybrid electric vehicles (PHEVs) have been discussed in detail since PHEVs became more popular. PHEVs can be considered as battery electric vehicles with ICE as a range extender, and thus emissions are heavily dependent on how often the battery is charged and the length of trips that are taken.

This project aimed to investigate CO_2, NO_x, and PN emissions in typical Finnish driving and ambient conditions. Four PHEVs were tested on different test routes. In addition, a diesel car was selected as a reference, and a van for investigating NO_x emissions in test route replicating typical delivery journeys in suburban areas.

The potential of PHEVs were also investigated by analyzing CO_2 emissions on a well-to-wheel (WTW) basis over typical Finnish daily mileages.

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

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Authors

Extended Summary

The increase in the share of plug-in hybrid electric vehicles (PHEV) among the total vehicle population has raised questions considering their pollutant and CO_2 emissions in typical commuter driving in changing environmental conditions. In addition, the role of PHEVs in CO_2 emissions reduction has been questioned due to their clearly lower electric range compared to BEVs, and high CO_2 emissions when driving with an empty battery. PHEVs can be considered as battery electric cars with ICE as a range extender and user possibility to select which energy source is used within the limitations of electric range.

In this project, the pollutant and CO_2 emissions of four PHEVs were investigated in different driving and Nordic ambient conditions. As a comparison, a Euro 6 d-temp diesel passenger car was selected as a reference. In addition, pollutant emissions from an RDE-compliant van were investigated on a test route replicating a typical package delivery journey, to provide information on the possible emission burden exposed to suburban areas.

The results showed that NO_x and PN emissions were well below the regulatory limit values with all the tested vehicles. The test trip that started with a cold engine in a cold ambient temperature did not effect PHEV NO_x emissions in practice. The change from electric drive to ICE propelled drive did result in a peak in NO_x emissions with some of the tested PHEVs. However, a three-way catalyst used for NO_x reduction did reduce NO_x emissions shortly after the ICE was turned on, leading to only a slight increase in cumulative emissions. In most test trips, the PHEVs resulted in an NO_x emission corresponding conformity factor (CF) of less than 0.17. The highest single NO_x emissions monitored with PHEVs was 0.032 g/km on a commuter route, corresponding to a CF of 0.53. The cold ambient temperature did show a clear effect on diesel car NO_x emissions, as a clear increasing trend was seen. However, on absolute levels, NO_x emissions were below the regulatory limit values. Two years of continuous NO_x concentration monitoring suggested that NO_x emissions were on average within the range of 0.05 g/km, corresponding to a CF of 0.63, which is rather well in line with the warm-start on-road test results. This suggestion excludes the cold start emissions, as the system was not able to capture those. The van performed surprisingly well on the delivery route producing NO_x emissions, corresponding to a CF value of 0.4.

PHEVs were capable of meeting the proposed Euro 7 regulatory limit values for NO_x emissions by some margin. Three-way catalysts used in the tested PHEVs did not suffer from cold ambient temperatures or sudden start-ups of the ICE. The tested diesel car met the proposed Euro 7 regulatory NO_x emission limit values only when the test was started with a warm engine. Cold start tests resulted in NO_x emissions clearly above the proposed limit values. The van was close to meeting the proposed Euro 7 regulatory NO_x emission limit values—only slightly surpassing the limit.

The best two PHEVs were capable of an electric range of around 50 km on an RDE route, which corresponds closely to the official electric range declared by the OEM. When the test started with an empty battery, the highest CO_2 emissions were measured on the commuter test route, where they varied between 154 g/km and 208 g/km, depending on the car and the ambient conditions. In comparison, the diesel car produced CO_2 emissions between of 125 g/km and 146 g/km. Interestingly, some of the PHEVs were capable of diesel car-like CO_2 emissions on the city route, when started with an empty battery and driving in battery sustaining mode, even though the lightest PHEV weighted more than 400 kg more than the diesel car. This suggests that the tested PHEVs were capable of rather high kinetic energy recuperation to compensate for the higher curb weight. Ambient temperatures of below 5 °C were found to greatly reduce the electric range of PHEVs. Depending on the tested PHEV, low temperatures even led to permanent hybrid propulsion from test start to end.

In addition to the testing activities, a WTW analysis was performed for evaluating the PHEVs' potential for contributing to transportation CO_2 emissions reductions. The study did not include CO_2 emissions emitted during the manufacturing process. However, it can be assumed that for example CO_2 emissions emitted in battery manufacturing are similar in $gCO_2/kWh_{battery}$ for BEV and PHEV batteries. The results showed that PHEVs could provide an effective additional measure for CO_2 reduction as they capable are in the best cases of covering typical sub-50 km daily trips driven in Finland fully electrically; see Figure 1.

Together with renewable fuels like ethanol blends up to E85, CO_2 emissions emitted while driving with an empty battery could also be greatly reduced. Up to the typical Finnish daily mileage of less than 50 km, regularly charged PHEVs could provide BEV-like CO_2 emissions. For greater daily mileages, BEVs provide clearly lower WTW CO_2 emissions due to lower energy consumption, as the PHEVs' propulsion is mainly produced by ICE. A diesel car with HVO fuel would provide BEV-like WTW CO_2 emissions.

The WTW analysis highlights that PHEVs, in combination with renewable fuels, could contribute strongly to reducing CO_2 emissions. Especially in uses cases where most of the driving is over short distance , i.e., within the electric range of the vehicle, energy consumption would be reduced and still provide the user with ICE car-like autonomy for longer trips but with a low carbon footprint. However, in some cases there are incentives that encourage users not to charge their car battery regularly, such as typical company car contracts, where fuel costs are included in the deal. All incentives should be changed in order to direct users to always select the option that provides lower CO_2 emissions and the use of renewable energy. Analysis also showed that for longer daily trips, BEVs provide a clearly more effective way of reducing CO_2 emissions. However, diesel cars with renewable fuels, like HVO, would reach close to BEV WTW CO_2 emission levels.

PHEVs provide a viable measure, in addition to BEVs, for reducing CO_2 emissions for a person having a charging possibility at home and in combination with renewable fuels, like E85 PHEV's, are capable of low CO_2 even on longer trips while driving with empty battery.

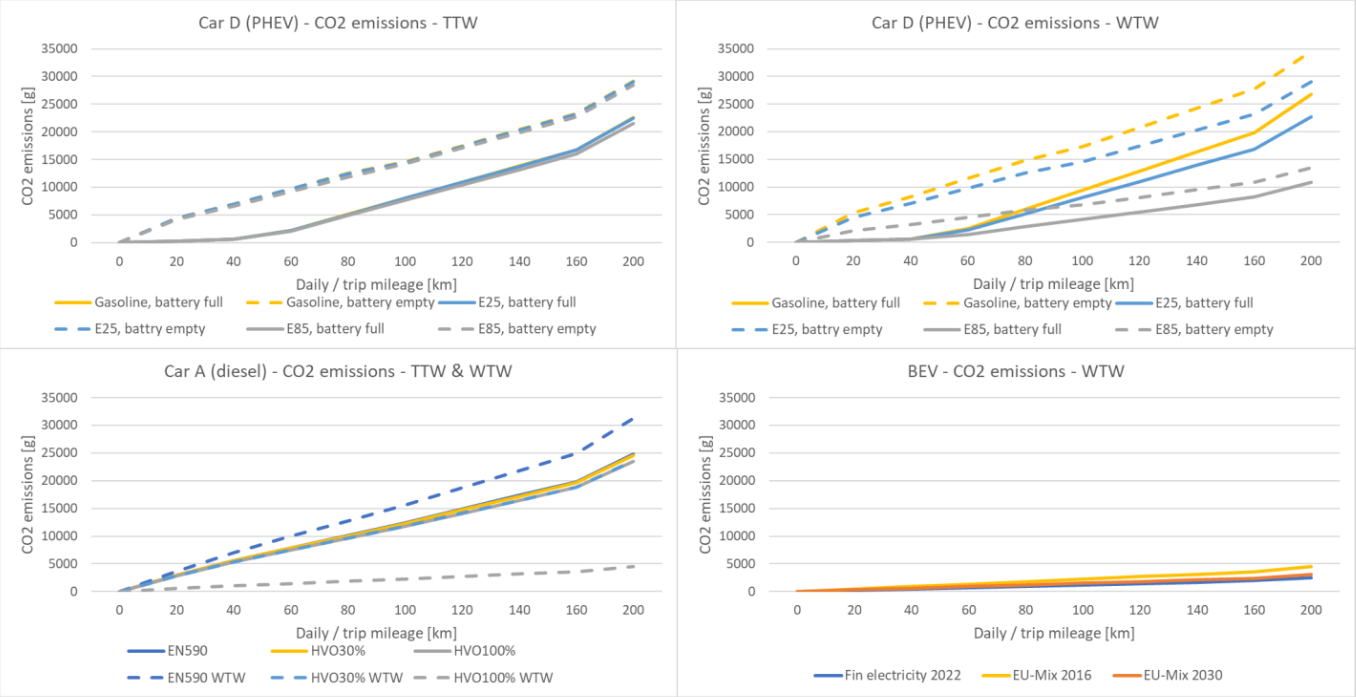

Figure 1: TTW and WTW CO_2 emissions of PHEVs, diesel cars, and BEVs with different energy options.

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1. Introduction

VTT, together with its partners the City of Helsinki, the Helsinki Region Environmental Services Authority, Neste, Traficom, and TØI—the Institute of Transport Economics, performed the on-road field monitoring project between 2018 and 2019 on four Euro 6 diesel passenger cars. This study highlighted that there is a marked difference in NO_x emissions based on the Euro 6 class (e.g., Euro 6 b vs Euro 6 d-TEMP)[1,2]. It also showed that on-road NO_x and CO_2 emissions do not correlate with the values measured on type approval cycles on a chassis dynamometer. During the project, continuous NO_x monitoring was also used. It showed that even Euro 6 d-TEMP cars might have up to 5–8 times higher NO_x emissions during cold periods. However, it was not possible to confirm this finding with PEMS measurements due to abnormally high temperature conditions during the winter PEMS measurement campaigns. Thus, based on this result a comprehensive conclusion cannot be made because the first indication is based on results obtained from only one car.

Current EU regulation for passenger cars regulates CO_2 emissions based on the tailpipe (tank-to-wheel, TTW) approach. The EU has implemented continuously tighter CO_2 regulation in the TTW approach. The regulation effectively pushed new fully electric and hybrid cars onto the market. There are two major questions concerning hybrid cars and cars equipped with a traditional powertrain (only an internal combustion engine):

1. CO_2 emissions in typical driving situations (city-based driving, commuter traffic, long distance driving) in different ambient conditions

2. Pollutant emissions in typical driving situations (city-based driving, commuter traffic, long distance driving) in different ambient conditions

CO_2 emissions of hybrid cars are dependent on how large a share of their mileage is made in electric mode, and how much the electric powertrain can reduce the use of its internal combustion engine. Additionally, from previous experience it is known that the exhaust aftertreatment devices pollutant reduction capability is extremely sensitive to the exhaust gas temperature. This has a huge effect on the tailpipe emissions as NO_x for both diesel- and gasoline- and for HC and CO for gasoline-fueled engines.

From January 2020 onwards, new diesel passenger car models are Euro 6 d type-approved and they are most likely to be mainly equipped with SCRs or a combination of SCR and LNT. SCR technology is extremely temperature sensitive. In the Euro 6 d regulation the conformity factor (CF) for NO_x is reduced from 2.1 in Euro 6 d-TEMP to 1.43. The lower CF sets significant requirements for the average reduction performance of the aftertreatment device during operation.

In gasoline cars, the three-way catalyst (TWC) is a robust and extremely effective device for reducing HC, CO, and NO_x emissions. However, TWCs are also sensitive to exhaust gas temperature, which might be a challenge in hybrid cars as the combustion engine is shut down (for an unknown period) and started again occasionally.

This might lead to situations that correspond to multiple cold start situations during a single driving trip, as the TWC or SCR in diesel hybrids is periodically cooled down during the shutdown period (pure electric drive) of the engine.

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[1] Project report, available at: https://cris.vtt.fi/en/publications/euro-6-diesel-passenger-cars-emissions-field-tests-project-final-

[2] Journal publication, available at: https://www.sciencedirect.com/science/article/pii/S0048969720345009?via%3Dihub

CO_2 emissions from plug-in-hybrid vehicles (PHEVs) are solely dependent on how much of the driving is performed with electricity and how much with the internal combustion engine.

The battery charging rate prior to or between driving trips has a direct effect on CO_2 emissions, as the internal combustion engine is typically only utilized when battery-powered propulsion is insufficient.

If the vehicle’s battery is not regularly charged, it can have a huge effect on CO2 emissions.

Question 1: What are the CO_2 and local emissions of a PHEV during typical home-to-work driving with battery full and battery empty?

Question 2: How do CO_2 and local emissions compare to a Euro 6 step d-TEMP/d diesel car, for example, if the PHEV is not charged regularly?

In addition to passenger car emissions, the current trend for increasing e-commerce means an increase in delivery vehicle traffic in city and suburban areas. These vehicles are mainly delivery vans and light trucks. This raises the question of how significant a factor do emissions from state-of-the-art delivery vans and light trucks comprise for local air quality in suburban areas.

2. Methodology

2.1 Test vehicles and cycles

One Euro 6 d-temp diesel passenger car was selected for the project as a reference. The objective was to compare its performance against gasoline plug-in-hybrid vehicles and against previous models[3] from the same OEM used in the previous project mentioned in the Introduction.

The main emphasis in the project was to investigate PHEVs' on-road CO_2 and pollutant emissions (CO, NO_x, PN) performance in typical yet varying Finnish weather conditions. The primary objective was to select four of the most common PHEVs and investigate their emissions performance over a two-year period during summer and winter conditions. However, it was also accepted that those exact same individual vehicles might not be available during all testing campaigns. Thus, sister models or even other brands were accepted for use in those circumstances. Two of the PHEVs were type-approved to comply with Euro 6 d-temp-evap-isc and two with Euro 6 d-isc regulations. The major difference between those two regulations is the used conformity factor (CF[4]) for NO_x emissions in on-road testing. When the on-road testing was implemented in the Euro 6 regulation, a conformity factor of 2.1 was introduced. In a later phase when the Euro 6 d-isc regulation was introduced, the conformity factor was decreased to 1.43.

In addition to the passenger cars, one van was selected for the investigation of emissions on typical package delivery journeys.

Table 1 shows the main technical information from the tested vehicles. Table 2 shows regulatory NO_x and PN emission limit values that apply to the tested vehicles.

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[3] In the previous project, two models from the same OEM as Car A were tested. Models were certified as Euro 6b. However before and after "Dieselgate", they were models from 2015 and 2017.
[4] Conformity factor = 1 + margin due to measurement uncertainty in the used test equipment

Table 1: Description of vehicles tested in the project.

ID	Type	Emission Class	Engine and EAT	Fuel	Hybrid powertrain	Transmission	Curb mass [kg]
Car A	Wagon	Euro 6d-TEMP	1.6 L diesel DOC+DPF+SCR[5] 85 kW	Diesel	-	6 gear automatic	1385
Car B[6]	Wagon	Euro 6d-ISC	1.4 L SI TWC 115 kW	Gasoline	PHEV – 12 kWh (net) / 13 kWh (gross) battery Electric power: 85 kW System power 160 kW E-motor positioned in front axle	6 gear automatic	1808
Car C[7]	SUV	Euro 6d-ISC	1.6 L SI TWC 147 kW	Gasoline	PHEV – 12.8 kWh (net) / 13.2 kWh (gross) battery Electric power: 164 kW System power 220 kW E-motor positioned in rear axle	8 gear automatic	1947
Car D	Sedan	Euro 6d-TEMP-EVAP-ISC	2.0 L SI TWC 135 kW	Gasoline	PHEV – 11.2 kWh (net) / 12.0 kWh (gross) battery Electric power: 83 kW System power 185 kW E-motor positioned in rear axle	8 gear automatic	1935
Van E	Van	Euro 6d-TEMP-EVAP-ISC	2.0 L diesel DOC+DPF+SCR	Diesel	MHEV 48V – Electric power: 11 kW System power 96 kW	6 gear manual	2275
Car F	SUV	Euro 6d-TEMP-EVAP-ISC	2.0 L SI TWC 223 kW	Gasoline	PHEV – 11.6 kWh (gross) battery Electric power: 65 kW System power 288 kW E-motor positioned in rear axle	8 gear automatic	2169

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[5] Driver is requested to use AdBlue on demand.

[6] Two different individuals were used in the testing, as the same vehicle was not available during every test campaign

[7] Two different individuals were used in the testing, as the same vehicle was not available during every test campaign

Table 2: Regulatory emission limit values for Euro 6 d-temp and Euro 6 d-isc LDVs.

Vehicle	Chassis dynamometer	On-road
Gasoline passenger car (cars B, C, D, F)	Euro 6 d-temp: NO_x: 60 mg/km PN: 6.0×10^{11} #/km Euro 6 d-isc: NO_x: 60 mg/km PN: 6.0×10^{11} #/km	Euro 6 d-temp: NO_x: 126 mg/km PN: 9.0×10^{11} #/km Euro 6 d-isc: NO_x: 86 mg/km PN: 9.0×10^{11} #/km
Diesel passenger car (car A)	Euro 6 d-temp: NO_x: 80 mg/km PN: 6.0×10^{11} #/km Euro 6 d-isc: NO_x: 80 mg/km PN: 6.0×10^{11} #/km	Euro 6 d-temp: NO_x: 168 mg/km PN: 9.0×10^{11} #/km Euro 6 d-isc: NO_x: 114 mg/km PN: 9.0×10^{11} #/km
N1 class III (van E) Euro 6 d-temp	NO_x: 125 mg/km PN: 6.0×10^{11} #/km	NO_x: 263 mg/km PN: 9.0×10^{11} #/km

In November 2022, the European Commission presented a proposal for Euro 7 regulation[8]. The whole content of the proposal is not covered in detail in this report. However, the essential elements of the proposal are summarized below, as the limit values proposed in Euro 7 proposal are discussed in the results section.

The Euro 7 proposal revises the whole vehicle testing methodology by combining both the light- and heavy-duty vehicle regulations into one regulation framework. It also proposes a new testing methodology where on-road testing has the highest emphasis. The proposed on-road testing methodology practically allows a wide spectrum of test routes that are considered valid tests. The proposal also acknowledges third parties (such as research institutes, etc.) to perform in-service conformity testing without direct assignment from the corresponding vehicle OEM. Pollutant emissions-wise, new components are proposed, such as THC, NMHC, PN10, and NH_3 for LDVs, and PN10, NH_3, N_2O, and HCHO for HDVs. Table 3 summarizes the proposal for regulated pollutant emissions.

Emissions limits are divided into two cases: test trips below 10 km and test trips over 10 km. For the first case, there is a fixed budget value in grams and for the latter case a limit value per driven kilometer. This mean that in cases where the test trip is over 10 km, the budget limit value is considered as a starting point and fixed emissions per kilometer are subsequently allowed.

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[8] European Commission proposal for upcoming Euro 7 regulation, https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6495

Table 3: Euro 7 proposal for pollutant emission limit values.

Pollutant emissions	**M_1, N_1 vehicles**	**Only for N_1 vehicles with a power-to-mass ratio of less than 35 kW/t**	**Emissions budget for all trips less than 10 km for M_1, N_1 vehicles**	**Emissions budget for all trips less than 10 km only for N_1 vehicles with a power-to-mass ratio of less than 35 kW/t**
	per km	per km	per trip	per trip
NO_x in mg	60	75	600	750
PM in mg	4.5	4.5	45	45
PN10 in #	6×1011	6×1011	6×1012	6×1012
CO in mg	500	630	5000	6300
THC in mg	100	130	1000	1300
NMHC in mg	68	90	680	900
NH3 in mg	20	20	200	200

2.2 Chassis dynamometer test set-up

In addition to the comprehensive on-road testing, it was decided to include a number of cars in chassis dynamometer testing. The objective was to perform testing both at the start and the end of the project. This would enable us to investigate whether mileage has an effect on emissions. Additionally, the electric range of PHEVs was recorded and compared to the value OEM declared in the CoC (Certificate of Conformity).

Vehicles were tested with their own summer tires. Prior to testing, rolling resistance tests on the chassis dynamometer were performed for each vehicle in order to define the parasitic losses that must be deducted from the total road load. The road load coefficients and test inertia were taken from the tested cars' CoC. Table 4 shows the dynamometer settings for WLTC testing. As shown in Table 1, car A is a diesel passenger car, whereas car B is a PHEV. Both cars were tested according to EC regulation 2017/1151 and its amendments. In short, for car B this mean multiple cycles driven back-to-back as long as the battery was empty following one full cycle with an empty battery. The energy taken from the grid was measured when the empty battery was charged again to full.

Table 4: Dyno settings in the WLTC.

Car	**Inertia [kg]**	**F0**	**F1**	**F2**
Car A	1556	52.3	0.311	0.0308
Car B	1906	12.2	0.092	0.0280

Testing procedures differ between the tested cars, as described earlier. For car A, the testing procedure included cold-start WLTC and for car B it was performed according to the regulation, i.e., the Euro 6 PHEV testing procedure. In total, car B required six WLTCs driven back-to-back before whole test segment was fulfilled, as described in the regulation. The test cell temperature was approximately 22 °C +/- 1 °C and relative humidity varied from 33% to 56% during the chassis dynamometer tests. Consumed electricity was measured from the charged energy from the charging connector.

VTT uses a standard full-flow dilution tunnel and bag sampling for emissions measurement on a light-duty chassis dynamometer. Figure 2 shows a schematic layout of VTT's light-duty vehicle emissions measurement system.

Table 5 below summarizes the instrumentation used for measurements on the light-duty chassis dynamometer.

Table 5: Summary of measurement devices used in the 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/NO_x), IRD (CO), IRD (CO_2 high/low)
Particulate number counter	Airmodus A23
Temperature, pressure, and humidity	Vaisala

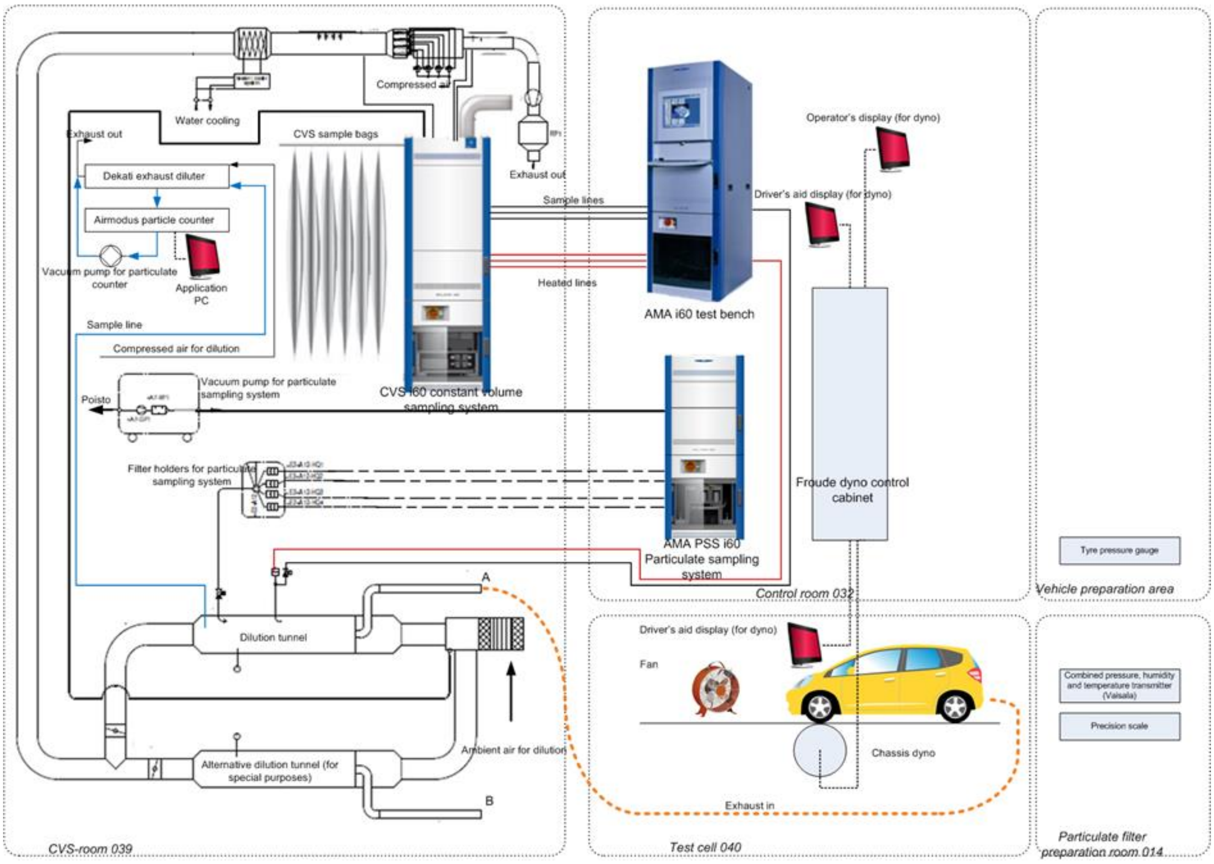

Figure 2: Schematic diagram of VTT's light-duty chassis dynamometer test setup.

2.3 On-road testing

The project's on-road tests were performed twice a year: one campaign in summer and one in winter conditions. Ambient temperature varied between -12 °C … +30 °C. In total, four on-road testing campaigns were performed. Only Car A was tested during all the campaigns. The PHEVs, cars B–D, and car F were tested as many times as the specific car was available. Van E was tested accordingly to the plan only once.

Measurements were performed for the passenger cars on four on-road routes: one route fulfilling the requirements of Euro 6d-TEMP RDE testing (VTT RDE), one representing typical commuting traffic (VTT Commuter), one representing normal city driving in Helsinki (VTT City), and one representing rural and motorway driving (VTT Motorway). In addition, a special route (VTT Delivery) was generated for investigating the emissions of van on a typical delivery route in a suburban area. Figure 3 shows the example of speed profiles of each of the test routes. VTT RDE and VTT Commuter was performed as a cold-start test, whereas VTT City and VTT Highway were tested as warm-start tests. During each test, cars were driven normally following the traffic stream.

PHEVs were tested in the specific drive mode the car adjusts itself to after turning the car on. Typically, this so-called normal mode is hybrid mode. How much battery the car uses as an energy source depends on the manufacturer.

VTT Delivery was tested as a warm-start test. Van E was equipped with start-stop functionality. Testing was performed both with start-stop functionality activated and deactivated.

Table 6 shows the main information on the test routes.

The post-processing of the measurement data was performed according to the RDE 4 package of Euro 6 legislation for the VTT RDE test route. A moving average window method was used for trip validity check and normalization. For other test cycles no data correction or data exclude was applied, i.e., the whole test cycle was considered in the results and only standard humidity corrections for NO_x emissions were applied.

The driving on 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 limit 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 tires to be used from December to Easter. The tires used on car A were of a non-studded “friction” type and on other vehicles a studded type was used.

Standard EN590 diesel and EN228 gasoline were used in the test vehicles during the testing.

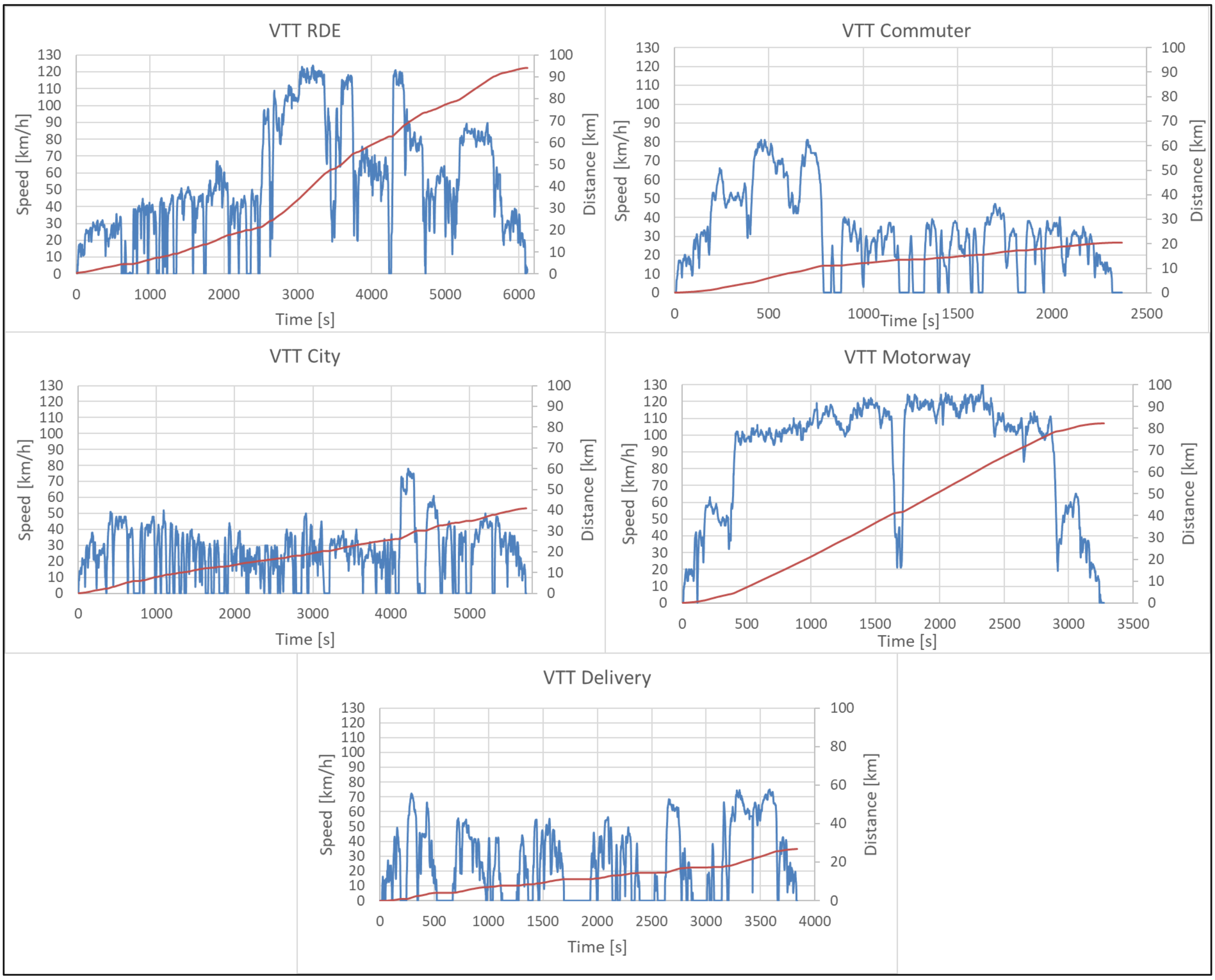

Figure 3: Schematic speed profiles and distances describing the on-road test routes.

Table 6: Description of test routes.

Test route / variable	**VTT RDE**	**VTT Commuter**	**VTT City**	**VTT Motorway**	**VTT Delivery**
Route mileage [km]	85	21	40	82	27
Trip share (urban/rural/highway) [%]	~42/~31/~27	~75/~25/0	~90/~10/~0	~17/~53/~30	~80/~20/0
Share of standstill [%]	~6	~15	~15	~0	~33
Cold/warm start	Cold start	Cold start	Warm start	Warm start	Warm start
Test fuel	EN590 diesel / EN228 gasoline	EN590 diesel / EN228 gasoline	EN590 diesel / EN228 gasoline	EN590 diesel / EN228 gasoline	EN590 diesel / EN228 gasoline
Maximum speed	120 km/h in summer conditions / 100 km/h in winter conditions	80 km/h	80 km/h	120 km/h in summer conditions / 100 km/h in winter conditions	80 km/h

A commercial AVL PEMS device was used in all tests for passenger cars. The PEMS device was either attached to the towing hook with a special mounting bracket, or placed inside the car depending on whether a towing hook was available or not. In Table 7, the main information of the device and an example figure of installation are shown.

The post-processing of the measurement data was performed according to the RDE 3 package of Euro 6 legislation for the RDE route test data. A moving average window method was used for trip validity check and normalization. Test results from other test routes were post-processed without any data extract, i.e. whole test was included.

Table 7: Main information on the AVL PEMS device used for passenger car 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.)

In addition to the AVL PEMS device, an on-board FTIR and PN measurement devices were used in van testing. Measurement devices were installed in the freight space. In Table 8, the main information on the device and an example figure of installation are shown.

Table 8: Main information of the onboard FTIR and PN measurement devices used in van testing.

Device	Information
A&D BOB-1000FT	CO, CO_2, NO, NO_2 emissions
Airmodus A23 + Dekati DEED	PN emissions
AVL MOVE EFM 2.5”	Exhaust gas mass flow
GPS (Suchy Data Systems xProGPS_nano)	Longitude, altitude, speed, and acceleration
Weather station	Ambient temperature, pressure, and relative humidity
OBD logger (integrated in FTIR device)	OBD information (engine speed, engine load, cooling water temp., etc.)

2.4 Continuous monitoring of NO_x concentration

Car A was equipped with an NO_x concentration monitoring device. One sensor was installed before the SCR system and one after the SCR system. The installed monitoring system contains the following equipment:

- GPS for determination of location, speed, and mileage
- NO_x sensor for determination of pre-EAT and tailpipe NO_x concentrations
- 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 concentrations before the sensor reaches the light-off temperature are not seen, such as vehicle cold-start concentrations and some short missions. This leads to the fact that some of the data is not stored. However, as the objective in continuous monitoring is to evaluate performance over a long duration, day-to-day performance during changing weather conditions is the most valuable data.

3. Results and discussion

In this section, project testing results are presented. First, the chassis dynamometer test results are presented, followed by on-road testing results starting with trip average results. They are presented as tests started with a full and an empty battery. After average test results, cumulative test results are presented individually for each tested car. The continuous NO_x concentration monitoring test results for car A are presented last. A discussion of results is presented after each section.

3.1 Chassis dynamometer results

Dynamometer testing was performed for cars A and B. The original target was to perform project start and end tests for both cars. However, car B was no longer available toward the end of the project. Thus, start and end tests were only possible with car A. Figure 4 presents the chassis dynamometer test results. The target in chassis dynamometer tests was to obtain possible emission level increases due to mileage accumulated during the project. However, as the COVID-19 pandemic reduced traveling, the accumulated mileage was clearly lower than anticipated at the project start. In total, 28,500 km were accumulated between the start and end of the chassis dynamometer testing project. This corresponds to roughly half of the anticipated mileage.

Car B was tested according to the Euro 6 PHEV testing procedure. This mean test starts with a full battery and charge is depleted until the battery is empty. After that, one full test cycle is driven starting with an empty battery. The weighted average result is calculated based on the pure electrical and ICE mileages.

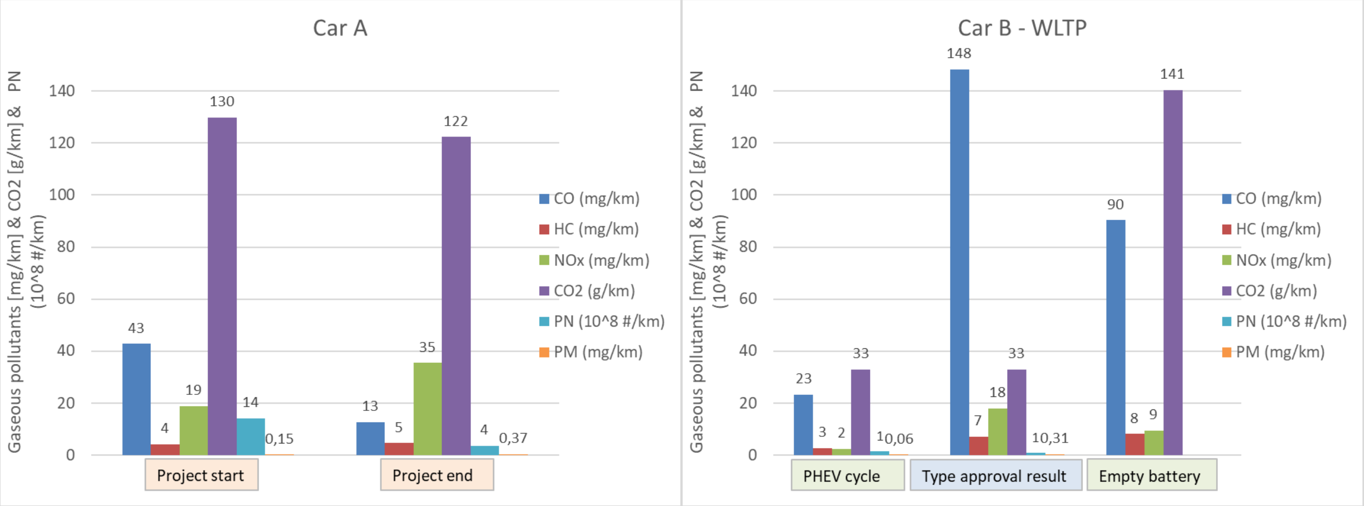

Figure 4: Test results from chassis dynamometer for cars A and B on a WLTP test cycle.

3.1.1 Discussion

Car A was tested at both project start and project end. Figure 4 presents the results on the left side of the chart. In general, the results do not suggest significant changes in the car emission behavior. CO_2 and CO emissions were actually at a lower level in the project end tests compared to the start tests, and NO_x emissions were almost double at project end compared to the start tests. This result matches the typical diesel engine efficiency-NO_x emissions trade-off, i.e., the lower the fuel consumption, the higher the NO_x emissions. However, as the car is equipped with a high efficiency SCR system, it is not possible to exclude that the reason for higher NO_x emissions could be related to SCR functionality. PN and PM emissions behavior goes in the opposite direction between the project start and end tests. This result is also typical of the trend in diesel engines' PN and PM emissions, i.e., lower PN emissions may be connected to higher PM emissions. However, as the car is equipped with a DPF, the result may also be connected to its functionality. Overall, results were well below the Euro 6 limit values in both testing events. NO_x emissions were less than 50%, PN emissions less than 25%, and PM emissions less than 8% of the regulated emission limits.

Car B was only tested at project start, as explained in the previous chapter. The right-hand chart in Figure 4 shows car B type approval values declared by the OEM, and tested values in the “PHEV cycle” columns. In addition, test results with an empty battery are shown. The results show that emissions from the PHEV cycle are rather close to the OEM declared values. In particular, CO_2 emissions are practically the same. Pollutant emissions are at such a low level that small changes in absolute levels result in high relative differences. The test cycle that started with an empty battery resulted in clearly higher CO_2 emissions, corresponding to around 6.0 L/100 km in fuel consumption. However, pollutant emissions were at the same level as in the PHEV test cycle, which suggests that the exhaust aftertreatment system in car B is working rather well, as a higher amount of burned fuel did not result in an increase in pollutant emissions.

3.2 On-road testing results

The following chapter presents the results of CO_2, NO_x, and PN emissions in on-road testing. As explained earlier, cars were tested based on their availability. This means that some of the cars were tested multiple times in different ambient conditions and some only once or twice, as they were no longer available for rent. PHEV testing was done both with an empty and a full battery. The van was tested on RDE and Motorway routes, in addition to the Delivery route. It was also tested with a different PEMS device than LDVs. The PEMS device was based on FTIR technology, which also allowed N_2O emissions to be measured.

3.2.1 Trip average results

Figure 5 to Figure 7 show the trip average CO_2, NO_x, and PN emissions for each vehicle individually. For PHEVs, tests conducted with the different battery states are marked with blue and dashed circles. In Figure 6, Euro 6 legislation limit values for NO_x emissions in on-road and chassis dynamometer testing are marked with a red dashed line.

RDE ROUTE 94 KM - CO2 EMISSIONS

COMMUTER ROUTE 21 KM - CO2 EMISSIONS

MOTORWAY ROUTE 83 KM - CO2 EMISSIONS

CITY ROUTE 41 KM - CO2 EMISSIONS

DELIVERY ROUTE 27 KM - CO2 EMISSIONS

Figure 5: Trip average CO_2 emissions on test routes.

Figure 6: Trip average NO$_x$ emissions on test routes.

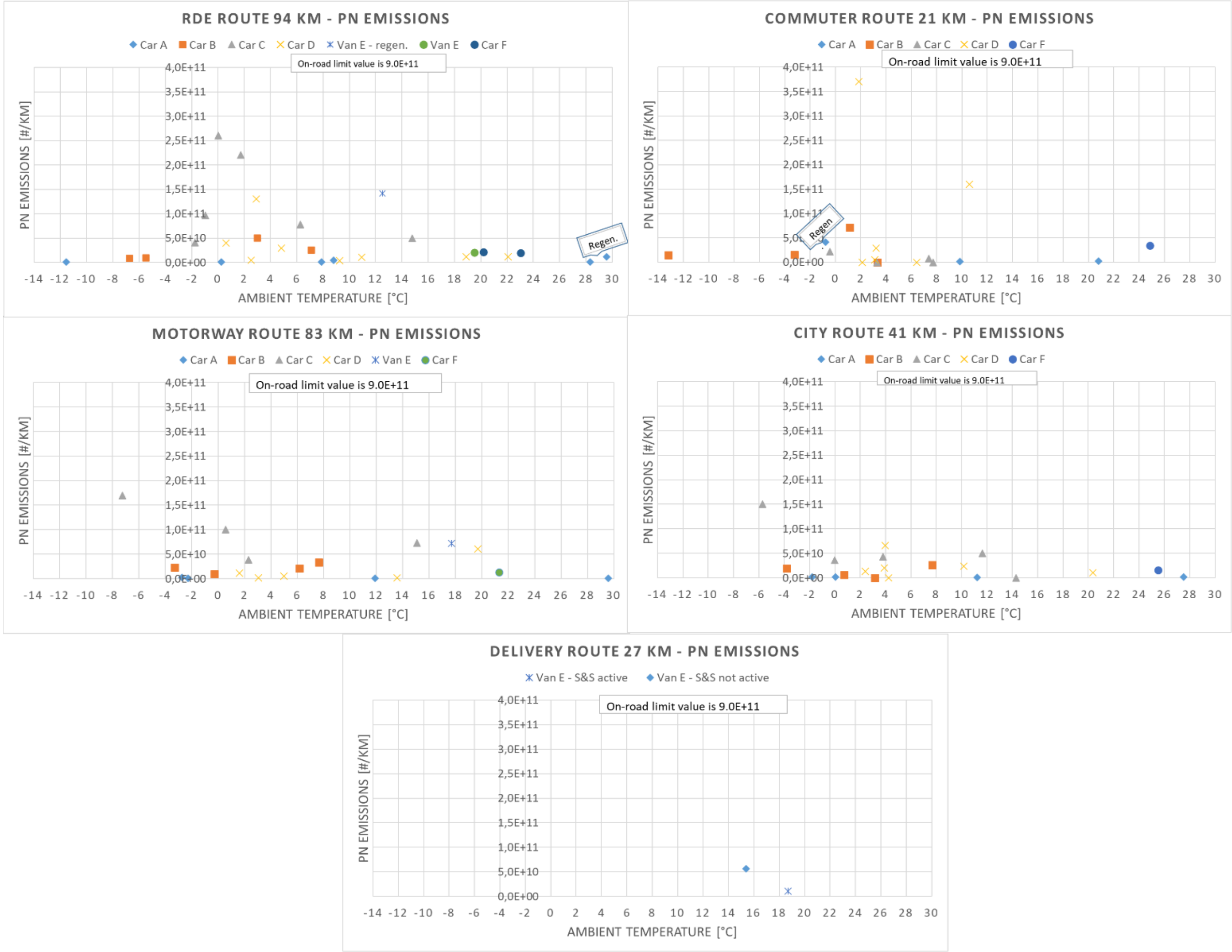

Figure 7: Trip average PN emissions on test routes.

3.2.1.1 Discussion on trip average results

In general, the results in Figure 5 toFigure 7 show the following two main findings. Firstly, if driving starts with a full battery, PHEVs can effectively reduce CO_2 emissions in daily mileages under 50 km, or whatever the maximum electrical range is with the specific vehicle. Conversely, if used with an empty battery they result in high CO_2 emissions. On short trips, like City and Commuter routes, when the trip is started with a full battery, CO_2 emissions are close to zero and in worst cases less than 25 mg/km. However, when the same trips are driven starting with an empty battery, CO_2 emissions are in the best case (car B and C in City) close to those of diesel car A and mostly above.

The second main observation is the low pollutant emissions with all tested cars. With PHEVs this is true even independently of test route or ambient temperature. Emissions are well below the limit values, even in temperatures down to -13 °C. NO_x emissions of tested PHEVs were mostly below 0.01 g/km and even the highest emissions (car D on RDE route) were 0.032 g/km. These correspond to a conformity factor (CF) of below 0.17 to 0.53. The NO_x emissions of diesel car A were also in general at a low level, ranging from 0.0016 to 0.092 g/km depending on the test route and ambient temperature. These correspond to CF values of between 0.02 and 1.53. Diesel car A conducted regeneration three times during the testing. During the regeneration event on the Commuter route, car A emitted NO_x emissions of 0.25 mg/km, which are well above the on-road limit value of 0.168 g/km. During the other two regeneration events on the RDE route, NO_x emissions were below the on-road limit value. Ambient temperature seems to have a rather significant effect on car A NO_x emissions on cold-start Commuter and RDE routes. On both routes, a clear increasing trend of NO_x emissions can be seen as temperature decreases.

Between 2018 and 2019 VTT, together with its partners, conducted a project related to Euro 6 diesel passenger cars field tests[9]. In this project, the same RDE, City, and Motorway routes were used. In addition, two of the diesel cars were earlier Euro 6 models (Euro 6b, pre and post 2017 MY) of car A. Thus, those were not type-approved as RDE compliant cars. The results showed that the older car produced NO_x emissions of between 0.268 and 0.417 g/km. The corresponding NO_x emissions for the newer car were found to be between 0.111 and 0.258 g/km, depending on route and ambient conditions. The results of car A show that there has been quite a development in emissions reduction from the previous model to the tested model. On average, car A produced NO_x emissions of less than half of the previous model.

Furthermore, the results indicate that a decreasing ambient temperature has a somewhat different effect on the tested PHEVs. For car C, ambient temperature seems to have the most effect on CO_2 emissions. This can especially be seen on Commuter and City routes when the test was started with an empty battery. Results also show that cold ambient temperature reduces full electric range. This can be seen with cars C and D on City and RDE routes.

Because the electric powertrain increases the weight of the PHEV, it is anticipated that the energy consumption and thus CO_2 emissions increase, especially in city-type driving conditions. However, as the electric powertrain should also be capable of regenerating kinetic energy during deceleration and braking, this should act as a countermeasure for reducing energy consumption and thus CO_2 emissions. In the case of cars B and C, City and RDE routes might suggest that kinetic energy regeneration reduces fuel consumption as the trip results are close to car A, which weighs over 400 kg less than car B and over 500 kg less than car C. On the Motorway route, which consists of very few decelerations, the difference in CO_2 emissions between cars B and C compared to car A are significantly higher.

All test vehicles resulted in very low PN emissions. The PHEVs resulted in PN emissions mostly below 1×10^{11} particulates/km or even in the range of 1×10^{10} particulates/km, as was seen for car B on the RDE route with an empty battery at temperatures of -7 °C. These correspond to a CF value of between 0.017 and 0.17. The diesel car (car A), which was equipped with a DPF, resulted in even lower PN emissions. For this model, the PN emissions ranged between 8×10^{8} to 2.1×10^{9} particulates/km depending on the route. These correspond to CF values of between 0.001 and 0.004. Even though DPF regeneration events on RDE and Commuter routes were found to increase NO_x emissions, a similar increase in PN emissions was not noted.

Van E was tested on a route representing delivery-type driving in a suburban area. Cyclical driving at low speeds, with multiple stops and idling periods are known to be challenging for diesel vehicles' SCR systems. On the Delivery route, van E was tested with start-stop functionality active and inactive. Results show that this had practically no effect on CO_2 or NO_x emissions. On the Delivery route NO_x emissions were around 0.05 g/km and thus well below the on-road limit value of 0.263 g/km. Compared to the type approval limit value of 0.125 g/km, the results are also clearly lower and correspond to the CF value of 0.4. Interestingly, on the RDE route van E produced between 156 and 175 g/km of CO_2, which is close to the results of cars D and F. This can be explained by the high curb weight of cars D and F, which is close to the curb weight of van E and the high efficiency diesel engine. In addition to CO_2 emissions, N_2O is an extremely powerful greenhouse gas as its GHG factor is around 300 times higher than CO_2. Van E resulted in N_2O emissions that are equivalent to 7 and 10 g/km CO_2 emissions. Van E also resulted in low PN emissions, which ranged between 1×10^{10} and 1.4×10^{11} particulates/km. These correspond to a CF value of between 0.017 and 0.23.

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[9] Euro 6 Diesel Passenger Cars' Emissions Field Tests: https://cris.vtt.fi/en/publications/euro-6-diesel-passenger-cars-emissions-field-tests-project-final-

3.2.2 Fully charged battery energy consumption

Energy consumption was analyzed for each of the PEHVs on those test routes where the test was started with a fully charged battery. Figure 8 shows the total, charged, and fuel energy consumption. Only the charged electric energy consumption was analyzed as there was no possibility for on-board continuous power analysis.

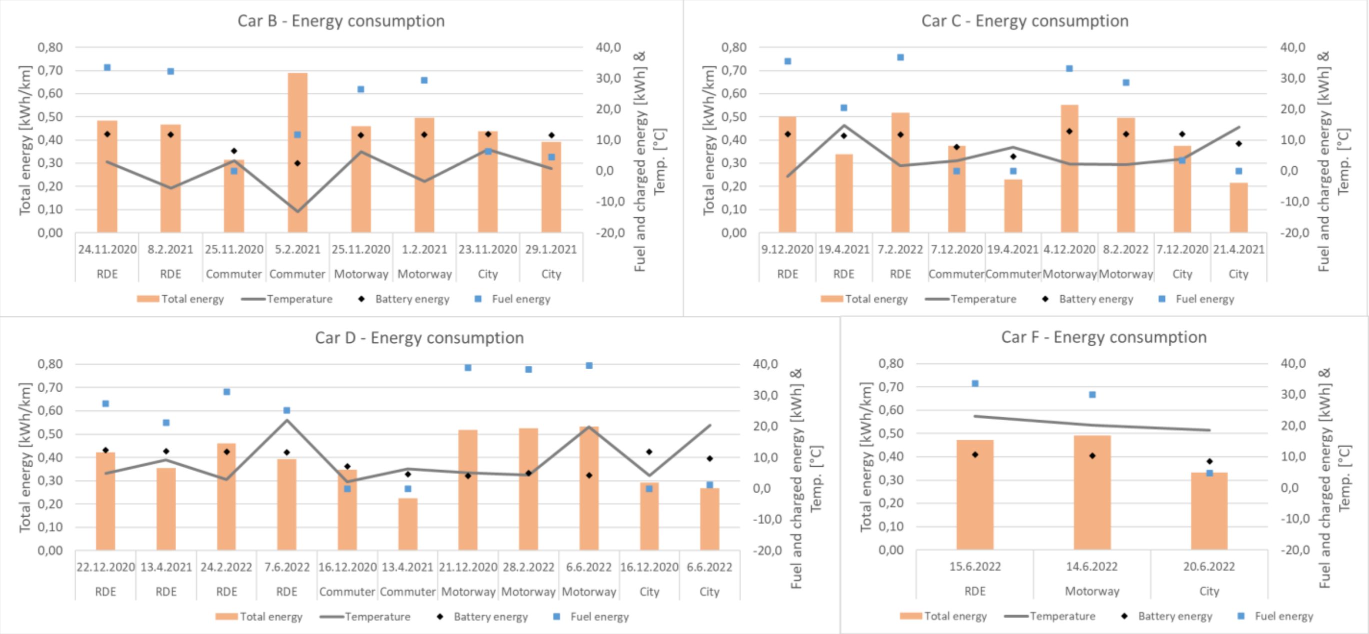

Figure 8: Energy consumption when test started with a fully charged battery.

3.2.2.1 Discussion on charged energy consumption

The effect of ambient temperature on energy consumption can be clearly seen in Figure 8. The same result can be seen with all tested PHEVs. When the temperature decreases below approximately 5 °C, this increases energy consumption remarkably. Cars C and D were tested multiple times and this trend can be seen in the City, Commuter and RDE results. As the City route was tested as a warm start, i.e., ICE warm, the results suggest that the increase in energy consumption is due to greatly increased electric consumption. This leads to shorter pure electric distance and eventually increased ICE usage. The results also show some differences in how energy management is handled with the tested PHEVs. On the Motorway route, car D consumed around 4 to 5 kWh of charged battery energy, whereas the other three PHEVs consumed around 10 to 12 kWh. Thus, for some reason car D is not utilizing battery energy in Motorway conditions as much as the others. This leads to higher energy consumption due to increased fuel consumption compared to others. This can also be seen from the trip average CO_2 emissions in Figure 5. The high curb weight of car F increases energy consumption, as can be seen especially from the City route when compared to the results of cars C and D during tests conducted at temperatures of above 10 °C. Energy consumption is around 22% higher compared to car D, and around 50% higher compared to car C.

3.2.3 Cumulative results

In this chapter, cumulative test results are presented. NO_x emissions in Figure 9 toFigure 18 are presented as distance-based (instantaneous cumulative emission divided by the driven distance) and as cumulative emissions. PN and CO_2 emissions in Figure 19 toFigure 30 are presented as distance-based emissions.

The distance-based NO_x emission limits corresponding to the Euro 6 regulation (Euro 6 d-temp/Euro 6 d-isc) are presented in the figures both as type approval (short, dashed line) and on-road (long dashed line) values. Van E is type-approved as an N1 class 3 vehicle and thus corresponding regulation limit values are presented in the diagram.

The Euro 7 limits proposed by the European Commission are presented in the cumulative NO_x figures in the form of dashed boxes and lines. The proposed regulation presents different limit values for passenger cars and light commercial vehicles in the form of van E. This is noted in the figures.

3.2.3.1 Cumulative NO_x emissions

Regeneration events indicated in Figure 5 those took place with car A and van E can be seen in the figures but are not specifically marked in those figures.

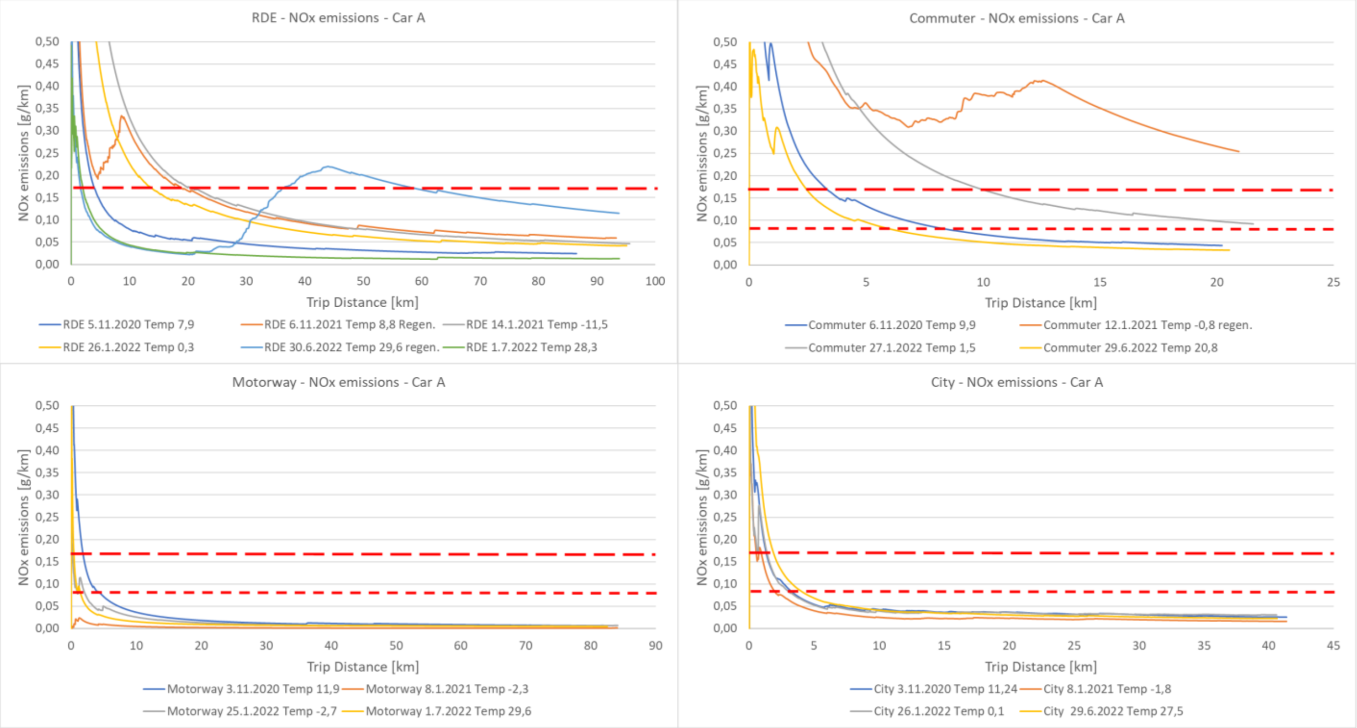

Figure 9: Car A distance-based NO_x emissions.

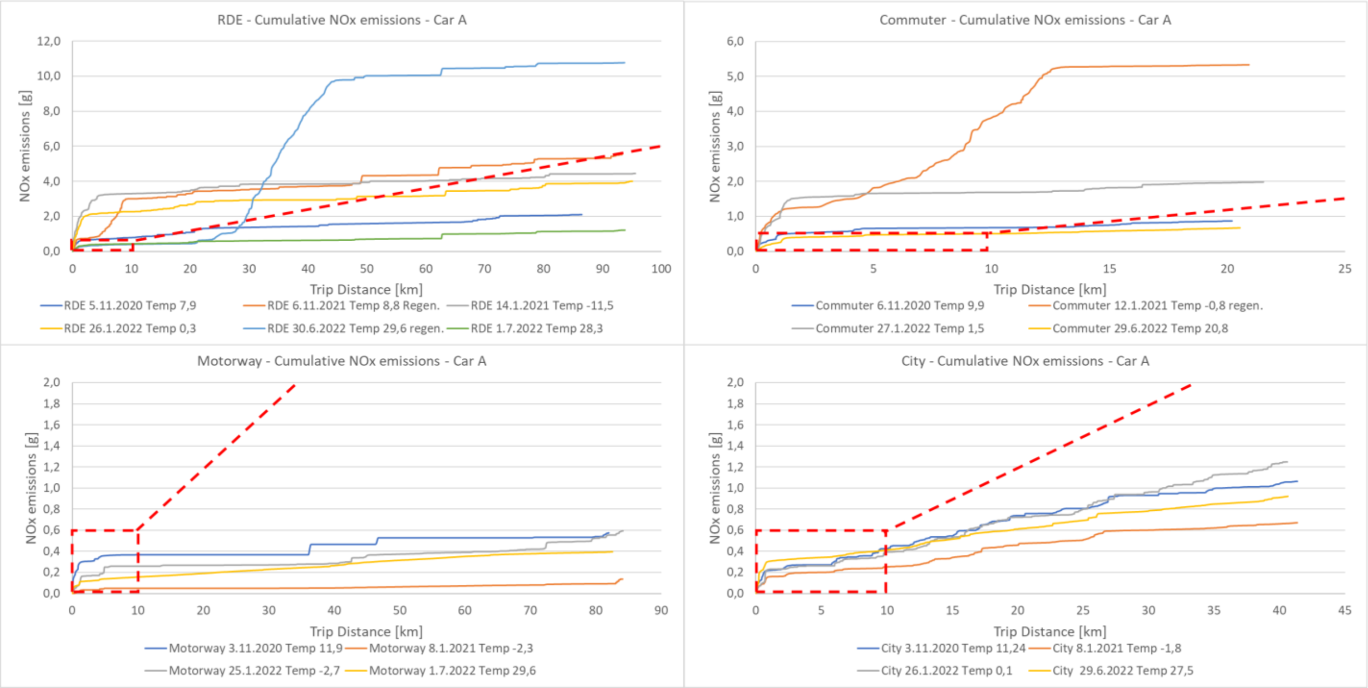

Figure 10: Car A cumulative NO_x emissions.

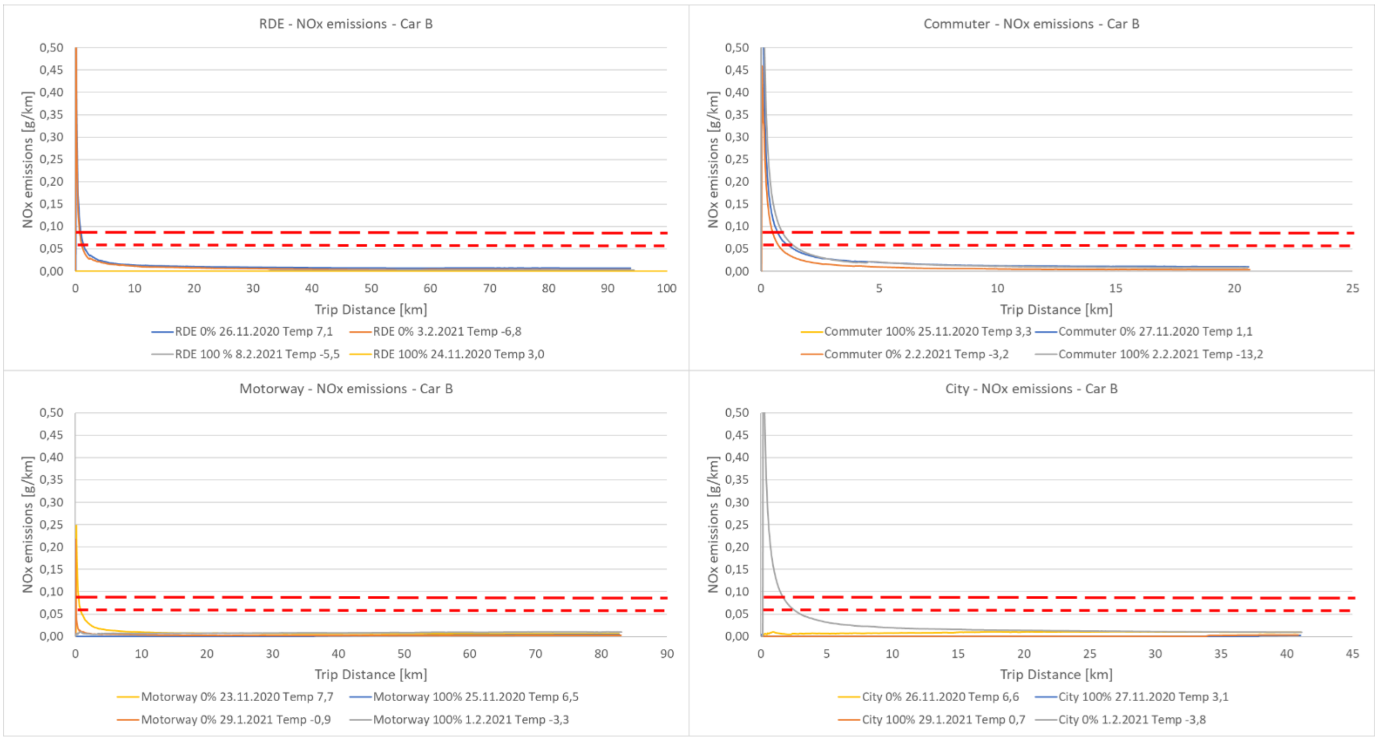

Figure 11: Car B distance-based NO_x emissions.

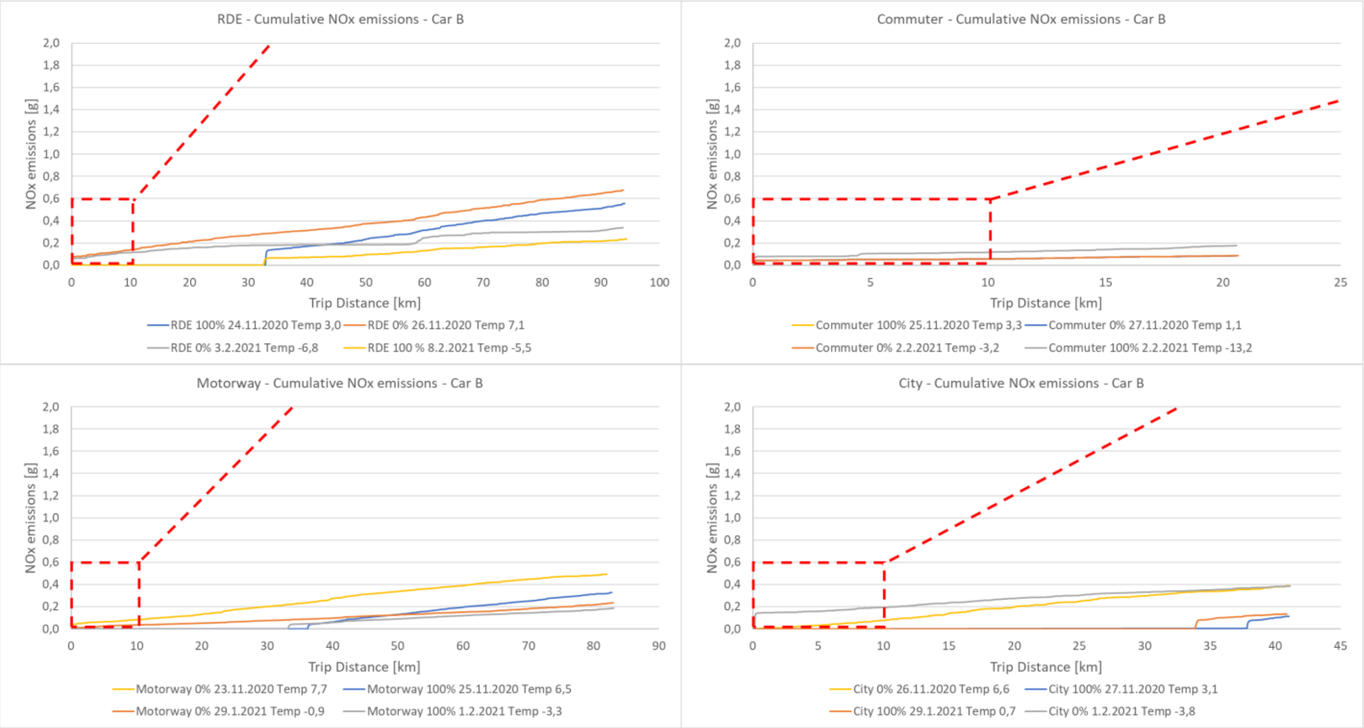

Figure 12: Car B cumulative NO_x emissions.

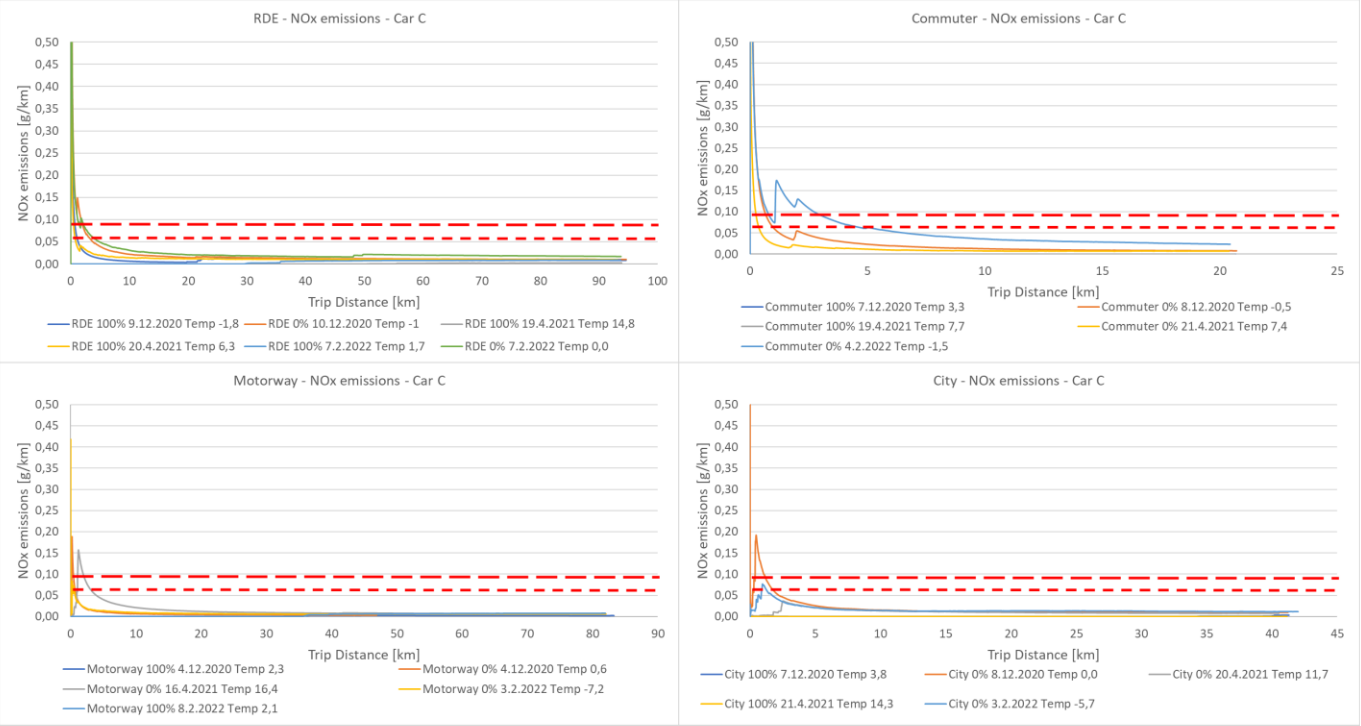

Figure 13: Car C distance-based NO_x emissions.

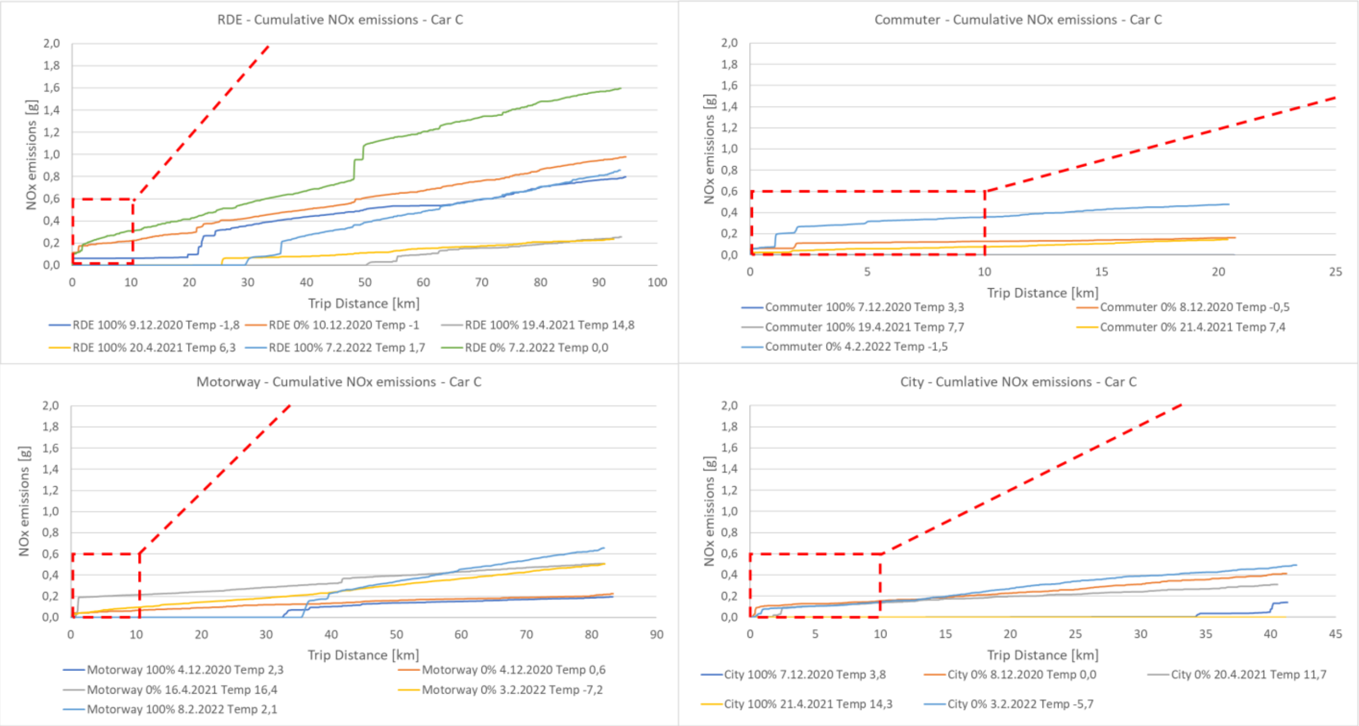

Figure 14: Car C cumulative NO_x emissions.

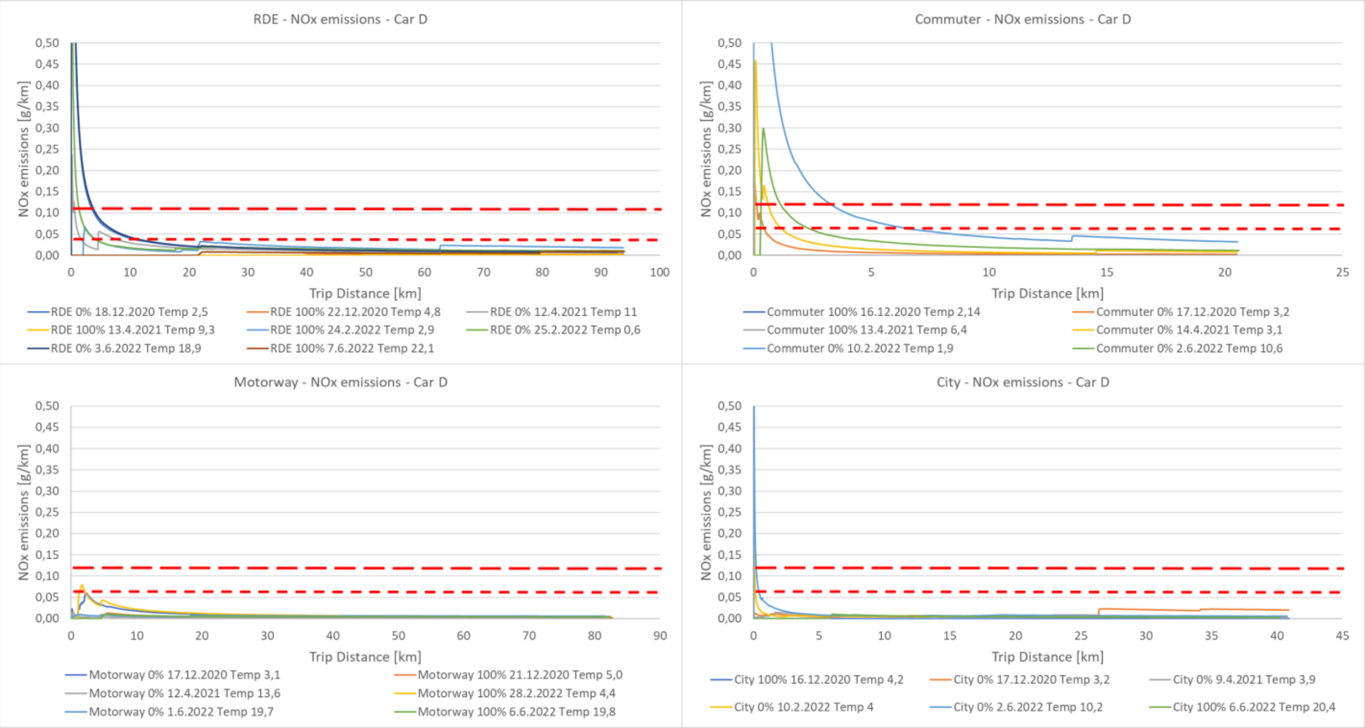

Figure 15: Car D distance-based NO_x emissions.

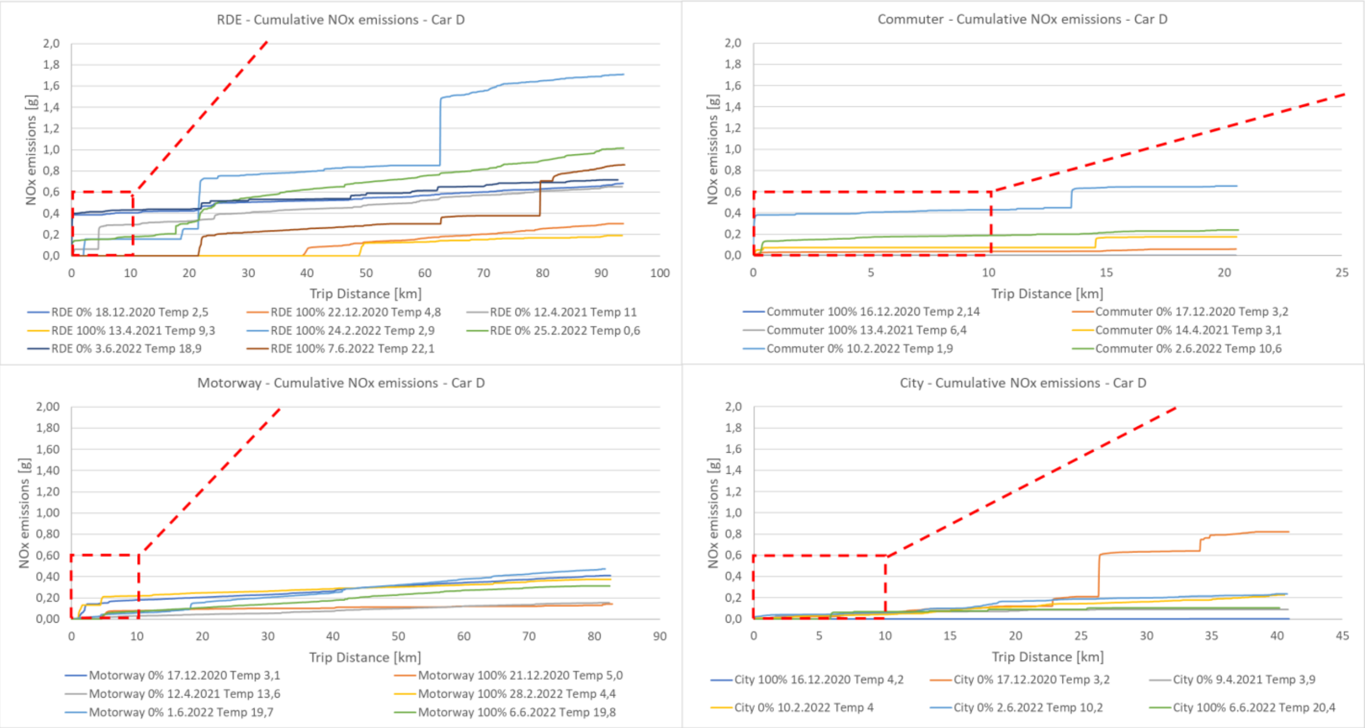

Figure 16: Car D cumulative NO_x emissions.

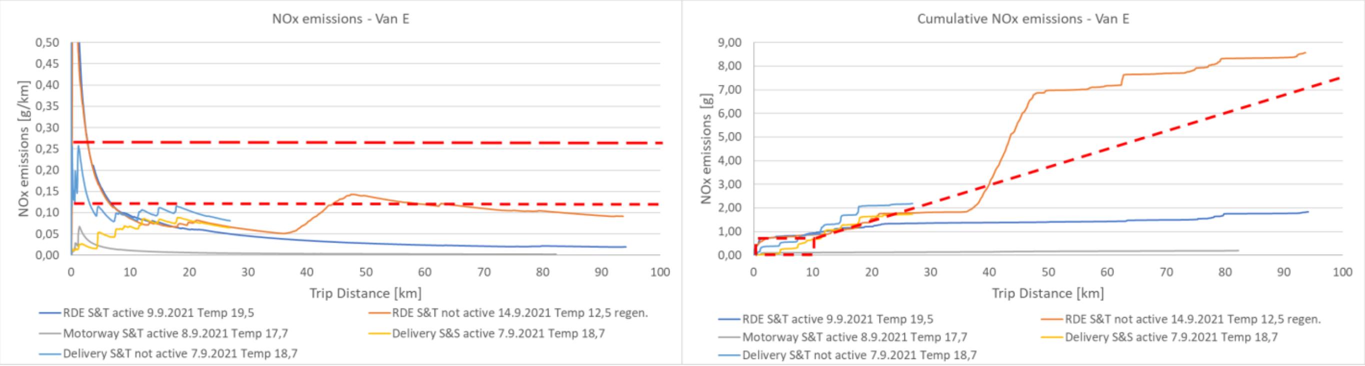

Figure 17: Van E distance-based and cumulative NO_x emissions.

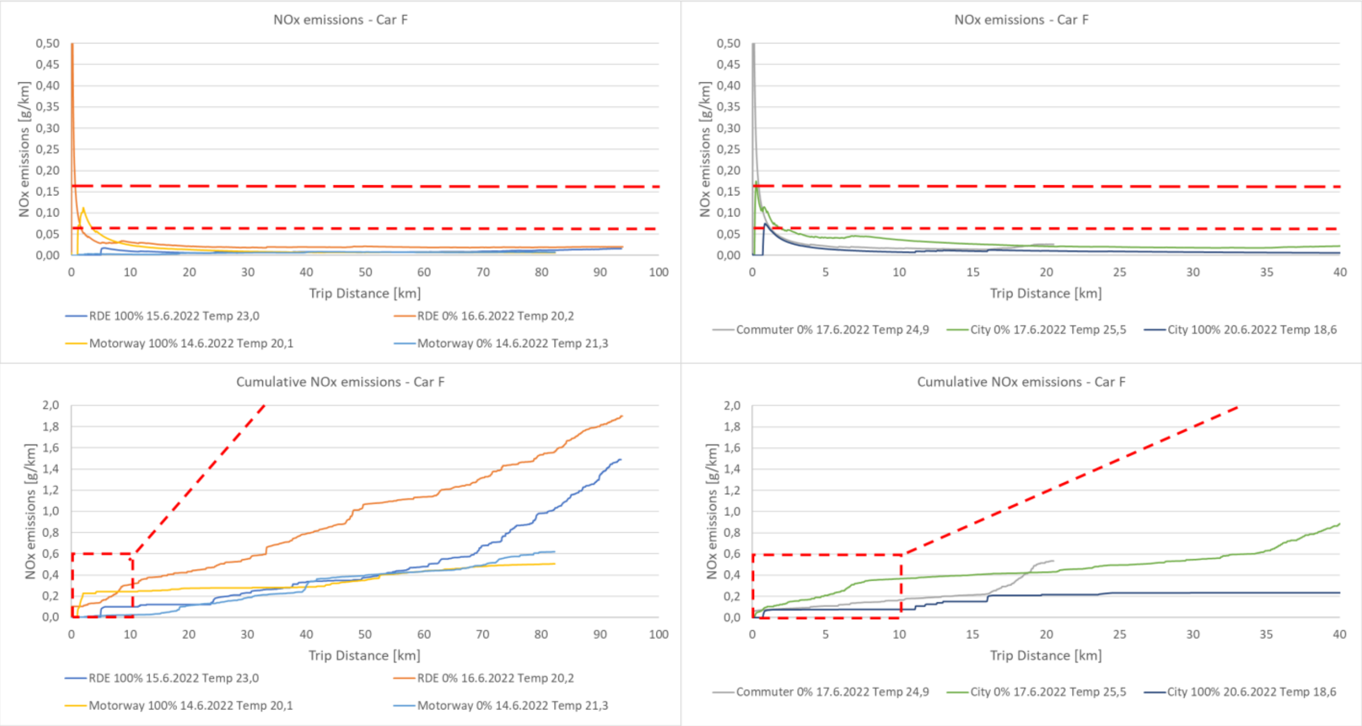

Figure 18: Car F distance-based and cumulative NO$_x$ emissions.

3.2.3.1.1 Discussion on NO$_x$ emissions

Car A

The results for diesel car A in Figure 9 and Figure 10 indicate two major findings. Firstly, it takes 2 to 20 km to meet the cumulative emissions in (g/km) the Euro 6 regulation on-road limit value, depending on ambient temperature. Eventually, NO$_x$ emissions are well below the legislative on-road limit value and in most cases even below the type-approval limit value. Secondly, and quite surprisingly, NO$_x$ emissions are at a low level on City route, which represents typical urban driving. This is also partly explained by the test start with the warmed-up engine. However, on the cold-start Commuter route, cumulative NO$_x$ emissions per kilometer are also eventually decreased to a low level, but the reduction takes roughly twice as far compared to the City route due to high emissions at the beginning of the trip. Under Motorway conditions, NO$_x$ emissions decreased rapidly to a low level, and at the end of the test they are less than 1 mg/km.

The results show that when DPF regeneration takes place (e.g., in RDE and Commuter tests), NO$_x$ emissions increase significantly at the time of regeneration and thus are produce remarkably high NO$_x$ emissions locally.

The cumulative results in Figure 10 show that cold-start trips are challenging for the tested diesel car. The red rectangles represent the proposed Euro 7 NO$_x$ emission budget for trips of less than 10 kilometers, and the dashed red line represents the limit value in tests longer than 10 km. On Commuter and RDE trips, cumulative NO$_x$ emissions rapidly increase well above the budget when tested in temperatures close to 0 °C or below 0 °C. After the SCR system reached the light-off temperature, cumulative NO$_x$ emissions increase by less than one third over the total emissions. This result was found in most of the tests, i.e., in NO$_x$ emissions that are within the proposed Euro 7 limits. In the warm-start test on Motorway and City routes, cumulative NO$_x$ emissions are well within the proposed Euro 7 emission budget and the proposed limit value after 10 km of testing. Furthermore, the results clearly show the rapid increase in emissions during the regeneration events that take place during the RDE and Commuter trips. Finally, it should be noted when compared to Euro 7 proposed limit values that the tested car A was compliant with Euro 6 d-temp regulation.

PHEVs

The cumulative NO_x emissions (expressed in g/km and g) recorded for all PHEVs support the findings in trip average NO_x emissions results in Figure 6. After the initial NO_x emissions peak during the test start, they decrease rapidly to a low level, resulting in low total trip emissions. Traction changes from pure electric to ICE can be seen as peaks in NO_x emissions with all tested PHEVs. However, with cars B and F, the peaks are rather low. Car D shows the highest peaks in NO_x emissions during RDE testing at temperatures of around 3.0 °C. Overall, the NO_x peaks are lower than previously expected. It seems that the three-way catalyst systems used in tested PHEVs heat up rapidly after engine start-ups, and thus reduce NO_x emissions effectively.

All tested PHEVs clearly satisfy the proposed Euro 7 regulation limits.

Van E

Cumulative emissions shown in Figure 17 for van E support the trip average results presented earlier. NO_x emissions decreased rapidly below the Euro 6 limit value in all tested trips. The effect of start and stop (S&S) system can be clearly seen in the results. With a deactivated S&S system, a greater increase in NO_x emissions is seen during acceleration (after periods of standstill). This is suspected to be a result of a cooler SCR system, as longer idling periods decrease exhaust gas temperature, and therefore the SCR temperature when the vehicle is standing still. Van E NO_x emissions are almost within the proposed Euro 7 budget at distances of 10 km, and after that emissions were satisfying the proposed limit value on Delivery (S&S active), RDE (S&S active) and Motorway routes. The regeneration event on the RDE (S&S inactive) route increased NO_x emissions; however, these were still below the limits of the current Euro 6 regulation.

3.2.3.2 Cumulative PN emissions

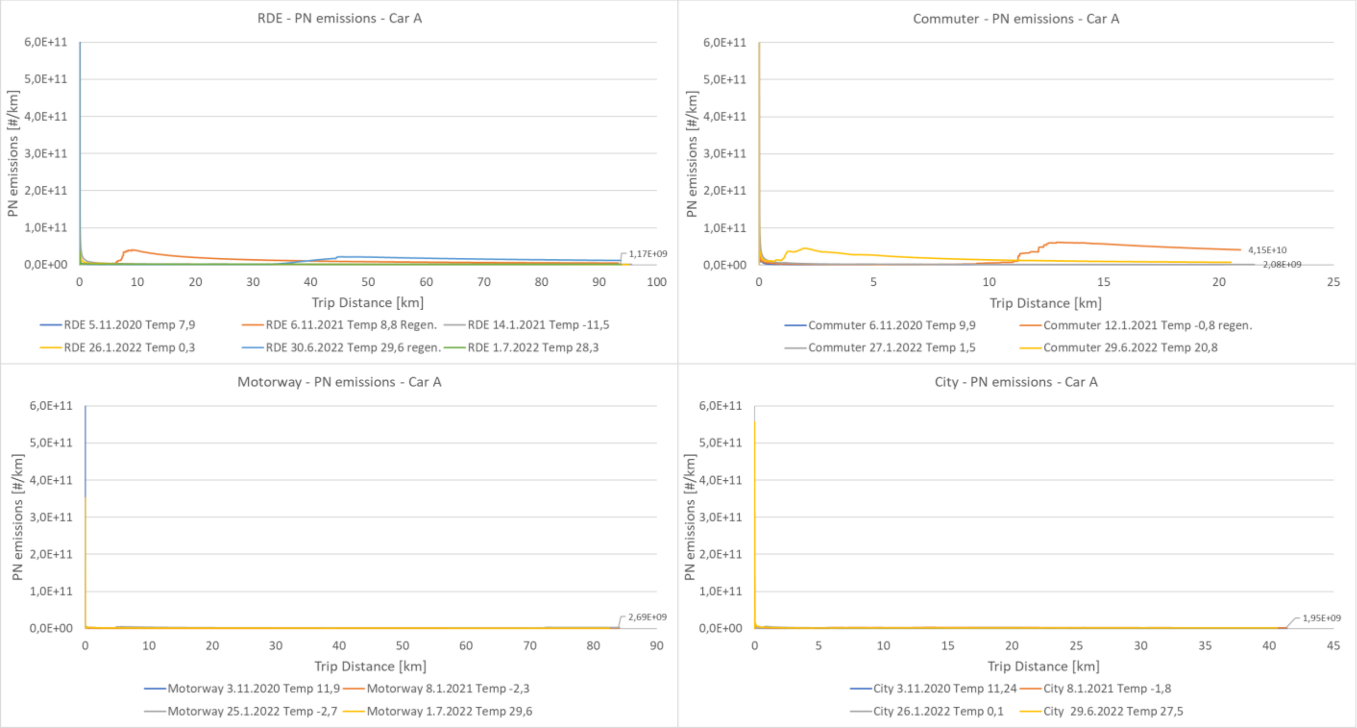

Figure 19: Car A distance-based PN emissions.

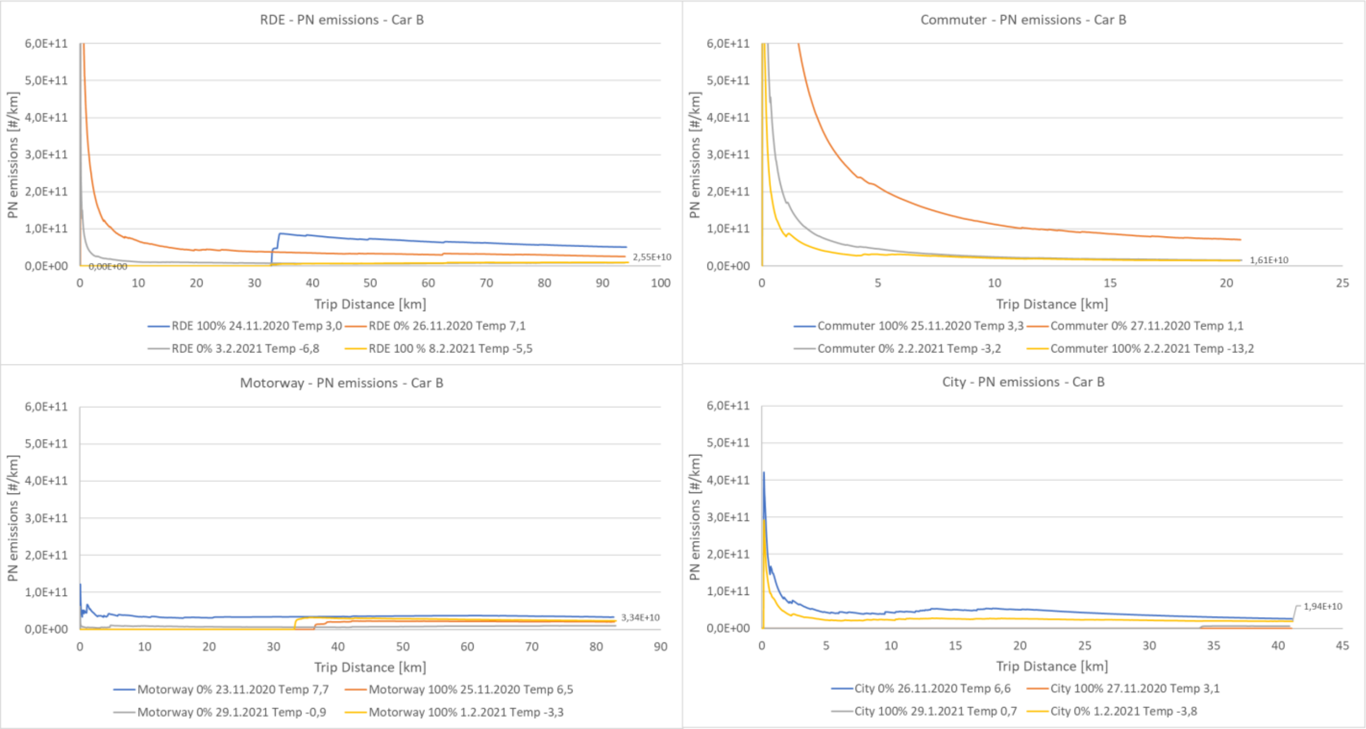

Figure 20: Car B distance-based PN emissions.

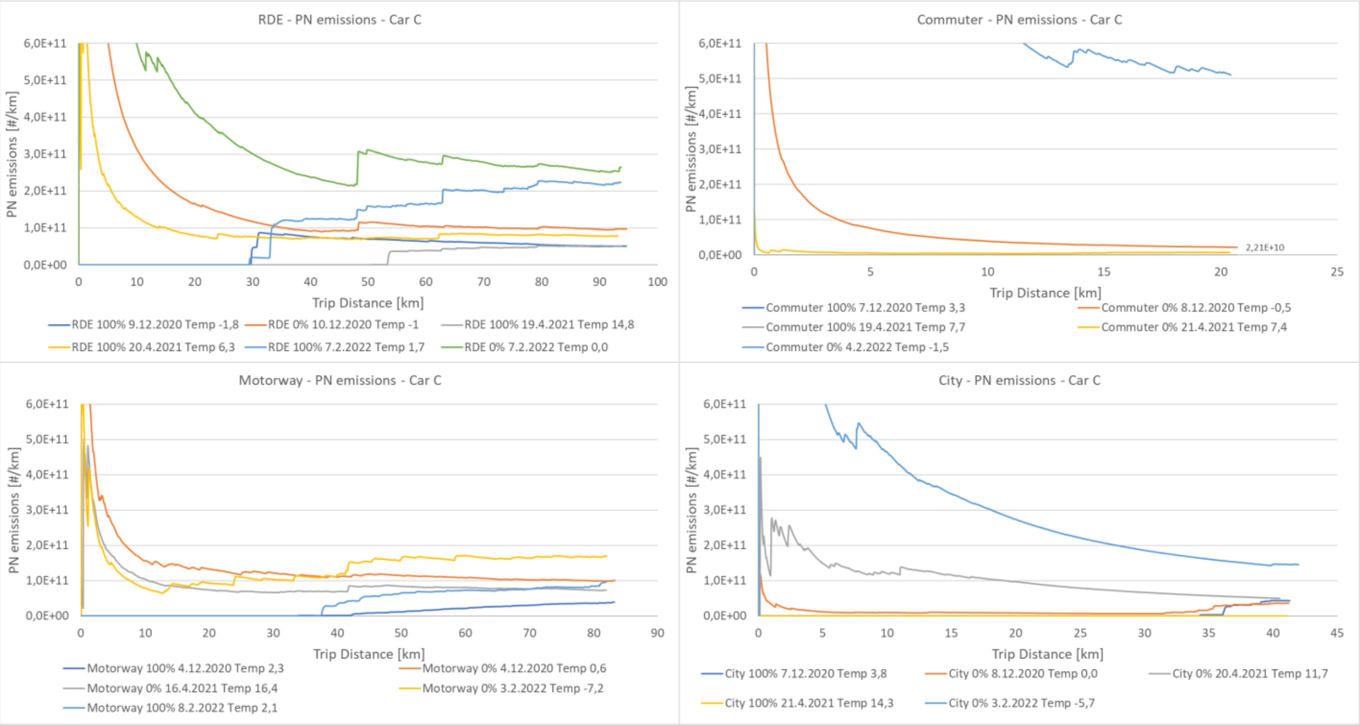

Figure 21: Car C distance-based PN emissions.

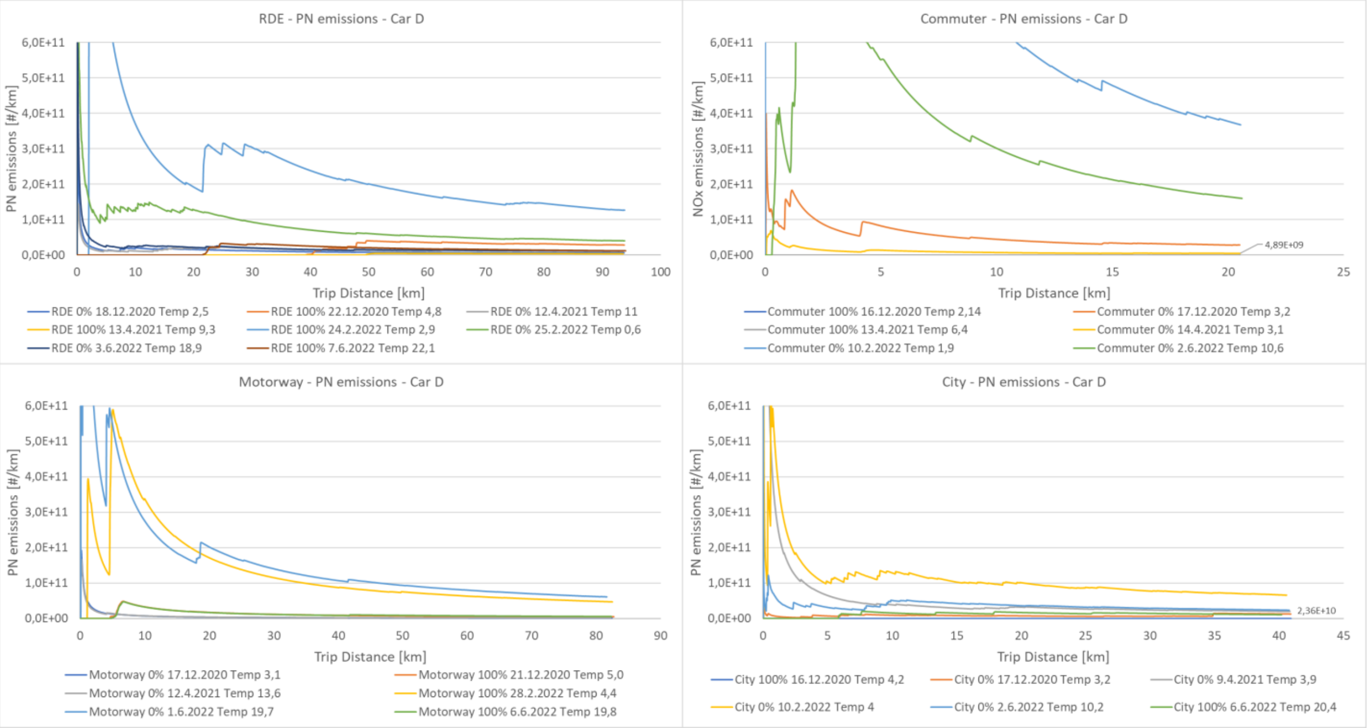

Figure 22: Car D distance-based PN emissions.

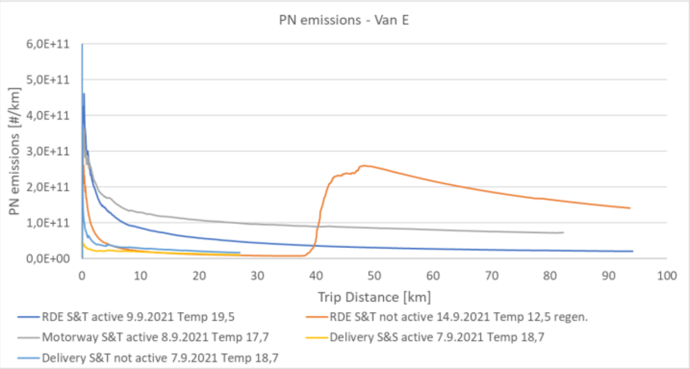

Figure 23: Van E distance-based PN emissions.

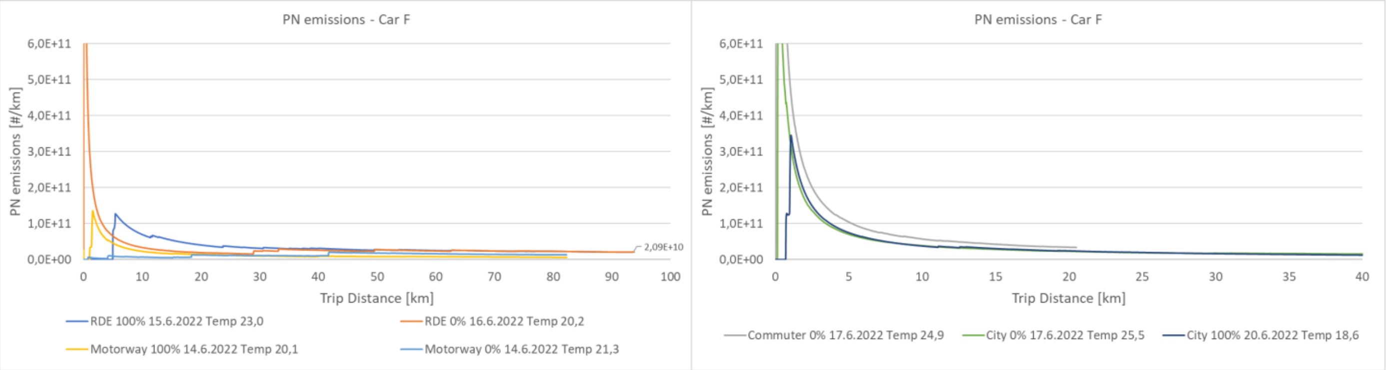

Figure 24: Car F distance-based PN emissions.

3.2.3.2.1 Discussion on cumulative PN emissions

Trip average results presented earlier showed that PN emission were low for all test vehicles. The cumulative results highlight this finding. Cold ambient temperatures did not affect the PN emissions of cars A and B. However, cars C and D showed elevated PN emissions in cold start tests (Commuter and RDE) at low ambient temperatures. However, all results were below the Euro 6 limit values. The change from pure electric propulsion to ICE-powered propulsion seems not to have a significant effect on PN emissions.

3.2.3.3 Cumulative CO_2 emissions

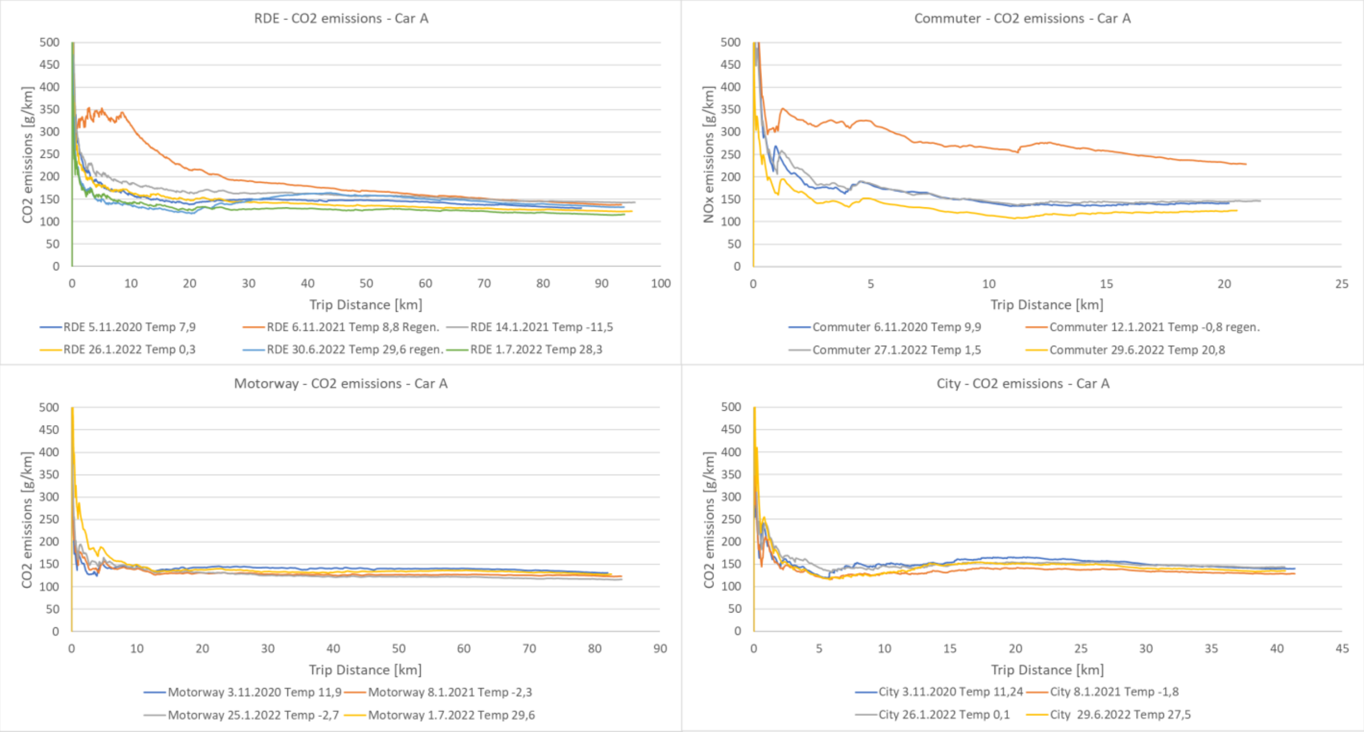

Figure 25: Car A distance-based CO_2 emissions.

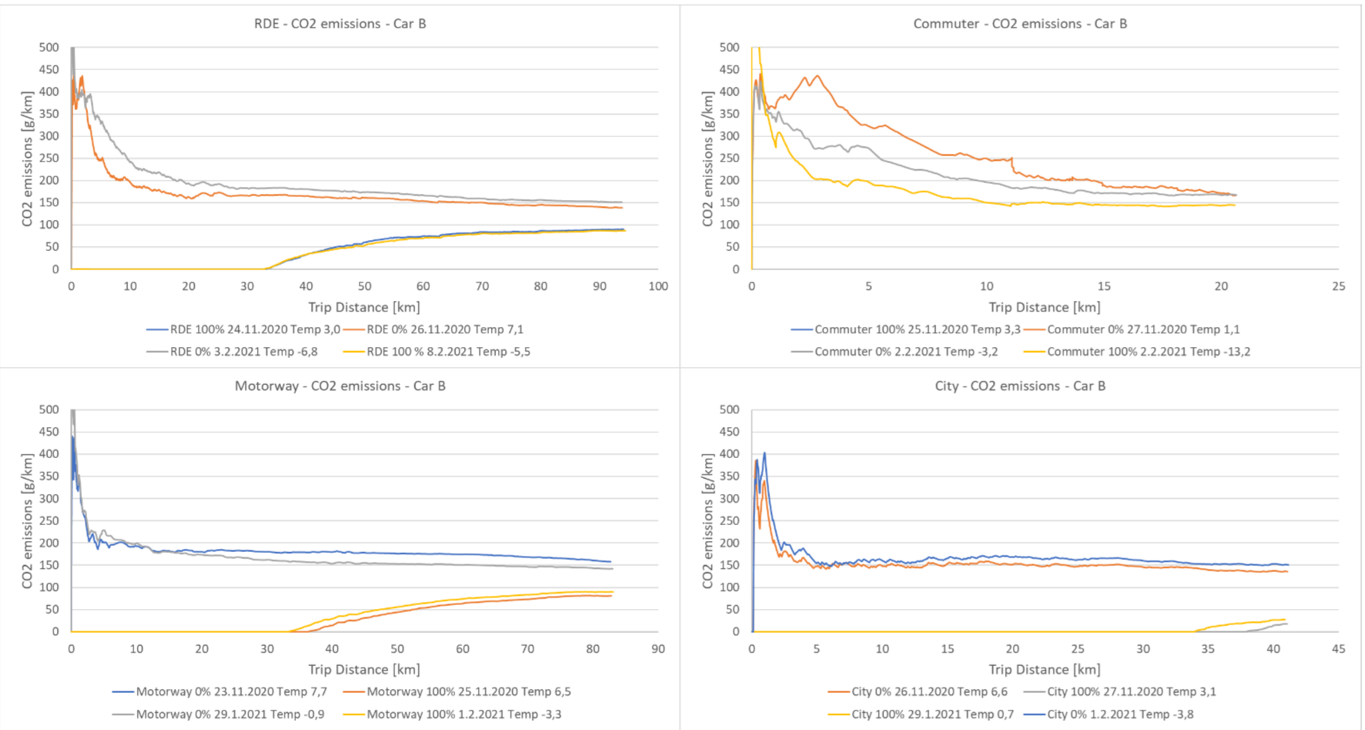

Figure 26: Car B distance-based CO_2 emissions.

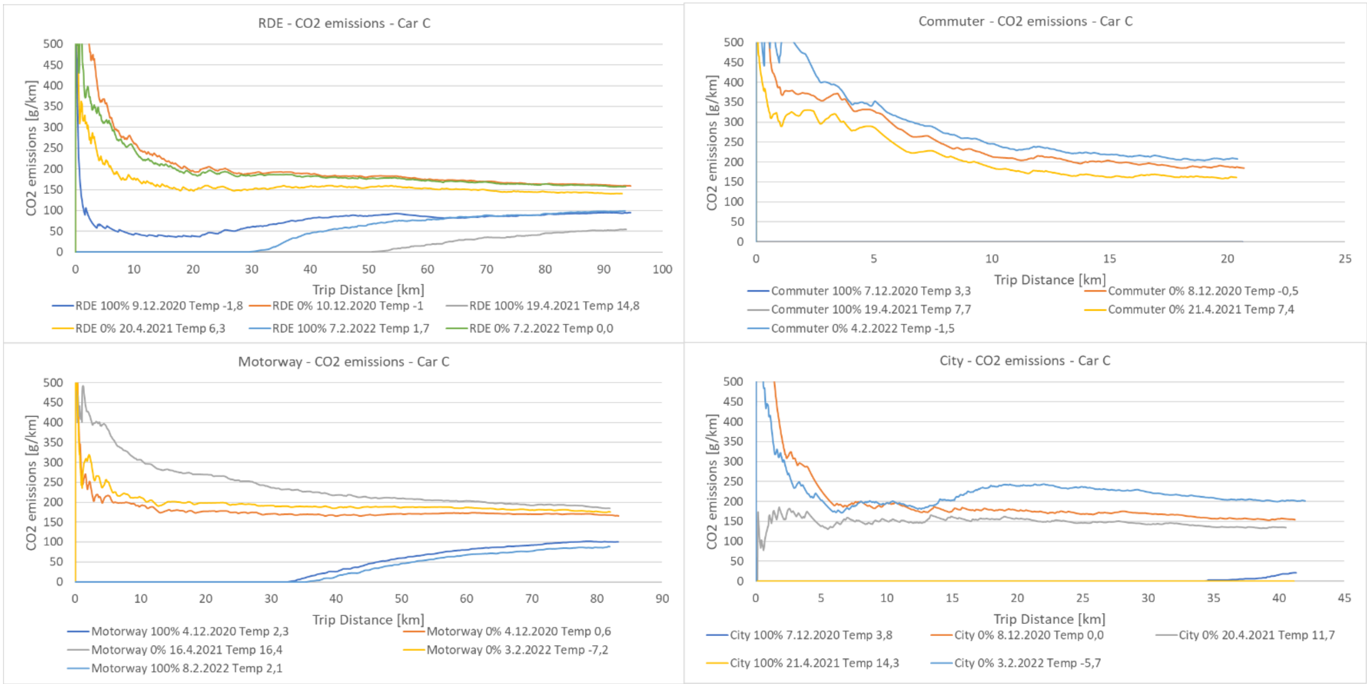

Figure 27: Car C distance-based CO$_2$ emissions.

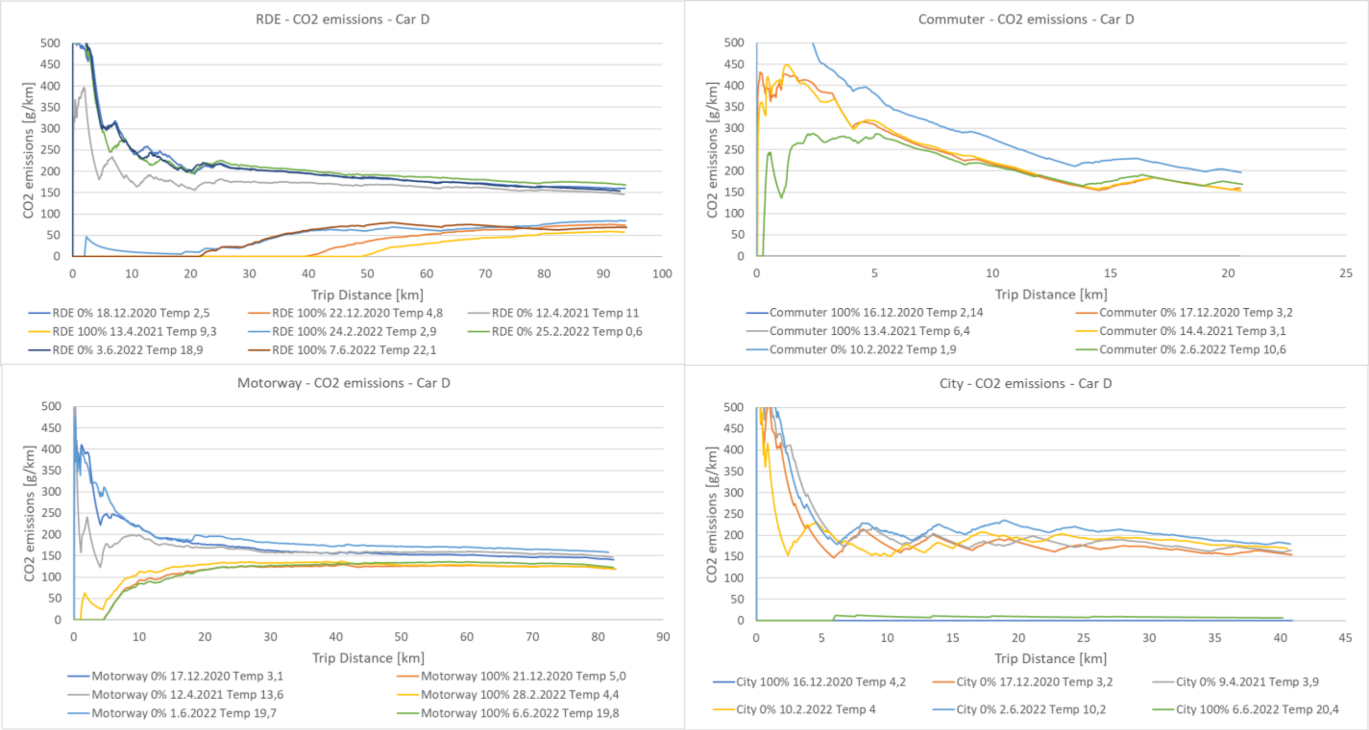

Figure 28: Car D distance-based CO$_2$ emissions.

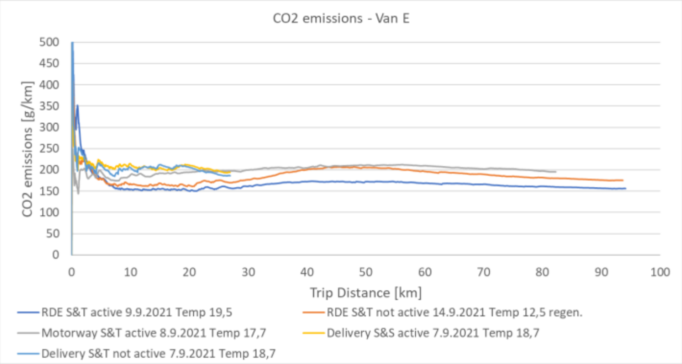

Figure 29: Van E distance-based CO_2 emissions.

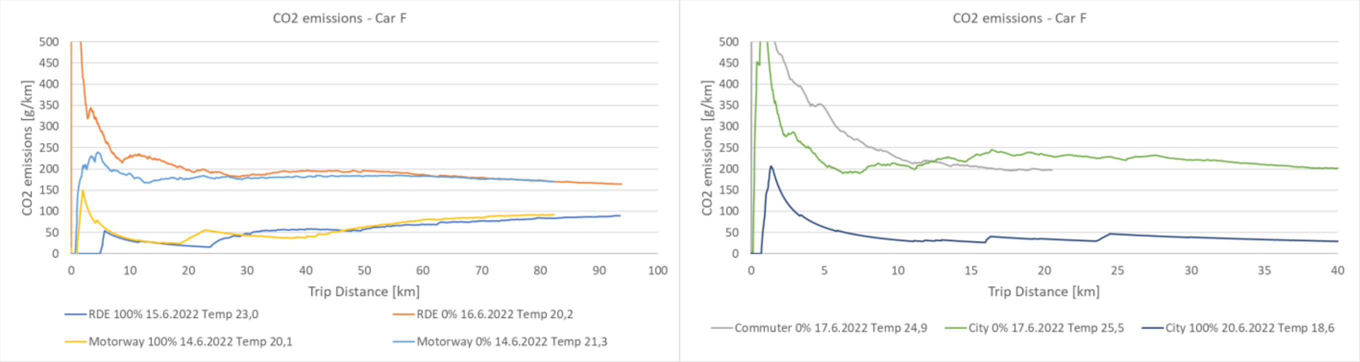

Figure 30: Car F distance-based CO_2 emissions.

3.2.3.3.1 Discussion on cumulative CO_2 emissions

Car A

The same effect of ambient temperature as was seen in trip average results can be seen from the cumulative CO_2 emissions in Figure 25. Cold ambient conditions increase CO_2 emissions. Overall, those were within +- 5 g/km to +- 10 g/km compared to the average result in each route.

PHEVs

Cumulative CO_2 emission results in Figure 26 clearly show each of the PHEV's pure electric range in different driving conditions. On the RDE route, car B was capable of slightly less than 35 km pure electrical range at temperatures down to -6 °C. On the City and Motorway routes, car B was capable of 34 to 38 km depending on the temperature.

Figure 27 shows that low ambient temperatures affected the electric range for car C on the RDE route more than car B. The electrical mileage was approximately 30 km at 2 °C, while the ICE was already active right from the start in conditions of -2 °C. At 15 °C, car C was capable of driving 51 km on electricity alone. On the City and Motorway routes the electric range of car C was similar to car B.

Car D was also capable of up to 50 km electrical mileage at 9 °C on the RDE route, as seen in Figure 28. However, in addition to reduced electrical mileage in sub-10 °C temperatures, the range was also lower in hot test conditions. By comparing the results obtained from the Motorway route with full battery charge at the start, the different driveline management methodologies are highlighted compared to other tested PHEVs, as the ICE was turned on almost right after the test start. This leads to higher CO_2 emissions. Tests that started with an empty battery on the City route show similar results, unlike the driveline management methodology, as this clearly indicates that ICE is periodically used heavily for charging the battery and then driven in charge depleting mode.

Car F was capable of the lowest pure electrical mileage, as seen in Figure 30. ICE started just few kilometers after the start on City, Motorway and RDE routes when the test was started with a full battery. Car F also resulted in the highest CO_2 emissions in tests started with a full battery.

Van E

Figure 29 highlights the finding that the S&S feature did not have an effect on van E CO_2 emissions. As seen from the figure, the characteristics of CO_2 emissions were similar for each comparable trip, and thus no notable difference can be seen. The regeneration event on the RDE route (S&S inactive) did elevate CO_2 rather moderately.

3.3 Continuous NO_x monitoring

Car A was equipped with a continuous NO_x monitoring device. The objective was to identify how well the NO_x emission reduction is maintained during normal day-to-day driving throughout the year in changing ambient conditions. The second objective was to identify if any deterioration in emission reduction performance occurs as the vehicle mileage increases. Unfortunately, the COVID-19 pandemic reduced the usage of test car A, and therefore the anticipated mileage was not achieved. In total, useful data was gathered from 148 days during the whole two-year monitoring period.

The average concentration from all on-road tests performed on different routes (City, Commuter, Motorway) was less than 14 ppm, and the corresponding gram-based emissions were around 0.043 g/km. These values can be used roughly in comparison with continuous monitoring. Figure 31 shows the daily average NO_x concentration throughout the whole project and the population of each concentration bin. The dashed line in the left diagram presents the moving average value. The results show that a majority, ca. 81%, of daily concentrations recorded were under 20 ppm. If it is assumed that the exhaust mass flow in normal daily driving corresponds to the mass flow measured during the performed on-road testing, this would this indicate that NO_x emissions mostly occurred during the monitoring period in the range of 0.05 g/km or below it. In addition, no clear correlation with ambient temperature and NO_x was found. However, it should be noted that the NO_x sensor used in the campaign was not capable of measuring any emissions until the exhaust gas temperature reached around 200 °C. This of course means that the NO_x emissions emitted right after the first few kilometers are not captured in the data.

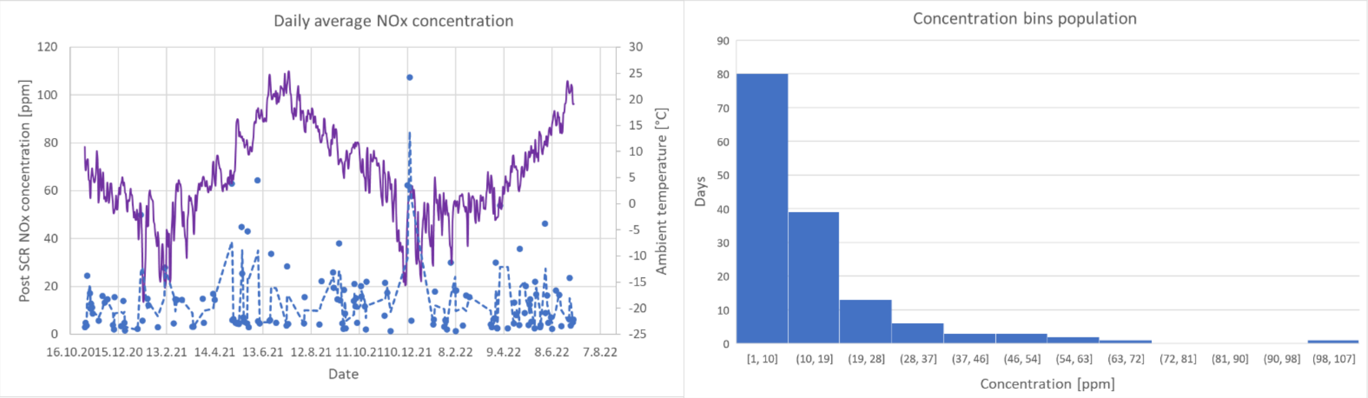

Figure 31: Daily average post-SCR NO_x concentration and bins population.

4. Estimation of well-to-wheel emissions

This project focused on the investigation of PHEV emissions in altering environmental and driving conditions. Pollutant emissions in such conditions are presented in the above chapters. In summary, testing results showed that PHEVs' NO_x and PN emissions are typically low in various driving and environmental conditions. In this chapter, the emphasis is on the evaluation of the potential of PHEVs for reducing CO_2 emissions in the passenger car segment based on both tank-to-wheel (TTW) and well-to-wheel (WTW) approaches. The first-generation PHEVs were introduced onto the markets between 2015 and 2021. These vehicles were typically equipped with battery packs that allow a pure electric range of up to 50 km. This was also the case for the PHEVs tested in this study. The current trend is for vehicle manufacturers to introduce new, longer-range versions onto the market. Consumer Reports listed some of the latest models sold in the USA, which are equipped with battery configurations enabling a pure electric range of up to 70 km (in the EPA testing cycle[10]). Most of those vehicles are also sold in Europe.

4.1 Basis for evaluation and assumptions used

The testing data generated during this project was used as the main source of information for energy consumption and thus CO_2 emissions evaluation. More precisely, car D was chosen for evaluation as it was tested multiple times in various conditions. Typically, passenger cars are driven in various driving conditions depending on user need, and thus no single typical route or speed profile can be used to represent all conditions and cases. Because of this, the results from the RDE test route were selected as a basis for the analyses as it combines urban, rural, and highway driving. It is also started with a cold engine, thus imitating typical use when a car is started from parking for the first time.

As seen in the results in 3.2.3, the pure electrical range depends heavily on the environment temperature. For this analysis, test results close to the average European temperature were selected. The analysis was performed for two cases: trips started with an empty (test id: RDE0%12.4.2021) and with a full battery (test id: RDE100% 13.4.2021). In addition to the PHEV (car D), a diesel car and a fully battery electric vehicle (BEV)[11] were selected as a comparison for the PHEV. The diesel car in question was the same car A that was tested during the project. Results from test RDE 5.11.2020 were selected as a baseline for the evaluation. Unfortunately, test results from the same test routes were not available for the BEV. Instead of that, energy consumption on a highway and commuting-type driving in summer conditions were available for analysis.

For both the PHEV and the diesel, the mileage-based energy consumption was drawn from the results obtained from the RDE route. As the RDE test is roughly only 90 km long, for trips above 90 km it was assumed that the energy consumption would converge at the level of the empty battery. For car D this is equivalent to approximately 146 gCO_2/km. Charged electric energy consumption for car D on the selected RDE route was around 24.4 kWh/100km. It was also assumed that the battery is charged only once per day. Of course, in many commuting cases there would be the possibility to charge the PHEV during the working day. Those cases were not considered. For car A, the energy consumption in trips above 100 km was assumed to be equivalent to the result at the end of the RDE test route. In this case, this was equivalent to approximately 124 gCO_2/km. For BEVs, average energy consumption on highway- and commuting-type driving was around 20 kWh/100km. The consumed electrical energy for the PHEV and BEV was determined based on the energy charged to the battery.

In principle, PHEVs use similar ICE technology to their ICE-only sister models. Mostly, the ICE in PHEVs are spark-ignition engines, and those currently available with alternative fuels are basically ethanol- and methane-driven. For PHEVs, methane is a challenging option as it requires high volumes for pressurized

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[10] EPA testing cycle, https://www.consumerreports.org/cars/hybrids-evs/is-a-plug-in-hybrid-vehicle-right-for-you-a9339147016/
[11] BEV main specification: SUV, 150 kW power, 82 kWh battery, 2111 kg curb weight

fuel tanks, which compete with the batteries for space. Ethanol is also not problem-free. It has a lower heating value compared to gasoline[12]. However, as a liquid fuel the bigger tank would be easier to fit in the car. Thus, ethanol could be an interesting option as a renewable fuel or component to blend with gasoline in higher quantities than are currently allowed in the EN228 standard, i.e., 95E10 and 98E5 fuels. The additional cost for OEMs for modifying and approving the use of ethanol in higher blends would be rather modest. Most modifications would be required for materials exposed to ethanol and injection equipment due to the need for increased injection quantities. A 2016 study conducted by Roland Berger estimated that the additional cost for an E20-compliant vehicle to be around €9 and for an E85/FFV-compliant vehicle around €180 based on 2030 prices[13].

The analysis conducted in this campaign was carried out for daily mileages or trips up to 200 km. The effect of multiple trips, i.e., engine cooling between the trips during the day, was not included. The study was done on a daily basis because annual mileage introduces challenges in that the battery charging frequency needs to be defined. It might also hide the potential of PHEVs in short trips. In fact, in 2018 Traficom published a survey of transportation practices in Finland. The study found that the typical daily mileage in Finland was around 31 km[14]. In addition, 93% of daily mileages were under 50 km. This highlights that the most interesting interval for evaluating PHEVs' potential for reducing CO_2 emissions should be daily mileages of up to 50 km.

The evaluation was performed with following energy options:

PHEV:

1. Gasoline 95E5
2. EN228 blended with 25% ethanol (E25)
3. EN228 blended with 85% ethanol (E85)

Ethanol production pathways from waste residual wood and waste wheat straw were selected. These resulted in an average Well-To-Tank (WTT) CO_2 intensity of around 26 gCO_2/MJ fuel.

Diesel:

1. EN590 diesel
2. EN590 blended with 30% HVO (HVO30%)
3. 100% HVO (HVO100%)

HVO production pathways from tallow and cooking oil were used. These produced an average Well-To-Tank (WTT) CO_2 intensity of around 14 gCO_2/MJ fuel.

BEV:

1. Finnish electricity mix in 2022
2. European electricity mix in 2016
3. Estimated European electricity mix in 2030

Fuel information and the European electricity mix in 2016 and in 2030 were based on the latest Concawe-Eucar-European Commission Joint Research Centre publication JEC Well-To-Wheels report v5[15]. Finnish

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[12] Ethanol volumetric heating value is approx. two-thirds that of gasoline's

[13] Roland Berger Integrated Fuels and Vehicles
Roadmap to 2030+
https://www.rolandberger.com/publications/publication_pdf/roland_berger_integrated_fuels_and_vehicles_roadmap_to_2030_v2_20160428.pdf

[14] Traficom National Travel Survey 2018 https://www.doria.fi/bitstream/handle/10024/149583/lti_2018-01_henkiloliikennetutkimus_2016_web.pdf?sequence=5&isAllowed=y

[15] JEC WTW report v5 https://publications.jrc.ec.europa.eu/repository/handle/JRC121213

electricity information was based on the data from the government-owned electrical network company Fingrid[16].
CO_2 emissions emitted in the vehicle manufacturing phase were not included. In this case, CO_2 emissions from manufacturing including a full life cycle assessment (LCA) would have been needed. LCAs lead to challenges in how to determine energy consumption and CO_2 intensity (gCO_2/MW) in used energy. However, it can be estimated that the CO_2 intensity ($gCO_2/kWh_{battery}$) in battery production is similar for BEV and PHEV batteries. In this case, this would mean that the production of the battery used in the PHEV emitted around 15% of the CO_2 emissions of the BEV's battery production.

4.2 WTW results and analyses

Figure 32 shows the results of TTW and WTW CO_2 emissions for PHEVs, diesel vehicles. and BEVs. As is known, PHEV CO_2 emissions (TTW) are greatly dependent on how large a share of the trips are driven electrically, i.e., how often the car is charged. Results indicate that for trips of up to 40 km that start with a full battery, a CO_2 reduction (TTW) of around 92% can be achieved. Correspondingly, for trips of up to 100 km, a reduction of up to ca. 45% is achievable. These are rather high reduction potentials. In addition, if the driving is started with a full battery and driven up to 200 km per day, the TTW CO_2 emissions are still less than a diesel car. Conversely, if a PHEV is not regularly charged, the CO_2 emissions (TTW) are around 50% higher at a distance of 20 km and 18% at 200 km compared to diesel. On a TTW basis, renewable fuels analyzed with PHEVs (E25 and E85) and diesel vehicles (HVO) do not demonstrate meaningful differences in TTW CO_2 emissions.

The results also suggest that when starting with a fully charged battery, PHEVs perform close to BEVs in distances of up to 40 km. This is explained by the pure electric driving and is close to BEV e-powertrain efficiency. However, PHEVs consumed around 21% more electricity compared to BEVs. Furthermore, if PHEVs are used more as a traditional ICE vehicle (no charging between trips) and the car is driven in charge-sustaining mode, the differences in CO_2 emissions compared to BEVs increase rapidly.

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[16] Fingrid data on Finnish electricity CO_2 emission intensity https://www.fingrid.fi/sahkomarkkinainformaatio/co2/

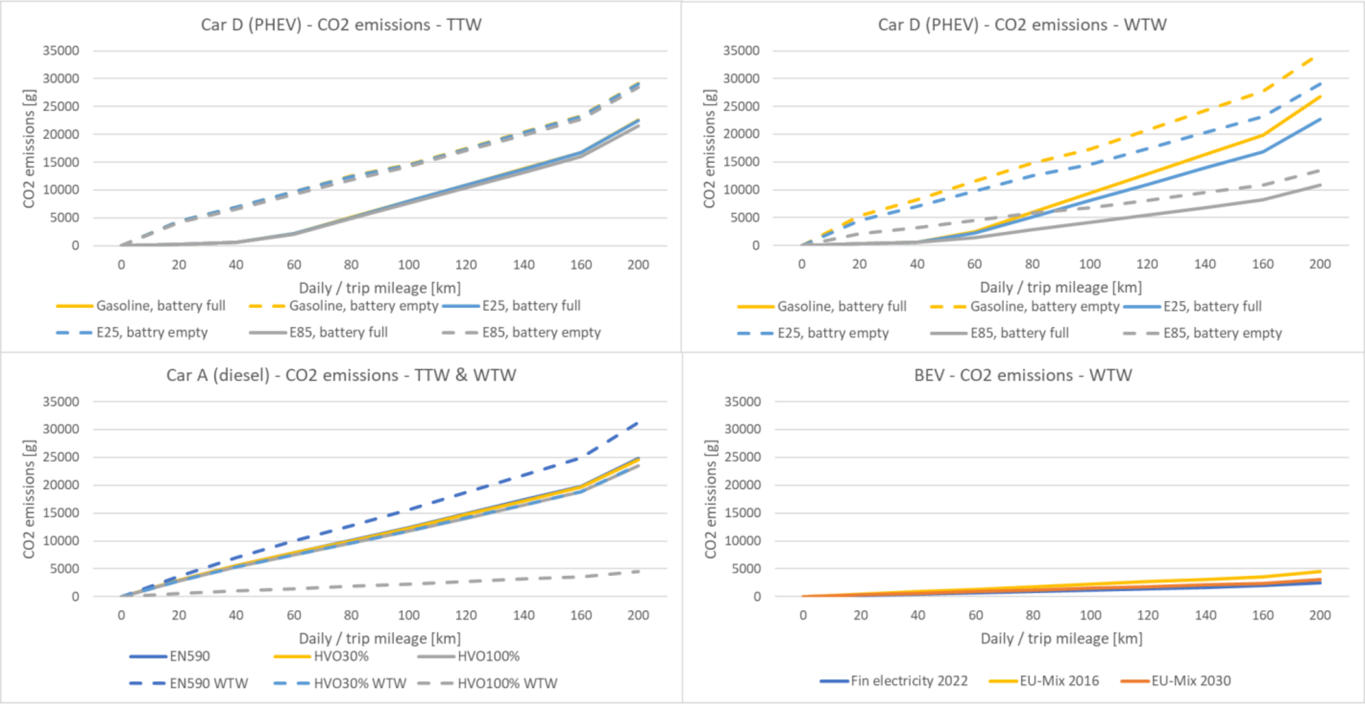

Figure 32: TTW and WTW CO_2 emissions as a function of daily or trip mileage for a gasoline PHEV, diesel car, and BEV with different energy sources.

The results in Figure 32 looks different when WTW methodology is used. Gasoline (95E5) and fossil diesel CO_2 emissions are increased compared to TTW emissions, but renewable fuels (E25 and E85) and HVO (30% and 100%) emissions are decreased significantly. E85 fuel would bring a reduction of around 61% in PEHV CO_2 emissions and HVO a reduction of around 100% and 86% for the evaluated diesel car.

As explained in section 4.1, the vast majority of the daily mileages driven in Finland are less than 50 km. The WTW analysis indicates that a PHEV, in combination with high ethanol blended fuels, could provide an interesting additional option for reducing CO_2 emissions. Charge depleting mode could cover most of the driven mileage, and renewable ethanol would reduce the WTW CO_2 emissions effectively when the car is driven in charge sustaining mode, i.e., on daily trips over 50 km if car driving is started with a full battery. In addition, reduced fuel consumption would also reduce the required total blending volume of ethanol across the whole vehicle population level. This would reduce the requirement of raw materials for ethanol production compared to direct use in E25- to E85-compliant ICE-only vehicles.

In summary, PHEVs together with renewable fuels could provide an effective additional measure for reducing CO_2 emissions in addition to BEVs and renewable fuel use in ICE-only vehicles. However, there are incentives set for PHEV owners that guide them to not to charge their cars regularly. One well-known challenge is related to company cars, where the benefit also includes fuel costs. In such cases the user is not paying for the consumed energy themselves and thus there is no incentive to charge the battery regularly. If the driver needed to cover the costs of the consumed energy, this would encourage the use of electricity in many European countries where the price of electricity is much lower than gasoline.

5. Summary and conclusions

This project focused on PHEVs' on-road CO_2 and pollutant emissions in varying environmental conditions. The main focus was to study the CO_2 and NO_x emissions of PHEVs in different types of driving situations, such as typical commuting driving, with fully charged and empty batteries. Four different PHEVs were tested. Depending on rental availability, some of the vehicles were tested multiple times on the same test routes in different environmental conditions. A diesel car was chosen as a reference to provide information about the then-current state-of-the-art diesel car on-road emissions performance. Possible NO_x emissions deterioration during the two-year project was investigated using chassis dynamometer tests by comparing the results first recorded at the start of the project with those obtained at the end of the study. Continuous NO_x concentration monitoring was applied for investigating NO_x emissions in normal day-to-day driving conditions. In addition, the on-road emissions of one van were tested on a driving route replicating a typical package delivery journey in a suburban area. The tested vehicles were compliant with Euro 6 step d-TEMP and Euro 6 step d-ISC regulation and those in between. Finally, the potential of PHEVs to reduce CO_2 emissions was evaluated on a WTW basis by comparing to diesel and BEV.

Because of the COVID-19 pandemic, the monitored diesel car was not used as often as before the pandemic. Mileage during this two-year period was only 28,500 km, which is equivalent to roughly half of the anticipated driving mileage. Chassis dynamometer tests showed no significant or trend-like deterioration in diesel car emissions.

In general, the tested vehicles' NO_x and PN emissions were at a low level. Mostly, they were even well below the type-approval limit value in laboratory testing. During empty battery driving, the PHEVs' NO_x emissions were mostly below 0.01 g/km even in cold ambient temperatures. This corresponds to a CF of 0.17. There was no observed significant increase in NO_x emissions during the change of traction from electric drive to ICE drive, and not even in sub-zero Celsius temperatures. This result can be explained by the close coupling of the three-way catalyst close to the engine exhaust outlet, and the fact that the exhaust gas temperature in spark-ignited stoichiometric combustion is always relatively high. PHEVs were even able to meet the proposed Euro 7 NO_x emission limits in all tested driving conditions.

NO_x emissions from the tested diesel car were also well below the legislative limit value. However, ambient temperature had a clear effect on NO_x emissions, as an increasing trend was observed as a function of decreasing ambient temperature. In general, the diesel car showed a remarkable improvement compared to older model results in the project performed two years earlier. NO_x emissions were reduced to half of the previous Euro 6 model. DPF regeneration, which occurred three times, clearly increased NO_x emissions above the legislative limit value. Two years of continuous NO_x monitoring suggested that the NO_x emissions were on average in the range of 0.05 g/km or below, corresponding to the CF of 0.63. This is rather well in line with the on-road tests that started with a warm engine. The estimation excludes cold start emissions as the system was not able to capture these. Thus, actual NO_x emissions are higher.

The tested van performed surprisingly well on a route that replicated a typical suburban area package delivery journey. NO_x emissions were around 0.05 g/km, corresponding to a CF value of 0.4. The start-stop functionality did not have a significant effect on NO_x emissions. The tested diesel car was not able to meet the proposed Euro 7 NO_x emissions limit values when the test was started with cold engine. This was due to the high NO_x emissions within the first few driving kilometers. On warm start routes it satisfied the limits with an approximate CF value of 0.7. Also, the van was close to the proposed Euro 7 NO_x emissions limit value in tested routes.

The PHEVs' PN emissions were mostly below $1x10^{11}$ #/km and even in the range of $1x10^{10}$ #/km, which correspond to a CF value of between 0.017 to 0.17. The diesel car performed even better, resulting in PN emissions of between $8x10^{8}$ to $2.1x10^{9}$ particulates/km, corresponding to a CF value of 0.001 to 0.004. DPF regeneration events did not significantly affect PN emissions.

The CO_2 emission of the tested PHEVs varied remarkably depending on the state of the battery at the start of the test, as was anticipated before the project. It was possible to drive the typical commuting route completely using electricity with all the tested PHEVs. On the same route, CO_2 emissions with an empty battery were between 150 g/km to 200 g/km depending on the car and the ambient temperature. The curb weight of the car had a huge effect on fuel consumption when battery was empty. Some of the PHEVs were also able to complete the longer 41 km long city environment-focused City route purely electrically. Other PHEVs had CO_2 emissions of around 25 g/km when started with a full battery and when ICE was turned on at some point on the route. Ambient temperature proved to have a clear effect on the PHEVs' capability to utilize electricity and electricity consumption in close-to and sub-zero Celsius temperatures. In the tests that were started with a full battery in close-to or below-zero Celsius temperatures, CO_2 emissions increased with all PHEVs tested. This suggests that electricity consumption increased, which led to an earlier introduction of the ICE and thus also increased CO_2 emissions.

The diesel car produced CO_2 emissions of between 115 g/km and 145 g/km depending on the test route and the ambient temperature. When compared to the PHEVs driven in battery sustaining mode, the tested diesel car performed better in the Commuter, Motorway, and RDE tests. On the City route, some of the PHEVs in battery sustaining mode were capable of similar CO_2 emissions. DPF regeneration events that took place during three test trips increased CO_2 emissions.

The van was tested on a special test route replicating a typical delivery journey profile. It was tested with start-stop functionality active and inactive. In general, the van produced low NO_x emissions that were well below the regulatory limit values. Start-stop functionality did not have an effect on CO_2 emissions. However, PN emissions were slightly lower and NO_x emissions slightly higher when start-stop functionality was active.

A WTW analysis was performed to investigate the potential of PHEVs for reducing CO_2 emissions in typical daily driving. The analysis was performed for three different fuel options: Gasoline, E25, and E85 fuels. In addition, a diesel car with fossil diesel and HVO, and a BEV were analyzed as a comparison. The results showed that a PHEV with renewable fuels could provide an effective additional measure for reducing CO_2 emissions on typical Finnish daily trips with mileage under 50 km, if the battery is regularly charged. Basically, this would require that the user must have charging possibility at home. Furthermore, in combination with renewable fuels—in this case ethanol blends—CO_2 emissions could also be reduced significantly when driven in battery sustaining mode. In addition, the possibility of operating with fuel provide a high level of autonomy for longer distances, for example when traveling on holiday or other similar trips that take place a few times a year. To utilize PHEVs as an electric car, users should be encouraged with incentives or other measures to charge them regularly.