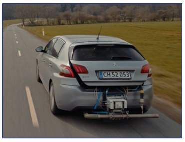
Annex 55-1




A Report from the Advanced Motor Fuels Technology Collaboration Programme

Real Driving Emissions and Fuel Consumption

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ADVANCED MOTOR FUELS
IEA-AMF
Technology Collaboration Programme on
Advanced Motor Fuels

Technology Collaboration Programme
by iea

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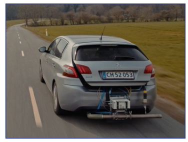


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February 2020

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Summary / Abstract

AMF TCP annex 55 on Real Driving Emissions and Fuel Consumption was created to answer the key question on how vehicle fuel economy, efficiency and emissions in real world driving compare to certification test results. The scope of the annex included the influence of various parameters including vehicle type and powertrain, environmental conditions, driving style and route as well as an overall assessment of benefits and challenges of real world driving testing compared to dynamometer testing.

The methodology determined suitable for answering the key question was assessment of real driving emissions (RDE) performance compared to dynamometer vehicle testing with RDE vehicle performance investigated over typical regional driving conditions such as city, highway, arterial, free-speed, and congested routes.

RDE CO_2 emissions for diesel vehicles agree well (<3%) with worldwide harmonized light vehicles test cycle (WLTC) data while larger gaps exist with the older NEDC cycle. Up to 11% between RDE and WLTC were observed for gasoline vehicles. The on road measured CO_2 emission rates from close to 50 North American vehicles were mostly above the fleet wide compliance levels. This translated to fuel consumption from real-world testing being on average, 22% higher than the observed fuel consumption from tests on a chassis. A bigger variation also exists for light commercial vehicles (LCV). Ethanol (E85) and compressed natural gas (CNG) vehicles showed similar deviations between WLTC and RDE results as gasoline vehicles while overall CO_2 levels of CNG vehicles were lower than comparable gasoline counterparts. The legacy diesel vehicles (before 2018) that were tested had no compliance challenges for PN, CO, but showed significant NOx emission issues and fuel economy were worse than advertised. While Euro 6d vehicles (Model Year 2018 on) have acceptable NOx levels, increased RDE NOx emissions levels were observed for Euro 6b vehicles with significant variations based on emissions control technology choices. Gasoline vehicles without dedicated particulate filter (GPF, Gasoline Particulate Filter) showed

larger PN level increases from new European driving cycle (NEDC) to WLTC while WLTC emissions levels were similar to RDE results. Ethanol (E85) vehicles showed a reduction in PN emissions compared to gasoline while relative NOx emissions trends were inconclusive. General emissions spikes with Plug-In Hybrid Electric Vehicles (PHEV) for cold starts were observed; however, the spikes had no significant impact on overall test cycle results.

Measurements of diesel vehicles at 0, 5 and 20°C showed scattered results with no clear trends. Highway driving of diesel vehicles showed little sensitivity to temperature; urban driving resulted in higher NOx emissions at lower temperatures. Low ambient temperature testing assures that after treatment systems are also effective at harsh ambient conditions.

Consistency between test cycle and real world driving can be achieved with test cycles that reflect real driving behavior. RDE testing further helps ensure compliance of vehicles with emissions targets across the entire operating range. Development and application of miniaturized portable emissions measurement systems (Mini-PEMS) could provide opportunities for larger-scale testing and support technical inspections.

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Swiss Federal Office for the Environment FOEN
Swiss Federal Office of Energy SFOE
United States
U.S. Department of Energy Vehicle Technologies Office

Content

Disclaimer

Appendix I – Full report from Canada

Comparison of exhaust emissions from on-road driving and chassis dynamometer tests

Emissions Research and Measurement Section

Air Quality Research Division
Environment and Climate Change Canada

Submitted by:

Deniz Karman

Professor Emeritus
Carleton University

September 2019

SUMMARY

This report has been prepared to document the contribution of the ***Emissions Research and Measurement Section*** (ERMS) of ***Environment and Climate Change Canada*** to a project under the ***International Energy Agency's*** *Advanced Motor Fuels Technology Collaboration Programme*: Annex 55 *Real Driving Emissions and Fuel Consumption*. The project led by Argonne National Laboratory, United States, involved participation from Canada, Denmark, Finland, Sweden, and Switzerland. The project aimed to develop an emission rate, fuel consumption, and energy efficiency inventory of vehicles driven on-road in varying countries in typical seasonal corresponding climates, using vehicles fuelled with advanced, renewable, and conventional fuel.

Methodology

The research carried out at the ERMS involved two parts:

1) Advanced Fuels: involving one flex-fuelled vehicle (FFV) using ethanol-gasoline blends at 10% and 85% ethanol (E10, E85); one dual fuel vehicle (DFV) using gasoline and compressed natural gas (CNG).
2) A fleet of light duty vehicles (LDVs) using gasoline or diesel fuel

Emissions of carbon monoxide (CO), carbon dioxide (CO_2), nitric oxides (NO_x), and total or non-methane hydrocarbons (THC, NMHC) were measured while the vehicles were driven on a chassis dynamometer in the ERMS laboratory with the FTP, HWY, US06 cycles, and on a 5-mode route designed by ERMS on roads around Ottawa to enable a mix of driving on arterial and highway roads at different speeds and congestion conditions. Additional emission measurements such as benzene, toluene, ethylbenzene and xylene (BTEX) were also available for laboratory tests.

This testing was conducted with support from the following programs:

1) Environment Climate Change Canada, Environmental Protection Branch, Oil Gas and Alternative Energy Division, Downstream Oil and Gas Section
2) Natural Resources Canada - Program of Energy Research and Development (PERD)/End Use Portfolio/Clean Transportation Systems Technology Area
    - Natural Gas: Impact on Internal Combustion Engine Emissions and Efficiency
3) Transport Canada - ecoTECHNOLOGY for Vehicles (eTV) Program
    - Project A1. Emissions and Energy Performance Testing of Advanced Light-Duty Vehicles including zero emission vehicles, advanced engines, and fuels
    - Project B15. Natural Gas Vehicle Emission Testing

Results

Alternative Fuel effects on emissions

CNG relative to E0 (for laboratory tests and E10 (5-mode on road test) showed reduced CO (HWY, US06), CO_2 (FTP, HWY, US06, 5-mode), and NMHC (FTP, US06), and BTEX (FTP) emissions over the indicated driving cycles, but increased THC (FTP)

emissions. E85 compared to E10 showed reduced CO (FTP, HWY, US06), CO_2 (FTP, HWY, US06, 5-mode), and BTEX (FTP) emissions over the indicated driving cycles, but increased NO_x (HWY, 5-mode on road) and THC (FTP, 5-mode on road) emissions.

Driving cycle effects on emissions – DFV and FFV

Driving cycle effects were examined by comparing the emissions with the FTP and the 5-mode on road driving with the target alternate fuel (CNG, or E85). For the DFV the only driving cycle effect observed was the increase in THC for the 5-mode on road driving cycle. It is noteworthy that NO_x emissions showed no significant increase. For the FFV, 5-mode on road driving cycle emissions compared to FTP (both with E85 fuel) showed lower emissions of CO, CO_2 and THC but higher emissions of NO_x.

Driving cycle effects on emissions – Fleet of gasoline and diesel LDVs

The effect of driving cycle on emissions for the vehicles in the fleet were examined by comparing on road measurements with the <u>certification (FTP) limits</u> for CO and NO_x emissions, by comparing on road measurements for individual vehicles with the <u>fleet average emission standards (FTP)</u> for CO_2, or by comparing on road measurements of NO_x with <u>FTP measurements</u> for the diesel portion of the fleet. No examination was attempted for the effect of driving cycle on THC emissions as the certification limits are based on NO_x+NMOG (non-methane organic gases) measurements and the measured THC values were too low and too variable to present a clear picture.

While there is significant variability among the on road tests (3-4 replicates) comparison with FTP limits show that none of the CO emission rates measured on road exceeded the respective FTP limit, and most of the fleet had on road CO emission rates well below 50% of the FTP limits.

CO_2 emission rates showed much less variation between tests compared to CO, NO_x and THC measured values. The average values for individual vehicles were mostly above the fleet average compliance levels. CO_2 emissions correlate strongly with fuel consumption and previous analysis of the fleet data has indicated a fleet average increase of 22% in fuel consumption on road relative to FTP measurements.

On road NO_x emissions for the diesel fleet showed significant increases over the emissions in FTP tests; most vehicles which had been below the 0.07 g/mile FTP NO_x emission limit exceeded the FTP limit with on road emissions as high as 1.4-7.5 times their FTP emissions. While it can be expected that on road driving compared to the laboratory FTP cycle presents some challenges in terms of NO_x emissions there are clearly differences in the ability of the tested vehicles to meet these challenges.

In summary, the research carried out at ERMS for IEA-AMF Annex 55 has contributed to the understanding of how advanced fuels and different driving patterns can affect the tailpipe emissions from light duty vehicles that are of concern from air quality and greenhouse gas emission perspectives.

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Abbreviations

CO	Carbon monoxide
CO2	Carbon dioxide, CO_2 (in graphs)
CVS	Constant Volume Sampling system
CFR	U.S. Code of Federal Regulations
DFV	Dual Fuel Vehicle
E0, E10, E85	Percentage by volume of ethanol content in gasoline ethanol blends
FFV	Flex Fuel Vehicle
FTP, FTP-75	United States Federal Test Procedure
GVWR	Gross Vehicle Weight Rating
HWY	Highway fuel economy test driving schedule (HWFET)
LDV	Light Duty Vehicle
LDT	Light Duty Truck, LDTx for regulatory class x
NMHC	Non-Methane Hydrocarbons
NMOG	Non-methane organic gases
NO_x	Nitric oxides ($NO + NO_2$)
PEMS	Portable Emission Measurement System
SFTP	Supplemental Federal Test Procedure (US06)
THC	Total hydrocarbons
US06	Unites States Supplemental Federal Test Procedure (SFTP)

1. Introduction

Over the last 20 years, the Emissions Research and Measurement Section (ERMS) of Environment and Climate Change Canada (ECCC) has been participating in the International Energy Agency's (IEA) transportation related Technology Collaboration Programmes (TCPs). TCPs are multilateral technology initiatives that encourage technology-related activities that support energy security, economic growth and environmental protection. The Advanced Motor Fuels (AMF) program provides an international platform for co-operation to promote cleaner and more energy efficient fuels and vehicle technologies.

The Emissions Research and Measurement Section is currently participating in an AMF project entitled: Annex 55 *Real Driving Emissions and Fuel Consumption*. The project is being led by Argonne National Laboratory, United States, with participation from Canada, Denmark, Finland, Sweden, and Switzerland. Annex 55 objectives are summarized[1] as:

> The levels of air pollutants from internal combustion engine (ICE)-powered vehicles that are being sold in the marketplace today are much lower than those from vehicles 4 to 10 years ago. This change is largely the result of technology forcing regulations to control the exhaust emission rates of various air pollutants such as hydrocarbons, carbon monoxide, oxides of nitrogen (NO_x), and particulate matter. Over time, changes to those regulations have reflected the extraordinary advances in fuels, engines, and emission control technologies that have been produced by automotive researchers/manufacturers over the past decades. There is evidence to suggest that the performance of vehicles may not be fully captured in compliance or type approval tests, even though they are conducted with varying driving cycles and in an environmentally controlled chamber.
>
> This project aims to develop an emission rate, fuel consumption, and energy efficiency inventory of vehicles driven on-road in varying countries in typical seasonal corresponding climates, using vehicles fueled with advanced, renewable, and conventional fuel. Vehicle performance will be investigated over typical regional driving conditions such as city, highway, arterial, free-speed, and congested routes. In short, the objective of this project is to explore the real driving emissions and real-world performance of vehicles operating under a range of worldwide driving conditions.

This report has been commissioned by the ERMS in support of Canada's contribution to the (IEA AMF) Annex 55 work: *Real Driving Emissions and Fuel Consumption*. The report is based on the analysis and preparation for presentation of the data obtained by ERMS. Section 2 summarizes the methodology for the emission testing with different vehicles, fuels, and driving cycles, Section 3 presents the results and their analysis, and Section 4 presents the key findings and conclusions that can be drawn.

[1] https://amf-tcp.org/content/projects/map_projects/55

2. Methodology

2.1 Vehicles and fuels

The work being reported can be broadly considered in two parts, the first involving advanced fuels and the second involving gasoline and diesel.

Part 1: Alternative Fuels

Two vehicles were tested both on laboratory test cycles and on-road driving.

1: A 2015 model year GMC Sierra flexi-fuelled vehicle (FFV) with a 6.0L V8 engine, tested with E0 (Tier 2) and E85 fuels in laboratory tests (FTP, HWY and US06), and with E10 and E85 fuels during on road tests using a 5-mode driving cycle.

2: A 2016 model year Chevrolet Impala dual fuel vehicle (DFV) with a 3.6L engine tested with E0 (Tier 2) and CNG in laboratory tests (FTP, HWY and US06) and on road tests using a 5-mode driving cycle.

Part 2: Diesel and Gasoline

A fleet of nominally 50 light duty vehicles covering model years 2010-2017 with gasoline or diesel engines was tested in the laboratory (FTP, HWY, and US06), and on-road, using their respective fuels.

2.2 Driving cycles

Chassis dynamometer tests

Three chassis dynamometer driving cycles coded as FTP, HWY, and US06 in presenting results were used:

- **FTP**: U.S. Federal Test Procedure (FTP)
- **HWY**: The Highway Fuel Economy Driving Schedule (HWFET) represents highway driving conditions under 60 mph.
- **US06**: The US06 is a high acceleration aggressive driving schedule that is often identified as the "Supplemental FTP" driving schedule.

The details of these tests are prescribed by *Title 40, U.S. Code of Federal Regulations* (40 CFR)[2] as the official source of EPA's vehicle/engine certification test procedures.

[2] https://www.epa.gov/laws-regulations/regulations#find

The HWY and US06 tests are single phase tests, i.e. the mass emission rates are determined from the mass of emissions collected during the test divided by the distance travelled during the test. The FTP consists of 3 phases and the calculation of a “composite” value of mass emitted per distance travelled for a single test is expressed by (40 CFR):

$$e_{\text{[emission]-FTPcomp}} = 0.43 \cdot \left(\frac{m_c}{D_{ct} + D_{cs}} \right) + 0.57 \cdot \left(\frac{m_h}{D_{ht} + D_{hs}} \right)$$

Eq. 1066.820-1

Where:

m_c = the combined mass emissions determined from the cold-start UDDS test interval (generally known as bag 1 and bag 2), in grams.

D_{ct} = the measured driving distance from the transient portion of the cold-start test (bag 1), in miles.

D_{cs} = the measured driving distance from the stabilized portion of the cold-start test (bag 2), in miles.

m_h = the combined mass emissions determined from the hot-start UDDS test interval in grams. This is the hot-stabilized portion from either the first or second UDDS (bag 2, unless you measure bag 4), in addition to the hot transient portion (bag 3).

D_{ht} = the measured driving distance from the transient portion of the hot-start test (bag 3), in miles.

D_{hs} = the measured driving distance from the stabilized portion of the hot-start test (bag 4), in miles. Set D_{hs} = D_{cs} for testing where the hot-stabilized portion of the UDDS is not run.

(c) Calculate the final composite PM test results as a mass-weighted value, $e_{\text{PM-FTPcomp}}$, in grams per mile as follows:

(1) Use the following equation for PM measured as described in §1066.815(b)(1), (2), or (3):

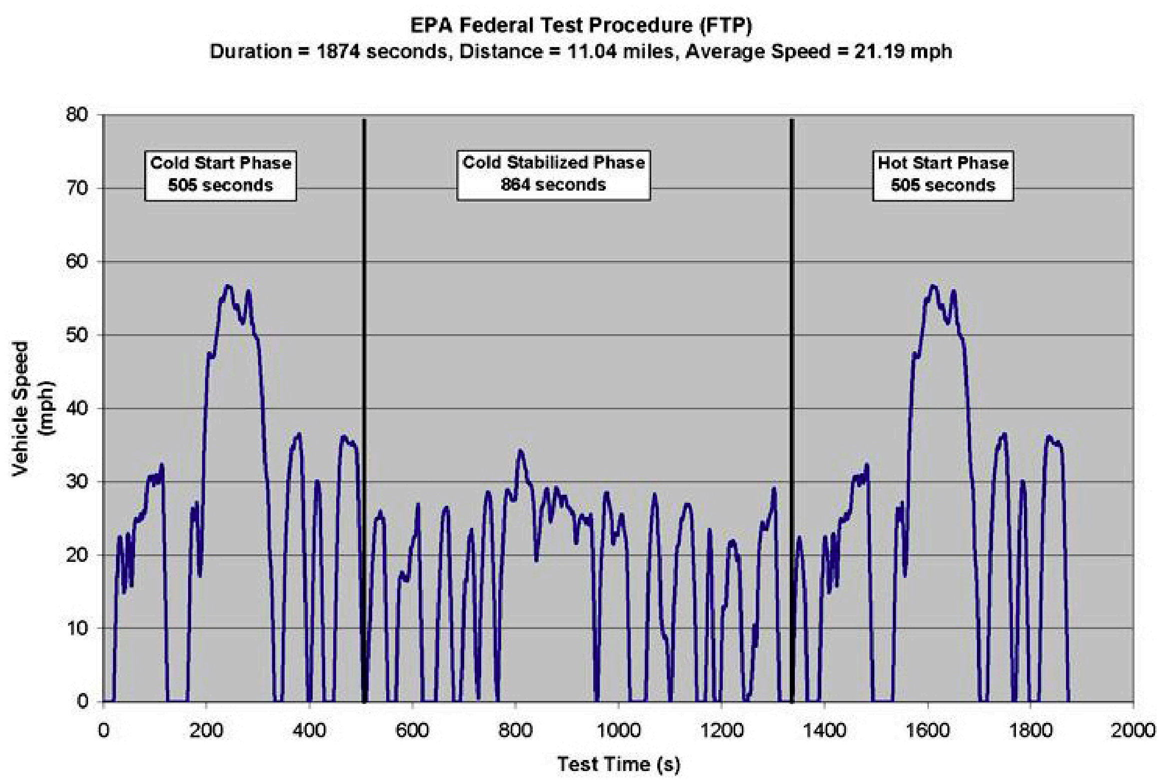

Figure 1 U.S. Federal Test Procedure

On road driving

A 5-mode on road driving cycle was designed in-house at ERMS. The route chosen around Ottawa enabled a mix of driving on arterial and highway roads at different speeds and congestion conditions as summarized in Table 1. It should be noted that this on road driving cycle is not the same as the RDE cycle used in EU regulations[3]. ERMS later developed a EURO VI-compliant test route in September 2017, which is now the current test route for in-use light-duty vehicle tests. However, the data for the fleet of 50 in this report is based on the ERMS 5-mode cycle.

Table 1 5-mode on road test conditions

Mode	Average Speed (kph)	Max Speed (kph)	Idle Time (%)	Distance (km)	Time (min)
1	30.3	82.6	29%	6.6	13.45
2	31.9	70.6	24%	4.9	9.48
3	23.1	56.5	26%	2.6	6.73
4	63.3	109.3	10%	15.4	14.60
5	41.9	90.4	25%	13.1	18.91

The mode weighted emission rate for the complete test is reported as:

$$e_{test} = 0.55(d_1 * e_1 + d_2 * e_2 + d_3 * e_3 + d_5 * e_5) + 0.45(d_4 * e_4)$$

where d_i is the distance for mode i and e_i is the average mass emission rate measured over mode i, 55% and 45% representing the share of real world driving postulated in the respective modes.

Figure 2 5-mode on road test route

[3] https://www.acea.be/industry-topics/tag/category/real-driving-emissions-test

2.3 Emission measurements

Laboratory testing (CFR 40)

The laboratory tests and the related measurements were completed in accordance with *40 CFR Subpart C - Measurement Instruments*[4]

PEMS On road measurements

On road emissions were measured on the basis of mass emitted per distance travelled using a commercially available Portable Emissions Measurement Systems (PEMs) that were compliant with US EPA 40 CFR, Part 1065 Subparts D and J.[5] Multiple PEMs units were used such as the SEMTECH® LDV system, Ecostar, DS. [6]

3. Results and Analysis

The mass emission rates for CO, CO_2, NO_x, THC were measured in both laboratory and on-road testing for two vehicles: the 2016 gasoline-CNG Dual Fuelled Vehicle (DFV), and the 2015 flexi-fuelled vehicle (FFV). These measurements are shown graphically in the respective sections (3.1 and 3.2) below. Further below, in Section 3.3 the laboratory and on-road measurements for the fleet of 50 gasoline and diesel light duty vehicles are presented.

For the two vehicles in Section 3.1 and 3.2 measurement results in addition to CO, CO_2, NO_x, THC are also shown for NMHC and BTEX laboratory tests. The laboratory tests also include measurements on other unregulated emissions not shown here. Three replicates were completed for each fuel-vehicle-driving cycle combination in laboratory tests, while four replicates are available for most of the 5-mode on road tests. The error bars in the column charts represent ± 1standard deviation. Statistical analysis by the comparison of small populations have been carried out to determine the significance of differences between fuels and driving cycles. Statistically significant differences (95% confidence level) are indicated below each graph, separately for fuel effects and driving cycle effects (FTP vs 5-mode for the base fuel). The fuel and driving cycle effects are summarized and discussed briefly at the end of Sections 3.1 and 3.2. General discussion common to both these sections is presented after Section 3.2, just prior to Section 3.3.

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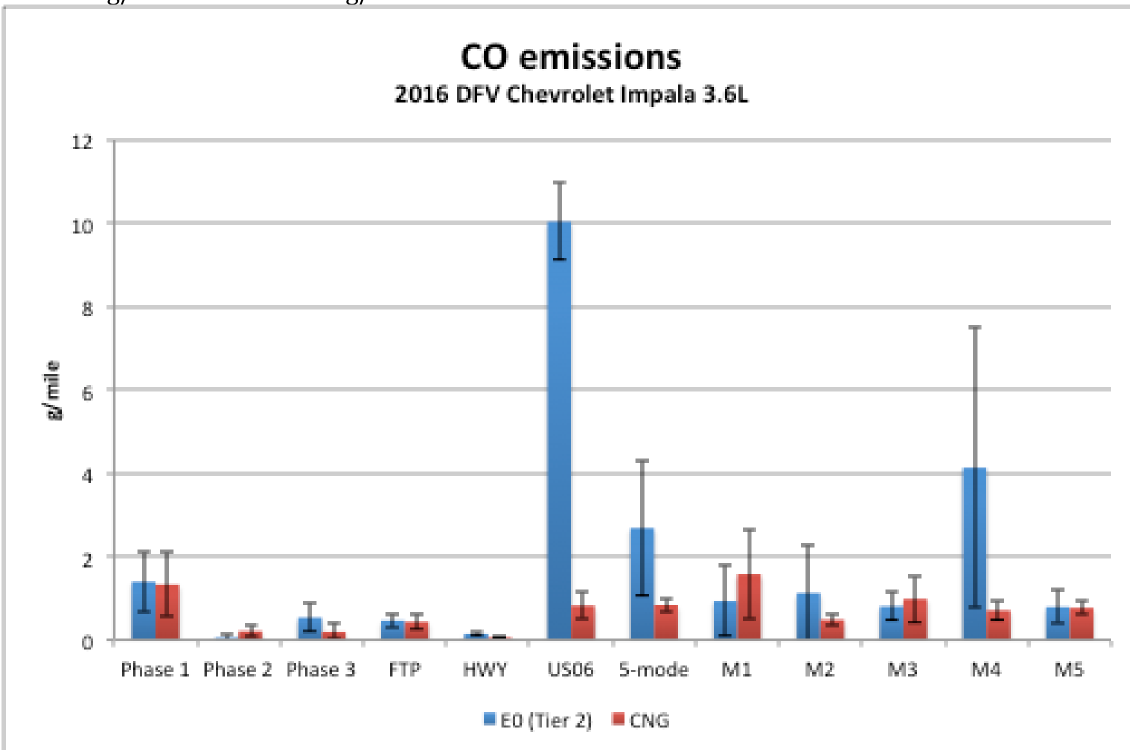
[4] https://www.law.cornell.edu/cfr/text/40/part-1065/subpart-C
[5] https://www.law.cornell.edu/cfr/text/40/part-1065/subpart-J
[6] http://www.sensors-inc.com/Applications/Vehicle_Emissions/Light_Duty_PEMS

3.1 E0 vs CNG, 2016 DFV Chevrolet Impala 3.6L

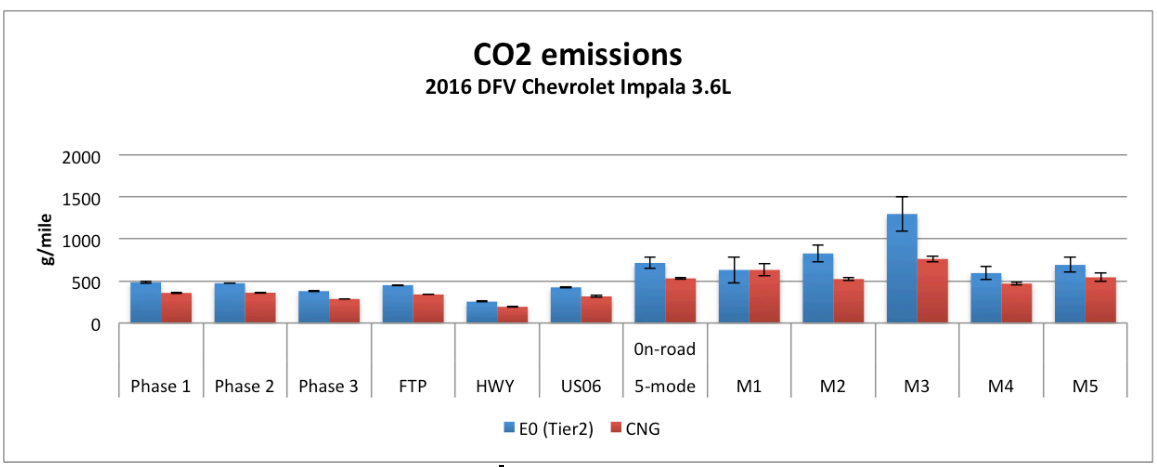
The CNG/gasoline DFV Impala is classed as an LDV (see Table 3) with emission certification limits defined by "Tier 2 Bin 4"[7], i.e. at Full Useful Life:

NO_x: 0.04 g/mile NMOG: 0.07 g/mile CO: 2.1 g/mile
PM: 0.01 g/mile HCHO: 0.011 g/mile



Significant (95% confidence) fuel effects : (↓) with CNG in HWY, US06
FTP vs 5-mode difference significant ? (95% confidence) : No, with E0; Yes (↑) with CNG

Figure 3 CO emissions for DFV Impala



Significant (95% confidence) fuel effects : (↓) with CNG in FTP, HWY, US06, 5-mode on road
FTP vs 5-mode difference significant ? (95% confidence) : Yes (↑) with E0, Yes (↑) with CNG

Figure 4 CO_2 emissions for DFV Impala

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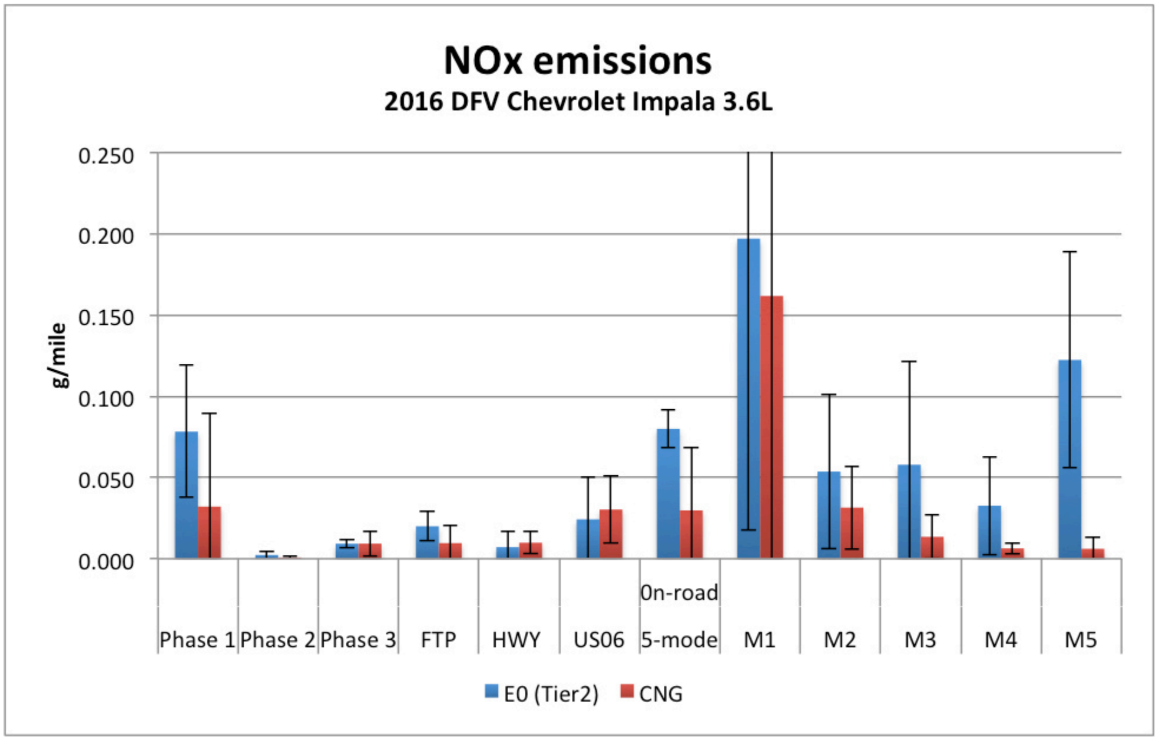
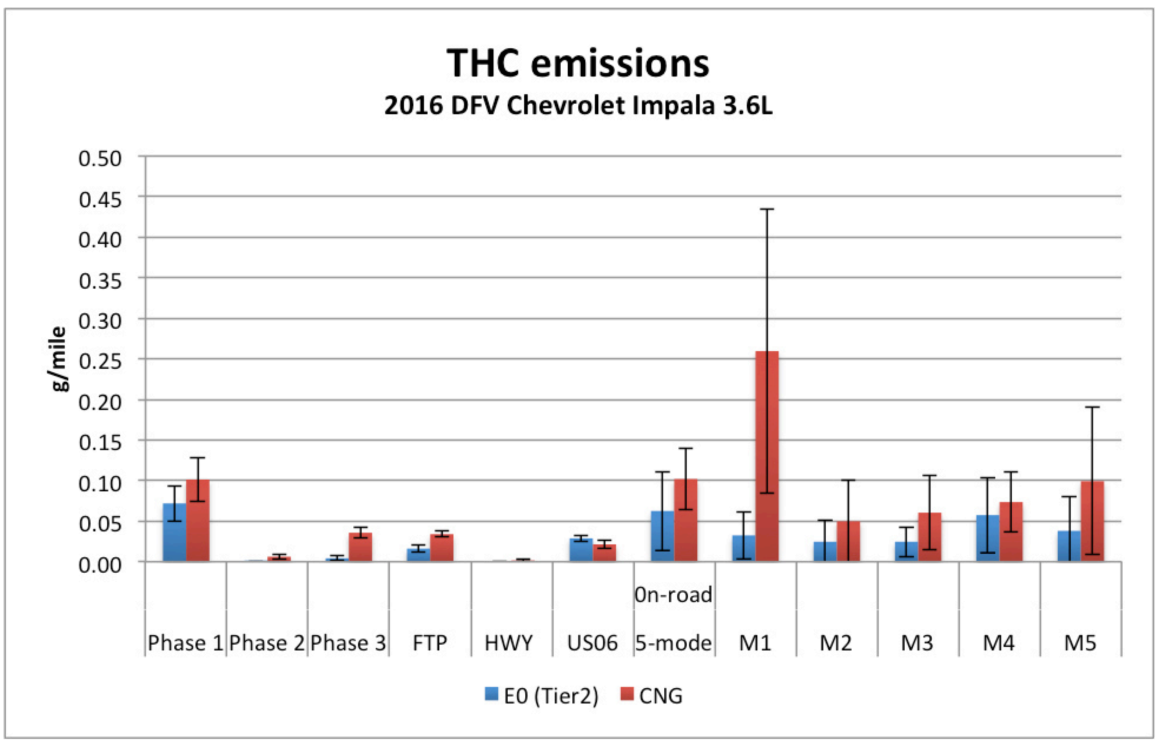
[7] https://nepis.epa.gov/Exe/ZyPDF.cgi/P100SMQA.PDF?Dockey=P100SMQA.PDF



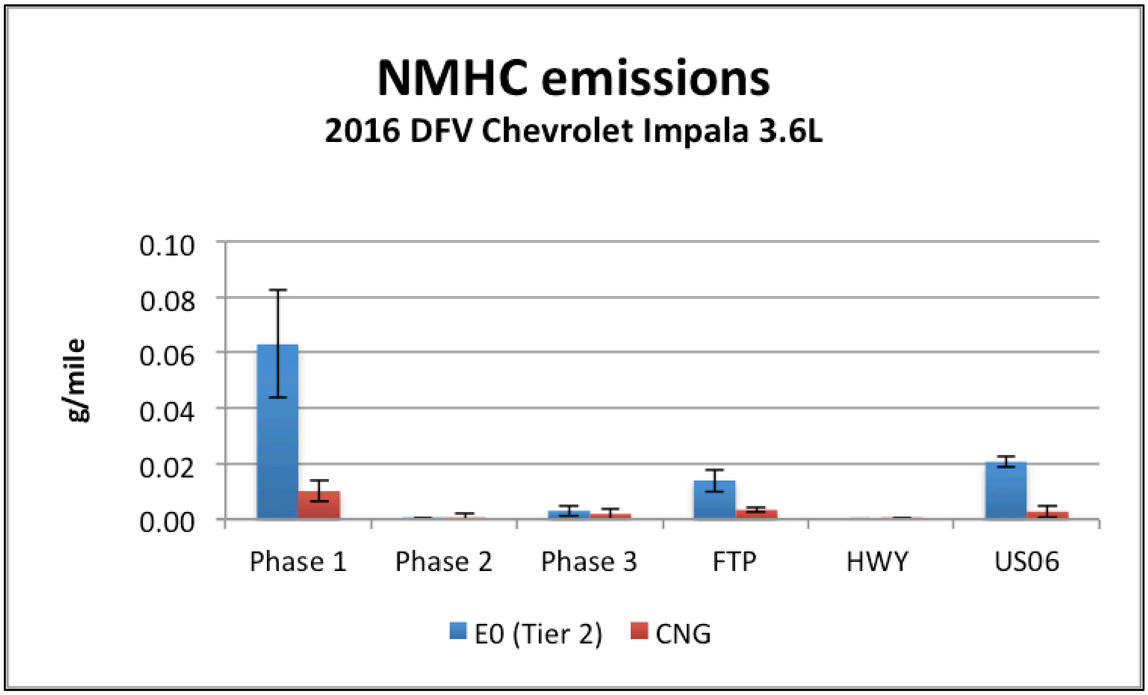
Significant (95% confidence) fuel effects : none of the driving cycles
FTP vs 5-mode difference significant ? (95% confidence) : Yes (↑) with E0, No with CNG

Figure 5 NO$_x$ emissions for DFV Impala



Significant (95% confidence) fuel effects : (↑) with CNG in FTP
FTP vs 5-mode difference significant ? (95% confidence) : Yes (↑) with E0, Yes (↑) with CNG

Figure 6 THC emissions for DFV Impala



Significant (95% confidence) fuel effects : (↓) with CNG in FTP, US06

Figure 7 NMHC emissions for DFV Impala

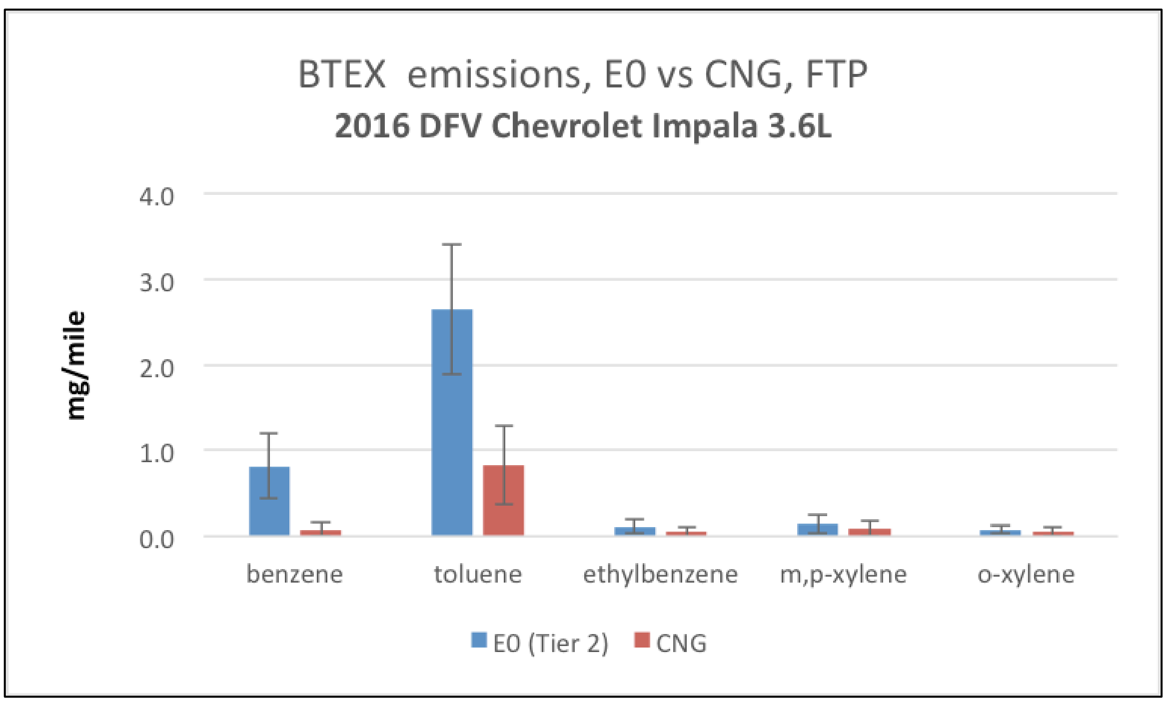


Figure 8 BTEX emissions for DFV Impala

Fuel effects on emissions

CNG relative to E0 (for laboratory tests and E10 (5-mode on road test) showed reduced CO (HWY, US06), CO_2 (FTP, HWY, US06, 5-mode), and NMHC (FTP, US06), and BTEX (FTP) emissions over the indicated driving cycles, but increased THC (FTP) emissions. The difference between the fuel effects on THC and NMHC can be directly attributed to the methane component of CNG. No effect was observed on NO_x emissions.

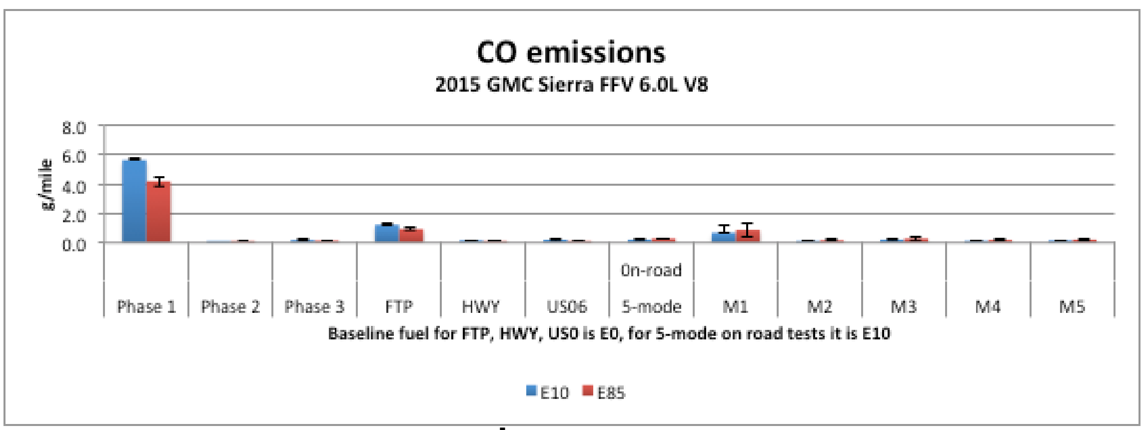
Driving cycle effects on emissions

In comparing the FTP and 5-mode on road cycles, the only driving cycle effect observed was the increase in THC for the 5-mode on road driving cycle. The emission measurements for the on road tests did not have the breakdown for methane and NMHC but it can be assumed that the increase was essentially due to methane. It is noteworthy that NO_x emissions showed no significant increase.

3.2 E0 and E10 vs E85, 2015 GMC Sierra FFV 6.0L V8

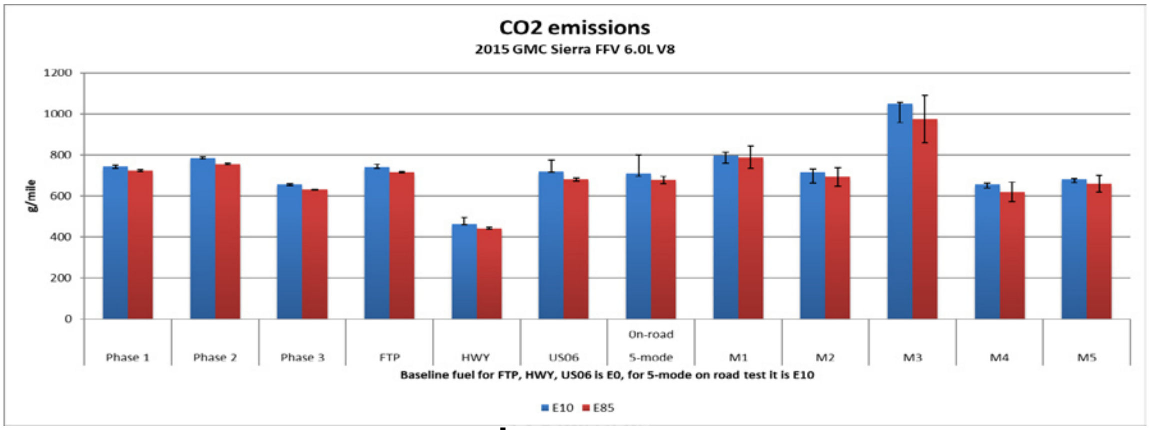
This vehicle is classified as HDV1 (Federal HD chassis Class 2b GVW 8501-10000) The certification limits for this for the FTP are :

CO = 7.3 g/mile
NO_x = 0.2 g/mile



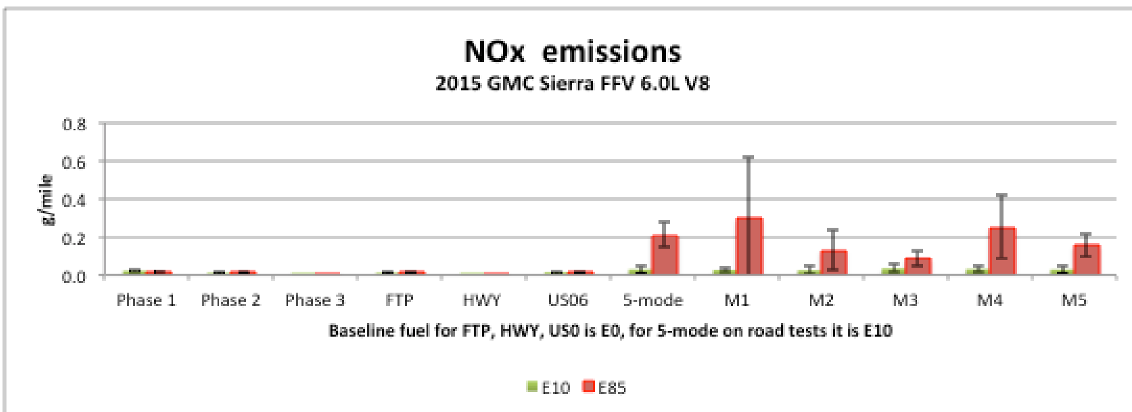
Significant (95% confidence) fuel effects : (🡇) with E85 in FTP, HWY, US06
FTP vs 5-mode difference significant ? (95% confidence) : Yes (🡇) with E10, Yes (🡇) with E85

Figure 9 CO emissions for FFV Sierra



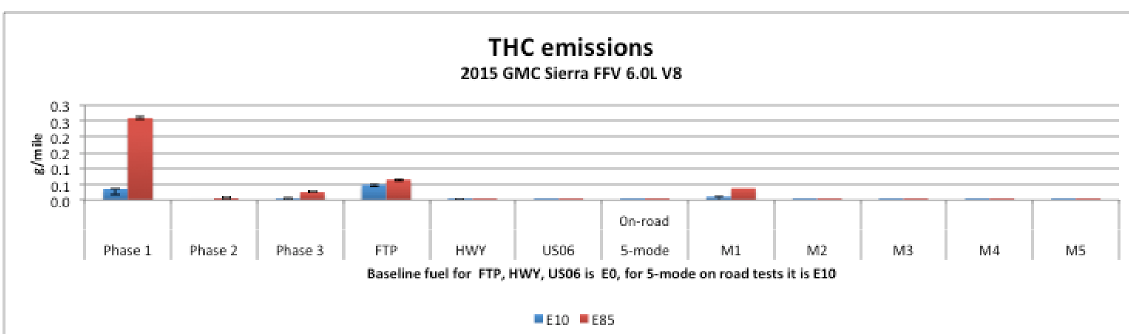
Significant (95% confidence) fuel effects : (↓) with E85 in FTP, HWY, US06, 5-mode on road
FTP vs 5-mode difference significant ? (95% confidence) : Yes (↓) with E10, Yes (↓) with E85

Figure 10 CO_2 emissions for FFV Sierra



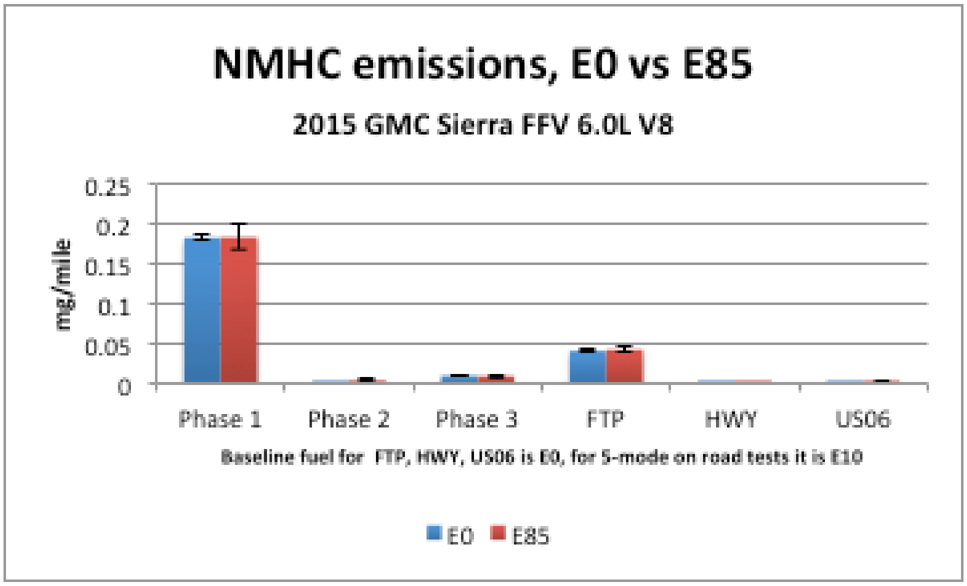
Significant (95% confidence) fuel effects : (↑) with E85 in HWY, 5-mode on road
FTP vs 5-mode difference significant ? (95% confidence) : No with E10, Yes (↑) with E85

Figure 11 NO_x emissions for FFV Sierra



Significant (95% confidence) fuel effects : (↑) with E85 in FTP, 5-mode on road
FTP vs 5-mode difference significant ? (95% confidence) : Yes (↓) with E10, Yes (↓) with E85

Figure 12 THC emissions for FFV Sierra



Significant (95% confidence) fuel effects : none

Figure 13 NMHC emissions for FFV Sierra

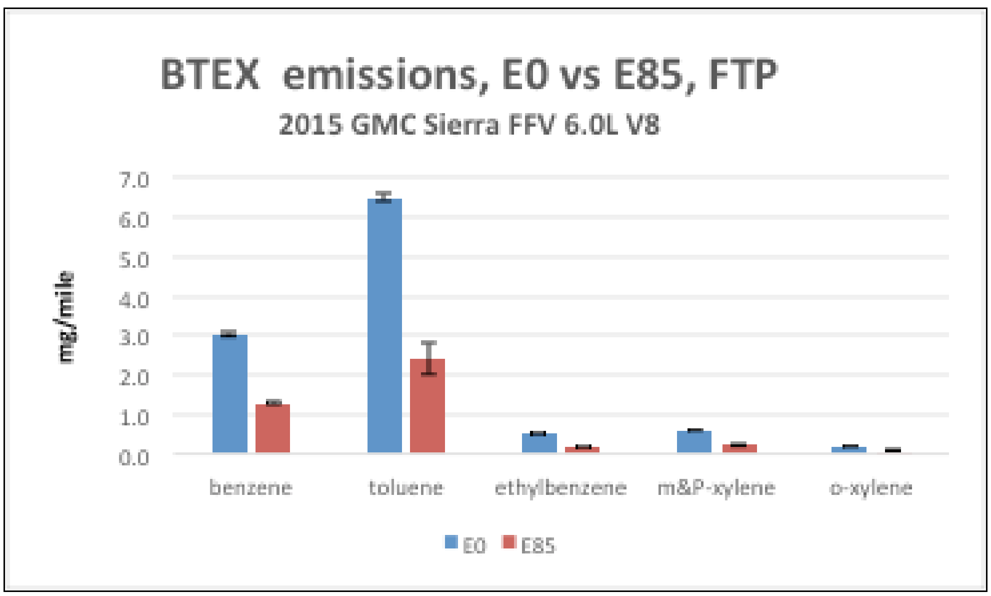


Figure 14 BTEX emissions for FFV Sierra

Fuel effects on emissions

E85 compared to E10 showed reduced CO (FTP, HWY, US06), CO_2 (FTP, HWY, US06, 5-mode), and BTEX (FTP) emissions over the indicated driving cycles, but increased NO_x (HWY, 5-mode on road) and THC (FTP, 5-mode on road) emissions.

The higher NO_x emissions with E85 compared to E10 are surprising in light of previously published data. For example, a study (Gramsch et al 2018) reviewed as part of Annex 54 work reports a decreasing trend for NO_x emissions as a function of increased ethanol content for two vehicles between E0-E85, and E22-E100. Yang et al (2019) report no statistically significant difference between the test fuels (E10, E30, E78) over cold and hot started LA92[8] driving cycles.

Elevated NMHC emissions for Phase 1 of the FTP stand out, similar to THC, due to the cold start effect, without difference between E0 and E85.

BTEX emissions show a marked decrease for E85, presumably due to the lower aromatics content of the E85.

Driving cycle effects on emissions

5-mode on road driving cycle emissions compared to FTP (both with E85 fuel) showed lower emissions of CO, CO_2 and THC but higher emissions of NO_x.
The speed vs time histories across the modes and runs for on-road driving can show variability because they are affected by other vehicle traffic during the test . Thus the difference between on-road emissions and dynamometer tests with fixed speed vs time traces are understandable but not easily interpreted.

General Discussion for alternative fuel vehicles

Sections 3.1 and 3.2 have presented data and analysis in support of the statements on the fuel and driving cycle effects on tailpipe emissions of CO, CO_2, NO_x, THC, NMHC and BTEX emissions from 2 vehicles. Care needs to be taken in recalling the context in which the statements about the significance of a particular effect are made:

First, the statements about fuel or driving cycle effects pertain to a single vehicle even though multiple tests are carried over many cycles.

Second, the observed effects in many of the cases studied are generally small in the face of the variability/uncertainty involved in the measurements, thus requiring statistical analysis. It is not uncommon to use 95% confidence level in making comparisons between the means of populations even when the populations are relatively small. However, using a 99% confidence level is also not out of the question and would lead to change in considering whether a particular difference is "significant" or not. Table 2 captures effects identified as significant at the 95% confidence level which would not be considered so at the 99% level. Thus, as examples: for the 2016 Impala, the Fuel effect on CO emissions in the HWY test

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[8] The California Unified Cycle (UC) is a dynamometer driving schedule for light-duty vehicles developed by the California Air Resources Board. The test has been also referred to as the Unified Cycle Driving Schedule (UCDS) or as the LA92 (also spelled LA-92) cycle. The test is often called the "Unified LA92", to distinguish it from a "short LA92", which includes the first 969 seconds of the Unified LA92.
https://www.dieselnet.com/standards/cycles/uc.php

identified as significant in Figure 4 would *not* be significant at the 99% confidence level, although the significance of fuel effects for the other cycles (FTP, US06, 5-mode on road) would not be affected. Similarly, for the 2015 Sierra, the FTP vs 5-mode driving cycle effect on CO_2 emissions identified as significant in Figure 10 for both E10 and E85 would *not* be significant at the 99% confidence level for E85.

Table 2 Statistics affected by confidence level

The indicated effects statistically significant at the 95% level would not be significant at the 99% level

Vehicle	Emission	Effect
2016 DFV Impala	CO ↓	Fuel, in HWY
	THC ↑	Driving cycle (FTP vs 5-mode on road, with E0 and CNG)
2015 FFV Sierra	CO ↓	Fuel, in US06
	CO_2 ↓ ↓	Fuel, in 5-mode on road Driving cycle (FTP vs 5-mode on road with E85)
	NO_x ↑	Fuel, in HWY
	THC ↑	Fuel, in 5-mode on road

3.3 Fleet of gasoline and diesel light duty vehicles

The fleet of nominally 50 light duty (LDV and LDT classifications) gasoline and diesel vehicles were tested on road using the 5-mode test developed at ERMS. The vehicles are identified by model year and regulatory classification under the U.S. EPA classification system[9]:

Table 3 U.S. EPA Vehicle Classification by GVWR

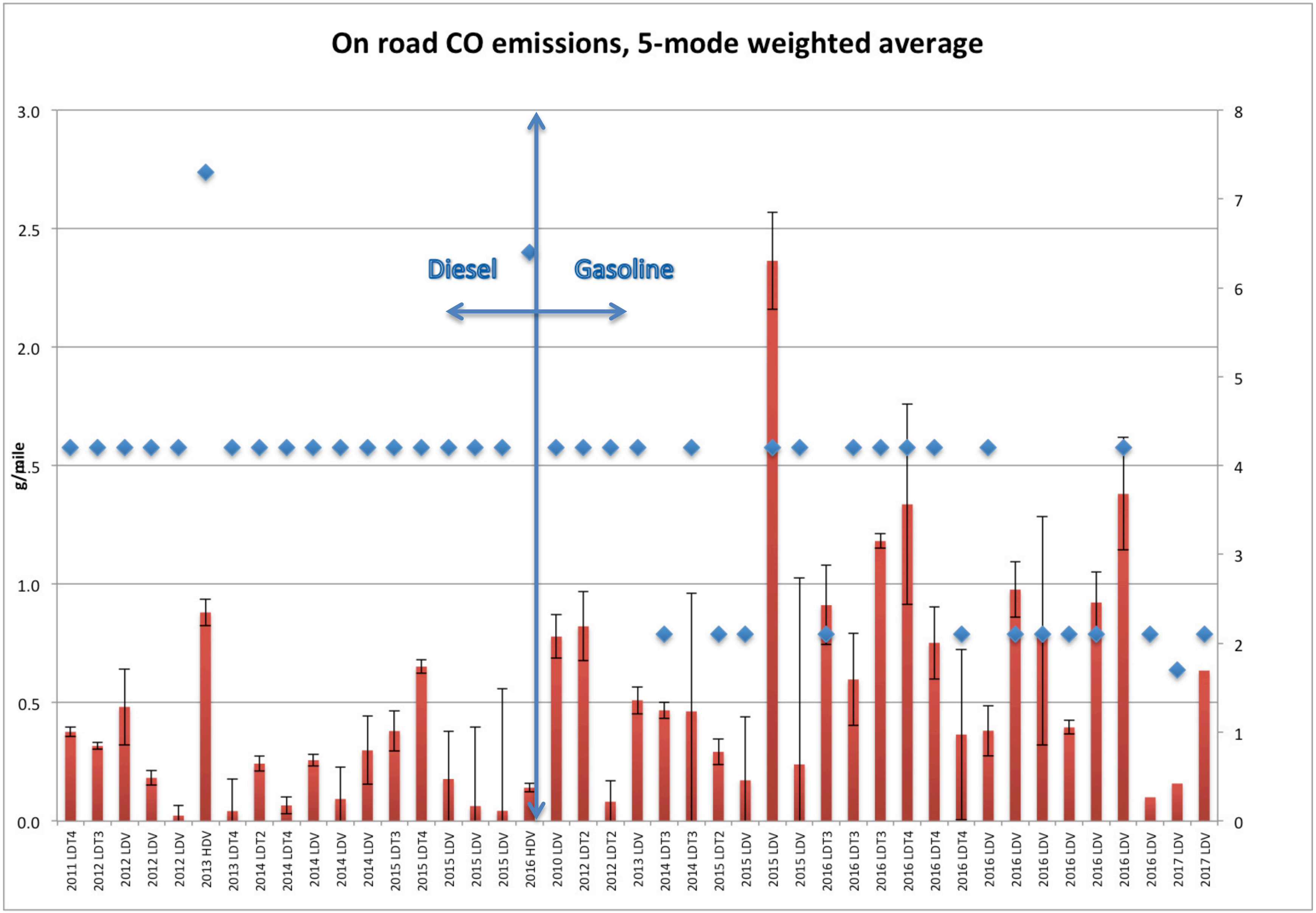
<table>
<tr><th colspan="11">Gross Vehicle Weight Rating (lbs)</th></tr>
<tr><th></th><th>6,000</th><th>8,500</th><th>10,000</th><th>14,000</th><th>16,000</th><th>19,500</th><th>26,000</th><th>33,000</th><th>60,000</th><th></th></tr>
<tr><td rowspan="4">Federal</td><td colspan="2">LDV</td><td>MDPV</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">LDT</td><td colspan="8">HDV / HDE</td></tr>
<tr><td>LLDT</td><td>HLDT</td><td colspan="4">LHDDE</td><td colspan="2">MHDDE</td><td colspan="2">HHDDE / Urban Bus</td></tr>
<tr><td>LDT 1 & 2 [a]</td><td>LDT 3 & 4 [b]</td><td>HDV2b</td><td>HDV3</td><td>HDV4</td><td>HDV5</td><td>HDV6</td><td>HDV7</td><td>HDV8a</td><td>HDV8b</td></tr>
</table>

a Light-duty truck (LDT) 1 if loaded vehicle weight (LVW) = 3,750; LDT 2 if LVW > 3,750
b LDT 3 if adjusted loaded vehicle weight (ALVW) = 5,750; LDGT 4 if ALVW > 5,750

The testing was carried out over a period of three years, with 3-4 replicates for each vehicle. The following figures demonstrate the overall results. The order of the data presented is by model year.

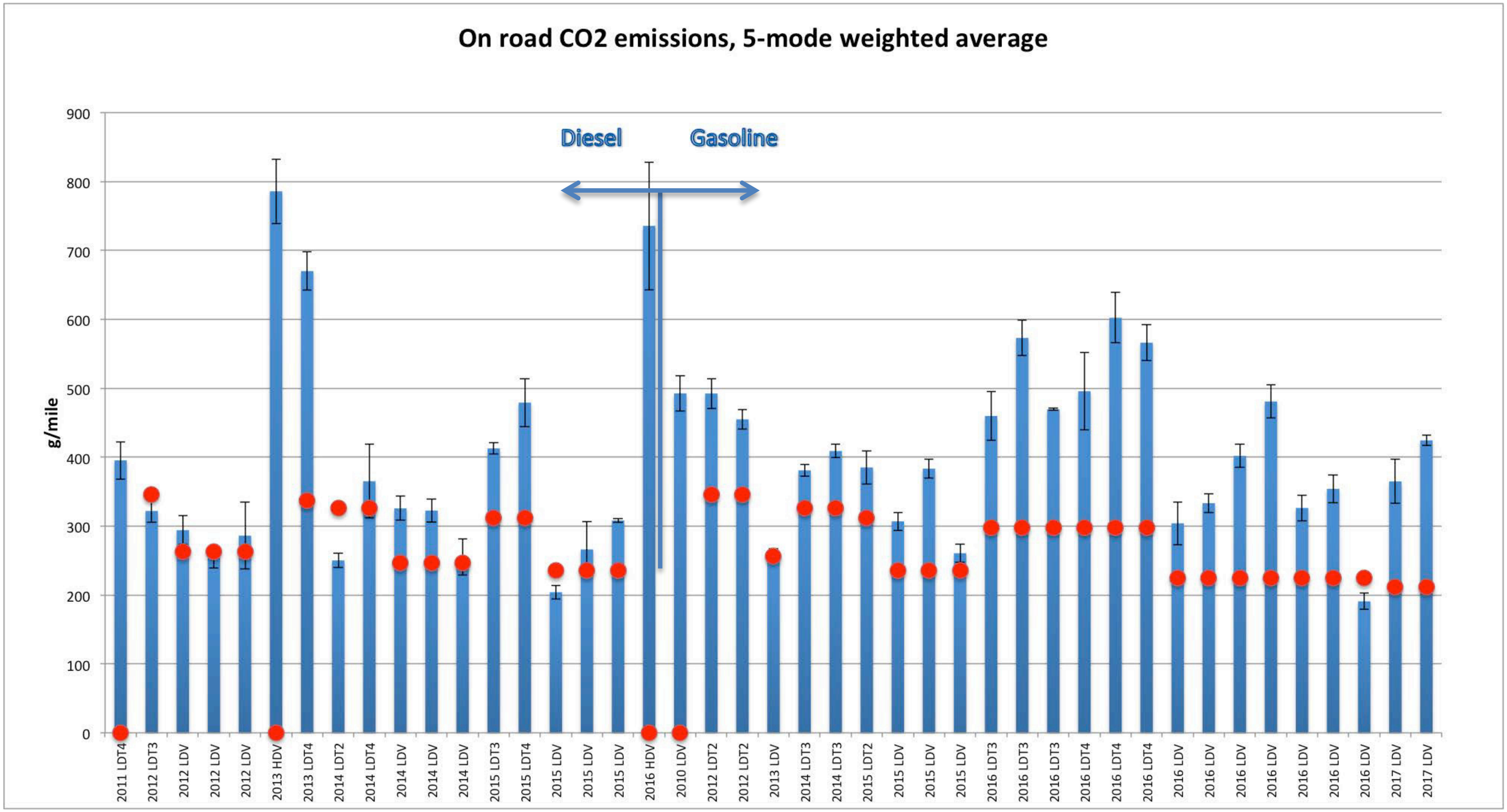
While there is significant variability in Figure 15 among the tests (3-4 replicates) comparison shows that none of the CO emission rates measured on road exceeded the respective FTP limit, and most of the fleet had on road CO emission rates well below 50% of the FTP limits.

[9] https://www.epa.gov/emission-standards-reference-guide/vehicle-weight-classifications-emission-standards-reference-guide



On road CO emission rates are represented by the red columns; the blue diamonds represent the FTP certification limits for the respective vehicles and should be read quantitatively from the right axis.

Figure 15 On road CO emissions from LDV fleet



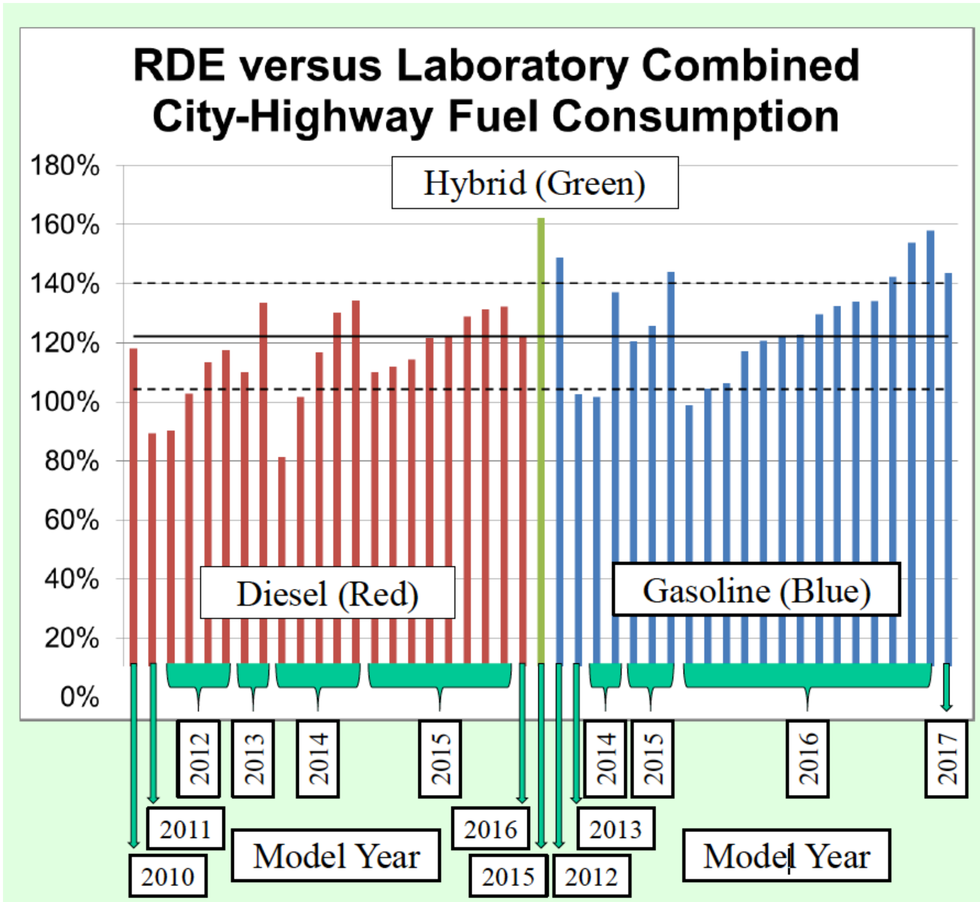
Red dots represent fleet average CO_2 standards for Passenger cars and Light trucks and do not apply to HDV (2013 and 2016), 2010 LDV and 2011 LDT4.

Figure 16 On road CO_2 emissions from LDV fleet

In Figure 16 the on road CO_2 emissions are compared with the fleet wide CO_2 compliance levels for Passenger cars and Light trucks which are available from 2012 onwards. The measured values of CO_2 emission rates showed much less variation between tests (3-4 replicates) compared to CO (Figure 15), NO_x (Figure 18) and THC (Figure 20) emission rates. The average values for individual vehicles were mostly above the fleet wide compliance levels. However, this cannot be taken as a particularly indicative comparison as the compliance levels are for the passenger car and light truck fleets of individual manufacturers, and the few vehicles from a particular manufacturer's fleet are not necessarily representative. It should also be noted that the ERMS on road 5 mode route was not developed to mimic the laboratory cycles but was developed to represent real world driving.

In a previous analysis of the fleet data, Conde & Rideout (2019) focused on the difference of fuel economy measured in laboratory testing and on road driving ("real driving"). The comparison was made between the average fuel economy for the entire fleet (gasoline and diesel) for the two driving conditions and concluding "*Fuel consumption from real-world testing is, on average, 22 % higher than the observed fuel consumption from tests on a chassis dynamometer*". The variation among the vehicles is shown in Figure 17 where the ratio of the on road fuel economy to laboratory fuel economy is indicated by the solid line at 122%, the dashed lines representing ± 1 standard deviation.

Figure 16 and Figure 17 highlight different aspects of essentially the same picture, given the strong correlation between fuel economy and CO_2 emissions, and the fact that CO_2 emissions for individual vehicles were mostly above the fleet wide compliance levels.



From: Conde & Rideout 2019. **Note:** RDE is used generically here and does not refer to the EU RDE cycle. The data in the figure are based on the 5-mode ERMS driving cycle

Figure 17 Fuel economy on road vs laboratory driving, LDV fleet

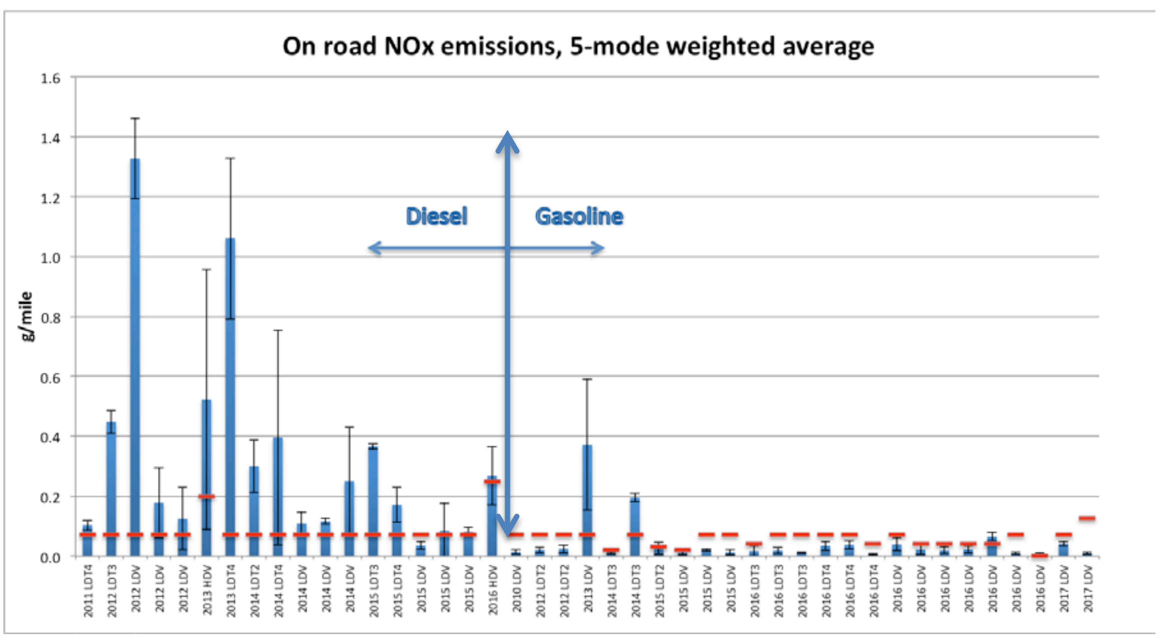


Figure 18 On road NO_x emissions from LDV fleet

Figure 18 highlights the difficulty for the diesel fleet to meet the FTP limits during on road driving (NO_x emission rates, blue columns, compared with the FTP emission limits, red lines for respective vehicles). Although there is higher variability among the tests for NO_x measurements than for CO, CO_2 and THC, most of the diesel fleet (along with three vehicles from the gasoline fleet) are clearly above the FTP limits. Conde & Rideout (2019) had observed: *"84% of vehicles that were tested on-road presented a statistically significant increase in NO_x when comparing real-world and laboratory results on a chassis dynamometer"*. As the actual FTP NO_x emission rates for individual vehicles are available in most cases, it is possible to directly compare these two measured values in Figure 19 below.

Figure 19 shows most of the tested vehicles are within a narrow range inside the 0.07 g/mile FTP NO_x emission limit while the on road emissions cover a higher range, exceeding the FTP limit going as high as 1.4-7.5 times their FTP emissions. The outlier with the high on road emissions is 19 times above the limit. While it can be expected that on road driving presents some challenges that the FTP might not, clearly there are differences in the ability of the tested vehicles to meet these challenges.

The measured THC emission rates were prominent mostly for the gasoline vehicles and showed relatively high variability among tests. There were also many instances when THC data could not be obtained with the PEMS device. A direct comparison with a regulatory limit is not meaningful as the regulations for the model years of interest are based on NMOG, and NO_x+NMOG limits.

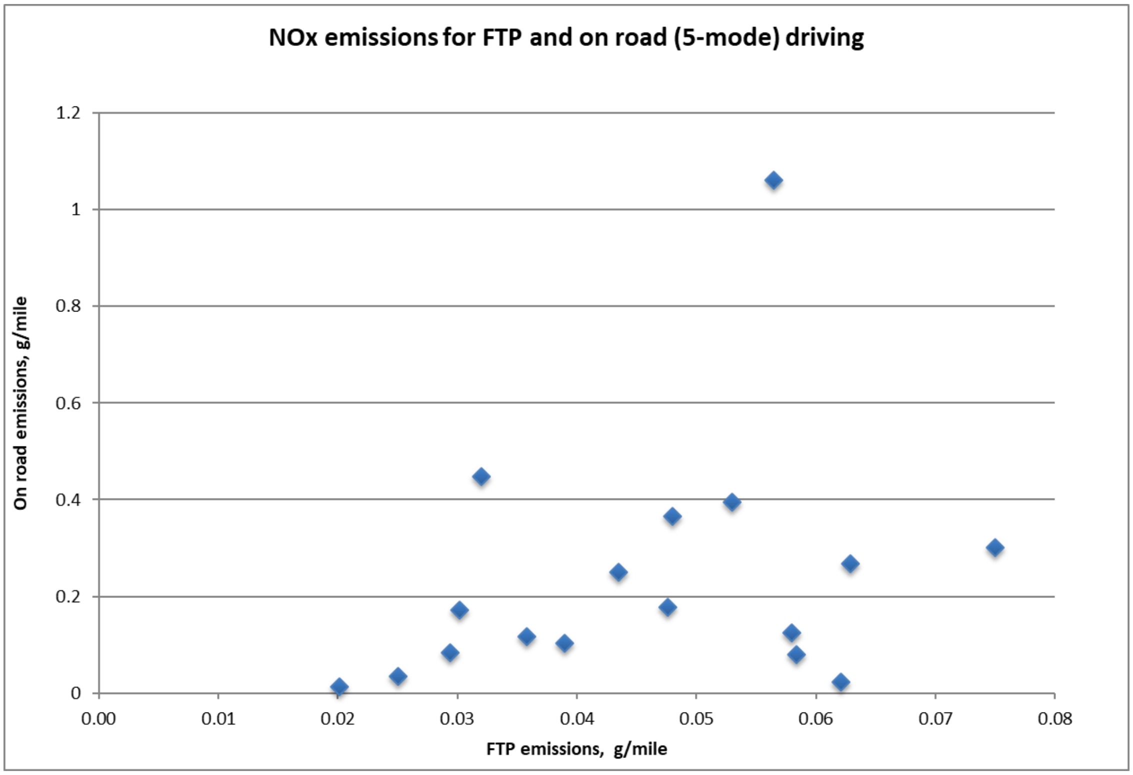
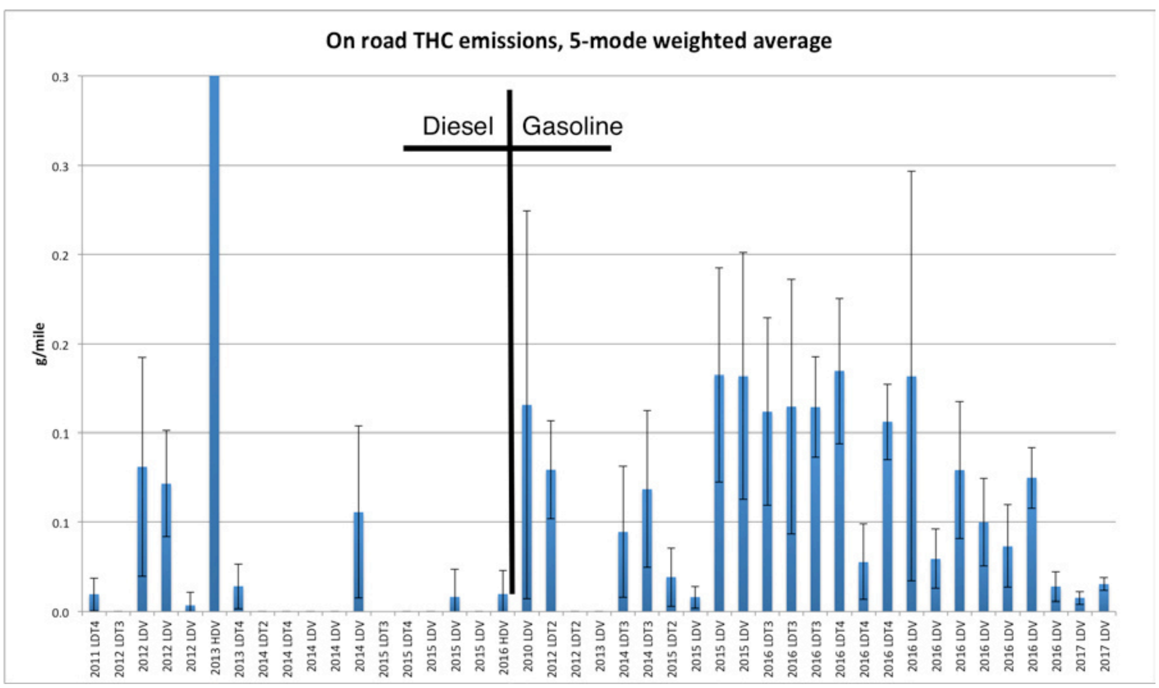


Figure 19 On road vs FTP NO_x emissions for diesel LDVs



Note: 2013 HDV off-scale with 0.426 ± 0.455

Figure 20 On road THC emissions from LDV fleet

4. Conclusions / Key Findings

The effect of two alternative fuels (CNG and E85) and driving types (laboratory tests vs on road driving) on tailpipe emissions were studied in detail using two vehicles. The effect of driving type for diesel and gasoline vehicles was studied with a fleet of 50 light duty vehicles and trucks.

Alternative fuel vehicles

- CO and CO_2 emissions were lower with both the alternative fuels (CNG and E85) relative to baseline fuels (E0 and E10)

- NO_x emissions were not significantly affected by CNG relative to E0 with the dual fuel vehicle. For the flex-fuelled test vehicle E85 showed an increase in NO_x relative to E10.

- BTEX emissions were significantly reduced with both CNG and E85 compared to E0.

- 5-mode on road driving led to higher test to test variability for all emissions and did not show significant difference from laboratory tests for the alternative fuels with the two vehicles.

Diesel and Gasoline Vehicle Fleet

The effect of driving type for diesel and gasoline vehicles was studied with a fleet of 50 light duty vehicles and trucks. The 5-mode on road driving cycle showed relatively high test to test variability in nearly all the measured parameters (CO, NOx, THC), with CO_2 emissions showing lowest variability.

The emissions from the vehicles in the fleet were compared with the respective FTP certification limits or FTP emissions.

- None of the CO emission rates measured on road exceeded the respective FTP limit, with most being well below 50% of the FTP limits.

- The measured values of CO_2 emission rates showed much less variation between tests (3-4 replicates) compared to CO, NO_x and THC measured values. The average values for individual vehicles were mostly above the fleet wide compliance levels.

- On road NO_x emissions for the diesel fleet showed significant increases over the emissions in FTP tests; most vehicles which had been below the 0.07 g/mile FTP NO_x emission limit exceeded the FTP limit with on road emissions as high as 1.4-7.5 times their FTP emissions.

References

Conde A., Rideout G., *Fuel Economy Comparison of Real-World Emissions and Chassis Dynamometer Tests,* 28th Coordinating Research Council Real World Emissions Workshop. March 18-21, 2018

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Yang, J., Patrick Roth, Thomas D. Durbin, Kent C. Johnson, David R. Cocker, III, Akua Asa-Awuku, Rasto Brezny, Michael Geller, and Georgios Karavalakis, *Gasoline Particulate Filters as an Effective Tool to Reduce Particulate and Polycyclic Aromatic Hydrocarbon Emissions from Gasoline Direct Injection (GDI) Vehicles: A Case Study with Two GDI Vehicles*, Environ. Sci. Technol. 2018, 52, 3275−3284.

Yang J., Patrick Roth, Thomas D. Durbin, Martin M. Shafer, Jocelyn Hemming, Dagmara S. Antkiewicz, Akua Asa-Awuku, Georgios Karavalakis. *Emissions from a flex fuel GDI vehicle operating on ethanol fuels show marked contrasts in chemical, physical and toxicological characteristics as a function of ethanol content,* Science of the Total Environment 683 (2019) 749–761

Appendix II – Full report from Denmark

IEA-AMF Annex 55:
Real Driving Emissions

EUDP J.nr. 64016-0005

DANISH TECHNOLOGICAL INSTITUTE

IEA-AMF Annex 55:
Real Driving Emissions

EUDP J.nr. 64016-0005

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July 2019

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1. Contents

2. Background and purpose

IEA-AMF Annex 55 was initiated in October 2016 by delegates from Canada, Sweden, USA, Finland, Switzerland and Denmark. With this report, we wish to contribute to the understanding of interactions between fuel properties, engine and after-treatment technologies, use patterns, traffic, road and weather conditions, efficiency requirements and real-world emissions.

The data and analysis from the work intends to enable researchers to understand the differences of real-world emissions and energy consumption compared to type approval emissions and energy consumption. A secondary purpose is to understand what research (i.e. After-treatment systems, powertrain system control, modeling…) could reduce these potential gaps. The data and analysis is also intended to help policy makers to have more informed discussions.

The Danish test program was organized as a joint project between FDM – the Danish Motor owner's association, member of FIA, and Danish Technological Institute. Funding was raised through the national Energy Development and Demonstration Program, EUDP (Journal 64016-0005).

The test program covers real road driving in cold weather with a focus on smaller diesel vehicles. This vehicle category is especially popular in Denmark due to the low tax on diesel fuel and a progressive vehicle registration tax which favors vehicles with a low CO_2-emission.

The motivation for testing diesel vehicles in cold weather was to investigate the so-called Thermal Window Protection, which allows certain emissions control systems to be switched off at lower ambient temperatures. Typically, the Urea Dosing System (aka AdBlue system) which as part of the NOx abatement solution on newer vehicles, will be switched of at temperatures below e.g. 10°C. This is done, presumably, to protect the system from damage arising from crystallization of urea etc... However, it may also be a convenient way to save on urea. Some vehicles have reportedly been fitted with suspiciously small urea tanks which would indicate that the real consumption of urea is not sufficient to clean the exhaust gasses.

FDM has pointed out that some of the smaller diesel vehicles on the market hardly use any urea at all. That would lead to a strong suspicion that real life NOx emissions are higher than they should be.

3. Vehicles

The Danish team was focused on smaller vehicles with 4-cylinder turbocharged diesel engines certified to European EURO 6. For reference one gasoline vehicle was included. The vehicles are highly representative of the Danish car market. Especially Skoda Octavia, Renault Kadjar, Citroen C3 and Peugeot 208 are among the bestselling family cars today. BMW X1 is slightly higher priced than the others but still a very popular model.

Table 1 Technical data of the vehicles tested

Car model	Skoda Octavia 1.4 TSI	BMW X1 Sdrive 18D	Renault Kadjar 130 dCi	Citroën C3 1.6	Peugeot 208 BlueHDi 100
Fuel	E5 Gasoline	B7 Diesel	B7 Diesel	B7 Diesel	B7 Diesel
EURO Class	5b	6b	6b	6b	6b
Reg. year	2015	2017	2016	2015	2017
Displacement, configuration	1395 cm^3, I4, turbo	1995 cm^3, I4, turbo	1598 cm^3, I4, turbo	1560 cm^3, I4, turbo	1560 cm^3, I4, turbo
Engine power	103 kW	110 kW	96 kW	73 kW	73 kW
Transmission	Automatic	Manual	Manual	Manual	Manual
AdBlue/SCR	No	No	No	Yes	Yes
Engine code (family)	CHPA (EA211)	B47C20A	R9M E4	BH02	BH02
CE approval no.	e1*2007/46*0243*13	e1*2007/46*1676*02	e2*2007/46*0475*04	e2*2007/46*0003*38	e2*2007/46*0070*37
Approval date	02-04-2014	19-06-2017	02-02-2016	03-09-2015	16-08-2016
Directive	715/2007*195/2013J	715/2007*2015/45W	715/2007*2015/45W	715/2007*2015/45W	715/2007*2015/45W
CO2 declared [g/km]	116	109	113	79	79
CO declared [mg/km]	597	222.2	191	195.5	195.5
NOx declared [mg/km]	21.4	37.3	37.2	34	34

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4. Equipment

The Danish team used an AVL M.O.V.E. PEMS Is system with PEMS-Pn particle counter. Main components of the system are shown in Figure 1.

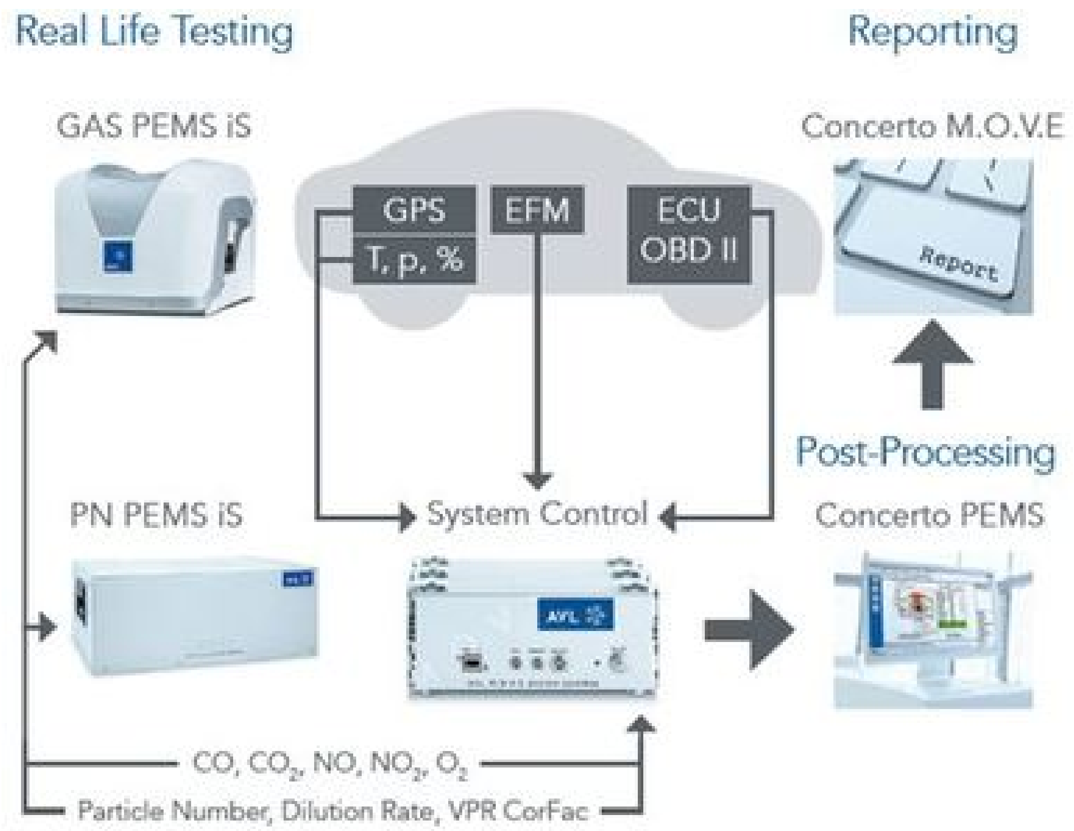

Figure 1 AVL M.O.V.E. PEMS Is measurement system

The measurement system itself is placed on the back of the vehicle on a trailer hook or inside the vehicle's luggage compartment. The latter option is best suited for station wagons, SUV's and hatchbacks, whereas the trailer hook is preferred for sedan type vehicles.

The measurement system includes a flow meter which is connected to the rear end of the exhaust pipe/s. The flow meter measures the total amount of gasses passing through the exhaust pipe, in m^3/h or in kg/h.

Inside the vehicle is an OBD-connector which allows monitoring of engine RPM, temperatures etc. On the roof sits a GPS-antenna and a weather station.

By combination of data from the gas analyzers, the flow meter and the GPS, it is possible to determine the exact amount of CO_2, CO, NO, NO_2 or particulates emitted for each kilometer driven.

The measurement system is designed to meet RDE Act 3 – Commission Regulation (EU) 2017/1154.

5. Test routes

The Danish team designed two regional RDE routes, one in Jutland and one on Zealand. Both routes were designed to meet RDE Act 1 – [Commission Regulation (EU) 2016/427] amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6).

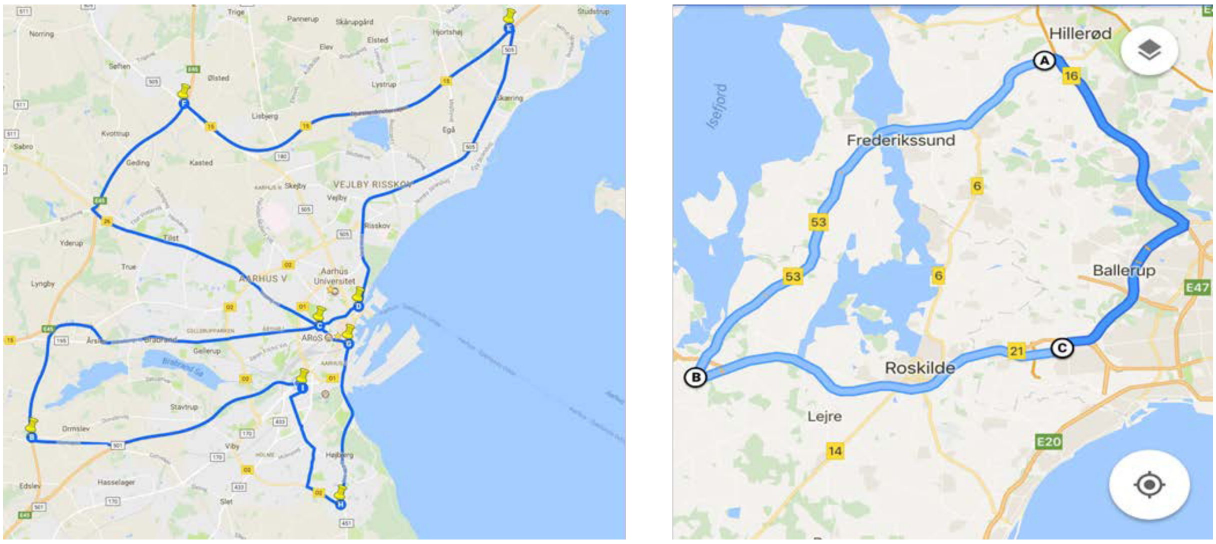

Figure 2 Two Danish RDE routes

The routes are 70-80 km long and the duration is 90 minutes.

The routes were positioned in connection to the DTI's main facilities in Aarhus and Taastrup respectively. This way, vehicles from the whole country can reach a test site in 1-2 hours.

Both routes are placed as public content on Google Maps:
https://drive.google.com/open?id=1Z26X_0OU6YqE3boxbpaCnfflP1o&usp=sharing
https://drive.google.com/open?id=1r5ejo9njd4dH_il9u5nfqbZyy18&usp=sharing

The routes will need minor adjustment as to comply with RDE Act. 4 from 2020.

As a supplement to the RDE routes a shorter track route was also used. The objective for this was to obtain result with a high reproducibility while using less time for testing. Inspired by the UITP SORT schedule, which is used for buses, the route was named SORDS (Standardized On-Road Driving Schedule). The SORDS route is a 3-minute drive over a 3 km track with 5 stops and speeds up to 130 km/h. The route is shown in Figure 3.

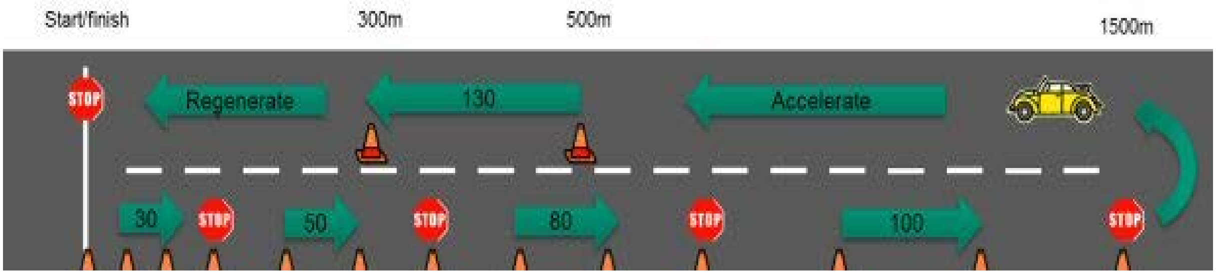

Figure 3 The SORDS track route layout

The SORDS route was set up on Roskilde Ring, a small racetrack/road safety center located near Taastrup. However, it turned out that the track was unsuited for SORDS testing due to being too short and the turns being too tight. It was not possible to safely reach 130 km/h with the PEMS equipment on board, so the test was restricted to 100 km/h. A perfect site for SORDS would be the old airfield at Værløse, also nearby Taastrup. However, that facility is nowadays used for recreative purposes and motor vehicles are not allowed.

6. Fuel and weather conditions

The fuel in Denmark is European spec. E5 gasoline and B7 diesel. This means that there is up to 5%vol ethanol in the gasoline and up to 7%vol biodiesel in the diesel. The Danish fuel companies do not currently add methanol to the gasoline. The biodiesel component is mostly hydrogenated vegetable oil (HVO) and rape-seed methyl-ester (RME) in winter months and animal-based tallow methyl-ester (TME) in summer.

Average density and energy content (LHV) are:

Diesel: 836 kg/m^3 and 35,7 MJ/l
Gasoline: 745 kg/m^3 and 32.2 MJ/l

The month of March was chosen for testing since it offers reasonably low temperatures without too much snow or ice on the roads.

The temperature profile for the Zealand region in that month is shown below.

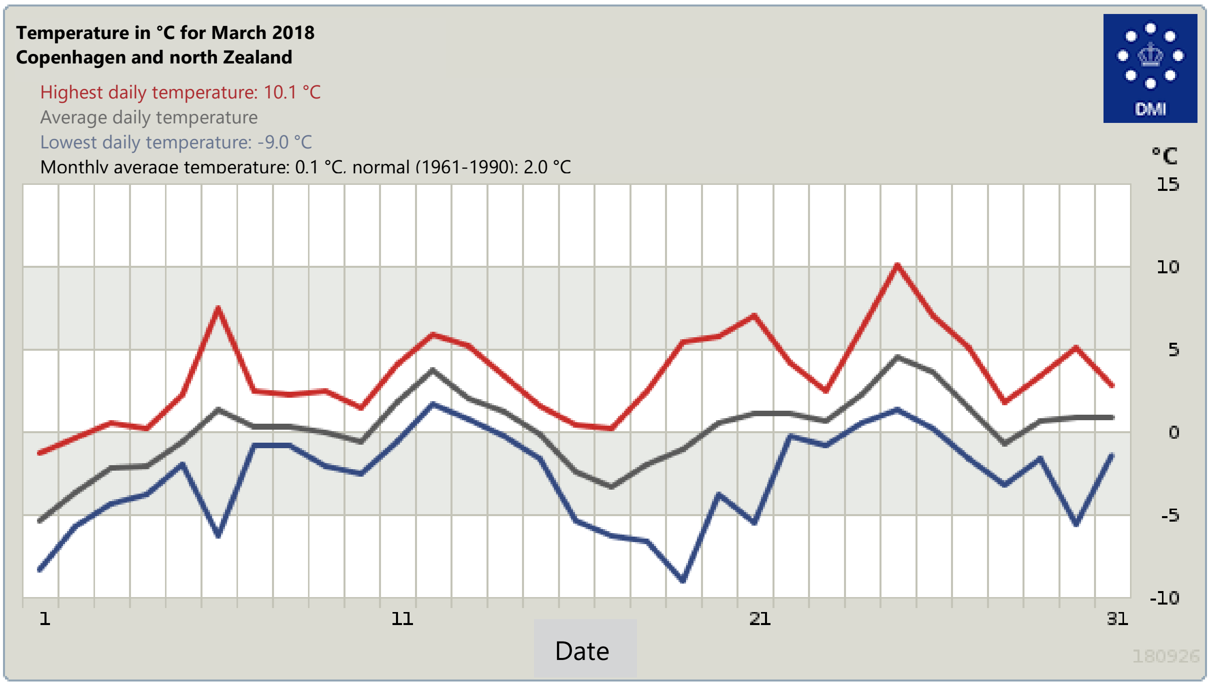

Figure 4 Temperature in Zealand during RDE testing

7. On-road results

The tests show clearly that NOx emissions lie above those mandated by EURO 6 (Figure 5). The highest average was 18 times the limit. Only the Skoda Octavia, which was running on gasoline and the more expensive BMW diesel showed acceptable NOx levels.

The Skoda was equipped with a 3-way catalyst which is effective in eliminating NOx because it operates in an almost oxygen free environment. This is not possible for diesels, due to the oxygen rich exhaust gas. However, as shown by BMW, diesels can also manage low NOx levels. This model didn't even have an SCR-type catalyst and thus did not use AdBlue. Even though it hardly seems necessary, an AdBlue system was added to the next X1 model shortly after, to the 2018-model, and is now standard on all BMW diesels.

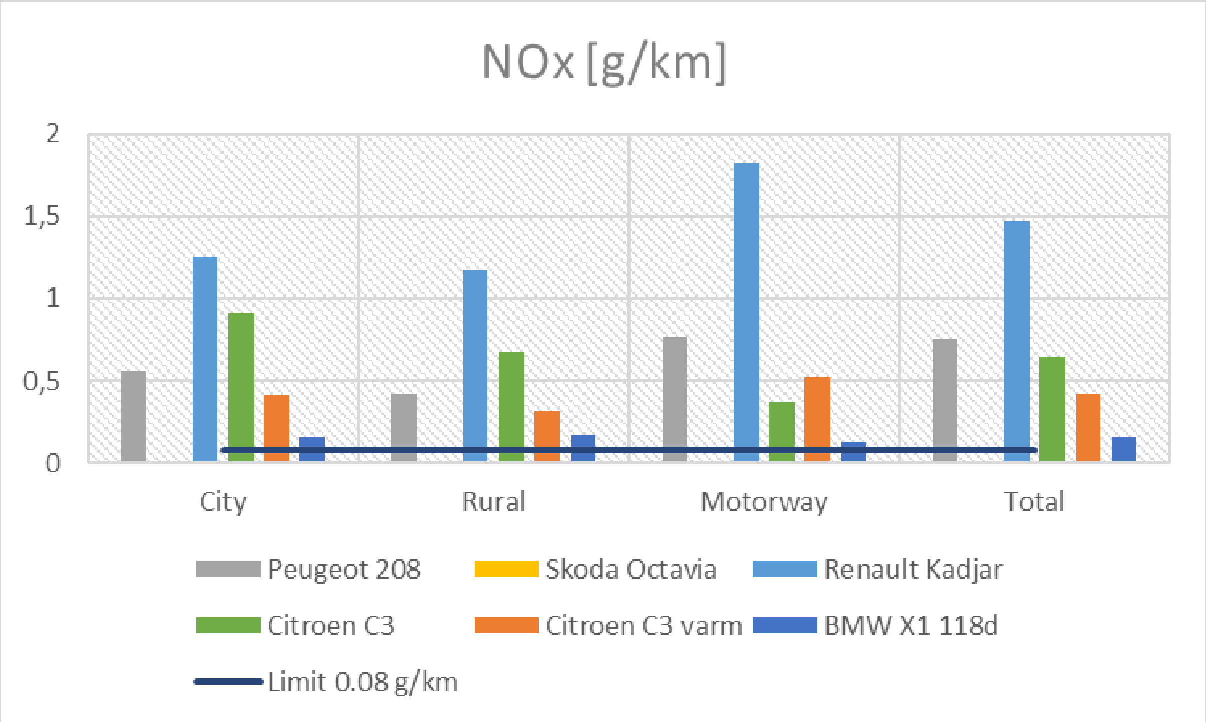

Figure 5 NOx emissions for EURO 6b diesels were significantly above the limit except for BMW X1. The gaso-line from Euro 5b did not emit any significant amount of NOx.

Warm weather was tried on the Citroën C3 and improved the NOx performance but not enough to meet the limit of Euro 6. Weather had little influence when driving on motorways. Probably because the engine always maintains good temperature on motorways.

NOx emission from the gasoline car was practically nil.

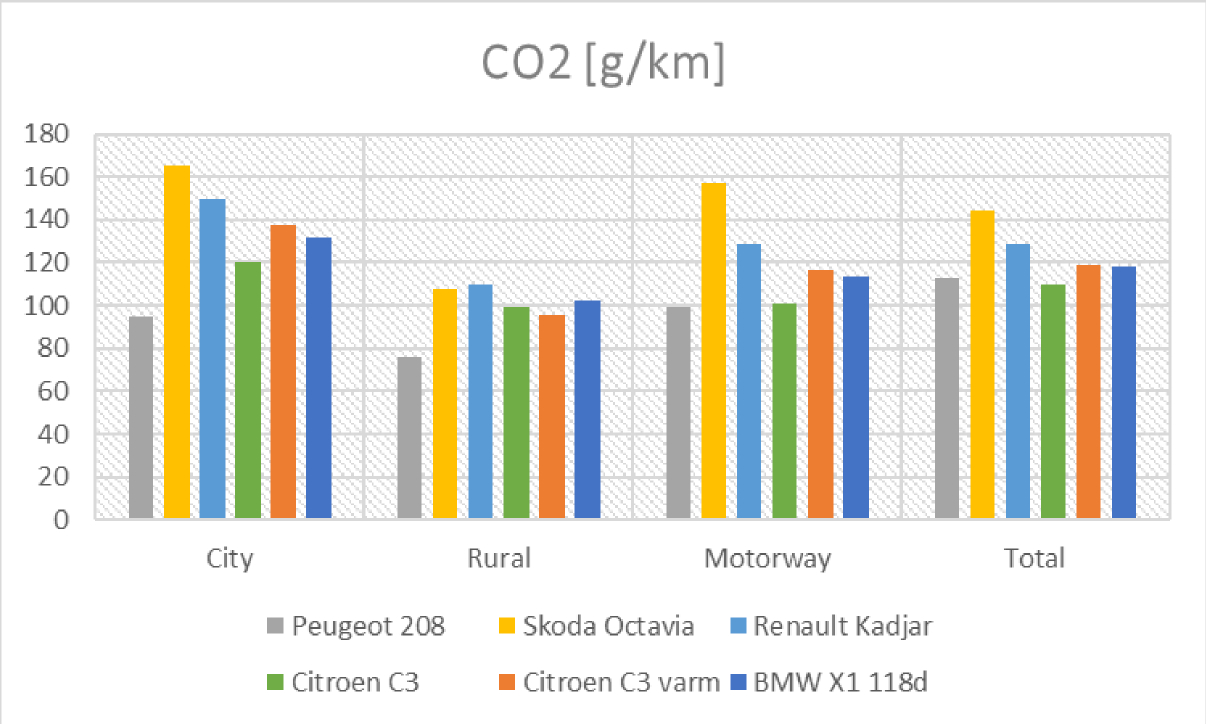

Figure 6 The CO2 emissions measured in RDE were fairly low, with diesels clearly lower than gasoline

The CO_2 emissions were somewhat higher than the declared values for each vehicle. This is mainly because type approvals were still based on the older NEDC drive cycle. It is a well-established fact that NEDC, and the way it has been practiced, delivers too low CO2 values. The values measured in RDE should correspond better to the new WLTP driving cycle. As WLTP figures were not available, however, an exact comparison could not be made.

The gasoline car had the highest CO_2 emission of the cars tested, as expected. The difference was also higher than expected from the declared values. The reason could be that the gasoline car was the only car with automatic transmission.

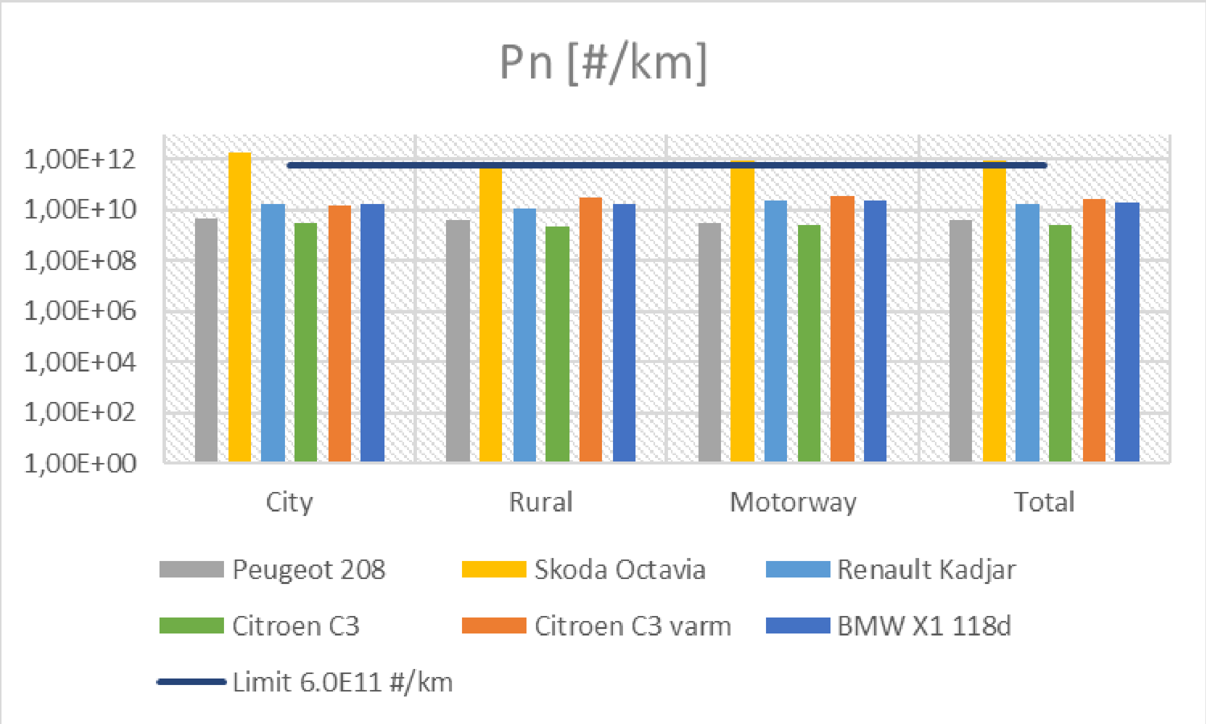

Figure 7 Particulate number emissions were well under the limit for diesels and just over the limit for gasoline

The particulate number emissions are measured with highly sensitive equipment. If the exhaust gas were as clean as ambient air the reading would be about 1.00E+10 #/km. This means that any value below 1.00E+10 #/km must be considered practically zero.

For all the diesel cars tested in this project we see a particulate number emission of practically zero. The gasoline car had particulate emissions just above the EURO 6 limit. However, it must be noted that the car was only a EURO 5b.

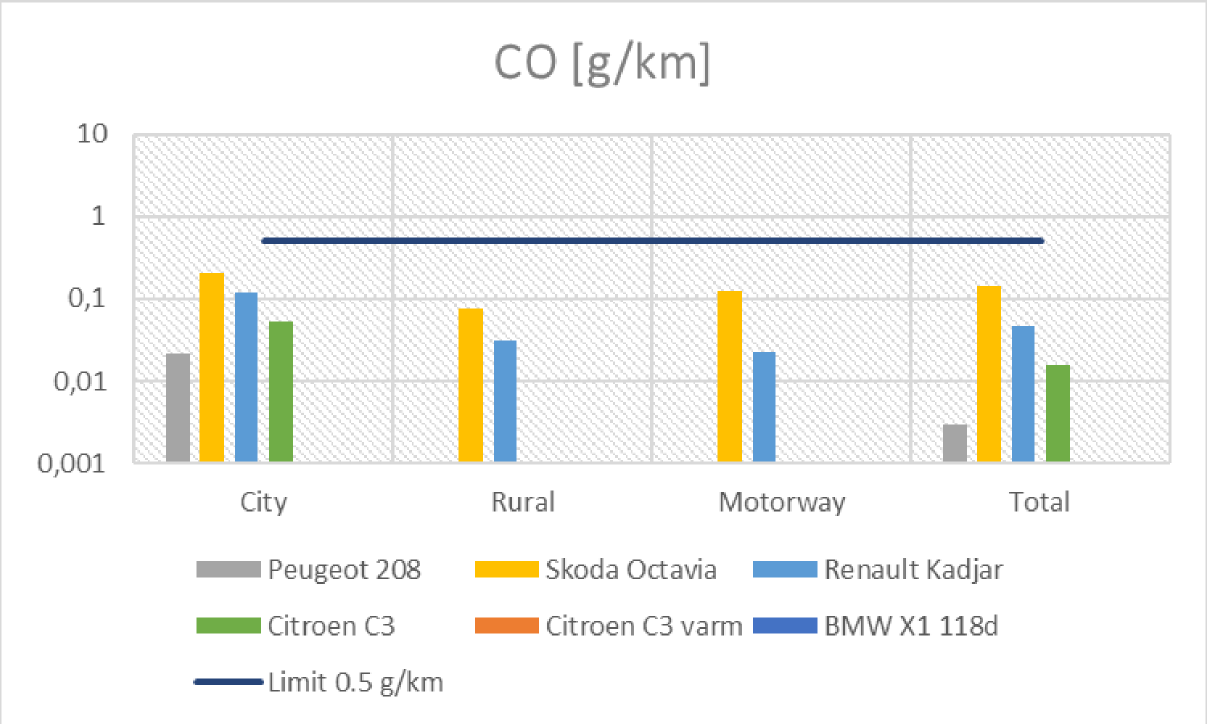

Figure 8 Carbon monoxide emissions were well under the limit. In some cases, CO could not be detected at all.

CO measurements confirmed the general perception that CO is not a problem for diesels. Due to the high amount of excess air in the diesel engine, CO combusts almost entirely on its own. The gasoline car emits CO mainly when the engine and catalyst are cold. However, the average emission is still way below 0,5 g/km. In earlier days, before catalysts were introduced, CO emissions for gasoline cars could reach up to 50 g/km.

8. Track results

The aggressiveness of driving can be measured by the factor v*a, speed times acceleration. An aggressive driver uses both brakes and accelerator at high speeds and thus uses much more engine and braking power. The SORDS cycle (see Figure 3) represents an aggressive, but not entirely unrealistic, driving style.

Figure 9 through Figure 18 illustrates the difference between SORDS and RDE.

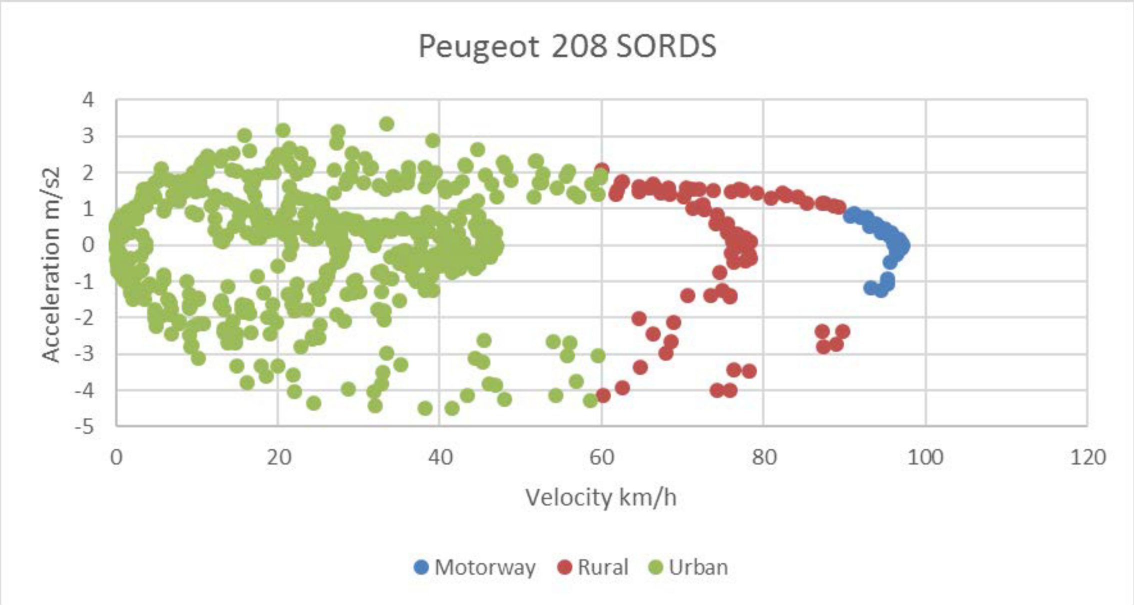

Figure 9 SORDS cycle has high acceleration rates in both positive and negative direction

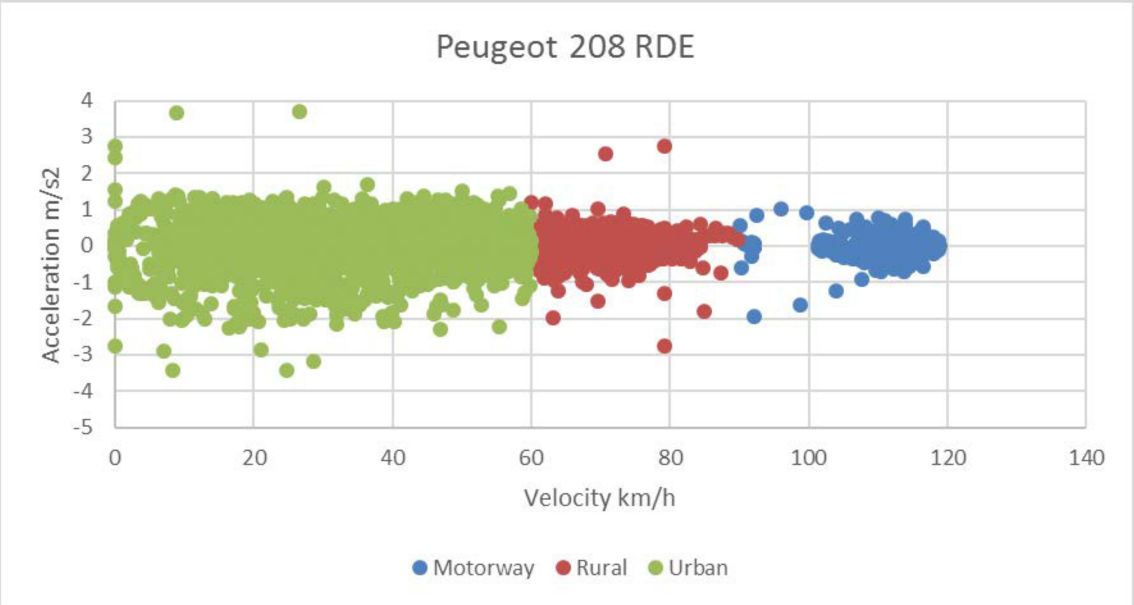

Figure 10 RDE cycle has modest acceleration and deceleration rates

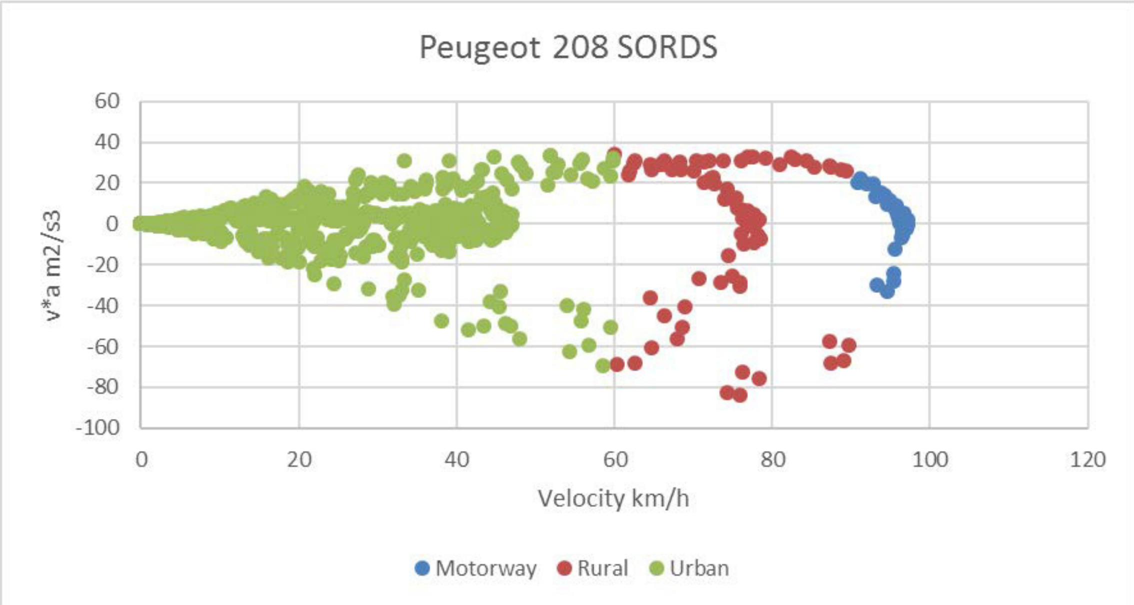

Figure 11 SORDS test show high levels of aggressiveness in terms of both positive and negative v*a

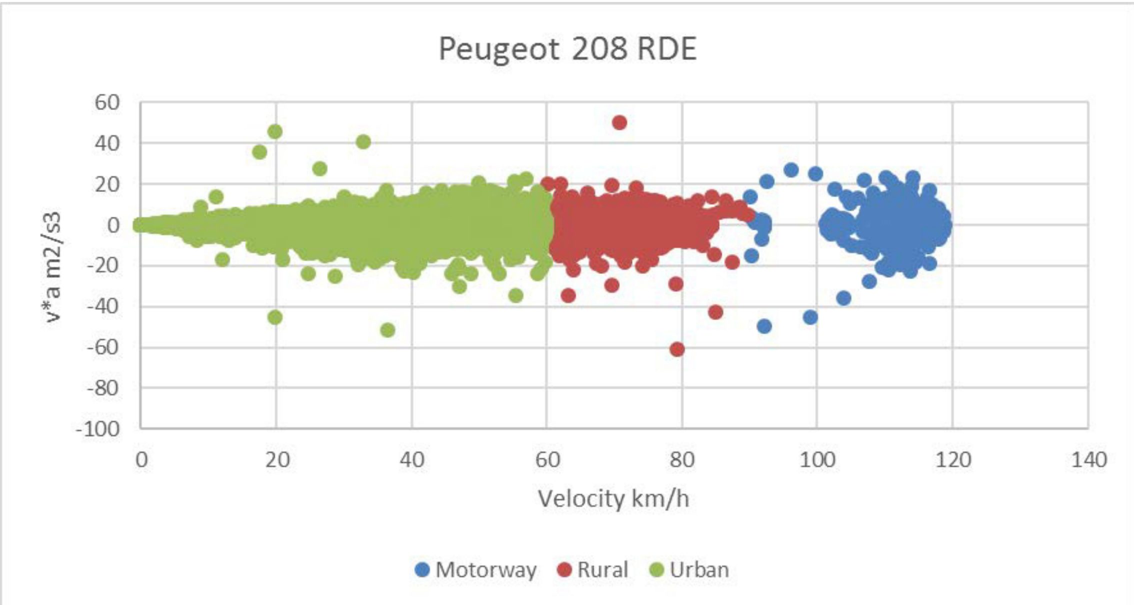

Figure 12 RDE test shows much less aggressiveness despite higher speeds

CO_2 mass flow depends strongly on v*a (Figure 13-Figure 14). This is not surprising since the RDE specific VELINE formula states that engine power is approximately proportional to CO_2 mass flow.

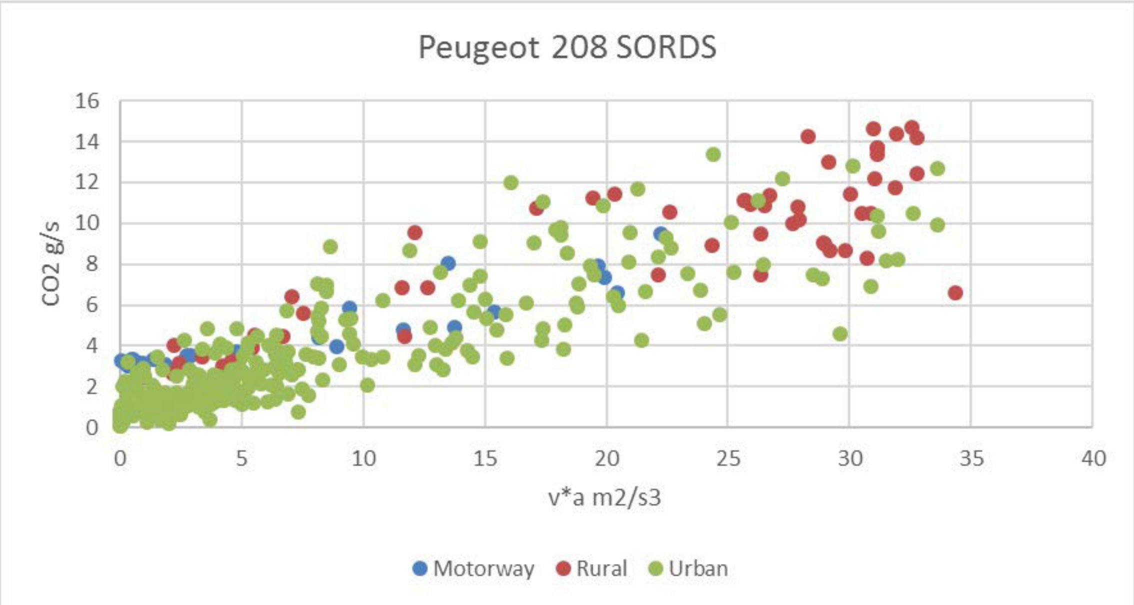

Figure 13 SORT requires high engine power thus a high CO_2 mass flow

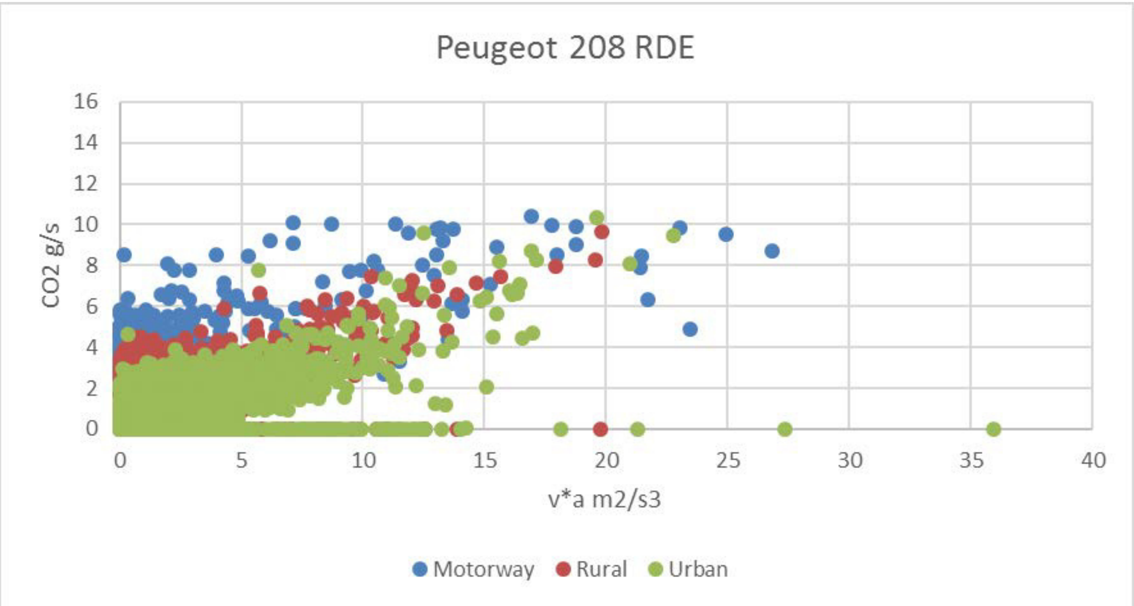

Figure 14 RDE requires less engine power thus less CO_2 mass flow

There seems to be a clear correlation between v*a and NOx mass flow (Figure 15-Figure 16).

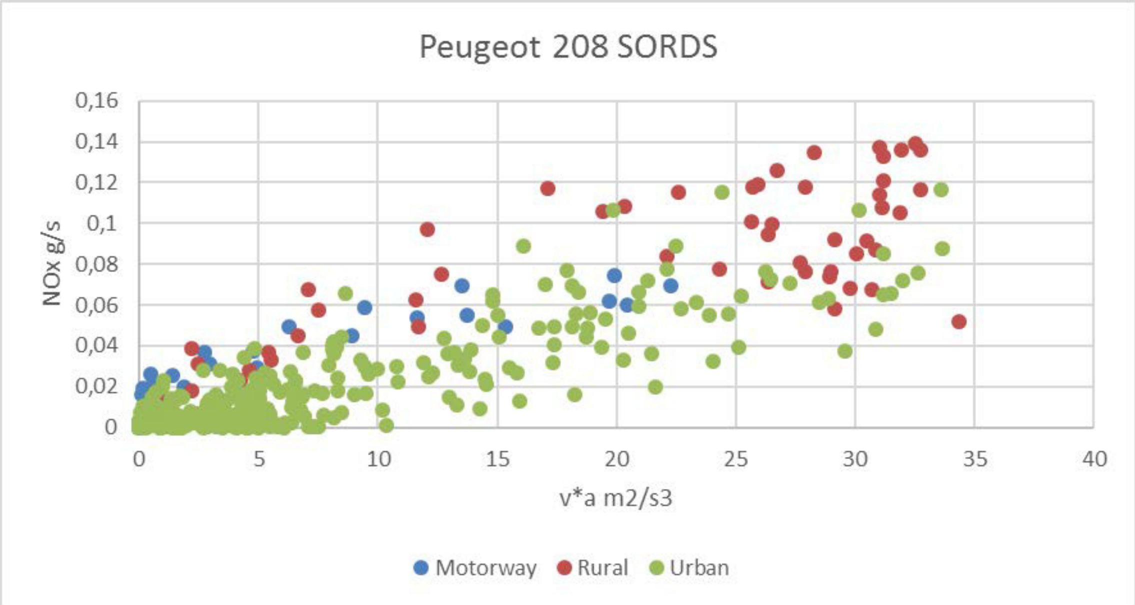

Figure 15 The aggressiveness of SORT results in higher NOx mass flows

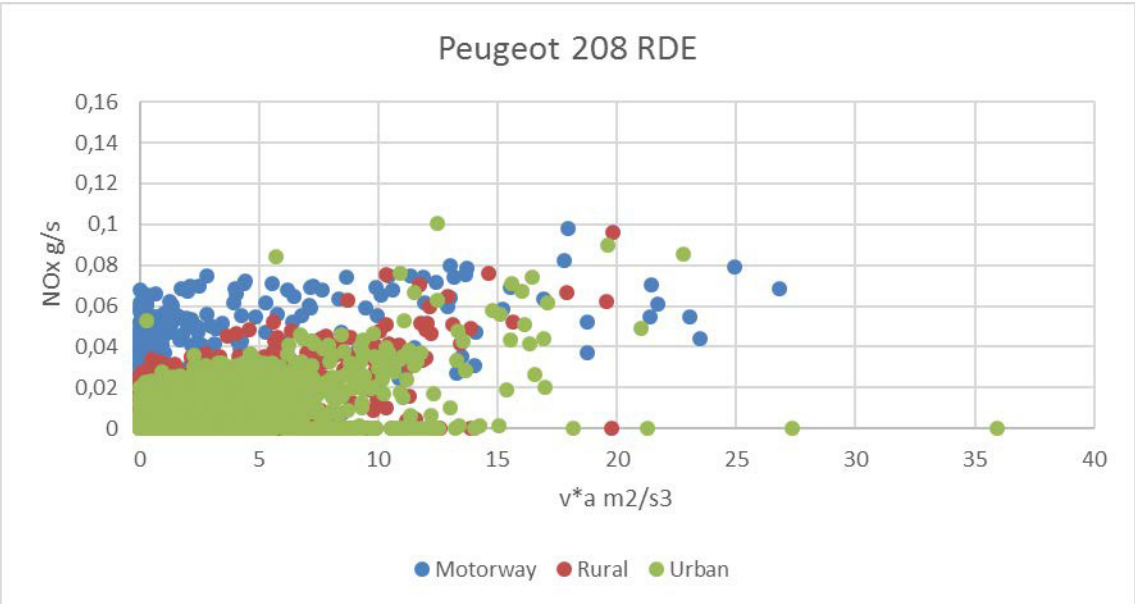

Figure 16 The lesser aggressiveness of RDE results in lower NOx mass flows

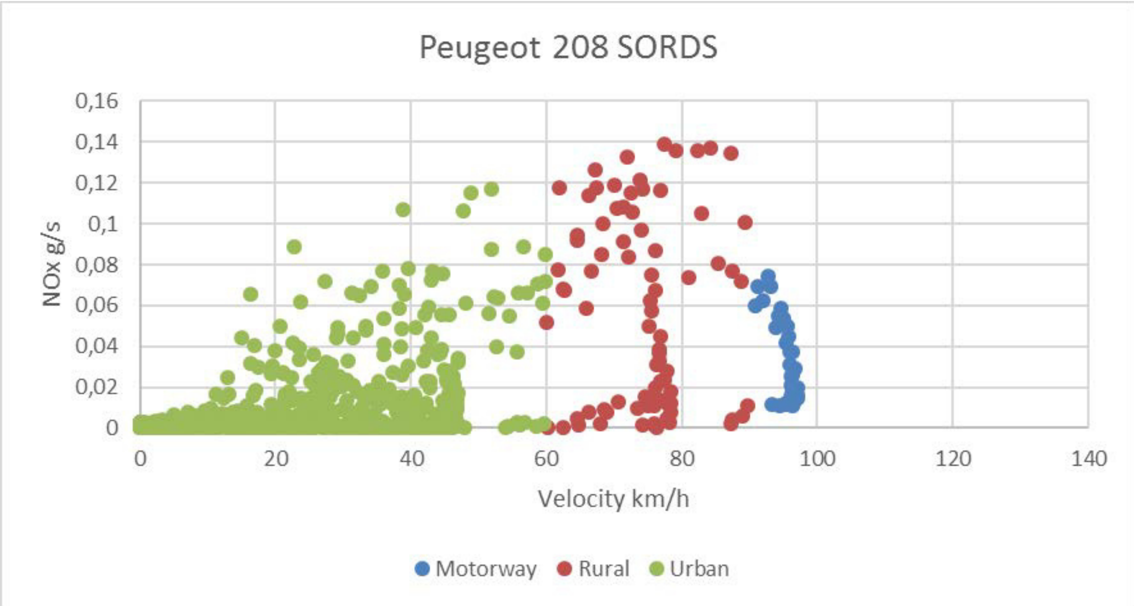

Figure 17 NOx mass flow in SORDS was speed dependent but did not capture a realistic motorway average due to the 100 km/h speed limitation

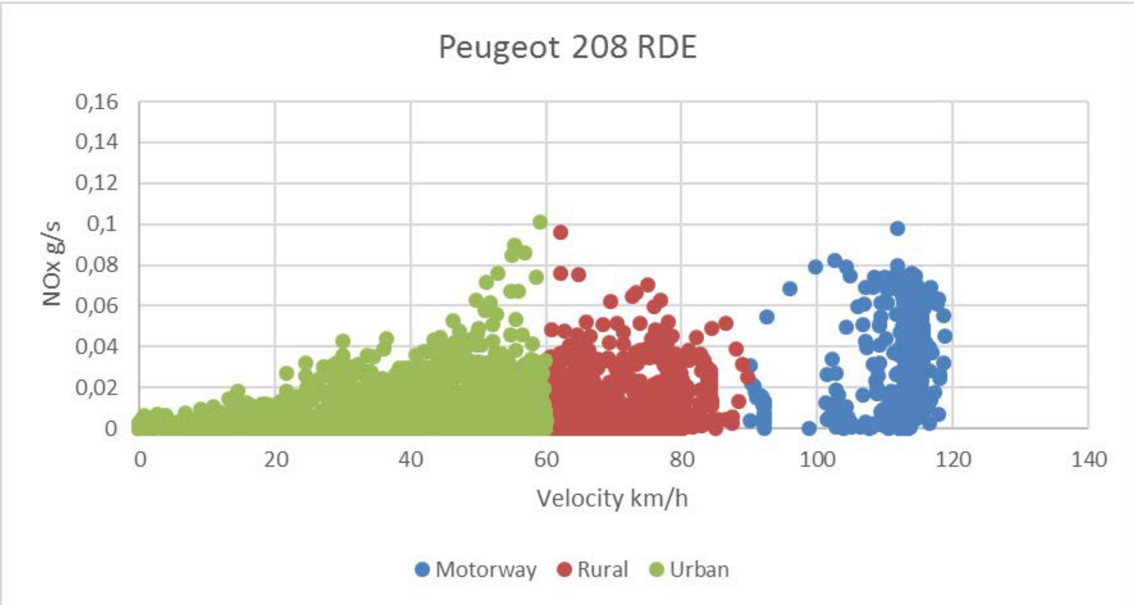

Figure 18 NOx mass flow in RDE was clearly speed dependent and captured a realistic motorway average

The SORDS track test did not give good average results. However, it gave insight in the more extreme situations of high acceleration and engine load.

9. Effect of data filtering

In RDE Act. 3 there are two methods of data filtering of which the manufacturer may choose one.

The methods are known as 'EMROAD' and 'CLEAR'.

The purpose of data filtering is to eliminate abnormal load points, such as very high engine loads or very high fuel consumption. The filtered data should then correspond better to the laboratory test WLTP. The actual process of data filtering is mathematically complex and will not be described in detail here.

For the purpose of investigating the impact on the data both methods were applied to the data shown in the Chapter 7.

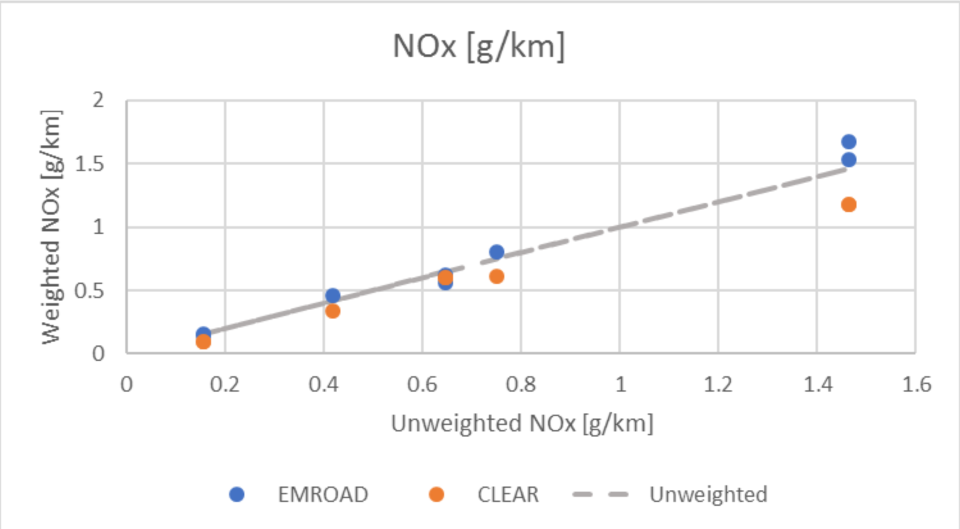

Figure 19 CLEAR reduced the higher NOx emissions whereas EMRAOD reduced them

The data filters had limited impact on the overall conclusions, and they did not seem to agree on the need for corrections. Sometimes EMROAD and CLEAR would pull in each different direction.

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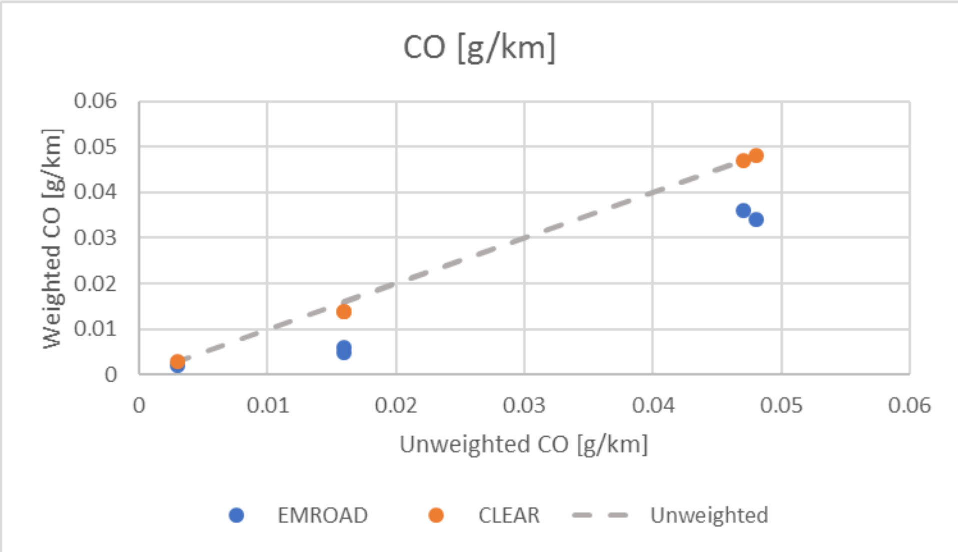

Figure 20 EMROAD significantly reduced CO whereas CLEAR was neutral

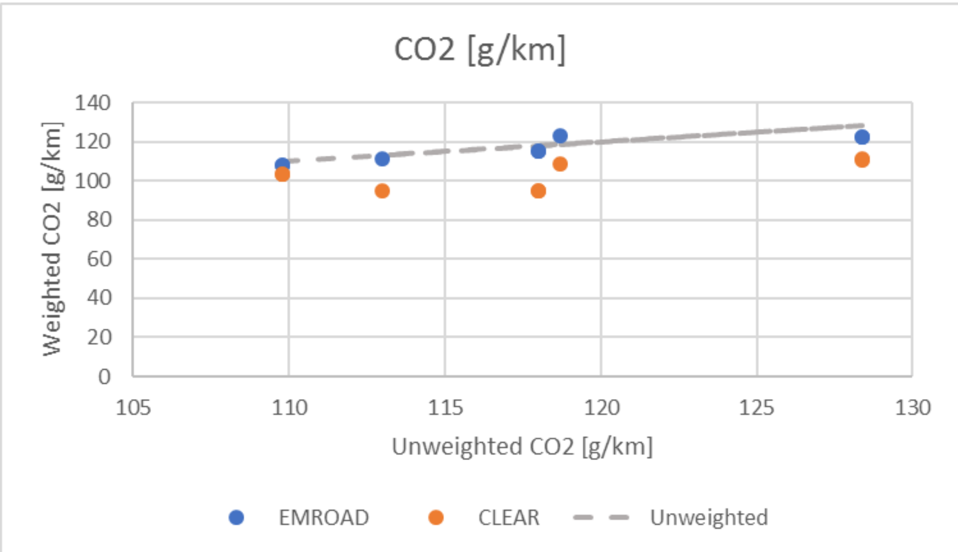

Figure 21 CLEAR reduced overall CO2 while EMROAD was neutral

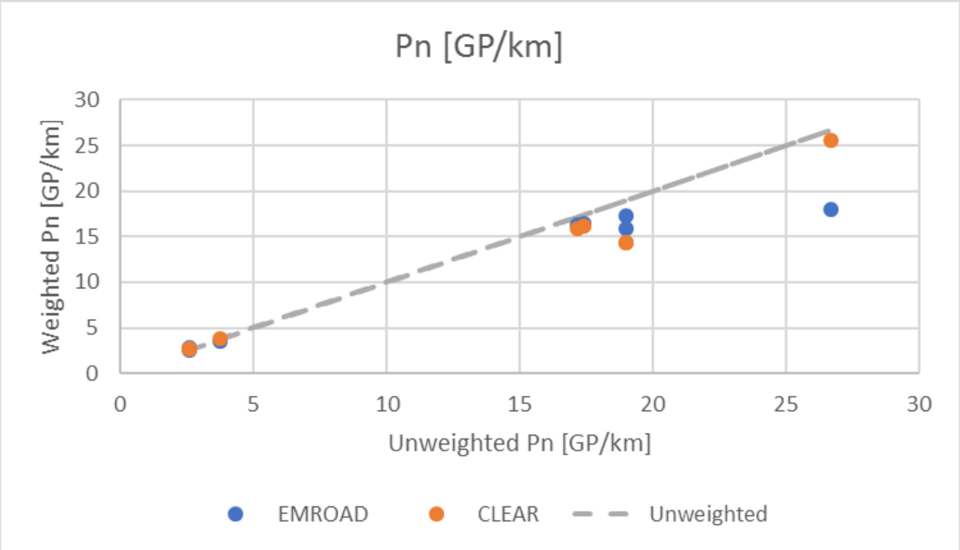

Figure 22 EMROAD reduced the higher Pn emission. CLEAR was almost neutral

Overall, the data filtering did not seem to improve the quality of data significantly. It is expected that EMROAD and CLEAR will be removed from the method with the introduction of RDE Act. 4.

10. Emissions mapping

RDE driving uses most of the engine's useful operation range, without abusing or overstressing the engine. The data can be used to map emission behavior versus engine load and speed. This is shown in Figure 23 through Figure 26.

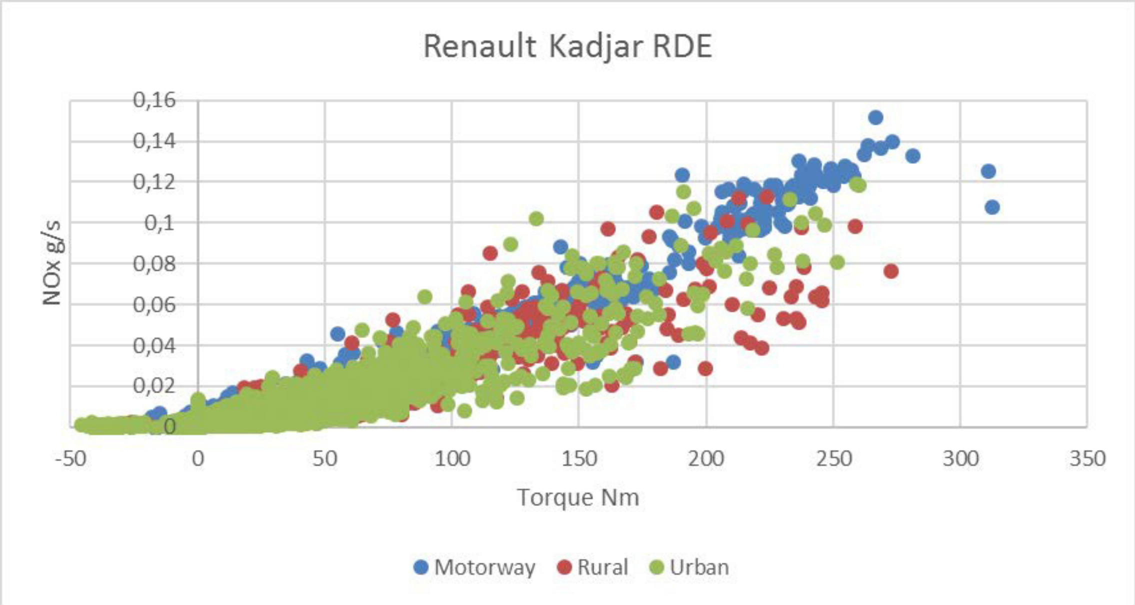

Figure 23 NOx depends exponentially on engine torque

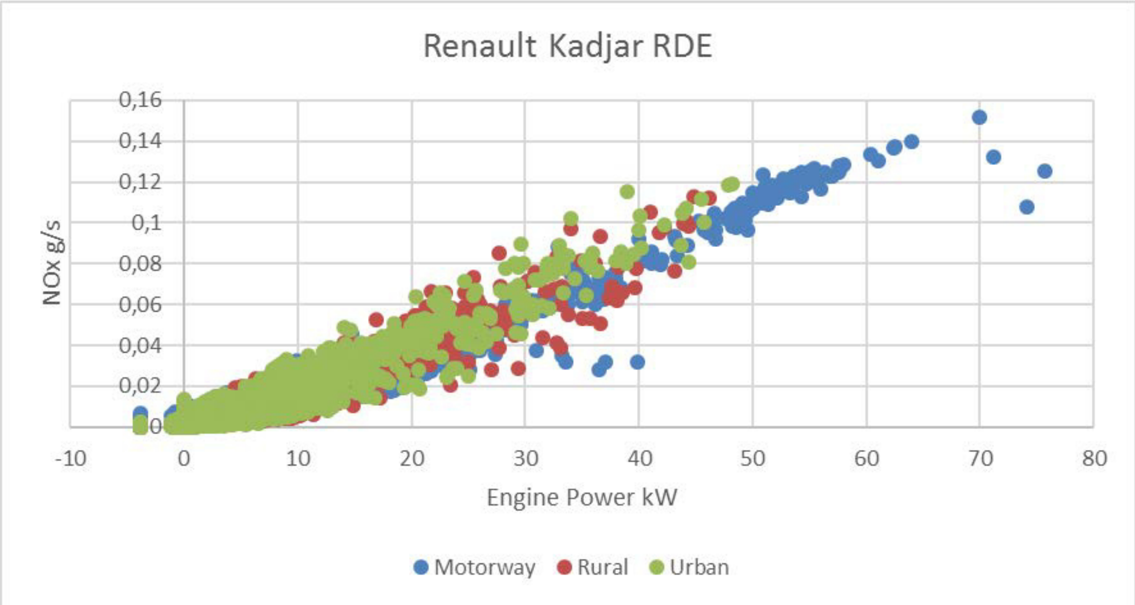

Figure 24 NOx depends almost linearly on engine power

The NOx clearly depended on engine torque and power, which is consistent with the common observation that engine NOx is developed at high combustion temperatures (thermal NOx). However, the data also seems to indicate that catalytic converters on passenger car are under dimensioned, such as the LNT catalyst on the Renault Kadjar DCi 130 shown in Figure 25.

When too small catalytic converters are used, a conflict arises between optimum fuel economy and low emissions. This is commonly known as the NOx Trade-Off. Figure 26 shows this effect; fuel consumption is low when the NOx is high. This is an undesired situation and thus properly sized catalysts or combinations of catalysts shall be recommended.

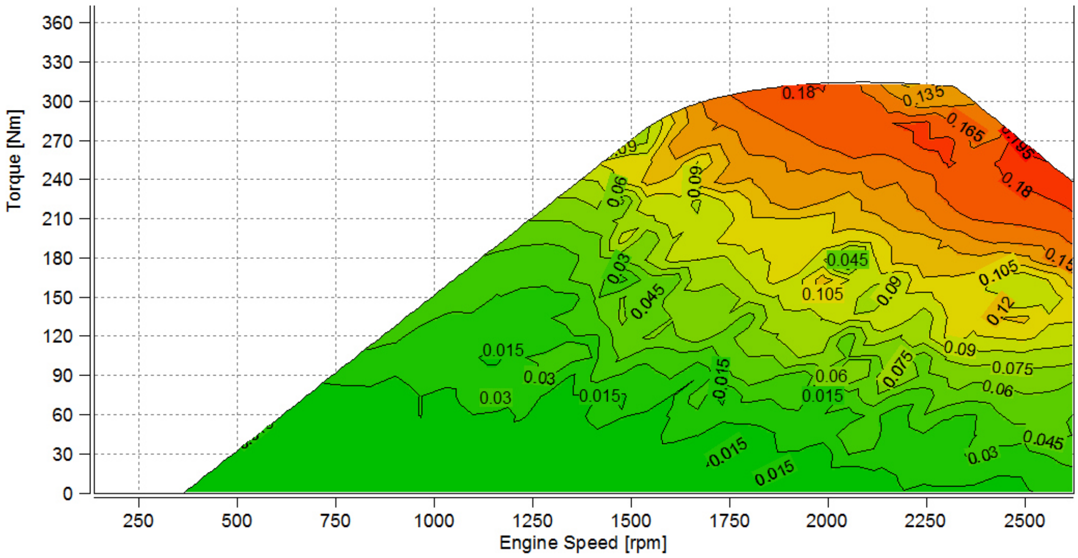

Figure 25 NOx mass flow was high in the high load region which indicates too small catalyst

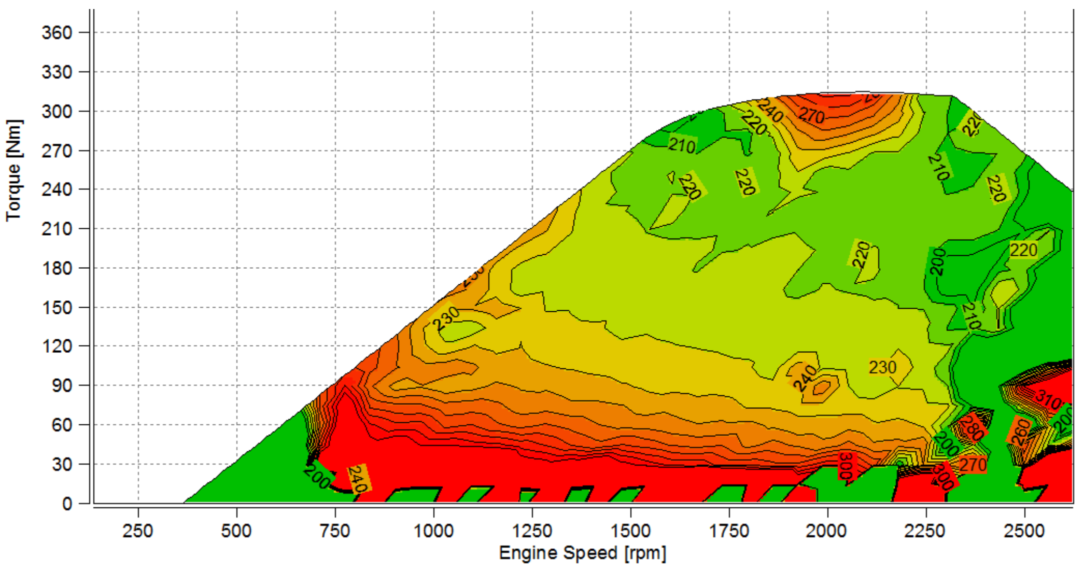

Figure 26 Optimum fuel consumption was colliding with the high-NOx regions.

11. Conclusions

In this project we have tested diesel cars of Model Year 2015-2017. They are all approved according to EURO 6b, which does not require RDE testing by the factory. Our finding were:

- EURO 6b diesels emit too much NOx – up to 18 times the limit.
- A large variation in NOx exists between car brands within the EURO 6b category.
- Temperature seriously affects the NOx emission of EURO 6b diesels.
- EURO 5b gasoline cars perform well on NOx
- EURO 6b diesel perform very well on particles, CO and CO2.
- EURO 5b gasoline cars emit more CO, CO_2 and particulate matter than EURO 6b diesels

When tested at cooler temperatures around 4°C the small EURO 6b diesel cars had alarmingly high NOx-emissions. Most were several times over the EURO 6 limit. Renault Kadjar even surpassed the limit by a factor of 18. Only the BMW X1 was close to fulfilling the EURO 6 limit for NOx. The gasoline Skoda had extremely low NOx, but higher CO_2 than the diesels, especially in city driving. The gasoline car also showed a higher particulate number emissions than the diesels, because it was the only car which was not equipped with a particulate filter.

When comparing the Citroen C3 diesel in winter driving at 4°C with summer driving at 23°C, NOx emissions in city and rural driving was roughly doubled in the cooler weather. At highway driving no such difference was observed.

With the introduction of EURO 6d-temp in 2019 it is expected that the diesel cars will perform much better on the NOx emission. This is expected as a result of the mandatory RDE testing. Some manufacturers have already released EURO 6d-temp data which look promising.

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Appendix III – Full report from Finland

RESEARCH REPORT

VTT-R-00636-19

IEA AMF Annex 55 Real Driving Emissions and Fuel Consumption - Project Report Finland

Authors: Petri Söderena and Juhani Laurikko, VTT
Christian Weber, Institute of Transport Economics Norway

Confidentiality: Public

VTT

Report's title	
IEA AMF Annex 55 Real Driving Emissions and Fuel Consumption - Project Report Finland	
Customer, contact person, address IEA-Advanced Motor Fuels, Annex 55 leader Thomas Wallner, Argonne National Laboratories, United States of America	**Order reference**
Project name Euro 6 diesel passenger cars emissions field tests	**Pages** 28/
Author(s) Petri Söderena and Juhani Laurikko, VTT Christian Weber, Institute of Transport Economics Norway	
Keywords diesel passenger cars, Euro 6, on-road emissions, PEMS	**Report identification code** VTT-R-00636-19

Summary

The focus of the IEA-AMF Annex 55 is on how vehicle fuel economy, efficiency and emissions in real world driving measure up to certification test results. The goal of Finnish tasks was to investigate the emissions performance of Euro 6 diesel passenger cars with different levels of certification on chassis dynamometer and on-road in different types of driving conditions.
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 both chassis dynamometer and in on-road tests with the conformity factor (CF) varying between 3.3...5.2. The second was able to provide NO_x, CO and PN emissions fulfilling the Euro 6d-TEMP RDE requirements with conformity factor around 1.8. The 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 conformity factor varying between 0.2...0.9 depending on the test route. The only Euro 6d-TEMP vehicle resulted in low NO_x emissions on 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.
Each car tested was equipped with diesel particulate filter (DPF), which reduces the PN emissions to a low level, well under the limit value. The highest measured PN emission on-road was half of the limit value. Near-zero ambient temperature was not found to increase the NO_x, CO and PN emissions in tests on RDE-route. Furthermore, one Euro 6b car showed slight increase in CO_2 emission, when tested close to zero ambient temperature compared to testing around 15 °C.
Two different diesel fuels were used in Euro 6 RDE route. One fulfilling the EN590 and one WWFC cat 5 diesel standard. None of the cars tested showed any observable difference between the emissions. There was no clear trend identified in respect of measurement accuracy in favour of either of the fuels.

Confidentiality	Public

Espoo 8.10.2019

Written by	Reviewed and accepted by
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Abbreviations

CF	Conformity Factor
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
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

"Real Driving Emissions and Fuel Consumption", Annex 55, was carried out within the IEA's Implementing Agreement on the Advanced Motor Fuels (AMF). The operating Agent of Annex 55 was Argonne National Laboratories, United States. Canada, Denmark, Finland, Switzerland and Sweden contributed with work to the Annex. This report describes the Finnish contribution to Annex 55.

The responsible partner in Finland was the VTT Technical Research Centre of Finland Ltd. The Finnish project was carried out in cooperation with the Finnish Transport and Communication Agency, City of Helsinki, Helsinki Region Environmental Services Authority HSY, Neste and Institute of Transport Economics Norway (TØI). We acknowledge operating agent and partners of Annex 55, as well as the IEA AMF Executive Committee, for a possibility to contribute in this interesting project.

Keijo Kuikka and Aki Tilli, Finnish Transport and Communication Agency
Anu Kousa and Outi Väkevä, Helsinki Region Environmental Services Authority HSY
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Espoo 8.10.2019

Authors

Contents

1. Introduction

Euro 6 legislation for passenger cars was set 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. World Harmonized Light-Duty Vehicle test procedure (WLTP) replaced old New European Driving Cycle (NEDC) test procedure in new type approvals, and is in force September 2018 onwards for all registrations of new cars. Furthermore, current Euro 6d-TEMP legislation, which introduced also real-driving emissions (RDE) testing, came into force also 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, or what was recorded in type approval testing. So-called cycle beating was found to be used while vehicles were tested on chassis dynamometer, and during on-road driving NO_x emissions were let to rise to high levels that were exceeding 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 not so much for the first generation of Euro 6 cars.

This ballyhooing often referred as “Dieselgate” broke loose in September 2016, and lifted the issue in knowledge of wide publicity and put high pressure on the renewal of the type approval process to contain a “real-driving test” to end the OEMs pretences that 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 been started as early as in January 2011. The European Commission then set up a working group involving all interested stakeholders for developing a real driving emission (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). Even the first “package” of the RDE test procedure was released in March 2016, way ahead of the massive media publicity.

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

This study is presenting Finnish contribution for the IEA AMF[1] Annex 55 “Real Driving Emissions and Fuel Consumption”, which was conducted during 2017-2019. Finnish project contributed to three of the six work packages of this Annex (WP’s 3-5, identified with bold typeface):

- Work package 1: Annex management
- Work package 2: Literature review and world regulation review
- **Work package 3: Fuel and technology effects on real-world driving emissions and efficiency**
- **Work package 4: Comparison of on-road testing to laboratory testing**
- **Work package 5: Assessment of weather conditions on real-world driving emissions and efficiency**
- Work package 6: Evaluation of different emissions measurement techniques

[1] International Energy Agency Technology Collaboration Programme on Advanced Motor Fuels

2. Objective

Euro 6 diesel passenger cars were not bringing the NO_x emissions to the level that the legislation was aiming at the time of introduction of the legislation. The purpose of this project was to shed light on the on-road performance of steps 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. More over, it should be considered as a tool for proofing that the harmful emissions of the specific vehicle are fulfilling 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 in nature more accurate, repeatable and thus suitable for direct vehicle-to-vehicle comparisons, but do not reflect enough the driving patterns those occur during real world driving.

Due to the above-mentioned reasoning, both chassis dynamometer and on-road tests were chosen to be performed. Chassis dynamometer tests provide a basis for direct vehicle-to-vehicle comparison and 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.

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. Main data can be found from the Table 1. Cars A and B are of the same model, but different model year. Cars A to C have been type approved following the NEDC procedure, and fulfil Euro 6b certification requirements. Car D is type approved for the Euro 6d-TEMP, and is thus tested according to the WLTP, as well as the RDE-procedure.

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

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

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 more realistic way than NEDC, it provides also a good base for assessing real-world emission performance of cars A to C. For car D, it provides a good comparison with on-road measurements.

The purpose of the emissions legislation should be that the vehicles produce emissions that are complying 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 test the vehicles also on-road, so that the whole engine operation map will be covered, as well as possible. Based on this reasoning, on-road measurements were decided to be performed on three different routes for estimation of the vehicles' emissions characteristics in different driving conditions covering whole engine operation map as far as possible. Of these three routes, one was fulfilling the trip requirements of Euro 6 d-TEMP RDE measurements, one was corresponding to normal driving in city and one represented driving in rural and highway environment.

3.2 Chassis dynamometer test set-up

Vehicles were tested with their own summer tyres. Prior to testing, a coast-down was 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"[2], which is an accepted method for NEDC, were used for determining the road load coefficients on the dyno. Test inertia was calculated and set according to the NEDC and WLTP practises. 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 provide often higher road load coefficients than those used by the manufacturers in type approval. This lead to higher emissions on a per kilometre basis as 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

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

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 vehicles' performance. After the oil change, each car was driven app. 50 km on a chassis dynamometer to guarantee similar aging for new oils. This procedure was performed for eliminating the effect on emission levels of the evaporative compounds originating from the fresh oil.

Table 5 shows the test programme that was performed for each car. Altogether two cold-start and six warm-start WLTC's and one cold-start and three warm-start NEDC's were carried out. In results diagrams average, minimum and maximum values of each sequence of three warm cycles is shown.

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

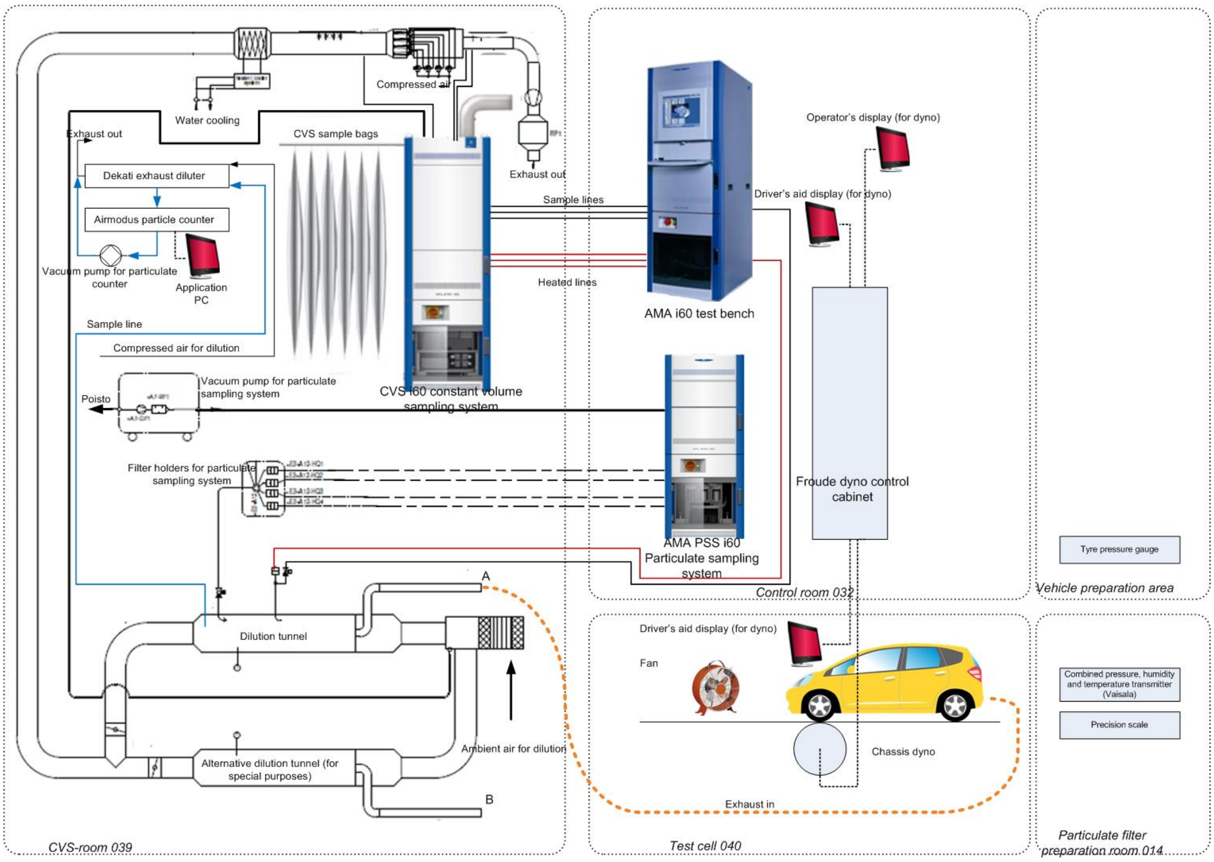

Figure 1: Schematic layout of VTT's light-duty vehicles chassis dynamometer measurement system.

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 analyser	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 on Table 7.

Table 5: Test programme in chassis dynamometer tests.

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

3.3 PEMS-measurements

On-road measurements were carried out in two different measurement campaigns. One depicting driving in warm weather, with ambient temperature above 10 °C, and the second depicting driving in winter conditions, with ambient temperature below 10 °C. The intension 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 appr. 10 °C above normal temperature levels in southern Finland.

Measurements were performed on three on-road routes. One fulfilling the trip requirements of Euro 6d-TEMP RDE testing (VTT RDE), one depicting normal city driving in Helsinki (VTT City) and one depicting 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 cold start test, but vehicle had soaked overnight inside at temperature app. 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 test routes.

The post processing of the measurement data was performed according to the RDE 3 package of Euro 6 legislation. 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 approximately between late October and early April. During that time on rural roads the maximum speed is 80 km/h (vs. 100 km/h during summer) and on highway 100 km/h (vs. 120 km/h during summer). Thus, the highest speed during the winter campaign were slightly lower than in summer conditions.

Furthermore, summer and winter tires were used depending on, if 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 studded type.

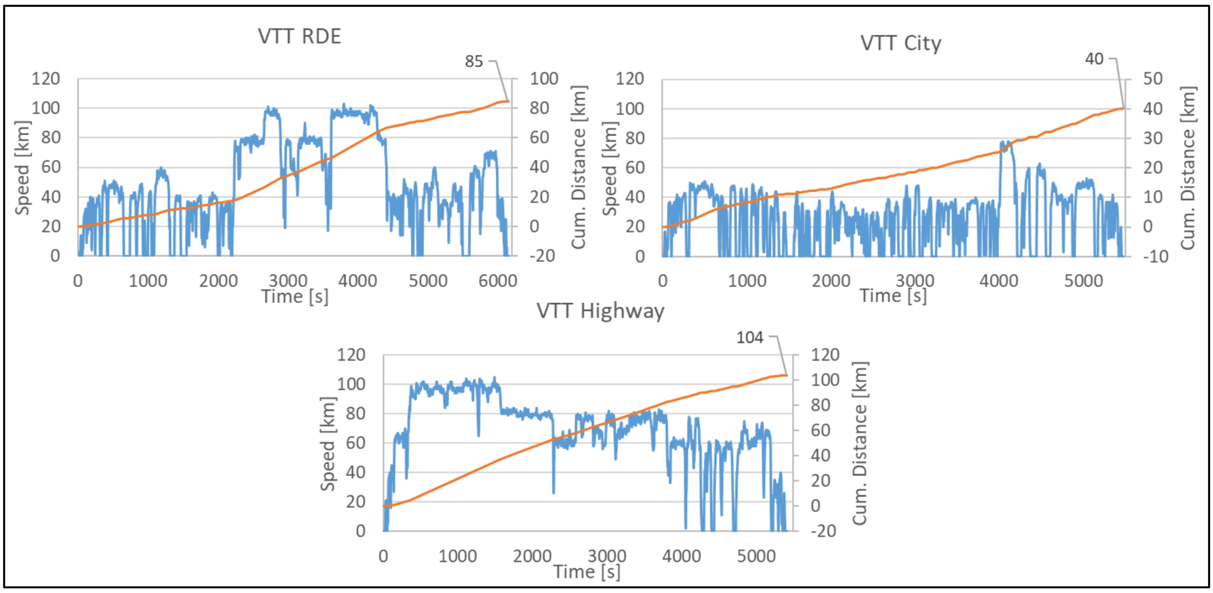

Figure 2: Example of test routes speed profiles and cumulative driving distance on winter conditions. Note during summer conditions maximum speed on highway is 120 km/h.

Table 6: Information of on-road measurement routes.

Test route / variable	Euro 6 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 /	80 km/h	120 km/h during summer condition /

	100 km/h during winter condition		100 km/h during winter condition

In addition, on some 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 VTT City and VTT Highway only the EN590 category fuel was used. Fuel consumption in on-road measurements was calculated from the measured CO_2 emission utilizing the JEC[3] well-to-tank CO_2 emission factor of 3.16 $kg_{,CO2}/kg_{,fuel}$.

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
FAME [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 on the towing hook with special mounting bracket. In Table 8, the main information of the device and an example figure of installation is 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..)

[3] 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

4. Results

On the chassis dynamometer, one cold-start WLTC run following three warm-start WLTC runs were 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 were also performed. An average result was calculated from the three warm cycles. Minimum and maximum bars are added in the diagrams depicting the results. If the bars are missing, only one cycle was recorded.

On-road measurements were conducted in two different occasions. One measurement campaign in 10 - 15 °C ambient temperature conditions, and another in 10 °C ambient temperature conditions during the winter. 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. As explained earlier in section 3.3 , winter driving speed limits are in force during the winter period in Finland (app. November-April), and thus on the same routes the speed profiles were different depending the time of the year.

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

4.1 NO_x emissions

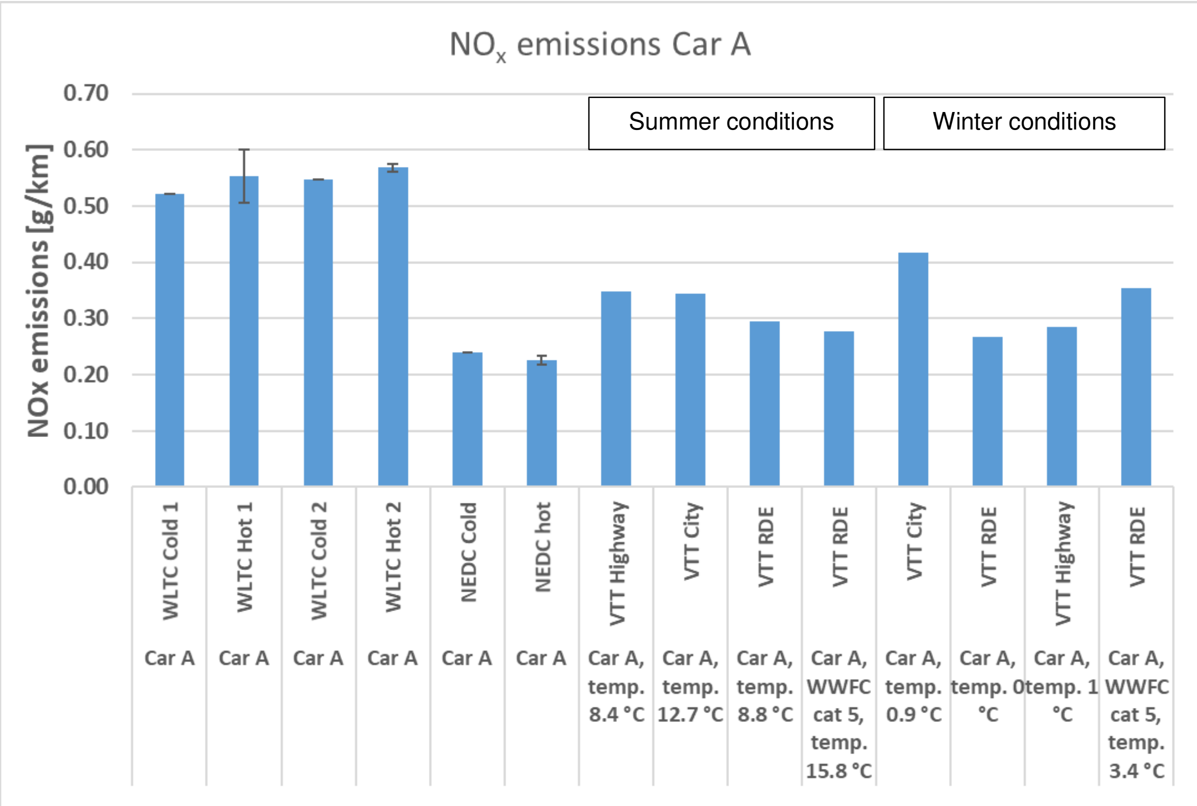

Figure 3: NO_x emissions of Car A on chassis dynamometer and on-road.

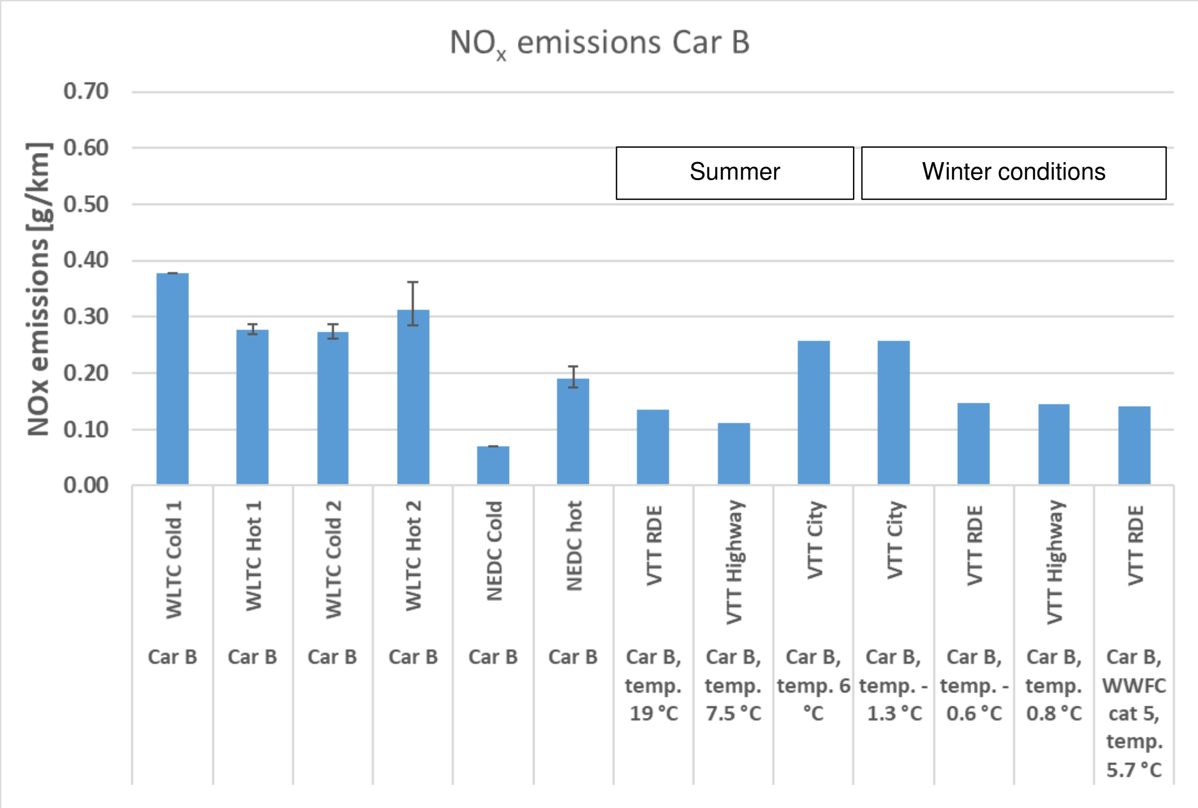

Figure 4: NO_x emissions of Car B on chassis dynamometer and on-road.

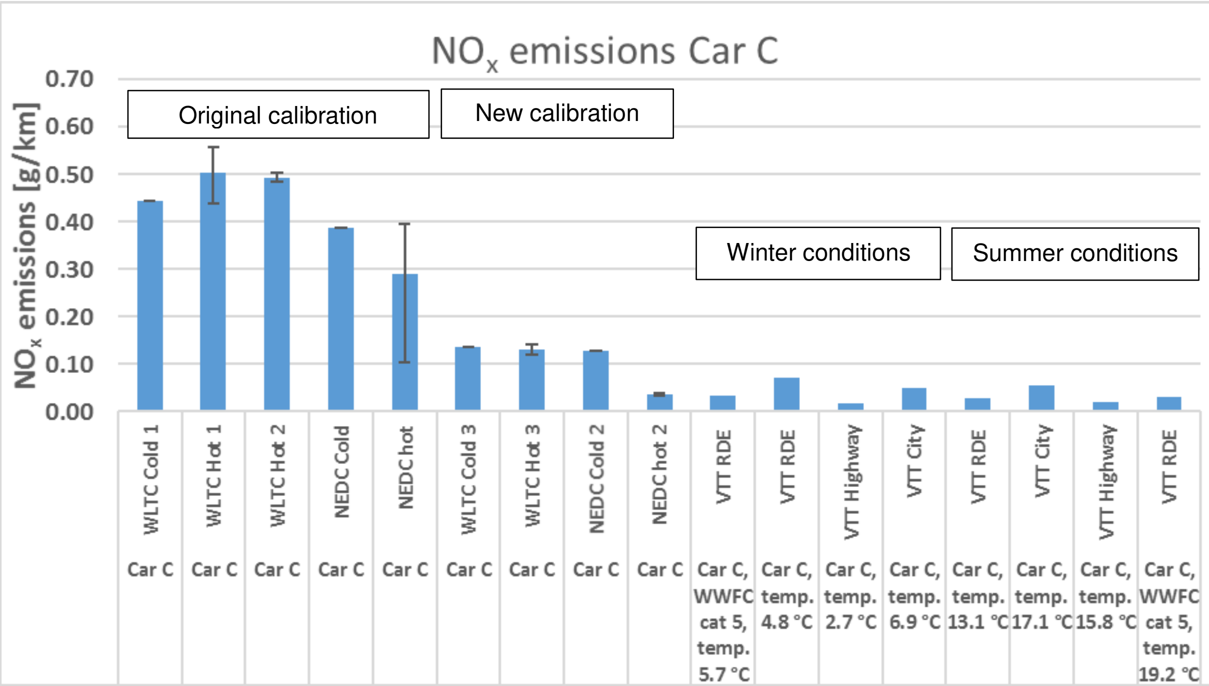

Figure 5: NO_x emissions of Car C on chassis dynamometer and on-road.

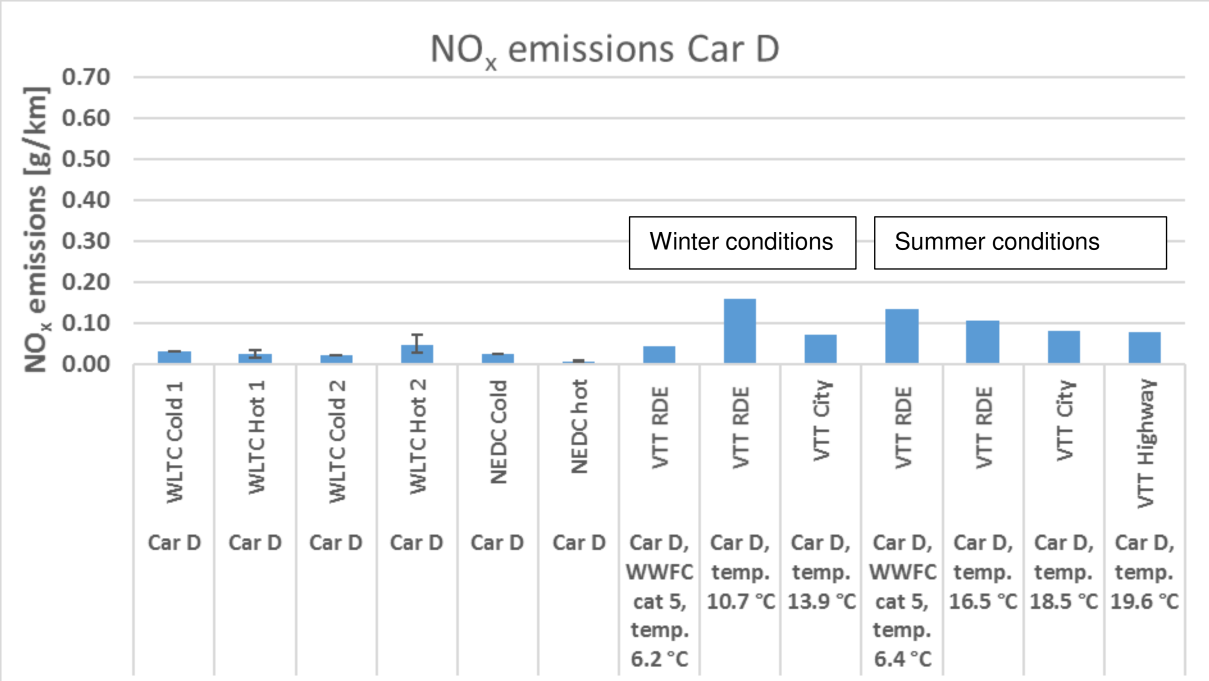

Figure 6: NO_x emissions of Car D on chassis dynamometer and on-road.

4.2 PN emissions

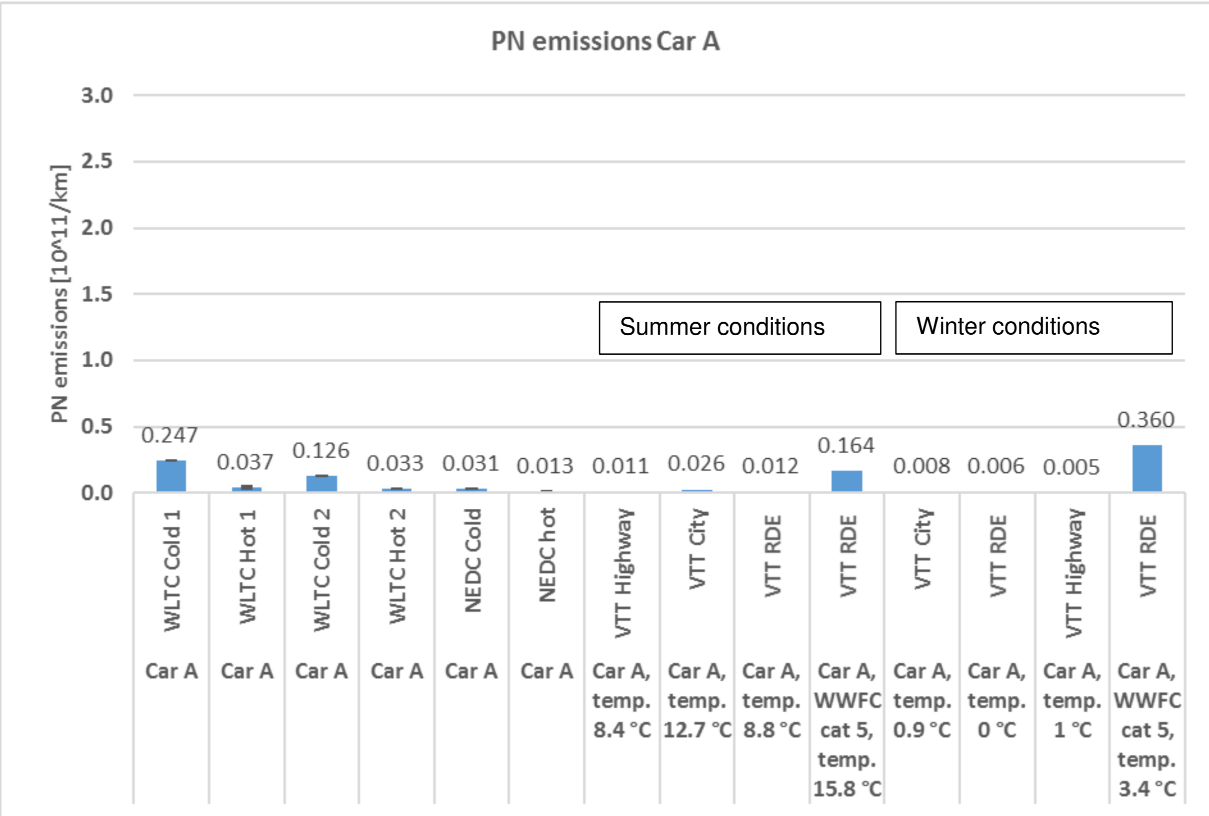

Figure 7: PN emissions of Car A on chassis dynamometer and on-road.

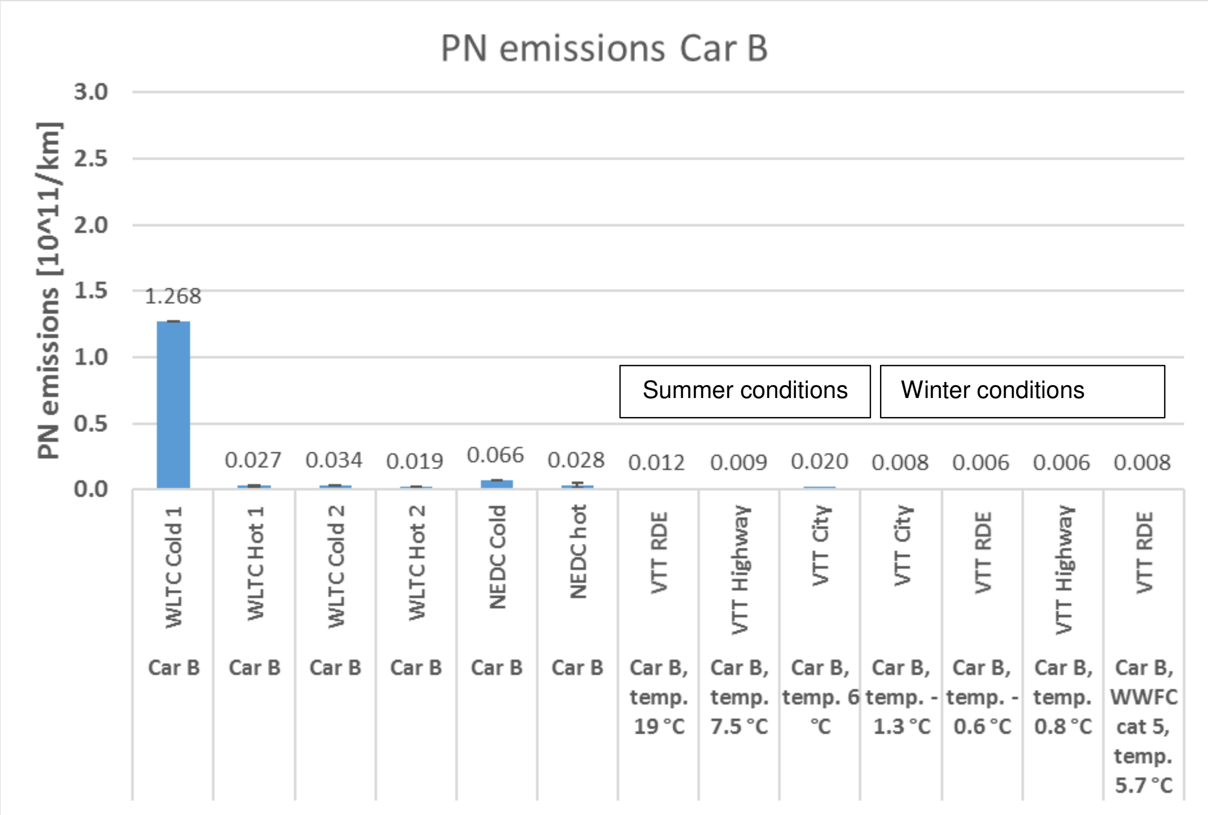

Figure 8: PN emissions of Car B on chassis dynamometer and on-road.

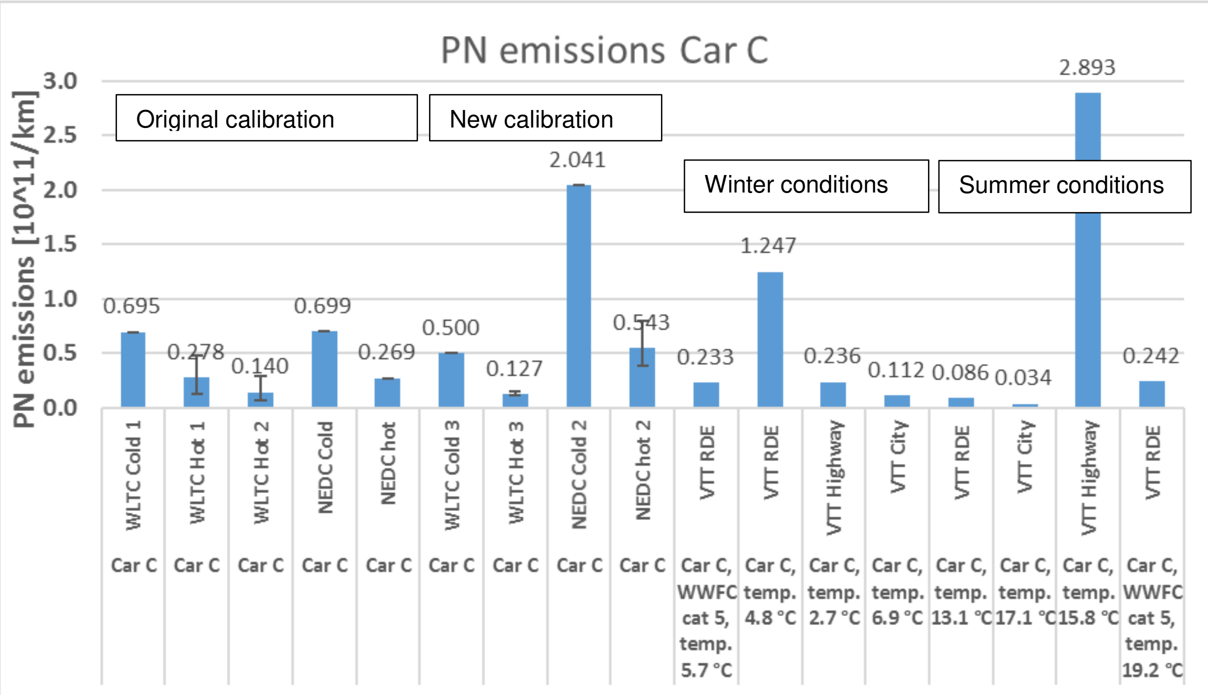

Figure 9: PN emissions of Car C on chassis dynamometer and on-road.

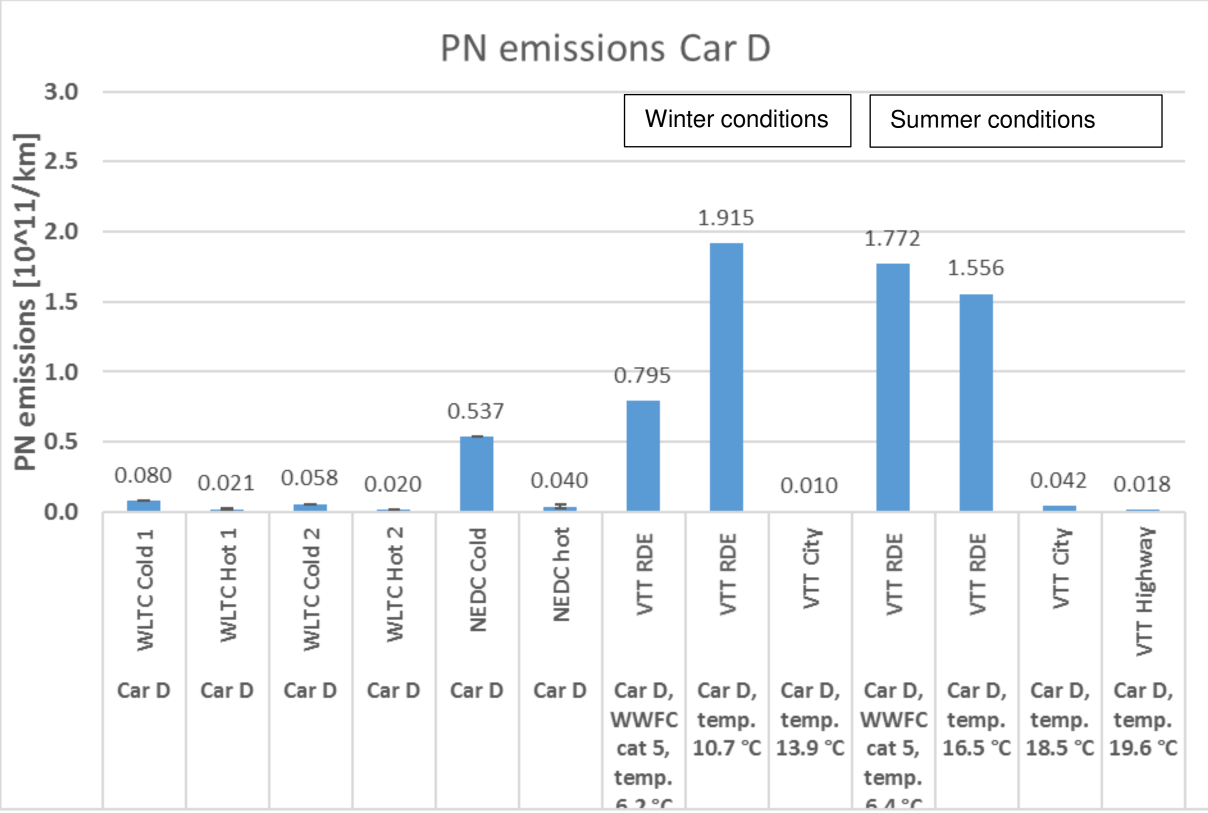

Figure 10: PN emissions of Car D on chassis dynamometer and on-road.

4.3 CO emissions

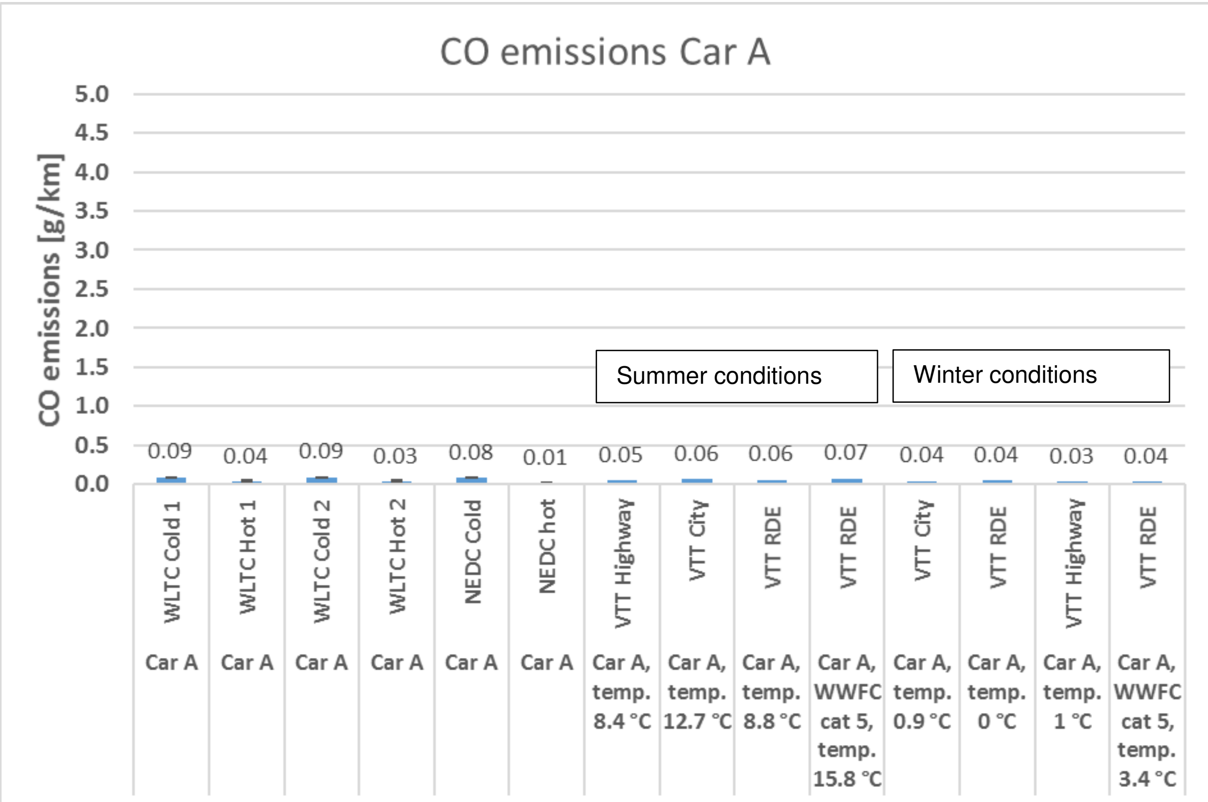

Figure 11: CO emissions of Car A on chassis dynamometer and on-road.

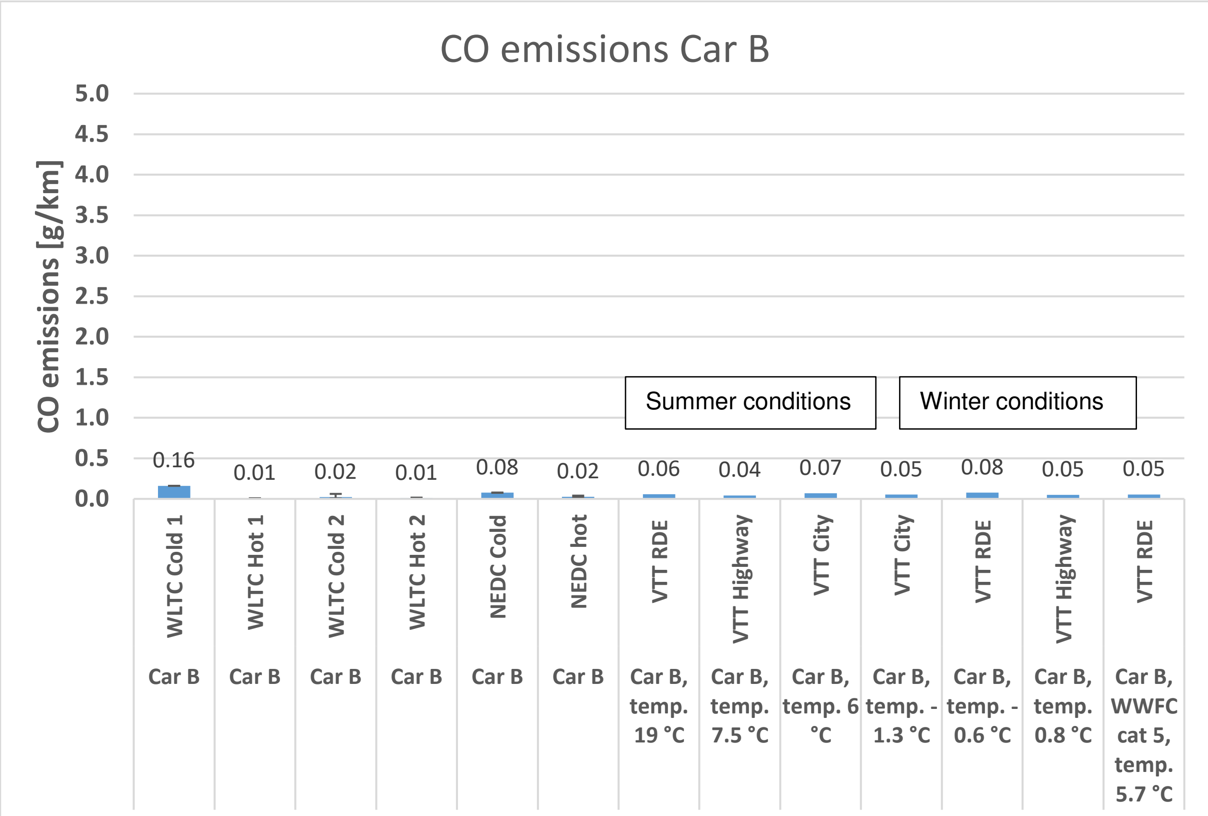

Figure 12: CO emissions of Car B on chassis dynamometer and on-road.

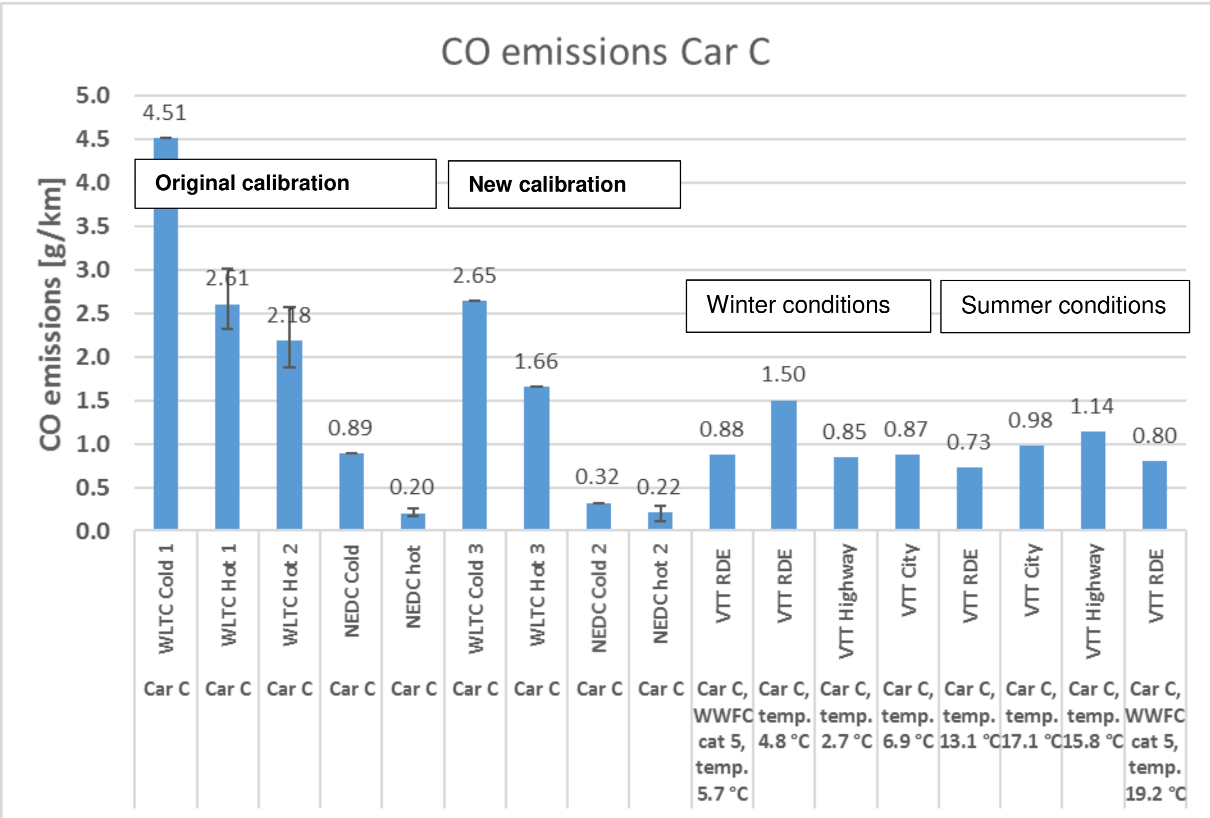

Figure 13: CO emissions of Car C on chassis dynamometer and on-road.

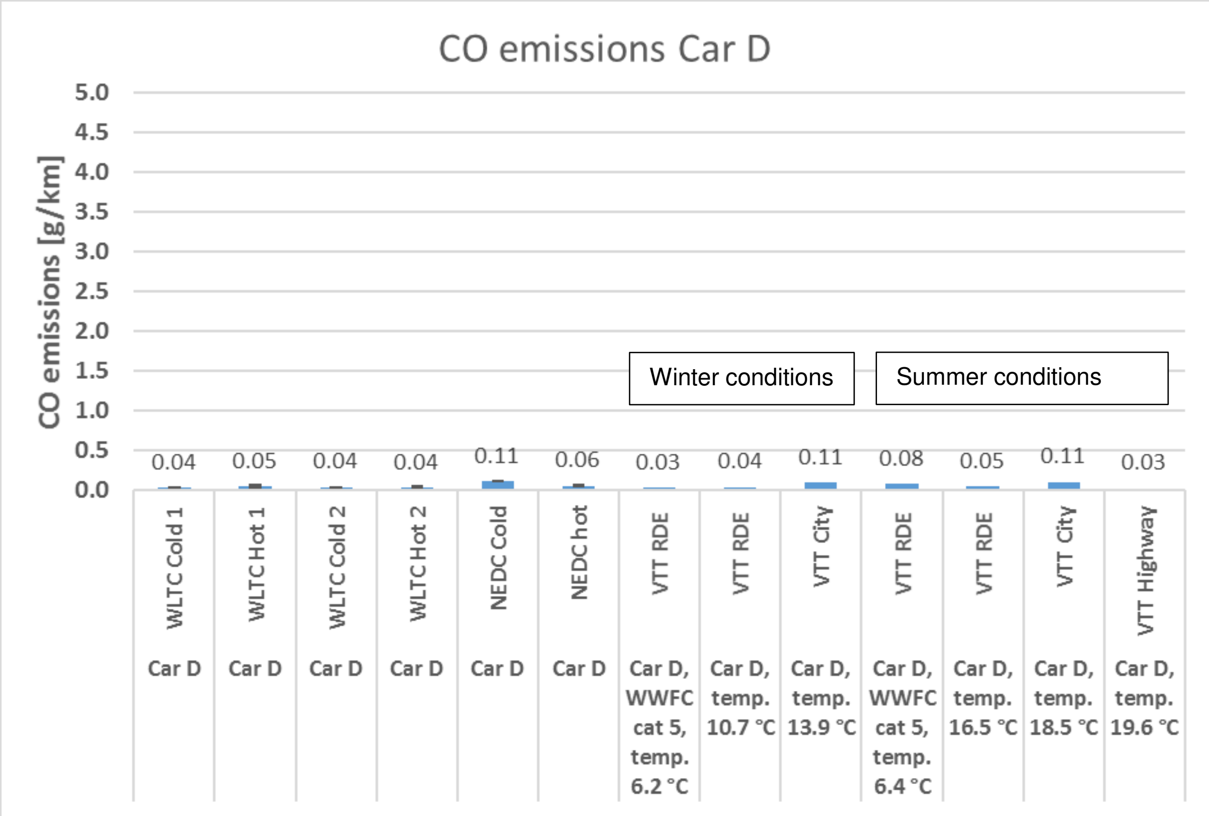

Figure 14: CO emissions of Car D on chassis dynamometer and on-road.

4.4 CO_2 emissions and fuel consumption

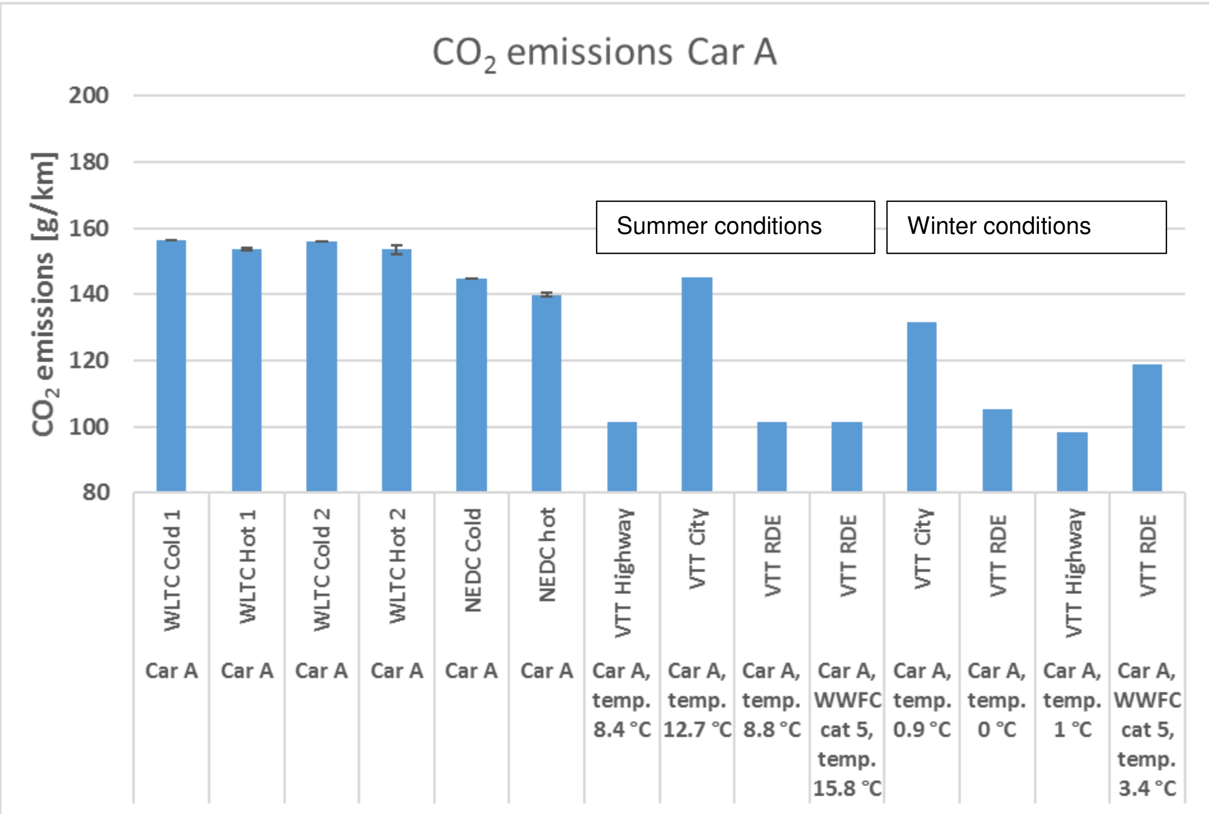

Figure 15: CO2 emissions of Car A on chassis dynamometer and on-road.

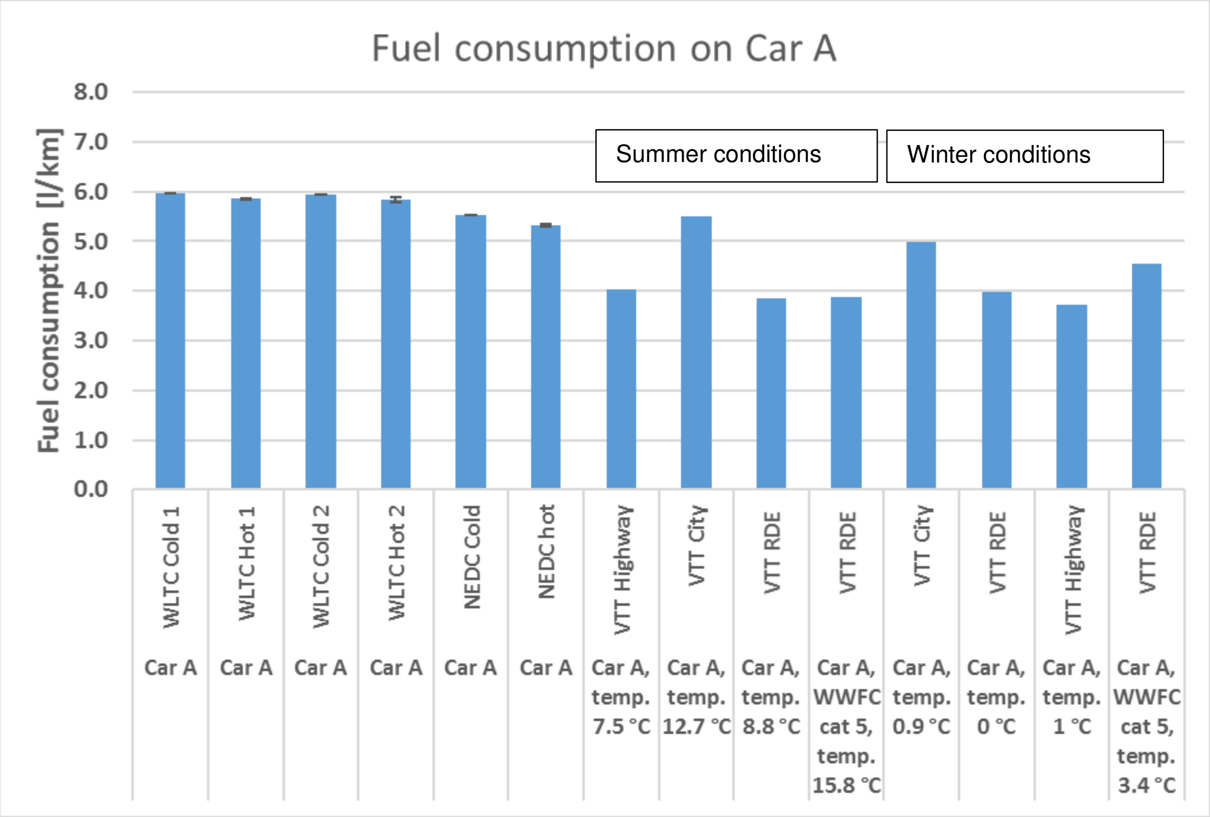

Figure 16: Fuel consumption of Car A on chassis dynamometer and on-road.

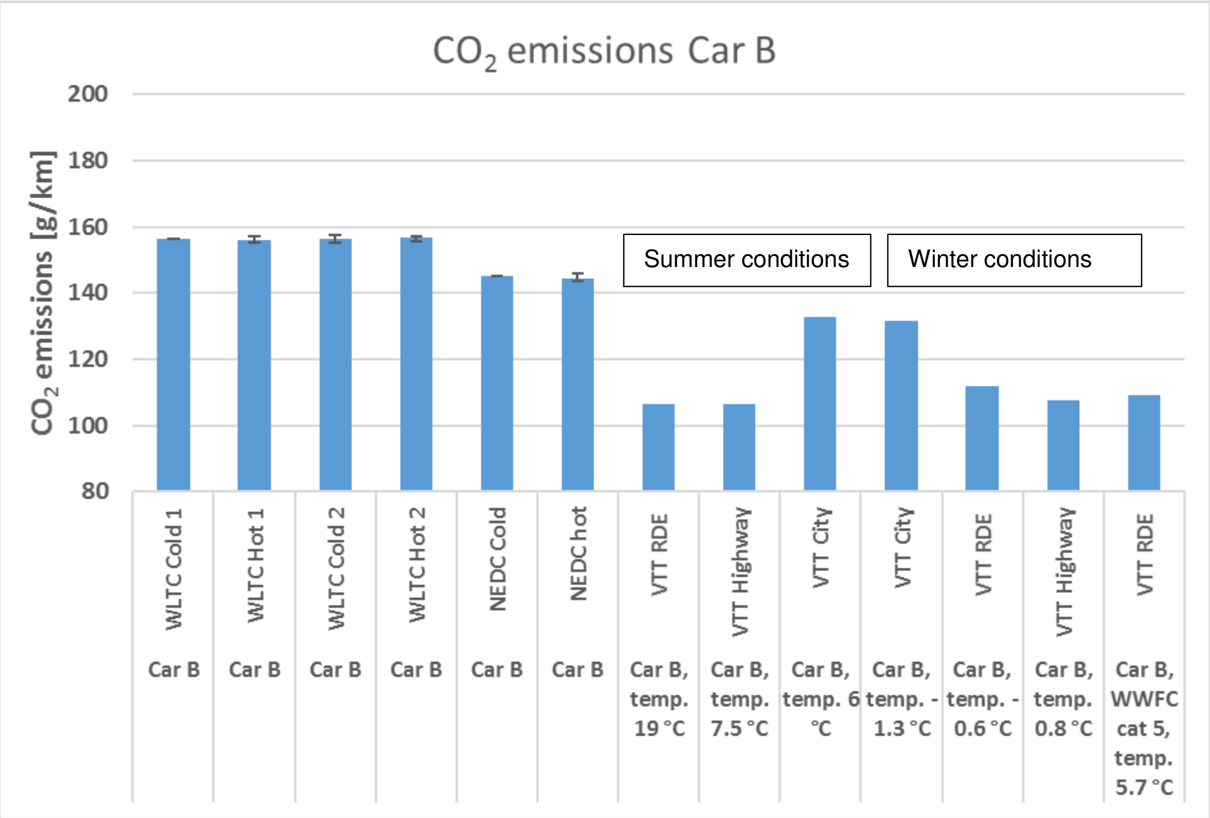

Figure 17: CO_2 emissions of Car B on chassis dynamometer and on-road.

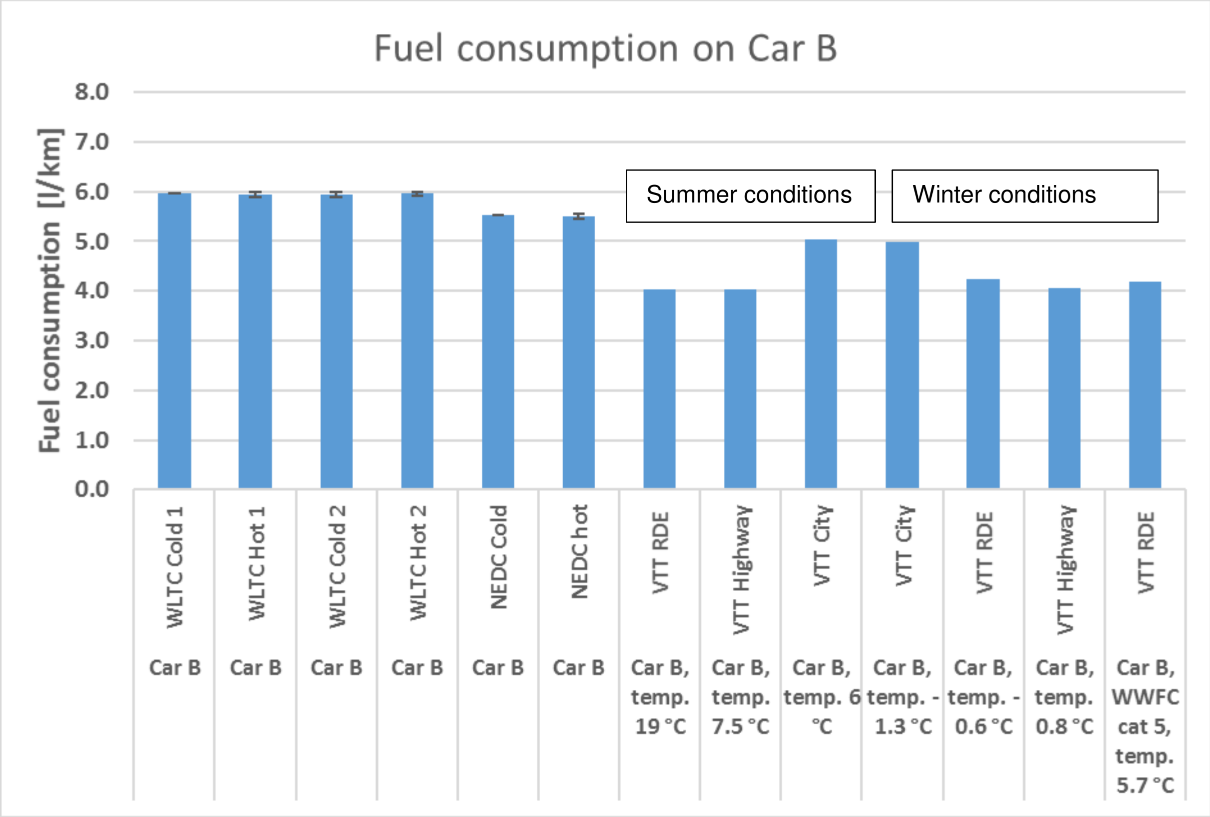

Figure 18: Fuel consumption of Car B on chassis dynamometer and on-road.

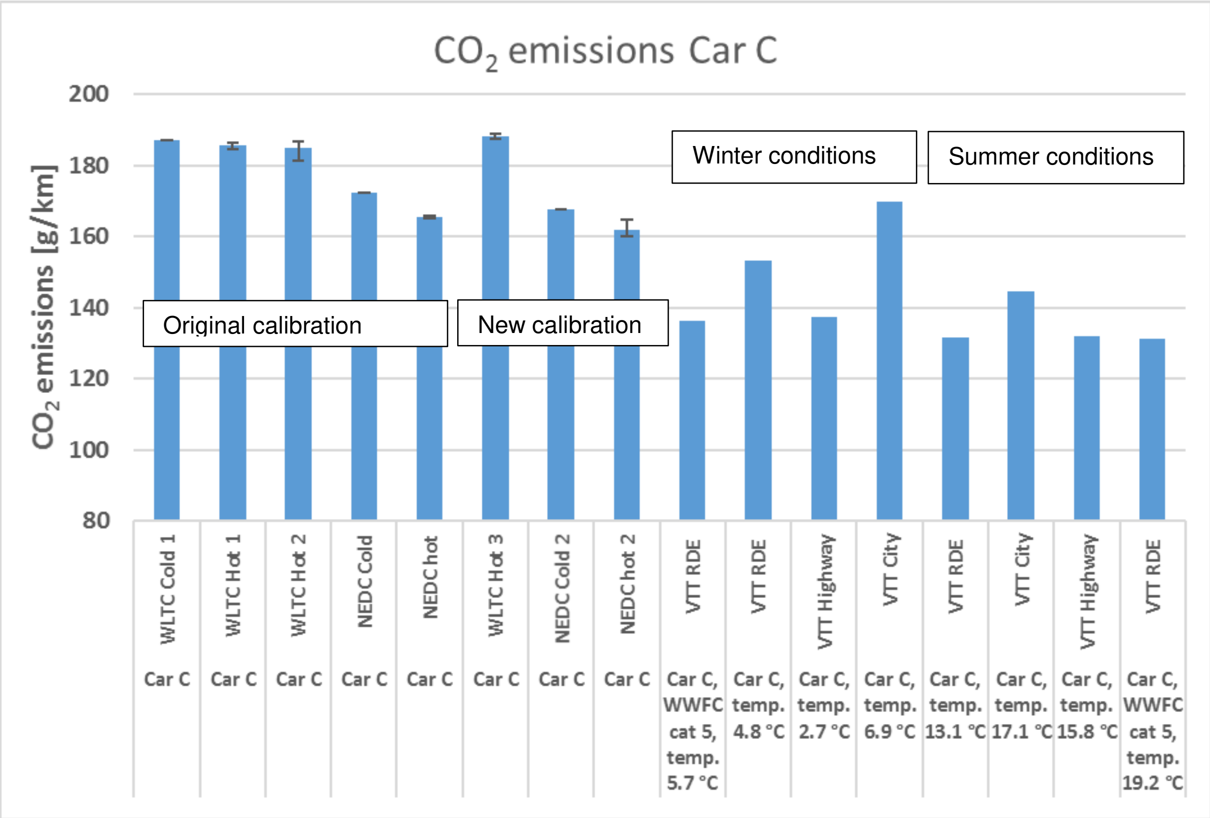

Figure 19: CO_2 emissions of Car C on chassis dynamometer and on-road.

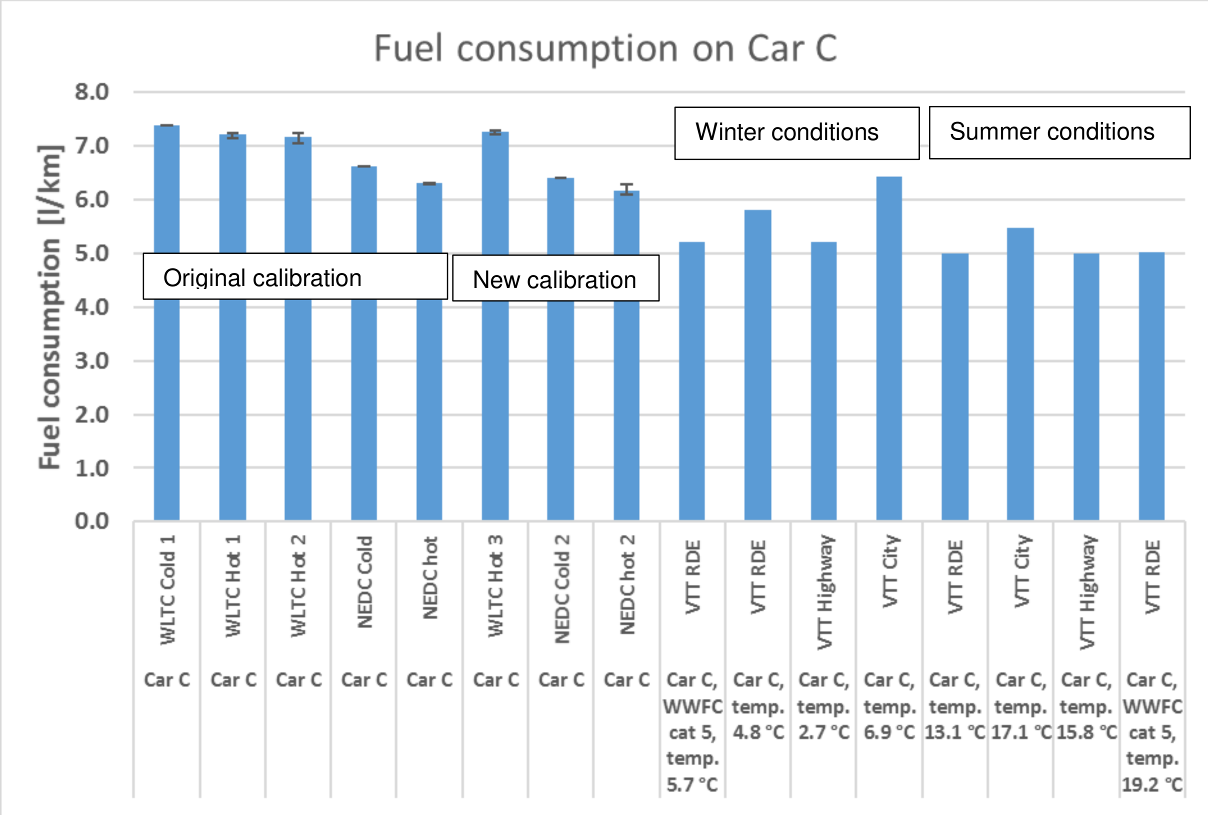

Figure 20: Fuel consumption of Car C on chassis dynamometer and on-road.

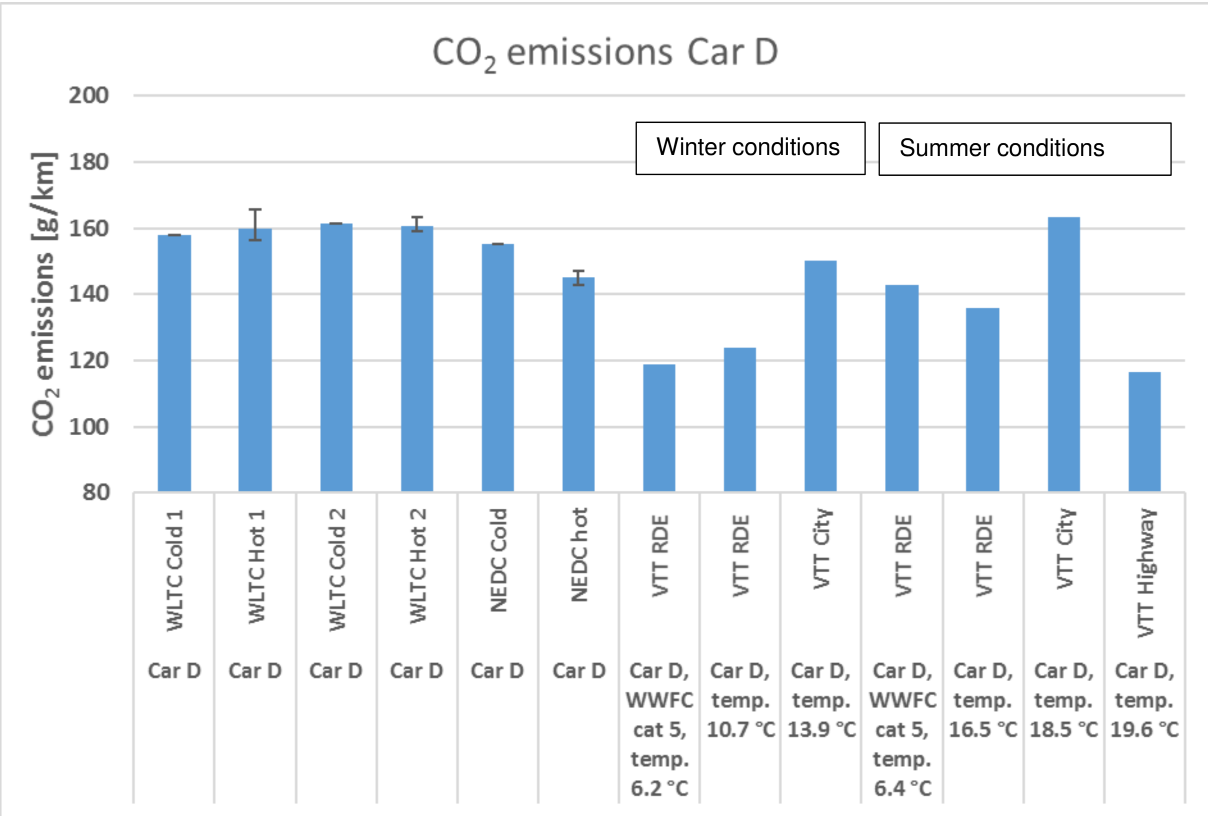

Figure 21: CO2 emissions of Car D on chassis dynamometer and on-road.

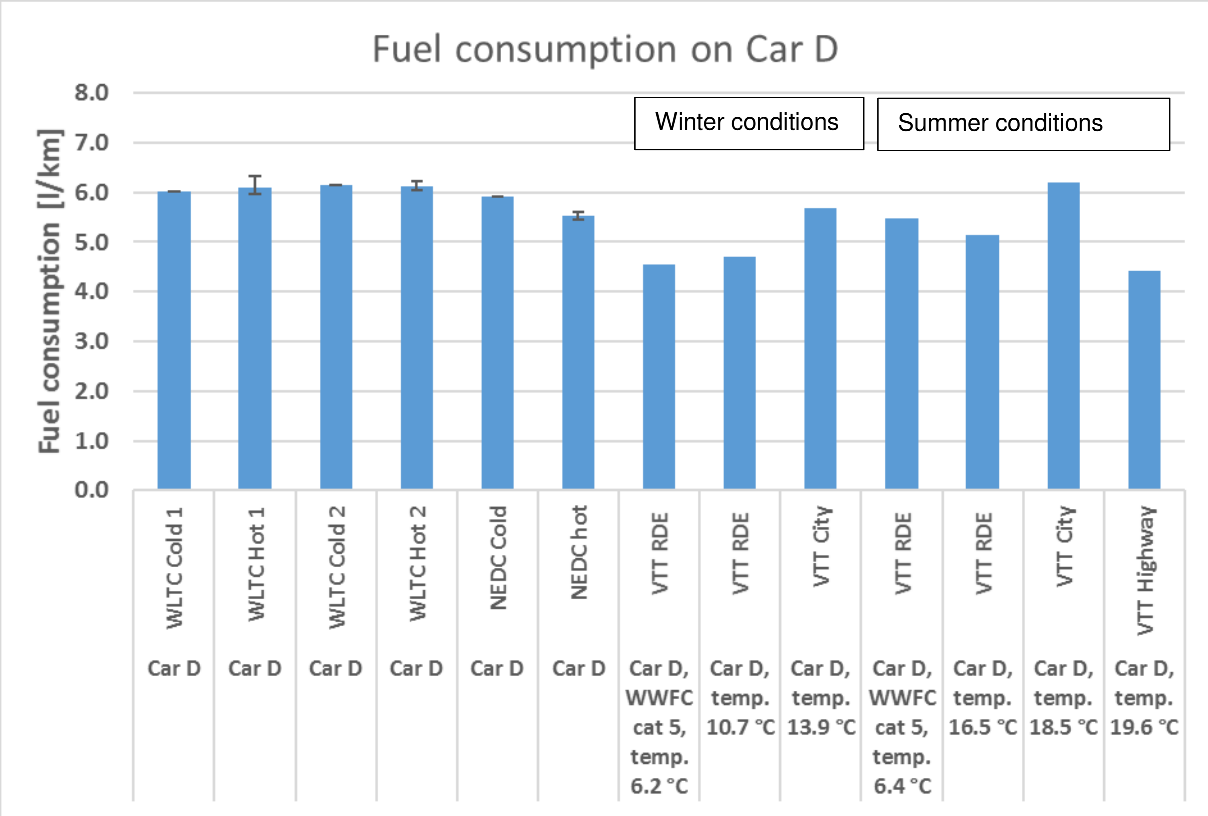

Figure 22: Fuel consumption of Car D on chassis dynamometer and on-road.

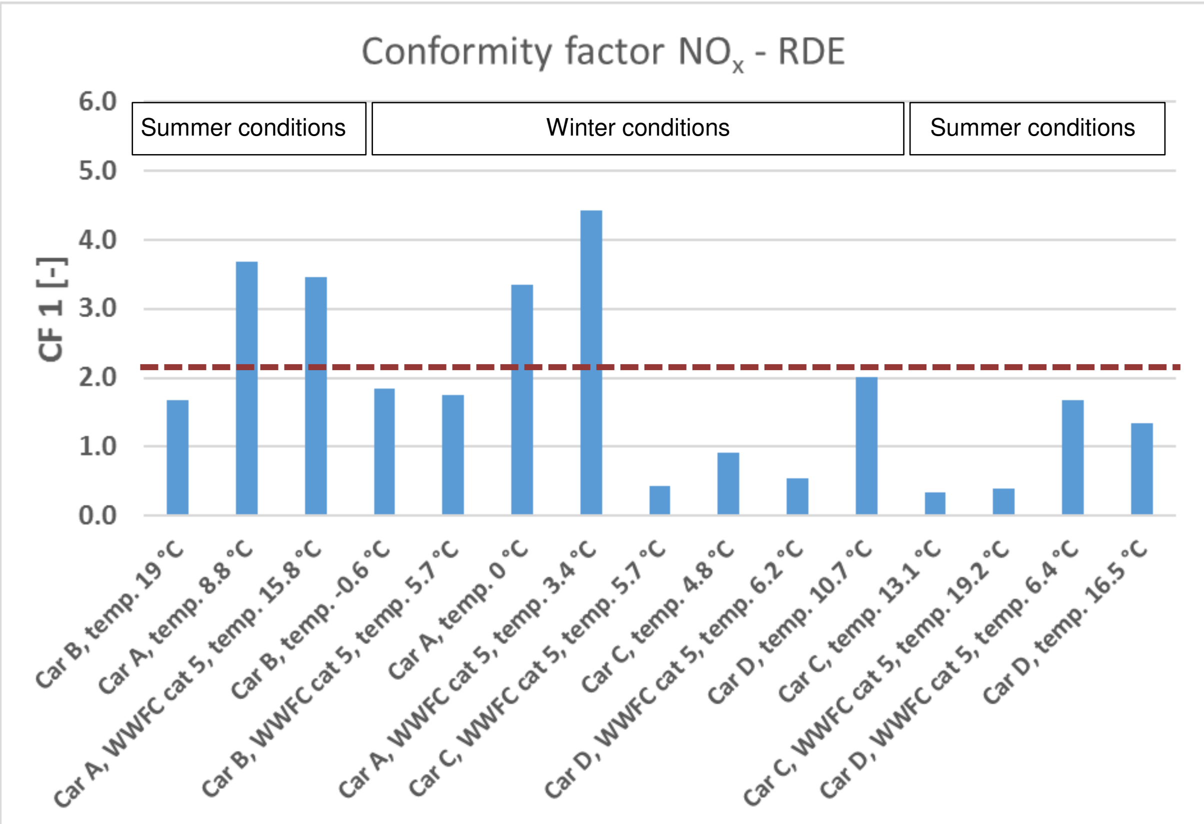

Figure 23: Conformity factor for NO_x on VTT RDE route. Red bar is illustrating the Euro 6 d-TEMP limit value for RDE (in effect on RDE route and officially applicable only for Car D).

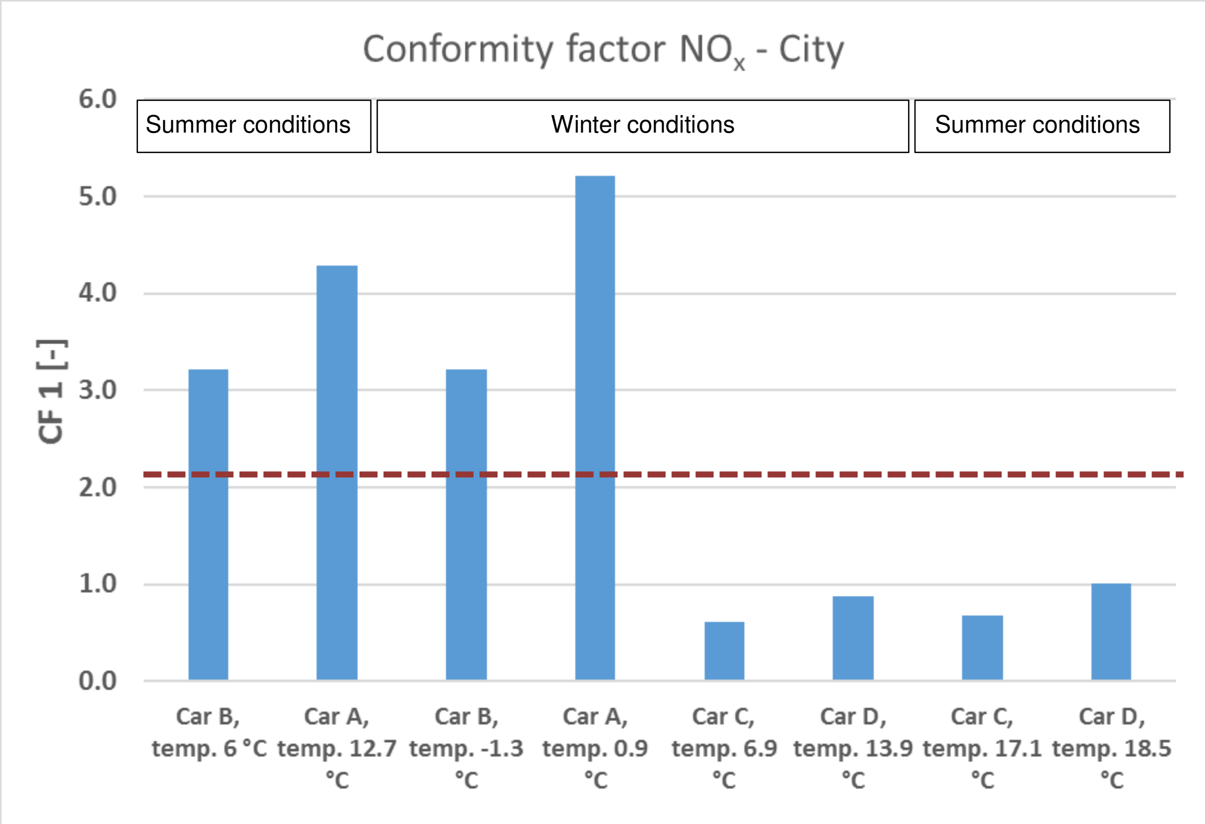

Figure 24: Conformity factor for NO_x on VTT City route. Red bar is illustrating the Euro 6 d-TEMP limit value for RDE (in effect on RDE route and officially applicable only for Car D).

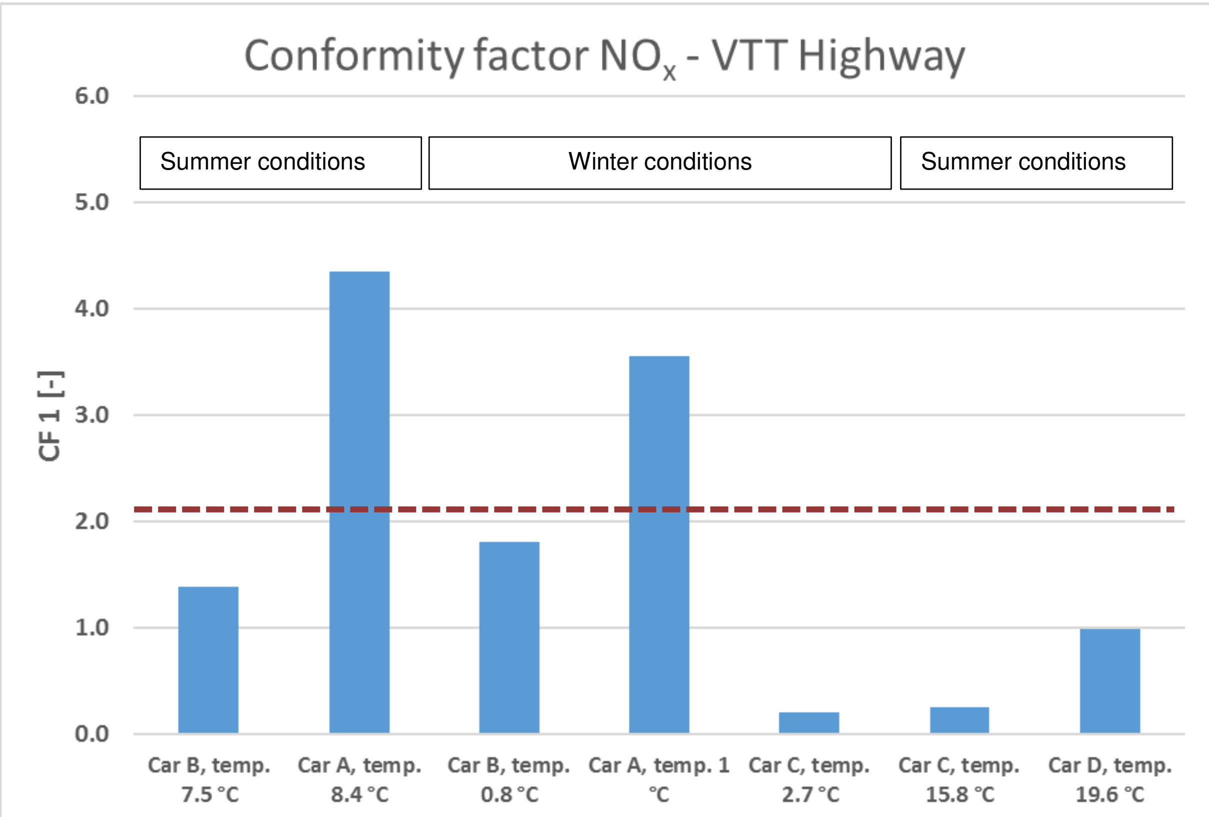

Figure 25: Conformity factor for NO_x on VTT highway route. Red bar is illustrating the Euro 6 d-TEMP limit value for RDE (in effect on RDE route and officially applicable only for Car D).

5. Discussion of 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 the OEM's have used 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.

5.1 Car A

In the chassis dynamometer tests, NO_x emissions of Car A were more than double on WLTC compared to NEDC. Absolute values on NEDC are over 2.5 times higher than the limit value of 0.08 g/km. Interestingly, the NO_x emissions in on-road measurements were lower over each of on-road routes compared to WLTC. In on-road, VTT RDE resulted the lowest NO_x emissions, which were 3.3-4.4 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 of test route. PN and CO emissions were both on chassis dynamometer and on-route low, and well below the type approval limits.

Car A is type approved according to NEDC with CO_2 emissions of 90 g/km. On chassis dynamometer, the CO_2 emissions were appr. 145 g/km on cold start and 140 g/km on hot start NEDC, which are clearly higher than the official type approval value. On on-road, VTT RDE and VTT Highway CO_2 emissions were surprisingly close to the type approval value, appr. 12.5 % higher.

Based on the measurements performed, it seems that ambient temperature difference of appr. 16 °C between the highest (appr. 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, and neither on CO_2 emissions.

5.2 Car B

Car B is a two years newer version of Car A 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 on warm NEDC and more than three times higher on WLTC compared to legislative limit value of 0.08 g/km. On VTT RDE and Highway routes, Car B resulted to a CF of 1.4…1.8 depending on route and measurement campaign, and on VTT City, the CF was 3.2 compared to limit value 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 or route or time of testing. Only the first WLTC cold cycle produced clearly higher PN emissions, which still are appr. 1/5 of limit value $6x10^{11}$ particulates/km.

Car B performed on chassis dynamometer similarly as Car A with CO_2 emissions of appr. 156 g/km on WLTC and 145 g/km on NEDC. On on-road measurements during summer conditions, Car B produced CO_2 emissions of 106…109 g/km on VTT RDE, 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 with Car B that temperature difference of some 18 °C (0.6 vs. 19 °C) have no effect on NO_x, PN and CO emissions, and neither on CO_2 emissions.

5.3 Car C

On 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 resulted appr. 70 % lower NO_x emissions on WLTC and 70…90 % on NEDC after the ECU update. On warm start NEDC, NO_x emissions were less than half of the limit value of 0.08 g/km. In on-road measurements, Car C performed extremely well. Car C resulted NO_x emissions with CF of 0.2…0.9 depending of test route. 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, PN emissions were clearly on a higher level than with Cars A and B, varying between $0.034x10^{11}$ and $2.9x10^{11}$ particulates/km.

Car C produced surprisingly high CO emissions. CO emission before the ECU update ranged from 2.18 g/km to 4.51 g/km on WLTC and from 0.2 g/km to 0.89 g/km on NEDC. After the ECU update, CO emissions declined to 2.65 g/km on cold-start WLTC and to 1.66 g/km on warm-start WLTC. Respectively, on cold-start NEDC CO emissions declined to 0.32 g/km, but on warm-start NEDC the ECU update did not have an effect. On on-road measurements, CO emissions altered from 0.73 g/km to 1.5 g/km depending on test route.

Based on the CO_2 emissions result on a chassis dynamometer, the ECU update did not have an effect on engine efficiency, or the difference was so small that it was at the same level that the repeatability of chassis dynamometer tests performed. Also with Car C, CO_2 emissions on chassis dynamometer were much higher than on on-route measurements.

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

5.4 Car D

Car D was tested last on both test campaigns. During the winter measurement campaign the ambient temperature level was abnormally high compared to typical ambient temperature at that time of year. Car D is type approved for Euro 6d-TEMP legislation, and it performs well in NO_x emissions that were well under the legislation limit value of 0.08 g/km ranging from 0.005 g/km on NEDC hot start to 0.048 g/km on WLTC cold start. On on-road measurements, NO_x emissions were slightly higher, varying from 0.043 g/km to 0.16 g/km over the VTT RDE route. Ambient temperature between the measurements campaigns varied between 6.2…19.6 °C. Car D resulted conformity factor values between 0.5…1.0 depending of test route. The time and conditions of the testing did not have effect that could be ascertained.

PN emissions on chassis dynamometer and on-road measurements were well under the limit value of $6x10^{11}$ particulate/km. Car D resulted quite variable PN emissions in on-route measurements depending on test route. Over the VTT RDE route, the emissions altered between $0.8…1.9x10^{11}$ particulate/km and on VTT City and Highway routes between $0.01…0.042x10^{11}$ particulate/km.

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

Car D resulted in CO_2 emissions of appr. 160 g/km on WLTC and 155 g/km on cold-start NEDC and 145 g/km on warm-start NEDC. On 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.

5.5 Effect of fuel on emissions

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

6. Summary

Within this project four Euro 6 diesel passenger cars representing typical vehicles in Finland were tested on chassis dynamometer and with on-road measurements. Three of the vehicles were Euro 6b class and one Euro 6d-TEMP class. 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 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 was run with two different fuels, one fulfilling EN590 and one WWFC cat 5 diesel standard.

On the chassis dynamometer, each car tested resulted in higher CO_2 emissions than the official type approval value. However, we must bear 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 CO_2 emissions, correspondingly.

Overall, each car resulted PN emissions, which were well under the limit value of $6x10^{11}$ particulate/km. Cars A, B and D resulted lowest PN emissions whereas PN emissions of Car C were remarkably higher on cold-start test cycles compared to warm-start cycles.

Cars A and B resulted much higher NO_x emissions on WLTC compared to NEDC. Car B, which was similar model as Car A but two years younger, resulted lower NO_x emissions than Car A. NO_x emissions of Car were ranging between 0.23...0.57 g/km depending of test cycle. Car B resulted NO_x emissions between 0.07…0.38 g/km depending of test cycle.

Car C was first measured on 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 test cycle and a reduction of 70…90 % compared to original software. In addition, a modest decline in CO emissions was identified as a result of software update. However, no change in CO_2 or PN emissions was identified.

Car D resulted in low NO_x emissions on both chassis dynamometer test cycles, both with cold and hot start conditions. NO_x emissions were well under the limit value of 0.08 g/km ranging between 0.005 g/km and 0.048 g/km.

Cars C and D resulted in low on-road NO_x emissions on each test routes varying from Car C lowest on VTT Highway with CF 0.2 to Car D highest on VTT RDE with CF of 2.0.

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

Based on the test results, PN emissions are not problem with Euro 6 diesel passenger cars. Euro 6 legislation forced OEM's to equip diesel vehicles with DPF, which seems to work extremely well also on-road driving conditions. The highest PN emission measured within the on-road measurements was 1/2 of the limit value.

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

The measurement programme performed showed that there is a marked difference especially in NO_x emissions within the Euro 6 cars depending of the certification level and the aftertreatment 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 a correctly designed exhaust after-treatment's control software, which is possible to update afterwards in ECU. Moreover, a Euro 6d-TEMP car with dual-LNT is capable of fulfilling the emission limits in every driving conditions, quite as expected.

There was not identified clear difference in NO_x, CO or PN emissions reduction performance on-road when tested at near-zero ambient temperature compared to tests performed app. 13 °C….20 °C temperature level. Only the Car C showed observable difference on RDE route NO_x emissions between the summer and winter measurement campaigns. One effecting aspect is the fact that during the winter measurement campaign ambient temperature were app. 10 °C higher than normally at that time of the year. This resulted in relative small difference in temperature during the summer and winter measurement campaigns.

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

Appendix IV – Full report from Sweden

Swedish In-Service Testing Programme on Emissions from <u>Passenger Cars and Light-Duty Trucks</u>

Main results year 2015-2017

2019-04-24

by

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Antrieb/Emissione
PKW/Kraftrad

TÜV NORD Mobilität

On behalf of the Swedish Transport Agency (STA) (Trafikverket)

Content

1. List of Abbreviations

A4 / A5 / A6	4-speed / 5-speed / 6-speed automatic gearbox
CI	Compression Ignition (diesel)
CO	Carbon monoxide
CO_2	Carbon dioxide
DI	Direct Injection
Euro 5, Euro 6	Type approval test in accordance with Directive 715/2007/EC
FC	Fuel consumption
GDI	Gasoline Direct Injection
HC	Hydro carbons; see THC
M1	Vehicles for passenger transportation with a capacity of max. 8 seats excluding the driver and a maximum total vehicle mass of 3,500kg
M5 / M6	5-speed / 6-speed manual gearbox
MPI	Multi Point Injection
NEDC	New European Driving Cycle according to Directive 715/2007/EC
NO_X	Nitrogen oxides
OBD	On-Board Diagnosis
PEMS	Portable Emission Measurement System
PI	Positive Ignition (gasoline)
PM	Particle Mass
PN	Particle Number
RDE	Real Driving Emission
RPA	Relative Positive Acceleration
SCR	Selective Catalytic Reduction
THC	Total Mass of hydro carbons emitted by a vehicle, given in C_1 equivalent
UDC	Urban Driving Cycle; Part 1 of the New European Driving Cycle
WLTP / WLTC	Worldwide harmonized Light vehicles Test Procedures/Cycles

2. Svensk sammanfattnig

Transportstyrelsen har ansvar för tillsyn av efterlevnaden av lagstiftningen om avgasrening för motorfordon registrerade i Sverige. I detta ansvar ingår att kontrollera att de fordon som är i bruk uppfyller avgaskrav enligt EU bestämmelser. Fordonstillverkare har enligt lag ett krav på att avgasreningen för ett nytt fordon fungerar en viss körsträcka eller en viss tid, exempelvis 10 000 mil eller 5 år. För att följa upp att detta gör Transportstyrelsen en kontroll av avgasrening från slumpmässigt utvalda fordon. Med hjälp av hållbarhetsprovningen vill Transportstyrelsen kontrollera att fordonstillverkaren följer kraven om avgasrensning för svenskregistrerade fordon. Kontrollen är även till för att fordonstillverkaren ska ta ansvar och vara medveten om att detta övervakas. Transportstyrelsen har genom en upphandling utsett TÜV Nord tillsammans med Ecotraffic AB att utföra hållbarhetsprovningen av lättafordon. Under 2015 till 2017 har totalt 198 bilar testats inom ramen för detta hållbarhetsprojekt (IUC, In-Service Conformity).

- 106 bilar med CI-motorer (diesel)
- 87 bilar med PI-motorer (bensin)
- 5 bilar med bensin/etanol-motor
- 45 % av bilarna var Euro 5 och 55 % Euro 6
- 57 bilar har testats i ett PEMS-program (Real Driving Emissions = tester i verklig trafik)
- Medeleffekt och motorstorlek för bilar med CI-motorer var 102 kW/1797 cc
- Medeleffekt och motorstorlek för bilar med PI-motorer var 75 kW/1320 cc

Tester har utförts enligt körcyklerna PEMS, WLTP, ERMES, NEDC typ I, II, III, IV, VI samt OBD-kontroll. Alla bilar har inte testats enligt alla testmetoderna. Nedan visas några av de viktigaste resultaten från hållbarhetstesterna under 2015 till 2017.

Viktiga resultat

Typ I test	I stort sett alla bilar uppfyllde kraven
Typ II, III, IV och VI	I stort sett alla bilar uppfyllde kraven
Bränsleförbrukning	Uppmätt förbrukning är oftast högre än vad tillverkarna deklarerat
Bränslen	NO_X signifikant högre från bilar drivna med diesel än från bilar drivna med bensin CO och partikelemissioner är signifikant högre från bilar drivna med bensin än från bilar drivna med diesel
Emissionsklass	NO_X emissioner från bilar med CI-motorer ser ut att minska från Eu5 till Eu6 Ingen signifikant skillnad för CO och partiklar mellan Eu5 och Eu6 (gäller både CI och PI-motorer)
Teknik	Användande av SCR (Adblue) ser ut att resultera i låga NO_X emissioner för bilar med CI-motorer – (jämförbara nivåer med NO_X emissioner från bilar med PI-motorer) Filter är viktiga för att nå låga partikelemissionsnivåer. Alla bilar med CI-motorer var utrustade med filter (DPF, Diesel Particle Filter). Ingen av bilarna med PI-motorer hade filter (GPF, Gasoline Particle Filter). Detta resulterade i mycket låga partikelemissioner från bilar med CI-motorer och relativt höga emissioner från bilar med PI-motorer. Några av bilarna med PI-motorer (och med DI, Direct Injection) visade relativt höga NO_X-emissioner
CO_2 från CI vs PI (diesel vs bensin)	Ett skifte från bilar med CI-motorer till bilar med PI-motorer (från diesel till bensin) ser ut att medföra i en ökning av CO_2-utsläpp med ca 20 %

Körcykler	RDE (Real Driving Emissions, körning i verklig trafik) resulterar i högre emissioner och bränsleförbrukning jämfört med tester på chassidynamometer (rullande landsväg). WLTP är den körcykel som kommer närmast (relativt nära) körning i trafik med avseende på CO_2, bränsleförbrukning och partikelemissioner. För NO_X från bilar med CI-motorer och CO från bilar med PI-motorer är skillnaden mellan WLTP och körning i verklig trafik är relativt stor.
Omgivningstemperatur	Lägre temperaturer resulterar i högre HC och CO-emissioner från bilar med PI-motorer samt högre NO_X-emissioner från bilar med CI-motorer.
Mini-PEMS vs Full-PEMS	Resultaten från Mini-PEMS är relativt nära resultaten från Full-PEMS med avseende på NO_X, CO_2 och bränsleförbrukning, men inte CO. Mini-PEMS behöver tillgång till bilens OBD-uttag (för att räkna ut avgasflödet behövs tillgång till massflödet luft till motorn, MAF-signalen) Denna signal finns inte att tillgå på alla bilmodeller.
Framåtblick	På senare tid har det kommit bilar av emissionsklass Euro 6d-TEMP, dessa bilar är certifierade enligt WLTP och med tester i verklig trafik. Initiala tester visar att bilar med CI-motorer har relativt låga NO_X-emissioner – och jämförbara med NO_X-emissioner från bilar med PI-motorer. I denna studie ingick bara en bil av denna euroklass. Den uppmättes till ca 20 mg NO_X per km i tester i verklig trafik, d.v.s. långt under gränsvärdet. Allt fler bilar med PI-motorer utrustas med partikelfilter (GPF) som sannolikt kommer att ge låga partikelemissioner. Detta sammantaget gör att framtidens bilar med förbränningsmotorer troligen kommer att ha låga emissioner av samtliga emissionskomponenter – ofta långt under lagstadgade nivåer.

Några kommentarer

Under NEDC test I var den uppmätta bränsleförbrukningen (och CO_2) högre än av tillverkarna deklarerade värden för 44 av 47 bilmodeller (94 %)

- Medel för alla bilmodeller var + 6,8 %
- Medel för bilar med PI-motorer var + 7,5 %
- Medel för bilar med CI-motorer var + 6,1 %
- För 9 modeller var förbrukningen mer än 10 % högre än deklarerat

Alla bilarna i PEMS-programmet uppfyllde kraven enligt NEDC typ I. Typ II- till typ VI-test var inte inkluderade i detta program.

Med det skifte som nu verkar ske från bilar med CI- till bilar med PI-motorer (från diesel till bensin) är det högst troligt att CO_2-emissionerna från personbilar kommer att öka. Detta kan komma att vända den kontinuerliga minskning i bränsleförbrukning och CO_2-utsläpp som skett under den senaste 20 årsperioden. Detta under antagande att det inte kommer att bli något skifte till mindre bilstorlekar – och att de "stora" bilarna som idag mestadels har CI-motorer – kommer att ersättas av bilar med PI-motorer.

I hållbarhetsprogrammet under 2015-2017 har tester med fyra olika körcykler utförts parallellt för 10 bilmodeller med CI-motorer och för 9 modeller med PI-motorer, NEDC, WLTP, ERMES och PEMS

WLTP är den körscykel som är "kommer närmast" körning i verklig trafik. För bilar med CI-motorer skiljer det ungefär 3 % i uppmätt bränsleförbrukning och för bilar med PI-motorer är skillnaden ungefär 11 %. ERMES körcykeln tycks ge lägre resultat än NEDC.

Vid tester i verklig trafik (PEMS) är CO-emissionerna i medel ungefär 10 gånger högre från bilar med PI-motorer jämfört med bilar med CI-motorer.

NO_X-emissioner var högst vid tester i verklig trafik (PEMS) och lägst vid NEDC-tester. Störst var skillnaden för bilar med CI-motorer. I medel 6.6 gånger högre NO_X-emissioner.

3. Summary

The Swedish Transport Agency (STA) is responsible for type-approval together with other obligations, for motor vehicle emission controls. With that follows the obligation to carry out evaluations of the in-service emission performance according to EU legislation. The STA has commissioned TÜV Nord (Germany) in collaboration with Ecotraffic (Sweden) to carry out the test programme on light duty vehicles. The objective of the Swedish test programme is to conduct screening tests on a number of vehicle models, picked out on a spot-check basis, to verify durability in the emission control concept. From year 2015 to 2017 in total 198 vehicles have been tested in the Swedish IUC program (In-Service Conformity)

- 106 cars with CI engines (diesel)
- 87 cars with PI engines (gasoline)
- 5 cars with gasoline/ethanol engines
- 45 % of the vehicles were of Euro 5 and 55 % of Euro 6
- 57 vehicles have been tested in the PEMS-program (Real Driving Emissions)
- Average power and engine size for the cars with CI engines was 102 kW/1797 cc
- Average power and engine size for the cars with PI engines was 75 kW/1320 cc

Tests were performed during the programs according to the test cycles PEMS, WLTP, ERMES, NEDC type I, II, III, IV, VI and OBD-control. Not all tests have been carried out on all cars. Below, some of the main findings during the Swedish IUC 2015 - 2017 program are shown.

Main Conclusions

Type I tests	Almost all vehicle models tested complied with the limits given by the directive
Type II, III, IV and VI	Almost all vehicle models tested complied with the limits given by the directive
Fuel consumption	Measured values are often higher than declared by manufacturers
Fuels	NO_X significantly higher from diesel- compared to gasoline cars CO significantly higher from gasoline- compared to diesel cars Particles significantly higher from gasoline- compared to diesel cars
Emission class	NO_X emissions from cars with CI engines seems to decrease from Eu5 to 6 No significant differences for CO and Particles between Eu5 and 6. (both CI and PI engines)
Technologies	SCR seems to give lower NO_X emissions for cars with CI engines and comparable with NO_X emissions from cars with PI engines. Filters are important for low particle emissions. All cars with CI engines were equipped with DPF (Diesel Particle Filter) but none of the cars with PI engines were equipped with GPF (Gasoline Particle Filter). This resulted in low emissions of particles from cars with CI engines (and relatively high from cars with PI engines) Some of the cars with PI engines and with DI (Direct Injection) showed relatively high NO_X emissions
CO_2 from CI vs PI	A shift from CI to PI (e.g. from diesel to gasoline) engine is likely to increase the CO_2 emissions by app. +20 %
Driving cycles	RDE (Real Driving Emissions) give higher emissions and fuel consumption compared to tests on chassis dynamometer. WLTP results are relatively close to results from RDE (PEMS tests) regarding CO_2, fuel consumption

	and particles. For NO_X from cars with CI engines and CO from cars with PI engines, the differences between RDE and WLTP are relatively high.
Ambient temperatures	Lower ambient temperature resulted in higher HC and CO emissions for cars with PI engines and higher NO_X emissions from cars with CI engines.
Mini-PEMS vs Full-PEMS	Results from Mini-PEMS are relatively close to results from Full-PEMS regarding NO_X, CO_2 and fuel consumption (but not CO). Mini-PEMS needs data from OBD connector (e.g. the Mass Air Flow signal). This signal is not available on all cars.
Outlook	Initial tests on cars with CI engine and of emission class Euro 6d-TEMP seems to give low NO_X emissions (also on RDE-tests) – similar NO_X values as from cars with PI engines. Only one of these car are included in this study, and the NO_X emission during RDE seems to be about 20 mg/km, i.e. far below the limit value. More and more cars with PI engines seems to be equipped with particle filters (GPF), which likely will give low particulate emissions. All in all, future cars with internal combustion engines will probably have low emissions of both NO_X. CO, HC and particles - often well under legislative limit values.

Some comments

During the Type I test on 47 vehicle types the measured fuel consumption (and CO_2) were higher than the values declared by the manufacturer for 44 of the 47 vehicle types (94 % of all vehicles).

- The average value for all types was +6,8 %
- The average value for vehicles with positive ignition engines was +7,5 %
- The average value for vehicles with compression ignition engines was +6,1 %
- 9 vehicle models exceeded +10 %

All tested vehicles in the additional PEMS-program complied with the limits given by the directive during Type I test. Type II to type VI were not included in the additional program.

With the current shift from CI to PI (e.g. from diesel to gasoline) engine in light-duty vehicles, it is likely that CO_2 emissions will increase in the future, albeit the current efforts in engine development to reduce fuel consumption and CO_2 from either type of engine/vehicle. This would contrast the trend of continuous reduction in CO_2 over the last period of ~20 years. This assumption is on the condition that there will be no major shift in vehicle size, i.e. that also the engines in larger vehicles – that mostly run on diesel fuel today – would be replaced by gasoline-fuelled powertrains.

In the IUC program year 2015 to 2017, tests using four (4) different driving cycles in parallel have been carried out for 10 vehicle models with compression ignition and 9 models with positive ignition engines.

WLTP is the driving cycle that is closest to the Real Driving Cycle PEMS with respect to CO_2-emission. (Within about 3 % lower for cars with CI engines and about 11 % lower for cars with PI engines). ERMES seems to give results lower than NEDC.

During test in real traffic (PEMS-test) the average emission of CO was about 10 times higher from cars with positive ignition engines compared with cars equipped with compression ignition engines.

The NO_X-emissions were highest for tests in accordance with PEMS and lowest in the NEDC test cycle. Especially high was the difference from Real Driving Emissions compared with the NEDC cycle for cars with compression ignition engines. In average, the difference between NEDC and PEMS was about a factor of 6,6.

4. Short background and description of the test programs 2015 – 2017

Swedish Transport Agency (STA) is responsible for type-approval, together with other obligations, for motor vehicle emission controls. With that follows the obligation to carry out evaluations of the in-service product performance. The STA has commissioned TÜV Nord (Germany) in collaboration with Ecotraffic (Sweden) to carry out the test programme on light duty vehicles. The objective of the Swedish test programme is to conduct screening tests on a number of vehicle models, picked out on a spot-check basis, to verify durability in the emission control concept. This is done in close collaboration with the vehicle manufacturers. This enables the manufacturers concerned to rectify any type-specific faults relevant to emissions of the vehicles on the road and serial production and to incorporate knowledge gained from the field monitoring in future developments. By proceeding in this way, this research programme contributes directly to lowering the environmental pollution from emissions caused by road traffic.

Besides In-Service Conformity testing it is also an additional objective of the programme to obtain information on emissions from vehicles during real world driving. These data will be used to update the European emission model HBEFA. HBEFA is used in Sweden for national emission inventories and as input to local air pollution calculations. To get more information about real world driving, the expert group of the European commission for Real Driving Emission on Light Duty Vehicles (RDE-LDV) declared the use of a Portable Emission Measurement System (PEMS) for type approval starting 2017. Up to now the RDE-LDV Group discusses how to carry out such measurements the right way. To update the database, and to support the ongoing process, different types of vehicles in this program where tested with PEMS. The collected data were provided to the Joint Research (JRC) Centre of the European Commission.

The In-Service Conformity test of vehicles in operation on the roads was introduced in October 1998 with the Directive is resumed in directive 715/2007/EC in the member states of the EU. Here privately-owned vehicles, which have been licensed under Directive 98/69/EC or 715/2007/EC, are examined after a statistical selection process in a complete test procedure according to the type approval cycle. It is the vehicle manufacturer who is responsible for this test. In addition to the manufacturer’s own In-Service Conformity tests, some countries in the EU have parallel national programs for In-Service Conformity. On a regular basis this started in Sweden in 1991, first based on the national emission regulation and later based on the EC directive.

In numerous programmes it has been shown that In-Service Conformity testing can reveal type-specific and design-related faults or inadequate maintenance regulations which, after an extended operating period of the vehicle, lead to an inadmissible increase in exhaust emissions.

Overview of tested vehicles year 2015 - 2017

From year 2015 to 2017, in total, 198 vehicles have been tested in the Swedish IUC program (In-Service Conformity):

- 106 cars with CI engines (diesel)
- 87 cars with PI engines (gasoline)
- 5 cars with gasoline/ethanol engines
- 45 % of the vehicles were of Euro 5 and 55 % of Euro 6
- 57 vehicles have been tested in the PEMS-program (Real Driving Emissions)
- Average power and engine size for the cars with CI engines was 102 kW/1797 cc
- Average power and engine size for the cars with PI engines was 75 kW/1320 cc

Year	Program	Engine	PEMS	WLTP	ERMES	Conditioning	Type I	Type II	Type III	Type IV	Type VI	OBD cehck
2015	IUC	CI		3 of 5		5 of 5	5 of 5					1 of 5
2015	IUC	PI		3 of 5		5 of 5	5 of 5	5 of 5	5 of 5	2 of 5	2 of 5	1 of 5
2016 + 2017	IUC	CI		3 of 5	3 of 5	5 of 5	5 of 5					1 of 5
2016 + 2017	IUC	PI		3 of 5	3 of 5	5 of 5	5 of 5	5 of 5	5 of 5	2 of 5	2 of 5	1 of 5
2015	PEMS	CI+PI	3 of 5	3 of 5	3 of 5		3 of 5					
2016+2017	PEMS	CI+PI	3 of 3	3 of 3	3 of 3		3 of 3					

Table 1. Overview of tests per categories of vehicles and program

The investigations were implemented with reference to Directive 715/2007/EC. In order to obtain a reliable assessment if type-specific defects are present on a vehicle type, initially five vehicles per type were measured with respect to exhaust emissions. After the vehicles had been received at the laboratory, a check was made as to whether the specified maintenance intervals had been conducted and that the vehicles were in a proper condition. Proof was provided by means of the service record manual. Before commencement of the measurements on the chassis dynamometer, the vehicles were checked with respect to the tightness of the exhaust system. For dynamometer setting the same inertia weight and coast down values were chosen as for the type approval test. A deterioration factor was not used for evaluating the Type I test results. The vehicle types were assessed in accordance with Directive 715/2007/EC. The vehicles were tested in a measuring programme which not only includes the tests applied for type approval, but also covers other test cycles like WLTP and ERMES to determine exhaust emission factors. It does not show the different tests in the order operated during the programme. The WLTP was driven according the GTR in the beginning of the test-program to implement an additional conditioning of the vehicles before starting the tests according to the directive. On the afternoon of the day before running the Type I tests, all vehicles were conditioned (NEDC for vehicles with positive ignition, 3 Extra Urban Driving Cycles (EUDC) for vehicles with compression ignition). Type II and III tests on vehicles with positive ignition engine were carried out immediately after the Type I test. The OBD check was done at the end of the test procedure to make sure that the simulation of emission relevant failures could not affect the results of the other tests. Driving cycles are described in the Appendix.

Overview of test program 2015-2015

2015 - In this In-Service Conformity testing programme, a total of 65 vehicles, spread over 5 vehicle types with positive ignition engine (within this 1 vehicle type with ethanol fuel, E85) and 8 vehicle types with compression ignition engine were tested with respect to the exhaust emissions limited by law.

2016 - In this In-Service Conformity testing programme a total of 45 vehicles, spread over 4 vehicle types with positive ignition engine and 5 vehicle types with compression ignition engine were tested with respect to the exhaust emissions limited by law. PEMS (drive emissions in real traffic) tests were carried out in an additional program of total 18 vehicles, 4 vehicle types with positive ignition and 2 vehicle types with compression ignition engine.

2017 - In this In-Service Conformity testing programme a total of 40 vehicles, spread over 4 vehicle types with positive ignition engine and 4 vehicle types with compression ignition engine were tested with respect to the exhaust emissions limited by law. PEMS (drive emissions in real traffic) tests were carried out in an additional program of total 30 vehicles, 5 vehicle types with positive ignition and 5 vehicle types with compression ignition engine.

Within the 2017 years program also a comparative PEMS-tests between Germany and Sweden were carried out. The background to these tests were to find out if it is any differences between using a PEMS-Route in Sweden or in Germany. Two passenger cars were used, one with CI- and one with SI engine, both Euro 6. During this year also several PEMS tests with a simplified test method using sensors (in this report denoted “Mini-PEMS”) were performed. Beside the comparative tests described above, in addition, about 25 tests with the Mini-PEMS method have been carried out on different modern passenger cars.

No	Program IUC	Program PEMS	Number #	Manufacturer	Model	Type	Fuel	Engine	Engine stroke	Power	Rated speed	Exhaust directive	Emission Standards	Milage min	Milage max	Type approval no	Registration
43	2015		5	Suzuki	Swift	NZ	Gasoline	K12B	1 242	69	6 000	715/2007*692/2008F	Euro 5b	37 453	72 202	e4*2007/46*0155*	Feb11 – Dec12
45	2015		5	Nissan	Qashquai	J10	Gasoline	MR20	1 997	104	6 000	715/2007*692/2008A	Euro 5a	39 166	79 632	e11*2001/116*0295*	Jun11 – Jun12
48	2015		5	Ford	Fiesta	JA8	Gasoline	SNJB	1 242	60	5 800	715/2007*692/2008A	Euro 5a	29 308	70 584	e9*2001/116*0069*	Jun11 – Oct13
54	2015		5	Mercedes	A180	245G	Gasoline	270910	1 595	90	5 000	715/2007*195/2013W	Euro 6b	21 284	42 630	e1*2001/116*0470*	Feb14 – Jan15
55	2015		5	Volvo	V70 (Flexifuel)	B	Gasoline/Ethanol	B4164T2	1 596	132	5 700	715/2007*566/2011J	Euro 5b	37 253	84 808	e9*2001/116*0065*	Jul12 – Feb 15
44	2015	2015	5	Audi	A3	AU	Diesel	CRKB	1 598	81	3 200	715/2007*630/2012J	Euro 5b	16 680	51 236	e1*2007/46*0607*	Dec13 – Dec13
46	2015		5	Toyota	Avensis	T27	Diesel	IAD-FTV	1 998	91	3 600	715/2007*692/2008F	Euro 5b	23 311	57 416	e11*2001/116*0331*	May12 – Feb13
47	2015	2015	5	Volvo	V60	F	Diesel	D4162T	1 560	84	3 600	715/2007*630/2012J	Euro 5b	22 159	31 706	e9*2007/46*0023*	Oct13 – Dec14
49	2015	2015	5	Volkswagen	T5	7J0	Diesel	CAA	1 968	103	3 500	715/2007*630/2012M	Euro 5b	27 620	50 773	e1*2007/46*0130*	Jun13 – Jun13
50	2015		5	Mazda	6	GH	Diesel	SH	2 191	129	4 500	715/2007*630/2012T	Euro 6b	18 811	33 562	e1*2001/116*0448*	May13 – Dec14
51	2015		5	Peugeot	508	8	Diesel	9H05	1 560	82	4 000	715/2007*692/2008A	Euro 5a	26 615	69 011	e2*2007/46*0080*	Aug11 – Apr12
52	2015		5	Ford	S-Max	WA6	Diesel	TXWA	1 997	120	3 750	715/2007*692/2008A	Euro 5a	35 604	67 650	e13*2001/116*018*	May11 – Jun13
53	2015		5	Volkswagen	Tiguan	5N	Diesel	CFF	1 968	103	4 250	715/2007*566/2011F	Euro 5b	34 310	62 508	e1*2001/116*0450*	Apr12 – Feb15
20	2016		5	BMW	118d	1K4	Diesel	N47D20C	1 995	105	4 000	715/2007*692/2008A	Euro 5a	32 582	74 860	e1*2007/46*0283*	Apr12 – Jun13
30	2016		5	Volvo	V40	M	Diesel	D4162T	1 560	84	3 600	715/2007*630/2012J	Euro 5b	34 262	69 719	e4*2001/116*0076*	Jul13 – Dec13
40	2016		5	Citroen	C3	S	Diesel	8H01	1 398	50	4 000	715/2007*630/2012F	Euro 5b	22 491	45 578	e2*2007/46*0003*	Jun12 – Aug13
80	2016		5	Kia	Ceed	JD	Diesel	D4FC	1 582	94	4 000	715/2007*566/2011J	Euro 5b	31 227	74 226	e11*2007/46*0195*	Mar13 – Jul14
100	2016		5	Skoda	Superb	3T	Diesel	CFGB	1 968	125	4 000	715/2007*630/2012J	Euro 5b	26 674	62 989	e11*2001/116*0326*	Sep13 – Feb15
50	2016		5	Toyota	Yaris	X13M(a)	Gasoline	1NR-FE	1 329	73	6 000	715/2007*630/2012F	Euro 5b	31 106	61 546	e11*2007/46*0152*	Feb13 – Jul13
60	2016		5	VW	Polo	6R	Gasoline	CJZ	1 197	66	4 400	715/2007*195/2013W	Euro 6b	12 717	33 561	e2*2007/46*0510*	Jun14 – Oct14
70	2016		5	Peugeot	208	C	Gasoline	HM01	1 199	60	5 750	715/2007*566/2011F	Euro 5b	19 555	53 143	e2*2007/46*0070*	Sep13 – Mar16
90	2016		5	Kia	Rio	UB	Gasoline	G4LA	1 248	62	6 000	715/2007*566/2011J	Euro 5b	33 054	60 665	e11*2007/46*0195*	Mar13 – Jun13
120		2016	3	Opel	Combo	D-VAN	Diesel	263A200	1 248	66	4 000	715/2007*195/2013L	Euro 5b	2 703	30 769	e3*2007/46*0076*	Mar13 – Mar16
170		2016	3	MB	A200D	245G	Diesel	651930	2 143	100	4 000	715/2007*136/2014W	Euro 6b	8 199	15 521	e1*2001/116*0470	May16 – Aug16
110		2016	3	Seat	Leon	5F	Gasoline	CYV	1 197	81	4 600	715/2007*136/2014W	Euro 6b	29 916	36 706	e9*2007/46*0094*	Mar15 – May15
130		2016	3	Peugeot	208	C	Gasoline	HM01	1 199	60	5 750	715/2007*136/2014W	Euro 6b	8 526	10 232	e2*2007/46*0070*	Sep15 – Oct15
140		2016	3	Opel	Corsa	S-D	Gasoline	B14XER	1 398	66	6 000	715/2007*136/2014W	Euro 6b	2 612	8 979	e1*2001/116*0379*	Feb16 – Feb16
160		2016	3	BMW	Mini	UKL-L	Gasoline	B38A15A	1 499	100	4 400	715/2007*2015/45W	Euro 6b	3 595	5 673	e1*2007/46*0371*	Aug16 – Sep16
280	2017		5	Volkswagen	Golf	AUV	Diesel	CUNA	1 968	135	3 500	715/2007*136/2014W	Euro 6b	12 557	35 496	e1*2007/46*0627*	Oct15 – Jun16
330	2017		5	Volvo	V70	BW738D	Diesel	D4304T5	1 969	133	4 250	715/2007*195/2013W	Euro 6b	36 858	77 137	e9*2001/116*0065*	Apr14 – Aug16
360	2017		5	Volkswagen	Passat	C3	Diesel	DFCA	1 986	140	4 000	715/2007*136/2014W	Euro 6b	35 763	61 651	e11*2001/116*0307*	Jun15 – Sep16
390	2017		5	Volvo	V40	M	Diesel	D4204T8	1 969	88	3 750	715/2007*136/2014W	Euro 6b	27 117	56 761	e4*2001/116*0076*	May15 – Dec15
300	2017		5	Ford	Fiesta	JA8	Gasoline	SFJD	998	74	6 000	715/2007*136/2014W	Euro 6b	8 662	40 930	e9*2001/116*0069*	May15 – Mar16
310	2017		5	Renault	Clio	R	Gasoline	4HBB4	898	65	5 000	715/2007*136/2014W	Euro 6b	7 203	32 260	e2*2001/116*0327*	Nov15 – Apr16
340	2017		5	Suzuki	Swift	NZ	Gasoline	K12B	1 242	69	6 000	715/2007*2015/45W	Euro 6b	7 656	29 377	e4*2007/46*0155*	Nov15 – May16
200		2017	3	Nissan	Qashqai	J11	Diesel	K9K	1 461	81	4 000	715/2007*2015/45W	Euro 6b	3 937	5 210	e11*2007/46*0963*	Oct16 – Oct16
230		2017	3	BMW	X1	UKL-L	Diesel	B47C20A	1 995	140	4 000	715/2007*2015/45W	Euro 6b	5 076	11 222	e1*2007/46*0371*	Nov16 – Dec16
260		2017	3	Ford	Mondeo	BA7	Diesel	UGCC	1 499	88	3 600	715/2007*2015/45W	Euro 6b	9 047	12 018	e13*2001/116*024	Dec16 – Dec16
320		2017	3	Audi	A4	AU	Diesel	DET	1 968	140	3 800	715/2007*2015/45W	Euro 6b	24 077	31 717	e1*2001/116*0430*	Sep16 – Oct16
350		2017	3	Kia	Ceed	JD	Diesel	D4FB	1 582	100	4 000	715/2007*2015/45W	Euro 6b	2 052	14 859	e4*2007/46*0496*	Dec16 – Jul17
210		2017	3	Opel	Astra	B-K	Gasoline	B14XE	1 399	92	4 000	715/2007*136/2014W	Euro 6b	12 840	16 451	e4*2007/46*0996*	Apr16 – May16
220		2017	3	Fiat	500	312	Gasoline	169A4000	1 242	51	5 500	715/2007*195/2013W	Euro 6b	1 951	4 484	e3*2007/46*0064*	Dec16 – Dec16
250		2017	3	Citroen	C3	S	Gasoline	8H01	1 398	50	5 750	715/2007*136/2014W	Euro 6b	3 652	6 126	e2*2007/46*0003*	Feb17 – Feb17
290		2017	3	Peugeot	300	L	Gasoline	HN02	1 199	96	5 500	715/2007*2015/45W	Euro 6b	11 735	13 899	e2*2007/46*0405*	Sep16 – Sep16
380		2017	3	Nissan	Qashqai	J11	Gasoline	HRA2	1 197	85	4 500	715/2007*2016/646W	Euro 6b	6 695	8 400	e11*2007/46*0963*	Jun17 – Jun17
370	2017		5	Toyota	Avensis	T27	Gasoline	2ZR-FAE	1798	108	6400	715/2007*2015/45W	Euro 6b	15192	40176	e11*2001/116*033*	Jun15 – Sep16

Table 2. Overview of testes vehicles in the Swedish IUC program year 2015 - 2017

5. Measurement Technologies

All chassis dynamometer tests have been carried out at TÜV NORD in Essen and PEMS test have been carried out both in Essen and in Gothenburg. The different driving cycles, PEMS-routes and test equipment used are described in Appendix 2.

6. Main Conclusions

Type I tests	Almost all vehicle models tested complied with the limits given by the directive
Type II, III, IV and VI	Almost all vehicle model tested complied with the limits given by the directive
Fuel consumption	Measured values are often higher than declared by manufactures
Fuels	NO_X significantly higher from diesel- compared to gasoline cars CO significantly higher from gasoline- compared to diesel cars Particles significantly higher from gasoline- compared to diesel cars
Emission class	NO_X emissions from cars with CI engines seems to decrease from Eu5 to 6 No significant differences for CO, and Particles between Eu5 and 6. (both CI and PI engines)
Technologies	SCR seems to give lower NO_X emissions for cars with CI engines and comparable with NO_X emissions from cars with PI engines. Filters are important for low particle emissions. All cars with CI engines were equipped with DPF (Diesel Particle Filter) but none of the cars with PI engines were equipped with GPF (Gasoline Particle Filter). This resulted in low emissions of particles from cars with CI engines (and relatively high from cars with PI engines) Some of the cars with PI engines and with DI (Direct Injection) showed relatively high NO_X emissions
CO_2 from CI vs PI	A shift from CI to PI (e.g. from diesel to gasoline) engine is likely to increase the CO_2 emissions by app. +20 %
Driving cycles	RDE (Real Driving Emissions) give higher emissions and fuel consumption compared to tests on chassis dynamometer. WLTP results are relatively close to results from RDE (PEMS tests) regarding CO_2, fuel consumption and particles. For NO_X from cars with CI engines and CO from cars with PI engines, the differences between RDE and WLTP are relatively high.
Ambient temperatures	Lower ambient temperature resulted in higher HC and CO emissions for cars with PI engines and higher NO_X emissions from cars with CI engines.
Mini-PEMS vs Full-PEMS	Results from Mini-PEMS are relatively close to results from Full-PEMS regarding NO_X, CO_2 and fuel consumption (but not CO). Mini-PEMS need data from OBD connector (e.g. the Mass Air Flow signal). This signal is not available on all cars.
Outlook	Initial tests on cars with CI engine and of emission class Euro 6d seems to have low NO_X emissions (also on RDE-tests) – similar NO_X values as from cars with PI engines. Only one of this car are included in this study, and the NO_X emission during RDE seems to be about 20 mg/km, i.e. far below the limit value. More and more cars with PI engines seems to be equipped with particle filters (GPF), which likely will give low particulate emissions.

Table 3. Short comment to some of the results on page 15 to 46

7. Comments to results

The main results/conclusions are presented shortly in the table in chapter 6 above

Effects due different measurements technics

The differences due to type of driving cycles and real driving tests are described separately in chapter "Effects due to different routes and driving cycles (page 28)" and chapter "PEMS route in Germany vs Sweden (and Mini-PEMS vs Full-PEMS)"

Before all "Full-PEMS" test a validation test on the chassis dynamometer are performed (WLTC test cycle). In these validation tests the results from the PEMS-analysers are compared with the results from the test cell analysers.

Effect due to fuels, technology and emission class

In this chapter data from tests in accordance with the WLTC driving cycle are assessed. The reasons for evaluating vehicles according to the WLTC are:

- WLTC data are available for all cars tested
- WLTC is the "new" tests cycle and therefore it will be possible to add data from future IUC programs to the same results series.

Effect due to fuels (e.g. diesel and gasoline)

During these test programs, only one car was using an alternative fuel, E85. This car was tested with two fuels, gasoline and E85. There were no significant differences in emissions due to the fuel type. The fuel consumption was about 36 % higher by using E85 compared with gasoline. This difference is fully explained by the difference in the energy content of the fuels.

The different in fuel consumption and CO_2-emissions by using diesel (CI-engines) or gasoline (PI-engines) as fuel are described on page 24 to 28.

The NO_X emission are significant higher from diesel cars (CI-engines) compared with gasoline cars (PI-engines), see Figure 1 below. Regarding CO and particle number[1] emissions it is in the opposite way, see Figure 2 and Figure 3 below.

[1] Two cars with compression ignition are excluded from the average calculation. Regeneration of the particle filter during the tests explain the temporally high particle emission.

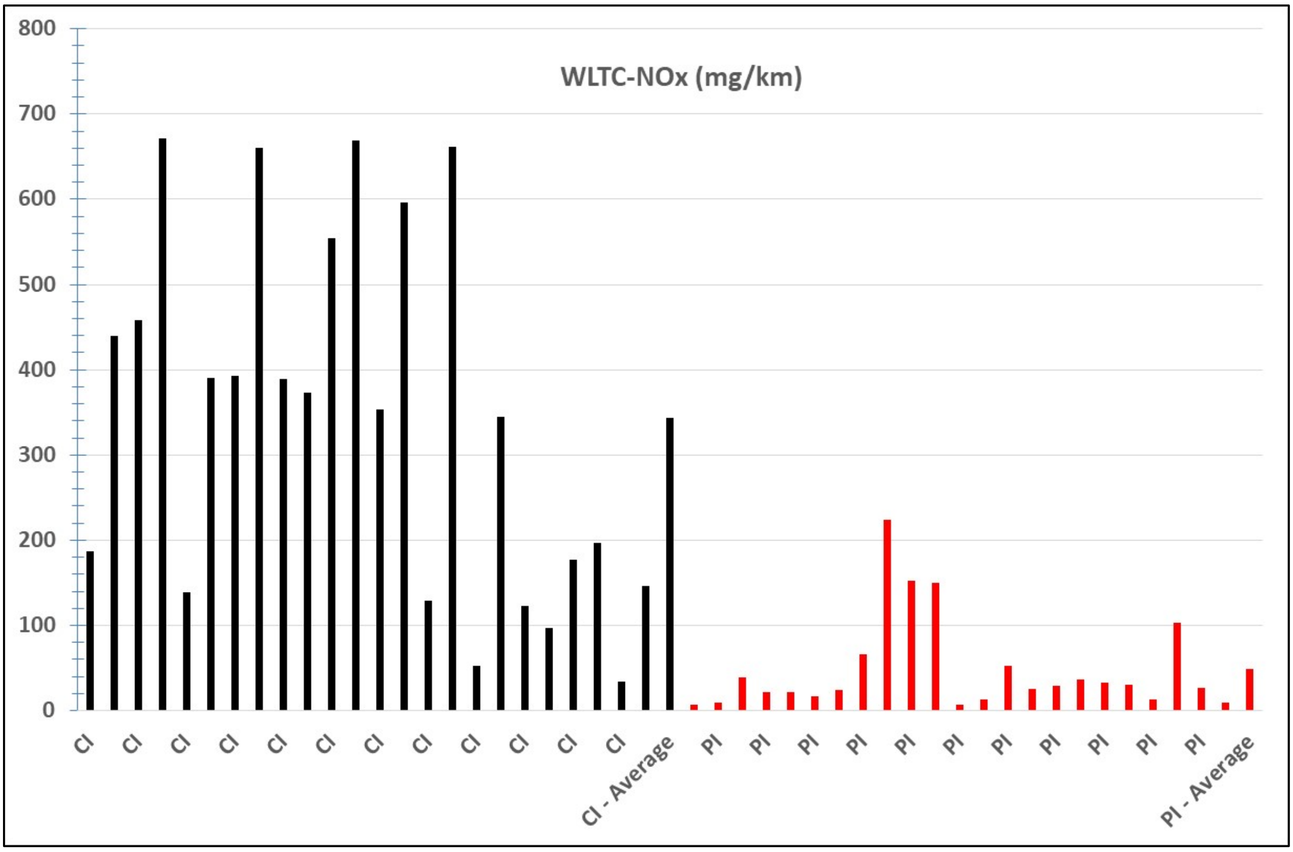


Figure 1. NO_X emissions during WLTC in mg/km. An average vehicle with Compression ignition engines emitted about 7 times more NO_X compared with an average vehicle with a Positive Ignition engine. The figure also show a relatively high difference within the group of vehicles (e.g. some of the cars with PI-engines show higher NO_X-emission than some of the CI-cars and vice versa)

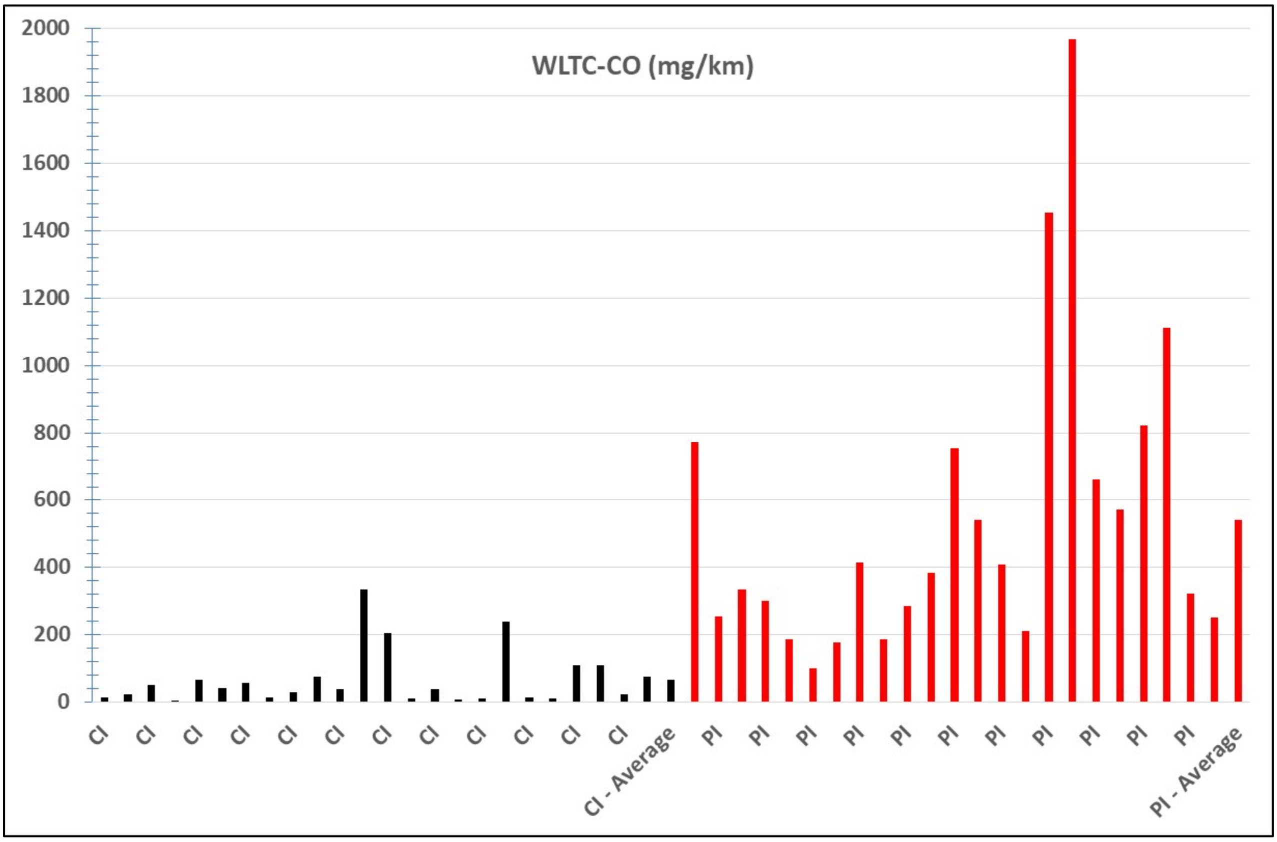


Figure 2. CO emissions during WLTC in mg/km. An average vehicle with Positive ignition engines emitted about 8 times more CO compared with an average vehicle with a Compression Ignition engine.

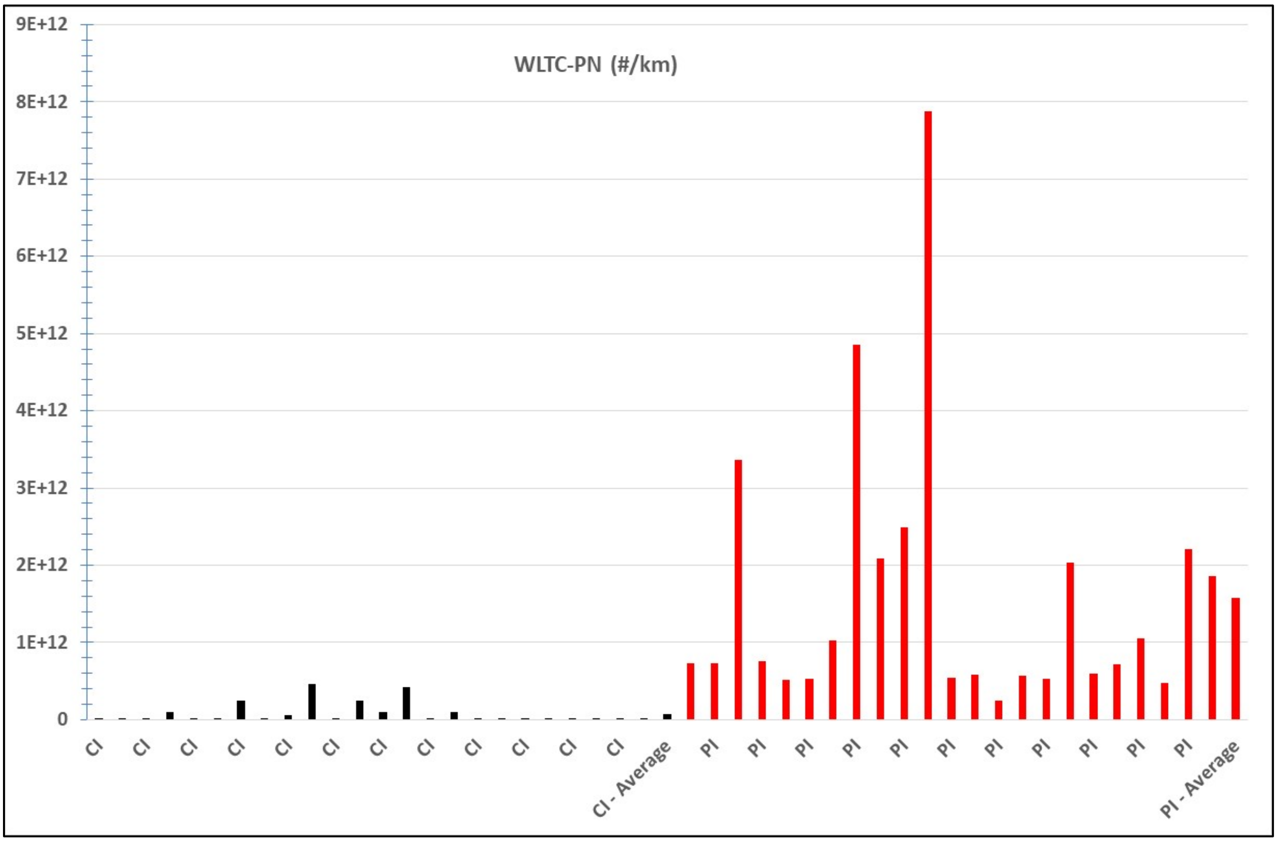


Figure 3. PN emissions during WLTC in mg/km. An average vehicle with Positive ignition engines emitted about 20 times more particles compared with an average vehicle with a Compression Ignition engine.

Effect due to emission class

In this study, cars of emission class Euro 5 (a, b) and 6 (a, b) are included. One car with emission class Euro 6d-TEMP is included in the MiniPEMS tests, see page 41.

The difference in fuel consumption and CO_2-emissions are described on page 24 to 28.

The NO_X emissions are relatively low for cars with positive ignition engines for both Euro 5 and 6 vehicles. Regarding cars with compression ignition engines the average NOx emission seems to be lower for cars of Euro 6 compared with cars of emission class Euro 5, see Figure 4 below.

CO emissions are relatively low from cars with compression ignition engines and no significant differences between Euro 5 and 6 are shown. Regarding cars with positive ignition engines it seems to be higher CO emissions (as average for the tested vehicles) for cars of emission class Euro 6 compared with Euro 5, se Figure 5.

No significant differences in particle emissions between Euro 5 and 6 are shown, see Figure 6.

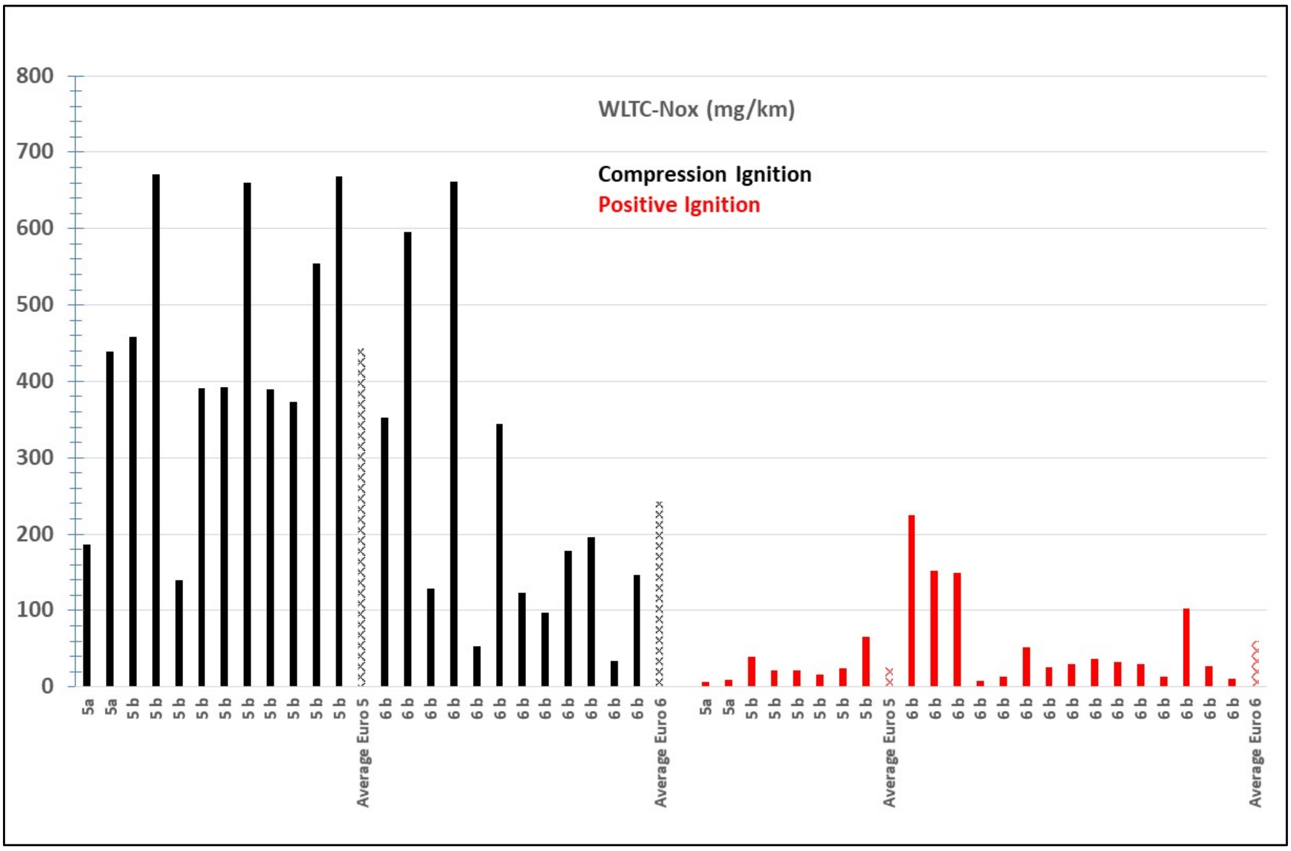


Figure 4. NO_X emissions during WLTC versus Euro class in mg/km. As average for the vehicles with compression ignition engines included in this study, Euro 6 vehicles emitted less NO_X compared with Euro 5.

Figure 4 above show a relatively high variation of NO_X-emissions within the group of vehicles. Therefore, it is not adviceable to give a typical value for a Euro 6 car with CI engine etc. Some of the variation may be explained due to different technologies, use of SCR, direct fuel injections etc., see chapter below.

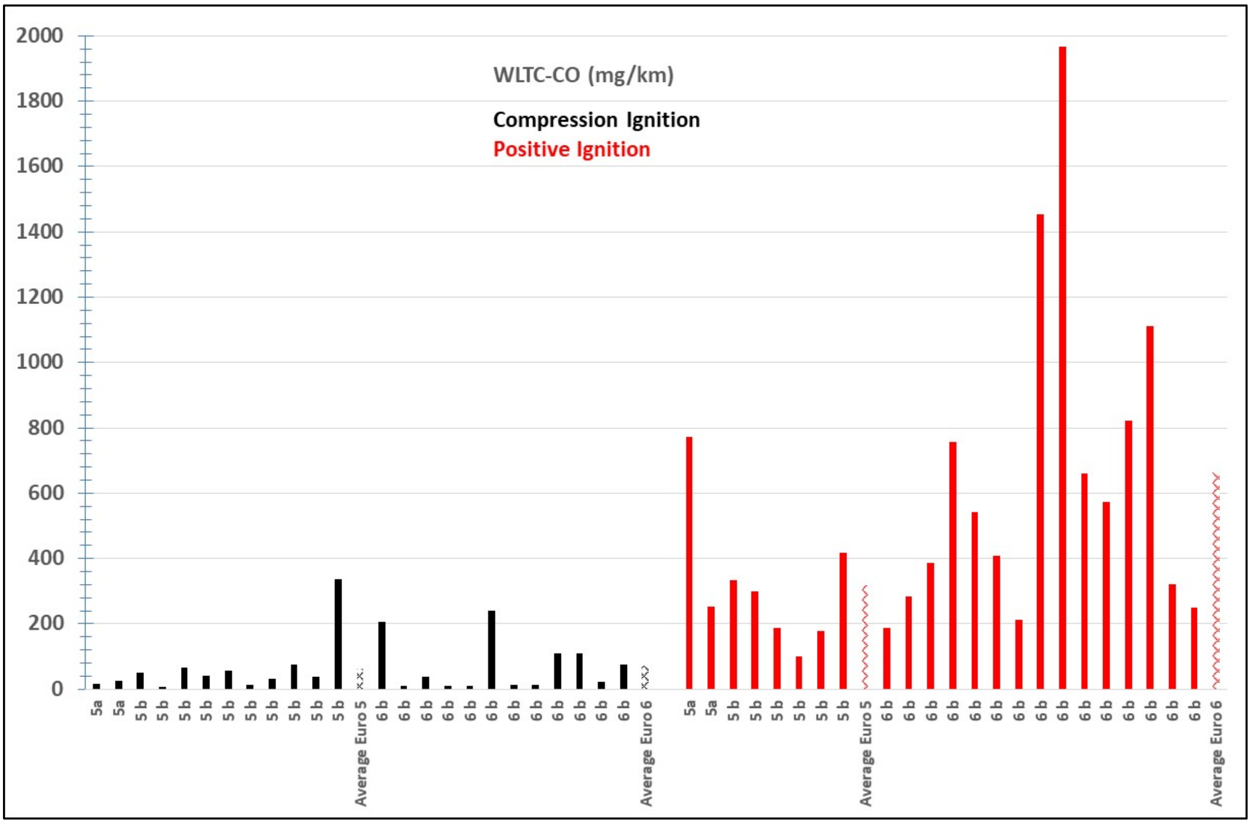


Figure 5. CO emissions during WLTC versus Euro class in mg/km. As average for the vehicles with positive ignition engines included in this study, Euro 6 vehicles emitted more CO compared with Euro 5.

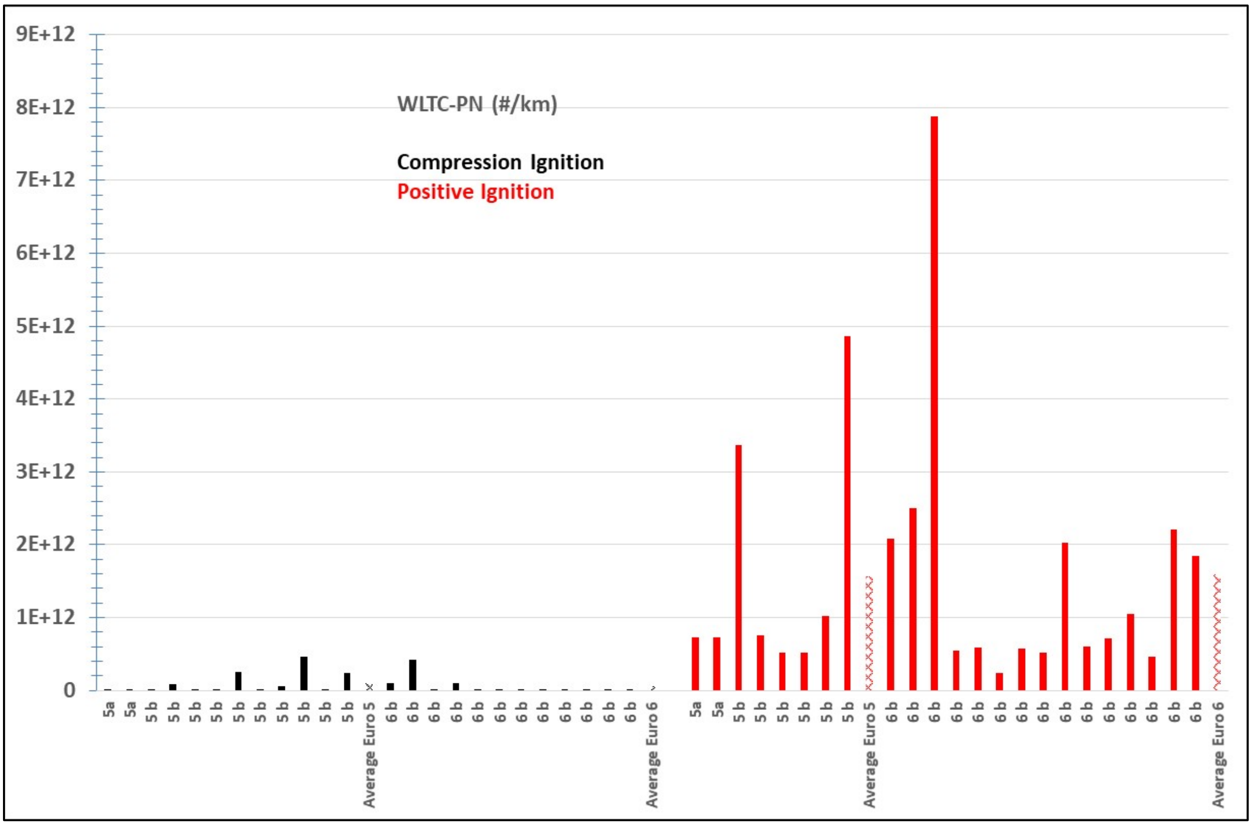


Figure 6. Particle emissions during WLTC versus Euro class in #/km. No significant differences between Euro 5 and Euro 6 are seen.

Effect due to technologies

The difference in Fuel consumption and CO_2-emissions are described on page 24 to 28

Two car models with compression ignition engines are equipped with Selective Catalytic Reduction (SCR). The use of SCR (urea as reduction agent) seems to be an effective way to reduce NO_X emissions from these types of cars. The three cars Euro 6 cars without any NOx aftertreatment had the highest NOx emissions of all Euro 6 cars. In total, 10 models were also equipped with exhaust gas aftertreatment catalyst containing NO_X storage capacity, se Figure 7 below.

All cars with compression ignition engines were equipped with particle filter (DPF) and none of the cars with positive ignition engines had a corresponding type of particle filter (GPF). This fact results in much higher emission of particles from cars with positive ignition engines compared with cars with compression ignition engines, see Figure 10 below.

Figure 7 to Figure 9 show that cars with positive ignition engine and a GDI fuel injection system seems to look more like cars with compression ignition engines than cars with fuel injection of MPI type. “GDI cars” seems to have higher NO_X and particle emissions and lower CO emissions compared to “MPI cars”.

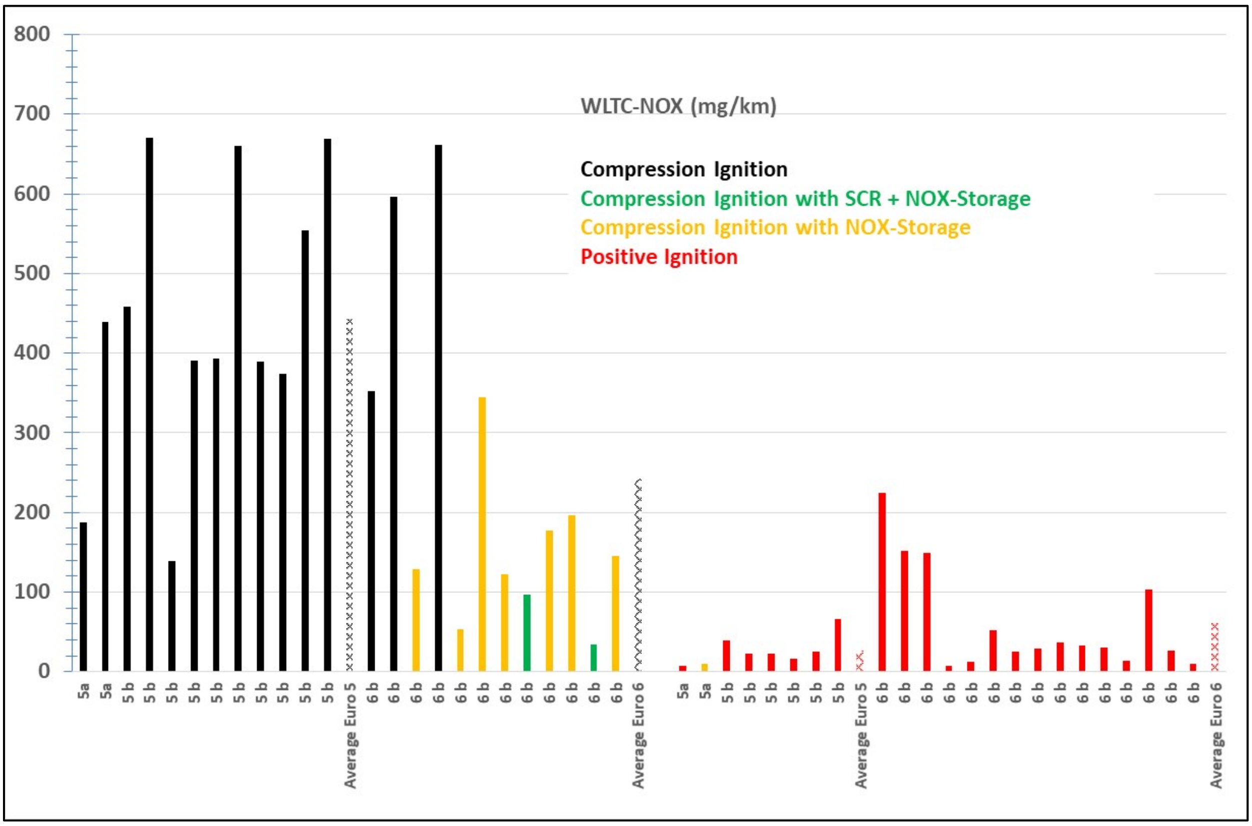


Figure 7. NO_X emissions during WLTC versus Euro class in mg/km. Two of the car models with compression ignition engines are equipped with SCR (urea as reduction agent).

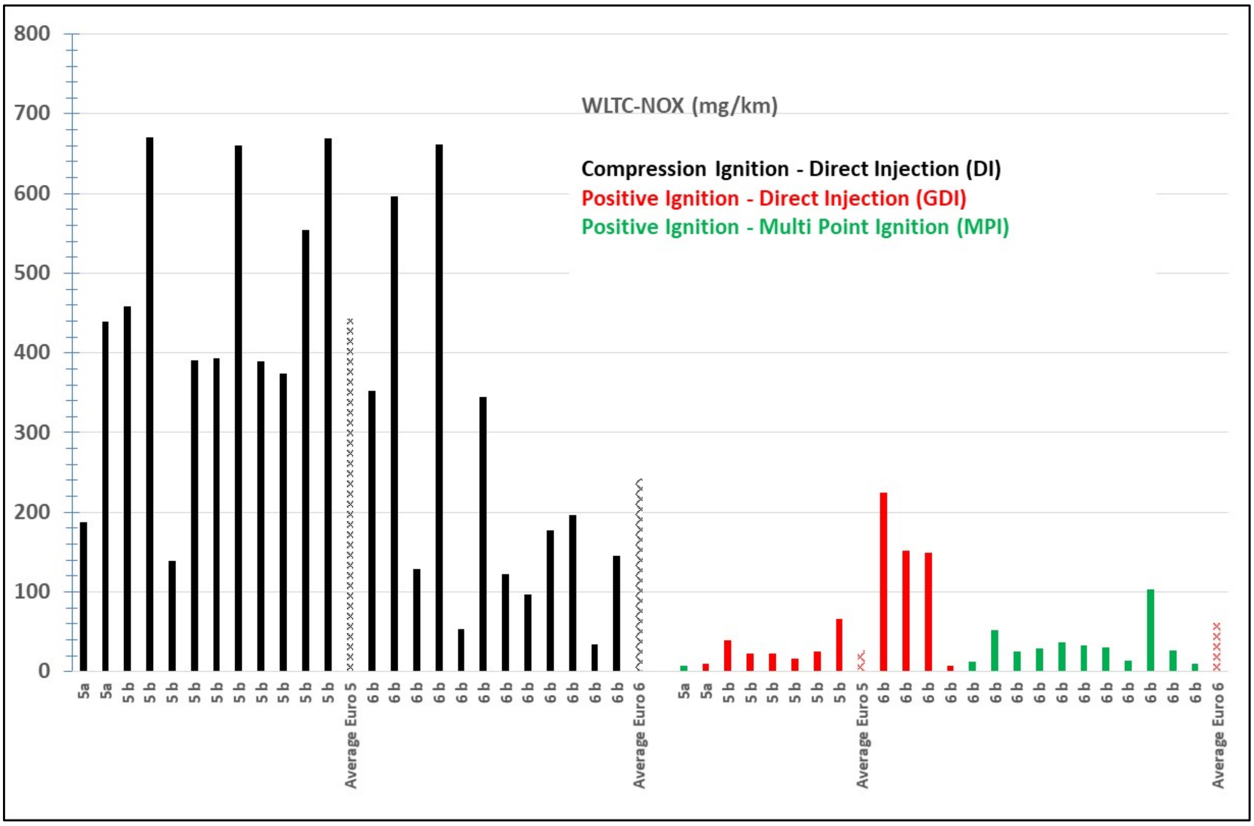


Figure 8. NO_X emissions during WLTC versus Euro class in mg/km and type of fuel injection

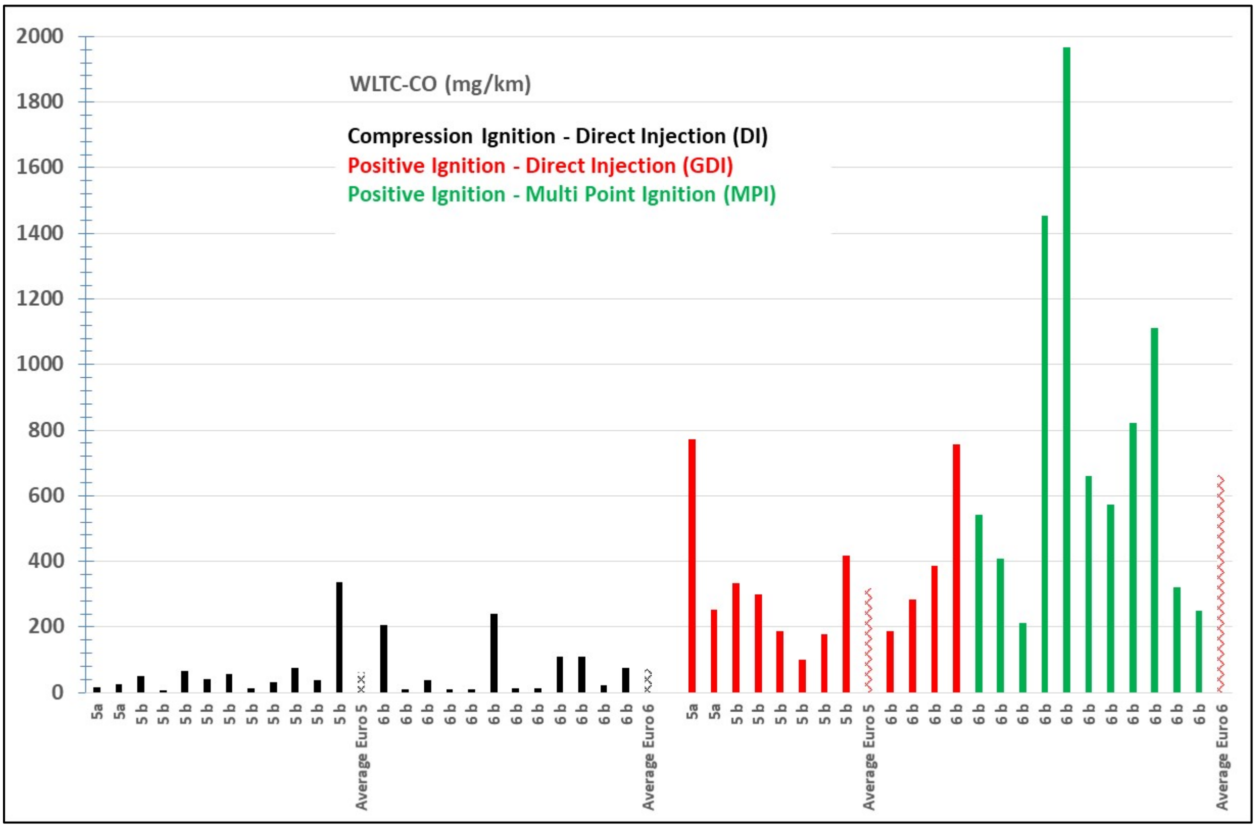


Figure 9. CO emissions during WLTC versus Euro class in mg/km and type of fuel injection

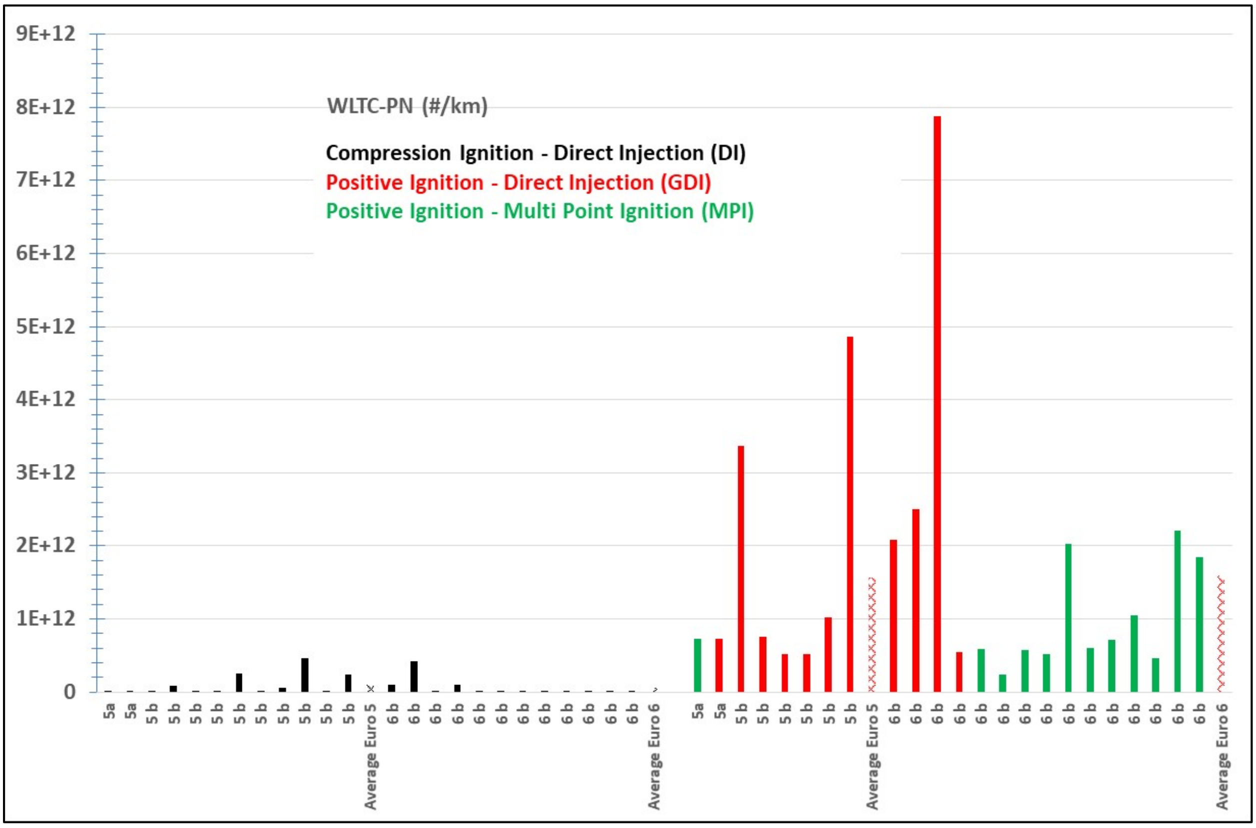


Figure 10. Particle emissions during WLTC versus Euro class in #/km and type of fuel injection

Comparison of CO_2-emissions between CI- and PI engines

Since the size and power differ between the tested vehicles it is not easy to compare the CO_2 emissions between different cars. The cars with CI engines are often heavier than cars with PI engines, see below.

- Average values for vehicles with CI engines was 102 kW / 1797 cc / 1578 kg curb weight
- Average values for vehicles with PI engines was 75 kW / 1320 cc / 1275 kg curb weight

One way to compare cars of different size is to use the "formula" for calculation of the Specific emission of CO_2 adjusted for the vehicles curb weight[2].

(*The formula shall be used to calculate specific emissions target for each manufacturer in a calendar year based on the vehicle mass. It is calculated as the average of the Specific Emissions of CO_2 (g/km) of each new passenger car registered in that calendar year, where)*

Specific Emissions of CO_2 = T + a × (M - M_0)

- In the above formula:

- T - CO_2 emission target. T = 130 g/km from 2012 through 2019; and T = 95 g/km from 2020.

  a - coefficient. a = 0.0457 from 2012 through 2019; and a = 0.0333 from 2020.
  M - Mass of the vehicle (kg) (curb weight)

  M_0 - average vehicle mass. M0 = 1372 kg for calendar years 2012-2015. M0 = 1392.4 kg for 2016 [3200].

- From 2016, the value of M_0 is adjusted annually to reflect the average mass of passenger cars in the previous three calendar years. Thus, the respective CO_2 target (130 or 95 g/km) is directly applicable to vehicles of an average mass, while lighter cars have lower CO_2 targets and heavier vehicles have higher CO_2 targets.

<u>In this study; a = 0,0457 and M_0 = 1372 have been used</u>

By using this formula on 22 CI models and 23 PI models results in:

Measured CO_2 emission was 6,6 % higher for the PI vehicles. But corrected to curb weight the specific CO_2 emission the <u>PI vehicles emitted 19,3 % more CO_2 compared to the vehicles with CI engine.</u>

	CI	PI
Measured CO_2 (g/km)	124,2	132,5
Specific CO_2 (g/km)	114,8	137,0

[2] ANNEXES to the proposal for a Regulation of the European Parliament and of the Council setting emission performance standards for new passenger cars and new light commercial vehicles as part of the Union's integrated approach to reduce CO_2 emissions from light-duty vehicles and amending Regulation (EC) No 715/2007 (recast)

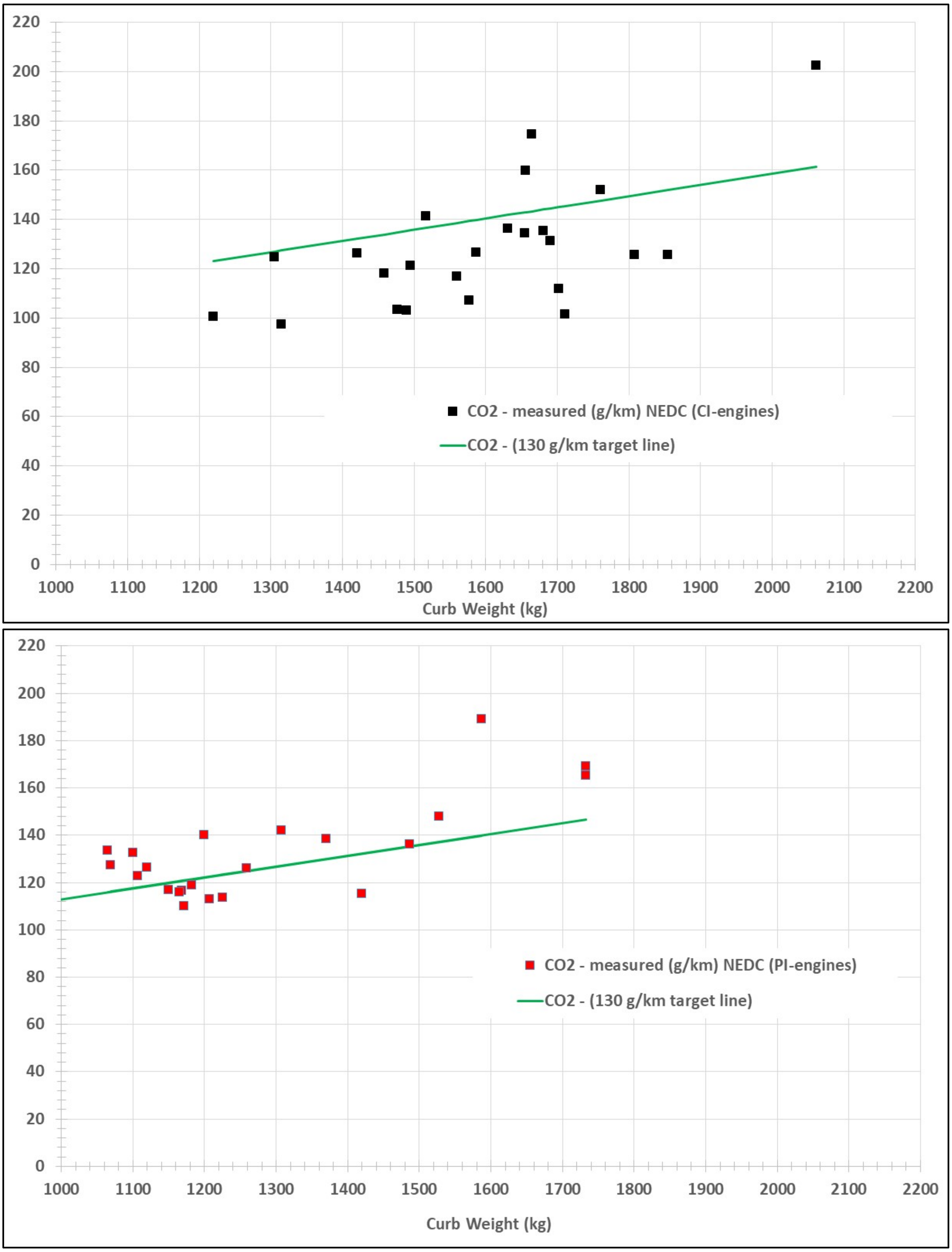


Figure 11. Measured CO_2-emissions compared with the 130 g target line. The CI cars are generally heavier than PI cars. Most of the CI cars are below the target line and most of the PI engines are above the target line.

Table 4. Measured and specific CO_2 emissions as average of 23 vehicles with PI engines (gasoline) and 22 with CI engines (diesel)

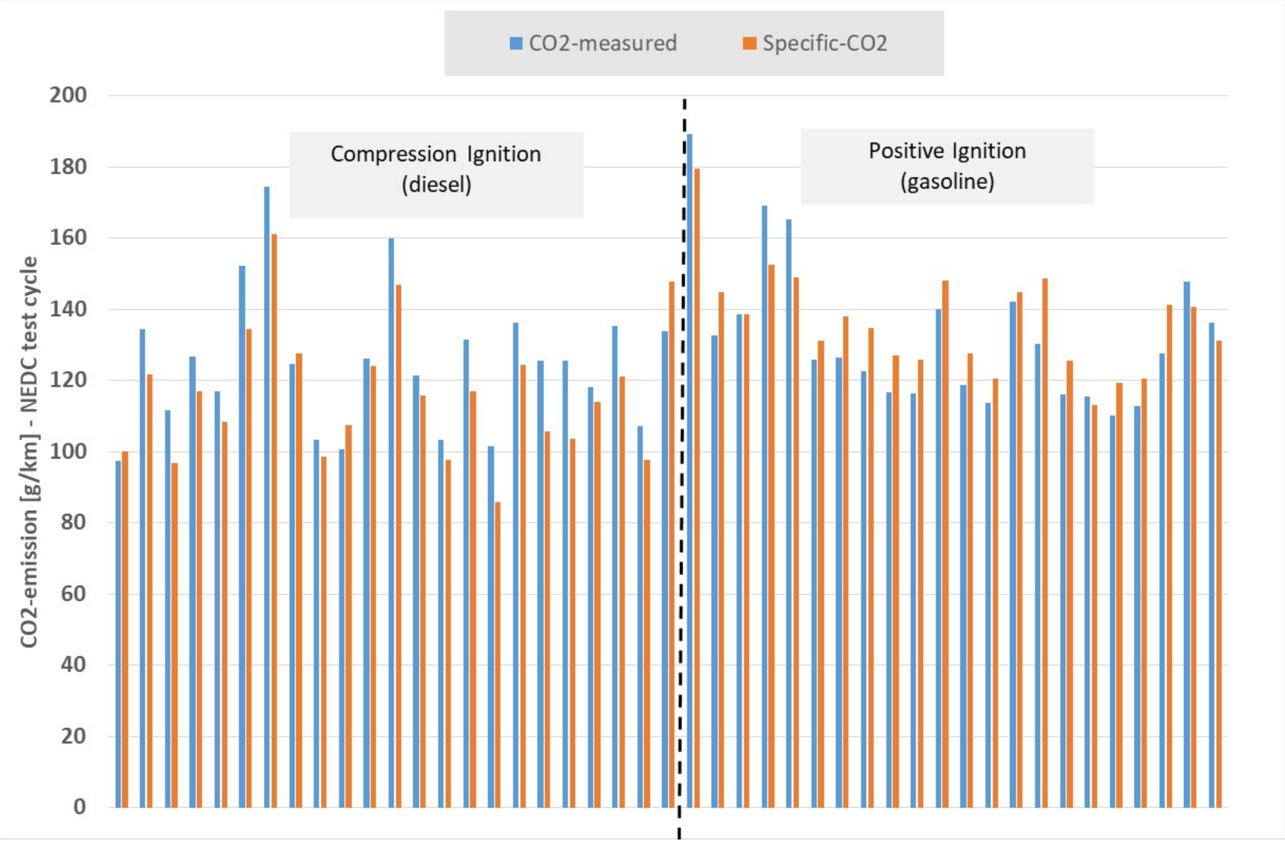


Figure 12. Measured and calculated specific CO_2 emissions for vehicles of different curb weights.

With the current shift from CI to PI (e.g. from diesel to gasoline) engine in light-duty vehicles, it is likely that CO_2 emissions will increase in the future, albeit the current efforts in engine development to reduce fuel consumption and CO_2 from either type of engine/vehicle. This would contrast the trend of continuous reduction in CO_2 over the last period of ~20 years. This assumption is on the condition that there will be no major shift in vehicle size, i.e. that also the engines in larger vehicles – that mostly run on diesel fuel today – would be replaced by gasoline-fuelled powertrains. Thus, the relative impact might be much closer to the corrected level of + 19,3 % in this study, rather than the un-corrected level of 6,6 %. It is likely that hybridization, in general will decrease fuel consumption in the future but this technology is applicable for both PI and CI engines. PHEVs and EVs could also contribute to a reduction in the future but still the market penetration of such vehicles is rather low, and it will take a long time before they have any major impact on the fleet CO_2.

The findings above are in line with a recent publication from the European Environment Agency, EEA[3]. The study is using manufacturer's data on CO_2 emissions for model year 2017 cars. For the first time in many years, CO_2 emissions were higher in 2017 than the year before. The study concludes (among other things) that: "*If similar petrol and diesel segments are compared, conventional petrol cars emit 10-40 % more than conventional diesel cars*". As mentioned above, the present study, which is based on independent measurements, got an average difference of 19,3 %. The large interval cited by EEA reflects the difference between individual vehicles, a fact

[3] Monitoring CO2 emissions from new passenger cars and vans in 2017, EEA Report No. 15/2018.

that can also be noted about the results in the present study. The EEA study also notes the shift from diesel to gasoline and the future trend of electrification of the powertrains.

Effects due to different routes and driving cycles

In the IUC program year 2015 to 2017, tests using four (4) different driving cycles in parallel have been carried out for 10 vehicle models with compression ignition and 9 models with positive ignition engines. Three cars per model give a total number of 57 cars. The driving cycles were:

- NEDC (described on page 48)
- WLTP (described on page 48)
- ERMES (described at page 52)
- PEMS (described at page 53)

In this study the effect of using two different PEMS routes have also been investigated. These results are described separately on page 28 to 38

CO_2 – Carbon dioxide

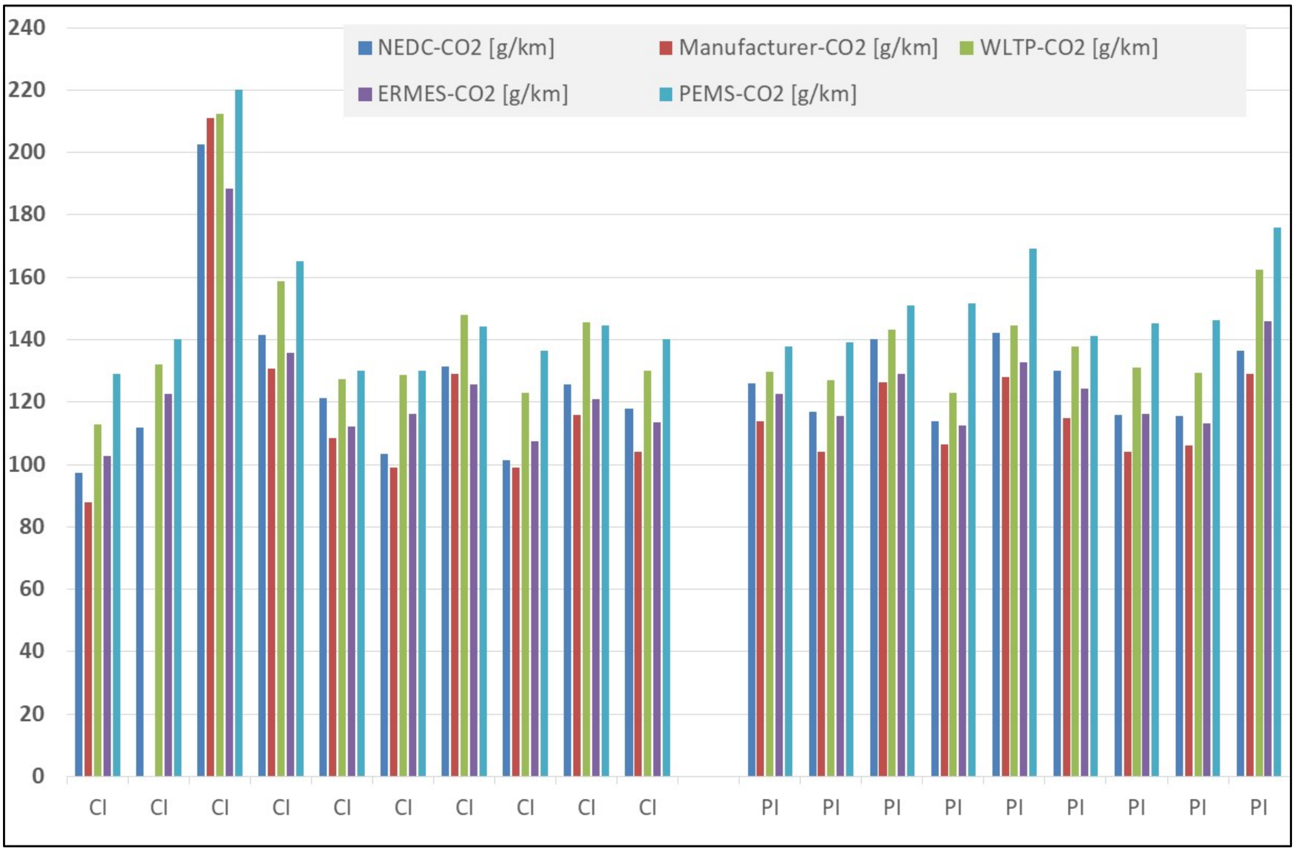


Figure 13. CO_2-emissions in g/km for different car models tested at different driving cycles.

The effect of using different driving cycles indicates that the CO_2-emission are highest by using PEMS test and lowest by using NEDC. The red bars are the value declared by the manufactures (certification tests, NEDC). In Figure 14 below the average values are presented. This indicates that the average difference from the declared values to PEMS test are about +23 % for cars with compression ignition engines and about +30 % for cars with positive ignition engines.

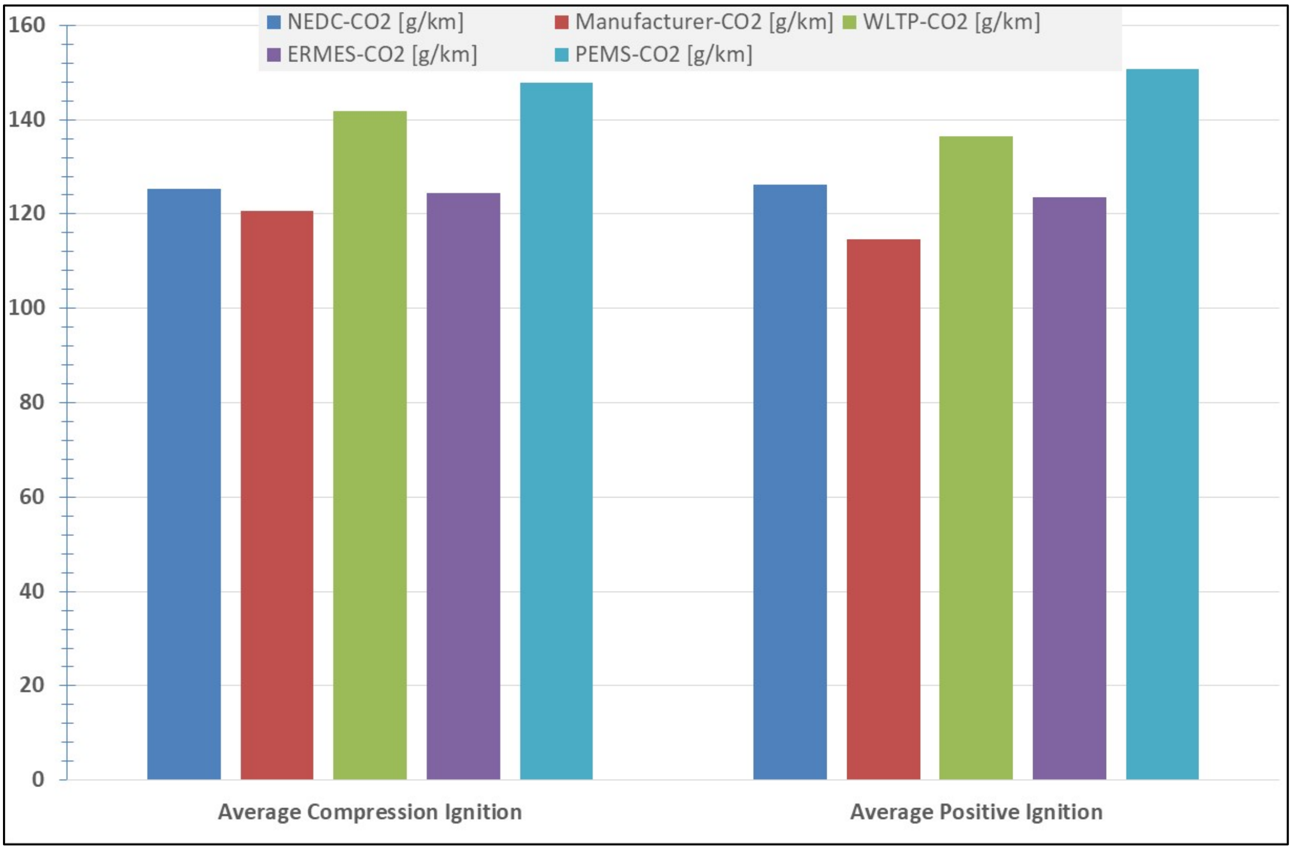


Figure 14. Average CO_2-emission in g/km for cars with compression ignition and positive ignition engines. The average values are calculated from the values in Figure 13

WLTP is the driving cycle who is closest to the Real Driving Cycle PEMS with respect to CO_2-emission. (Within about 3 % lower for cars with CI engines and about 11 % lower for cars with PI engines). ERMES seems to give lower results than NEDC.

FC - Fuel Consumption

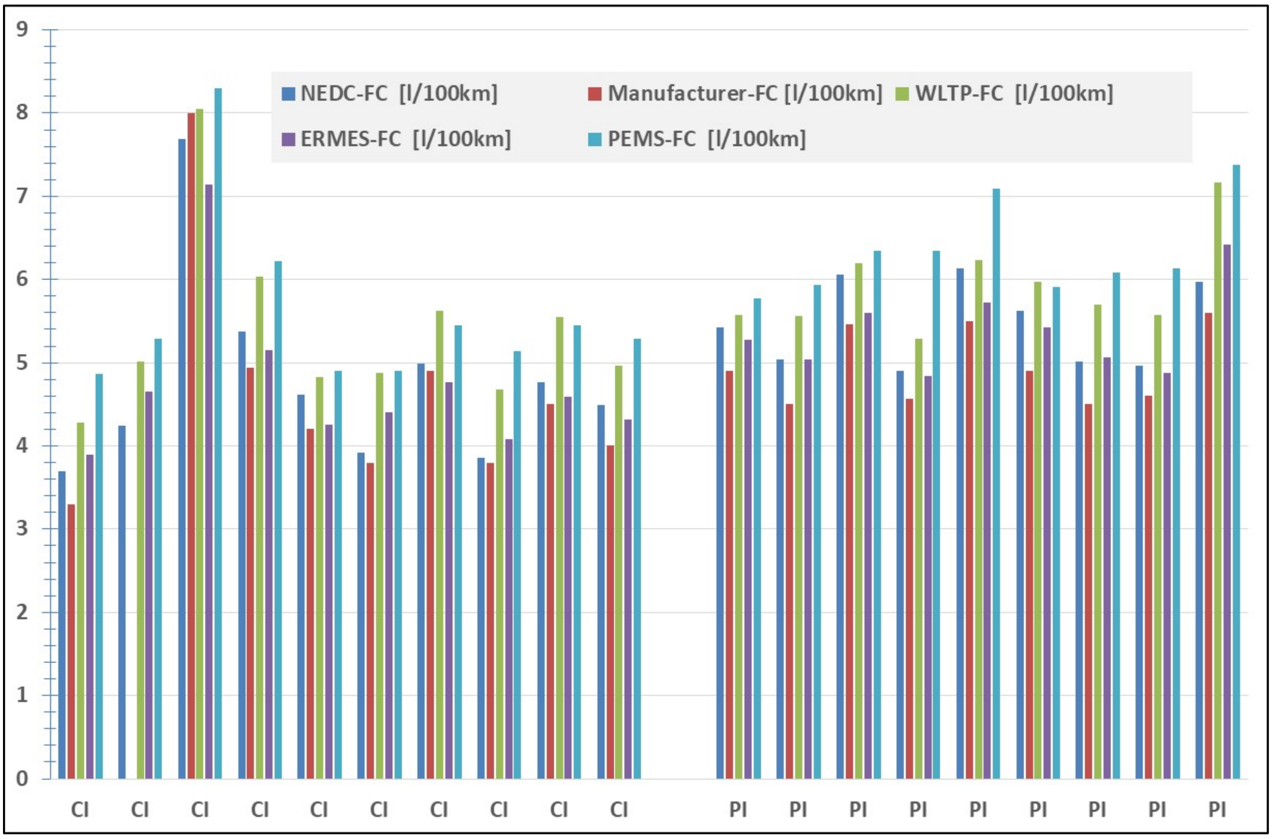


Figure 15. Fuel consumption in l/100 km for different car models tested at different driving cycles.

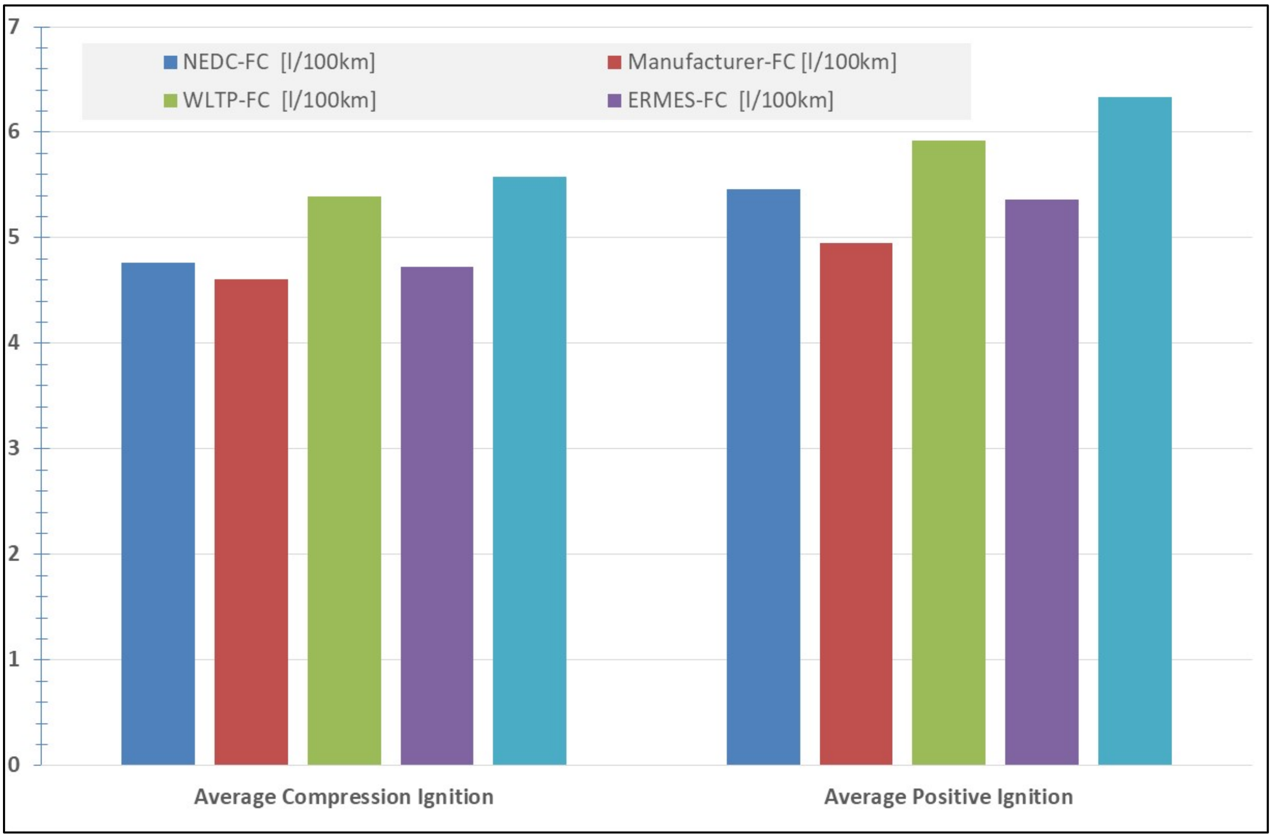


Figure 16. Average Fuel consumption in l/100 km for cars with compression ignition and positive ignition engines. The average values are calculated from the values in Figure 15

The effect of using different driving cycles indicates that the Fuel consumption in legislative test cycles is highest by using PEMS test and lowest by using NEDC. The red bars are the value declared by the manufactures (certification tests, NEDC). In *Figure 16* above, the average values are presented. This indicates that the average different from the declared values to PEMS test are about + 21 % for cars with compression ignition engines and about + 28 % for cars with positive ignition engines.

WLTP is the driving cycle who is most close to the Real Driving Cycle PEMS with respect to Fuel consumption. (Within about lower 3 % for cars with CI engines and about 7 % lower for cars with PI engines). There is some logic behind these results, since WLTP is based on (relatively) recent vehicle logging of real-world driving and thus, should represent contemporary driving style and traffic pattern better than older driving cycles. ERMES seems to give results lower than NEDC.

CO –Carbon Monoxide

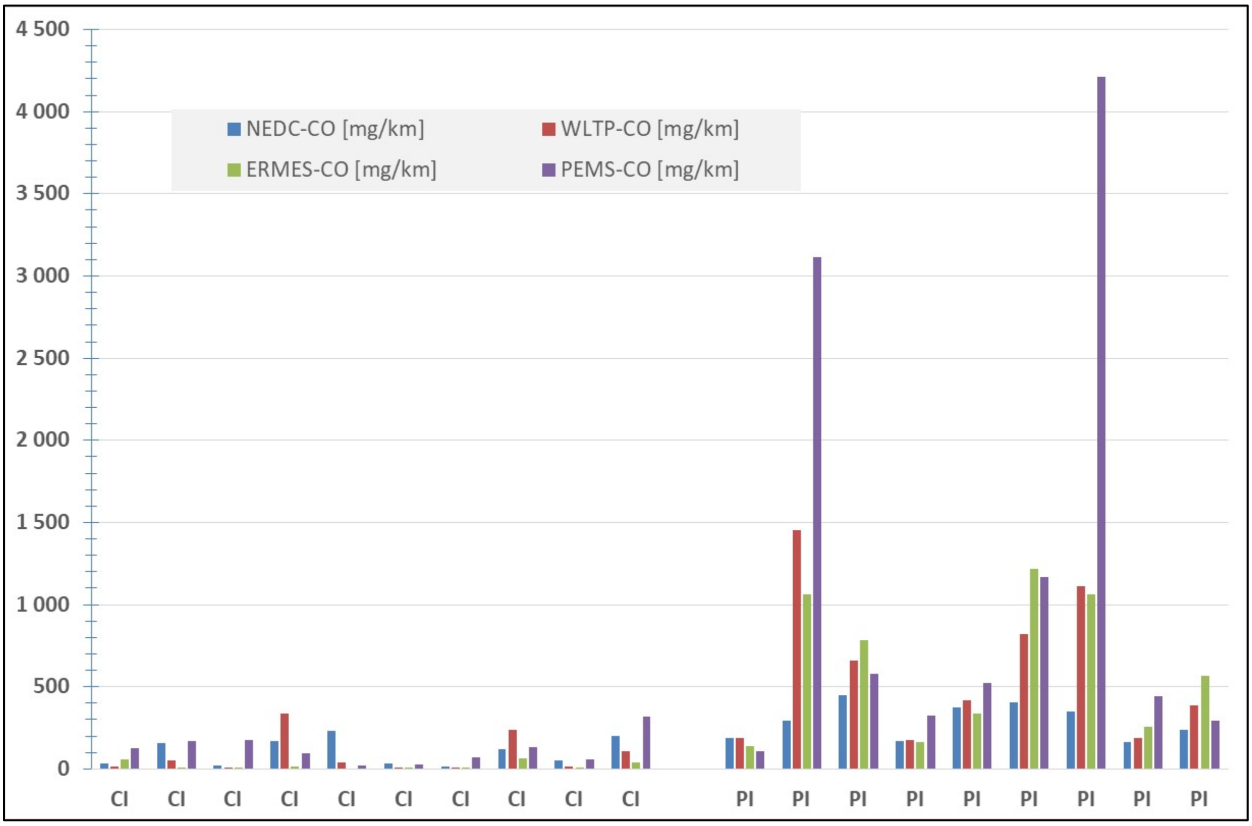


Figure 17. CO-emissions in mg/km for different car models tested at different driving cycles.

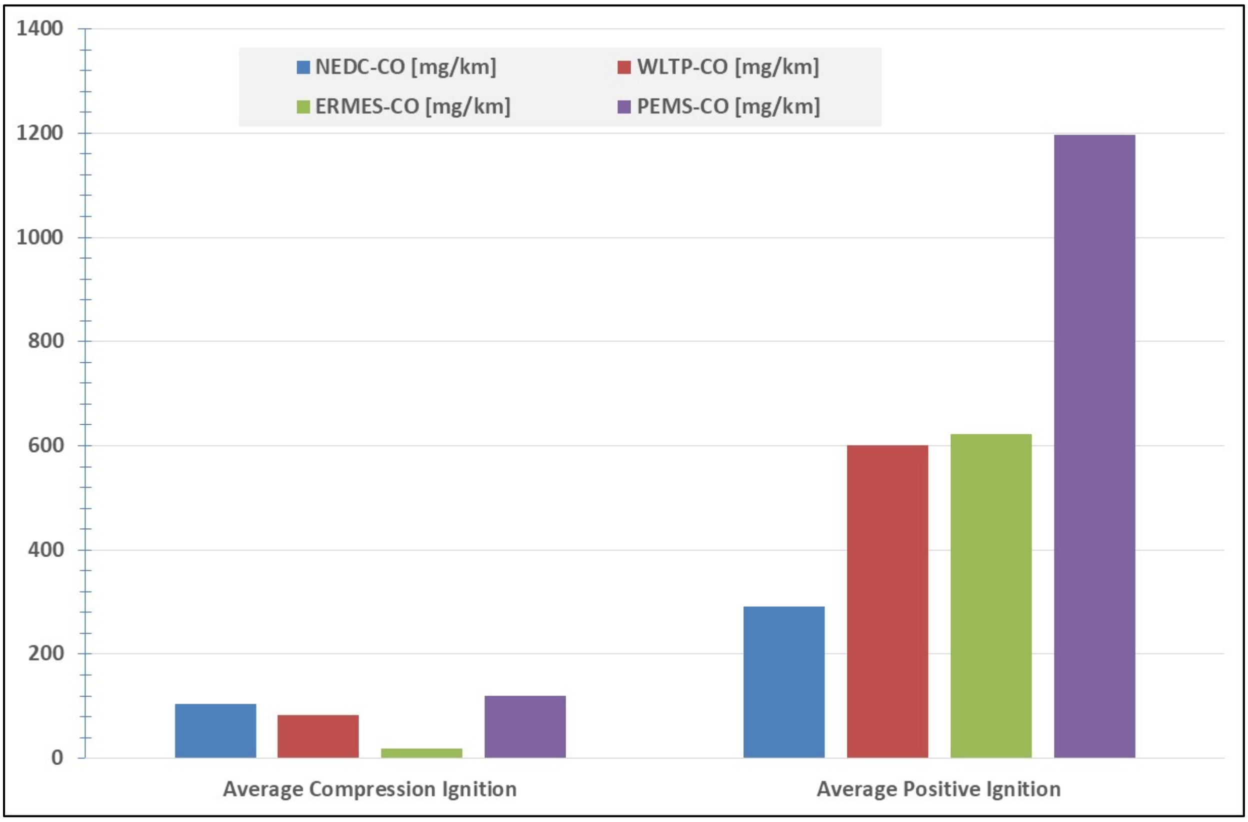


Figure 18. Average CO-emission in mg/km for cars with compression ignition and positive ignition engines. The average values are calculated from the values in Figure 17

For cars with compression ignition engines the emissions of CO are overall relatively low. For some of the cars with positive ignition engines the emissions of CO were relatively high during PEMS test.

During test in real traffic (PEMS-test) the average emission of CO was about 10 times higher from cars with positive ignition engines compared with cars equipped with compression ignition engines, se Figure 18 above

NO_X – Nitric Oxides

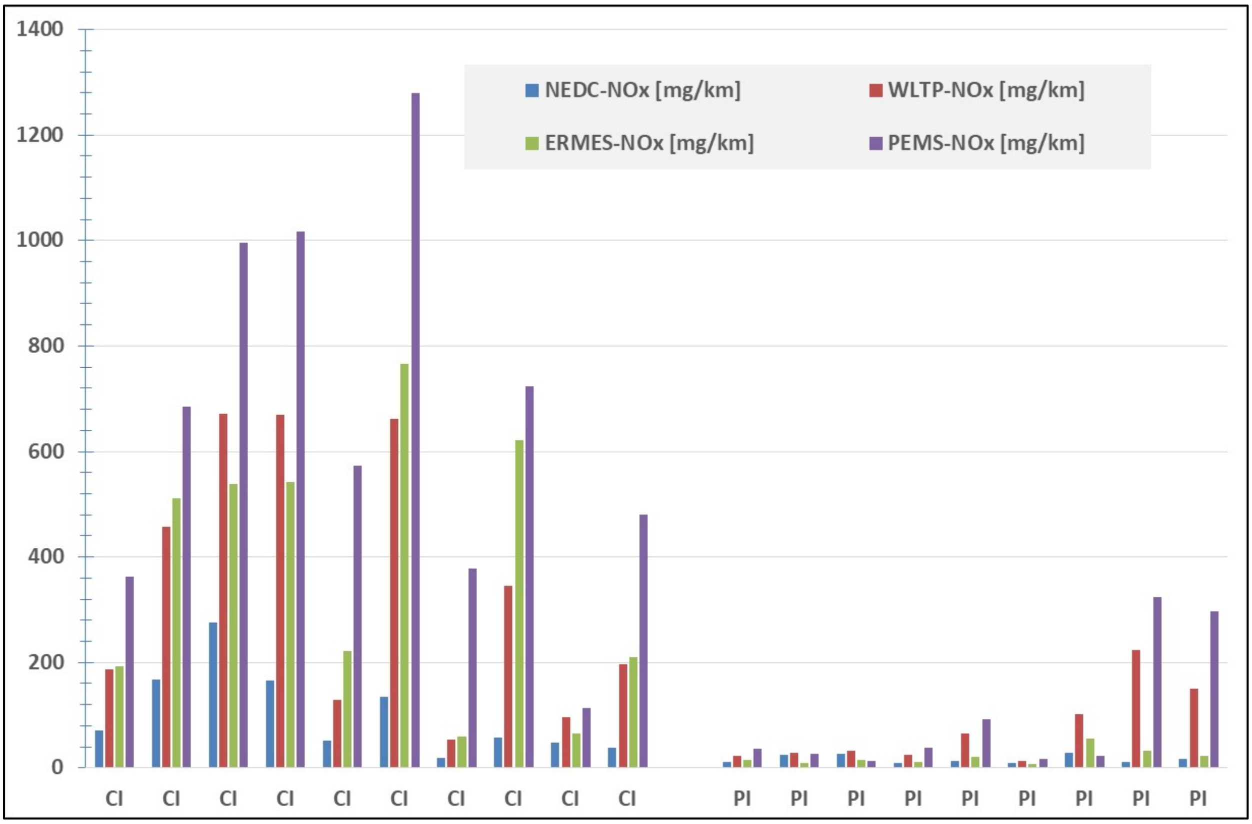


Figure 19 NOx-emissions in g/km for different car models tested at different driving cycles

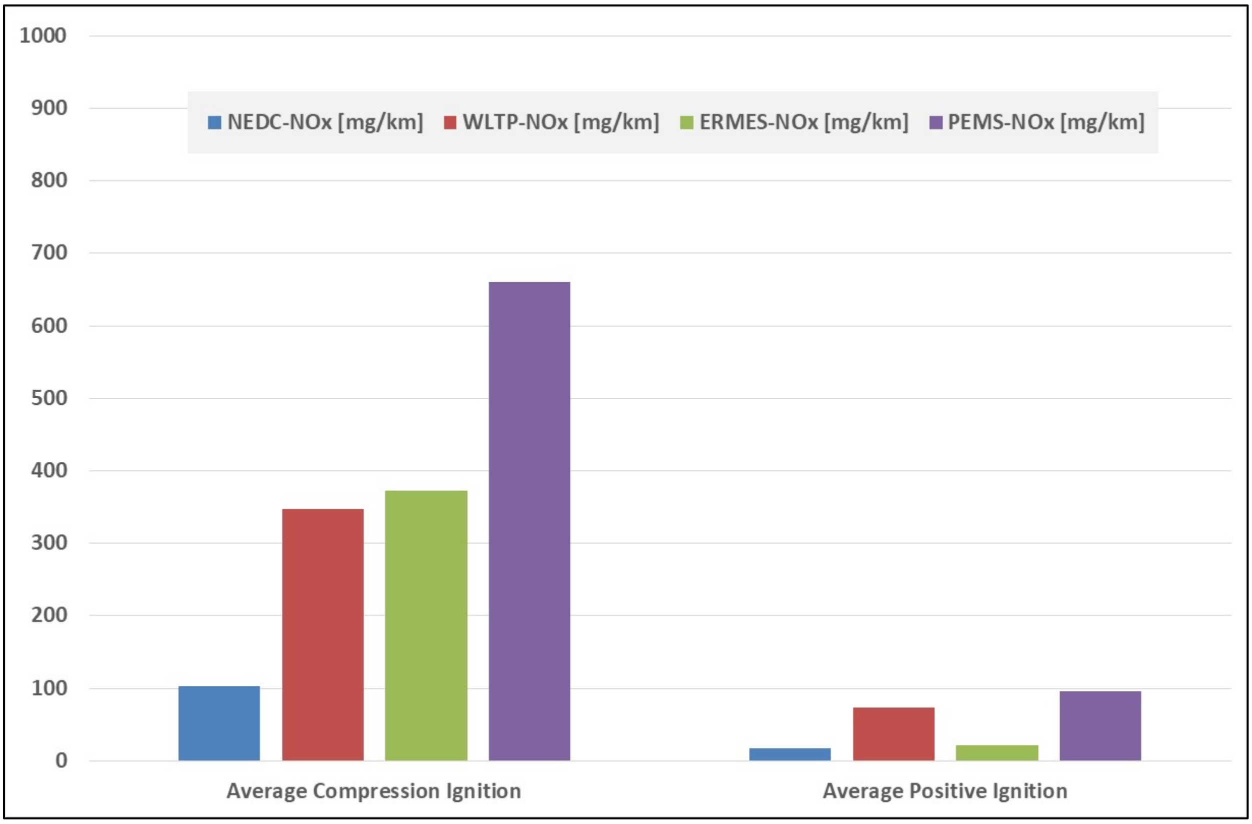


Figure 20 Average NOx-emission in g/km for cars with compression ignition and positive ignition engines. The average values are calculated from the values in Figure 19

The NO_X-emissions were highest for tests in accordance with PEMS and lowest in the NEDC test cycle. Especially high was the difference from Real Driving Emissions compared with the NEDC cycle for cars with compression ignition engines. In average, the difference between NEDC and PEMS was about a factor of 6.6.

Overall, the emissions of NO_X were significantly lower for cars with positive ignition engines compared with cars with compression ignition engines. However, two of the tested cars with positive ignition showed relatively high NO_X-emission in test in real traffic (PEMS-test). Both of these cars were using GDI (Gasoline Direct Injection).

PN and PM – Particle Number (#) and Mass (mg)

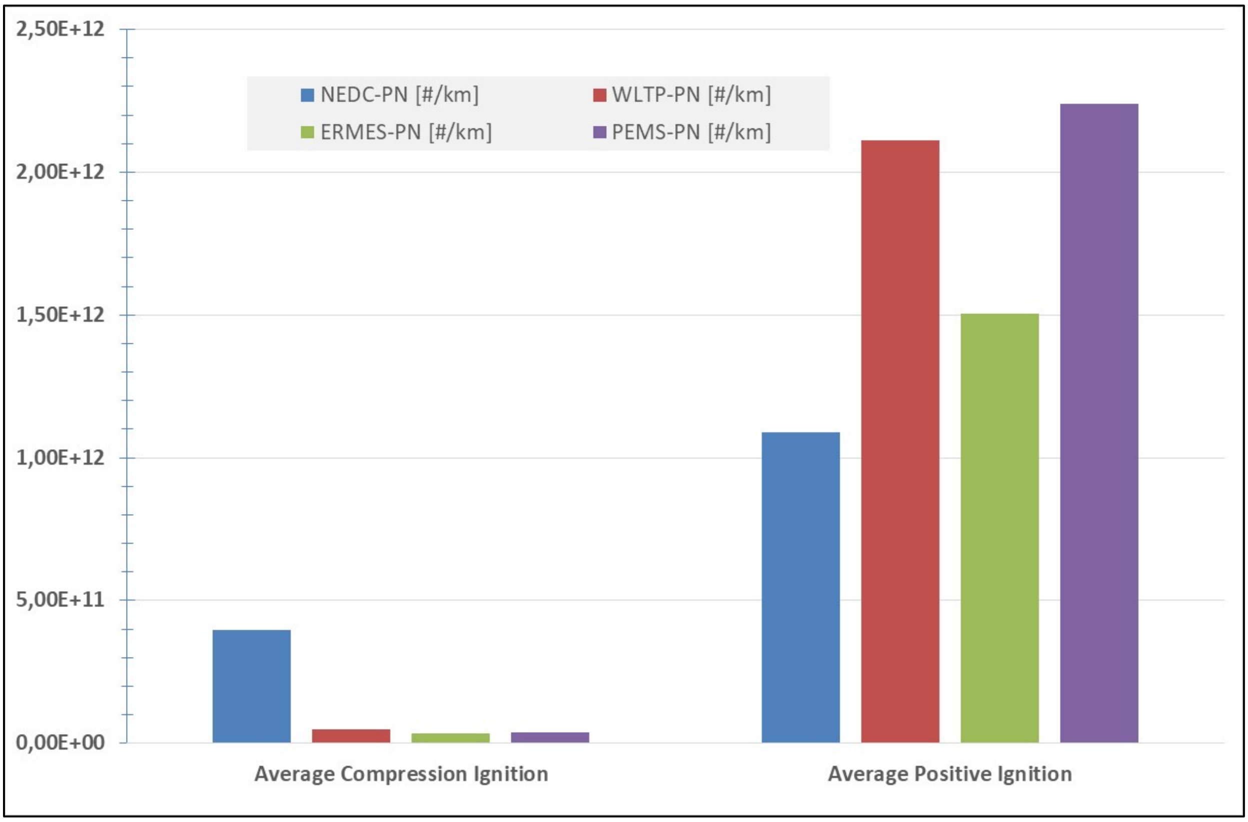


Figure 21. Average particle number emission in #/km for different car models tested at different driving cycles

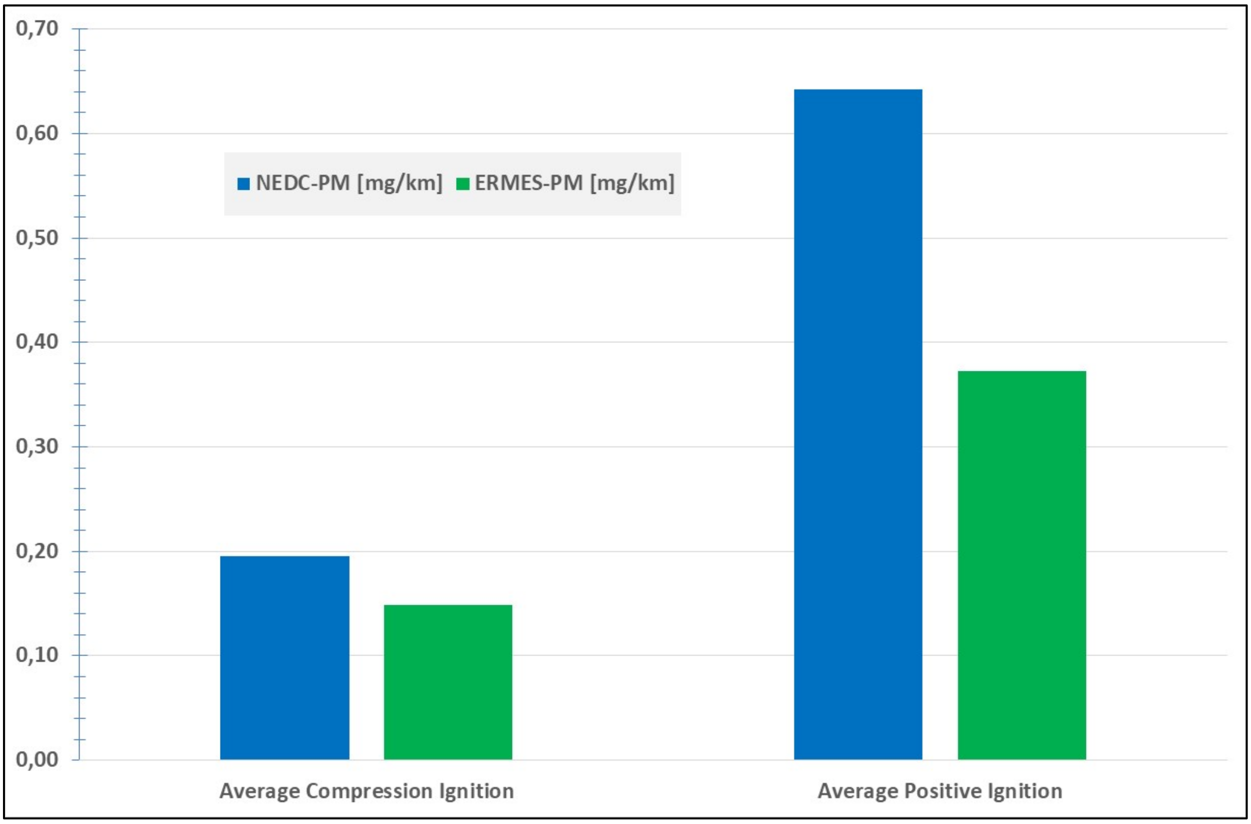


Figure 22. Average particle mass emission in mg/km for different car models tested at different driving cycles.

The emission of particles are generally higher from cars with positive engines compared with cars with compression ignition engines, see Figure 21 and Figure 22 above. All cars with CI engines were equipped with particle filter and none of the cars with PI engines had a corresponding filter. That fact may explain the relatively high particle emission from cars with PI engines.

Effect due to ambient conditions

Directive 98/69/EC introduced an exhaust emission test at low ambient temperatures for vehicles with positive ignition engine. In addition, in directive 715/2007/EC, the test at low temperature is mandatory. The test includes a cold start at -7°C and the urban part of the NEDC test cycle. The purpose of this Type VI test is the adaptation of type approval testing to realistic driving conditions. Carbon monoxide and hydrocarbon emissions are limited by the Directive. During this In-Service Conformity testing programme, two vehicles per type with positive ignition engine were tested at low ambient temperatures. The Type VI test is not relevant for vehicles with compression ignition engine. During the exhaust emission test at low ambient temperatures, all tested vehicles complied with the limits according to Directive 715/2007/EC, see Table 5 and Figure 23 below.

	UDC Type I		**UDC Type VI** - 7 °C	
	CO mg/km	**THC** mg/km	**CO** mg/km	**THC** mg/km
Average	409	51	4 165	660
Limit	n.a	n.a	15 000	1 800

Table 5. Type I versus Type VI (- 7C) for 13 vehicle models with positive ignition engines.

Regarding the cars with compression ignition engines additional tests at two lower temperatures (5 respective 0°C) have been carried out for 4 vehicle models, see Figure 24 below. For cars with CI engines there are no limit values for test at low temperature. These tests indicate that emission of NO_X may increase with decreased temperatures for some of the car tested. CO emissions show relatively low values at all temperatures.

In the MiniPems-program (see page 55) one car (Euro 5) with compression ignition engine has been tested at two different temperatures, (+ 15 respective – 10 C). These tests indicated increased NO_X emission at test in low temperature for this car. (Increased by a factor of app. 4,5 times).

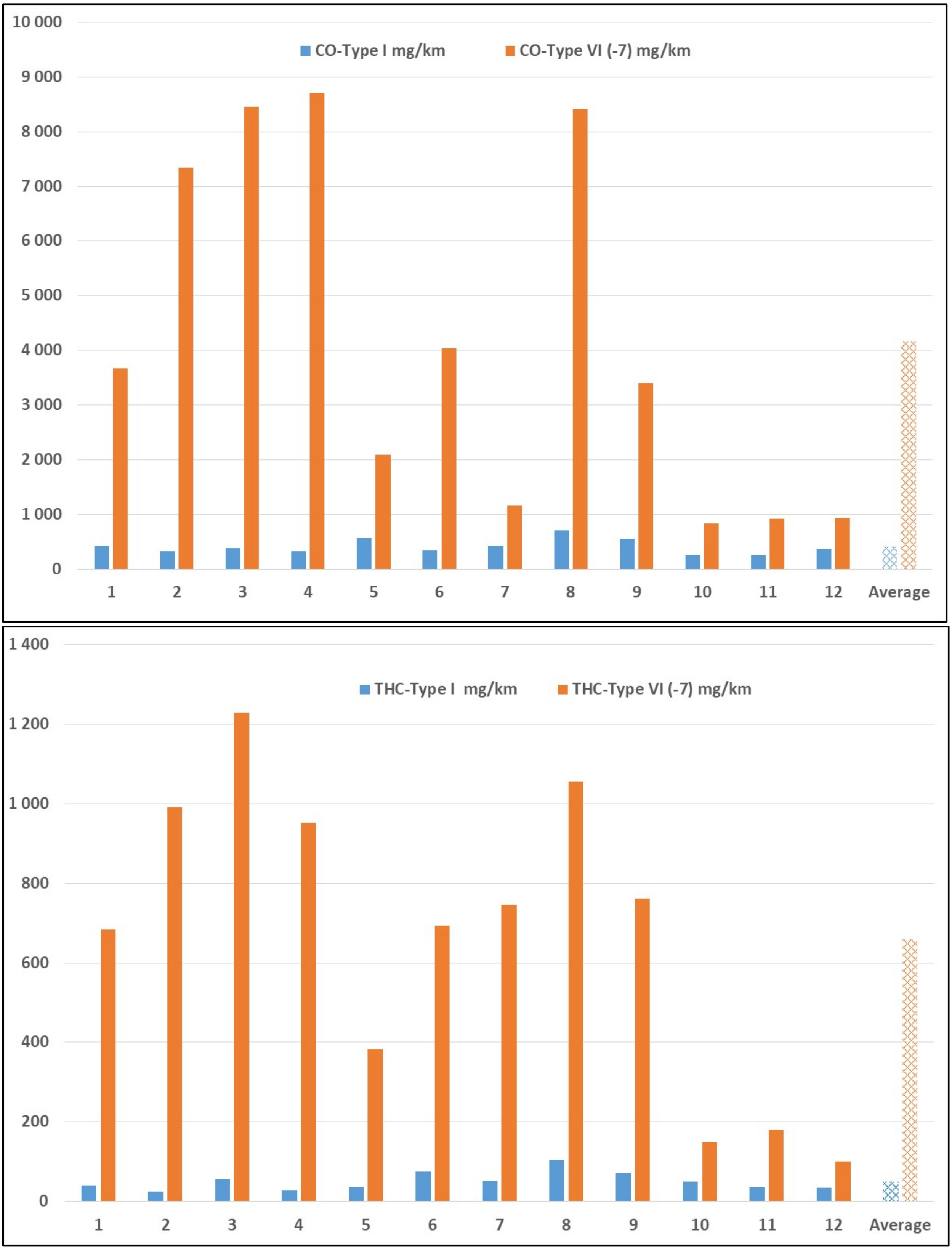
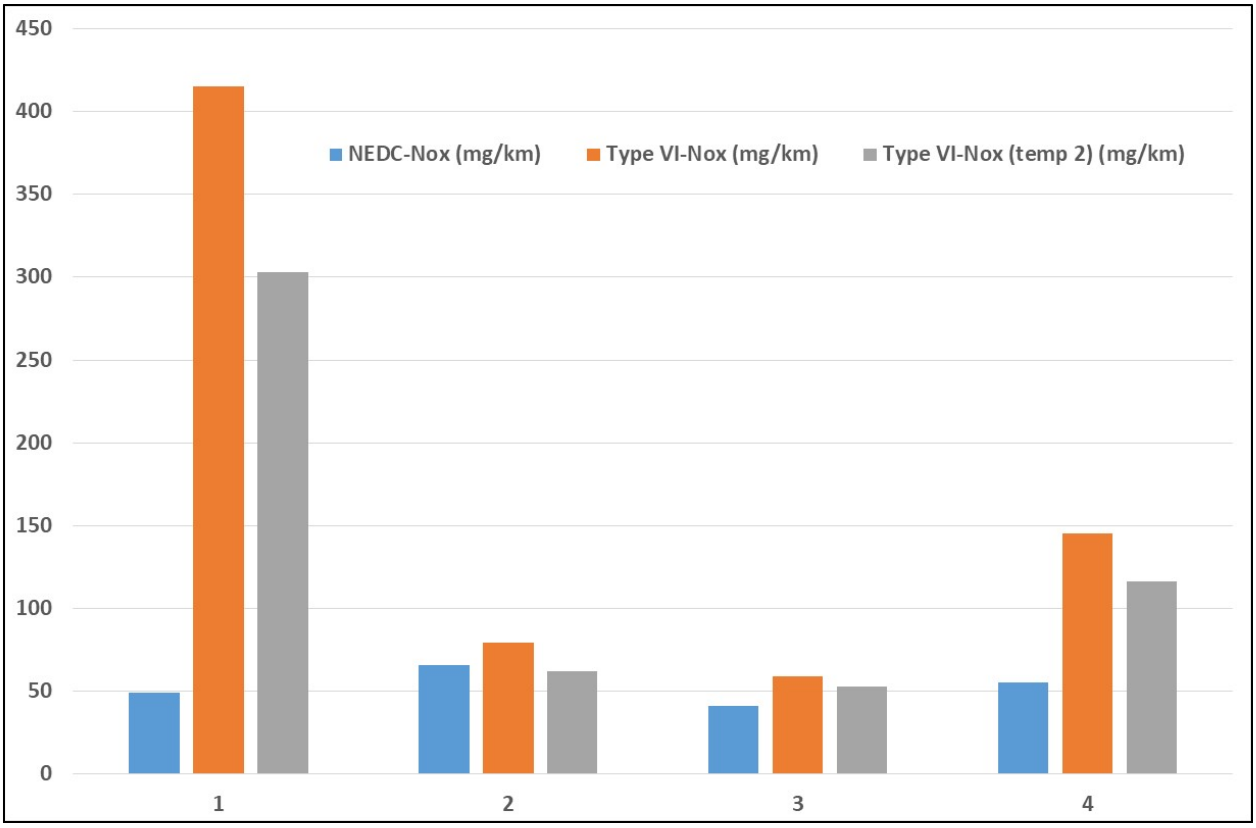


Figure 23. CO and THC emissions from Type I respective Type VI (-7 C) tests (PI-engines).



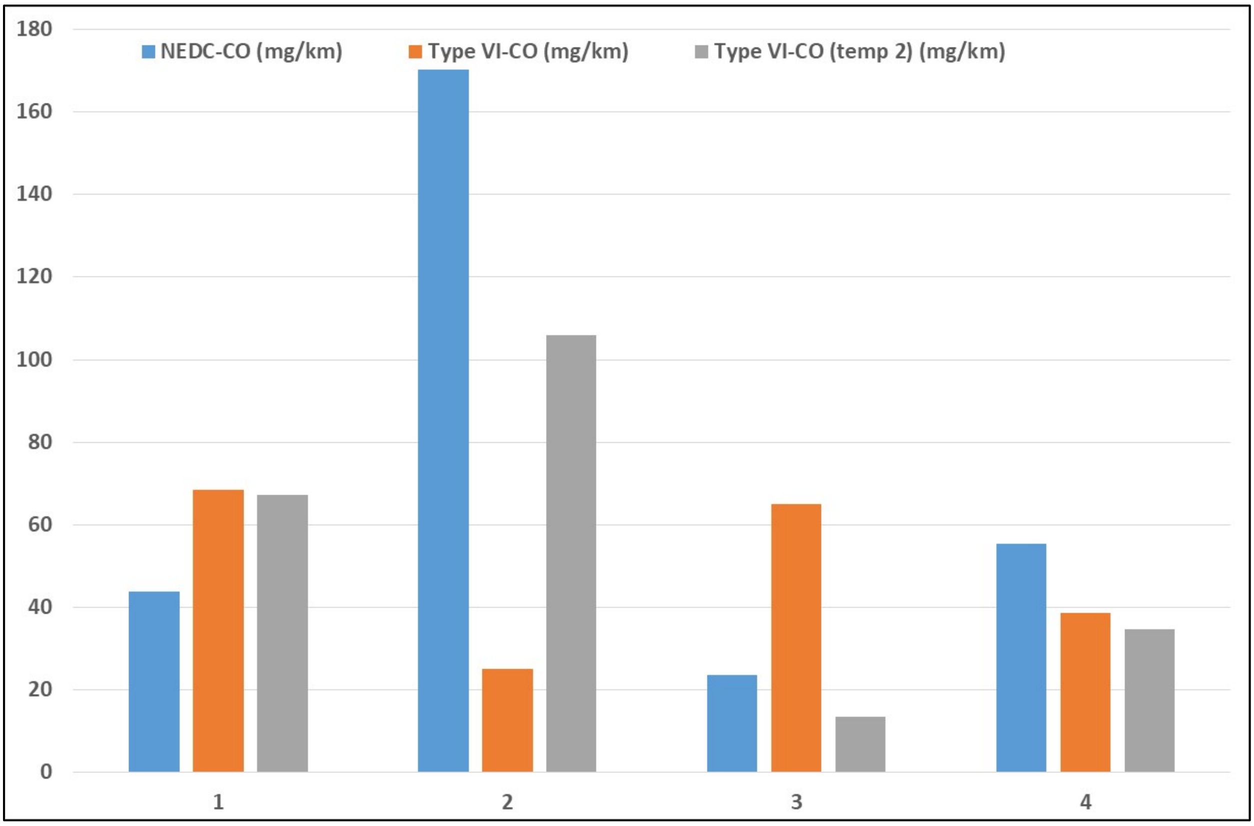


Figure 24. CO and NO_X emissions from Type I respective Type VI (5°C respective 0°C (temp 2)) tests (CI engines)

PEMS route in Germany vs Sweden (and Mini-PEMS vs Full-PEMS)

The tests show a relatively high correlation between the sensor bases Mini-PEMS system and the system equipped with heated sample lines and gas analysers, Full-PEMS, see Figure 25, below.

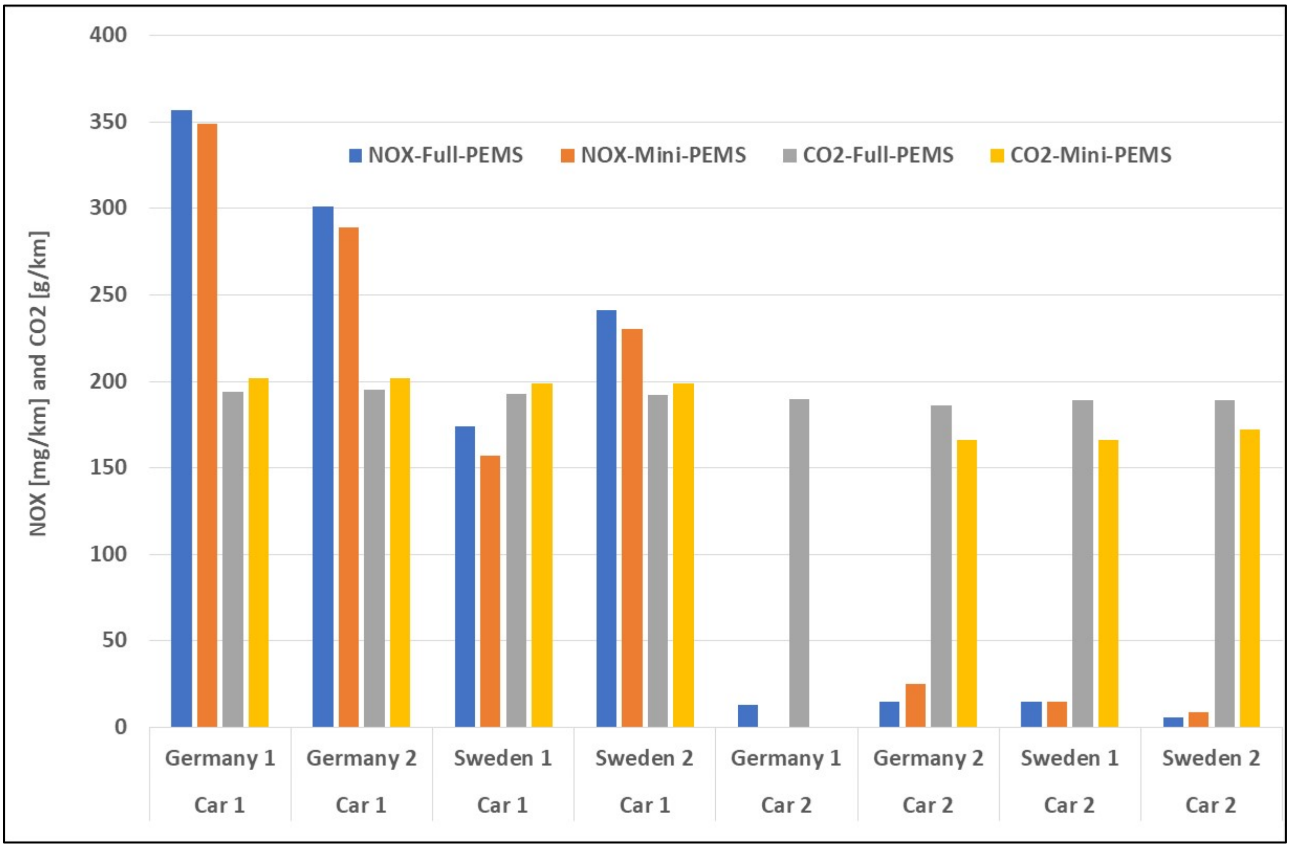


Figure 25. Results from PEMS-tests in Göteborg and Essen. There is a relatively high correlation between Mini-PEMS (sensor based) and the Full-PEMS system for both NO_X and CO_2. (Mini-Pems was not measured on Car 1 / Germany 1)

The NO_X-level for the car with CI-engine (diesel) seems to be higher during PEMS-tests in Germany compared with tests in Sweden. This may due to higher driving speeds and higher accelerations on the German Motorways (Autobahn) compared with the conditions on the Swedish Motorways, see Figure 26, below. For the car with SI engine (gasoline) the emissions of NO_X were low for all tests (and for the Mini-PEMS system also close to the detection limit).

There were not any significant differences in fuel consumption (and CO_2 emissions) between the two PEMS test routs used.

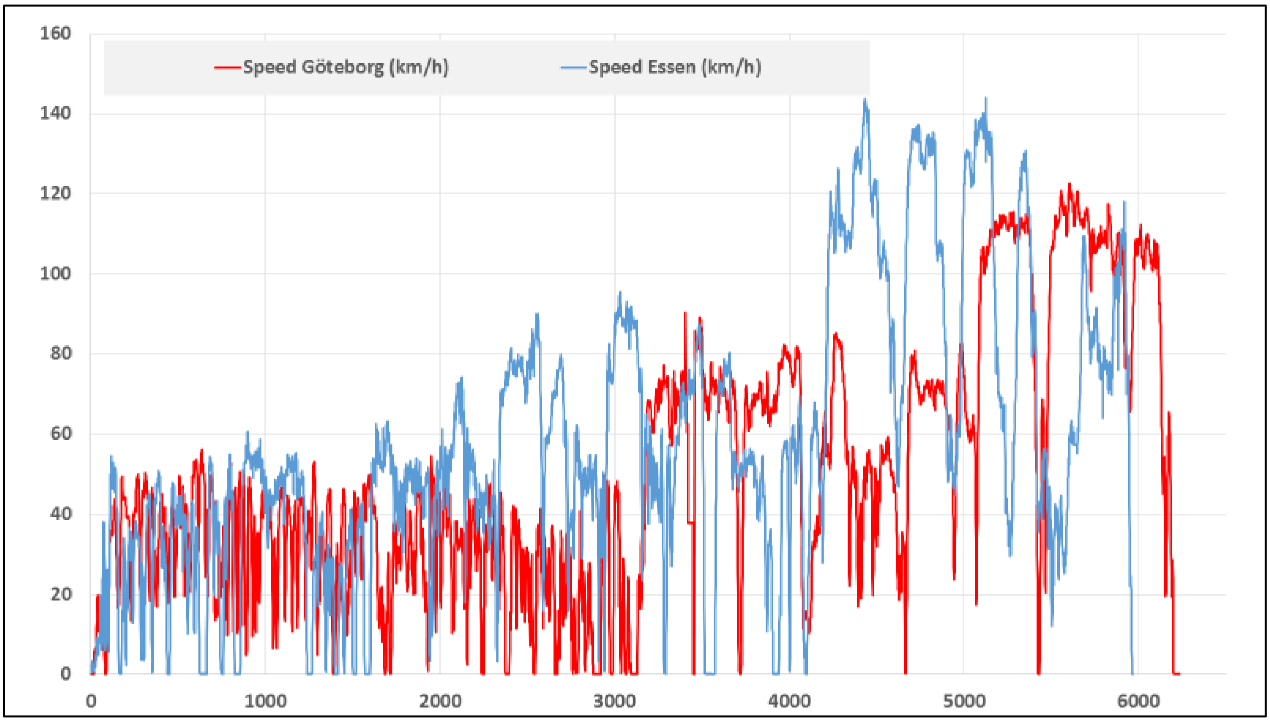


Figure 26. Typical speed pattern during PEMS tests in Germany and in Sweden

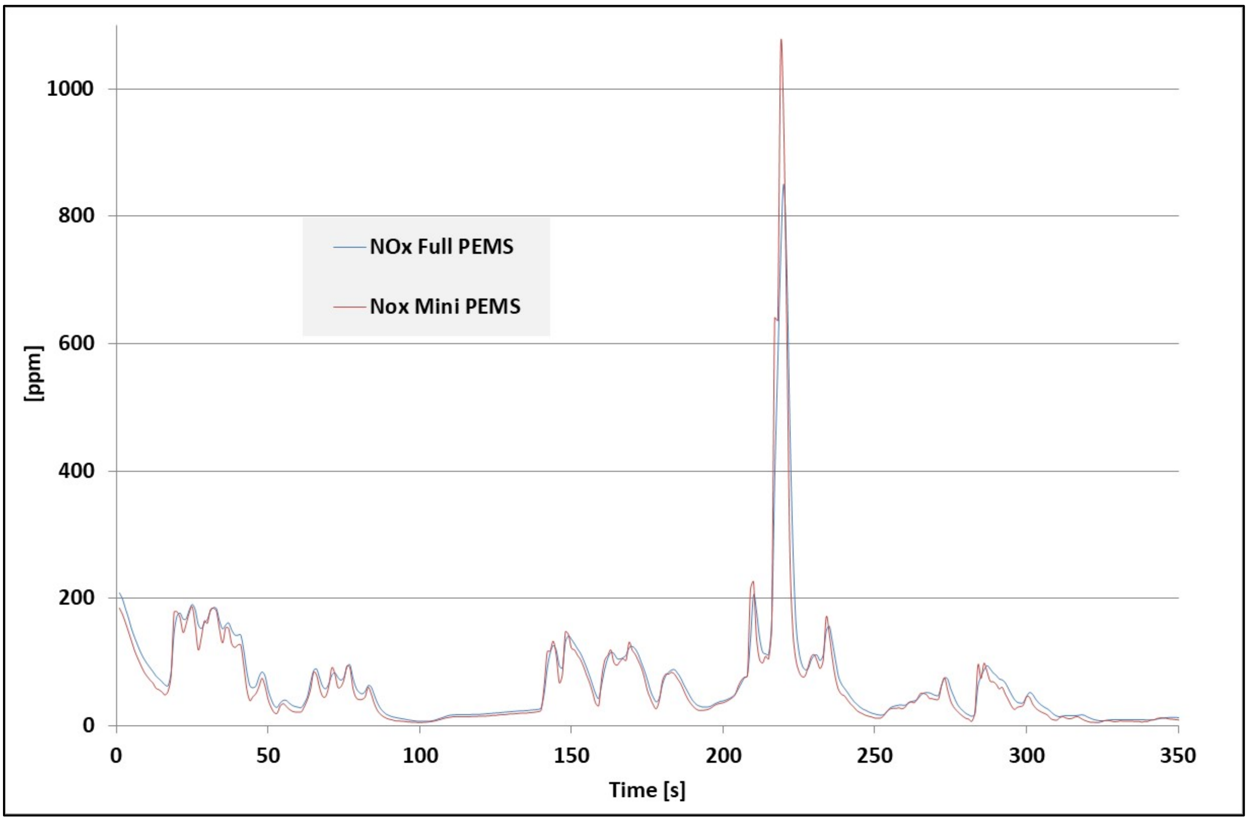


Figure 27. NO_X signals from the Mini-PEMS and the Full-PEMS system

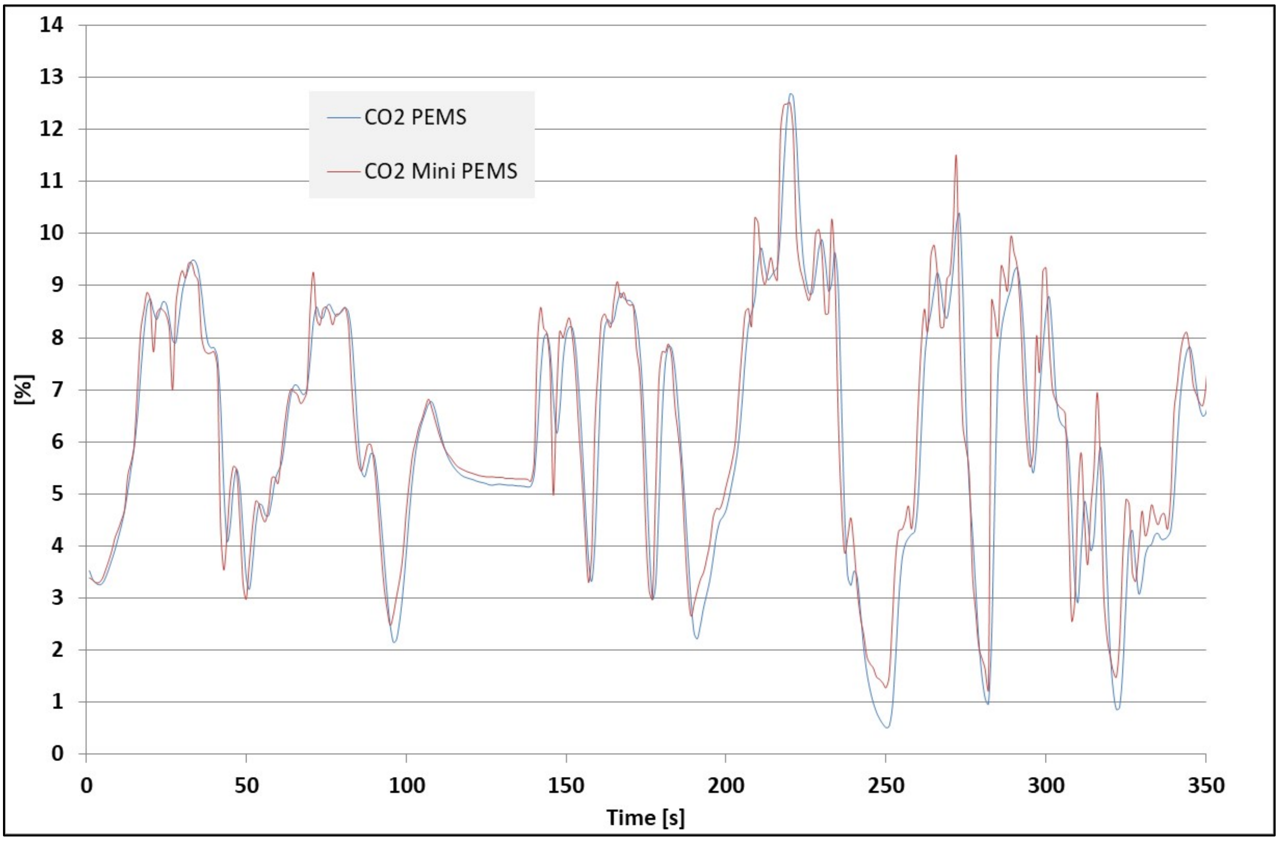


Figure 28. CO_2 signals from the Mini-PEMS and the Full-PEMS system

Figure 27 and Figure 28, shows the modal signals from the sensor based Mini-PEMS system compared with the signals from the Full-PEMS system. The correlation between the two ways to measure NO_X and CO_2 seems to be relatively high. In some cases, a higher "spike" of NOx can be seen for the Mini-PEMS results. This might be due to a somewhat better response time for the Mini-PEMS sensor compared to a gas analyser.

Figure 29. Example of PEMS-installations. Mini-PEMS and Full-PEMS are measured in parallel

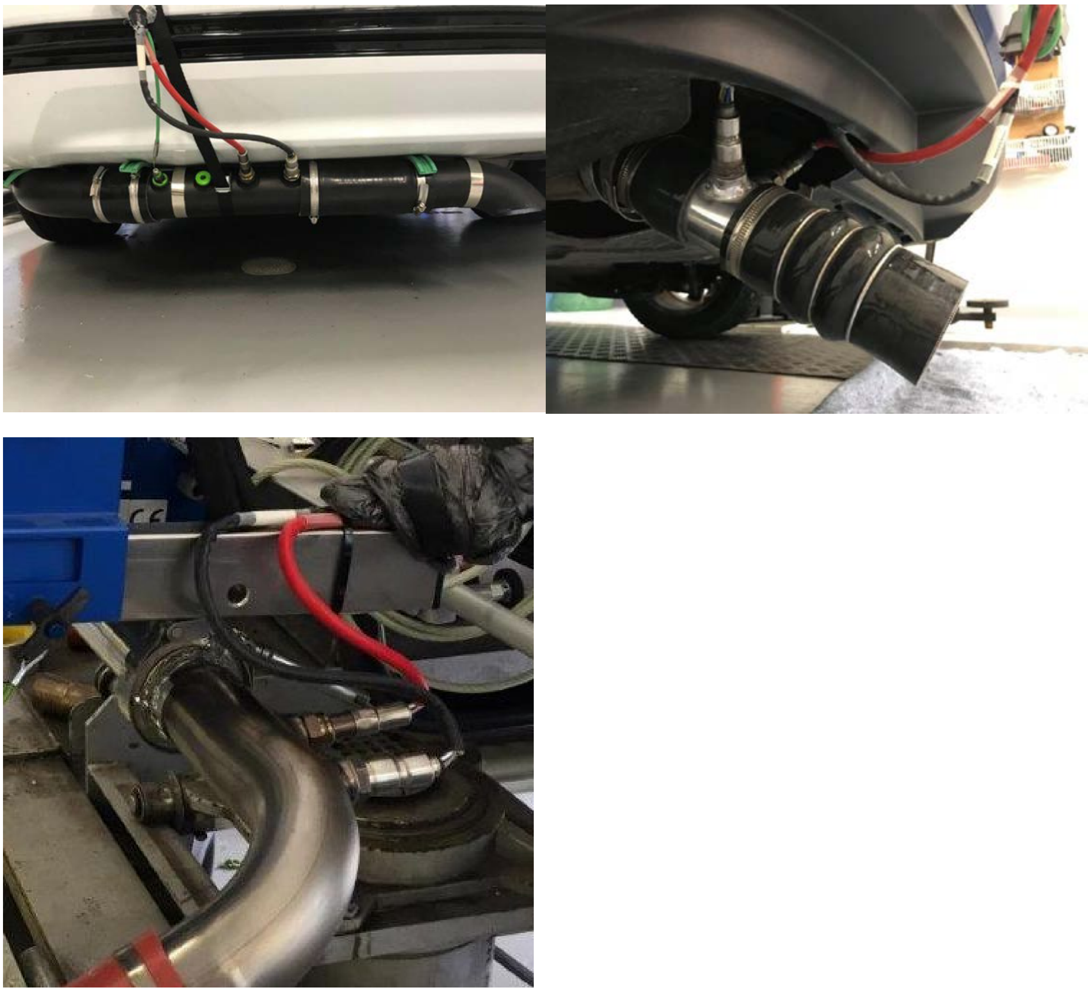


Figure 30. Example of installation of MiniPems. Red cable show the CO/CO_2-sensor and black NO_X and lambda sensor

Measurement scatter

Some final words on measurement scatter might be appropriate in this context. It can be seen in the results above that there sometimes is a big scatter between some of the vehicle models. The problem of measurement scatter is complex, and it was beyond the scope of this report, so only a few general remarks will be made below.

When it comes to regulated gaseous and particle emissions, a general comment is that there should be no apparent problems with measurement accuracy for the instruments at the level of the emission limits[4]. When an emission level of 90% lower the limit – or even lower than that – is reached, the measurement scatter for sure becomes a real problem. To give a concrete example: one should hesitate to say that a car that has NOx emissions of 95% below the RDE limit is "better" than a car that has a level "only" 90% below the limit. In reality, an infinite number of tests might reveal that both cars could be quite similar. One single test is just a snapshot and at such low levels, scatter becomes an issue. It is not all about instrumentation, either. We know that conditions in the laboratory can be much more constant than on the road in RDE tests but there is still some variation in the test procedure. We still have influence of factors other than instrumentation, such as e.g. the driving

[4] An appropriate comment here is that PM emissions might be an exception here, particularly at the Euro 6 diesel level. However, we have the metric of PN emissions as an alternative and the accuracy of this method is far better at the level of the corresponding emission limit and even significantly lower.

style, regardless of if the vehicle speed trace in the test was within given limits. For RDE testing, it is obvious that the traffic situation can never be exactly the same in two tests. Likewise, RDE test routes are always different at different locations. Even the cars themselves are individuals. There is some scatter in vehicle production but, since we are dealing with in-use cars, the previous pre-history of the car will also matter. For that reason, as many as 3 to 5 individual cars are selected for testing. In general, laboratory testing is more accurate but RDE testing is, nevertheless, very good as complimentary testing and it might reveal problems that otherwise would be hidden.

Also fuel consumption show some scatter. As mentioned above, cars are always individuals and a small scatter can always be noted from car to car of the same model. Between car models, we have, of course, much bigger scatter. First, we have the engine technology. As discussed above, there is a considerable difference between the thermodynamic cycle, e.g. between otto (PI) or diesel (CI). There are also various energy-saving technical features of the engines, which might – or might not – be applied on the particular engine. Most additional features come with an incremental cost, which limits its application. Second, the transmission type (e.g. manual, automatic, hybrid, etc.) will have an impact on fuel economy. Third, the car body and chassis have decisive impact on fuel consumption. For example, an SUV with big frontal area, high aerodynamic drag coefficient, excess weight and 4-wheel drive can never be as an efficient as a conventional sedan type of car body. Finally, a car can have various accessories and additional features what might increase fuel consumption. In summary, we can identify numerous factors that affect the fuel consumption and many of them might not even be known to us. Thus, when comparing a wide range of cars, we can find such striking contradictions as e.g. that a certain gasoline vehicle can have lower fuel consumption than a somewhat similar diesel vehicle of same size. Nevertheless, if we compare a larger number or cars and consider some of the factors, as e.g. weight, we can get a quite large difference on average between vehicle categories. This example just illustrates the importance of an apples-to-apples comparison. To be able to draw more decisive conclusions the impact of various technologies and features on fuel economy, a large number of cars need to be the basis of comparison but also the conditions for comparison must be carefully scrutinised.

8. Appendix 1

Test facilities and test equipment

Test site TÜV NORD Essen

All tests on chassis dynamometer have been carried out at TÜV NORD's test site in Essen.

Climatisation	-20°C - +35°C WEISS
Chassis Dynamometer	MAHA ECDM 48L 4x4
Control Unit	MAHA
CVS-Unit	MAHA-CVS
Analytical System for gaseous emissions (CO, CO_2, THC, NMHC, NO, NO_X)	MAHA-AMA D1
Particle Collector	MAHA-PTS
Particle Balance for particle mass	SARTORIUS SE2-F
Particle Counter	MAHA

Table 6. 4-wheels driving test cell (MAHA)

Capacity	60 m^3
Outlet temperature	18 – 41 C
Variable volume enclosure	TWIN-BAG
Minimum graduation	0,1 C
Accuracy	0,1 C
HC-analyser	Ratfisch, RS 55-T
CH_4-anaylser	Amluk Fidamat
Canister loading system	PEUS-System (PEGASys)
Canister weight measuring device	Sartorius BP 41005

Table 7. VT-SHED (York International) – test cell for evaporative emissions – Type IV-tests

NO and NO_2	NDUV
CO and CO_2	NDIR
PN	SEMTECH LDV CPN
	condensation particle counter (CPC) using Butanol
Sample conditioning system	SEMTECH LDV SCS
Exhaust flow meter	SEMTECH LDV EFM4
Weather probe system	VAISALA HMP155

Table 8. Full-PEMS system (Sensors). The entire system fulfils requirements in regulation (EU) 2017/1347

NO_X , O_2 and lambda	CAN Module (ceramic sensor) for NO_X (also lambda, O_2, AFR) 0-5000 ppm NO_X (+/- 20 ppm, 200-1000 ppm, +/- 2,0 % elsewhere). Lambda (+/- 0,008 at lambda 1, +/- 0,016 at lambda 0,8 to 1,2, +/- 0,018 elsewhere). Response time < 1 s (NO_X), < 150 ms (Lambda, AFR, O_2)
CO and CO_2	0-20% CO/CO_2 (+/-0,15). 0,4-25 lambda, 0-25% O_2 (+/- 0,1%), AFR 6,0-364. Response time < 200 ms.
CAN Module 1	10 analoge signals (mA, V, Hz)
CAN Module 2	OBD-parameters
CAN Module 3	GPS (including antenna) – 10 Hz
Logger	Kaser Memorator

Table 9. Mini-PEMS system (ECM)

New European Driving Cycle (NEDC)

After conditioning the vehicle for at least 6 hours at an ambient temperature of 20 °C up to 30 °C the New European Driving Cycle (NEDC) begins with a cold start. The Urban Driving Cycle (UDC) has duration of 780 seconds, a driving distance of 4.1 km, an average speed of 19 km/h and a maximum velocity of 50 km/h. It is followed by an Extra Urban Driving Cycle (EUDC) with a duration of 400 seconds, a driving distance of 6.9 km, an average speed of 62.6 km/h and a maximum velocity of 120 km/h. Exhaust emissions of both UDC and EUDC are combined to get a total test result.

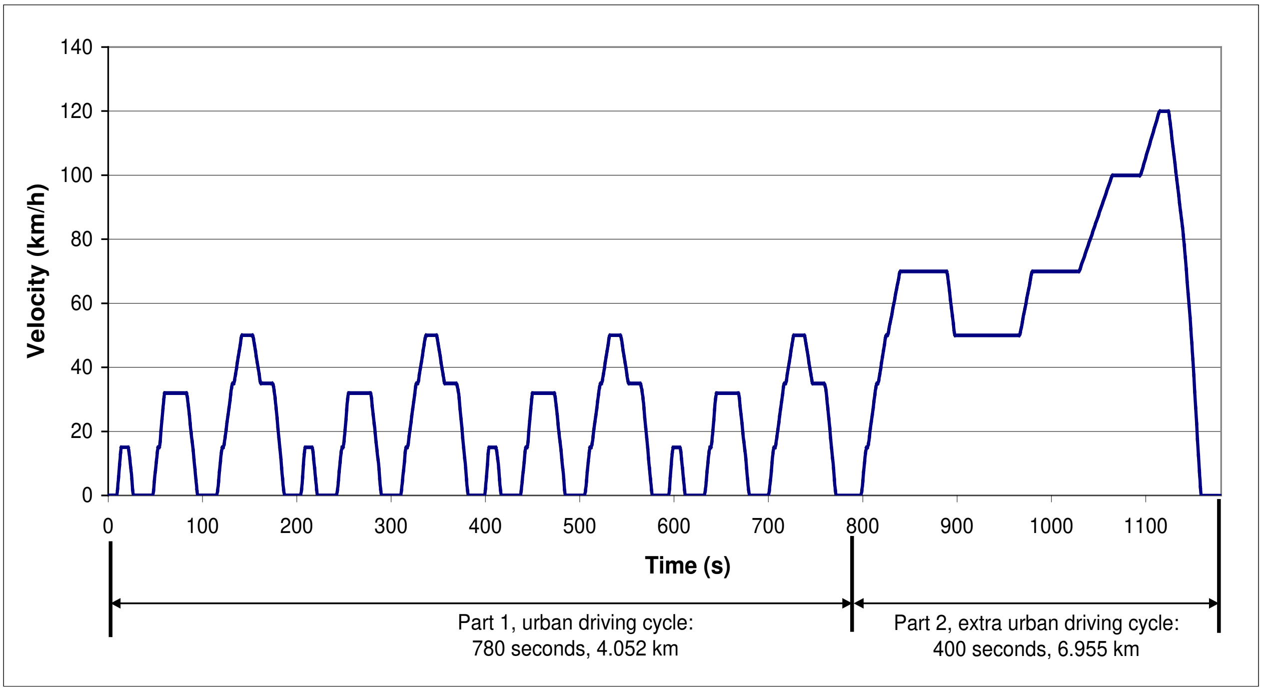


Figure 31. New European Driving Cycle (NEDC)

Worldwide light-duty test cycle (WLTC)

The Worldwide light-duty test cycle is part of the worldwide light-duty testing procedure (WTLP). The WLTC (class 3) consists of four phases:

- Phase Low, duration 589 seconds
- Phase Medium, duration 433 seconds
- Phase High, duration 455 seconds
- Phase Extra High, duration 323 seconds

In **Figure 32** to **Figure 35** below, the different WLTC phases are shown.

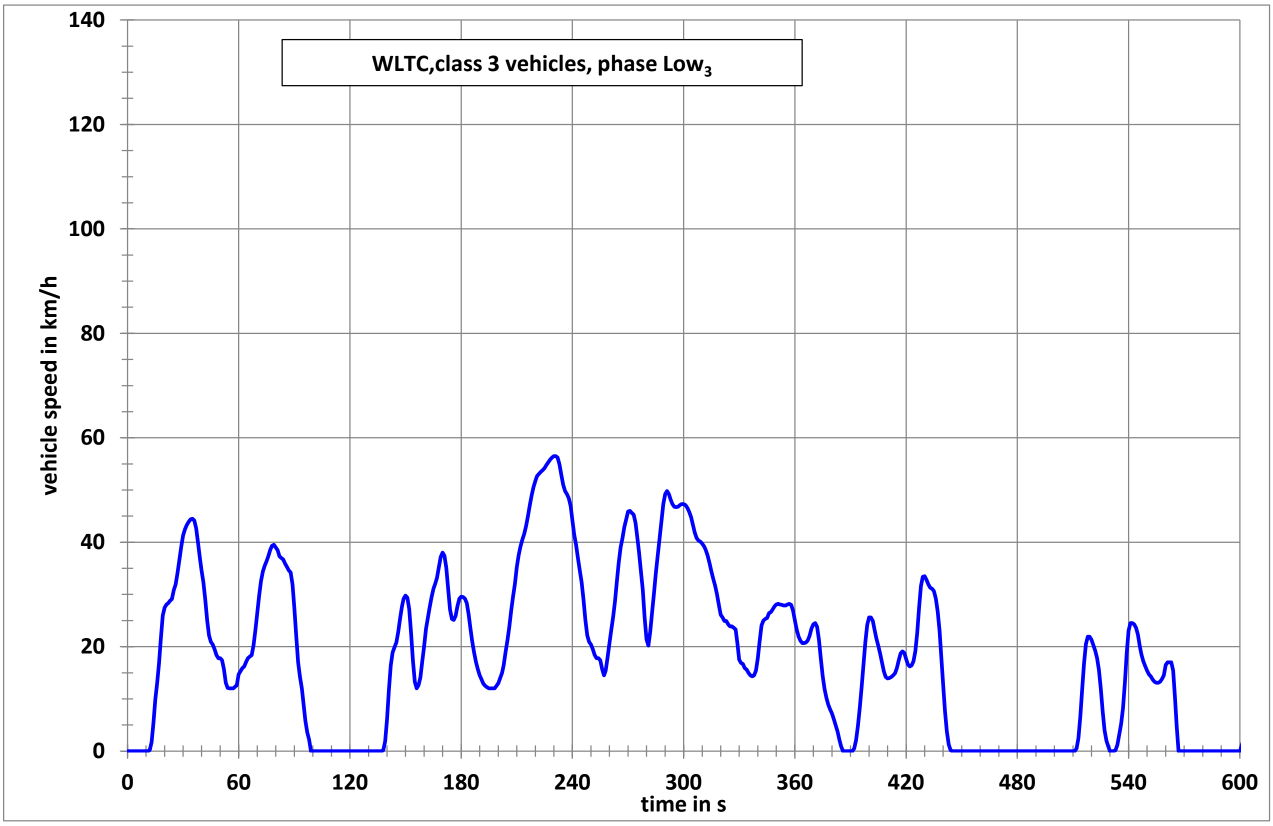


Figure 32. *Phase Low*

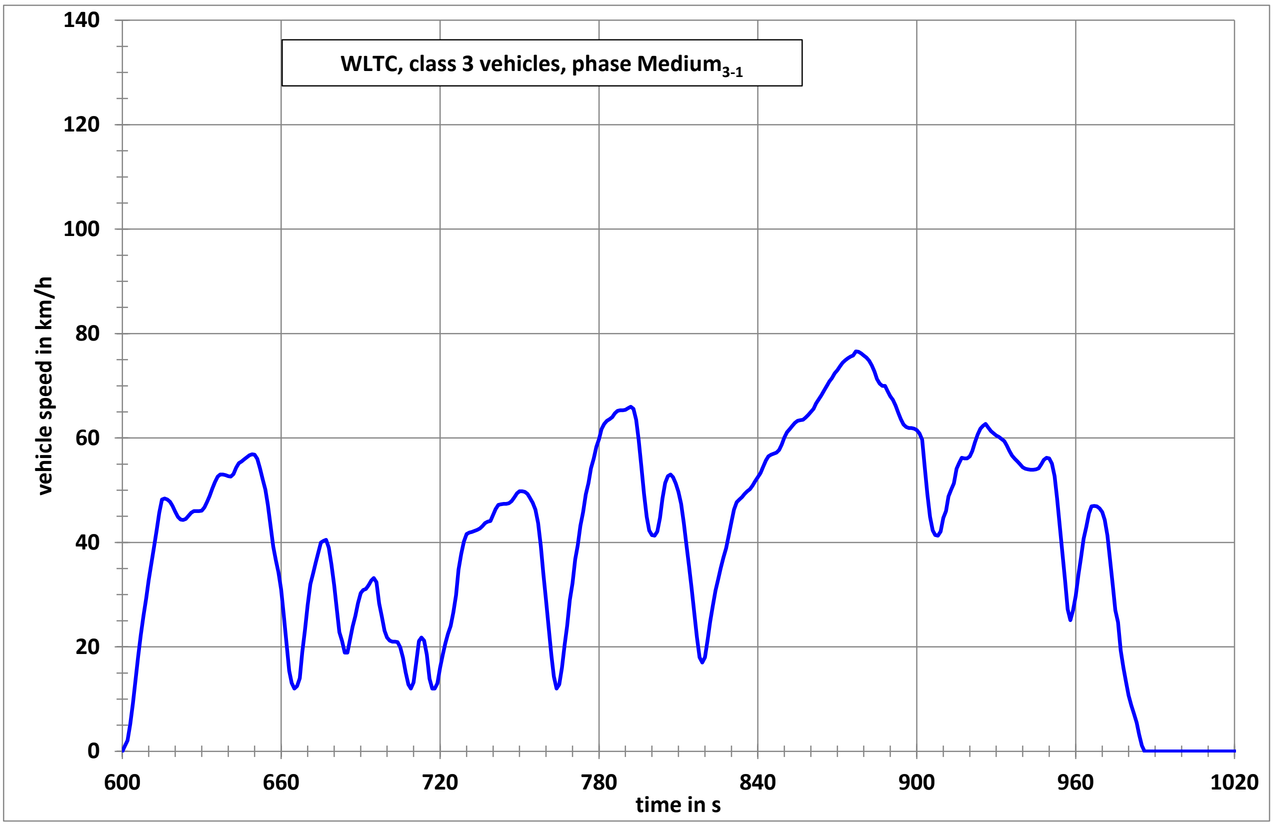


Figure 33. *Phase Medium*

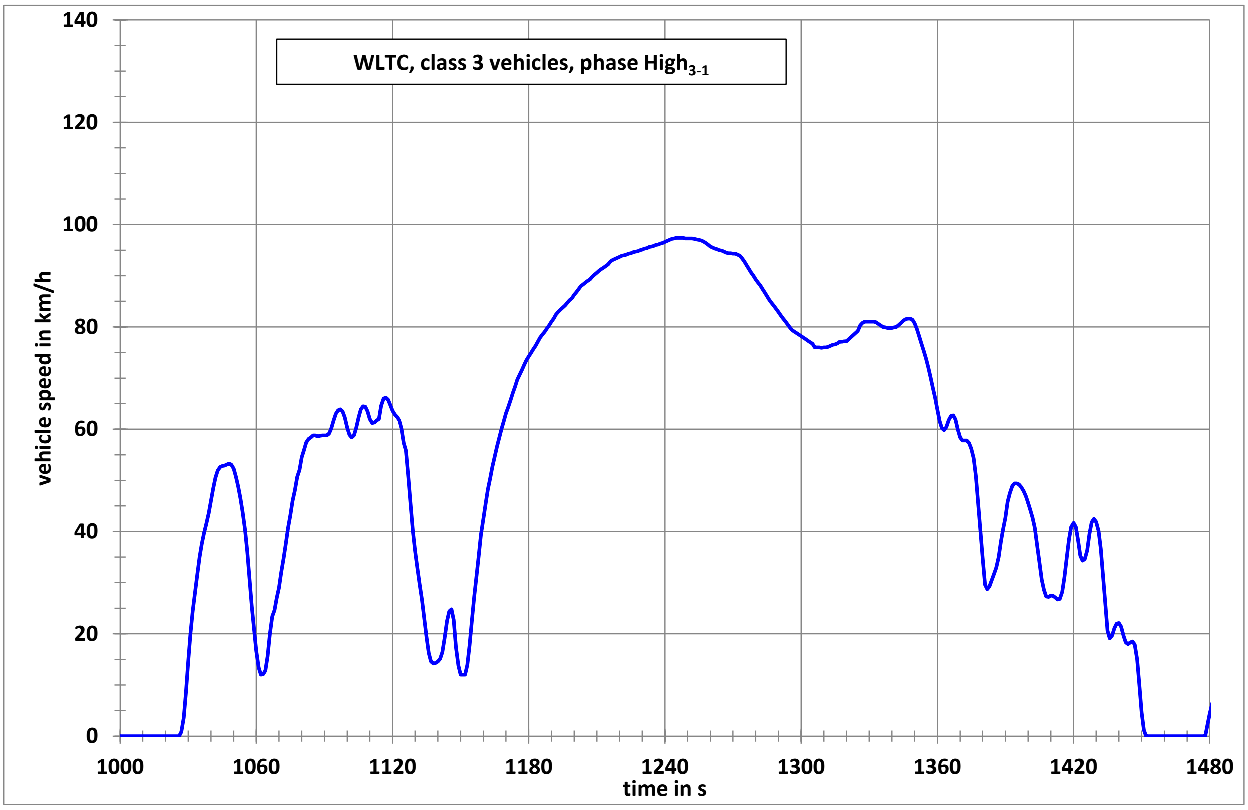


Figure 34. *Phase High*

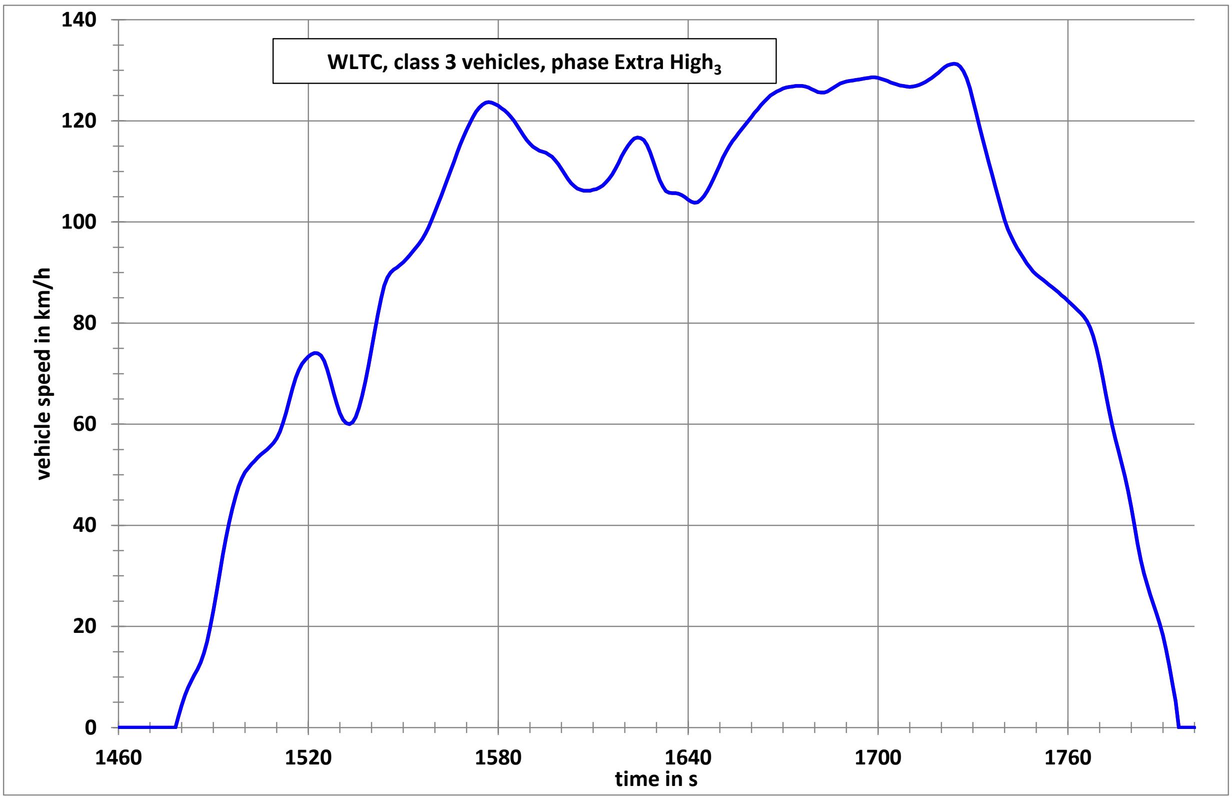


Figure 35. Phase Extra High

A comparison of the sub-cycles of NEDC and WLTC is given in **Table 10.** The average speed of UDC is comparable to WLTC LOW. The same is valid for EUDC and WLTC HIGH. However, the WLTC cycles are much more dynamic as can be seen from the Relative Positive Acceleration (RPA). The gear shifting points are determined in accordance with the vehicle's weight, engine power and engine revolutions.

Driving cycle	**NEDC**		**WLTC – class 3**			
	UDC	**EUDC**	**LOW**	**MEDIUM**	**HIGH**	**EXT-HIGH**
Distance [km]	4,1	7,0	3,1	4,8	7,2	8,3
Average Speed [km/h]	19	63	19	40	57	92
RPA [m/s^2]	0,13	0,09	1,5	1,6	1,6	1,6

Table 10. Comparison of driving cycles NEDC and WLTP

Gaseous emissions in all driving cycles were measured integrally and in parallel continuously every second (modal measurement). The results of the modal measurements may serve as the basis for determining the exhaust emission behaviour in all relevant traffic situations.

European Research group on Mobile Emission Sources (ERMES)

Text and **Figure 36** are from ERMES-webpage (http://www.ermes-group.eu/web/about_ermes)

"The European Research for Mobile Emission Sources (ERMES) is a group of research institutions, competent authorities, industry associations, whose mission includes the support of cooperative research in the field of transport emission modelling. The ERMES group emerged from the collaboration since early 2000 of two groups engaged in developing the models HBEFA (DACHNL group headed by INFRAS and TUG) and COPERT (EEA/JRC/LAT/Emisia). Both groups have been active in emission measurements and modelling since the 90s. The group, chaired by JRC since 2009, strives to bring together the knowledge produced in Europe, to facilitate the exchange of information and to promote the cooperation among the actors involved in the measurement and modelling of emission from road vehicles."

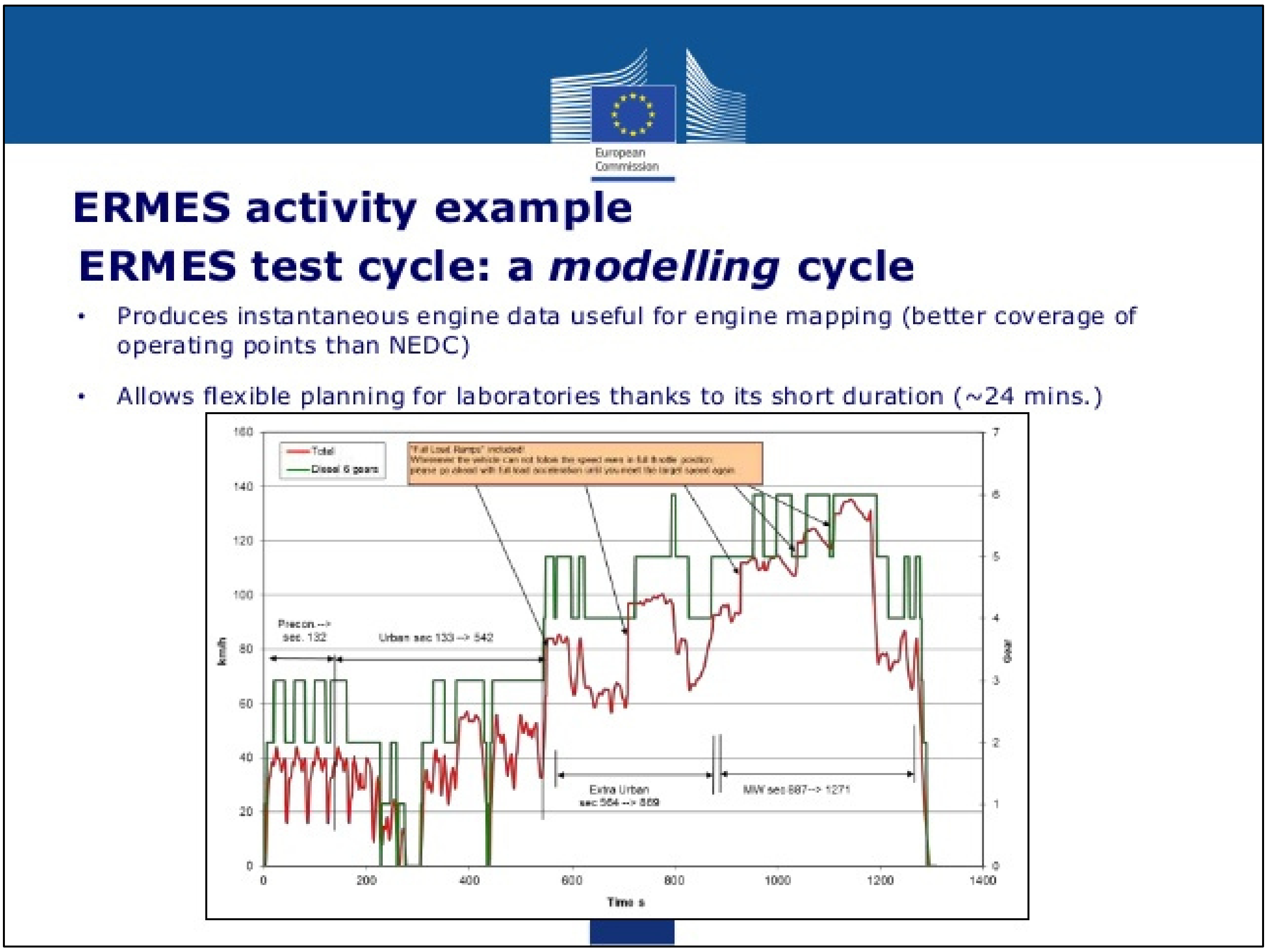


Figure 36. ERMES-driving cycle

PEMS-Routes

Two different PEMS-routes have been used, see Figure 37 and Figure 38. One in Essen and one in Gothenburg. Both routes fulfil the requirements given in Regulation (EC) no. 692/2008 as regards emissions from light passenger and commercial vehicles. Both rotes are about 90 km and takes between 90-120 minutes to drive.

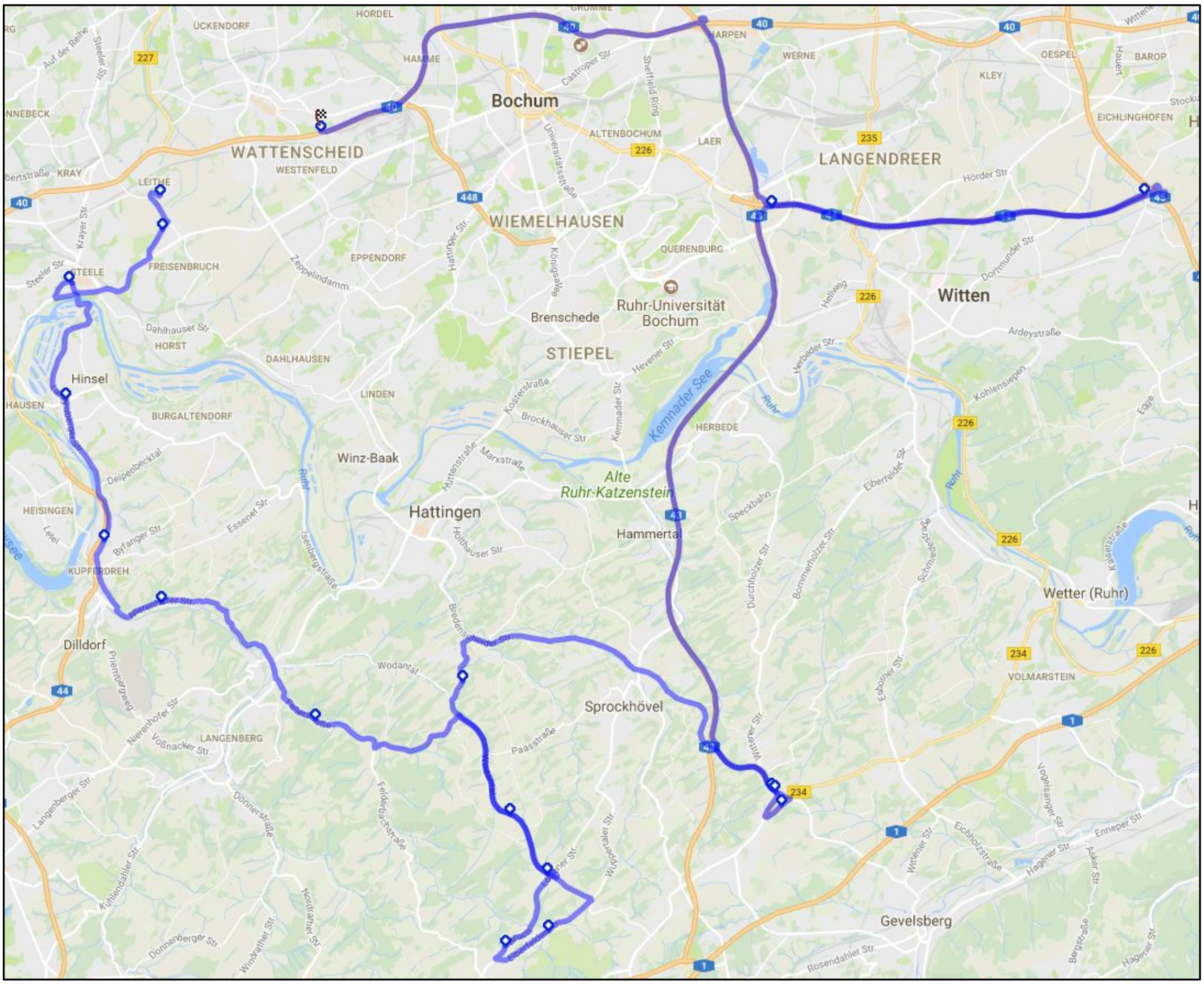


Figure 37. PEMS route Essen

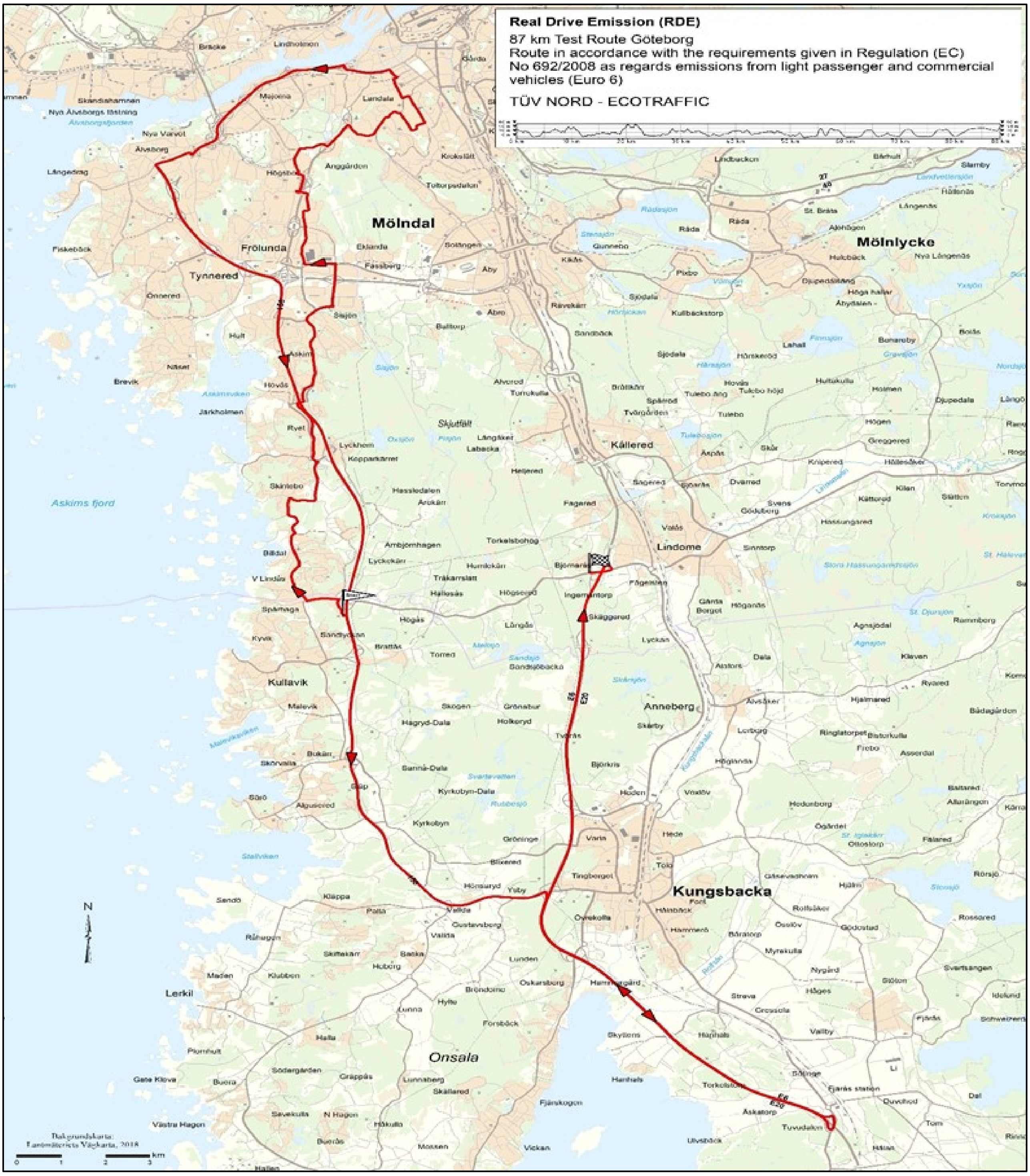


Figure 38. PEMS route Gothenburg

9. Appendix 2 - Mini-PEMS tests

The main focus in the Mini-PEMS tests were NO_X. These tests indicate no big differences between Euro 5 and Euro 6, with respect to CI engines and NO_X. But there are differences between using SCR or not. Cars equipped with SCR give emit significantly lower NO_X-emission compared with cars without SCR.

Introduction

Within this program 25 vehicles have been tested. All cars with CI engine except one, a plug-in-hybrid (SI).

Vehicles

Most of the cars in the Mini-PEMS program have been carried out on the test Route in Göteborg, see **Figure 38**. Two of the cars have been tested also on the test route in Essen (7 and 8 in the table) an additional two have been tested during a long PEMS-trip (950 km) from Göteborg to Essen. One of the cars were tested by a remote system on a test Route outside Stockholm (21). One car has also been tested with and without being tuned.

Make	Model	
VW	Sharan	Eu5 (CI)
VW	Sharan	Eu5 (CI)
Mercedes	180 A	Eu6 (CI)
Volvo	V70	Eu5 (CI)
Ford	Mondeo	Eu6 (CI)
Kia	Optima	Eu6 (CI)
Volvo	XC60	Eu6 (CI)
Volvo	V40	Eu6 (SI)
Mercedes	GLE 350	Eu6 (CI)
Mercedes	C-klass	Eu6 (CI)
Mercedes	E-klass	Eu6 (CI)
Kia	Ceed	Eu6 (CI)
Nissan	Qashqai	Eu6 (CI)
Ford	Kuga	Eu6 (CI)
BMW	118 D	Eu6 (CI)
Renault	Traffic	Eu6 (CI)
Volvo	V90	Eu6 (CI)
VW	Passat GTE	Eu6 (SI)
VW	Passat GTE	Eu6 (SI)
Audi	A6	Eu6 (CI)
Ford	Focus	Eu5 (CI)
Skoda	Octavia	Eu6 (CI)
Volvo	V70	Eu5 (CI)
Volvo	XC60	Eu6 d TEMP
Volvo	XC60	Eu6 d TEMP

Table 11. Overview of the cars in the Mini-PEMS program

Figure 39. Example of installation of the sensors during tests with the Mini-PEMS system.

Results

In Figure 40, below, the NO_X-values from the PEMS measurements are shown. The vehicles are shown in Table 11, above.

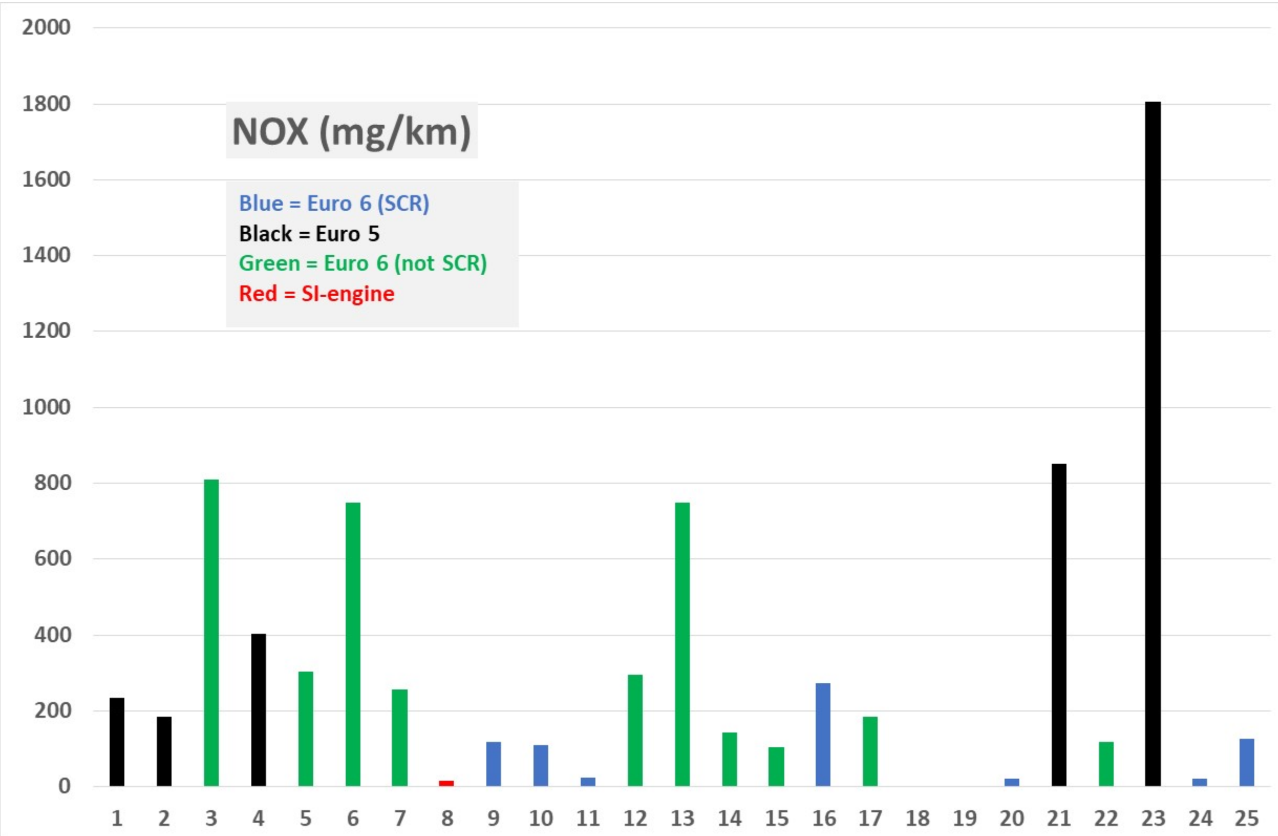


Figure 40. NO_X-values during MiniPEMS-tests.

Some comments about the results.

- Euro 6 cars with SCR came down to relatively low NO_X-values, also under relatively tough test conditions. (956 km driving from Göteborg to Dortmund)
- Test 23 is from a test with an ambient temperature of –10°C. (test 4 is the same vehicle tested at ambient temperature of + 17 C)
- Car 1 where tested with and without a tuning software from a tuning company. This tuning software is installed by the OBD-connector. By using the tuning software, NO_X increased > 20 % and the fuel consumption increase was about 10 % compared to use the OEM program (engine map from the car manufacture). However, the number of tests are too few to draw a final conclusion.

CI-engine (Euro 6 with SCR) – Long PEMS-route (Göteborg – Dortmund)

Mini-PEMS (remote data collection via FTP-server)

Distance (km)	956,2
NO_X (mg/km)	127
CO_2 (g/km)	250
FC (l/100 km)	9,45
Ambient temp (C)	-1 to + 17

Figure 41. Driving route from Göteborg to Dortmund with main results in the table above

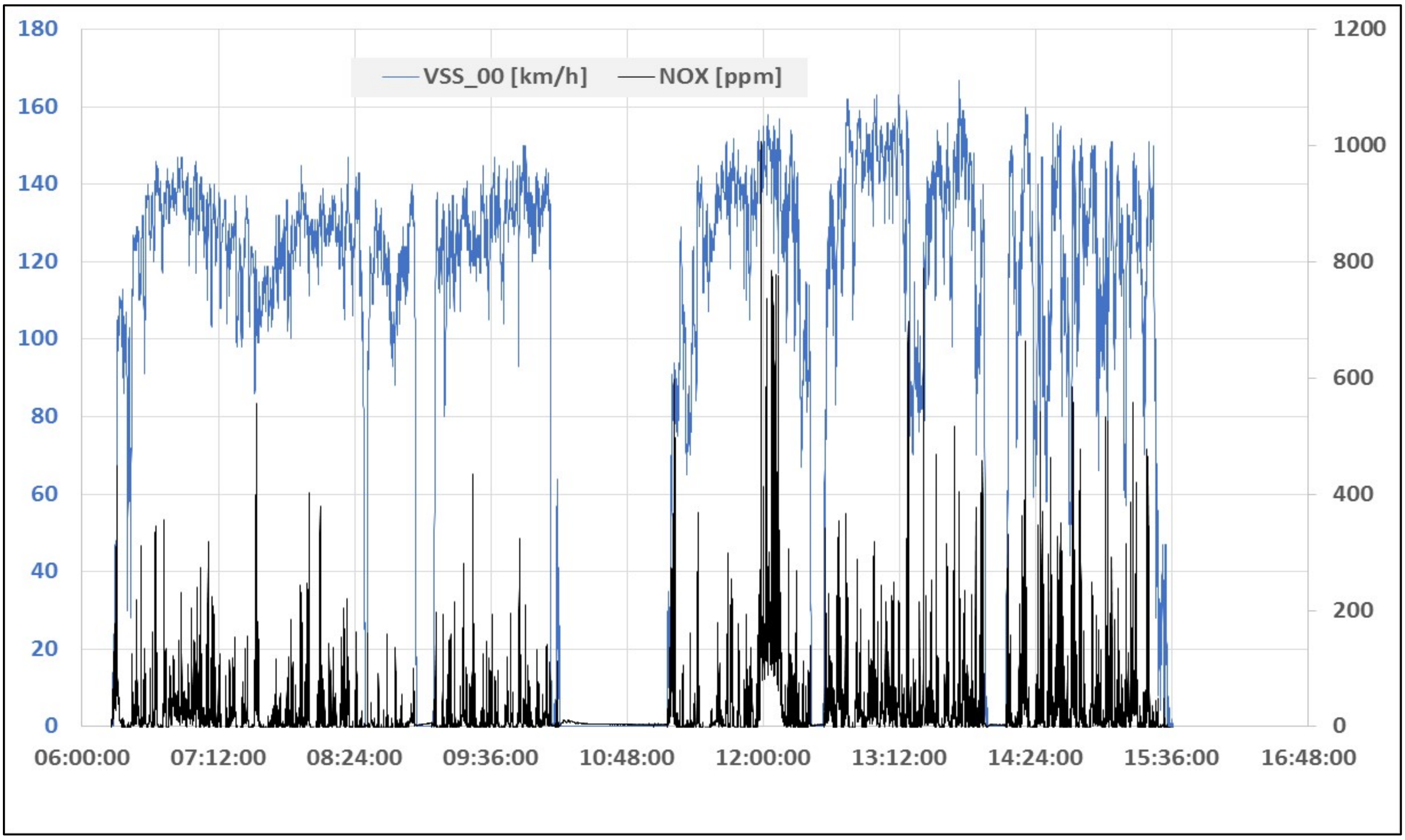


Figure 42. NO_X and speed pattern during the driving from Göteborg to Dortmund

Appendix V – Full reports from Switzerland

Research of Real Driving Emissions (RDE) with E85 and Two Flex Fuel Vehicles (FFV)

and

Research of Real Driving Emissions (RDE) – HEV Toyota Prius III

Swiss contribution to IEA AMF Annex 55

Imprint

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Note:
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The contractor bears sole responsibility for the content.

March 2019 B525

*) Abbreviations see at the end of report

CONTENTS

1. SUMMARY

The control of real driving emissions (RDE) by means of portable emission measuring systems (PEMS) is generally an accepted way to further reduce the air pollution of traffic.
In several research activities with different PEMS open questions resulted concerning the methodology of testing and of evaluation. On the other hand, there are questions about RDE from specific types of vehicles, or alternative fuels.

In the present report, the results of two subjects (working packages) are given:

- emissions of two flex-fuel vehicles (FFV's) with E85 and
- emissions and control strategies of a hybrid electric vehicle (HEV).

E85

Comparisons of emissions obtained with two FFV's with E0 and E85 on chassis dynamometer in $WLTC_{cold}$ and in RDE-circuit confirmed, that the use of E85 fuel is advantageous for emission reduction: with E85 fuel there is a reduction of NO_x and PN for both investigated vehicles in all driving conditions.

HEV

As a typical HEV a Toyota Prius III (Euro5) was investigated on chassis dynamo-meter and on-road. This vehicle offers to the driver the choice between different modes of driving behaviour: "Normal", "Power" or "ECO" and also a limited possibility of electric driving "EV" or battery charging "B".
The present report compares the emissions with different state of charge (SOC) of the batteries pack and with different driving modes. It also gives some insights in the control of strategies (EGR, throttle) of this vehicle.

The most important statements concerning the technology of the investigated HEV are:

- Depending on temperature of batteries and different other parameters the SOC is maintained by the system between approximately 40% and 80%.
- The tested vehicle has very low emissions and fuel consumption and these values are only slightly influenced by different modes, such as SOC, Power, Economy and cold start.
- A rapidly controlled EGR is an important measure to reduce NO_x-emissions in addition to the 3WC-technology and variocam-Atkinson-cycle.
- The engine switching strategy, sometimes lean engine operation and EGR offer very low fuel consumption and low, near-to-zero NO_x-emissions.
- In the real world driving on the RDE-circuit the engine works between 39% and 59% of the total cycle time, with the highest share in driving mode "Power".
- In the driving modes "Power" or "Economy", there are different control strategies of throttle position versus accelerator position, which support the wish of the driver.
- The maximal charging of the battery pack, up to SOC ~80%, is possible only in the operating mode "B".

2. TEST VEHICLES, FUELS AND LUBRICANTS

The vehicles and their data are presented in Fig. 1 and in Table 1.
Vehicles ① and ② are FFV and were used for the tests with E85. Vehicle ③ is a HEV.

Fig. 1 shows the vehicle V1 (Volvo V60 FFV) equipped with PEMS.

Vehicle ① Volvo V60 T4F FFV in the laboratory

Vehicle ② Audi A4

vehicle ③Toyota Prius III

Fig. 1: The tested cars

All vehicles were operated with the Swiss market fuels (also Swiss market E85) and with the lubricating oil, which was actually present in each vehicle.

Vehicle	① **Volvo V60 T4F FFV gasoline**	② **Audi A4 2.0 TFSI FFV gasoline**	③ **Toyota Prius III**
Number and arrangement of cylinder	4 / in line	4 in line	4 in line
Displacement cm³	1596	1984	1798
Power kW	132 @ 5700rpm	132@4000rpm	Total power: 136 hp
Torque Nm	240 @1600rpm	320@1500rpm	Max. torque: 142 Nm
Injection type	Direct Injection (DI)	Direct Injection (DI)	Multipoint injection (MPI)
Curb weight kg	1554	1570	1500
Gross vehicle weight kg	2110	2065	1805
Drive wheel	Front-wheel drive	Front-wheel drive	Front-wheel drive
Gearbox	a6	m6	continuously variable transmission
First registration	2012	2010	2013
Exhaust	EURO 5a	Euro 5	Euro 5b

Table 1: Data of tested vehicles

All vehicles were operated with the Swiss market fuels (also Swiss market E85) and with the lubricating oil, which was actually present in each vehicle.

3. TEST METHODS AND INSTRUMENTATION

3.1. Chassis dynamometer and standard test equipment

- roller dynamometer: AFHB GSA 200
- roller diameter: 502 mm
- driver conductor system: Tornado, version 3.3
- CVS dilution system: Control Sistem R03-700 with roots blower
- air conditioning in the hall automatic for intake- and dilution air
  temperature: 20 ÷ 30°C
  humidity: 5.5 – 12.2. g/kg

3.2. Test equipment for regulated exhaust gas emissions

This equipment fulfils the requirements of the Swiss and European exhaust gas legislation.

- regulated gaseous components:
  exhaust gas measuring system Horiba MEXA-7100
  CO, CO_2… infrared analysers (IR)
  HCFID... flame ionisation detector for total hydrocarbons
  CH_4FID... flame ionisation detector with catalyst for only CH_4
  NO/NO_X... chemoluminescence analyser (CLA)

The dilution ratio DF in the CVS-dilution tunnel is variable and can be controlled by means of the CO_2-analysis.

3.3. PEMS

Most important data of the used PEMS are given in the Table 2. Some pictures of PEMS assembling on the test vehicles are given in annex A1.

GAS PEMS

	HORIBA MEXA 7200	**HORIBA OBS ONE**
	4x4 chassis dyno CVS	PEMS① wet
CO	NDIR	heated NDIR
CO_2	NDIR	heated NDIR
NO_x	CLD	CLD
NO	CLD	CLD
NO_2	calculated	calculated
O_2	-	-
HC	FID	-
PN	not measured	-
OBD logger	-	yes
GPS logger	-	yes
ambient (p, T, H)	yes	yes
EFM	-	pitot tube

OBS - one H_2O monitored to compensate the H_2O interference on CO and CO_2 sample cell heated to 60°C

Table 2: Overview of used measuring systems.

3.4. PN PEMS

In the working package "E85", the PN PEMS for Real Driving Emissions the NanoMet3-PS from Matter Aerosol-TESTO (NM3) was used. The exhaust gas conditioning, as described below for chassis dynamometer, is integrated in this analyzer and it indicates the solid particle number concentration and geometric mean diameter in the size range 10-700 nm.

For the dilution and sample preparation an ASET system from Matter Aerosol was used (ASET … aerosol sampling and evaporation tube). This system contains:

- Primary dilution air - MD19 tunable minidiluter (Matter Eng. MD19-2E)
- Secondary dilution air – dilution of the primary diluted and thermally conditioned measuring gas on the outlet of evaporative tube.
- Thermoconditioner (TC) - sample heating at 300°C.

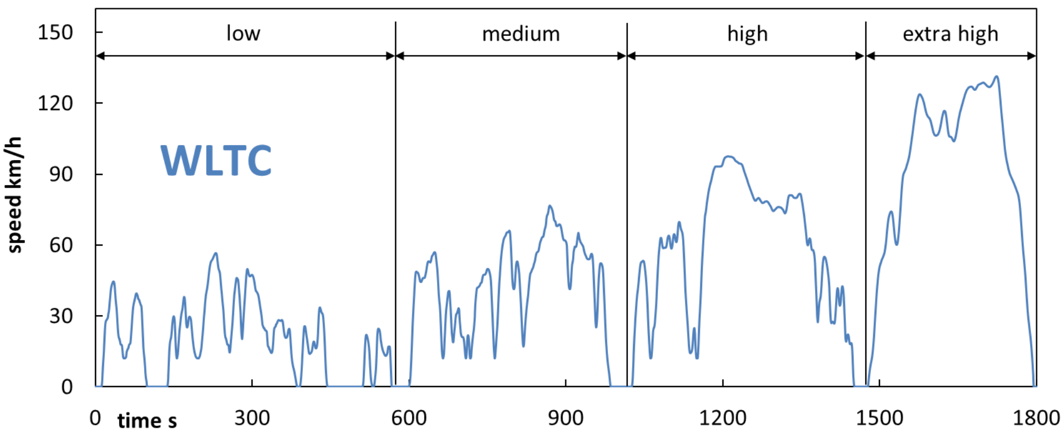
As PN PEMS for Real Driving Emissions in the working package "HEV", the Horiba OBS-ONE-PN PEMS was used. This system has two-step dilution, a catalytic volatile particle remover (350°C) and a Isopropanol-based CPC as a main measuring unit.

4. TEST PROCEDURES

The measurements were performed on chassis dynamometer in $WLTC_{cold}$, $NEDC_{cold}$ and on-road in a circuit, which is valid for RDE-requirements. The chronological overview of the performed test series is tabulated in annex A2.

4.1. Driving cycles on chassis dynamometer

The vehicles were tested on a chassis dynamometer in the dynamic driving cycles WLTC and NEDC, Fig. 2. The braking resistances were set according to legal prescriptions.



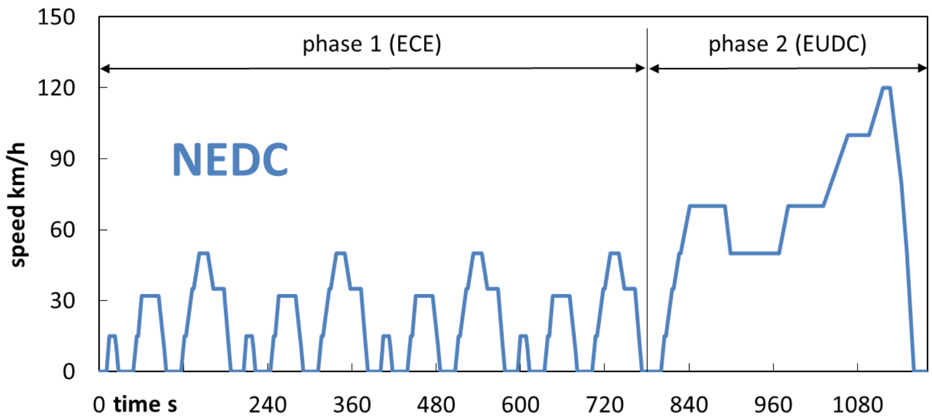


Fig. 2: Driving cycles WLTC and NEDC

4.2. On-road testing

Several road tests were performed with the test vehicle. The used road circuit was always the same, with approximately 1.5h duration and parts of urban, rural and highway roads, see annex A3.

Fig.3 shows an example of a driving cycle from the road circuit (RDE).

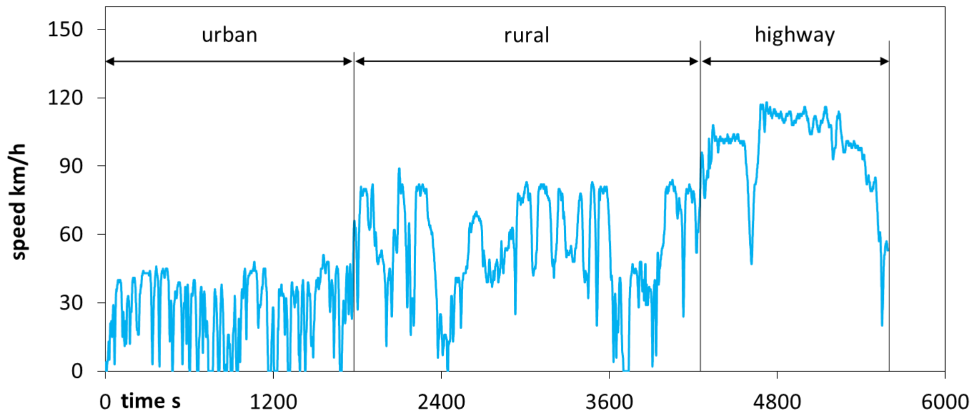


Fig. 3 Example of RDE cycle

5. RESULTS

The results are graphically represented in the attached figures.

5.1. Comparison of emissions with E0 & E85

The comparisons can be regarded from different points of view:

- Influence of fuel E0 – E85
- Influence of vehicle V1 – V2
- Measuring method on chassis dynamometer Bags (CVS) – PEMS
- WLTC – RDE

Fig. 4 represents the comparisons of NO_x, CO and CO_2 in $WLTC_{cold}$.
It can be stated that:

- NO_x is generally reduced with E85,
- for V1 NO_x diminishes stronger (with E85), than for V2,
- NO_x is in most cases underestimated with PEMS (relatively to CVS),

- CO is not influenced by E85 for V1, but CO is reduced with E85 for V2,
- V2 has higher level of CO than V1,
- the measuring method (CVS – PEMS) has nearly no influence on CO,

- CO_2 is normally decreased with E85,
- V2 has lower level of CO_2,
- the influences of measuring method (CVS – PEMS) are different and many of them opposite to each other; as average no tendency can be declared.

The cumulated emissions increase strongly in the last high-speed-phase of the cycle. In certain cases, cold starts or acceleration events contribute highly (or in majority) to the cumulated emission results.

Fig. 5 shows the gaseous emissions in road operation (RDE).

The tendencies depicted here are similar as in WLTC:
- E85 instead of E0: reduces NO_x, has no influence on CO and only slight reducing tendency on CO_2 for V2,
- Both vehicles attain similar levels of emissions at the end of RDE cycle, while the dispersion of results for each vehicle/fuel variant is much larger than on the chassis dynamometer (in WLTC).

Figures 6 and 7 confirm in $WLTC_{cold}$ and in RDE-circuit that E85 reduces the PN emissions of both vehicles in similar way. The PN emissions with E0 are for both vehicles at the same level.

Fig. 8 compares the fuel consumption measured with both fuels E0 & E85 on chassis dynamometer in $WLTC_{cold}$ with both sets of instruments (BAGS & PEMS). At the bottom of this figure, there are comparisons of fuel consumption measured in the road circuits (RDE) with PEMS.
It can be remarked, that the volumetric fuel consumption with E85 is generally higher, due to the lower heat value of this fuel. The results obtained with BAGS (CVS) and with PEMS on chassis dynamometer correlate well with each other. There is a stronger dispersion of the results from the RDE-circuit, than from chassis dynamometer.

5.2. Emissions overview and comparisons of HEV

The results are graphically represented in the attached figures (part HEV) and in annexes.
The logical sequence of representation is:

4 WLTC cold with SOC low 1 WLTC cold with SOC high 1 NEDC cold with SOC low	chassis dynamometer
3 RDE warm with SOC low 1 RDE cold with SOC low 1 RDE warm with SOC low, mode "Eco" 1 RDE warm with SOC low, mode "Power" 1 RDE warm with SOC high	on-road circuit

In addition to PEMS/RDE several parameters, like: vehicle speed, engine speed, coolant temperature, battery SOC, load factor, EGR control and Lambda are registered from the engine ECU.

5.2.1 Comparison CVS vs. PEMS

Fig. 4 (in attachment) represents the comparison of results obtained on chassis dynamometer with PEMS and with the stationary measuring system (CVS/bags). It can be remarked that PEMS indicates higher CO_2-values and consequently higher fuel consumption (f.c.) and it indicates lower readings of NO_x and CO, comparing to the values from CVS/bags. The emissions of NO_x and CO are for this vehicle very low, so the differences PEMS-CVS can be regarded as insignificant.

5.2.2 Repeatability of results

Several WLTC with cold start were repeated. The cycles with SOC_{low} (Fig. 4) show (except of the 1st cycle) very equal results of NO_x and CO and they can be declared as very well repeatable. The reason of higher emissions in the 1st cycle is not clear, but the difference of vehicle conditioning is supposed (remember, that the absolute emission differences are very small).

Fig. 5 shows the results from the performed RDE-tests. Regarding the first three cycles with "SOC_{low}, warm start" also a good repeatability of results can be stated.

5.2.3 Influence of SOC

The state of charge (SOC) of the batteries pack of this vehicle is indicated by the OBD. Depending on temperature of batteries and different other parameters the SOC is maintained by the system between approximately 40% and 80%.
The lowest SOC can be caused by driving the vehicle in electric (E) mode up to the point when the engine is started. The highest SOC can be obtained by motoring the vehicle on the chassis dynamometer (CD). After performing the driving cycles, the final SOC results in the range of about 60%. With higher SOC the probability of electric driving and the frequency of engine switch off/on increase. The effect of this is visible in WLTC (Fig. 4), where the test with "SOC_{high}" indicates lower CO_2 and lower fuel consumption. The emission of CO is tendentially higher than the average of cycles with "SOC_{low}". Nevertheless, the differences are small, and they are in the dispersion range of the repeated cycles with "SOC_{low}". In RDE-tests (Fig. 5), there is no tendency of lower fuel consumption with "SOC_{high}", this, because the higher SOC influences mostly the urban driving, which represents only a part of the cycle. CO-values with "SOC_{high}" are similar to the values with "SOC_{low} cold start" and they are at the upper limit of the dispersion range.

5.2.4 Further tendencies

Fig. 6 represents the cumulated emissions over the distance in all performed RDE-tests. This representation supplements the Fig. 5. It can be remarked, that the cold start is the mayor reason for the increased NO_x-emissions (still the absolute values of NO_x are very low). The CO-emissions with cold start are on the upper limit of the dispersion range of all cycles. The use of driving mode "Power" (+P) shows the tendency of higher fuel consumption, but the emissions are in the usual dispersion range of all cycles. Driving in mode "Economy" (+E) does not cause any particular differences.
Finally, it can be said that this tested vehicle has very low emissions and fuel consumption and that these values are only slightly influenced by different modes, such as SOC, Power, Economy and cold start.

5.3. Technical details of some control strategies of HEV

5.3.1 EGR and NO_x- control

The strategy of Toyota uses the EGR as an important measure to reduce NO_x-emissions in addition to the 3WC-technology and use of variocam-Atkinson-cycle. The EGR-valve is electrically driven, which enables a quick and precise control.

Fig. 7 shows the functionality of EGR-valve opening in the initial phase of the RDE-test with cold start. During the warm-up (first 1.2 km) EGR stays closed. After that it is controlled according to the events with running engine and with higher engine load, with lean operation. The lean Lambda-excursions, when the 3WC cannot reduce NO_x, result from engine switching off/on. The engine speed zero-value indicates, that the engine is switched-off quite often.
The engine switching strategy, sometimes lean engine operation and EGR offer very low fuel consumption and low, near-to-zero NO_x-emissions.
The openings of EGR-valve coincide in most cases with the peaks of CO & PN.

5.3.2 Considerations of city part

Fig. 8 compares the urban parts of two RDE-test with cold and with warm start. Even if the "cold start" was not quite cold (engine coolant temperature at 40°C), the catalyst temperature and batteries SOC at start were equal, the influence of the cold start on the emission results was significant. The cumulated values of all measured toxic compounds (NO_x, CO and PN) were increased with the cold start.

Fig. 9 represents the vehicle and engine stops in the urban part of the RDE-test with cold start. The table at the bottom of this figure informs about the vehicle- and engine stops in the other RDE-cycles (urban parts) with different operating modes: Eco, Power and SOC_{high}.
It can be concluded that the vehicle stops, in the urban part of RDE-test, are in the range between 10% and 15% of the total cycle time and the engine works between 39% and 59% of the total cycle time. In the operating mode "Power", there is the highest portion of the "engine on time".

5.3.3 Positions of accelerator vs. throttle

Fig. 10 shows the correlations of throttle positions and accelerator positions for different modes of vehicle operation. These values are extracted from the OBD. It can be commented that in the mode "Eco", more accelerator pedal action is necessary to obtain a certain opening of the throttle valve. Inversely, in the mode "Power", the throttle opening reacts more sensibly on the accelerator positions. It can be concluded that this way of throttle control underlines or supports the subjective attitude of the driver.

5.3.4 Battery pack charging

Tests of battery pack charging were performed by means of motoring the vehicle on chassis dynamometer.
Two tests were driven in mode "D" (normal driving) and one test in mode "B" (braking, battery charging).

Fig. 11 represents the used speed profile, the resulting engine speeds and SOC. In mode "B", the charging progress is much quicker and the engine speed is stronger increased to promote the charging. In mode "D", the battery charging is slower and when SOC attains c.a.50% the engine is stopped and due to the motoring (by CD) the SOC continues to increase slowly.

By the attempts of discharging the battery pack on CD, it was observed that at SOC around 40% the engine is automatically started to recharge the batteries and attaining nearly SOC 50% the engine switch-off and the electric driving are again enabled.
The SOC of this vehicle can vary between 40% and 80%.

6. CONCLUSIONS

Following conclusions can be mentioned:

E0 & E85

- The use of E85 fuel is advantageous for emission reduction: with E85 there is reduction of NO_x and PN for both investigated vehicles in all driving conditions.
- The volumetric fuel consumption with E85 is generally higher, due to the lower heat value of this fuel.
- Both vehicles attain similar levels of emissions at the end of RDE cycle, while the dispersion of results for each vehicle/fuel variant is much larger than on the chassis dynamometer (in WLTC).

HEV

- There is a good repeatability of results obtained with PEMS on the chassis dynamometer and on-road.
- Depending on temperature of batteries and different other parameters the SOC is maintained by the system between approximately 40% and 80%.
- The tested vehicle has very low emissions and fuel consumption and these values are only slightly influenced by different modes, such as SOC, Power, Economy and cold start.
- There are: higher CO- and NO_x-emissions at cold start and higher fuel consumption in the driving mode "Power".
- A rapidly controlled EGR is an important measure to reduce NO_x-emissions in addition to the 3WC-technology and variocam-Atkinson-cycle.
- The engine switching strategy, sometimes lean engine operation and EGR offer very low fuel consumption and low, near-to-zero NO_x-emissions.
- The openings of EGR-valve cause often CO- and PN-peaks.
- In the real world driving on the RDE-circuit the engine works between 39% and 59% of the total cycle time, with the highest share in driving mode "Power".
- In the driving modes "Power" or "Economy", there are different control strategies of throttle position versus accelerator position, which support the wish of the driver.
- The maximal charging of the battery pack, up to SOC ~80%, is possible only in the operating mode "B".
- The evaluation with MAW (EMROAD) shows for this vehicle higher CO- and PN- and lower NO_x-values than the evaluation with integral method. Nevertheless, this can vary depending of the driving dynamics and respective instantaneous emission values.

7. LIST OF FIGURES

Figures in text:

E0 & E85

HEV

8. ANNEXES

9. ABBREVIATIONS

AFHB	Abgasprüfstelle FH Biel, CH
ASTRA	Amt für Strassen (CH)
BAFU	Bundesamt für Umwelt, (Swiss EPA)
BC	board computer
CADC	Common Artemis Driving Cycle
CAST	Combustion Aerosol Standard
CD	chassis dynamometer
CLA	chemiluminescence analyser
CLD	chemiluminescence detector
CPC	condensation particle counter
CVS	constant volume sampling
DAQ	data acquisition
DC	diffusion charging
DF	dilution factor
DI	Direct Injection
DiSC	diffusion charge size classifier
E0	gasoline (zero Ethanol)
E85	85% vol Ethanol
EC	European Commission
ECE	Economic Commission Europe
ECU	electronic control unit
EFM	exhaust flow meter
EMPA	Eidgenössische Material Prüf- und Forschungsanstalt
EMROAD	RDE emissions evaluation program
ETC	European Transient Cycle

EUDC	Extra Urban Driving Cycle
GDI	gasoline direct injection
GMD	geometric mean diameter
HC	unburned hydrocarbons
ILCE	Inter- Laboratory-Comparison-Exercise
INT	integral average values
JRC	Joint Research Centre (EC)
LFE	laminar flow element
MAW	moving averaging windows
MFS	mass flow sensor
NEDC	New European Driving Cycle (ECE+EUDC)
NM3	NanoMet3
NO	nitrogen monoxide
NO_2	nitrogen dioxide
N_2O	nitrous oxide
NO_x	nitric oxides
n.v.	non valid
OBD	on-board diagnostics
OP	operating point
PCRR	Particulate Counts Reduction Rate
PEMS	portable emission measuring systems
PF	Pitot flow meter
PMP	EC Particle Measuring Program
PN	particle number
PN-PEMS	PEMS with PN measuring device
RDE	real driving emissions
TFZ	Technologie- und Förderzentrum für Nachwachsende Rohstoffe, Straubing, D
TP	tailpipe
TWC	three way catalyst
V1	vehicle 1
V2	vehicle 2
ViPR	nanoparticle sample preparation with volatile particles remover
WLTC	worldwide harmonized light duty test cycle
WLTP	worldwide harmonized light duty test procedure
3WC	three way catalyst

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Research of Real Driving Emissions (RDE) with E85 and Two Flex Fuel Vehicles (FFV)

Commissioned by the Federal Office for the Environment (FOEN)
Project BAFU (ResRDE)*), contract nbr: 15.0002. PJ/Q223-0515, 5th report

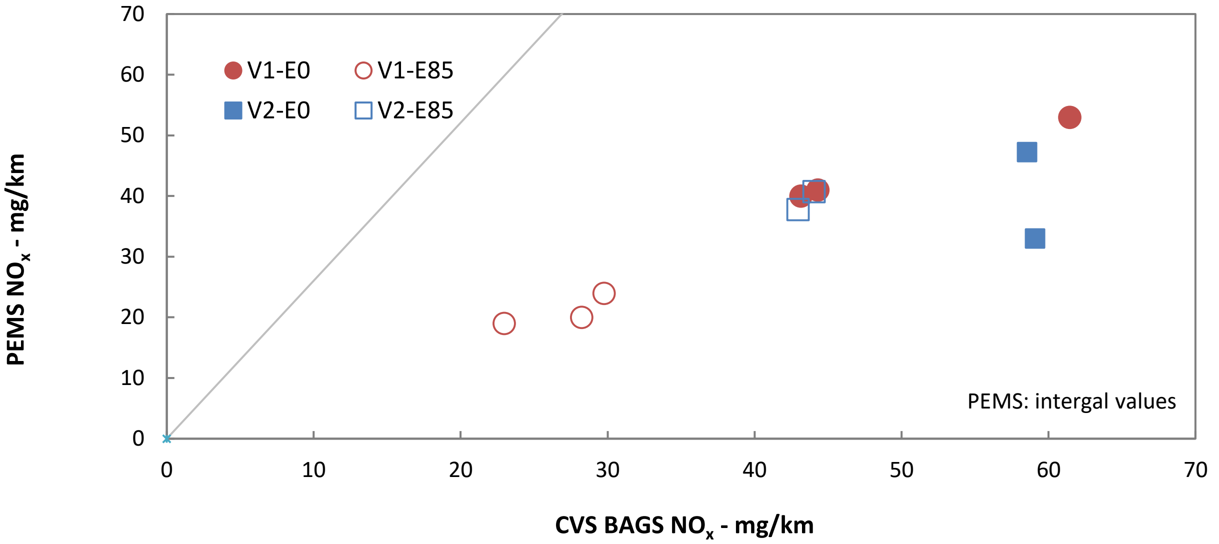
Figures

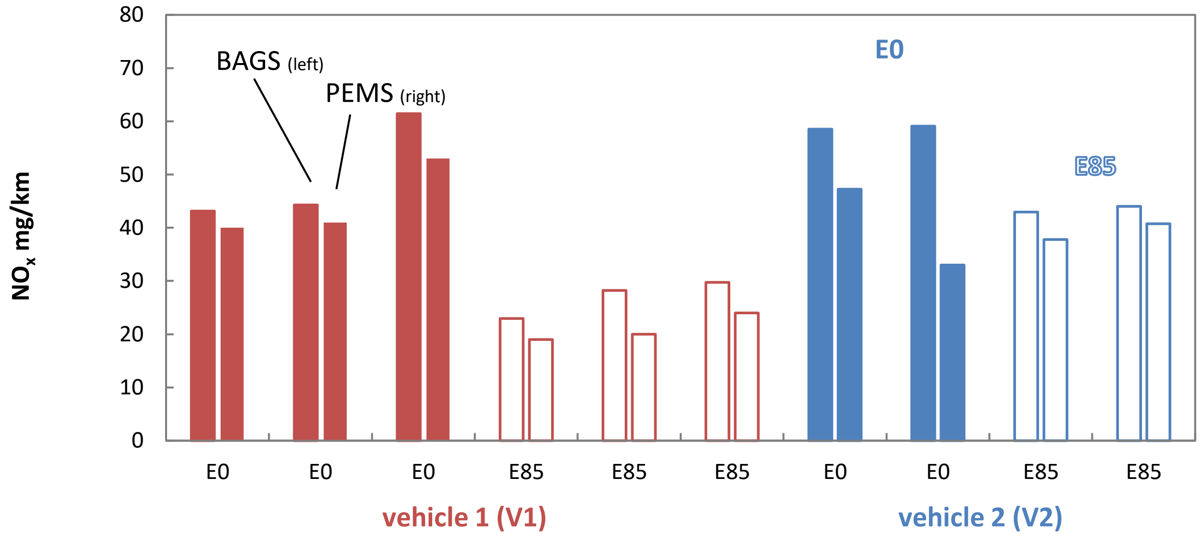
November - December 2017 B501

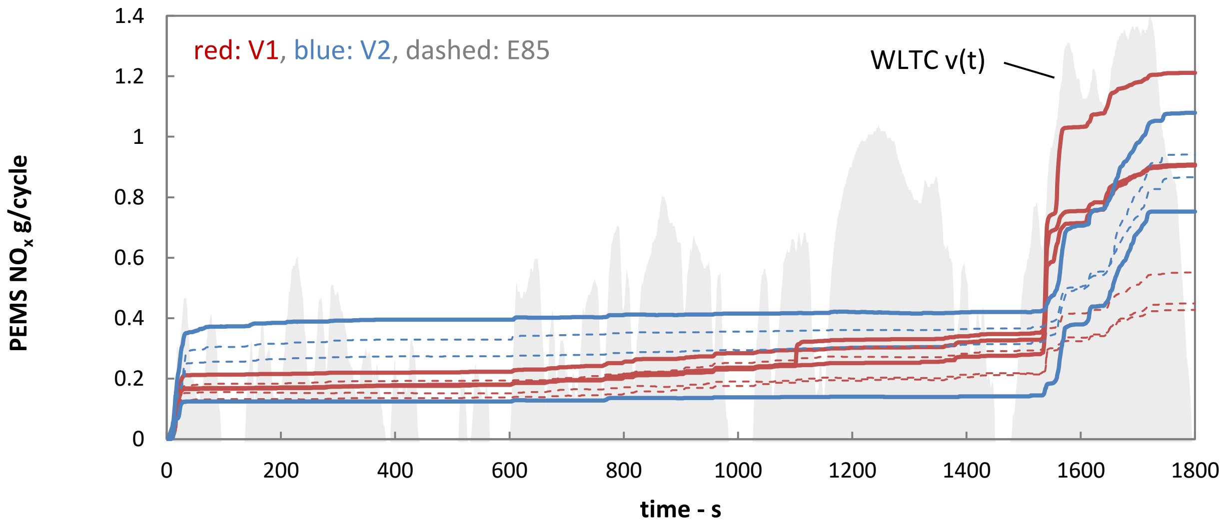
Chassis Dynamometer Measurements

NO_x - Emissions in WLTC cold with E0 and E85

Volvo V60 Flexfuel (V1); Audi A4 Flexifuel (V2)



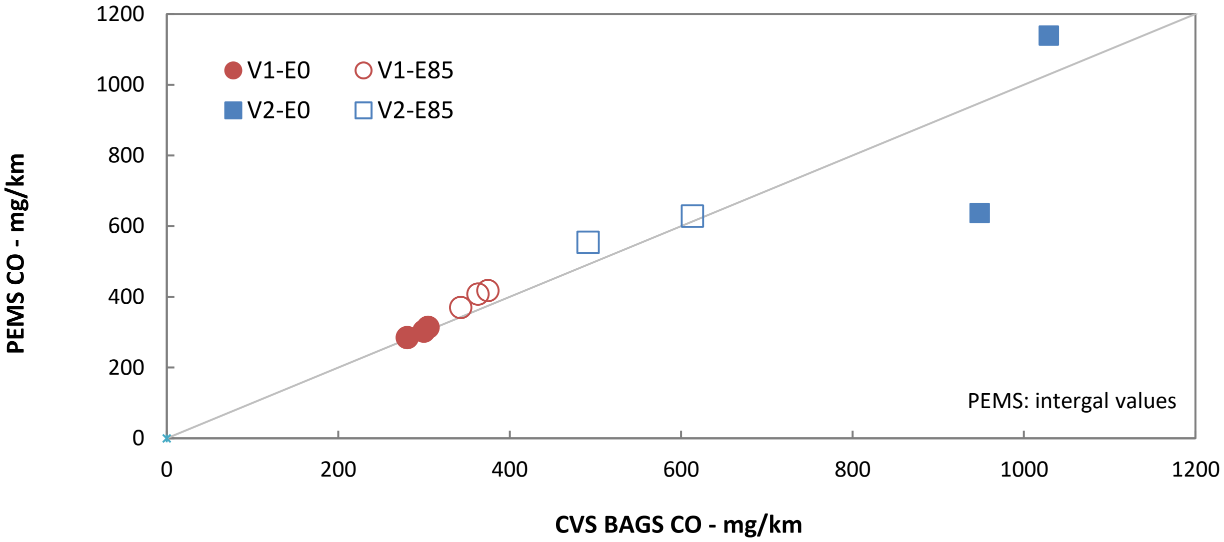


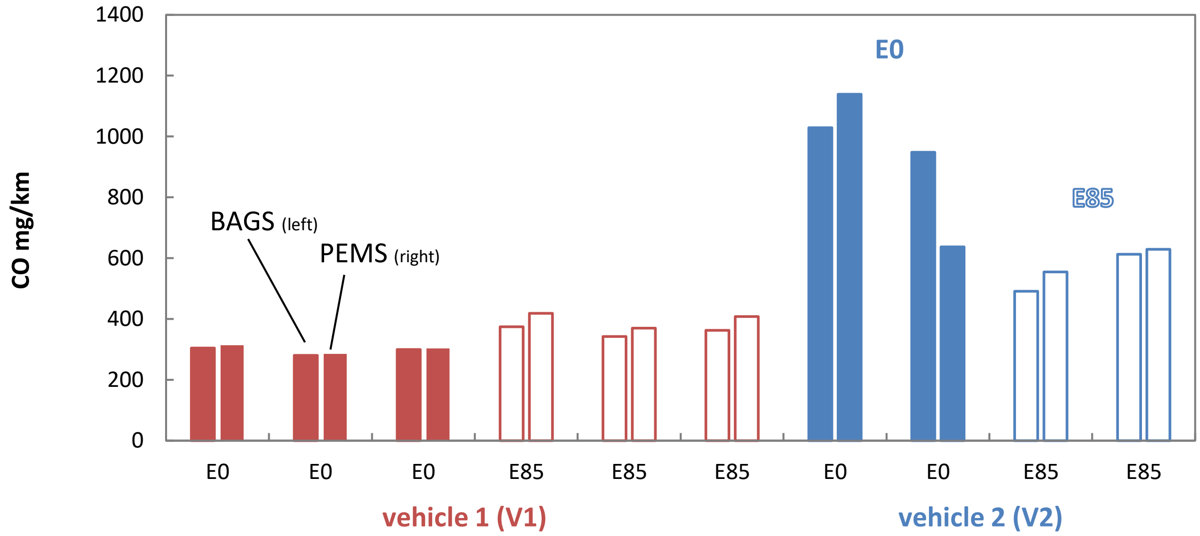


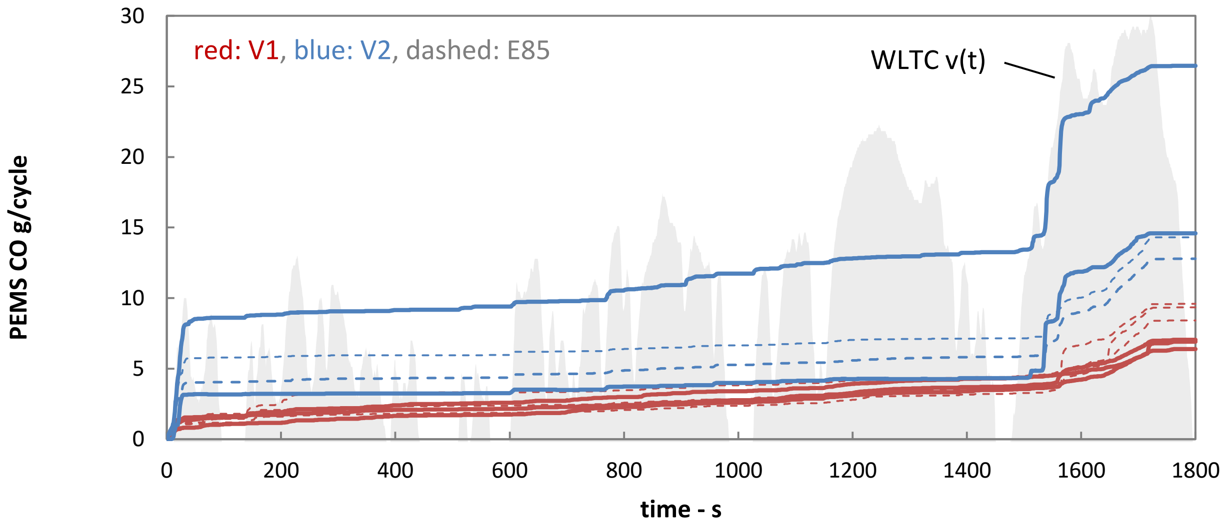
Chassis Dynamometer Measurements

CO - Emissions in WLTC cold with E0 and E85

Volvo V60 Flexfuel (V1); Audi A4 Flexifuel (V2)



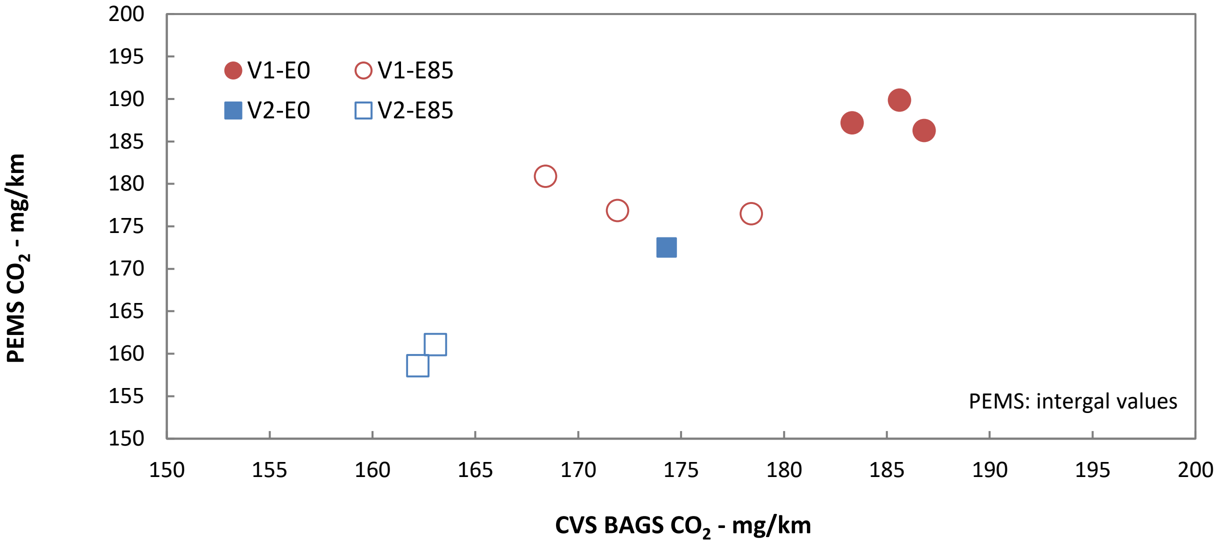


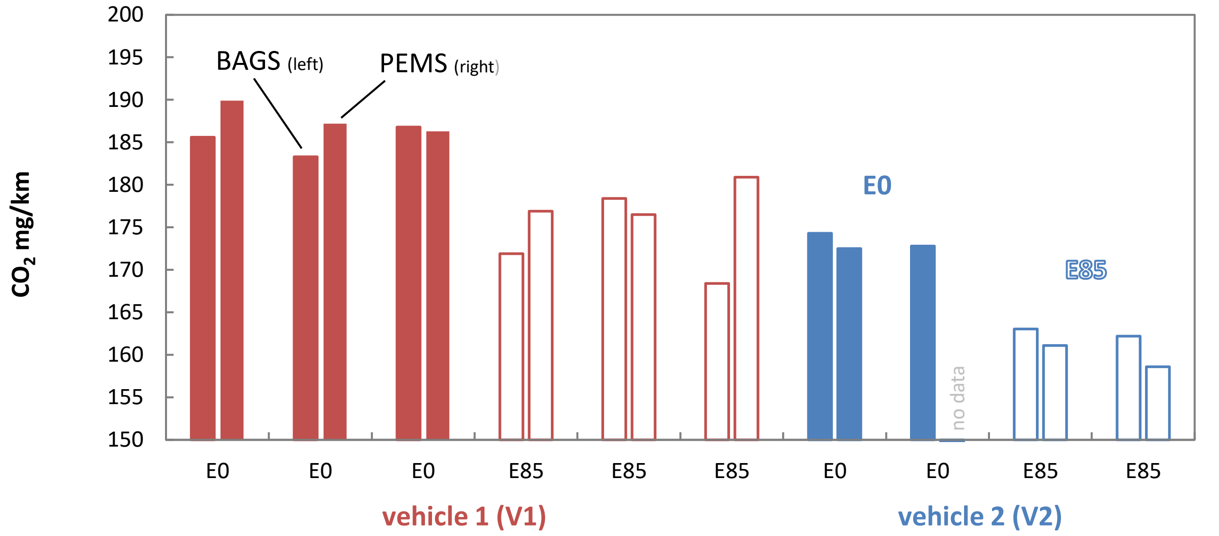


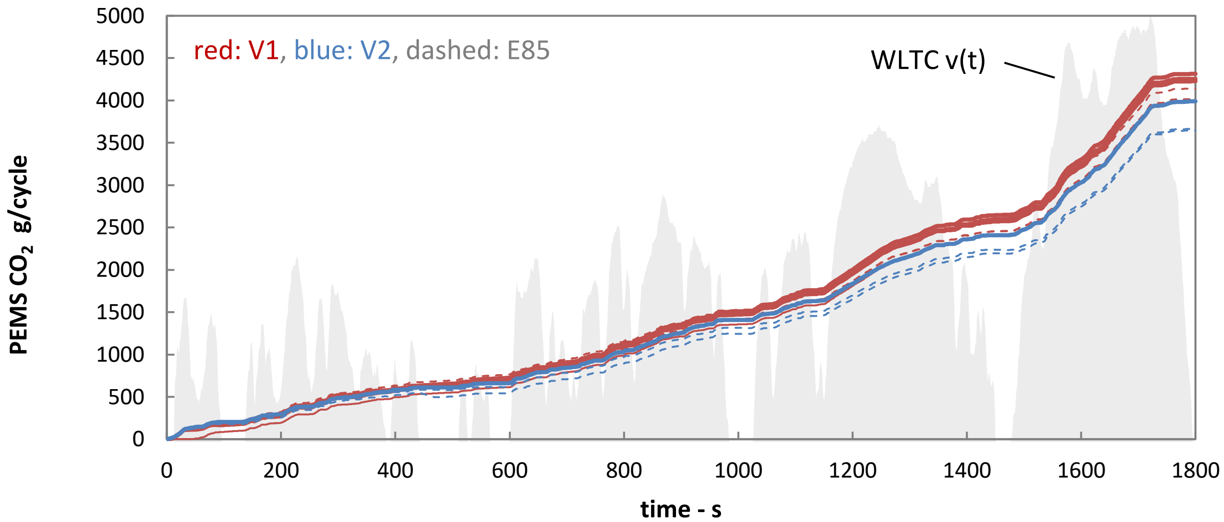
Chassis Dynamometer Measurements

CO_2 - Emissions in WLTC cold with E0 and E85

Volvo V60 Flexfuel (V1); Audi A4 Flexifuel (V2)



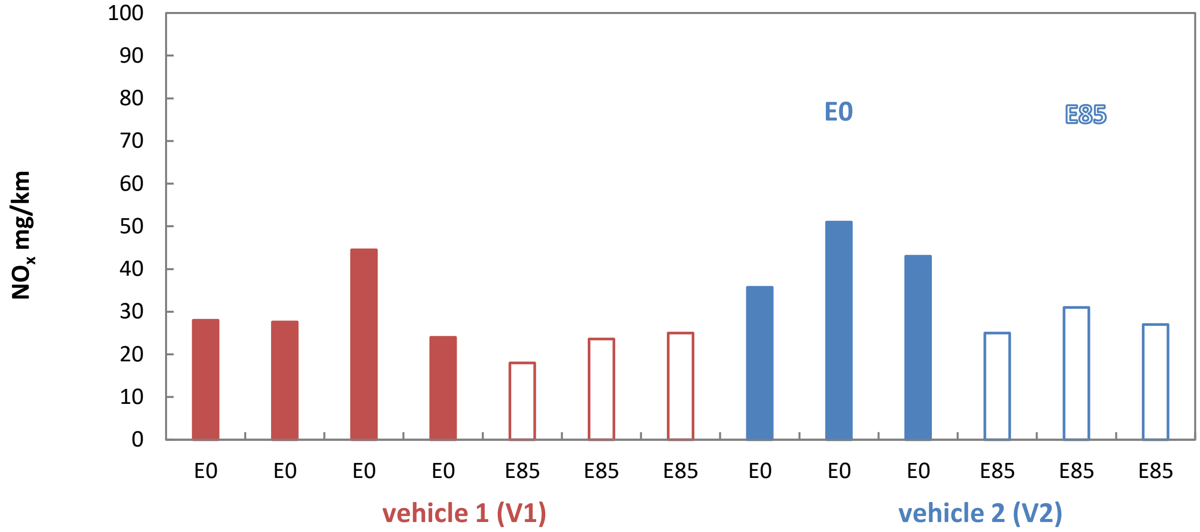


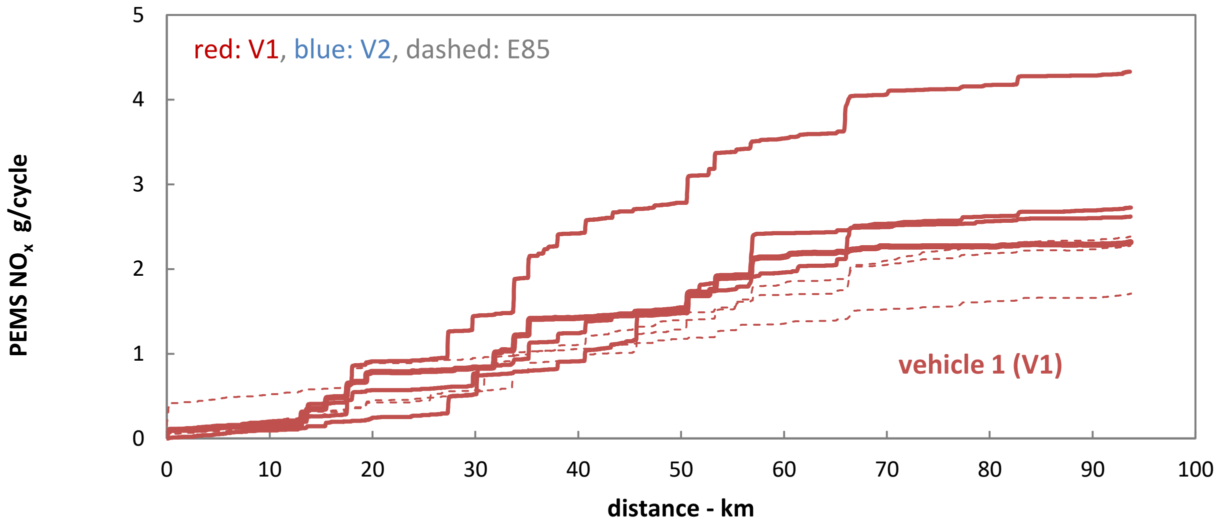


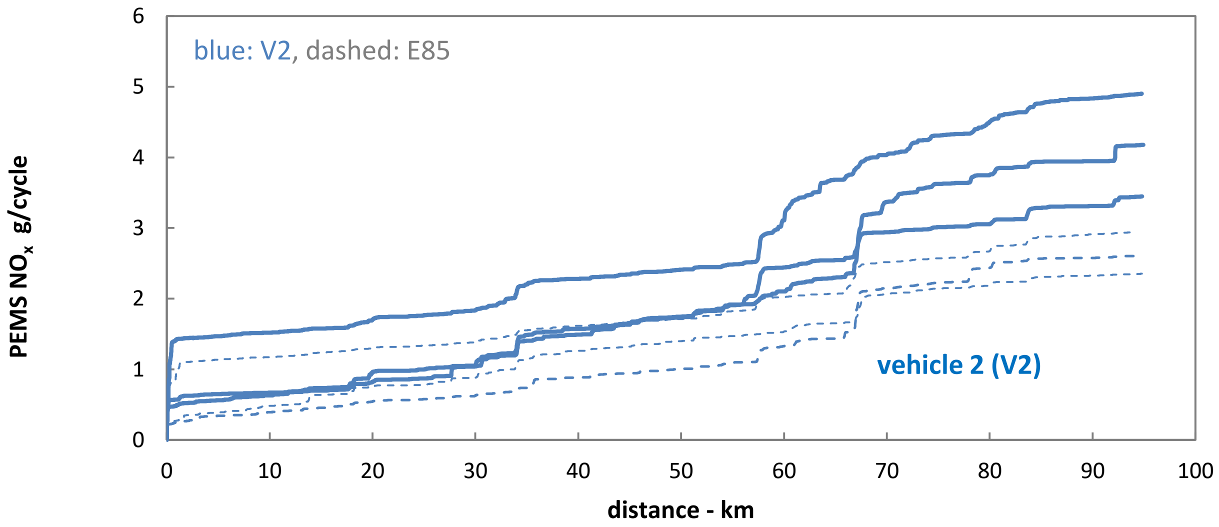
On-Road Measurements

NO_x - Emissions during RDE with E0 and E85

Volvo V60 Flexfuel (V1); Audi A4 Flexifuel (V2)



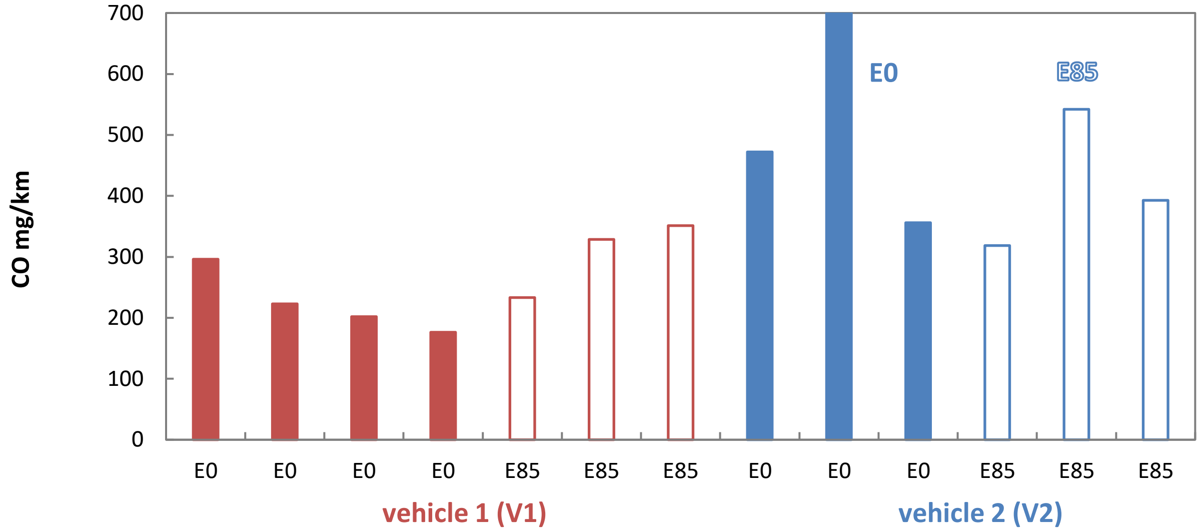


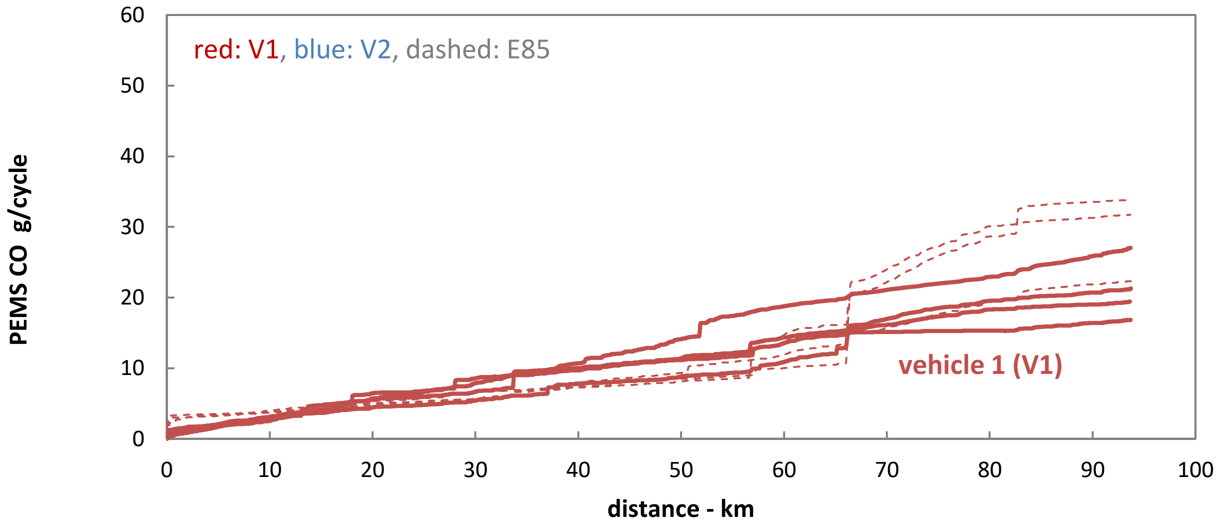


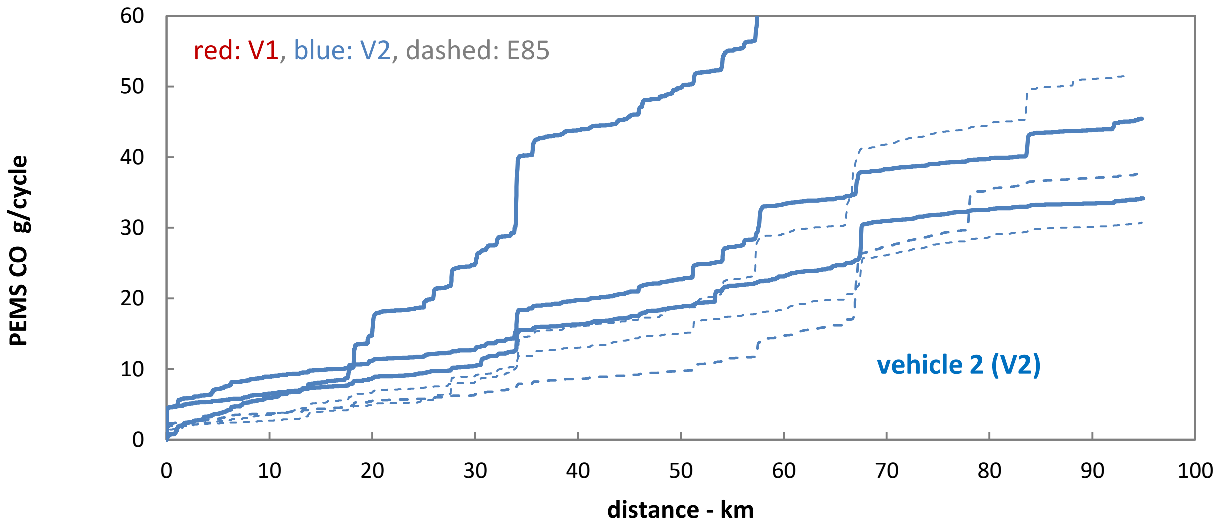
On-Road Measurements

CO - Emissions during RDE with E0 and E85

Volvo V60 Flexfuel (V1); Audi A4 Flexifuel (V2)



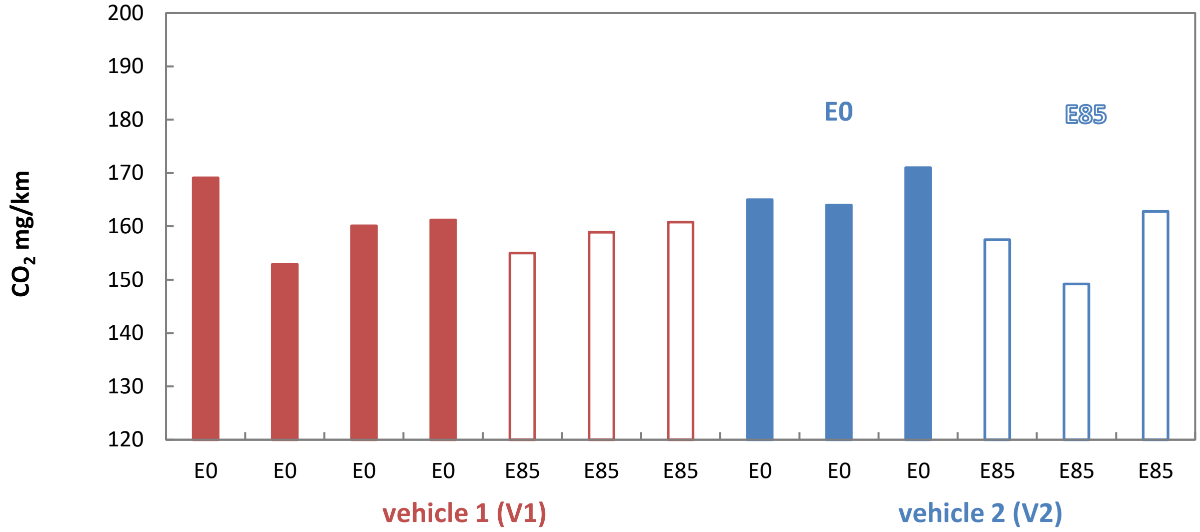


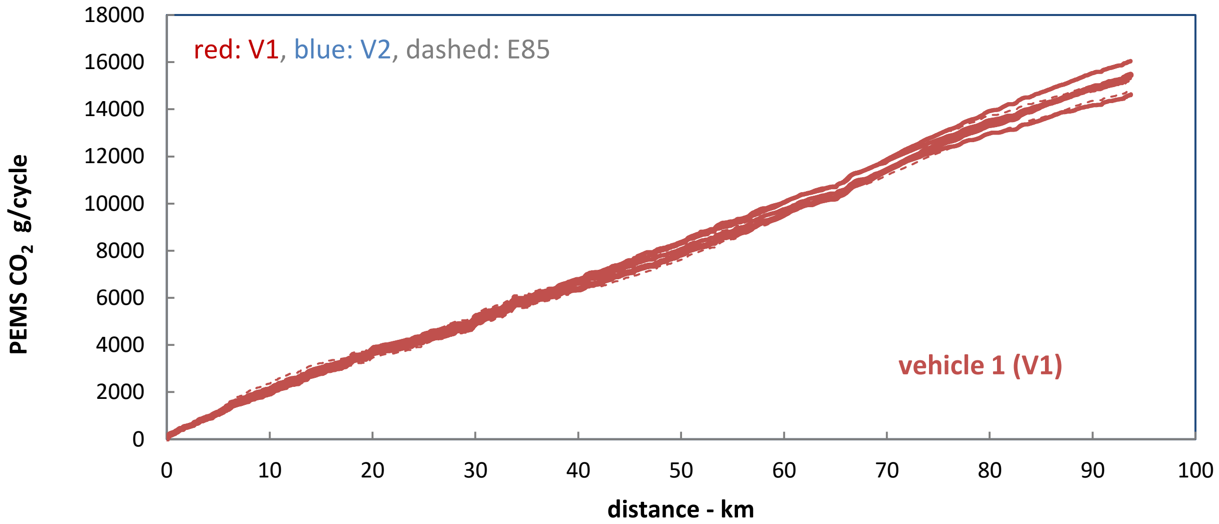


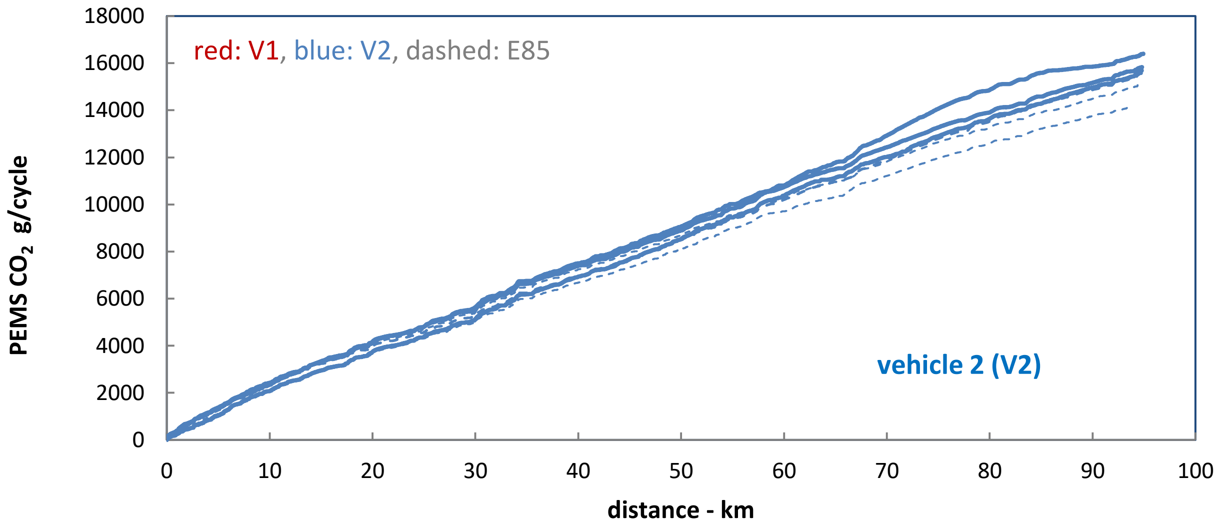
On-Road Measurements

CO_2 - Emissions during RDE with E0 and E85

Volvo V60 Flexfuel (V1); Audi A4 Flexifuel (V2)



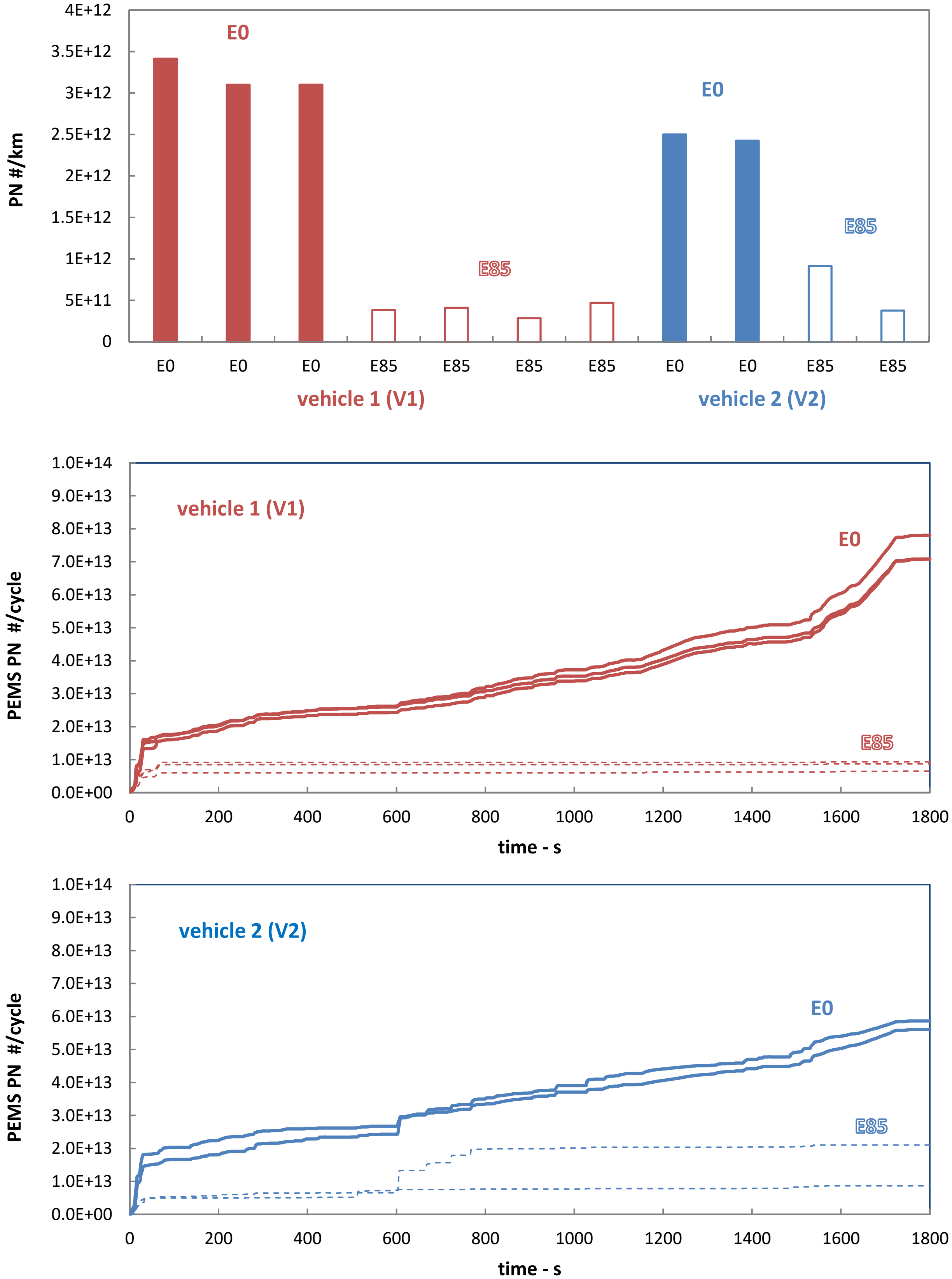




Chassis Dynamometers Measurements

PN - Emissions during WLTC cold with E0 and E85

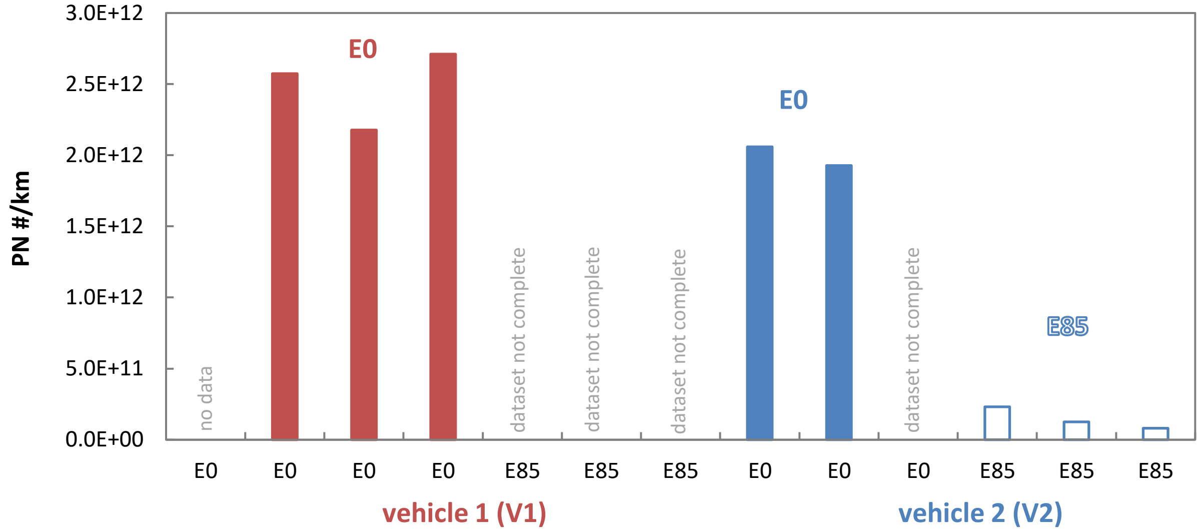
Volvo V60 Flexfuel (V1); Audi A4 Flexifuel (V2)

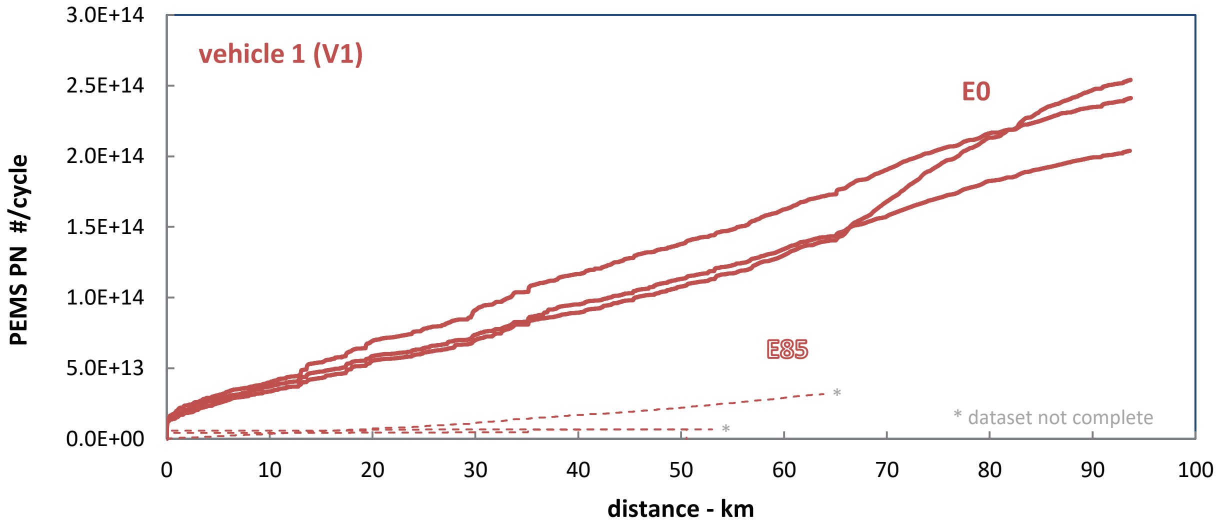


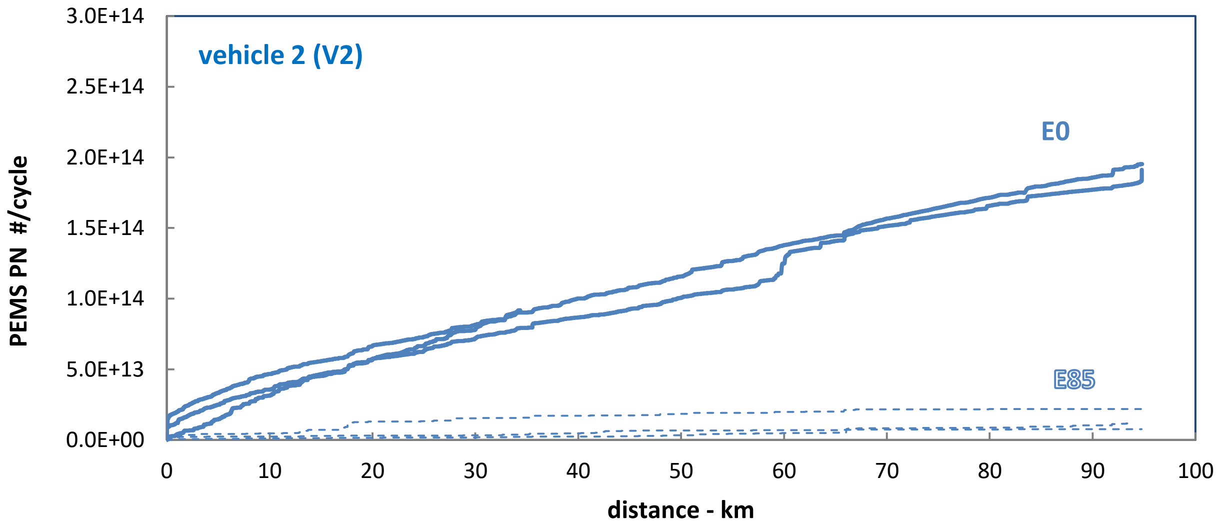
On-Road Measurements

PN - Emissions during RDE with E0 and E85

Volvo V60 Flexfuel (V1); Audi A4 Flexifuel (V2)



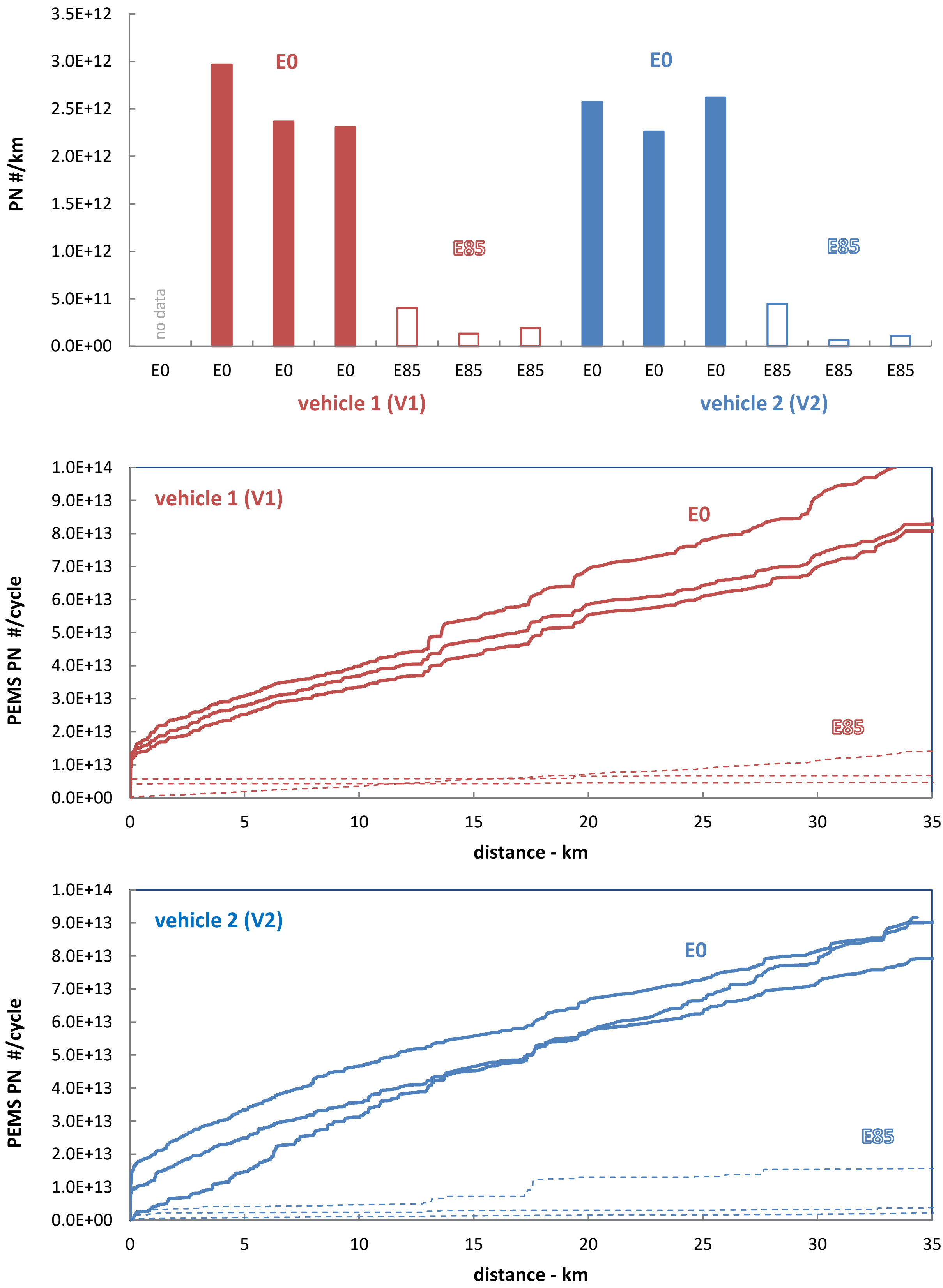




On-Road Measurements

PN - Emissions during RDE urban part with E0 and E85

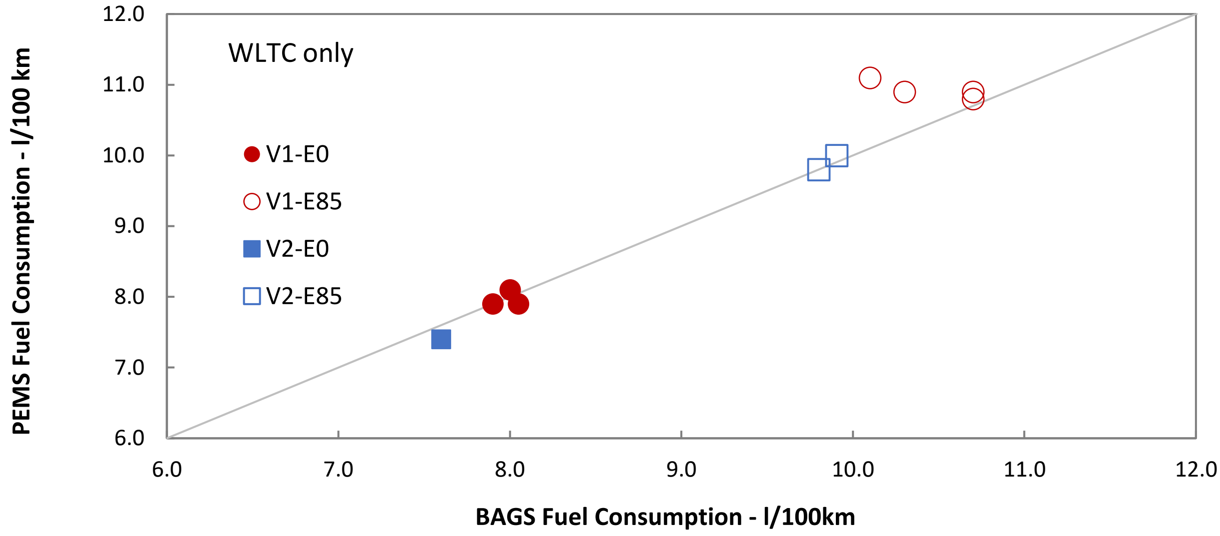
Volvo V60 Flexfuel (V1); Audi A4 Flexifuel (V2)

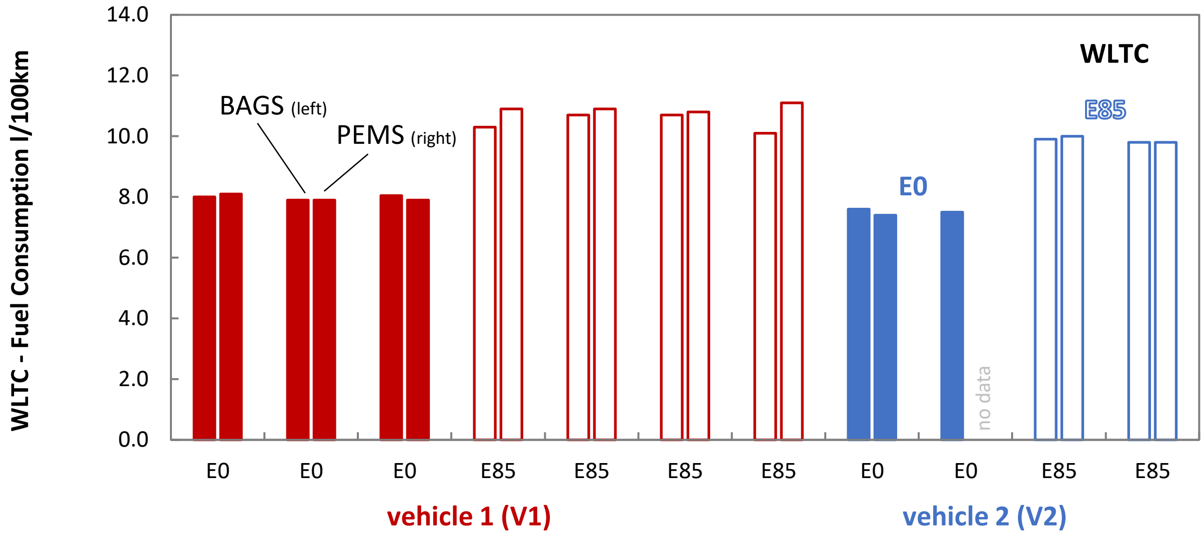


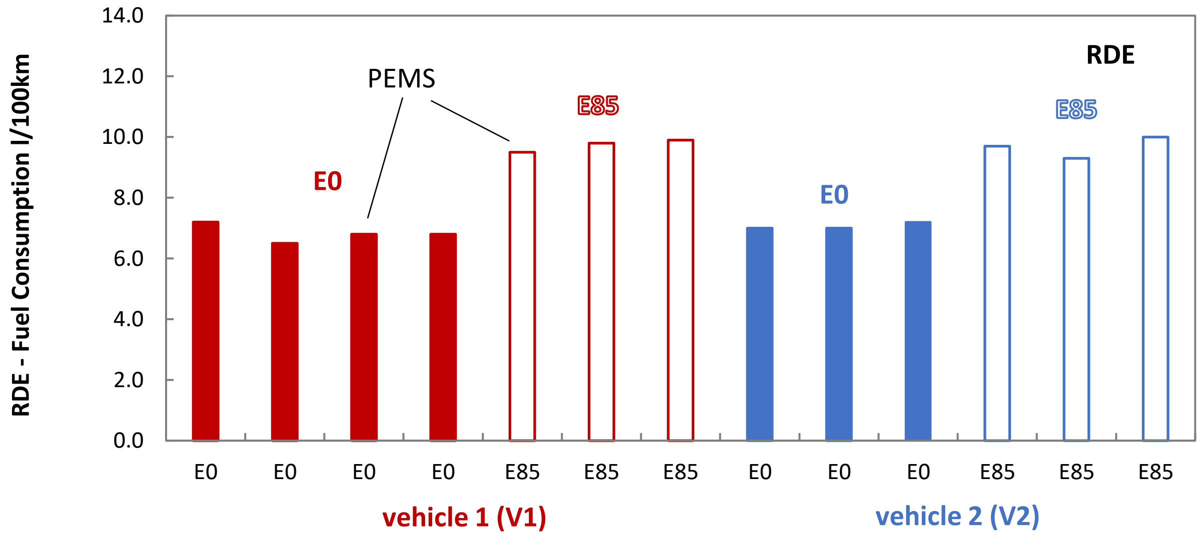
Chassis Dynamometer & On-Road Measurements

Fuel Consumption Averages for WLTC Cold and RDE with E0 and E85

Volvo V60 Flexfuel (V1); Audi A4 Flexifuel (V2)







B501_Fig08_ResRDE_Fuel_consumption

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Research of Real Driving Emissions (RDE) – HEV Toyota Prius III

Commissioned by the Federal Office for the Environment (FOEN)

Project BAFU (ResRDE)*), contract nbr: 15.0002. PJ/Q223-0515, 5th report

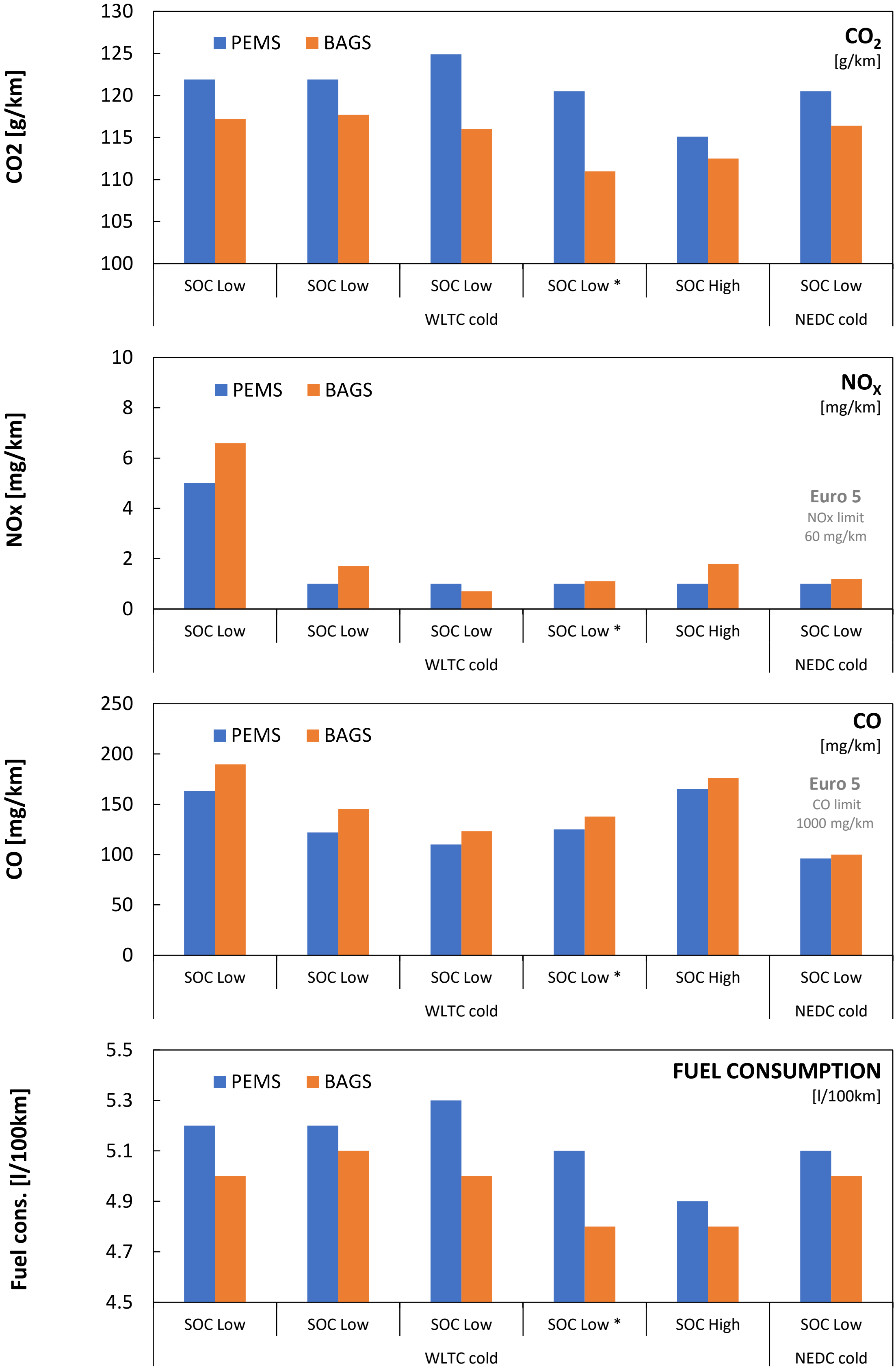
Figures

October - November 2018 B519

Comparison of Emissions Measured with CVS and PEMS on Chassis Dynamometer

MEXA 7200 | HORIBA OBS One

Toyota Prius III / HEV Gasoline

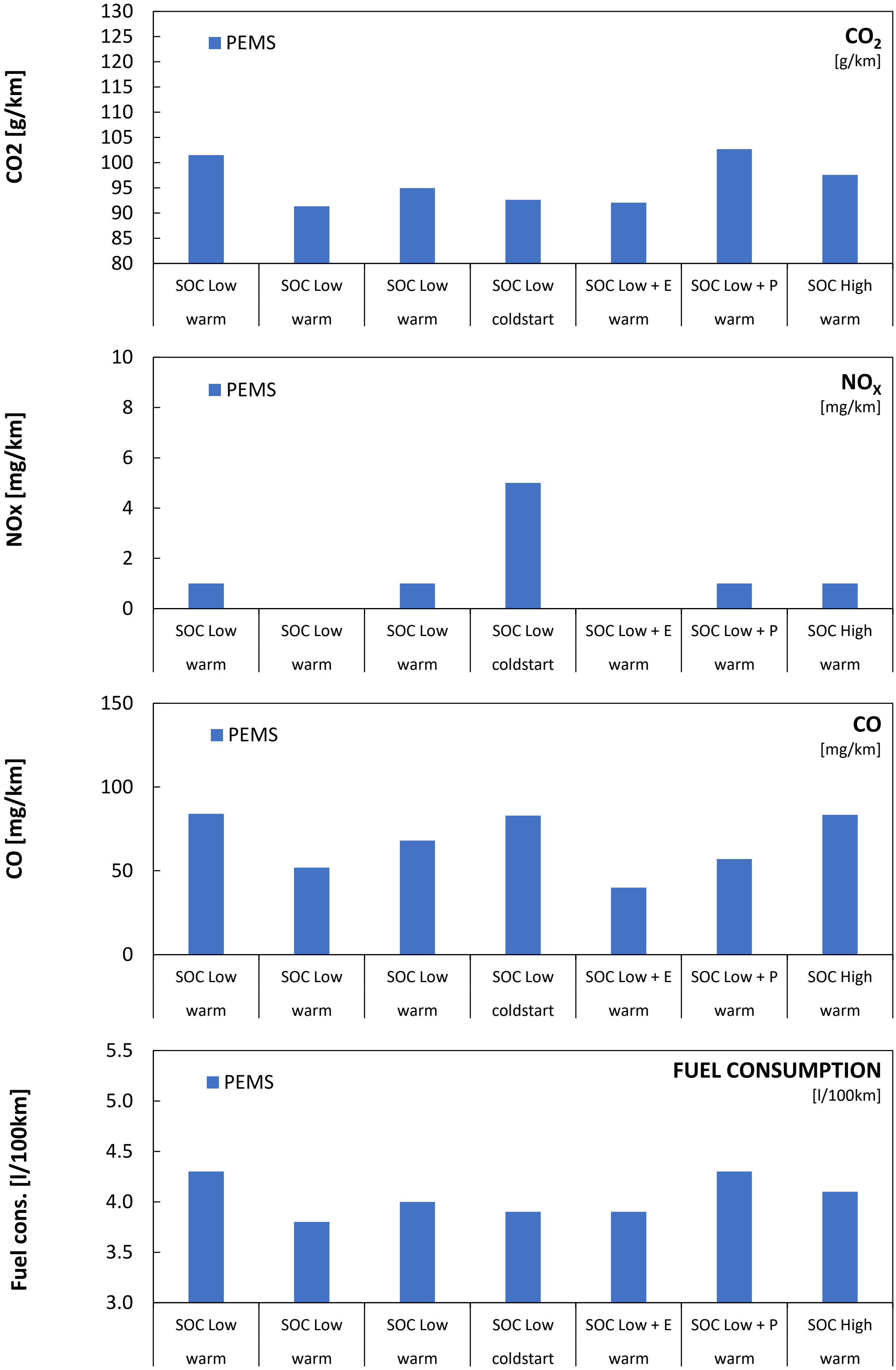


* Test performed with vehicle in certification mode

Emissions measured with PEMS in the RDE - Tests

PEMS | HORIBA OBS One

Toyota Prius III / HEV Gasoline

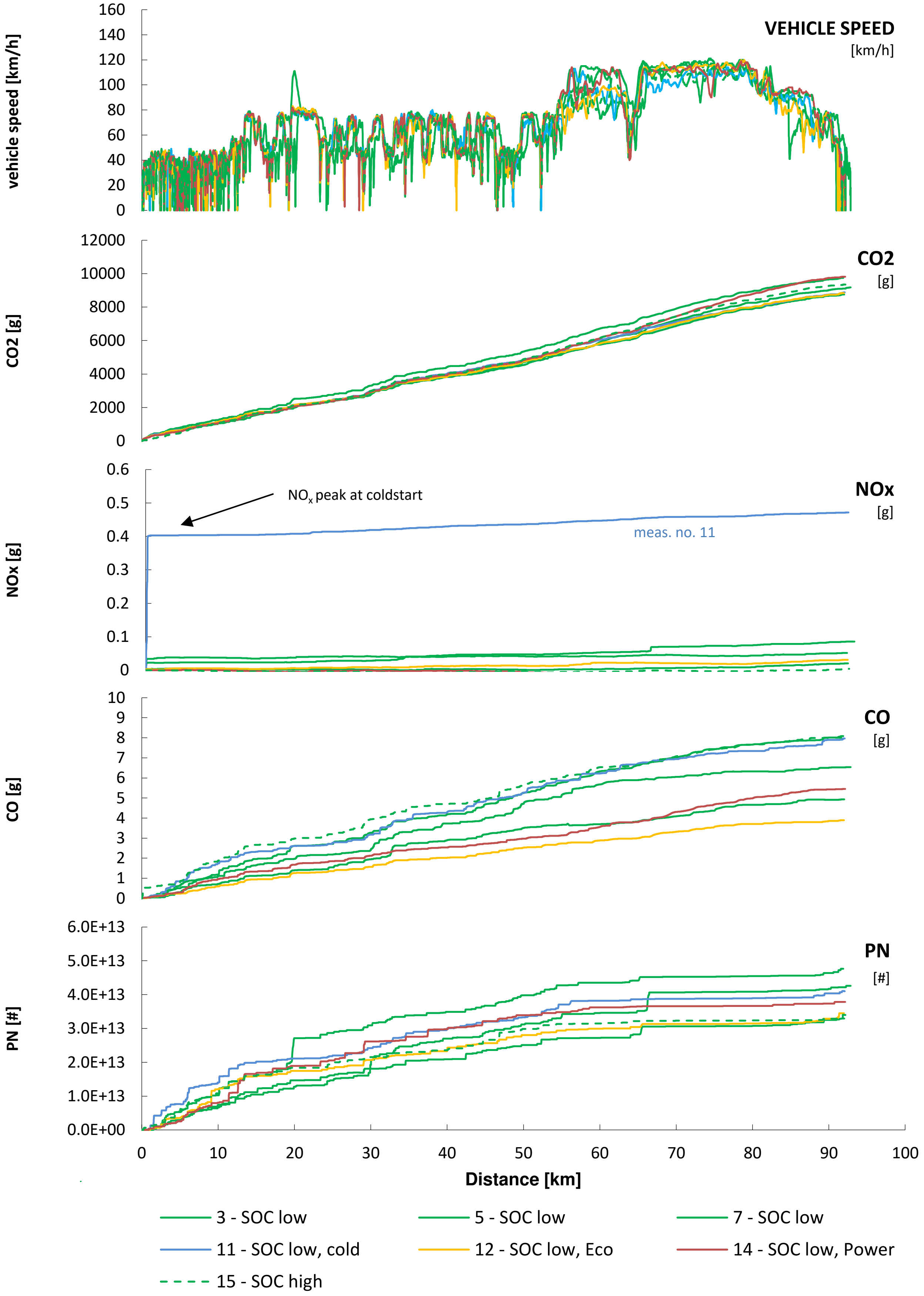


SOC - State of charge; **E** - Eco mode, **P** - Power mode

Comparison of Cumulated Emissions in the RDE - Tests

PEMS | HORIBA OBS-1

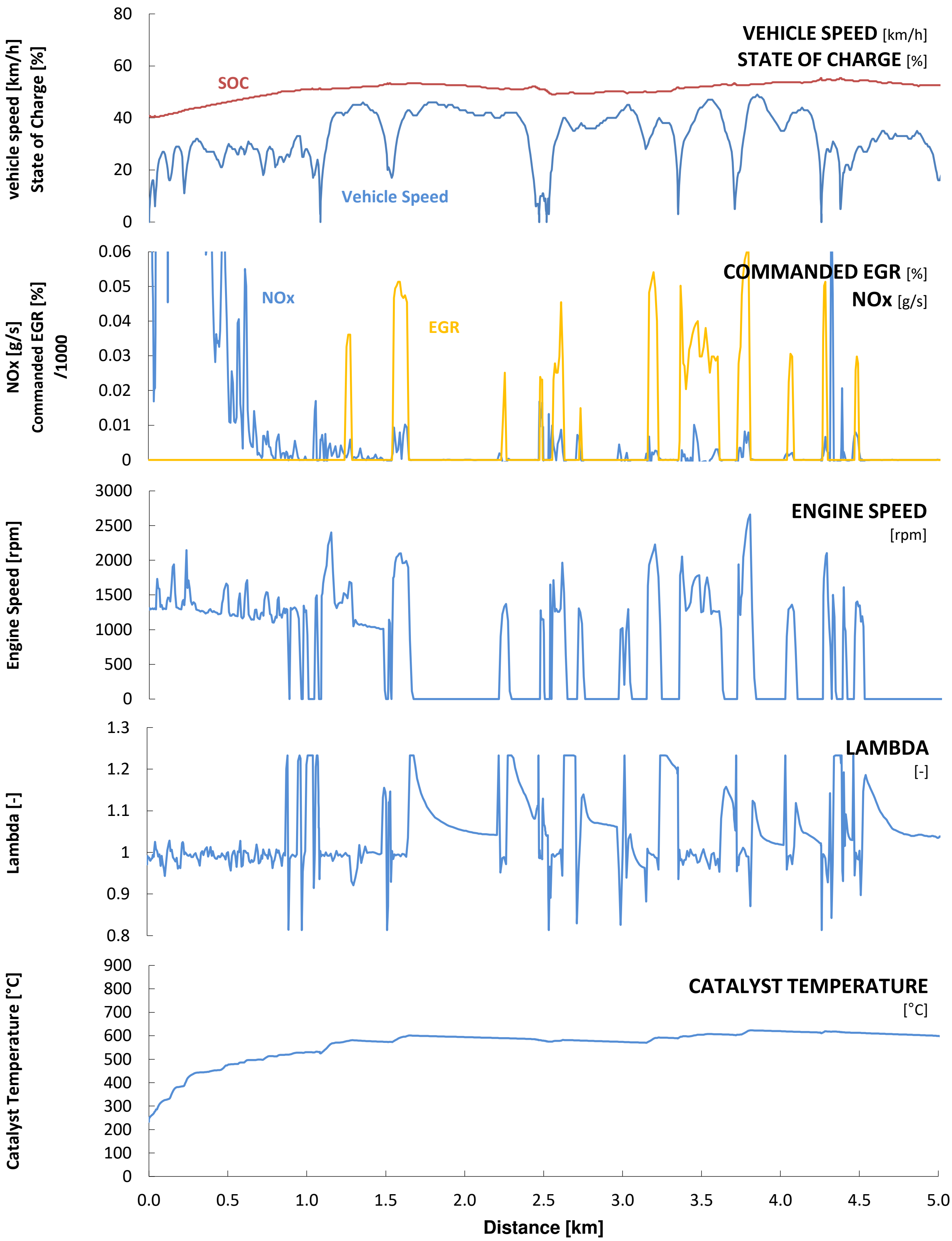
Toyota Prius III / HEV Gasoline



Influence of EGR on NOx
Example RDE Cold, no. 11, Urban Part

PEMS | HORIBA OBS-1

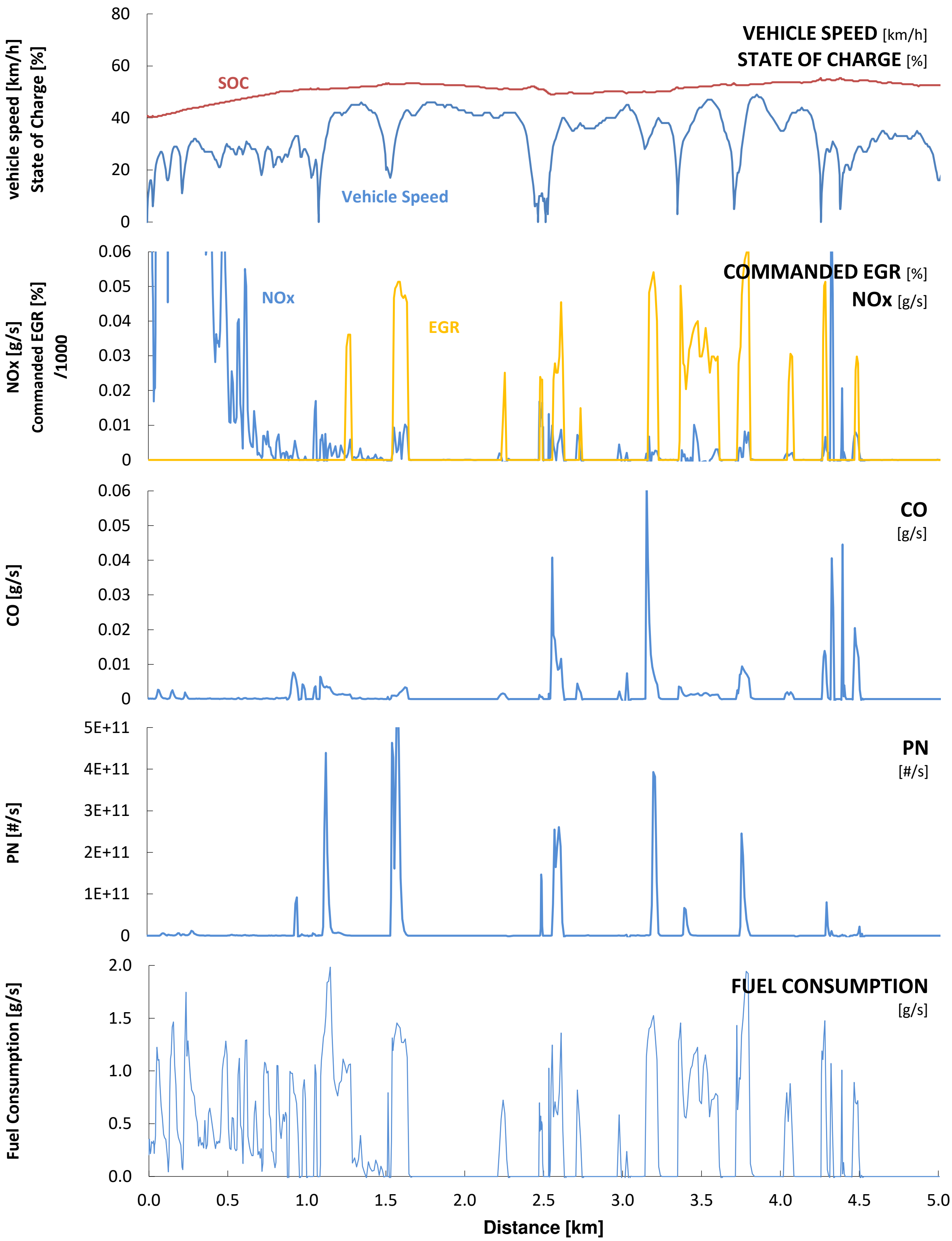
Toyota Prius III / HEV Gasoline



Influence of EGR on NOx
Example RDE Cold, no. 11, Urban Part

PEMS | HORIBA OBS-1

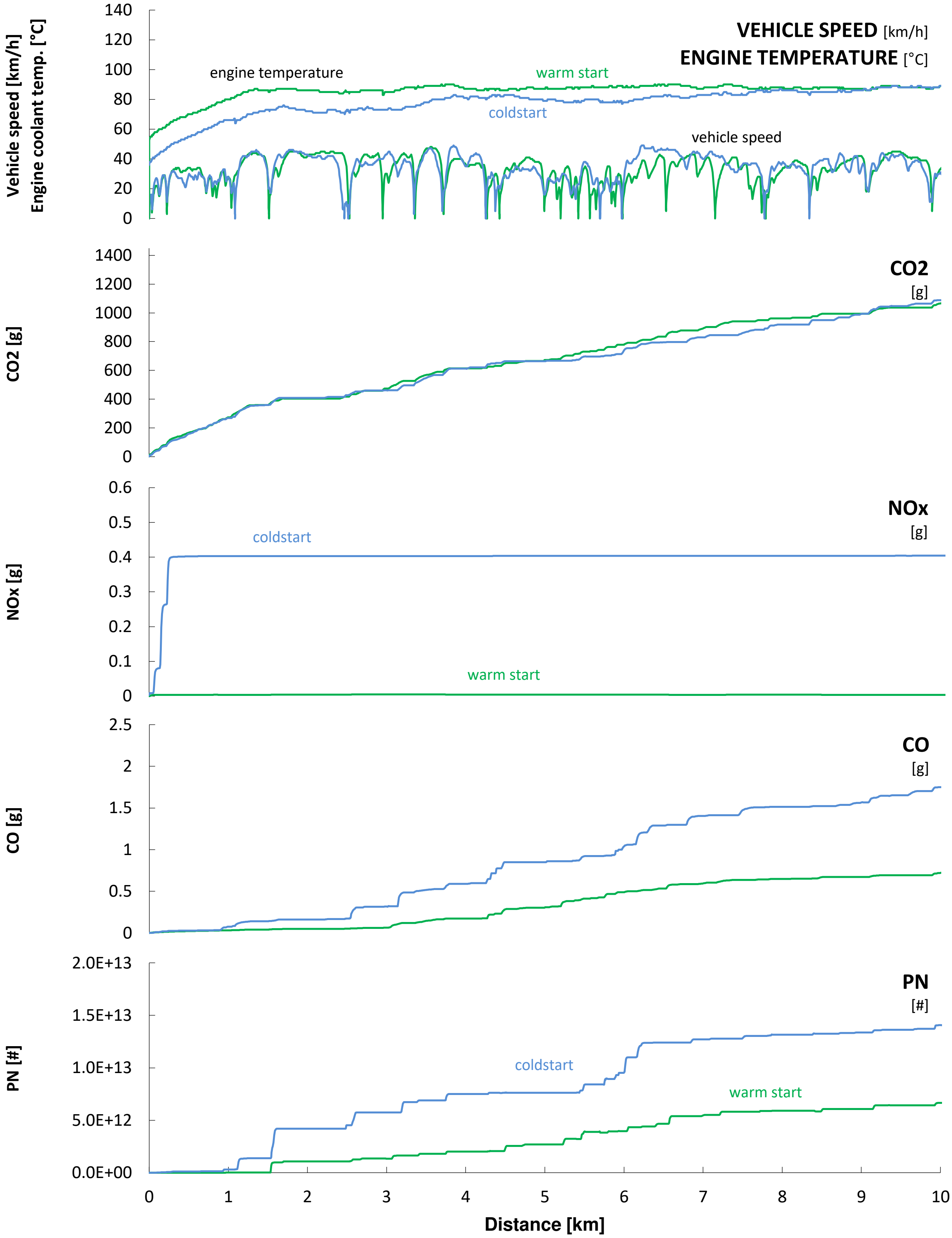
Toyota Prius III / HEV Gasoline



RDE in Urban Part Cold / Warm
Cumulated Emissions in the RDE - Tests

PEMS | HORIBA OBS-1

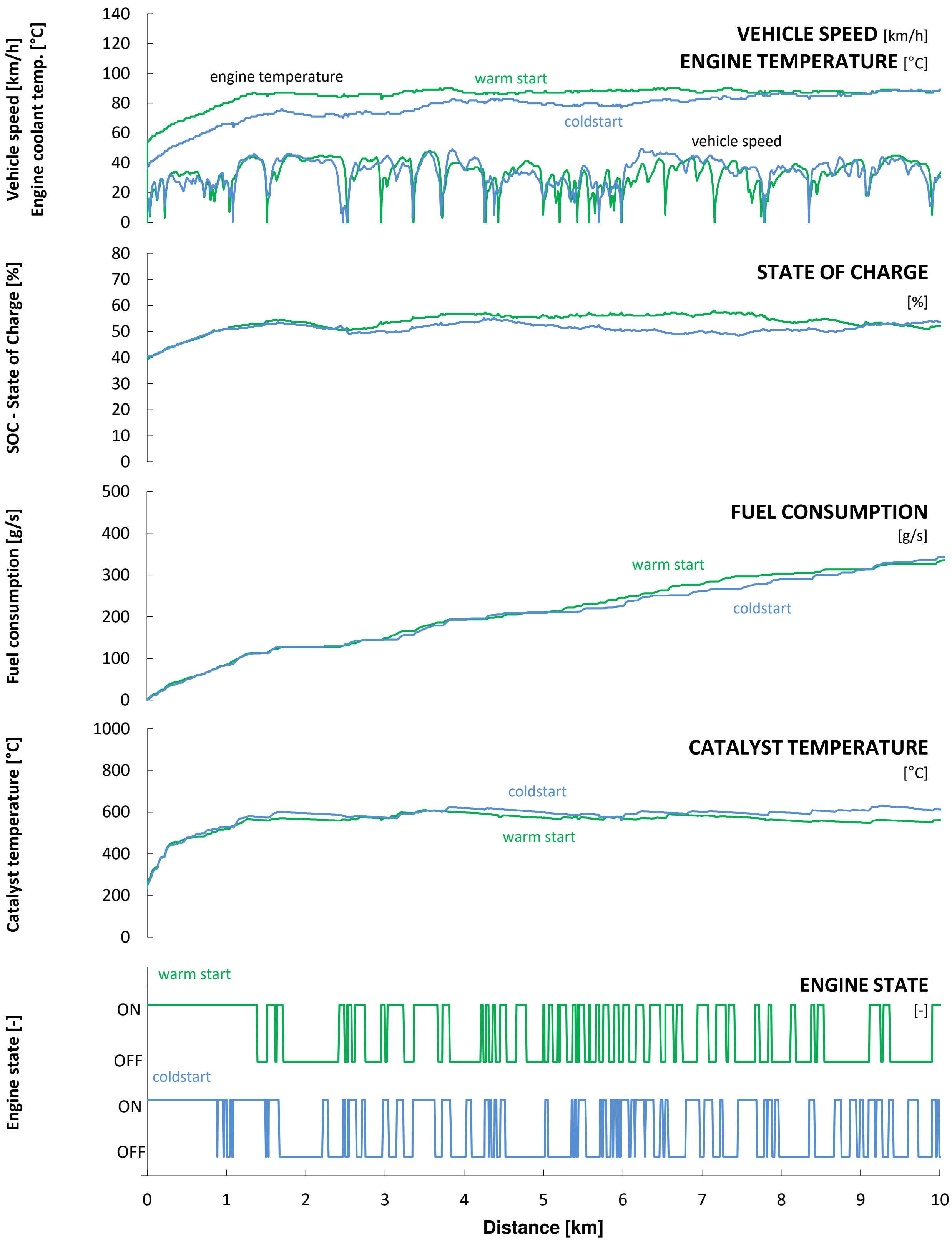
Toyota Prius III / HEV Gasoline



RDE in Urban Part Cold / Warm
Cumulated Emissions in the RDE - Tests

PEMS | HORIBA OBS-1

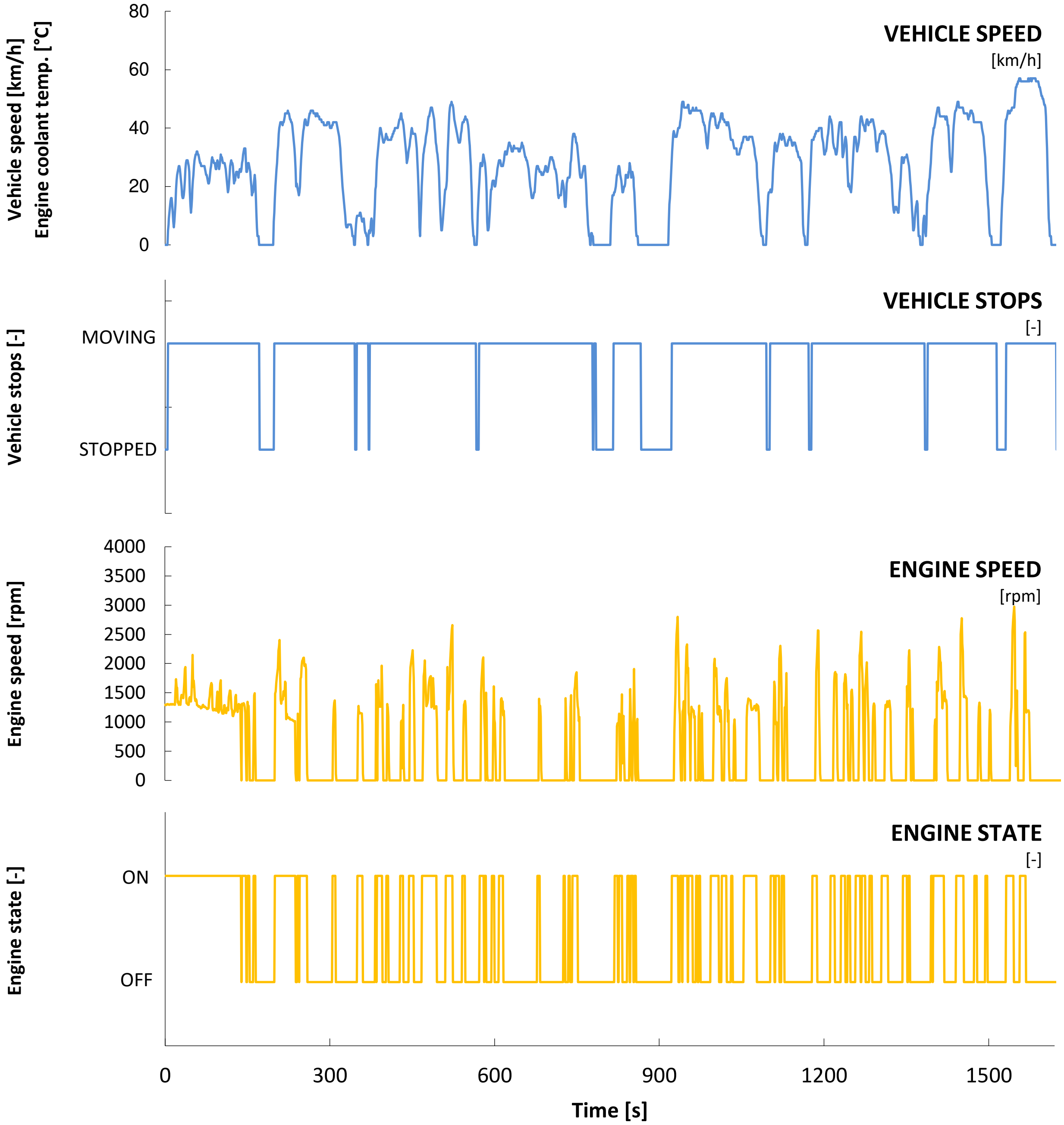
Toyota Prius III / HEV Gasoline



Vehicle and Engine Stops in the Urban Part
Example RDE Cold, no. 11

PEMS | HORIBA OBS-1

Toyota Prius III / HEV Gasoline



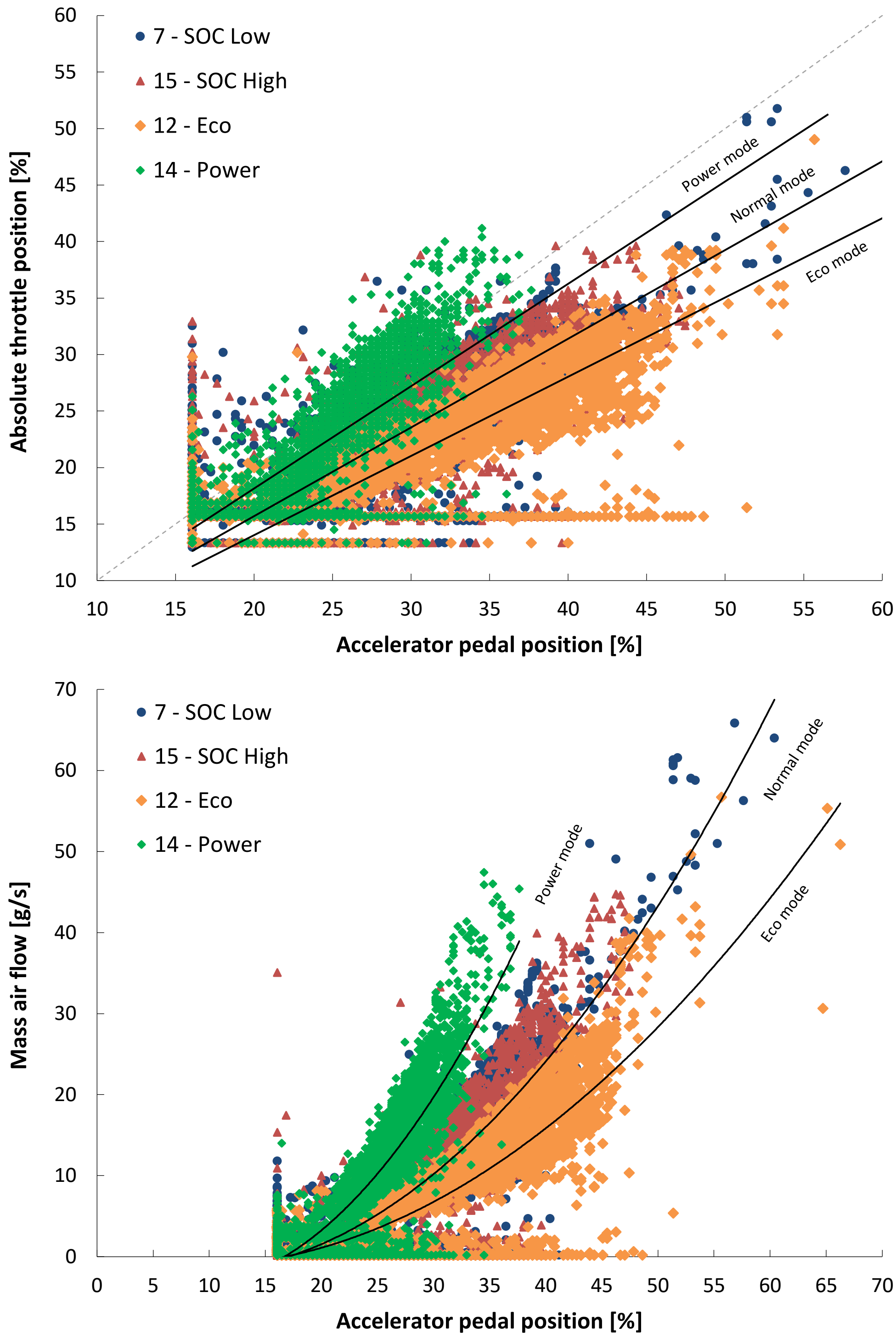
RDE	meas. no.	mode -	Distance km	Duration s	Engine ON s	Vehicle Moving s	Stopped s	Time shares Stops %	Engine ON %	Engine ON * %
URBAN	11	SOC low	12.6	1620	626	1456	164	10	39	43
	12	Eco	12.6	1719	741	1529	190	11	43	48
	14	Power	12.6	1743	1034	1513	230	13	59	68
	15	SOC high	12.6	1719	691	1466	253	15	40	47
FULL	11	SOC low	92.1	6027	3721	5792	235	4	62	64
	12	Eco	92.0	6290	3734	5979	311	5	59	62
	14	Power	92.1	6001	5048	5766	235	4	84	88
	15	SOC high	92.2	5967	3751	5690	277	5	63	66

* while vehicle speed > 0km/h

Distribution of Throttle vs. Accelerator Positions in Different Driving Modes

Tests no. 7, 12, 14, 15

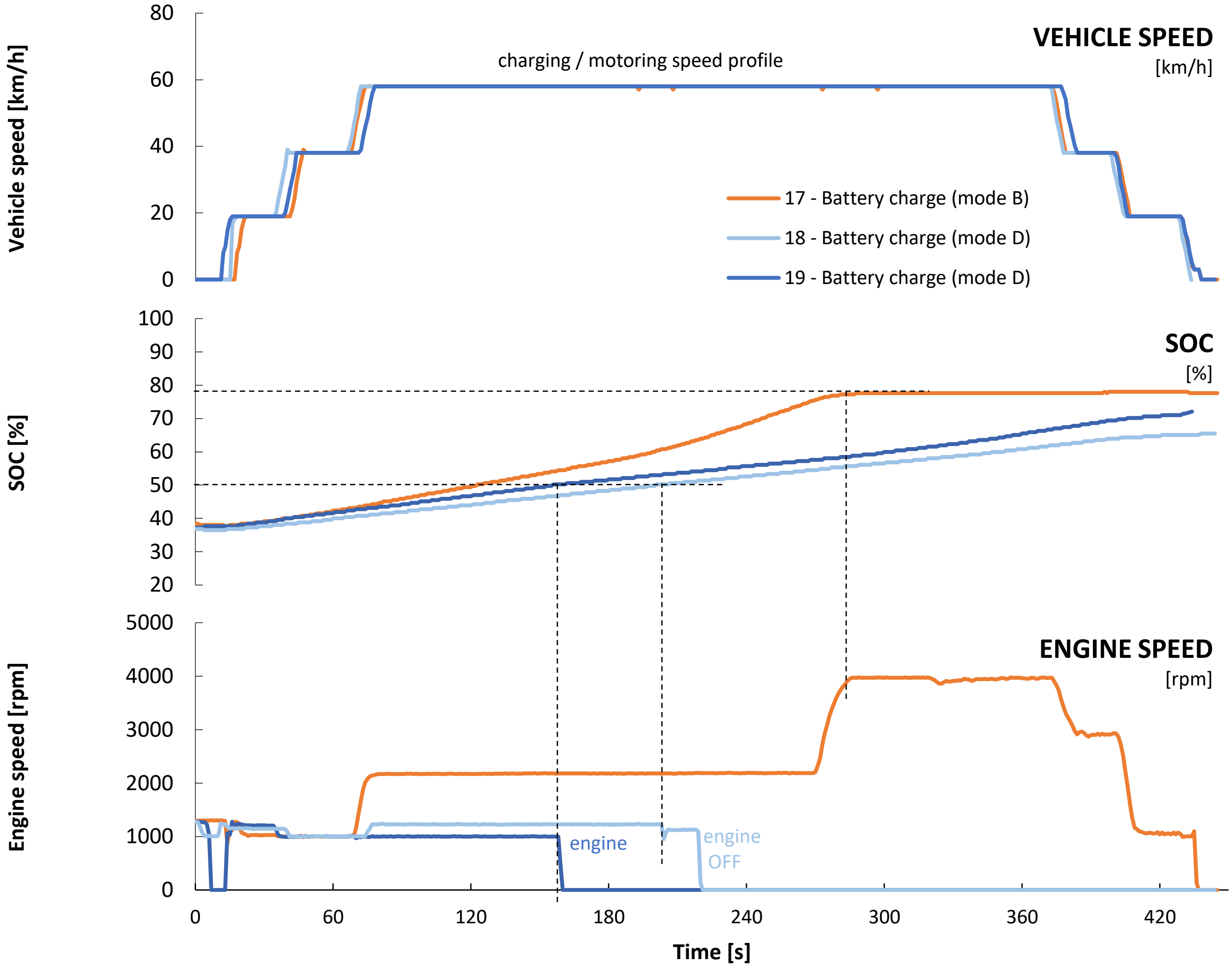
Toyota Prius III / HEV Gasoline



Attempts of Battery Charging in Modes "B" (Braking) and "D" (Drive)

Chassis Dynamometer in Motored Mode

Toyota Prius III / HEV Gasoline



238, 239, 240

Abgasprüfstelle (AFHB)
Contrôle des gaz d'échappement
Gwerdtstrasse 5
CH-2560 **Nidau**
Tel./Tél. +41 (0)32 321 66 80

Research of Real Driving Emissions (RDE) with E85 and Two Flex Fuel Vehicles (FFV)

and

Research of Real Driving Emissions (RDE) – HEV Toyota Prius III

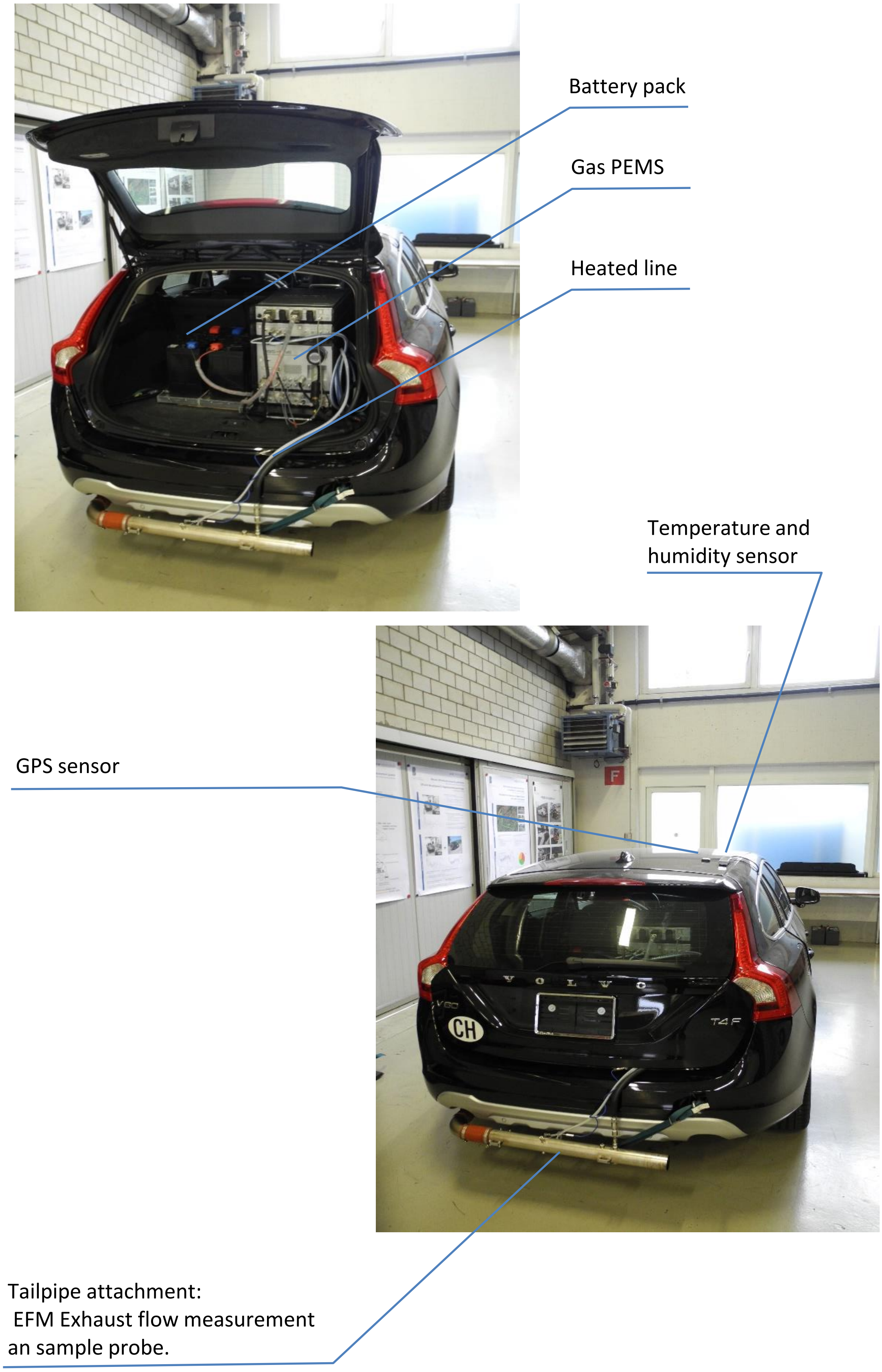
Swiss contribution to IEA AMF Annex 55

Annexes

March 2019 B525

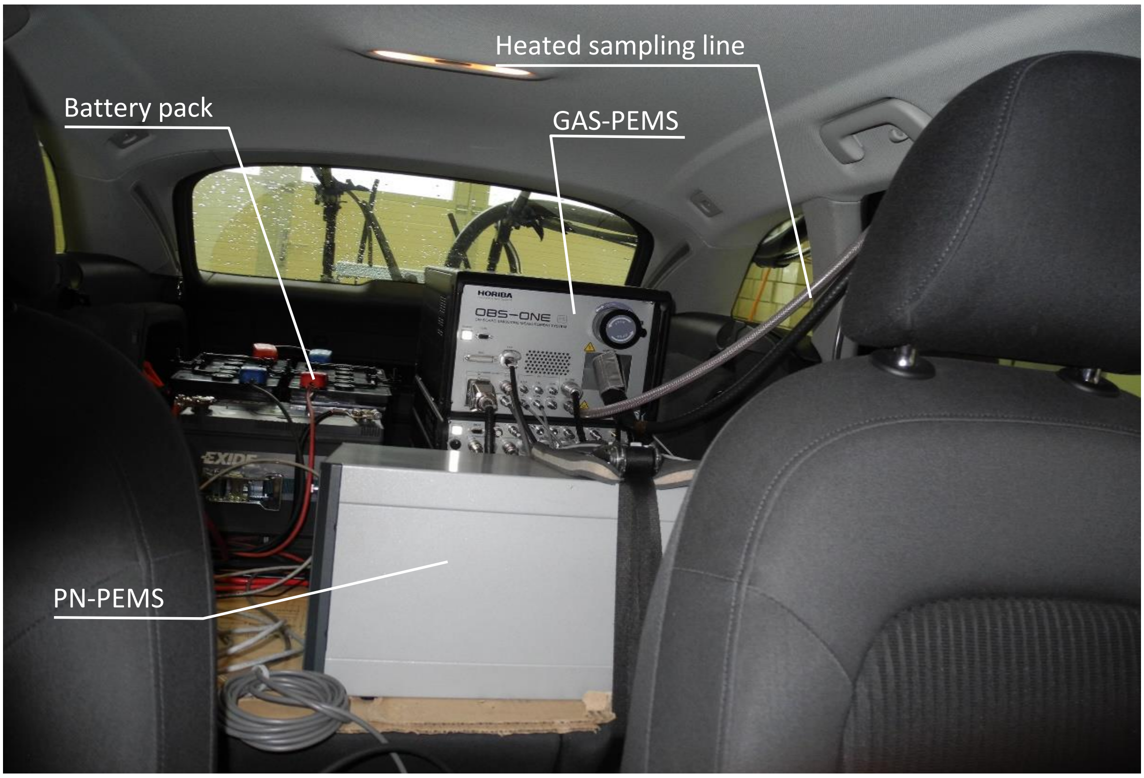
PEMS assembling on the Test Vehicles

Volvo V60 Flexfuel (V1)



PEMS assembling on the Test Vehicles

Audi A4 Flexifuel (V2)

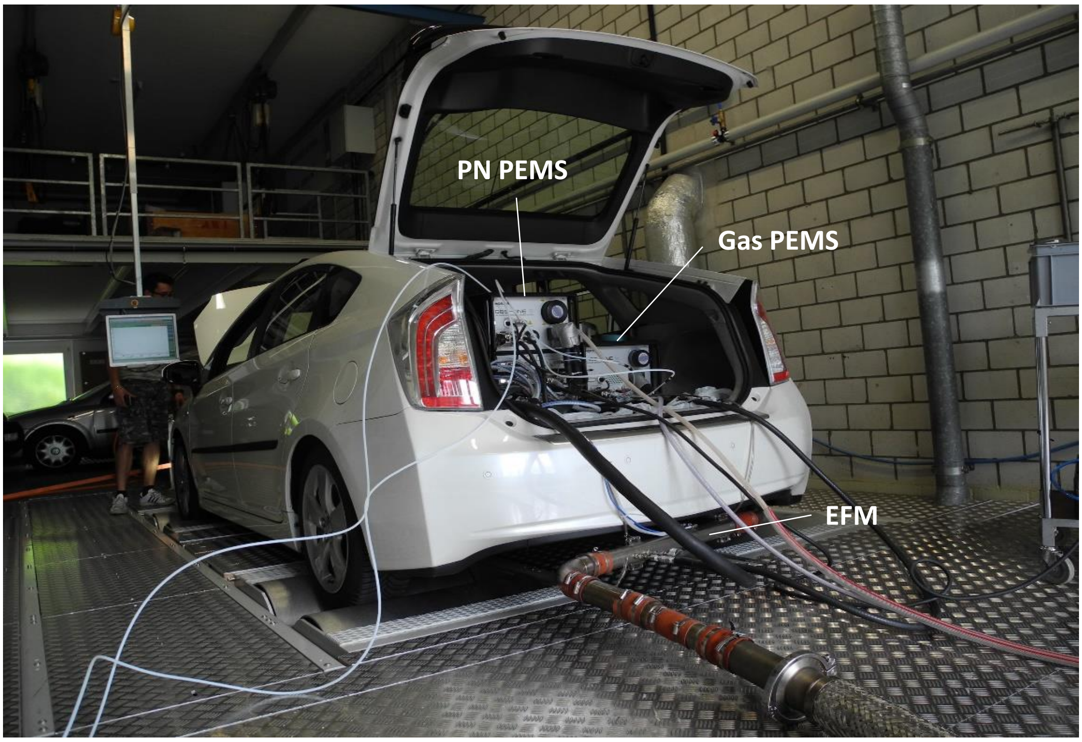


Real Driving Measurements

Set-up of the Vehicle for the RDE-Test

Toyota Prius III / HEV Gasoline / Euro 5b

June 2018



Test vehicle on the chassis dynamometer with Gas and PN-PEMS

Test vehicle on the road equipped with PEMS

Chronological List of Measurements

Chassis Dynamometer and Road

test nr.	date	vehicle	kilo-metrage	cycle	engine state	comments
001-VoE0RDE	05.05.17	Volvo V60 Flexfuel	28642	AFHB06f *)	cold	
002-VoE0Wc	08.05.17	Volvo V60 Flexfuel	28737	WLTC	cold	not valid
003-VoE0Wc	09.05.17	Volvo V60 Flexfuel	28763	WLTC	cold	
004-VoE0RDE	09.05.17	Volvo V60 Flexfuel	28786	AFHB06f	cold	
005-VoE0Wc	10.05.17	Volvo V60 Flexfuel	28881	WLTC	cold	
006-VoE0RDE	10.05.17	Volvo V60 Flexfuel	28904	AFHB06f	cold	
007-VoE0Wc	11.05.17	Volvo V60 Flexfuel	29021	WLTC	cold	
008-VoE0RDE	11.05.17	Volvo V60 Flexfuel	29044	AFHB06f	cold	
009-AuE85Wc	16.05.17	Audi A4 Flexifuel	207468	WLTC	cold	
010-AuE85RDEc	16.05.17	Audi A4 Flexifuel	207492	AFHB06f	cold	
011-AuE85RDEw	16.05.17	Audi A4 Flexifuel	207588	AFHB06f	warm	
012-AuE85Wc	17.05.17	Audi A4 Flexifuel	207684	WLTC	cold	
013-AuE85RDEc	17.05.17	Audi A4 Flexifuel	207707	AFHB06f	cold	
014-AuE0Wc	18.05.17	Audi A4 Flexifuel	207844	WLTC	cold	
015-AuE0RDEc	18.05.17	Audi A4 Flexifuel	207867	AFHB06f	cold	
016-AuE0RDEw	18.05.17	Audi A4 Flexifuel	207063	AFHB06f	warm	
017-AuE0Wc	19.05.17	Audi A4 Flexifuel	208060	WLTC	cold	
018-AuE0RDE	19.05.17	Audi A4 Flexifuel	208083	AFHB06f	cold	
030-VoE85Wc	06.06.17	Volvo V60 Flexfuel	29263	WLTC	cold	
031-VoE85RDEc	06.06.17	Volvo V60 Flexfuel	29286	AFHB06f	cold	

*) AFHB06f … actual version of AFHB RDE circuit (see annex A3)

Chornological List of Performed Test
Chassis Dynamometer and RDE

Toyota Prius III | HEV Gasoline

Toyota Prius HEV | Gasoline

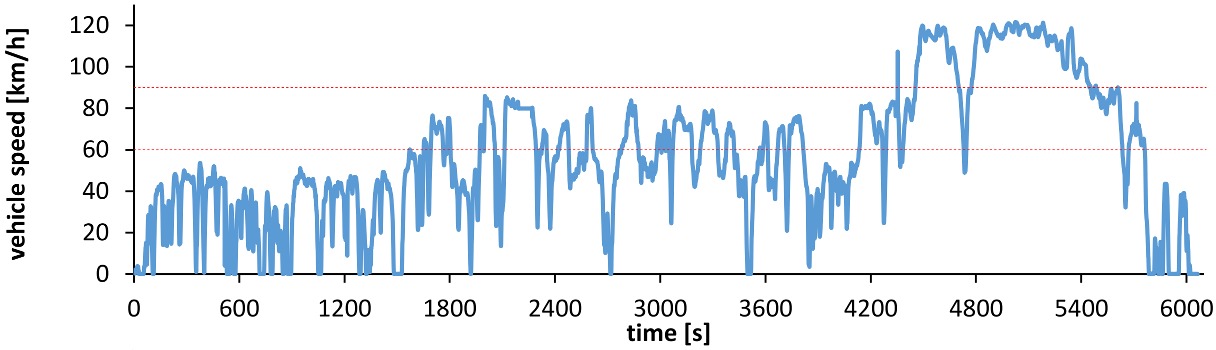
Test no.	Date	Test Name	Cycle	Tw	State	SOC		Mode
-	-	-	-	°C		%		
1	04.06.18	ToPrGa001Wc	WLTC	25	cold	37	low	normal
2	05.06.18	ToPrGa002Wc	WLTC	26	cold	38	low	normal
3	05.06.18	ToPrGa003RDEw	RDE	43	warm	36	low	normal
4	06.06.18	ToPrGa004Wc	WLTC	26	cold	38	low	normal
5	06.06.18	ToPrGa005RDE1	RDE	51	warm	38	low	normal
6	07.06.18	ToPrGa006Wc	WLTC	27	cold	38	low	normal
7	07.06.18	ToPrGa007RDE1w	RDE	58	warm	40	low	normal
8	07.06.18	ToPrGa008Test_D_60w	SOC test	-	warm	38	low	normal
9	07.06.18	ToPrGa009Test_B_60w	SOC test	-	warm	41	low	normal /B
10	07.06.18	ToPrGa010Test_D_60w	SOC test	-	warm	39	low	normal
11	08.06.18	ToPrGa011RDE1c	RDE	36	cold	40	low	normal
12	08.06.18	ToPrGa012RDE1w	RDE	58	warm	38	low	eco
13	11.06.18	ToPrGa013Wc	WLTC	25	cold	79	high	normal
14	11.06.18	ToPrGa014RDE1w	RDE	70	warm	35	low	power
15	11.06.18	ToPrGa015RDE1w	RDE	62	warm	79	high	normal
16	12.06.18	ToPrGa016NEDCc	NEDC	26	cold	38	low	normal
17	12.06.18	ToPrGa017Test_B_60w	SOC test	-	warm	39	low	normal /B
18	12.06.18	ToPrGa018Test_D_60w	SOC test	-	warm	38	low	normal
19	12.06.18	ToPrGa018Test_D_60w	SOC test	-	warm	38	low	normal

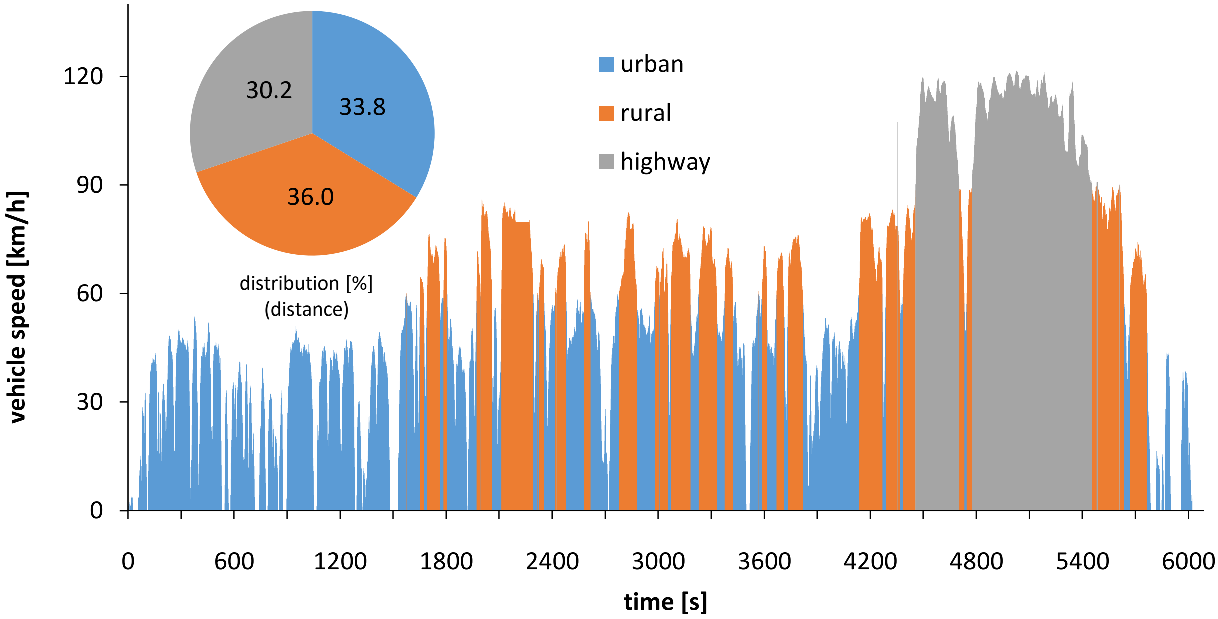
Tw - engine coolant temperature at test start
RDE - route afhb06f

Road Trip for RDE

RDE at 11.05.2017

VolvoV60 FlexFuel| Horiba OBS One & NanoMet 3

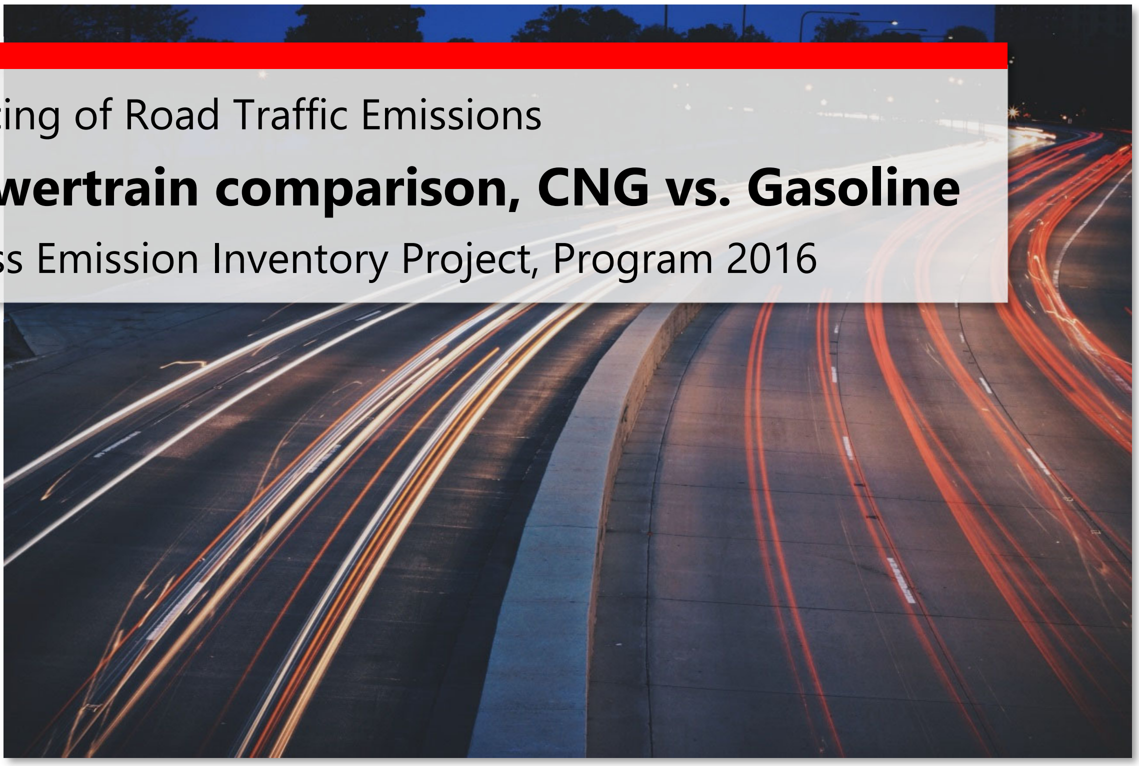




distance	
urban	32.4 km
rural	34.6 km
highway	29.0 km
total	**96.0 km**
time	
urban	51.1 min
rural	27.9 min
highway	15.6 min
stops	6.5 min
total	**101.1 min**
average speed	
urban	38.1 km/h
rural	74.2 km/h
highway	111.7 km/h
max	121.0 km/h

AFHB road-test route (AFHB06f)

Empa-Report 5214004257/1 - PG6/PB6-2016



Tracing of Road Traffic Emissions

Powertrain comparison, CNG vs. Gasoline

Swiss Emission Inventory Project, Program 2016

Authors:

Thomas Bütler, Christian Bach, Mathias Huber

Empa, Automotive Powertrain Technologies Laboratory

Dübendorf, the 2nd of September 2019

Table of contents

Imprint

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Contractor:	Empa, Automotive Powertrain Technologies Laboratory
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Legal notice:	This report was prepared on behalf of the Swiss Federal Office for the Environment (FOEN). The Contractor is solely responsible for the content.
Cover picture:	Photo by Caleb George on unsplash.com

1 Outline

1.1 Tasks and objectives

The FOEN research project "Air polluting emissions from road traffic in Switzerland 1990-2035" aims at quantifying the pollutant emission levels of the different emitters of road traffic in Switzerland. There, the chosen approach is to determine emission factors of the corresponding emitters in their single operating situations and then extrapolate its total emission level by considering the respective hours of operation. The present report states the experimental campaign carried out to compare two Euro 6b vehicles, one equipped with a CNG (compressed natural gas or biogas) engine and one with a gasoline engine, with similar powertrain specifications.

1.2 Summary

- The total greenhouse gas emissions (TGHG) of the CNG vehicle are 19 - 22% lower than those of the gasoline version. The TGHG emissions only differ from the pure CO_2 emissions during cold started cycle sections, as only then significant amounts of CH_4 and N_2O emissions are present.

- The ozone reactivity of the exhaust emissions of the CNG vehicle is 50 - 80% lower than that of the gasoline version due to the much lower ozone reactivity of the hydrocarbons (according to EPA 2010). The NOx emissions of the CNG vehicle are significantly lower in the WLTP compared to the gasoline car.

- The health hazard of the exhaust emissions of the CNG car is lower than that of the gasoline vehicle due to the 15 - 70 times lower number of particles. CO emissions are also significantly lower for the CNG version, while NO_2 and HCOH (formaldehyde) emissions are on a similar level, whereas NH_3 emissions are higher for the CNG version during highway driving.

- The observed NOx emissions of both vehicles are lower higher during the chassis dyno test according to WLTP compared to the road measurements; the values of the CNG version are 3 - 4 times lower than those of the gasoline car. The CO_2 emissions from road measurements are on average 10% higher for the CNG car and 20% higher for the gasoline version in comparison with the WLTP measurements on the chassis dyno.

2 Project description

2.1 Vehicle characteristics

The vehicles have been chosen to as common drive train characteristics as possible. The gasoline vehicle has a slightly higher engine power, but the rest of the vehicle specification is alike. For both vehicles, similar road load settings have been used, only the difference in the vehicle weight was compensated with the F0 value. For both NEDC and WLTC measurements, the same chassis dyno settings have been used.

	Audi A3 g-tron	Audi A3 TFSI
empty weight [kg]	1410	1365
test weight [kg]	1435	1390
road load (F0/F1/F2) [N, N/km/h, N/(km/h)^2]	98.1 / 0.37 / 0.0274	95.1 / 0.37 / 0.0274
displacement [cm3]	1395	1395
rated power [kW]	81	92
Fuel [-]	CNG	Gasoline
gearbox [-]	M6	M6
cert. Category [-]	Euro 6b	Euro 6b
1st certification [mm.jj]	3.14	9.14
type approval [CH]	1AD312	1AD379
mileage [km]	29275	21176

Table 1: Vehicle characteristics of the two Audi A3, once in the CNG configuration (g-tron) and as the lowest powered 1.4 TFSI gasoline version

2.2 Fuel characteristics

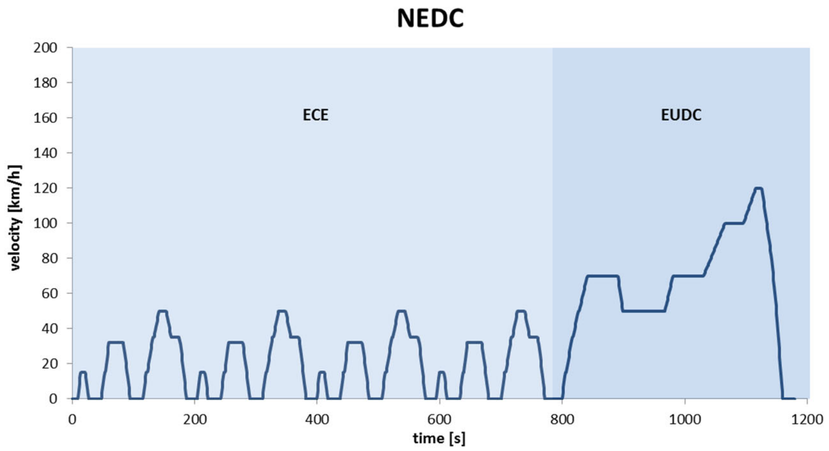
Both vehicles have been fuelled with standard Swiss market fuel. The table shows the fuel characteristics that have been used for the post processing calculations (values according to fuel analysis and the specification of SWISSGAS for the gas composition of 2015).

	Density [g/dm^3 or g/m^3]	Carbon mass fraction [%]	H:C ratio (molar) [-]	Net heating value [MJ/kg]
Gasoline Marketfuel	741.2	87.0	1.77	43.38
CNG Marketfuel	750.5	71.5	3.80	45.74

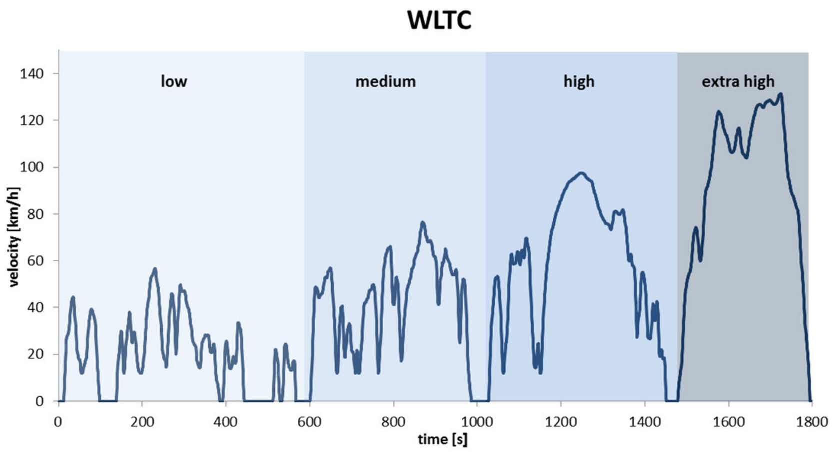
Table 2: Swiss market fuel characteristics for gasoline and for CNG from the natural gas grid.

2.3 Driving cycles (chassis dyno)

The experimental program carried out includes the current legislative driving cycle NEDC and the future legislative driving cycle WLTC. Both cycles have been driven with the same road load settings and at standard ambient conditions (23°C and 50% RH). The cycle characteristics can be found in Figure 1.



section name	start time [s]	end time [s]	duration [s]	v_mean [km/h]	distance [km]
ECE	0	779	780	18.7	4.1
EUDC	780	1180	401	62.6	6.9
total	0	1180	1180	33.6	11



section name	start time [s]	end time [s]	duration [s]	v_mean [km/h]	distance [km]
low	0	589	590	18.9	3.1
medium	590	1022	433	39.5	4.8
high	1023	1477	455	56.7	7.2
extra high	1478	1800	323	92.0	8.3
total	0	1800	1800	46.5	23.3

Figure 1: Driving cycle characteristics for the NEDC (top) and the WLTC (bottom)

2.4 RDE cycle

Empa's Std. RDE route includes a city tour in Dübendorf (flat terrain), an overland trip along Lake Greifensee to Uster (flat terrain) and a motorway trip back to Dübendorf (flat terrain). The driving time per round is approx. 45 minutes.

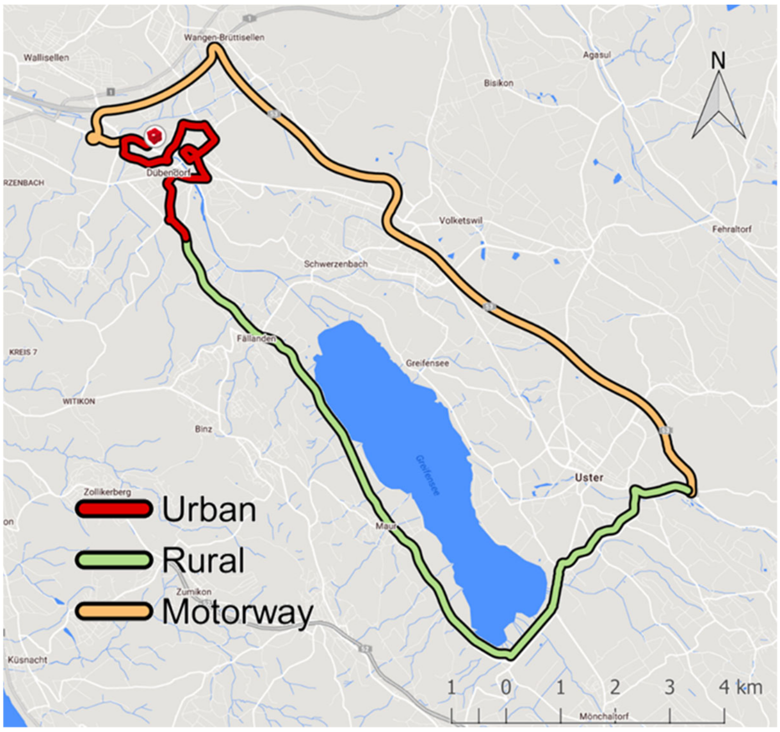
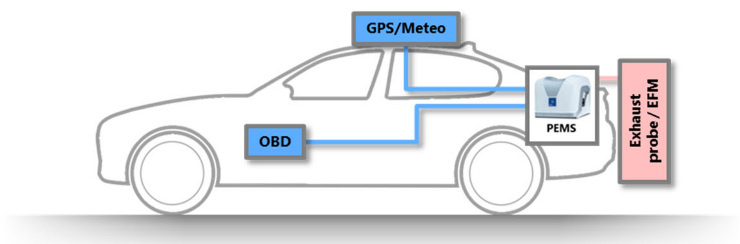


Figure 2: Map of the Empa Std. RDE route in the area of Dübendorf-Uster in Switzerland

Distance	Urban Distance Share	Rural Distance Share	Motorway Distance Share	Total Duration	Av. Speed	Positive Elevation Gain
~ 38 km	~ 36 %	~ 34 %	~ 30 %	~ 41 min	~ 55 km/h	~ 440m/100km

Table 3: Main characteristics of the Empa Std. RDE route

2.5 Test and measurement equipment



- PEMS: Portable Emission Measurement System
- EFM: Exhaust Flow Meter
- OBD: On Board Diagnostics
- GPS: Global Position System
- Meteo: Weather station

Figure 3: PEMS setup for RDE measurements. Not shown are: the user interface (tablet) to inform the driver about the PEMS status, the power supply and distribution, the control units and the CO detector for driver safety

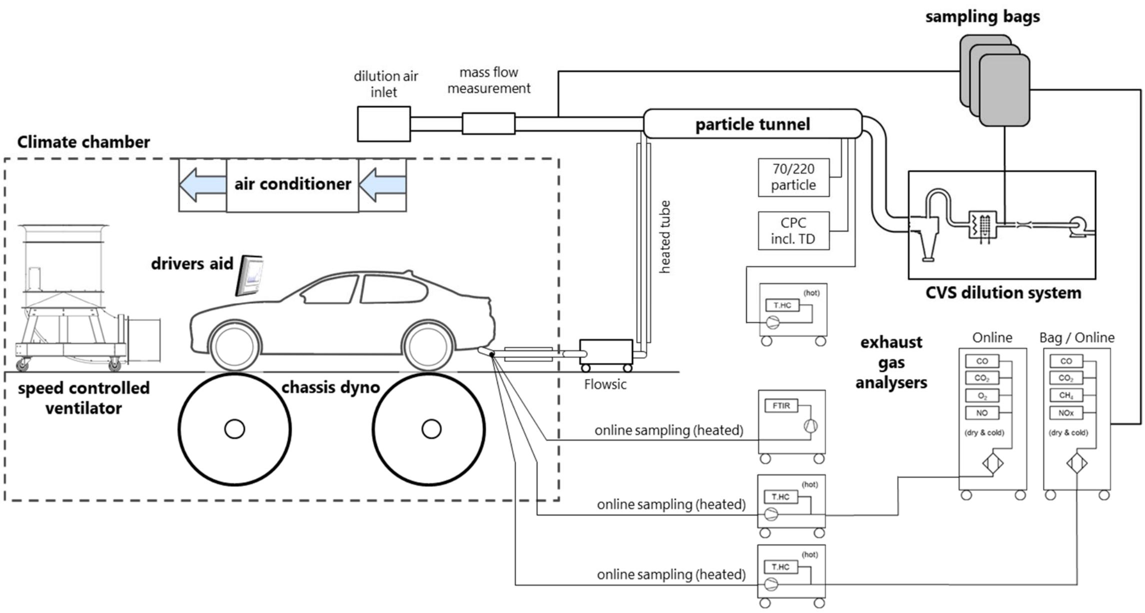


Figure 4: Vehicle setup on chassis dynamometer in climate chamber. All measurement systems are placed outside the climate chamber

Chassis dynamometer

- AVL Roadsim 48"MIM 4WD LIGHT TRUCK

Ventilator, speed controlled

- DLK-Pollrich, Toromax Pro AANM01-1000-B
- Outlet area: 0.55m^2, Max. air speed: 140 km/h (@ 53kW)

Emission measurement, chassis dyno

- Exhaust gas analysers: Horiba Mexa 7400 H
- Empa particle sampler (US2007,ECE R83)
- CPC: TSI, Condensation Particle Counter 3790
- Exhaust volume flow: Sick Maihack Flowsic150

Emission measurement, RDE

- AVL M.O.V.E PEMS iS SYSTEM
- without PN measurement

Emission measurement for unregulated pollutants

- Gasmet FTIR, CR-2000 S, low-resolution spectrometer(7,72 1/cm)

Test rig control / DAQ system

- Empa/Sotronic; CAVETS, drivers aid and DAQ
- Analog inputs: 22 x 10Hz, 8 x 1kHz
- Temperature Inputs: 32 x Type-K (10Hz)

2.6 Data post processing

The measured concentrations of the single exhaust components detected are processed to absolute values using the respective volume flow. The latter is measured too, but has to be corrected because of the sample volume flows that are extracted by the employed measuring devices.

Additionally, the online signal traces recorded need to be corrected regarding time and mixing delay due to the length of the sample lines and the measuring delay time of the analysers. The time alignment of the online concentration measurement and the exhaust mass flow measurement is calculated according to a special lambda probe located at the sampling points of the online analysers. This methodology has been developed within an associated research program and has already been successfully applied in earlier measurement campaigns.

The CVS system is equipped with three sampling bags. For the WLTC cycle, the phases "high" and "extra-high" are sampled in the same sampling bag (bag 3). The emission values for the cycle sections "high" and "extra-high" are calculated based on the online emission measurement

Remarks to setup and measurement data analysis

- The standard exhaust gas composition is determined according to the European Council Directive 70/220/EEC for passenger cars.
- The chassis dynamometer and its settings were applied according to the provisions of Council Directive 692/2008/EC.
- The measured bag values had to be corrected due to the sample volume flows that are extracted by the online measuring devices employed.

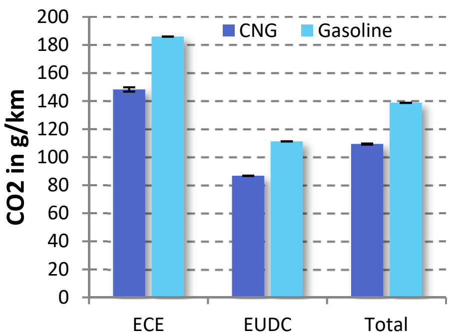
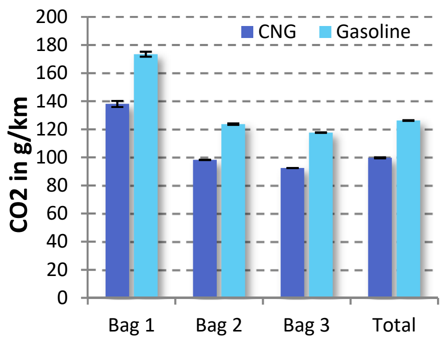
3 Emission Performance

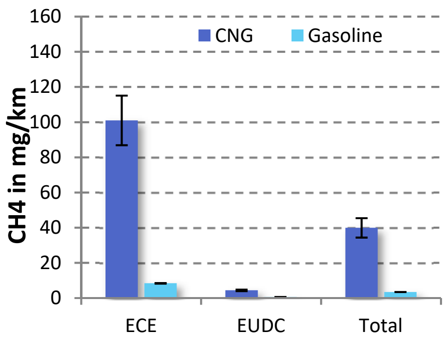
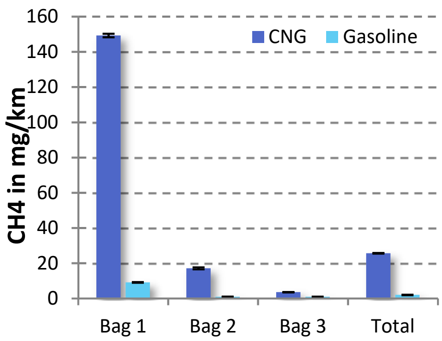
To analyse the emission performance in comparison of the drive trains, the emission values of the chassis dyno and the on road tests have been grouped in to three impact groups, greenhouse gas emissions (global warming potential), ozone reactivity and health risks.

3.1 Greenhouse gases

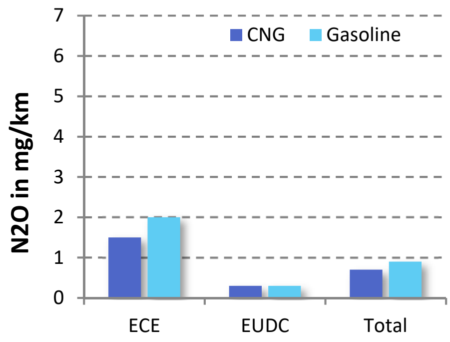
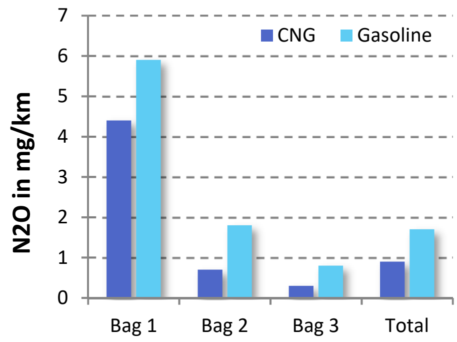
For the assessment of the greenhouse gases, the emissions of CH_4 and N_2O have been adjusted according to their global warming potential[1] and have then been summed up with CO_2 to calculate the total greenhouse gas emissions as CO_2-equivalent.

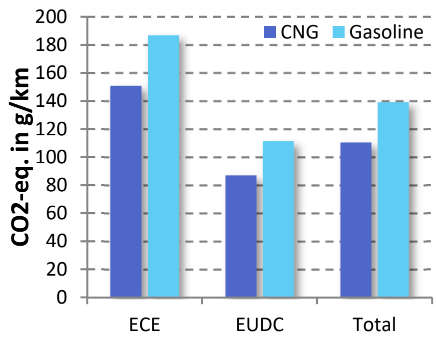
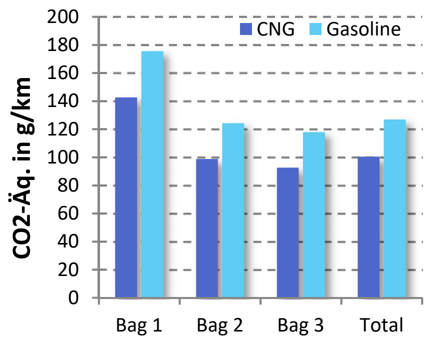
$$CO2eq = CO_2 + 21 * CH_4 + 310 * N_2O$$

CO_2 emissions	NEDC	WLTC
In comparison to the gasoline vehicle, the CNG vehicle shows a 20-22% reduction in CO_2 emissions The CO_2 emissions measured in the WLTC are 9% lower than those in the NEDC (same chassis dyno settings).		

CH_4 emissions	NEDC	WLTC
The CH_4 emissions of the gasoline vehicle are very low and nearly negligible. The CH_4 emissions of the CNG vehicle during cold start are around 100-150 mg/km, which corresponds to 2.1 – 3.2 g CO_2-eq/km. The hot emissions are between 10-30mg/km, which corresponds to 0.2 – 0.6 g CO_2-eq/km.		

[1] Global warming potential with a time horizon of 100 years according to the United Nations; Climate Change 1995, The Science of Climate Change: Summary for Policymakers and Technical Summary of the Working Group I Report, page 22. https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials

N_2O emissions	NEDC	WLTC
The CNG vehicle shows generally lower N_2O emissions compared to the gasoline vehicle. It has to be noted, that only one cycle has been measured to analyze the N_2O behavior.		

T.GHG emissions	NEDC	WLTC
T.GHG = Total greenhouse gas emissions expressed as CO_2-eq. The T.GHG emissions of the CNG vehicle are 19 to 22% lower in comparison to the gasoline vehicle. The T.GHG emissions mainly differ from the CO_2 emissions during cold start. .		

3.2 Ozone reactivity

For each fuel used, a certain amount of ozone can be produced from the exhaust gas in the atmosphere, mostly caused by the hydrocarbon emissions of the. But since not all hydrocarbons have the same impact on the ozone formation, a corresponding correction is carried out with a reactivity adjustment factor (RAF). The RAF is the ratio of the ozone formation potential per gram of VOC emitted (gram of ozone/gram of VOC) of a vehicle. Methane is not taken into consideration due to its extremely low contribution to the calculation of the ozone formation potential, therefore only the so-called "non-methane organic gases" (NMOG) are used. The total ozone reactivity is then calculated as the sum of NMOG and the NOx emissions of the corresponding driving cycle.

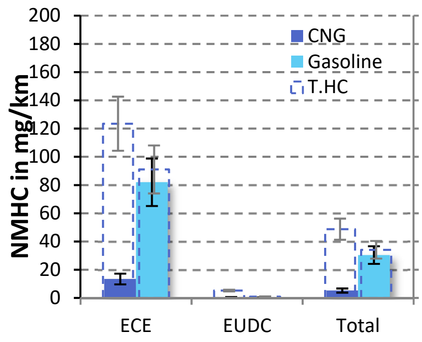
$$NMOG = T.HC * RAF_{Fuel}$$

$$RAF_{CNG} = 0049$$
$$RAF_{Gasoline} = 0.943$$

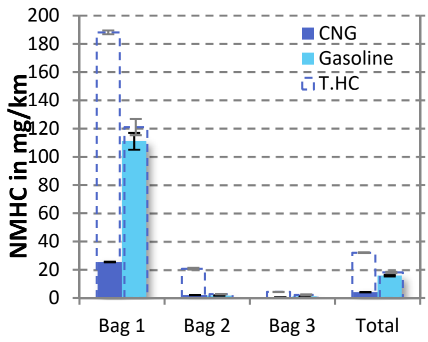
NMHC emissions

The NMHC emissions of the CNG vehicle are 80% lower compared to the gasoline vehicle during the cold started cycle sections. But the T.HC emissions of the CNG vehicle are 30 to 100% higher in comparison with the gasoline vehicle.

NEDC



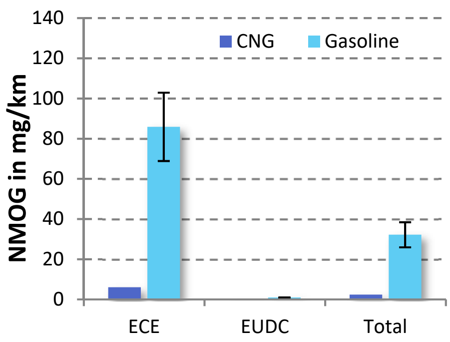
WLTC



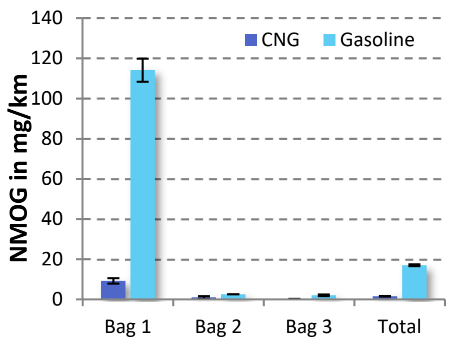
NMOG emissions

The ozone reactivity of the hydrocarbons from the gasoline vehicle is 10 times higher than the one of those from the CNG vehicle

NEDC



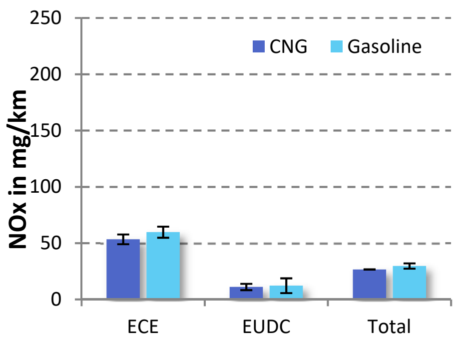
WLTC



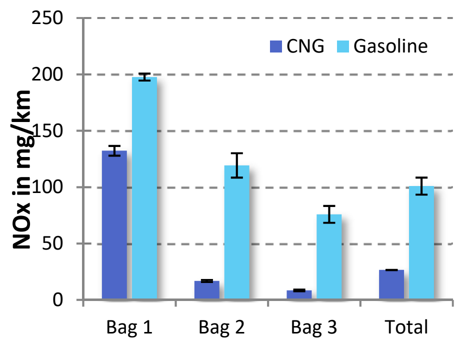
NOx emissions

The NOx emissions in of the NEDC cycle are on the same level for both fuels, but differ a lot in the WLTC

NEDC



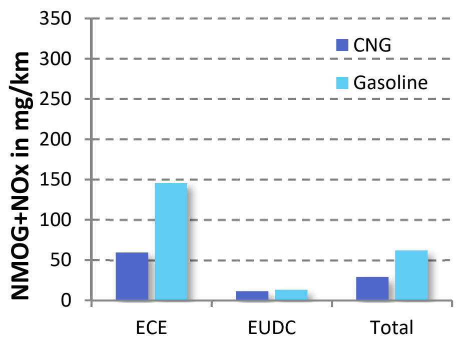
WLTC



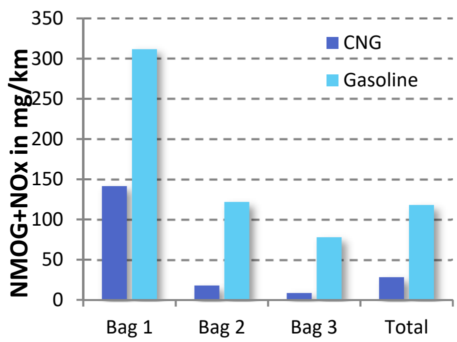
Ozone reactivity

The ozone reactivity of the exhaust gases of the CNG vehicle are 50 to 80% lower compared to the gasoline version

NEDC



WLTC



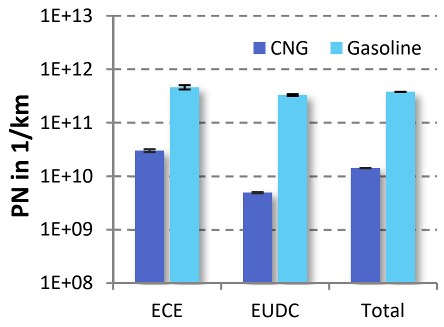
3.3 Health risks

Some exhaust components have been proven to have a major impact on general health risks. The main influence comes from the emitted particles, but also other components can have an impact on the health of the respiratory system.

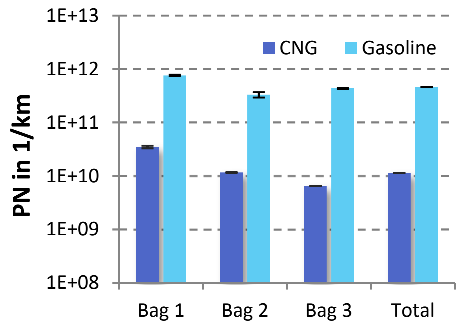
PN emissions

The particle number is 15 to 70 times lower for the CNG vehicle in comparison to the gasoline vehicle

NEDC



WLTC

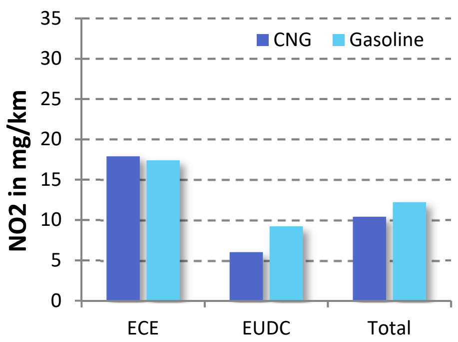


NO_2-Emissionen

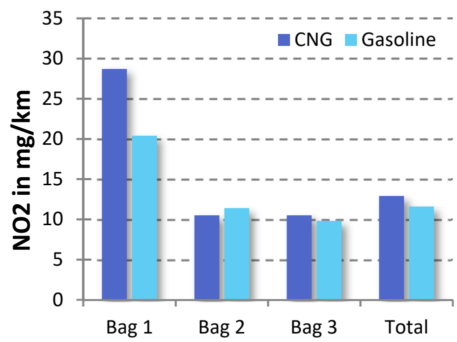
Even though the NOx emissions for the CNG vehicle are lower than for the gasoline, the NO_2 emissions are slightly higher for the CNG variant.

It has to be noted, that only one cycle has been measured to analyze the NO_2 behavior.

NEDC



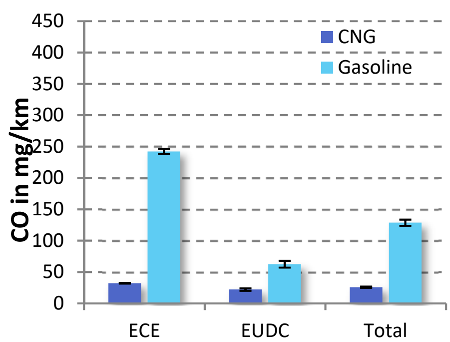
WLTC



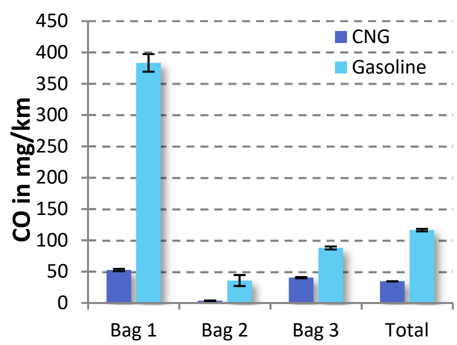
CO emissions

The CO emissions of the CNG variant are 70-80% lower than for the gasoline vehicle.

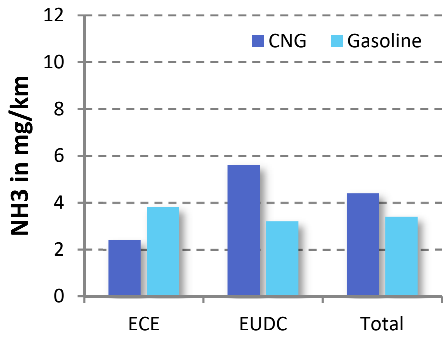
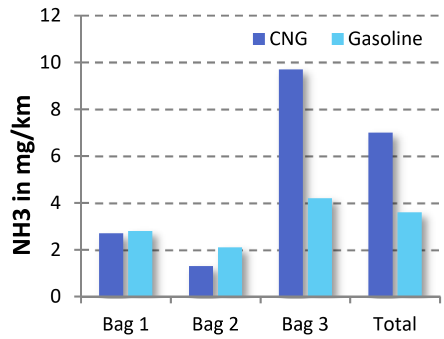
NEDC

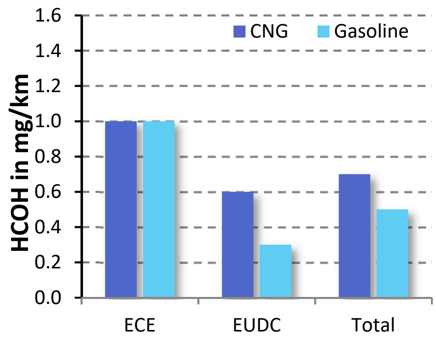
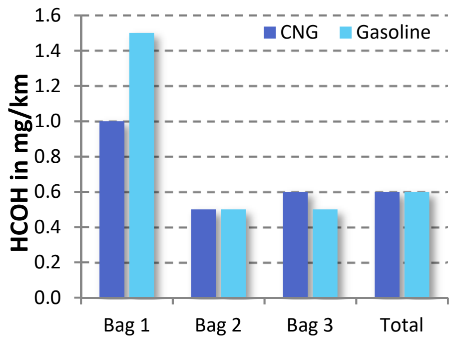


WLTC



<table>
<tr><th>NH_3 emissions</th><th>NEDC</th><th>WLTC</th></tr>
<tr><td>During cold start, the NH_3 emissions are on a comparable level, but increase significantly for the CNG vehicle during the hot, high load sections.

It has to be noted, that only one cycle has been measured to analyze the NH_3 behavior</td><td>
</td><td>
</td></tr>
</table>

<table>
<tr><th>HCHO emissions</th><th>NEDC</th><th>WLTC</th></tr>
<tr><td>The formaldehyde (HCOH) emissions are on a similar level for both vehicle types, with slight disadvantages for CNG in the EUDC and slight disadvantages for the gasoline variant during the WLTC cold start</td><td>
</td><td>
</td></tr>
</table>

3.4 RDE

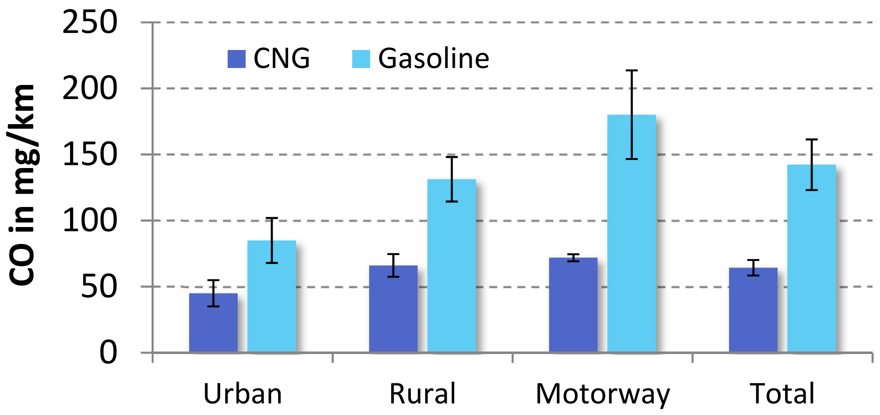
The RDE measurements during real world operation have been used to validate the findings during the chassis dyno tests. It has to be noted, that the emission results have not been calculated according to the legislative method (Moving Average Window, MAW), but have been calculate for each regional section (Urban, Rural, Motorway; see 2.4) and as a total result over the complete driving distance of the route. No values have been excluded in the emission calculation.

To get a more stable picture of the exhaust emissions during real world operation, the same route has been repeated three times. Due to the traffic situation on the motorway, the gasoline vehicle shows a slightly lower average speed in this section in comparison with the CNG vehicle.

The average emission results of these tests are listed below.

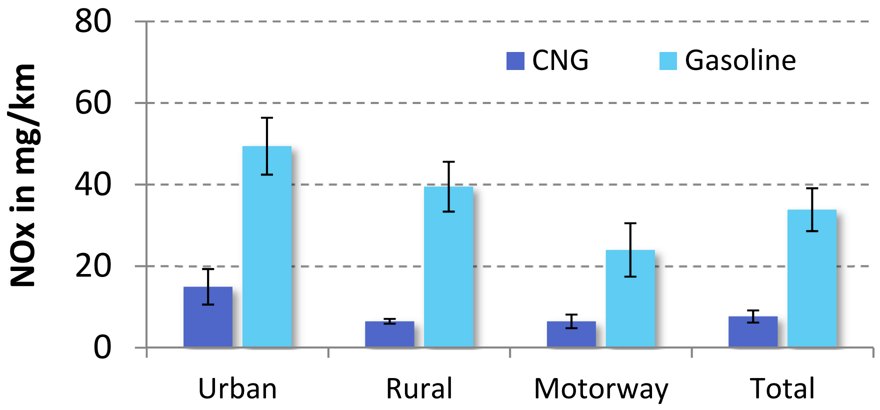
CO emissions

The CO emissions are lower and more constant for the CNG vehicle compared to the gasoline vehicle (8-70%)



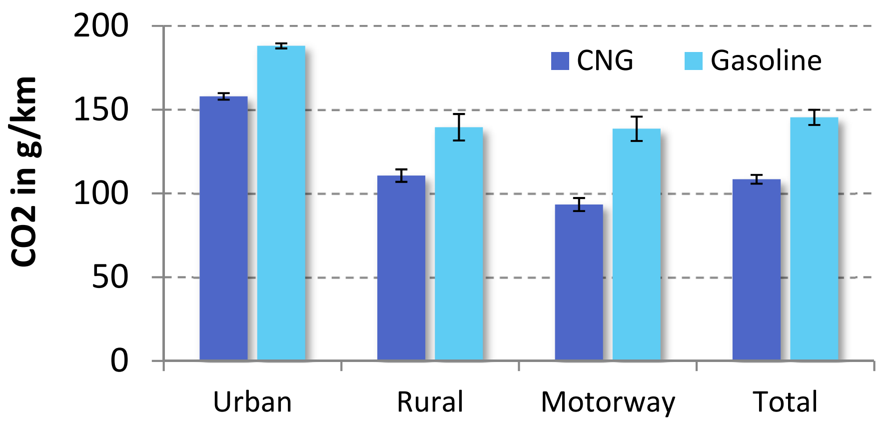
NOx emissions

The NOx emissions of the CNG vehicle during the on road measurements are lower (60-85%) than those of the gasoline vehicle



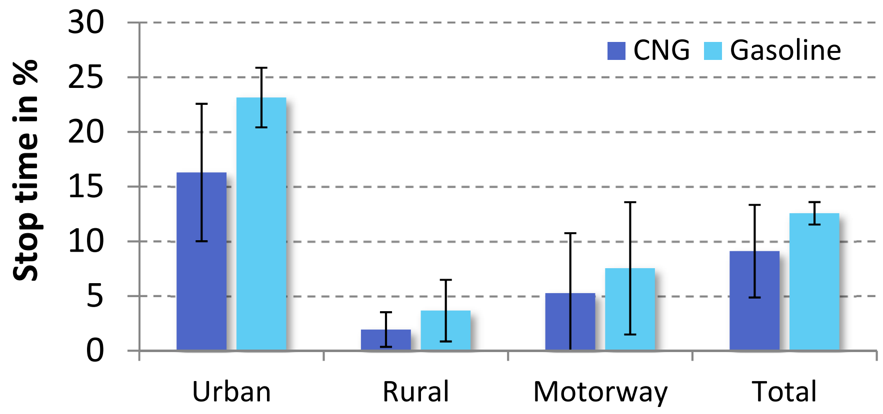
CO_2 emissions

In comparison to the chassis dyno measurements, the gap between the two fuels increased with respect to the CO_2 emissions (16 - 34%).



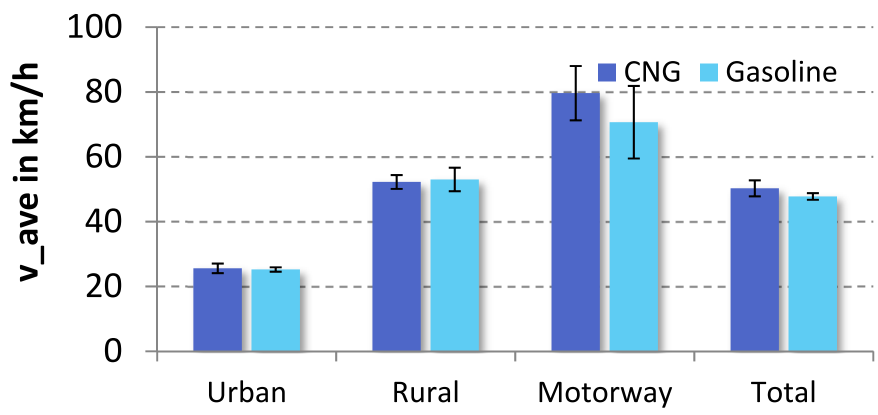
Stop time

The stop times during the on road measurements are comparable for both vehicles, with slightly lower shares for the CNG vehicle.



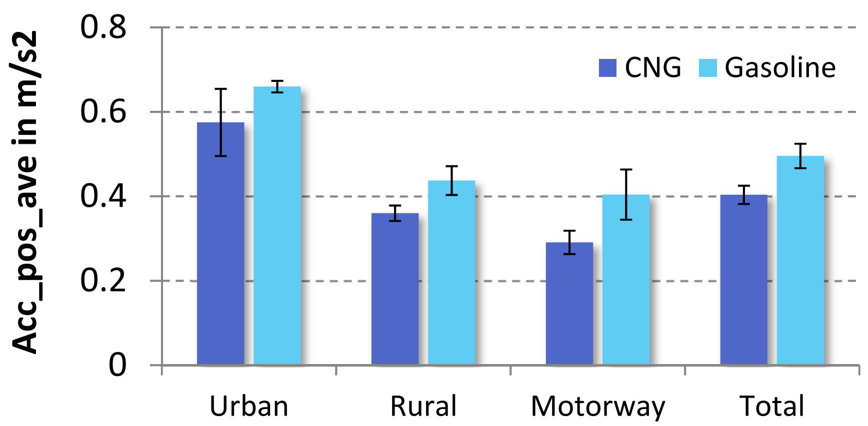
Average speed

The average speeds during the on road measurements are comparable for both vehicles, with slightly lower speeds for the gasoline vehicle in the motorway section.



Av.pos.acceleration

The average positive acceleration during the on road measurements are slightly lower for the CNG vehicle.



4 Data tables

CO_2 [g/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	148.3	86.7	109.4		138.1	98.2	92.4	99.7
Gasoline	186.0	111.2	138.7		173.5	123.7	117.6	126.3

CH_4 [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	101.0	4.4	39.9		149.3	17.1	3.6	25.7
Gasoline	8.4	0.6	3.4		9.1	1.0	0.9	2.0

N_2O [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	1.5	0.3	0.7		4.4	0.7	0.3	0.9
Gasoline	2.0	0.3	0.9		5.9	1.8	0.8	1.7

THG [g/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	150.9	86.9	110.4		142.6	98.8	92.6	100.5
Gasoline	186.8	111.3	139.1		175.5	124.3	117.9	126.8

NMHC [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	13.4	0.5	5.2		25.5	2.1	0.4	4.1
Gasoline	81.9	0.3	30.4		111.0	1.6	1.2	15.8

T.HC [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	123.5	5.3	48.7		188.2	20.7	4.3	32.1
Gasoline	91.1	1.0	34.1		121.0	2.7	2.2	18.0

NMOG [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	6.0	0.3	2.4		9.2	1.0	0.2	1.6
Gasoline	85.9	0.9	32.2		114.1	2.6	2.0	17.0

NOx [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	53.4	11.0	26.6		132.2	16.8	8.3	26.5
Gasoline	59.7	12.2	29.7		197.6	119.3	75.8	100.9

NMOG+NOx [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	59.4	11.3	29.0		141.5	17.8	8.6	28.1
Gasoline	145.6	13.1	61.9		311.7	121.8	77.9	117.9

PN [1/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	3.01E+10	4.92E+09	1.42E+10		3.48E+10	1.16E+10	6.45E+09	1.13E+10
Gasoline	4.61E+11	3.30E+11	3.78E+11		7.58E+11	3.30E+11	4.35E+11	4.56E+11

NO_2 [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	17.9	6.0	10.4		28.7	10.5	10.5	12.9
Gasoline	17.4	9.2	12.2		20.4	11.4	9.8	11.6

CO [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	32.2	22.1	25.8		52.6	3.6	40.5	34.5
Gasoline	242.2	62.5	128.6		383.2	35.8	87.8	116.3

NH_3 [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	2.4	5.6	4.4		2.7	1.3	9.7	7.0
Gasoline	3.8	3.2	3.4		2.8	2.1	4.2	3.6

HCOH [mg/km]	ECE	EUDC	NEDC		Bag 1	Bag 2	Bag 3	WLTC
CNG	1.0	0.6	0.7		1.0	0.5	0.6	0.6
Gasoline	1.0	0.3	0.5		1.5	0.5	0.5	0.6

Table 4: Chassis dyno results, average of two consecutive tests for regulatory emissions, results of one test for non-limited pollutants; Bag 3 of WLTC tests represents the results of phase 3 and 4 of the WLTC

CO [g/km]	Urban	Rural	Motorway	RDE Total
CNG	45.0	66.1	71.9	64.3
Gasoline	85.0	131.3	180.1	142.3

NOx [mg/km]	Urban	Rural	Motorway	RDE Total
CNG	14.9	6.5	6.5	7.6
Gasoline	49.4	39.5	24.0	33.8

CO_2 [g/km]	Urban	Rural	Motorway	RDE Total
CNG	157.9	110.6	93.4	108.4
Gasoline	188.1	139.5	138.6	145.4

Stop time [%]	Urban	Rural	Motorway	RDE Total
CNG	16.3	1.9	5.3	9.1
Gasoline	23.1	3.7	7.5	12.6

V_{ave} [km/h]	Urban	Rural	Motorway	RDE Total
CNG	25.6	52.2	79.6	50.3
Gasoline	25.2	53.0	70.7	47.8

Acc_{pos} [m/s^2]	Urban	Rural	Motorway	RDE Total
CNG	0.6	0.4	0.3	0.4
Gasoline	0.7	0.4	0.4	0.5

Time [s]	Urban	Rural	Motorway	RDE Total
CNG	789.0	994.4	737.5	2'520.9
Gasoline	969.0	983.1	897.9	2'850.0

Table 5: On road test results, average of three consecutive tests

Empa Report N° 5211.01067/1

CNG mobility
State-of-the-art technology

NFP70 project

Renewable Methane for Transport and Mobility

Sub-contracting project report 1

Empa
Swiss Federal Laboratories for Materials Science and Research
Ueberlandstrasse 129
CH-8600 Dübendorf

Automotive Powertrain Technologies Laboratory

Duebendorf, 20st of June 2017

Content

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1. Summary

Currently, 18 million CNG vehicles and 22'000 CNG fueling stations are in operation worldwide, 1.9 million CNG vehicles and 4'500 CNG fueling stations in Europe and 12'500 CNG vehicles and 140 CNG fueling stations in Switzerland. Only 4 countries in Europe don't have any CNG fueling station. Market penetration is increasing, although slowly, in most countries. It is expected, that this will be accelerated due to CO_2 laws and renewable energy initiatives worldwide.

CNG powertrains are available in the small, compact and mid-size vehicle class as well as in the van segment, as delivery vehicles and trucks/busses. Before 2000, in the passenger car sector, CNG vehicles were retrofitted from gasoline vehicles (1st generation). Afterwards, car manufacturers started to bring to market CNG vehicles using existing naturally aspirated gasoline engines with minor modifications (2nd generation). Today, the actual turbo-charged CNG vehicles are on a similar technical level as gasoline vehicles regarding powertrain technology (3rd generation). While the part-load performance is similar to gasoline vehicles, the maximum power output of the engine is slightly lower due to thermal limitations. However, especially in passenger cars, this effect is not really noticeable in reality.

The pollutions of CNG vehicles are typically lower than of gasoline or diesel vehicles, in particular concerning the ozone formation potential and the cancerogenic risks. The greenhouse gas emissions are roughly 20% lower in the passenger car segment than those of gasoline vehicles (15% lower than those of diesel vehicles) due to the lower carbon-content per energy unit. In the bus and truck segment, they are similar to those of diesel vehicles despite the lower carbon-content due to the lower efficiency of the actually used CNG combustion process.

In Switzerland, roughly 20% of the CNG is based on renewable energy (domestic biogas), which is reducing the greenhouse gas lifecycle emissions of CNG vehicles correspondingly. Taking this into consideration, the CO_2 emissions are 30 - 35% lower than those of gasoline vehicles. Using 100% renewable methane, the greenhouse gas lifecycle emissions are similar to a renewable energy operated battery electric vehicle.

In the passenger car sector, CNG vehicles are 10 - 20% more expensive than similar gasoline vehicles, leading to higher capital costs (CAPEX). However, due to the lower CNG price, the operational costs (OPEX) are lower. One important reason for the lower CNG price - despite significantly higher fueling station costs - is the reduced fuel tax compared with gasoline and diesel. Analyzing the costs of CNG fueling stations, reveals, that the capital cost of CNG fueling stations are highly relevant for the initial phase of the market penetration (up to 150 – 200 vehicles per fueling station), while their relevance is strongly decreasing with increasing vehicles numbers. Assuming a market penetration of 400 vehicles per fueling station, they would be economically profitable even with standard fuel taxation.

Due to the CO_2-legislation, CNG vehicles are of growing interest for car manufacturers. CNG vehicles already comply with exhaust aftertreatment technology to all foreseeable pollution limits, at least in Europe, while gasoline and especially diesel engines in the passenger car segment need substantial, additional technical effort in the future.

All-in-all, CNG vehicles are a cost-effective solution for sustainable mobility, if renewable energy based methane is used and a 1% market penetration barrier can be overcome. Some countries, as for example Germany, and fleet operators, as for example European city bus operators, are more and more evaluating the use of CNG vehicles.

2. **CNG mobility**

CNG vehicle statistics

Compressed Natural Gas (CNG) was first used in Europe as a motor vehicle fuel in Italy after the 2nd World War[1]. The main reason for this was the limited availability of gasoline and diesel at the time. In the 80's, more stringent emissions legislation for passenger cars in the EFTA-states was introduced and the motivation for using CNG shifted to pollution reduction. Later, in the 90's, the use of Biogas in CNG vehicles started in several countries. In Switzerland, for example, CNG actually contains about 20% Biogas. Since the introduction of the CO_2 emissions legislation for passenger cars in 2009[2], CNG was "discovered" by the automotive industry, as being an increasingly interesting fuel. Today, energy systemic studies show the potential to reduce CO_2 by methane, produced in Power-to-Gas facilities[3].

Today, more than 1.9 million CNG vehicles and 4'500 CNG fueling stations are in operation in Europe[4]. Only 4 European Countries (Cyprus, Ireland, Malta and Romania) have no CNG fueling stations. However, the penetration of CNG fueling stations and vehicles in most European countries is rather low. The overall proportion of CNG vehicles in Europe is at 0.55% with only a few countries such as Italy, Bulgaria or Ukraine having higher values (2.2%, 1.8% and 5.1% respectively). Due to the importance of alternative vehicles in Europe in achieving compliance with future requirements (energy supply security, CO_2 reduction), the European Commission launched the 2014/94/EC regulation for the coordinated establishment of alternative fuel infrastructure. This obliges all member states to develop strategies for a nation-wide deployment of charging stations for electric vehicles, as well as refueling stations for hydrogen and CNG by the end of 2016. It is probable that this will lead to a significant increase of CNG refueling stations in Europe.

Taking a worldwide perspective, today nearly 18 million CNG vehicles and more than 22'000 CNG fueling stations are in operation in 82 countries. Some countries shows a high CNG vehicle market share (Bangladesh: 62%, Bolivia: 28%, Colombia: 15%, Iran: 27%, Pakistan: 80%, Peru: 10%, Uzbekistan: 26%)[4].

One important reason for CNG mobility is the lower fuel price compared to gasoline and diesel in many countries. Fig. 1 shows that the price of CNG fuel in most European countries is less than half that of gasoline or diesel.

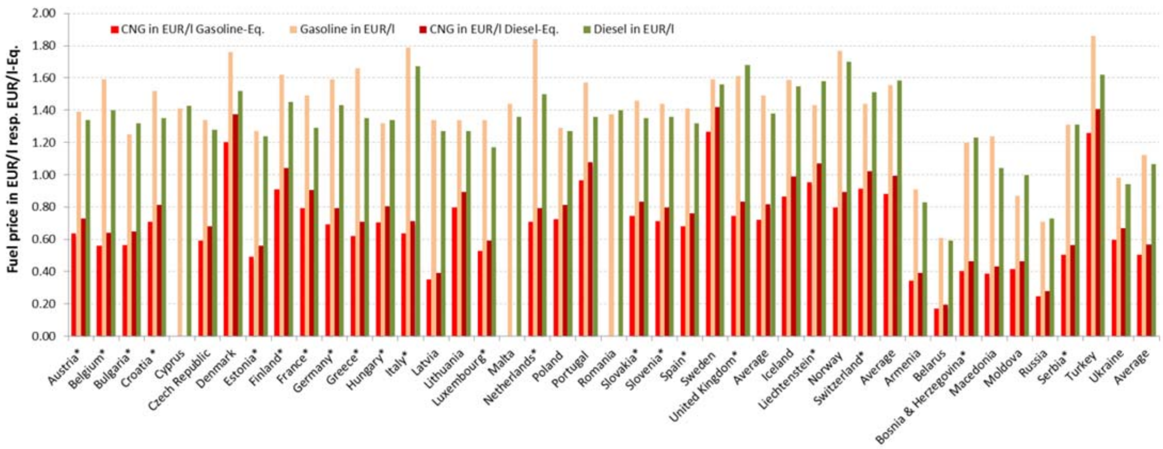


Fig. 1 CNG fuel price in European countries compared with gasoline and diesel (2014)[4]

[1] http://www.gocleanng.com/learn/cng-history

[2] Regulation (EC) No 443/2009 of 23 April 2009 (CO2 emissions from light-duty vehicles)

[3] Fraunhofer, Interaktion EE-Strom, Wärme und Verkehr (Sept. 2015)

[4] http://www.ngvaeurope.eu/european-ngv-statistics

CNG passenger car technology

Before the year 2000 (when Euro-0 to Euro-2 emissions legislation was in force), almost no European passenger car manufacturer produced CNG vehicles. CNG vehicles were converted from gasoline vehicles using retrofit systems with a CNG steel cylinder (designated as "type I") in the trunk, which of course reduced the utility-value of the vehicle. The typical range in CNG operation was 200 – 250 km. Such vehicles with naturally aspirated engines often suffered reduced engine power due to the gaseous nature of the fuel, which inhibited the intake of fresh air for combustion, thereby reducing the volumetric efficiency of the engine. Engine control in CNG operation was done at this time by an additional engine control unit (ECU), translating the gasoline ECU output signals for ignition and injection by simple maps into signals appropriate for CNG operation. The comparably low requirements for on-board-diagnosis (OBD) at that time made such retrofitted solutions possible. Due to the well behaved combustion characteristics of CNG it was possible to achieve low pollution values despite such limited engine control technology[5].

Before 2000	2000 – 2005	2006 – 2020
Retrofit aftermarket "Tank in trunk vehicles"	**OEM 1st generation** CNG operated, naturally aspirated gasoline engines	**OEM 2nd generation** CNG operated, turbo charged gasoline engines
		
Advantage: Most gasoline vehicle were convertible. **Disadvantages:** Poor technology level; Loss of utility value (trunk) **CNG range:** 150 – 250 km **Engine power:** -10 ... -15% **Additional cost:** +3'000 ... +5'000 CHF	**Advantage:** Good working, robust technology **Disadvantage:** few vehicle models available only **CNG range:** 250 – 450 km **Engine power:** -10 % **Additional cost:** +5'000 ... +7'000 CHF	**Advantage:** Same technology level as gasoline vehicles **Disadvantage:** no disadvantage for end-user **CNG range:** 400 – 500 km **Engine power:** as gasoline engine **Additional cost:** +2'000 ... +4'000 CHF

Table 1: Development of CNG passenger car concepts pre-2000 to 2020

From 2000 - 2005 (when Euro-3 emissions legislation was in force), car manufacturers started to produce their own, purpose built CNG vehicles. These OEM CNG vehicles were still typically based on a naturally aspirated gasoline engine but used much more advanced engine control technologies and underfloor CNG steel cylinder storage (type I) allowing a vehicle range of 250 - 350 km. These OEM CNG vehicles were much more reliable and had fewer disadvantages for the user. At the time, CNG vehicle pollutant emissions were already at a very low level. In the USA, for example, the first "SULEV" (Super-Ultra-Low-Emission-Vehicle) – the most stringent pollution regulation world-wide – was a CNG vehicle, a Honda Civic GX[6].

[5] Bach C. et al; Effect-based Assessment of Automotive Emissions; MTZ Motortechnische Zeitschrift (1998)

[6] Honda press-release; Honda Civic GX Leads The Environmental Pack as 'World's Cleanest' (2003)

Since 2006 (the period covered by Euro-4 to Euro-6 emissions legislation) car manufacturers have been using modern state-of-the art turbo-charged gasoline engines as the power plant for CNG vehicles. Some are so-called "dedicated" CNG concepts with a gasoline emergency tank of maximum 14 l capacity, whilst others are fully bivalent CNG/gasoline concepts with a larger gasoline tank. The CNG equipment led typically to an additional vehicle weight of 100 – 150 kg, predominantly due to the mass of the CNG steel cylinders with 60 - 120 l water volume. The weight of such type I CNG steel cylinders is roughly 1 kg/l water volume. In the recent past, car manufacturers have started to use fully composite CNG cylinders (designated as type IV), resulting in significant lower additional mass (0.4 kg/l).

State-of-the-art 2016 passenger cars have a typical CNG range of 350 – 500 km and, in addition, a similar range under gasoline operation (respectively 150-250 km for dedicated CNG vehicles). Using Type IV cylinders, the additional weight penalty is less than 50 kg. The engine power is comparable to the gasoline engine due to the turbocharging, which compensates for the volumetric efficiency losses of the gaseous fuel. Apart from the roughly doubled CNG refueling interval compared with a gasoline or diesel vehicle, the end-user suffers no utility-value reduction, meaning that trailer hauling or other modes of high continuous load operation are possible.

CNG utility vehicles (>3.5 tons gross vehicle weight)

In the utility vehicle sector (>3.5 tons gross vehicle weight), CNG vehicles are typically used as city buses, waste collecting trucks and delivery vehicles. The motivation for these applications was, in the past, mainly the lower exhaust gas pollution levels compared to diesel vehicles. The first so called "Enhanced Environmentally friendly Vehicles" (EEV), a voluntary special certification class for heavy duty engine applications with reduced pollution limits, were gas-fueled buses[7]. In the meantime, diesel buses now also comply with EEV standards, although this is achieved through the use of more expensive exhaust aftertreatment technology.

In the past, CNG utility vehicles showed a significantly higher energetic fuel consumption than diesel vehicles (up to >50 %), due to the additional weight for CNG storage in steel cylinders (up to 1'000 kg for a city bus), the use of older diesel engines with high friction losses as a basis for the CNG engine, the throttle based load control or not fully optimized engine parts (e.g. turbo charger, valve timing, pistons). Recently, engine manufacturers have increasingly focused on CNG engines for utility vehicles due to the increasing marked demand in the USA, Asia and the European city bus sector. New Euro-VI CNG engines for buses show CO_2 values 5 - 10% below comparable diesel engines, which means a reduction of the additional consumption to 10 – 15% above the diesel engine. At the same time, the exhaust gas aftertreatment system is much simpler (and much lower cost) than that for a diesel engine.

[7] S. Hausberger et al; Emissions and Fuel Consumption of Clean City Bus Concepts (2007)

It is expected that the market for CNG fueled utility vehicles will grow in Europe due to the increasing sensitivity to using renewable energy and the increasing costs of clean diesel engine technology. A survey carried out as part of the EU project “3iBS” (intelligent, innovative and integrated Bus Systems in Europe), for example, with 70 stakeholders in 63 European cities, totaling a fleet of 70,000 buses, revealed intended changes in the propulsion modes for city buses (Fig 2). The current high market share of 80% for diesel buses is predicted to drop to 25%, while the proportion of CNG and biogas buses will increase from 10% to 30%. Fig. 2 shows that in the city bus segment, CNG could in future play a similar role to that of electric vehicles.

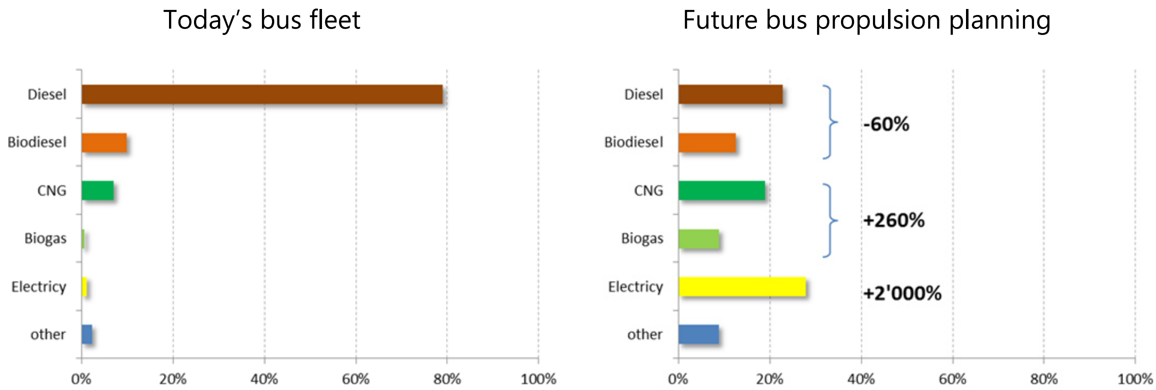


Fig. 2 Today’s bus fleet powertrain distribution and stakeholder plans for the future (source: www.3ibs.eu)

For medium and long distance transport, natural gas can be liquefied at a temperature of -162 °C, reducing the volume by a factor of 600 and making it possible to store large amounts of natural gas in cryogenic tanks. A long-haul truck needs about 700-900 l LNG to achieve a similar level of autonomy as a diesel truck. The necessary LNG tank would easily fit in such vehicles. There is an ongoing project to establish and demonstrate the use of heavy duty vehicles and LNG filling stations on transit corridors across Europe[8]. However, the use of LNG only makes sense if natural gas is already transported and distributed as LNG, which is increasingly the case for long distance supply chains.

In all cases, the use of CNG as fuel is receiving more attention due to the CO_2 emissions legislation in the vehicle sector. This began in Europe in 2012 - 2015 for passenger cars (with 130 g/km as a fleet average limit and 95 g/km beyond 2020) and in 2014 - 2017 for light duty delivery vehicles (with 175 g/km and 147 g/km beyond 2020). CO_2 limits for heavy duty vehicles are expected to come into force in 2021 – 2022.

Today, road-transport based CO_2 emissions in Europe are dominated by passenger cars, with a fraction of nearly 60%, while light duty delivery vehicles are responsible for 10% and heavy duty vehicles (trucks and buses) for 30%[9].

[8] LNG Blue Corridors project, http://lngbc.eu/

[9] Transport & Environment; Too big to ignore – truck CO_2 emissions in 2030 (September 2015)

CNG fueling station technology

In Europe the final CNG fueling pressure is 200 bar at 15°C. The fueling process is leading in a first phase (expansion) to a decrease of the gas temperature in the gas-cylinder of the vehicle. Thereby, the incoming gas is then increasingly compressed up to the final fueling pressure. This compression in the gas-cylinder increases the gas temperature. After some time, the gas temperature in the CNG cylinder stabilizes to ambient temperature due the heat exchange with the surroundings, leading to a slight decrease in pressure. Modern CNG fueling stations compensate for these gas temperature effects during the fueling process.

In some countries (e.g. USA), a higher final fueling pressure of 248 bar (3'600 PSI) at 70 °F (21 °C) is allowed. Higher pressure is interesting due to increased vehicle range; however, higher pressure means higher energy losses. Up to 250 bar and 323 K (50°C) the coefficient of compressibility for methane is below 0.9 (Fig. 3). At higher pressures, the coefficient of compressibility increases, which explains why the mass of methane (CNG) in the tank does not increase proportionally to with pressure.

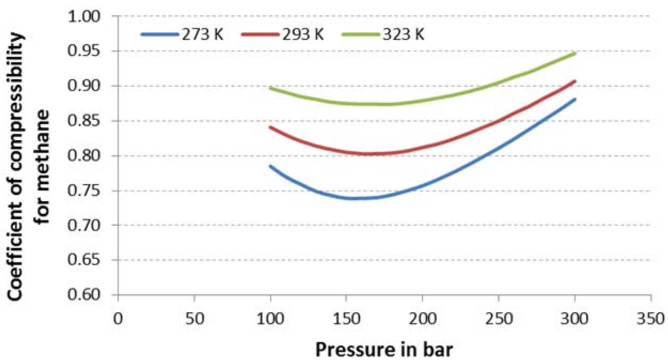


Fig. 3: Coefficient of compressibility for methane (CNG)

Typical CNG fueling stations in Switzerland are equipped with an 80 - 160 Nm^3/h compressor, a usable CNG storage (at 240 - 280 bar) of 60 - 120 kg and a dispenser with 1 - 2 fueling lines. This allows the consecutive fueling of 6 - 8 vehicles per hour without significant increase in fueling time compared to gasoline or diesel vehicles. The CNG flow during fueling is on average 8 – 12 kg/min, resulting in a fueling time for 20 kg CNG storage in a mid-size passenger car of 2 - 3 Min.

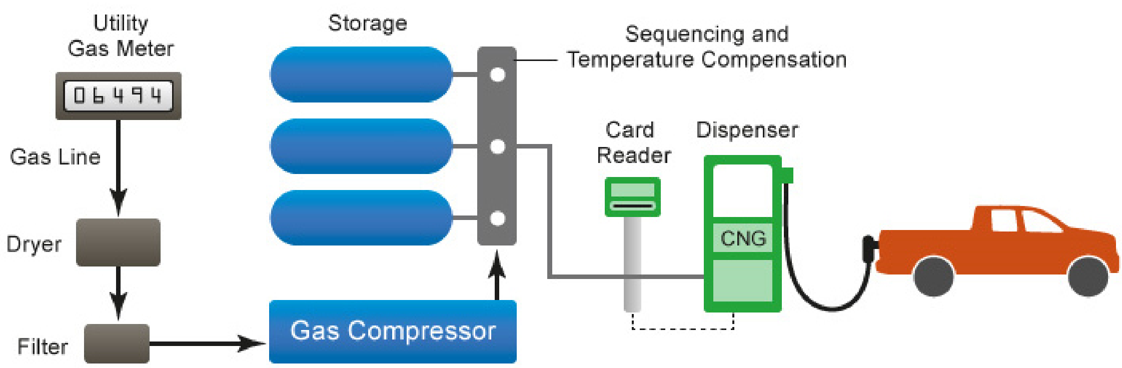


Fig. 4: CNG fueling station for passenger cars/delivery vehicles with gas compressor, storage and dispenser as main parts (Source: US DoE)

Economic operation of CNG fueling stations depends strongly on the sales volume. Fig. 5 shows the CNG total cost per gasoline liter equivalent for different sales volumes, indicated as average CNG vehicle number per fueling station or CNG sales volumes (turnover) per fueling station with total investment cost of 550 kCHF, depreciation time of 15 years, CAPEX return of 3% p.a., gas price from 0.05 CHF/kWh (for 500 MWh/a) – 0.04 CHF/kWh (5'000 MWh/a), electricity cost of 0.15 CHF/kWh and a margin of 5%.

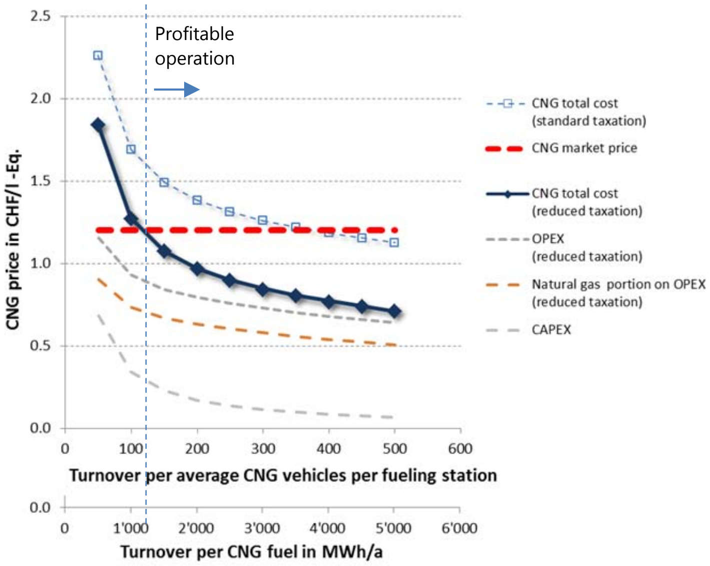


Fig. 5: CNG end user cost as a function of the CNG vehicle or CNG sales volume at a CNG market price of 1.20 CHF/l-eq. Solid bold line for reduced fuel taxation of 0.2222 CHF/kg CNG and dotted line for standard fuel taxation of 0.8092 CHF/kg CNG)

Today, 12'500 CNG vehicles and 140 CNG fueling stations are in operation in Switzerland, resulting in an average of 90 vehicles per fueling station (for comparison: 1'500 gasoline/diesel vehicles per fueling station). This means according to Fig. 5, the CNG fueling stations are not yet profitable on average. For a profitable operation at a CNG market price of 1.2 CHF/l-eq (reduced taxation), 120 - 140 vehicles per fueling station, or roughly 17'000 – 20'000 CNG vehicles in Switzerland would be necessary. Above 400 CNG vehicles per fueling station, CNG stations are profitable on average even with standard taxation.

With a low market share of CNG vehicles, the investment costs (CAPEX) for fueling stations are crucial, while above the profitability limit, the OPEX (mainly natural gas) becomes the most important cost fraction, accounting for up to 70% of the total CNG costs at high market share values.

Taxation rates for alternative fuels such as CNG vary widely across Europe. Some countries have very low taxes, others like Switzerland or Germany impose similar taxation rates as for gasoline or diesel but have temporarily reduced taxation during a market implementation phase. In Switzerland, a reduced taxation of 0.2222 CHF/kg (0.0163 CHF/kWh) is currently in force, until 30.06.2020. The standard taxation is 0.8092 CHF/kg (0.0594 CHF/kWh if the average natural gas specifications 2015 are assumed[10]). For comparison, the taxation for gasoline is 0.0840 CHF/kWh and 0.0780 CHF/kWh for diesel.

[10] Erdgas - Zusammensetzung der Swissgas - Importe im Jahre 2015 (2016)

The European Union is planning the establishment of a coordinated area-wide fueling station infrastructure for alternative fueled vehicles with 1 public electric charging station per 10 battery electric vehicles, a CNG fueling station every 150 km as well as hydrogen and LPG stations[11]. For hydrogen and LPG no quantitative requirement is intended. For Switzerland with 70'000 km road network, this would mean roughly 500 CNG fueling stations. To economically operate this number of fueling stations (see Fig. 4), at least 60'000 CNG vehicles would be necessary (the reduced tax scenario), or 200'000 – 250'000 CNG vehicles for the standard taxation case.

The service potential of 500 fueling station however would be much higher. 500 one-dispenser CNG fueling stations with 2 independent fueling lines would allow the refueling of more than 300'000 CNG vehicles with 20 kg fueling capacity, assuming today's fueling distribution rate over day-time (90% of refueling takes place during the period 06.00 – 18.00 h with peaks at 07.00, 12.00 and 16.00 h). This translates to roughly 600 vehicles per CNG dispenser. This value is nearly double that for gasoline/diesel fueling stations in Switzerland (320 vehicles per dispenser) but similar to the figure for Germany, with roughly half the fueling stations per passenger car[12]. With larger CNG storage volumes at the fueling stations and multi CNG dispenser stations, the potential for CNG vehicle refueling can be easily increased. Assuming today's conditions, it is therefore possible from a technical point of view to operate a large number of CNG vehicles on an economic basis. This, however, is interesting because the potential for renewable methane is also high.

The fueling of heavy duty vehicles is very similar; however, the refueling stations have to be designed for higher fueling rates and with higher storage capacities.

[11] EU Directive 2014/94/EG

[12] Scope Investor Services; Branchenstudie Tankstellenmarkt Deutschland 2015 (März 2016)

3. CNG internal combustion engine technology

Gasoline engine based CNG engines (passenger car and light delivery vehicles)

State-of-the-art gasoline engine based CNG vehicles (passenger cars and light duty delivery vehicles) show similar energetic fuel consumption during normal operation and slightly increased efficiencies at higher loads (motorway driving) than gasoline vehicles. Similar energetic consumption is caused by similar engine friction, similar combustion process, similar gas-exchange, similar turbo-charging and similar exhaust aftertreatment. But CNG sold in Switzerland has a higher octane number than gasoline, which enables engine operation at higher compression ratios and/or higher boost pressure levels without knock problems. This leads to an efficiency increase of 1 - 3%. On the other hand, the curb weight of CNG vehicles with type I gas cylinder (steel) is increased by 80 – 120 kg which raises the vehicle's energy demand by 1 – 3%, thus nullifying the octane number advantage. The somewhat higher efficiency during high-load driving is a result of the commonly used fuel enrichment technique with gasoline engines for exhaust valve and turbo-charger protection using the evaporation-heat of the added liquid fuel for combustion temperature reduction. This cooling effect is not possible for gaseous CNG, which is why CNG engine parts have to be designed for higher temperatures. Despite the similar energetic fuel consumption, CNG vehicles show 20 - 22% reduced CO_2 emissions than gasoline vehicles due to the lower carbon-content in the fuel (see chapter 4). If some fraction of biogas or synthetic methane is used instead of 100% fossil-derived natural gas, the reduction of greenhouse gases is even larger.

As mentioned above, methane, the main component of CNG, has a significantly higher knock resistance than gasoline (up to 130 octane) and would therefore allow the designing of combustion concepts with higher in-cylinder peak pressures without the danger of uncontrolled self-ignition (knock-events). Higher peak pressures are possible with higher compression ratios and higher boost pressures, resulting in higher thermal efficiency. However, in today's gasoline based CNG engines, peak pressures are limited to about 100 bar due to the mechanical design of the engine block. Higher peak pressures cannot be used with gasoline engines due to the knock limitations of gasoline. This situation is actually the major obstacle to improving gasoline based CNG engine efficiency.

The engine load is typically measured as torque or – independent from engine displacement - as "break mean effective pressure" (BMEP), representing the average pressure in the combustion chamber during the combustion cycle. The behavior of the combustion pressure (and as a result also of BMEP) depends on combustion parameters such as engine charge, compression ratio, fuel knock resistance, ignition and inflammation processes, and turbulent flame speed. BMEP values of actual gasoline based CNG engines are shown in Fig. 6.

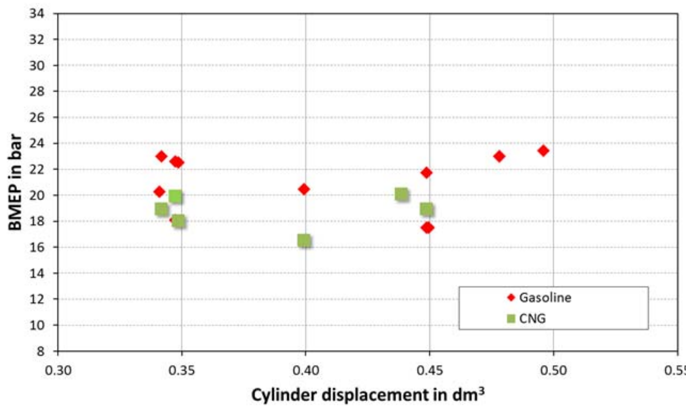


Fig. 6: Break Mean Effective Pressure (BMEP) over cylinder displacement for gasoline and CNG passenger car engines

Fig. 6 shows that today's CNG engines are designed with slightly lower BMEP values. However, this does not mean "lower efficiency" but slightly lower power. This could be because thermal overload at high power output is simpler to solve for gasoline than for CNG engines. In addition, Fig. 5 shows that CNG engines do not yet make use of their intrinsic high knock resistance potential.

While high knock resistance is very welcome in terms of overall combustion, it is a challenge for the ignition phase because high knock resistance means, in other words, "poor ignitability". CNG in Switzerland is composed mainly of methane (>90%), which is the smallest possible hydrocarbon without carbon double bonds. This molecule is much harder to crack by the spark break-through during ignition than the long-chained and/or unsaturated hydrocarbons in gasoline. The hydrocarbon cracking process which occurs during ignition creates highly reactive components and radicals (OH or HO_2) which are crucial for the following exothermic chemical reactions, the second inflammation step. These radical reactions continuously increase the local temperature and finally initiate thermal flame kernels, which is the third step in inflammation and the start of the (thermal) combustion process.

Current CNG passenger car engines use the same ignition technology as gasoline engines, sometimes slightly modified (e.g. with higher ignition energy and improved spark plugs). During normal engine start conditions and with well-maintained engines, no significant difference to gasoline engine starting is noticeable. For more difficult conditions (e.g. ambient temperatures below freezing point, high humidity, worn spark-plugs) the engine crank time may be 1 – 2 seconds longer for CNG than for gasoline engine. Adapted ignition systems might therefore be needed for future CNG engines.

Diesel engine based CNG engines (utility vehicles)

CNG engines for utility vehicles are based on diesel engines. The diesel injectors are replaced by spark plugs with ignition coil(s) – in some cases, a so called "pilot diesel injection" is used for ignition instead of the spark plug ignition system. In both cases, the gas is injected into the manifold and the typical swirl-oriented diesel engine piston with pronounced piston bowl is usually replaced by a flattened open chamber piston, leading to a more tumble-oriented gas-mixing process. The compression ratio is normally reduced from 17 – 20 (diesel) to 13 - 14 (CNG). CNG engine load control is performed with a throttle valve. Due to the thermal limitations of the engine materials, CNG engines based on diesel engine must be operated with lean mixtures or with a high exhaust gas recirculation (EGR) rate, if they are not adapted for use at high exhaust gas temperatures.

Modern diesel based CNG heavy duty vehicle engines show 5 – 15% lower efficiencies than the comparable diesel engines but, due to the lower carbon content per energy unit, slightly lower CO_2 emissions (Fig 7). If the current biogas blending fraction of 20% is considered, CO_2 emissions of CNG engines are significantly lower.

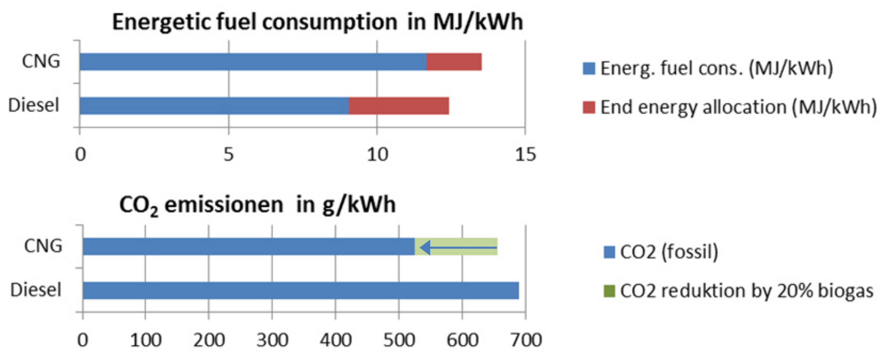


Fig. 7: Energetic fuel consumption (upper diagram) and CO_2 emissions of a 265 kW Euro-VI Diesel engine and a 250 kW Euro-VI CNG truck engine for the official heavy duty truck test cycle (WHTC)

The lower efficiency is a result of the lower compression ratio, the load control by intake air throttling and stoichiometric air/fuel operation. Diesel engine based CNG engines often have somehow lower power output than comparable diesel engines due to mechanical limitations in high engine speed.

Fig. 8 shows BMEP over cylinder displacement for diesel engine based CNG engines and diesel engines for light duty (LD) and heavy duty (HD) applications. As is the case for passenger car engines, CNG engines for utility vehicles generally have power and torque outputs below the average diesel engines.

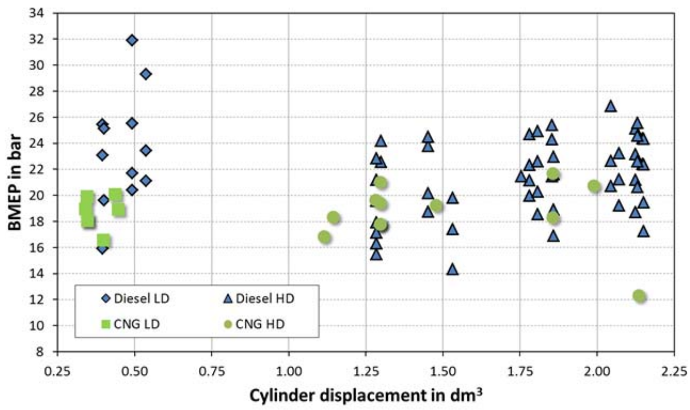


Fig. 8: Break Mean Effective Pressure (BMEP) against cylinder displacement for diesel and CNG light duty (LD) and heavy duty (HD) applications

4. Air pollution from CNG passenger car vehicles

It can be assumed that in future car manufacturer will be increasing looking for "zero pollution concepts" under real-world conditions instead of merely complying with specific emission legislation under laboratory conditions. Other concepts will probably not survive due to limited access to environmental zones.

Already, under the current European heavy duty pollution legislation (Euro VI), emission limits have to be confirmed during normal vehicle operation on the road, measured by portable emission measurement equipment (PEMS). Such legislation will come into force for passenger cars soon. This increases the pressure on manufacturers to develop technologies which are "clean" under all relevant operating conditions.

The polluting emissions of CNG passenger car vehicles in real-life operation are already today in general much lower than those of gasoline vehicles, as the following comparison of one CNG and one gasoline vehicle shows. The emissions investigations were performed in the laboratory (Fig. 9) using the current NEDC mandatory cycle as well as the new WLTC more realistic driving pattern, which will replace the NEDC in 2017 (Fig. 10).

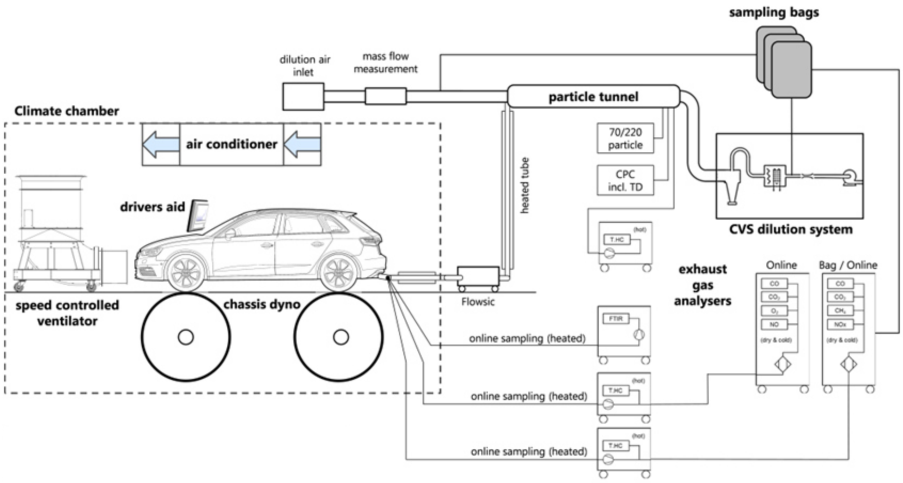
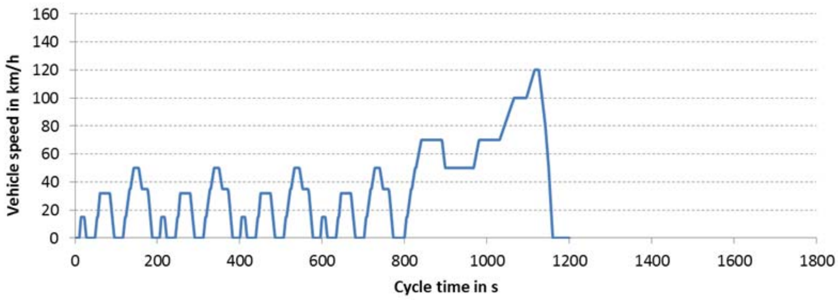


Fig. 9: Laboratory test setup for emissions investigations

NEDC

Actual mandatory driving cycle



WLTC

New mandatory driving cycle (2017)

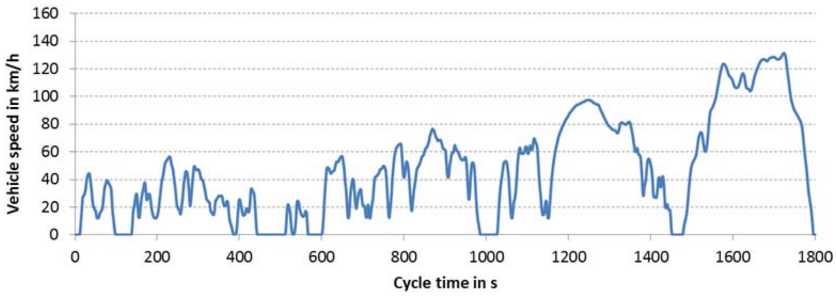


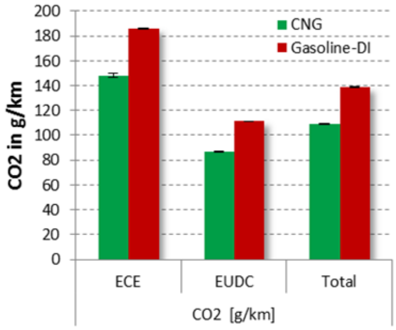
Fig. 10: Driving cycles used for emission investigations

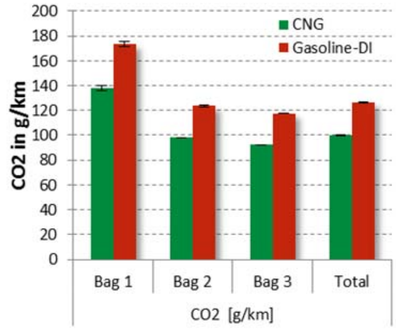
Greenhouse gases	**NEDC**	**WLTC**

CO_2 emissions

The CNG vehicle shows a CO_2 reduction of 20 – 22% compared with the Gasoline-DI vehicle.

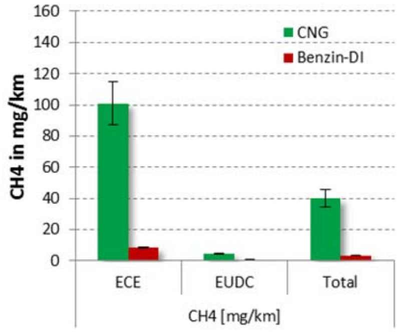
(Biogas fraction not considered)

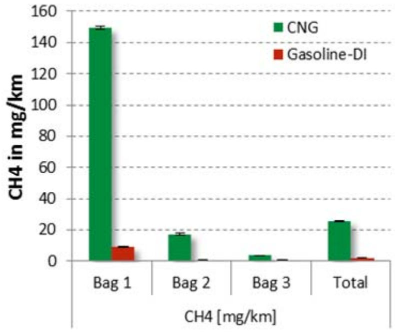




CH_4 emissions

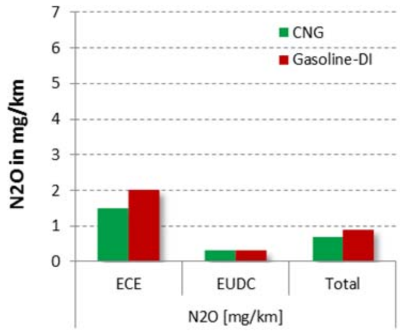
The CH_4 emissions of the Gasoline-DI vehicle are practically negligible. Those of the CNG vehicle after cold start are at 100 – 160 mg/km, compensating 2.1 – 3.2 g of CO_2 advantage.

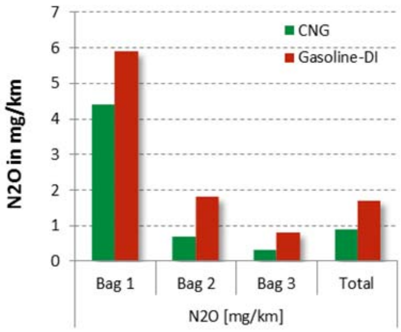




N_2O emissions

The N_2O emissions of the CNG vehicle are slightly below the Gasoline-DI vehicle in NEDC and significantly lower in WLTC.

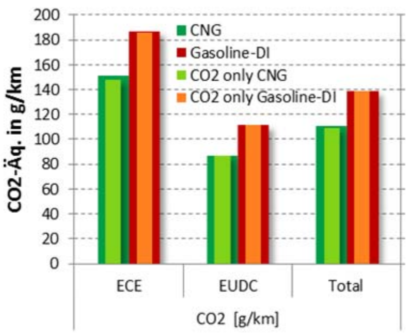




Total greenhouse gas emissions (GHG)

$CO_2 + 21 \times CH_4 + 310 \times N_2O$

The GHG emissions of the CNG vehicle are 19 – 22 % below those of the Gasoline-DI vehicle.



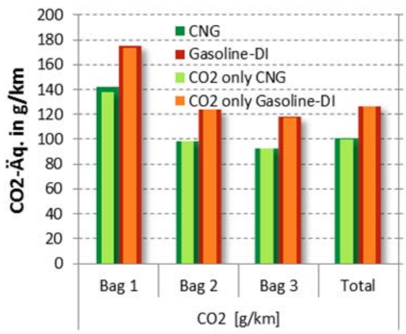


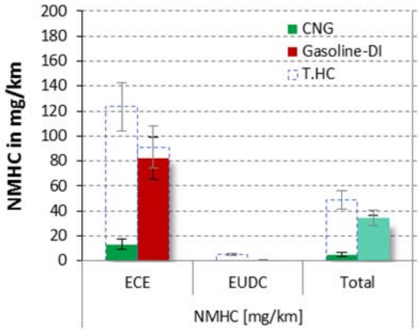
Fig. 11: Greenhouse gas emissions of a CNG (green) and gasoline (red) vehicle in NEDC (left) and WLTC (right)

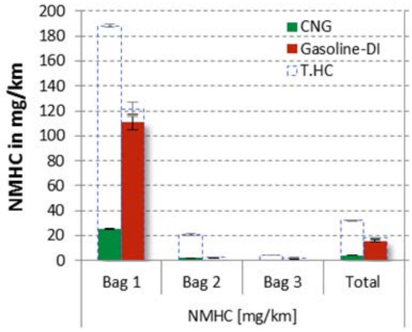
Ozone reactivity **NEDC** **WLTC**

NMHC emissions

The NMHC emissions of the CNG vehicle are 80% lower during cold start than those of the Gasoline-DI vehicle.

During warm engine driving, the NMHC emissions.



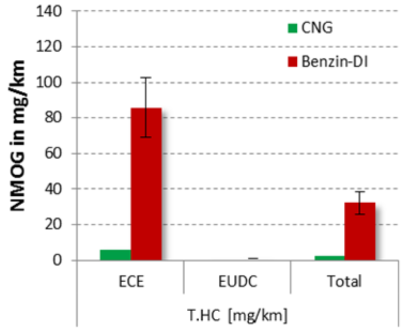


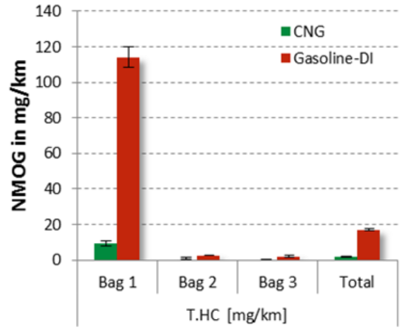
NMOG emissions

NMOG = T.HC x RAF
RAF: Reactive Adjustment Factor (EPA 2010)

RAF CNG: 0.049
RAF Gasoline-DI: 0.943

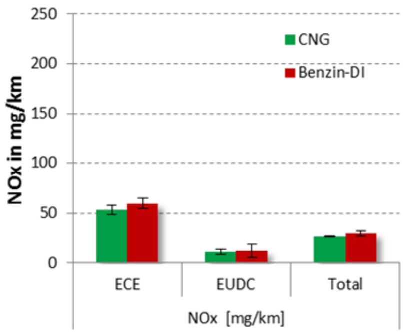
Ozone reactivity of the hydrocarbon emissions is 10 times lower for CNG vehicle than for Gasoline-DI vehicle.

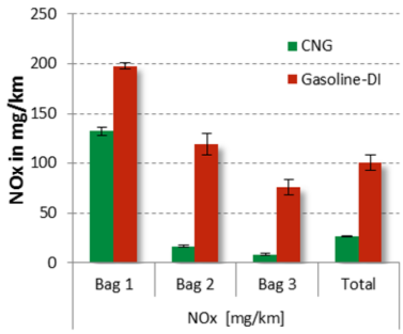




NOx emissions

In NEDC, NOx emissions are similar for CNG and Gasoline-DI; in WLTC, the emissions are significantly lower for CNG.

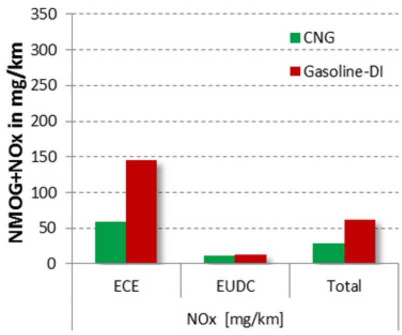




Total ozone reactivity

NMOG + NOx

Total ozone reactivity of CNG vehicle is 50 – 80 % lower than those of the Gasoline-DI vehicle.



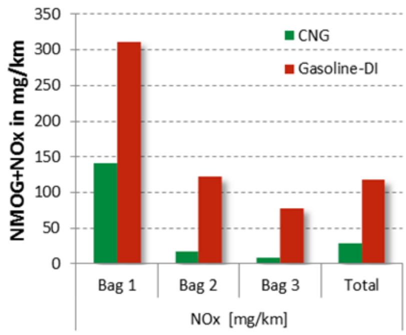
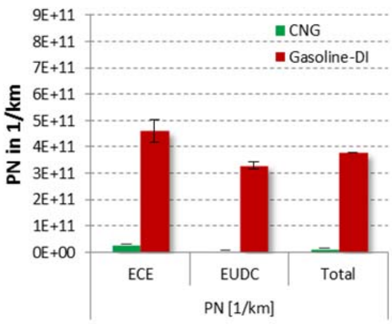


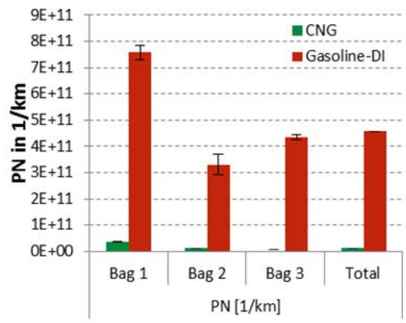
Fig. 12: Ozone reactivity of the exhaust emissions of a CNG (green) and gasoline (red) vehicle in NEDC (left) and WLTC (right)

Health risks	**NEDC**	**WLTC**

PN emissions

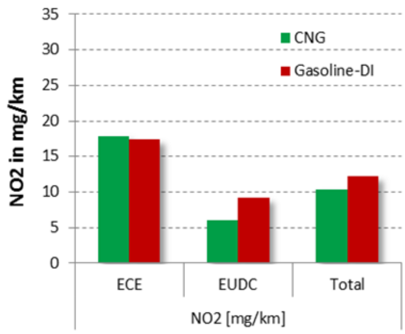
Particle number emissions of the CNG vehicle is 15 – 70 times lower than those of Gasoline-DI vehicle.

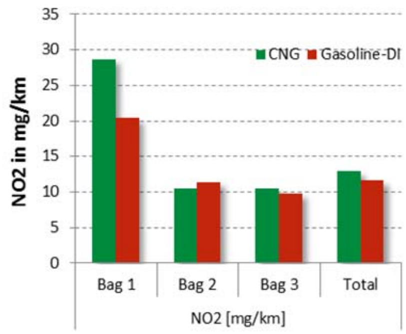




NO_2 emissions

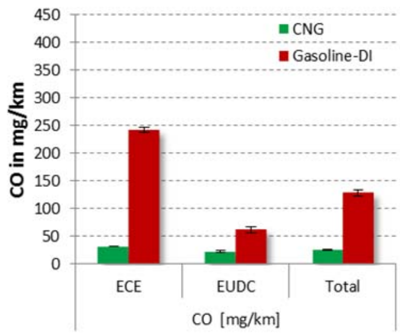
NO_2 emissions of the CNG vehicle are similar for CNG and Gasoline-DI vehicle and at a very low level. During cold start, the NO_2 emissions of the CNG vehicle are slightly higher.

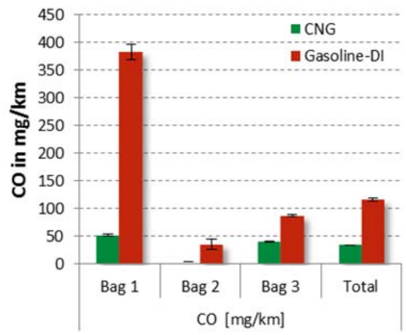




CO emissions

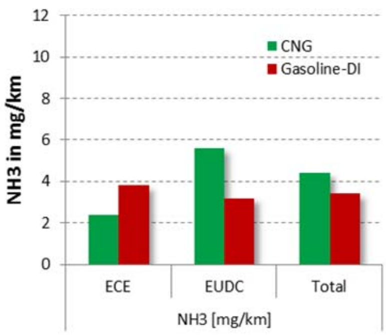
CO emissions of the CNG vehicle are 70 – 80% lower than those of Gasoline-DI vehicle.

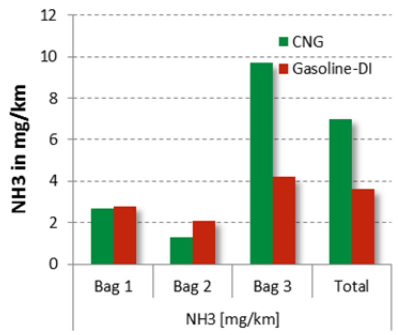




NH_3 emissions

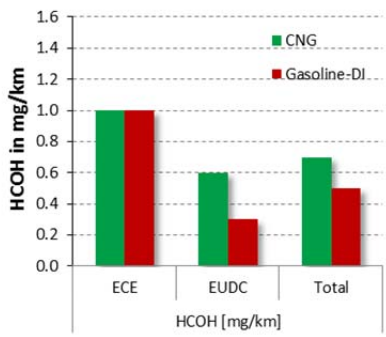
NH_3 emissions for both vehicles are at a very low level. Those of the CNG vehicle are slightly lower during cold start and warming up and slightly higher with warm engine.





HCHO emissions

Formaldehyde emissions are at a very low level. Those of the CNG vehicle are higher in NEDC and similar in WLTC.



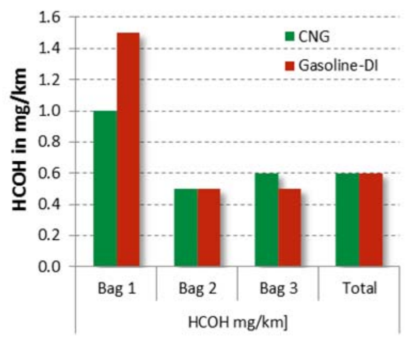


Fig. 13: Harmful components of a CNG (green) and gasoline (red) vehicle in NEDC (left) and WLTC (right)

All in all, the CNG vehicles showed a similar emissions profile as the gasoline vehicle, if the legislatively limited components or classes of components are compared. However, the picture is different, when the impacts of the exhaust gases are assessed:

- The total greenhouse gas emissions of the CNG vehicle is roughly 20% lower than those of the Gasoline-DI vehicle. If the biogas blending is considered; the total greenhouse gas emissions are correspondingly lower.
- The ozone reactivity of the pollutant emissions of the CNG vehicle is significantly lower than those of the Gasoline-DI vehicle.
- The health risks of the CNG vehicle are significantly lower than those of the Gasoline-DI vehicle.

5. CNG vehicles in the context of the Swiss energy strategy

Fossil natural gas

Natural gas is the cleanest fossil fuel in terms of greenhouse gas emissions. In Switzerland, it consists of about 90% methane and about equal concentrations of inert gases (CO_2 and N_2) and higher hydrocarbons. Distribution is mainly via pipelines where a global network exists and is being continuously extended. In addition to the pipeline distribution, an LNG distribution system (LNG = Liquefied Natural Gas) is in deployment, which enables more flexible supply and market channels for natural gas.

Today roughly 30’000 GWh of natural gas are imported into Switzerland, of which approximately 90 GWh are consumed as fuel[13]. In 2015 Switzerland imported natural gas from the EU (39% of total), from Russia (33%), from Norway (20%) and from other countries (8%)[14]. Global trade in natural gas is complex and based on long-term contracts in which the price of gas was, in the past, linked to the oil price. Due to revised contracts, the oil price link has been weakened in recent years, so that at present only a fraction of Swiss natural gas imports are based on the prices of petroleum products (about 33%).

The Life Cycle Analysis (LCA) of natural gas varies depending on origin and transport distance. The Joint Research Center (JRC) of the European Commission, in collaboration with the Association of European Oil Industry (Concawe) and the European Association of Automotive Developers (EUCAR), has analyzed various fuel paths to determine their "well-to-wheel" footprints[15]. For the European gas-mix, an average energy cost of 2% for mining and processing is assumed. Furthermore, GHG emissions of 1 vol% CO_2 and 0.4 vol% CH_4 emitted during exploration and processing is included in the greenhouse gas balance. European natural gas has a mean transport distance of 4’000 km. The gas is compressed to 60 - 80 bar which consumes an average energy expenditure of 9.6% of the transported energy content. As a comparison: the cost in energy for the liquefaction of natural gas is about 5%[16].

The distribution of natural gas has a methane leak rate that is the subject of various studies. In the JRC / CONCAWE / EUCAR investigation several studies were evaluated and a leak rate of 0.13% of the transported gas per 1’000 km was obtained. All in all, the natural gas supply is responsible for a greenhouse gas emission in the range 5 g CO_2-eq/km for natural gas vehicles, which is similar to that for the greenhouse gases of gasoline and diesel supplies.

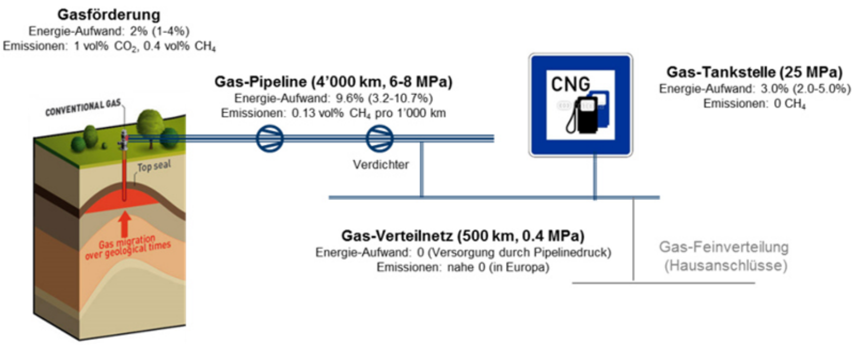


Fig. 14: Energy demand and greenhouse gas emissions from natural gas production and distribution (“well-to-tank”)

[13] BFE Gesamtenergiestatistik 2015

[14] Swissgas, Geschäftsbericht 2015

[15] JRC Technical Reports; Well-to-Tank Report Version 4.0 (2013)

[16] http://ec.europa.eu/transport/sites/transport/files/themes/urban/studies/doc/2016-01-alternative-fuels-implementation-good-practices-appendix-d.pdf

Biogas

Natural gas can be blended with preprocessed biogas (bio-methane) without any adjustments to the gas grid, the fueling station or the vehicle. For biogas injection, the Swiss gas industry had taken a pioneering role in the town of Samstagern, where Biogas was injected into the natural gas grid in 1997 for the first time. This was possible by specifying the rules for biogas blending in the SVGW regulation G13. According the total energy statistics of the Swiss Federal Office of Energy (SFOE), today almost 600 GWh of biogas are produced and used in Switzerland of which approximately 90 GWh are fed into the natural gas grid[17].

Switzerland has a sustainable biomass potential of about 23'000 $GWh_{biomass}$ for energy production, only about 50% of which is exploited today. The unused biomass consists of about one half of slurry, manure, organic waste and sewage sludge and the other half wood. However, this material has a limited usability due to various conditions (for example, availability of co-substrates).

The Life-Cycle-Assessment (LCA) of biogas from organic waste shows very low greenhouse gas values and also very good values for most other impact categories[18]. Fig. 15 shows that a gas vehicle powered with bio-methane from modern biogas plants emits about 80% less greenhouse gas than an equivalent vehicle powered by fossil natural gas. Over the whole life cycle, biogas driven gas vehicles can be counted on, together with renewable electricity driven electric vehicles, as being the cleanest vehicles.

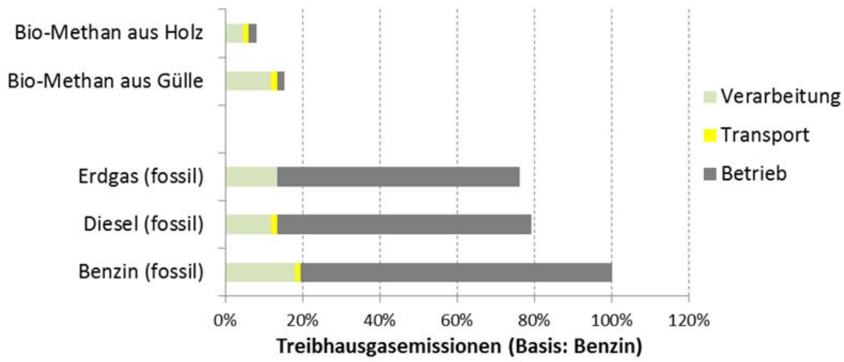


Fig. 15: Relative comparison of greenhouse gas emissions for a car-middle class vehicle with Euro 3 emission standard, based on gasoline. Source: Empa (2012)

[17] BFE, Schweizerische Gesamtenergiestatistik 2012

[18] Faist Emmenegger M. et al; Harmonization and extension of the bioenergy inventories and assessment (Empa, ART, PSI, Doka Ökobilanzen 2012)

Due to the lower carbon content per energy unit, CNG vehicles have 20 - 25% lower CO_2 emissions than a comparable gasoline vehicle (10 - 15% lower than diesel vehicle). In Switzerland, CNG currently contains 24% biogas[19] with a very low CO_2-value[20], resulting (in combination with the lower carbon content in the fossil CNG part) in 35 - 40% lower CO_2 emissions. CNG vehicles can be operated with 100% biogas without any modification. Such a vehicle/fuel combination is one of the cleanest possibilities for passenger car or delivery vehicle operations (Fig. 16).

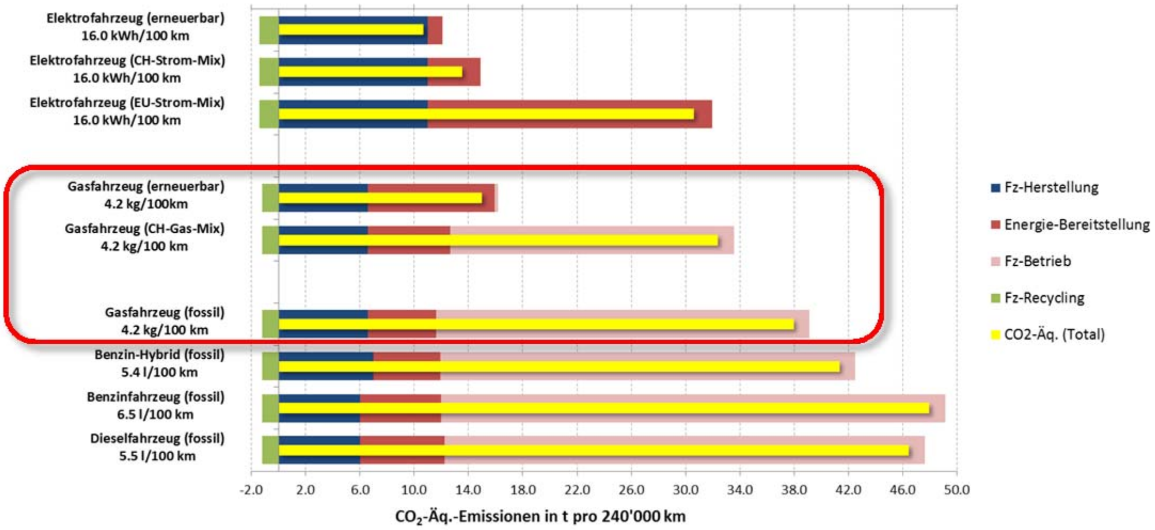


Fig. 16 LCA-Vergleich verschiedener Antriebskonzepte basierend auf Bauer et al, Applied Energy (2015), Fuchs et al. ATZ (2014), Audi Präsentation (2015) und Verbrauchsdaten gemäss Spritmonitor.de für VW Golf 81-85 kW und Toyota Auris HEV (MJ 2015-2016). BCM-Biogas gemäss LCA-Studie Empa-PSI-Agroscope-Doka (2012) und Quantis (2015); EU-Strom-Mix: 547 g CO2-eq/kWh (treeze Strommixrechner), CH-Strom-Mix: 102 g CO2-eq /kWh, erneuerbarer Strom: 28 g CO2-eq/kWh (BAFU 2014).

For roughly 10 years now, the blending of natural gas with organic waste or manure based biogas has been practiced in Switzerland, and for several years, more than 20% of the CNG sold has been 100% biogas. Biogas has an end-user price of roughly twice that of fossil natural gas (0.12 – 0.14 CHF/kWh) and is exempt from fuel taxation. Taking into account the current biogas blending for CNG, CNG passenger cars with the Swiss Gas-Mix are emitting 30 – 35% less CO_2 than gasoline vehicles due to the lower fossil carbon content.

[19] VSG, Press release from 23.03.2016

[20] Faist Emmenegger M. et al; Harmonisation and extension oft he bioenergy inventories and assessment (Empa, ART, PSI, Doka Ökobilanzen (2012)

Synthetic Methane (Power-to-Gas)

Analysis of renewable electricity production shows that the extension of fluctuating renewable electricity production (such as PV and wind energy) without compensatory measures leads to the rising risk of throttling power plants. This is the case either when the network capacity is not sufficient to transport the generated power or when too few consumers are on the network. Since renewable electricity has been prioritized in many countries, the throttled electricity mentioned above (which means "not produced electricity") must be reimbursed. The throttled energy and the reimbursement figures for Germany, are published by the Bundesnetzagentur (BNetzA) (Fig. 17).

Since 2011, throttled energy has almost quadrupled in Germany from approximately 420 GWh to 1'580 GWh in the year 2014, where the throttled energy was 1.16% of renewable electricity. In 2013 this was 0.44% only. In 2015, the throttled energy tripled again over the previous year to 4'722 GWh and reimbursements have increased six-fold from 83 to 478 Mio-EUR.

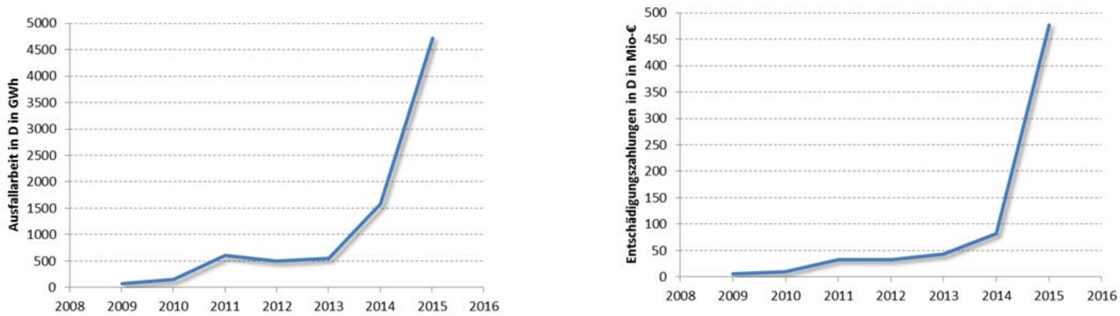


Fig. 17: Throttled energy 2009 – 2015 in Germany (left) and reimbursements in million EUR (right) (Source: BNetzA)

This trend in the throttled energy in Germany is not easily transferable to the case in Switzerland, because the latter has a significantly lower proportion of wind turbines and more pumped storage power plants than does the former. An analysis by Empa of the electricity flow data for 2015 from Swissgrid shows, that - though for different reasons - a similar problem with the use of PV electricity is foreseeable in Switzerland. Already today, more electricity is produced in summer than can be used within the country (Fig. 18). This CO_2-lean electricity (primarily non-controllable nuclear and river-water power) today can still be exported (typically to Italy), where it is substituting fossil produced electricity. Because northern Italy is heavily investing in PV systems, is at best unclear whether the excess Swiss electricity in summer can still be exported in the future (or at what price).

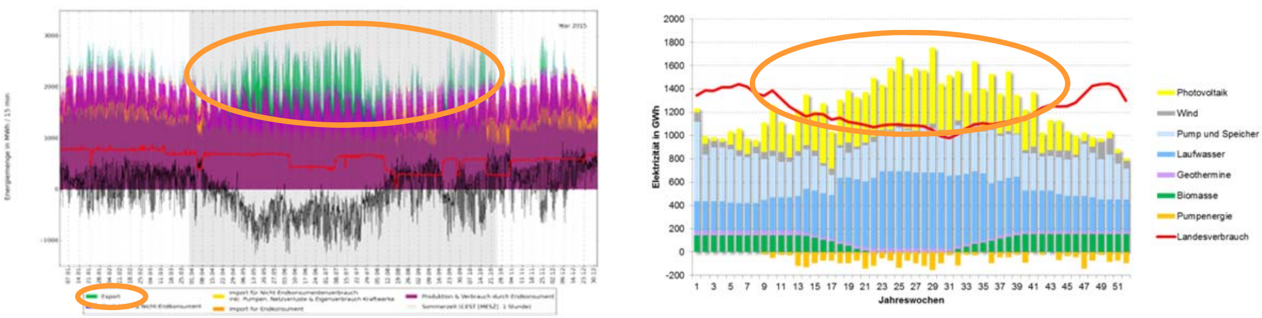


Fig. 18: Analysis of electricity flow data 2015 from Swissgrid by Empa (left) (source: Empa) and Swiss electricity market scenario "Sun2035" from Swissgrid (right) (Source: Swissgrid)

However, the export of Swiss electricity during the summer months also increases the pressure on the electricity price, which is reducing the economy of electricity-saving measures and the production of renewable energy in the summer. The conversion of this excess into fuel thus has the potential to minimize the risk of throttling renewable energy and to reduce the pressure on "unhealthy" low electricity prices during the summer months.

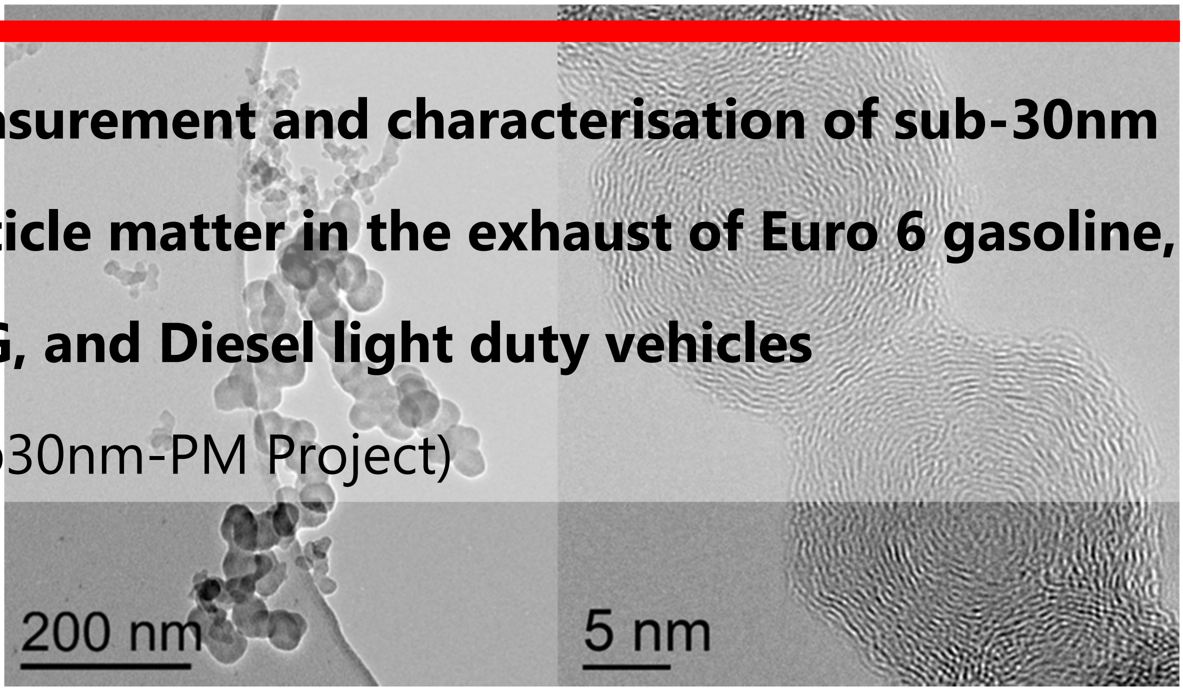
If only 50% of the excess electricity market scenario of Swissgrid (5 TWh) were to be converted into methane or other synthetic fuels, several hundred thousand vehicles could be powered with green Swiss electricity.

All in all, CNG vehicles are fitting well with the targets of the Swiss energy strategy. They allow a significant CO_2 (and pollution) reduction even under fossil fuel operation compared with gasoline and diesel vehicles. Furthermore, CNG vehicles already use conventional domestic renewable energy (biogas) and they would also be very suitable for using renewable excess electricity based synthetic methane in future.

Empa Report Nr. 5211.00968

Measurement and characterisation of sub-30nm particle matter in the exhaust of Euro 6 gasoline, CNG, and Diesel light duty vehicles

(Sub30nm-PM Project)



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Automotive Powertrain Technologies Laboratory

Panayotis Dimopoulos Eggenschwiler, Daniel Schreiber, Jacqueline Tschudin

Dübendorf, den 26.01.2017

Content

1. Executive summary

In this project, particle emissions of six Gasoline, one CNG and six Diesel vehicles were examined. All vehicles were according the current standard of Euro 6b. The particle number emissions of all vehicles have been measured using in parallel different measurement analytics.

Three different particle counting systems have been used:

- a PMP compliant system with a particle counter, counting all particles above 23 nm, connected at the CVS tunnel,
- a similar system with a particle counter counting all particles above 10 nm connected at the tail pipe, and
- a second system with a particle counter counting all particles above 10 nm with a catalytic stripper (CS) as VPR connected at the CVS tunnel.

All particle analytic systems had an integrated Volatile Particle Remover (VPR).

An overall comparison of the particle emissions of all vehicle technologies reveals:

Taking into account all particles >23nm during the NEDC cycle and no active DPF regeneration:

- The lowest particle numbers have been emitted by the Diesel DOC/DPF vehicles. Taking these as a reference then:
- The Diesel DOC/DPF/SCR vehicles emitted in average 2.5 times more particles,
- The CNG vehicle emitted in average 5 times more particles,
- The Diesel DOC/NSC/DPF emitted in average 13 times more particles,
- The gasoline MPI emitted in average 110 times more particles,
- The gasoline DI emitted in average 105 times more particles

The differences among the vehicle technologies decrease when taking into account particles >10nm, in particular emissions of the gasoline vehicles are 50 times more than those of the Diesel DOC/DPF.

Diesel DPFs have to be periodically regenerated. Considering 3 active regenerations per 1000km (a reasonable assumption) and using the increased particle emissions during and directly after an active regeneration as measured (section 3.2.2) the conclusion is

- Active DPF regenerations lead to an increase of the average particle number emissions of the Diesel vehicles per km by a factor of 10.

A different ranking in respect to particle emissions is observed when taking only cold start emissions into account:

- The lowest particle numbers have been emitted by the CNG vehicle.

In respect to the particle emissions of the CNG vehicle:

- The Diesel DOC/DPF vehicles emitted some 12 times more particles,
- The Diesel DOC/DPF/SCR vehicles emitted 8 times more particles,
- The Diesel DOC/NSC/DPF emitted 10 times more particles,
- The gasoline MPI emitted in average 40 times more particles,
- The gasoline DI emitted in average 40 times more particles,
- All these trends were identical when comparing also particles >10nm.

Particle number emissions of Euro 6 gasoline vehicles (all vehicles equipped with similar exhaust aftertreatment, i.e. a Three Way Catalyst, TWC):

Taking into account only the particles larger than 23nm:

- All gasoline vehicles had particle number emissions at the NEDC cycle below the Euro 6b limit.
- The particle emissions of all vehicles are close to the Euro 6c limit, some of the vehicles exceed it.
- The average Euro 6 gasoline vehicle emits 5.5×10^{11} 1/km particle at the NEDC cycle including the cold start at 23°C.
- At the more realistic WLTC cycle the average Euro 6 gasoline vehicle emits 1.6 times more particles (incl. the cold start at 23°C).

Comparison of particle emissions of DI to MPI gasoline vehicles:

- The particle number emissions of the MPI vehicles are higher than expected (based on comparisons of Euro 4 vehicles), having small differences to the corresponding emissions of the DI vehicles.
- The tested MPI vehicles had significant cold start particle emissions, sometimes higher than the DI vehicles.
- Particle emissions of the DI vehicles have been significantly higher than MPI vehicles at high engine loads.

Comparison of the particle number emissions counting particles > 10nm:

- At the CVS all particles >10nm counted at the NEDC and WLTC cycle (with cold start 23°C) have been 1.8 times higher than particles bigger than 23nm.
- The CVS particles >10nm counted at the NEDC and WLTC cycle (with cold start 23°C) are 2.5 time higher in respect to particles >10nm at the tailpipe. If the WLTC is driven at -7°C the difference between the >10nm particles in the CVS and in the tailpipe is much higher.
- Detailed analysis evidence that CVS and associated transfer pipes are source of additional small particles which are not attributable to the engine. It is thus questionable whether the CVS is adequate for measuring particles >10nm.

The IUFC cycle is a three times repetition of identical cycle parts and therefore ideal for evaluating the effect of the cold start:

- The particle number emission of the first IUFC part was roughly 12 times higher in respect to the second IUFC part. No significant changes of particle number emissions have been measured between the second and third IUFC part.
- This was the case at 23°C and -7°C and for particles>23nm as well as for particles >10nm.

The current trend for downsized engines (increased power output form small displacement) seems to affect the particle emission of gasoline engines. However, the particle emissions of Euro 6 gasoline vehicles were substantially lower than those of Euro 4 as measured in our laboratory:

- Particle number emissions of Euro 6 gasoline vehicles show a clear positive exponential correlation with the engine rated power to displacement ratio during all cycle parts where the engine is warm.
- Cold start particle emissions were not correlated to the engine rated power to displacement ratio.

Main insight from comparing the particle emissions of the individual cycles:

- The two DI vehicles had completely different particle emission characteristics, one having predominantly high particle emissions during transients the other having more steady particle emissions
- The MPIs particle emissions were similar in the characteristics differed though significantly in magnitude. Peak emissions could be identified at strong accelerations for all four vehicles
- In general all vehicles had higher particle emissions when a cycle was driven at lower ambient temperatures (comparison of the identical cycle driven at 23°C and -7°C).

With an FMPS the counted particles could be separated in three size classes, small (10.8-22nm), mid (25-70nm) and big (81-523nm).

- The size class separation was considered as reasonable only if the sum of the three classes resulted in particle numbers approx. equal to those measured by a further, independent CPC 3010, measuring total particle numbers.
- No reasonable results could be obtained by the FPMS at emissions below 4 10^9 1/s
- Particle numbers measured in the size class 10.8-22nm were not always complete and the trends not always plausible.
- In the very beginning of the cold start DI and MPI engines emit small and mid-sized particles only.
- After approx. the first 10secs big particles are dominant and small particles decrease.
- After roughly the first 20secs the most particles are in the mid-size (25-70nm) class. The smallest particles (10.8-22nm) are the second abundant class while the bigger particles are one order of magnitude less.
- Low ambient temperatures (-7°C) favour the emission of larger particles and reduce the number of the smallest particles.

Particle number emissions of Euro 6 Diesel vehicles (all vehicles equipped with a diesel oxidation catalyst, DOC and a particle filter, DPF, but different NOx aftertreatment technologies):

Taking into account only the particles larger than 23nm and no active DPF regenerations:

- All diesel vehicles had particle number emissions at the NEDC cycle below the Euro 6b limit.
- The particle emissions of all diesel vehicles are more than 10 times lower than the Euro 6b limit.
- The average Euro 6 diesel vehicle emits 1.9×10^{10} 1/km particles at the NEDC cycle including the cold start at 23°C.
- Assuming 3 active DPF regenerations every 1000km, then the average Euro 6 diesel vehicle emits 1.9×10^{11} 1/km.

Comparison of particle emissions of the different exhaust aftertreatment systems and no active DPF regenerations:

- The DOC/NSC/DPF equipped vehicle had clearly the highest particle emissions in all measured cycles. It should though be kept in mind that only one vehicle, equipped with such a system, was available and measured.

- The DOC/DPF (no additional NOx aftertreatment device) vehicles had the lowest particle number emissions.
- The particle emissions differences among the 3 measured DOC/DPF/SCR vehicles have been significant and much higher than the differences among the DOC/DPF vehicles.

Comparison of the particle number emissions counting particles >10nm and no active DPF regenerations:

- At the tailpipe all particles >10nm counted during the NEDC cycle have been in average 1.3 times higher than particles >23nm counted at the CVS.
- The corresponding particle number ratio during the CADC cycle (higher loads without cold start), i.e. particles > 10nm measured at the tailpipe to particles >23nm measured at the CVS was 3.1.

The IUFC cycle is a three times repetition of identical cycle parts and therefore ideal for evaluating the effect of the cold start and no active DPF regenerations:

General insights:

- DOC/DPF vehicles had the highest cold start particle emissions
- The particle emission of the DOC/NSC/DPF was the lowest affected by the cold start
- Particle emissions of the DOC/DPF/SCR vehicles have stabilized fastest showing practically no difference between the second and third IUFC repetition.

Detailed insights:

- During cold start, particularly during the first part of the IUFC cycle particle emissions of DOC/DPF were almost three orders of magnitude higher than during the second repetition.
- Particle emissions of DOC/DPF/SCR vehicles were also higher during the first IUFC part in respect to the second, but only by a factor of roughly 100.
- In contrast, the DOC/NSC/DPF vehicle had only a modest increase (factor of 2) of particle emissions during the first IUFC part.
- The described behaviour of all vehicles and associated ratios was very similar regardless the starting temperature of the IUFC (-7C or 23C).

Active regeneration of the DPF had a strong effect on the particle emission characteristics of the Diesel vehicles. Only a limited number of active regenerations could be studied. The observations can be summarized as follows:

- During DPF active regeneration increased particle emissions by 2-3 orders of magnitude have been measured
- This increase was evident during the active regeneration as well as in the following cycle part where the DPF was “clean” i.e. without a developed soot cake.
- The additional particle number emissions during active regeneration are mainly big particles (>23nm).
- The influence of particle number emissions during active DPF regeneration in the overall particle emission depends from the occurrence frequency of such regenerations. Using the results measured in this study and assuming a limited number (1-6) of active DPF regenerations every 1000km, the weighted particle emission average increases by a factor of 4, should only one active regeneration occur every 1000km. Should 6 active regenerations occur every 1000km then the particle emissions increase by a factor of 20.

- Taking the worst case into account (i.e. 6 active regenerations every 1000km) the DOC-DPF as well as the DOC-DPF-SCR vehicles are below the Euro 6b limit with a good safety margin. The DOC-NSC-DPF vehicle will reach the Euro 6b limit. Active DPF regenerations, however, are less frequently needed in DOC-NSC-DPF systems.

The analysis of the individual cycles has confirmed the above observations. Additional insights can be summarized as follows:

- Only the one DOC/NSC/DPF and one (of the three) DOC/DPF/SCR showed significant small (>10nm) particles emission. For the other vehicles particles >10nm were practically identical with particles >23nm, indicating a very low fraction of the smallest nanoparticles.
- Particle emissions of the DOC/NSC/DPF were not affected by the temperature of the test (at 23°C or -7°C) except during idling engine. While particle emission during idling can be neglected at 23°C, at -7°C they are significantly higher.

With an FMPS the particles measured could be separated in three size classes, small (10.8-22nm), mid (25-70nm) and big (81-523nm). The size class separation was considered as reasonable only if the sum of the three classes resulted in particle numbers approx. equal to the total measured by a further, independent CPC. Main insights can be summarized as follows:

- No reasonable results could be obtained by the FPMS at emissions levels below 6 10^8 1/s
- Particle numbers measured in the size class 10.8-22nm were not always complete and the trends not always plausible
- The DOC-DPF vehicle has PN emissions only during cold start. The contribution of the smallest particles to the overall result is rather modest.
- The one (out of three) DOC-DPF-SCR vehicle shows significant particle emissions mainly in the first part of the NEDC cycle. Here the size class of the smallest particles is a significant fraction. In the second half of the NEDC cycle particle emissions are very low.
- The second DOC-DPF-SCR vehicle had a rather low small particle quantity. During an active DPF regeneration particle emissions increased while the mid and large size class are predominant.
- In a subsequent started cycle, with a clean DPF, particle emissions have been high, with the mid and the large size class being predominant.

2. Driving cycles, vehicle specifications, measurement setup and analytics

2.1 Driving cycles

The vehicles have been tested at different international established driving cycles every vehicle was tested at the (still valid) certification, NEDC cycle. The driving cycle velocity profiles with specific indication of each cycle phase are shown in the following graphs.

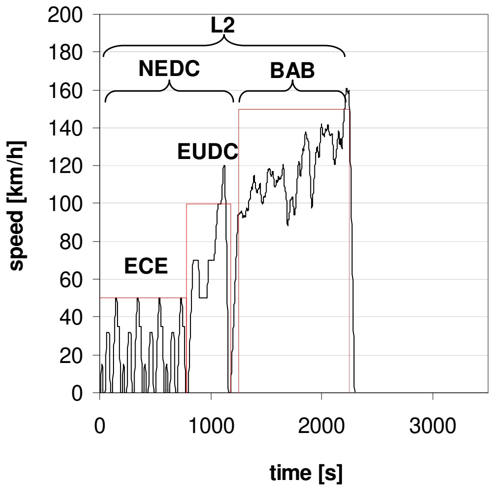


Figure 1: L2 (NEDC & BAB), New European Driving Cycle and Bundes Autobahn. The cold start is at 23°C.

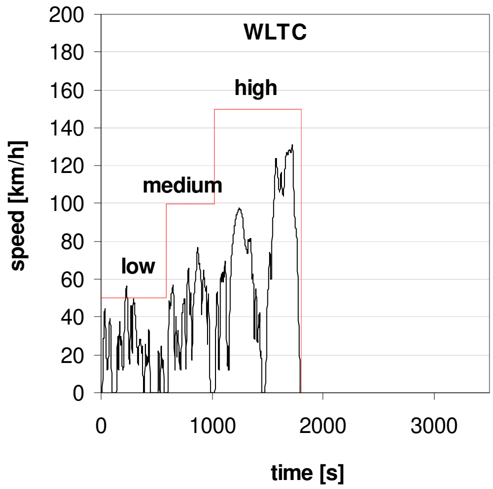


Figure 2: WLTC 23°C, WLTC -7°C, World-wide harmonized light duty test cycle, Tests with cold start at 23°C, or at -7°C.

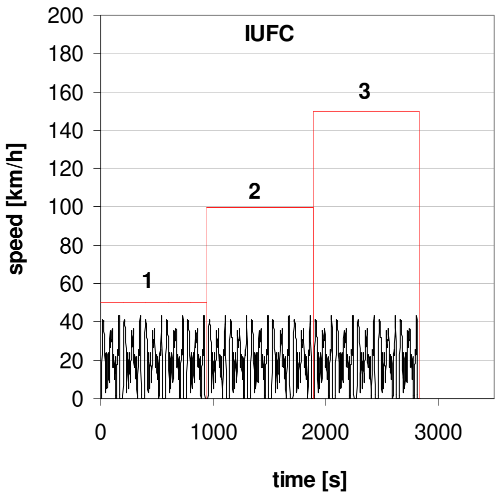


Figure 3: IUFC 23°C, IUFC -7°C, cycle at 23°C and -7°C ambient temperature, (incl. cold start).

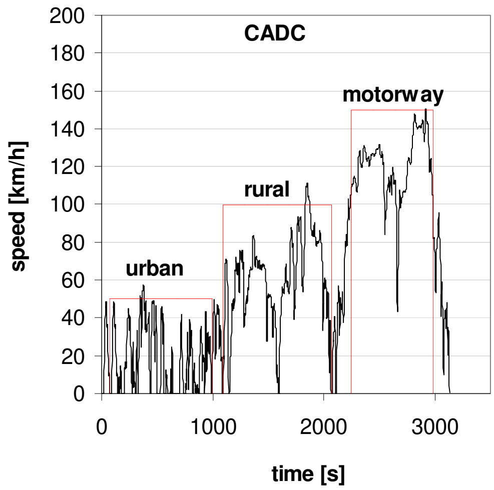


Figure 4: CADC, Common Artemis Driving Cycle, warm start.

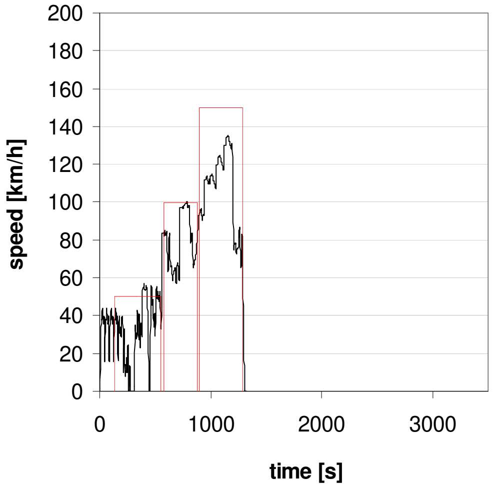


Figure 5: ERMES, European Research Group on Mobile Emission Sources, warm start.

Table 1: Gasoline and CNG vehicles, executed test cycles.

	L2	NEDC	CADC	IUFC	IUFC -7°C	WLTC	WLTC -7°C	ERMES
PB6-01		x	x	x	x	x	x	x
PB6-02		x	x	x	x	x	x	x
PB6-03		x	x	x	x	x	x	x
PB6-04		x	x	x	x	x	x	x
PB6-05		x	x	x	x	x	x	x
PB6-06		x	x	x	x	x	x	x
PCNG6-01		x	x	x	x	x	x	

Table 2: Diesel vehicles, executed test cycles.

	L2	NEDC	CADC	IUFC	IUFC -7°C	WLTC	WLTC -7°C	ERMES
PD6-02	x		x	x	x			
PD6-03	x		x	x	x			
PD6-05	x		x	x	x			
PD6-06	x		x	x	x			
PD6-07		x	x	x	x	x	x	x
PD6-10		x	x	x	x	x	x	x

Additional clarification:

A warm start cycle is the case when the cycle is started with pre warmed engine and oil temperature at 80°C.

A cold start cycle is started with cold engine having the ambient temperature. So cold start cycles can be performed at different ambient temperatures. In this study the cold start cycles have been performed at 23°C and -7°C. Standard is a cold start at 23°C and is not mentioned explicitly.

2.2 Vehicle specifications

The examined Euro 6 vehicles were equipped with different injection and exhaust after treatment systems, see Table 3.

Table 3: Vehicle specifications

Vehicle Label	PB6-01	PB6-02	PB6-03	PB6-04	PB6-05	PB6-06	PCNG6-01
Fuel type	Gasoline	Gasoline	Gasoline	Gasoline	Gasoline	Gasoline	CNG
European emission limit standard	Euro 6b	Euro 6b	Euro 6b	Euro 6b	Euro 6b	Euro 6b	Euro 6b
Power-to-Displacement-Ratio	111.4 kW/l	90.1 kW/l	91.4 kW/l	88.0 kW/l	73.4 kW/l	55.5 kW/l	58.1 kW/l
Fuel injection system	Direct Injection	Direct Injection	Multi Point Inj.	Multi Point Inj.	Multi Point & Direct Injection	Multi Point Injection	Multi Point Inj.
Exhaust after treatment	TWC	TWC	TWC	TWC	TWC	TWC	TWC

Vehicle Label	PD6-02	PD6-03	PD6-05	PD6-06	PD6-07	PD6-10
Fuel type	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
European emission limit standard	Euro 6b	Euro 6b	Euro 6b	Euro 6b	Euro 6b	Euro 6b
Power-to-Displacement-Ratio	50.2 kW/l	63.5 kW/l	52.3 kW/l	60.1 kW/l	56.8 kW/l	58.3 kW/l
Fuel injection system	Direct Injection	Direct Injection	Direct Injection	Direct Injection	Direct Injection	Direct Injection
Exhaust after treatment	DOC, DPF	DOC, DPF, SCR	DOC, DPF	DOC, DPF, SCR	DOC, NSC, DPF	DOC, DPF, SCR

2.3 Measurement setup

The setup of the particle number measurement was chosen so that an additional counting system (AVL498-cs) with a 10nm counting efficiency of 50% was connected at the CVS-tunnel in parallel with the PMP compliant counting system (23nm counting efficiency of 50%). The AVL System was specially developed for sub 23nm particle counting and was equipped with a catalytic stripper (Zheng Z. et al., 2011).

In order to assess the influence of the CVS system in the sub-23nm particle number, a third sub-23nm counting system was connected directly to the tail pipe.

For additional information on the transient particle number size distribution a TSI FMPS was connected in parallel to the particle number counter (PNC) of the third counting system.

Two different electrostatic particle sampling systems were connected downstream a heated dilution which in turn was connected at the tail pipe. One of them was a total particle sampler and the other a combination of an ELPI and an electrostatic sampling system, which is connected at the outlet of the ELPI. With this configuration the second system samples particles in the range of the ELPI back-up stage (<30nm). To increase the number of charged particles the Ion-Trap of the ELPI was turned off (Ouf et al., 2009).

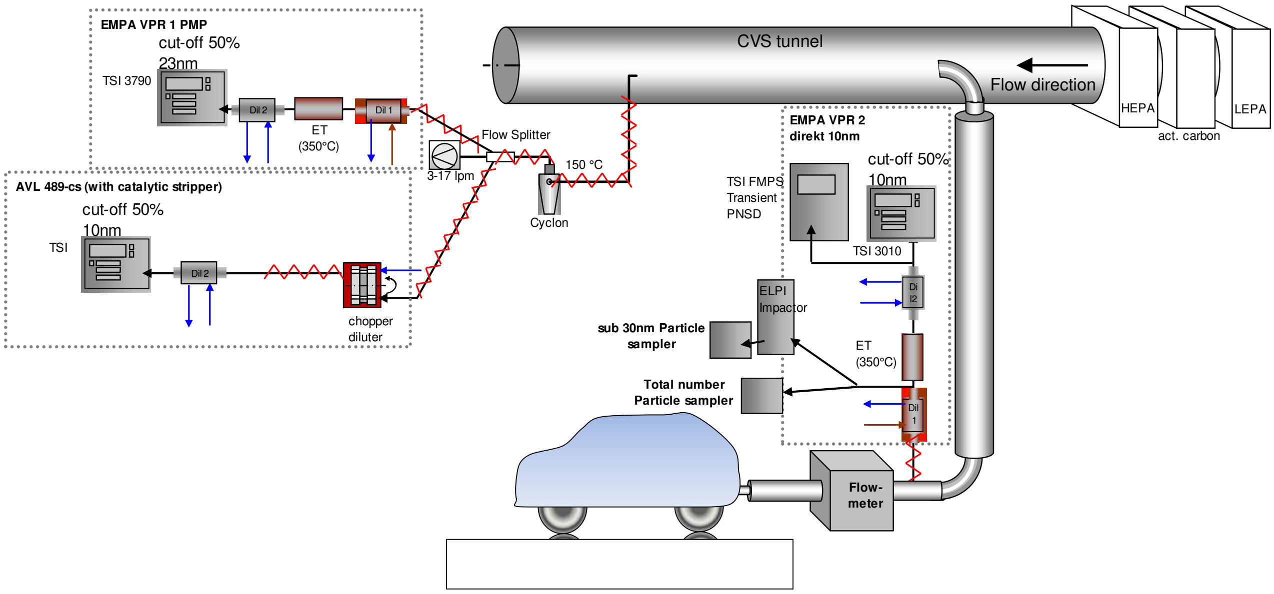


Figure 6: Number particle measurement Setup with the two systems connected at the CVS-tunnel (EMPA VPR1 23nm PMP and AVL489-cs) and one (EMPA VPR2 10nm) connected directly at the tail pipe. The total and the selected electrostatic particle samplings were connected after the first heated dilution of the VPR 2.

2.4 Particle Analytic techniques

2.4.1 Particle Number (PN)

In Table 4, the applied particle number analytics for every vehicle are indicated.

Table 4: Particle number analytics

	CVS, >23nm	CVS, >10nm, CS	Tail pipe,>10nm	FMPS
Veh. PB6-01	X		X	X
Veh. PB6-02	X	X	X	X
Veh. PB6-03	X	X	X	
Veh. PB6-04	X	X	X	
Veh. PB6-05	X	X	X	X
Veh. PB6-06	X	X	X	X
Veh. PCNG6-01	X		X	
Veh. PD6-02		X	X	X
Veh. PD6-03	X	X	X	X
Veh. PD6-05	X		X	
Veh. PD6-06	X		X	
Veh. PD6-07	X		X	
Veh. PD6-10	X		x	

System setup and calibration:

- The PMP compliant system was equipped with a first heated injector pump dilution an Evaporation Tube (ET) heated at 350°C and a second cold injector pump dilution. A PNC model TSI CPC 3790 with counting efficiency of 50% for particles with a diameter of 23nm (cut-off 23nm) was connected at this VPR. The DF of this VPR could be extended with a third dilution. The Particle Total Reduction Factor (PTRF) from this VPR was calculated from calibration measurements with diffusion flame soot at 30, 50 and 100nm.
- The VPR connected at the tail pipe was a similar system with a PNC model TSI CPC 3010 (cut-off 10nm) and the DF of this VPR could be extended also with a third dilution. For this VPR the PTRF was calculated from calibration measurements with diffusion flame soot at 10, 30, 50 and 100nm.
- The AVL system was also calibrated with diffusion flame soot at 10, 30, 50 and 100nm (detailed system description (Appendix 1).

3. **Results**

3.1 Particle Number emission (PN) gasoline vehicles

3.1.1 Gasoline injection system comparison

The bar charts below compare the particle number emissions of different injection systems. Red bars indicate the emission of vehicles with direct injection (DI) and blue bars with multipoint injection (MPI). The emissions of the vehicle PB-06 equipped with both injection systems was included in the bars of the MPI vehicles. Its emissions corresponded almost always to more or less the average of the emissions of the MPI vehicles. This is not surprising given the fact that vehicles equipped with both injection systems use the MPI at low loads and switch to DI only at higher loads. All cycles used and under discussion are predominantly at low loads. Only the last parts of the CADC and the WLTC cycles contain higher loads.

Summary of the main findings

General for particle number counting (particles >23nm):

- All measured vehicles had particle number emissions at the NEDC cycle below the Euro 6b limit.
- The particle emissions of all vehicles are close to the Euro 6c limit, some of the vehicles exceed it.
- The average Euro 6 gasoline vehicle emits $5.5x10^{11}$ /km particle at the NEDC cycle including the cold start at 23°C.
- At the more realistic WLTC cycle the average Euro 6 gasoline vehicle emits 1.6 more particles (incl. the cold start at 23°C).
- If a WLTC cycle is performed at -7°C (incl. cold start) the average Euro 6 gasoline vehicle emits 4 times more particles in respect to the WLTC at 23°C
- During the CADC, a realistic cycle comparable to WLTC but with no cold start, the average Euro 6 vehicle emits 1.6 times less particles (similar level as at the NEDC which is a rather slow cycle but including cold start)

Comparison of particle emissions of DI to MPI vehicles:

- The particle number emissions of the MPI vehicles are higher than expected, having small differences to the corresponding emissions of the DI vehicles. The differences are significantly smaller in respect to the particle emission differences of Euro 4 DI and MPI vehicles (Schreiber et al. 2007).
- The tested MPI vehicles had significant cold start particle emissions, sometimes higher than the DI vehicles. Therefore the entire particle emissions of the MPI vehicles at the cycles with cold start are very similar to those of the DI vehicles (cycles NEDC Fig. 7, IUFC Figs 10 and 11, WLTC figs 12 and 13)
- Particle emissions of the DI vehicles have been higher than MPI vehicles at cycles with no cold start (CADC Fig. 8, Ermes Fig. 9).

Comparison of the particle number emissions counting particles > 10nm:

- At the CVS all particles bigger than 10nm counted at the NEDC and WLTC cycle (with cold start 23°C) have been 1.8 times higher than particle bigger than 23nm. A slightly higher ratio was determined for the WLTC cycle at -7°C and a lower but in the same order of magnitude ratio for the CADC without cold start.
- The CVS particles bigger than 10nm counted at the NEDC and WLTC cycle (with cold start 23°C) are 2.5 time higher in respect to particles bigger than 10nm at the tailpipe. If the WLTC is driven at -7°C the difference between the <10nm particles in the CVS and in the tailpipe is much higher
- The CVS particles bigger than 10nm counted at the CADC cycle (no cold start) are 1.9 times higher in respect to particles bigger than 10nm at the tailpipe.
- The two latter observations evidence that CVS and associated transfer pipes are source of additional small particles which are not attributable to the engine. It is thus questionable whether the CVS is an adequate way to measure sub 30nm particles.

The IUFC cycle is a three times repetition of identical cycle parts and therefore ideal for evaluating the effect of the cold start:

- The particle number emission of the first IUFC part was roughly 12 times higher in respect to the second IUFC part. No significant changes of particle number emissions have been measured between the second and third IUFC part.
- This was the case at 23°C and -7°C and for particles>23nm as well as for particles >10nm.

NEDC gasoline, cold start

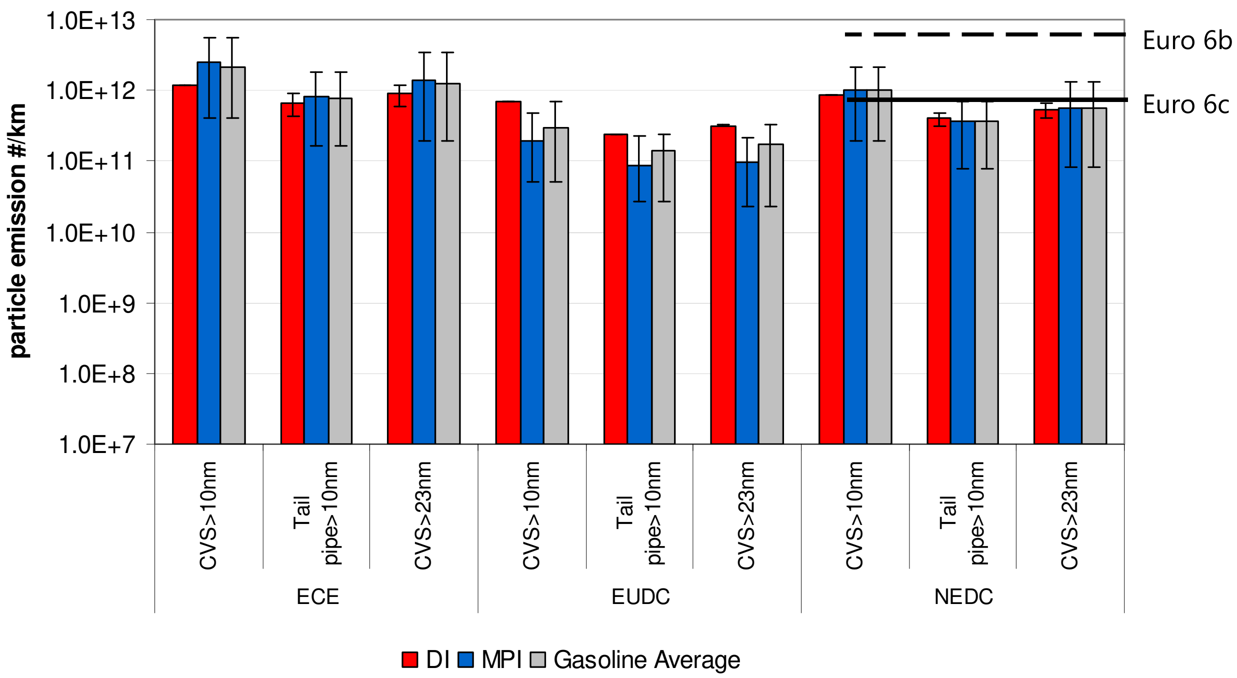


Figure 7: NEDC cycle phase (ECE, EUDC) and total cycle average emissions with minimum and maximum indication.

CADC gasoline, warm start

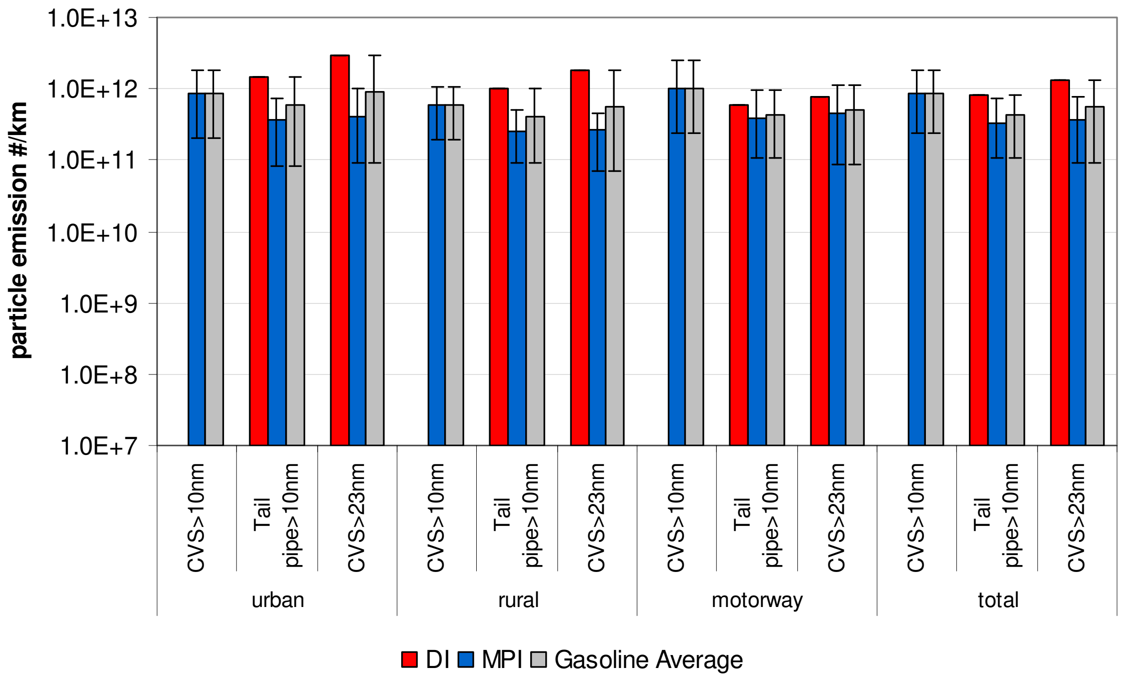


Figure 8: CADC cycle phase (urban, rural, motorway) and total cycle average emissions with minimum and maximum indication.

ERMES gasoline, warm start

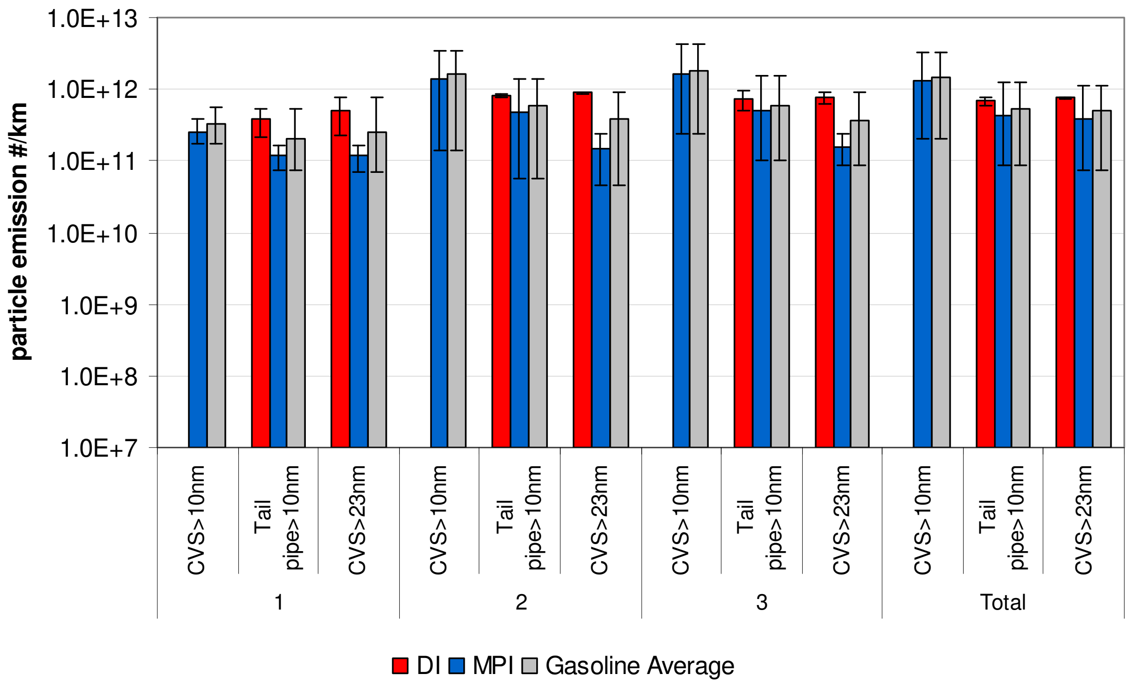


Figure 9: ERMES cycle phase (1, 2, 3) and total cycle average emissions with minimum and maximum indication.

IUFC 23°C gasoline, cold start

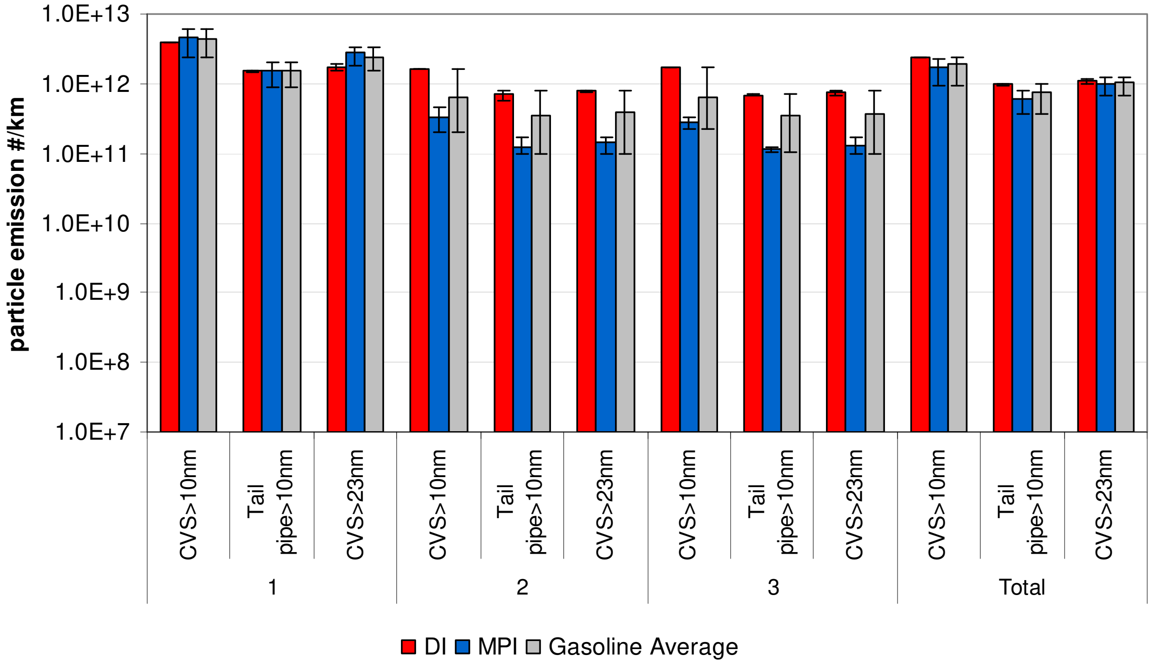


Figure 10: IUFC cycle phase (1, 2, 3) and total cycle average emissions with minimum and maximum indication.

IUFC -7°C gasoline, cold start

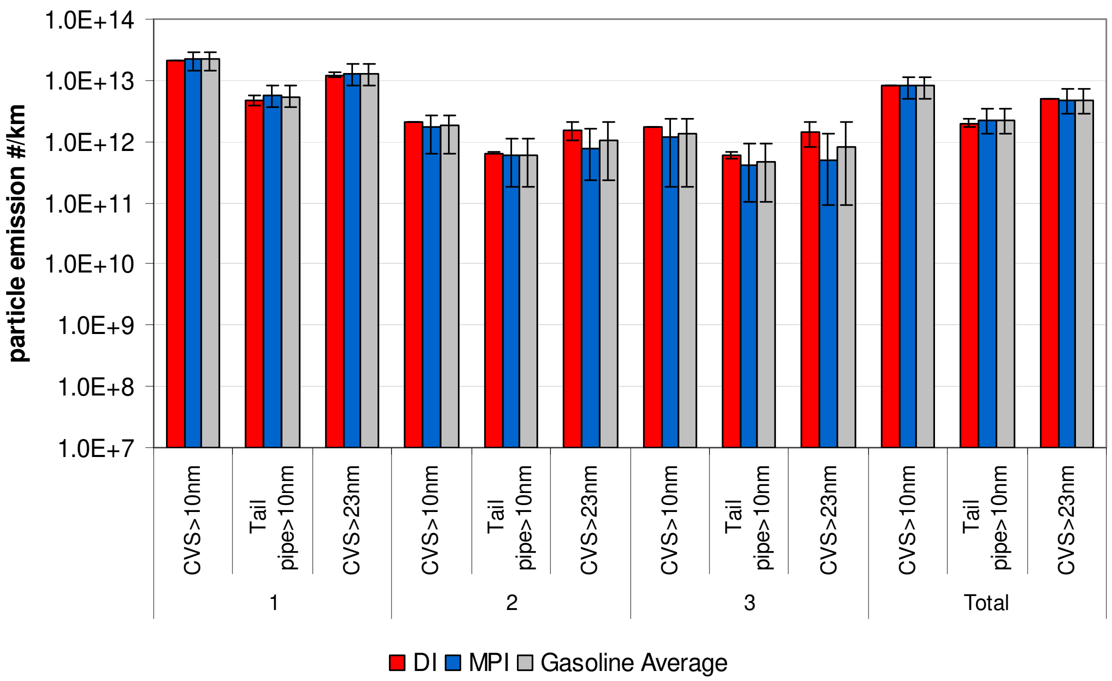


Figure 11: IUFC cycle phase (1, 2, 3) and total cycle average emissions with minimum and maximum indication. Cycle executed at low temperature.

WLTC gasoline, cold start

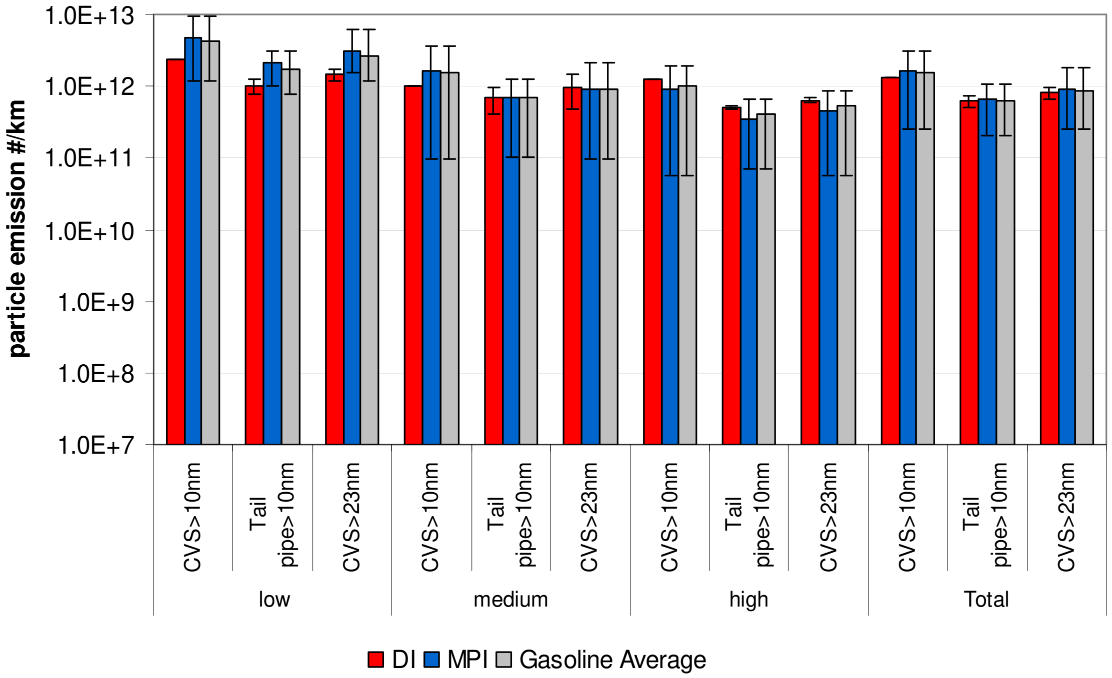


Figure 12: WLTC cycle phase (low, medium, high) and total cycle average emissions with minimum and maximum indication.

WLTC -7°C gasoline, cold start

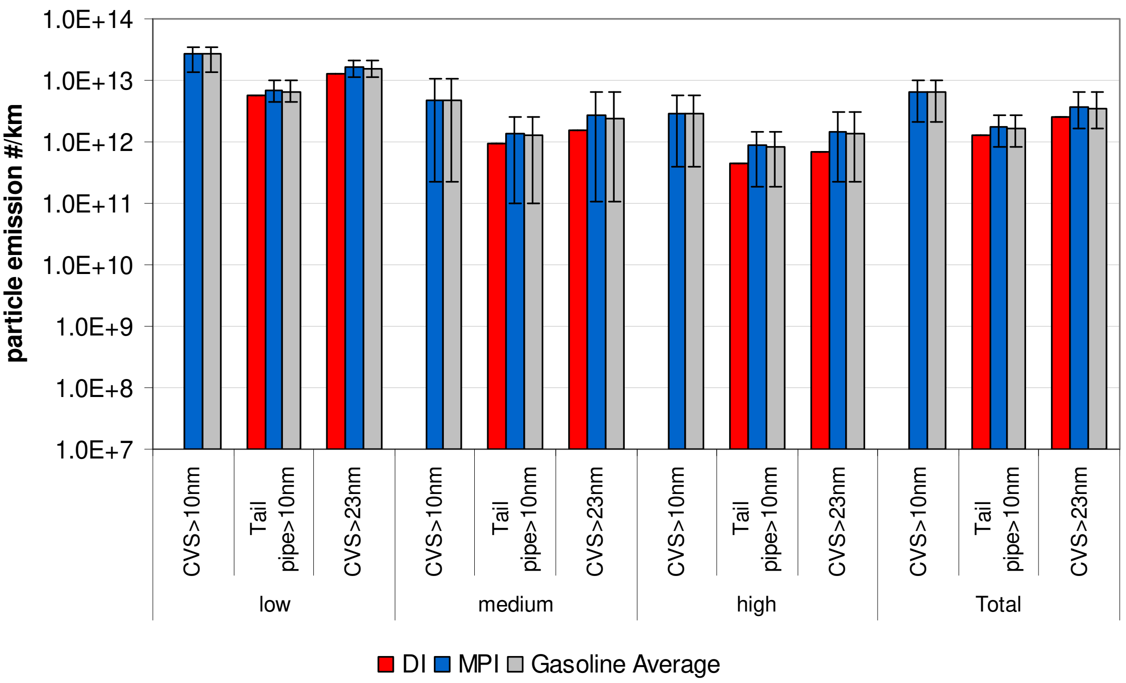


Figure 13: WLTC cycle phase (low, medium, high) and total cycle average emissions with minimum and maximum indication. Cycle executed at low temperature.

3.1.2 Particle Emission vs. engine rated Power-to-Displacement Ratio (PDR)

The small differences of the particle emissions of the MPI gasoline vehicles in respect to the DI vehicles was surprising. In general, MPI gasoline vehicles had 1-2 orders of magnitude less particle number emissions than comparable DIs (Schreiber et al. 2007). In the last years and nowadays engines have been designed according to the current trend of engine "downsizing", i.e. engines of rather small displacement with turbochargers for reaching higher power. Turbocharging increases the amount of the air intaken by the engine and also the amount of fuel injected (stoichiometric mixture) and leads to increased power output. However available ducts, valves and cylinder dimensions are either identical or can only be slightly increased. Thus, the possibilities increase for forming liquid fuel wall films during intake and subsequent inhomogeneities during compression and prior to injection.

In the following charts the particle emissions of each vehicle at the tested cycles are presented as a function of the rated power to displacement ratio (PDR). The different cycle phases are marked in red (start phase), blue (medium phase) and green (final phase).

<u>Summary of the main findings</u>

- Particle number emissions of Euro 6 gasoline vehicles show a clear positive exponential correlation with the engine rated power to displacement ratio during all cycle parts where the engine is warm (figs. 14-20).
- Cold start particle emissions were not correlated to the engine rated power to displacement ratio.
- Particle number emission of Euro 6 gasoline passenger vehicles are lower than Euro 4 gasoline vehicles.
- In particular, DI gasoline particle number emissions are significantly lower for Euro 6 vehicles in respect to the Euro 4 DI gasoline engines.

NEDC gasoline, cold start

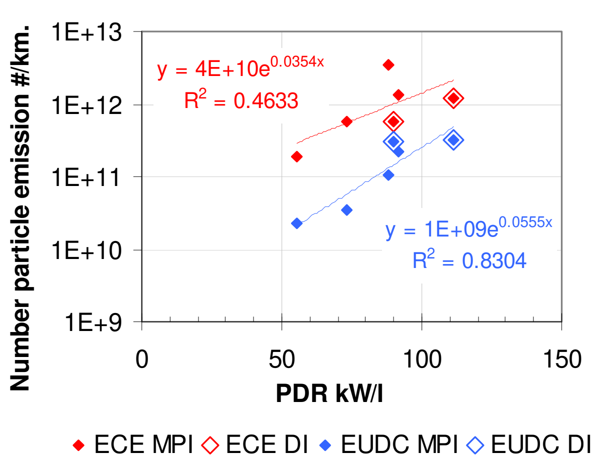


Figure 14: NEDC cycle emissions ECE and EUDC vs. rated power-to-displacement ratio (PDR).

CADC gasoline, warm start

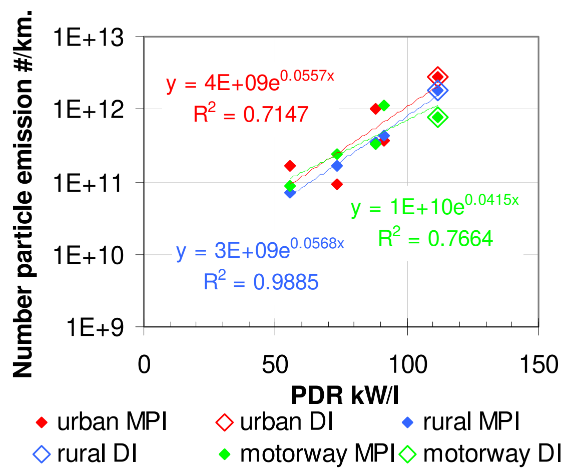


Figure 15: CADC cycle phase emissions vs. rated power-to-displacement ratio (PDR).

ERMES gasoline, warm start

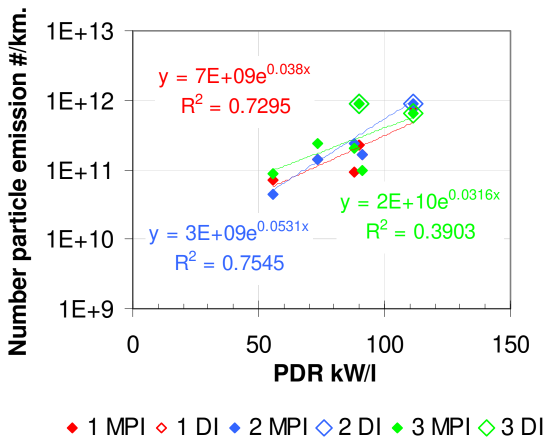


Figure 16: ERMES phase emissions 1, 2 and 3 vs. rated power-to-displacement ratio (PDR).

WLTC gasoline, cold start

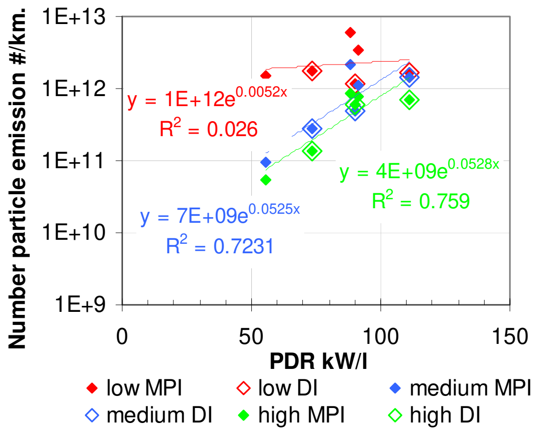


Figure 17: CADC phase emissions vs. rated power-to-displacement ratio (PDR).

WLTC -7°C gasoline, cold start

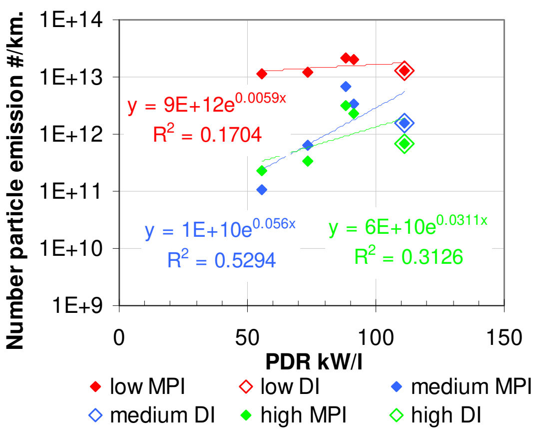


Figure 18: WLTC -7°C phase emissions low, medium and high vs. PDR.

IUFC gasoline, cold start

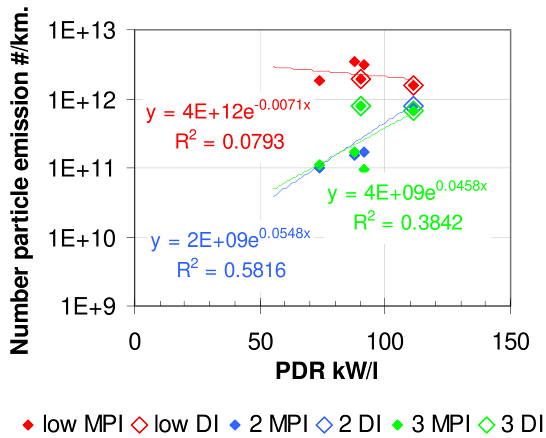


Figure 19: IUFC phase emissions 1, 2 and 3 vs. PDR.

IUFC -7°C gasoline, cold start

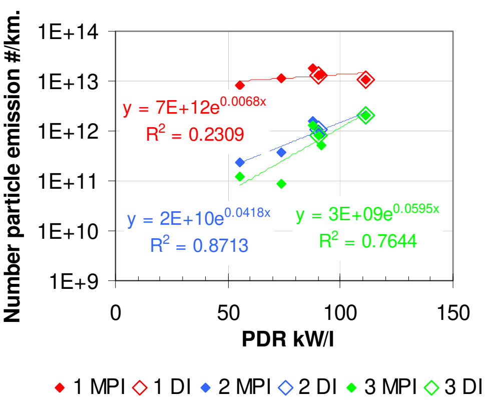


Figure 20: IUFC -7°C phase emissions 1, 2 and 3 vs. PDR.

Comparison of Euro 4 to Euro 6 gasoline engines (NEDC gasoline, cold start)

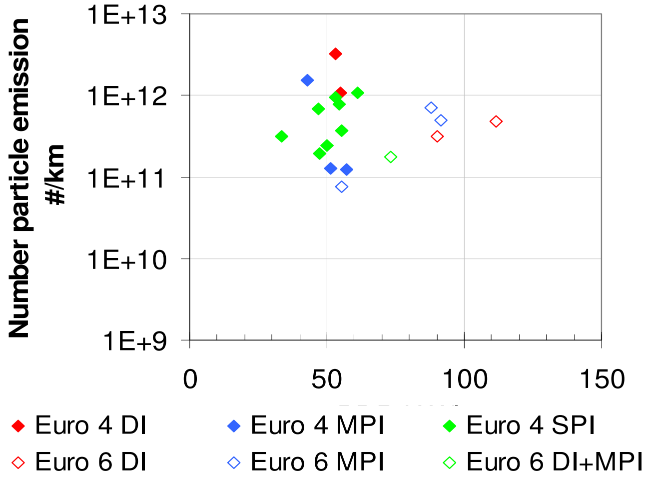


Figure 21: NEDC Euro 4 and 6 cycle emissions vs. Power-to-Displacement Rate.
DI: Direct Injection, MPI: Multipoint Injection, SPI: Single Point Injection.

3.1.3 Particular characteristics of vehicle particle emissions and measurement technology

Particle emissions measured at the tail-pipe could be separated in three size classes. The black line indicates the total particle number >10nm measured with a CPC 3010, the purple line indicates the calculated total particle number >10nm measured with a TSI FMPS and the additional lines (red, blue, green) indicate the FMPS measured particles separated in three size classes: 10-22μm, 25-70μm and 81-523μm

Summary of the main findings

The two DI vehicles had completely different particle emission characteristics, one having predominantly high particle emissions during transients the other having more steady particle emissions with only weak dependency from the transients imposed by the driving cycle (Figs 22, 23 showing the NEDC cycle).

The MPIs particle emissions were similar in the characteristics differed though significantly in magnitude. Peak emissions could be identified at strong accelerations for all four vehicles (Fig 24). However vehicle 3 had also some particle emission peaks during higher load phases (Fig. 25).

In general all vehicles had higher particles emissions when a cycle was driven at lower ambient temperatures. A comparison of a WLTC at 23°C and a WLTC at -7°C (Fig. 26) between two MPI vehicles shows very similar tendencies but different orders of magnitude.

The comparison among the three different sampling systems revealed a striking difference during some vehicle decelerations: Particle emission decrease was at the two, CVS connected systems, sometimes decisively slower than at the direct tailpipe connected system (Figs 27 and 28). The possible reasons therefore can be attributed either to storage and release effects of the CVS or to gas run time differences due to the different locations. Since the incident occurred only sporadically no exact reason could identified or excluded.

NEDC (ECE) cold start DI vehicles

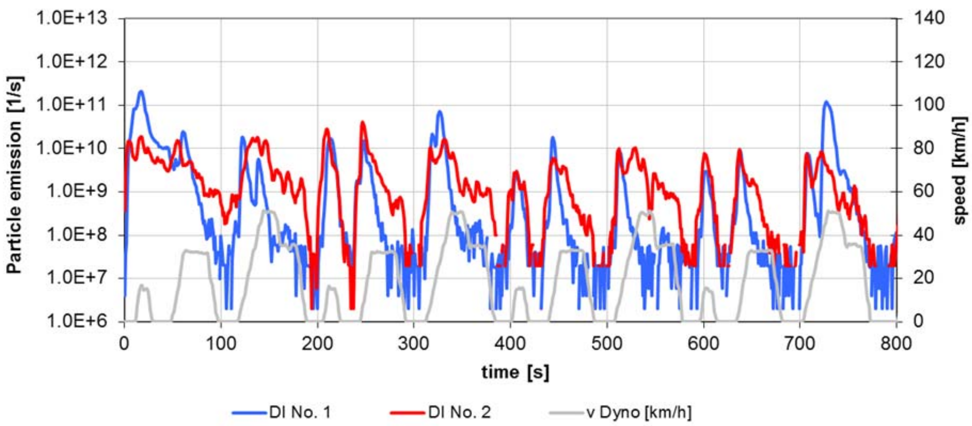


Figure 22: NEDC (ECE) cycle, particle number emissions and chassis dynamometer velocity.

NEDC (EUDC) DI vehicles

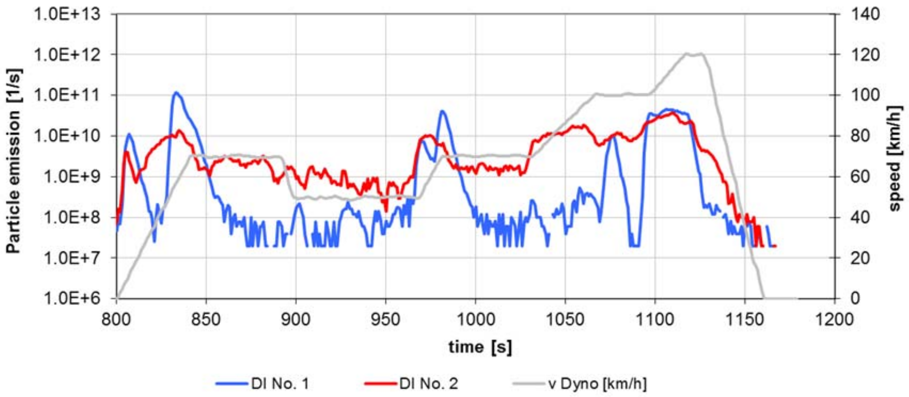


Figure 23: NEDC (EUDC) cycle, particle number emissions and chassis dynamometer velocity.

NEDC (ECE) cold start MPI vehicles

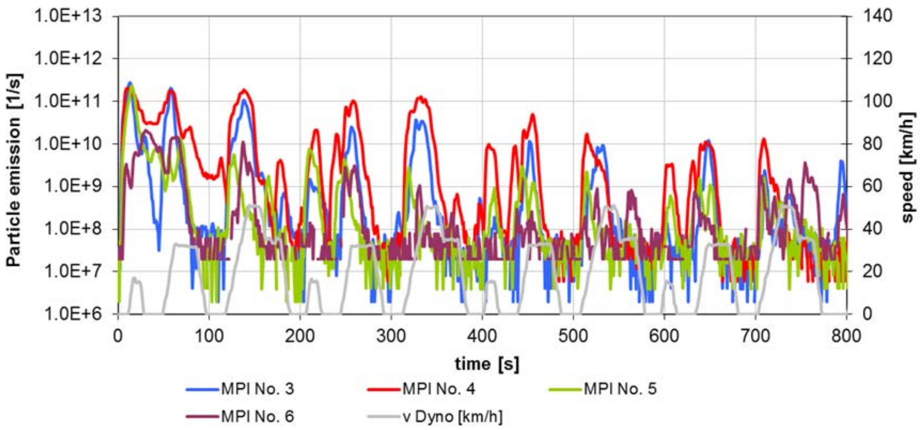


Figure 24: NEDC (ECE) cycle, particle number emissions and chassis dynamometer velocity MPI vehicles.

NEDC (EUDC) MPI vehicles

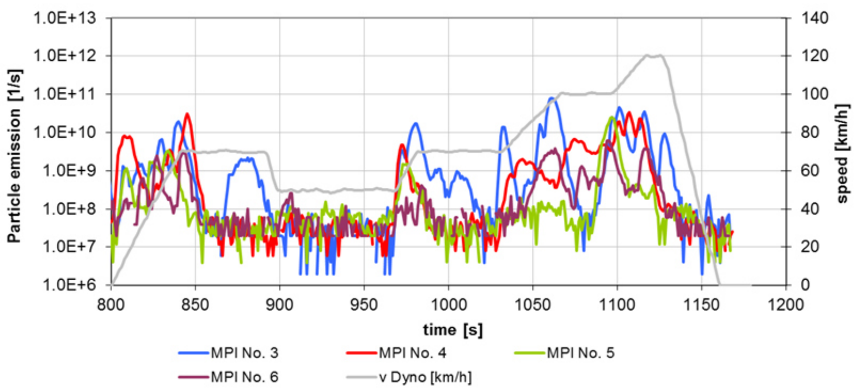


Figure 25: NEDC (EUDC) cycle, particle number emissions and chassis dynamometer velocity MPI vehicles

WLTC cold start MPI vehicles

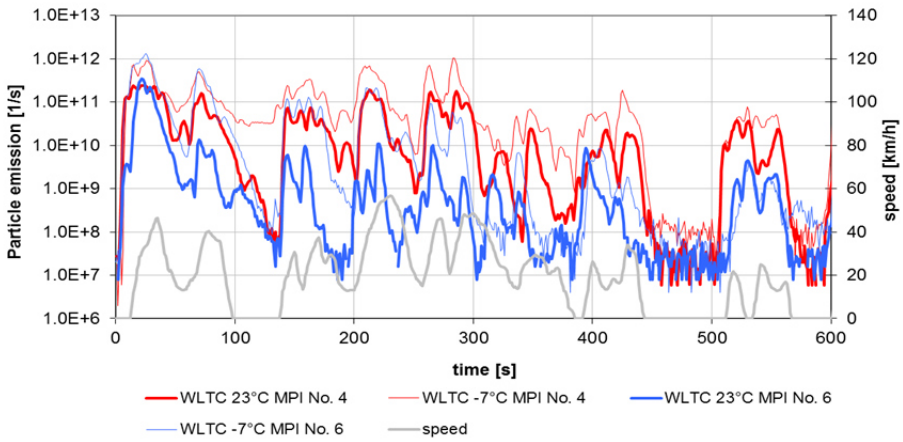


Figure 26: WLTC cycle at -7°C and at 23°C (both cycles with a cold start), particle number emissions and chassis dynamometer velocity MPI vehicles.

NEDC (ECE) cold start DI, vehicle No. 2

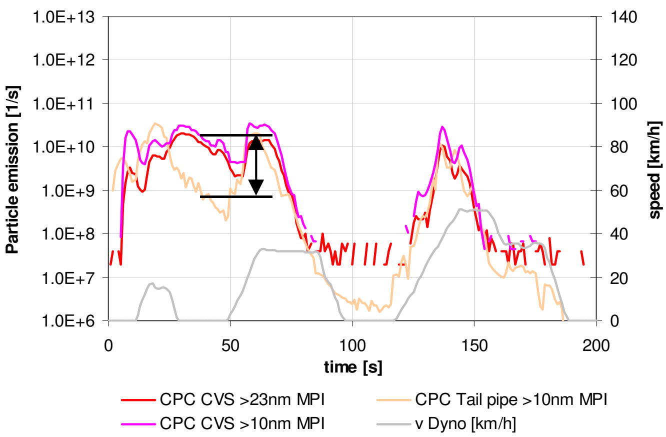


Figure 27: NEDC (ECE) cycle, particle number emissions measured with three different systems and chassis dynamometer velocity.

NEDC (EUDC) MPI vehicle No. 6

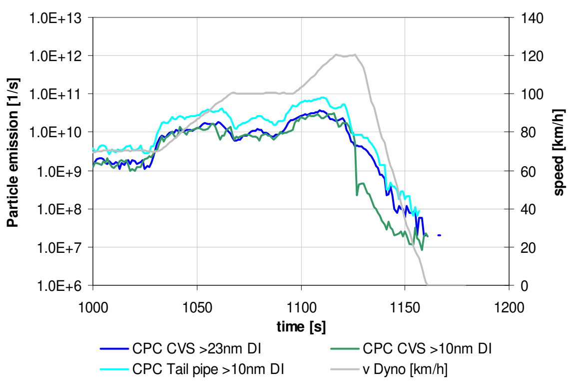


Figure 28: NEDC (ECE) cycle, particle number emissions measured with three different systems and chassis dynamometer velocity.

3.1.4 Particle emissions, separated in three size classes, gasoline vehicles

Particle emissions measured at the tail-pipe could be separated in three size classes. The black line indicates the total particle number >10nm measured with a CPC 3010, the purple line indicates the calculated total particle number >10nm measured with a TSI FMPS and the additional lines (red, blue, green) indicate the FMPS measured particles separated in three size classes: 10-22μm, 25-70μm and 81-523μm

Summary of the main findings

- The size class separation was considered as reasonable only if the sum of the three classes resulted in particle numbers approx. equal to those measured by the CPC 3010.
- No reasonable results could be obtained by the FPMS at emissions below 4 109 1/s
- Particle numbers measured in the size class 10.8-22nm were not always complete and the trends not always plausible
- In the very beginning of the cold start DI and MPI engines emit small and mid-sized particles (Figs. 29-33).
- After approx. the first 10secs big particles are dominant and small particle decrease (Figs. 29-33).
- After roughly the first 20secs the most particles are in the mid-size (25-70nm) class. The smallest particles (10.8-22nm) are the second abundant class while the bigger particles are one order of magnitude less (Figs 29-31).
- Low ambient temperatures (-7°C) favour the formation of larger particles and reduce the number of the smallest particles (Figs 32, 33).

NEDC cold start, DI vehicle No. 1

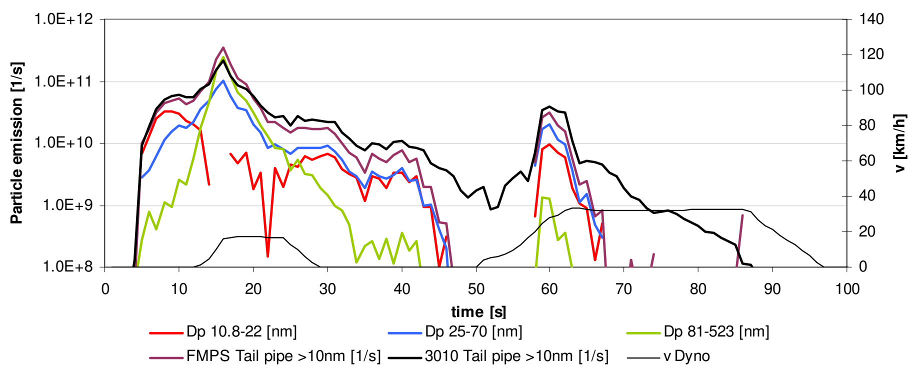


Figure 29: NEDC (ECE) cycle, DI gasoline engine, particle number emissions measured with a CPC3010, and an FMPS separated in three size classes.

NEDC cold start, MPI vehicle No. 5

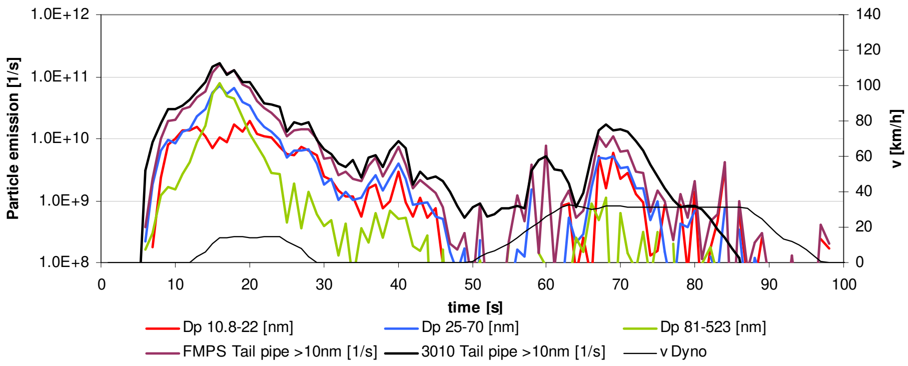


Figure 30: NEDC (ECE) cycle, MPI gasoline engine, particle number emissions measured with a CPC3010, and an FMPS separated in three size classes.

WLTC 23°C cold start, DI vehicle No. 1

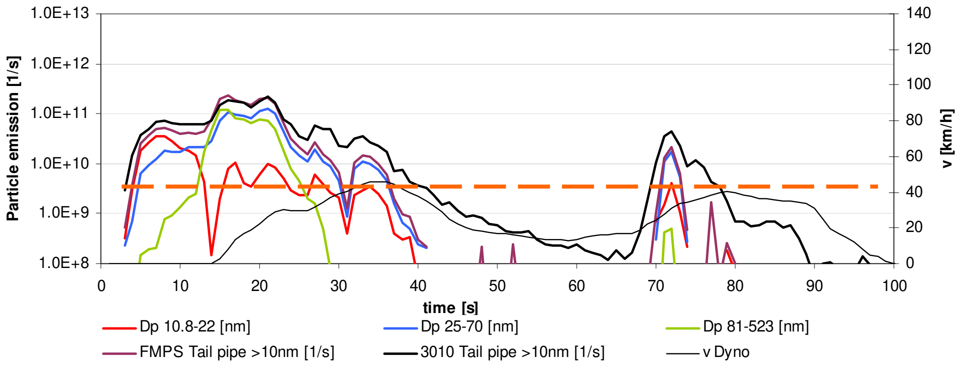


Figure 31: WLTC 23°C cycle, DI gasoline engine, particle number emissions measured with a CPC3010, and an FMPS separated in three size classes.

WLTC 23°C cold start, MPI vehicle No. 5

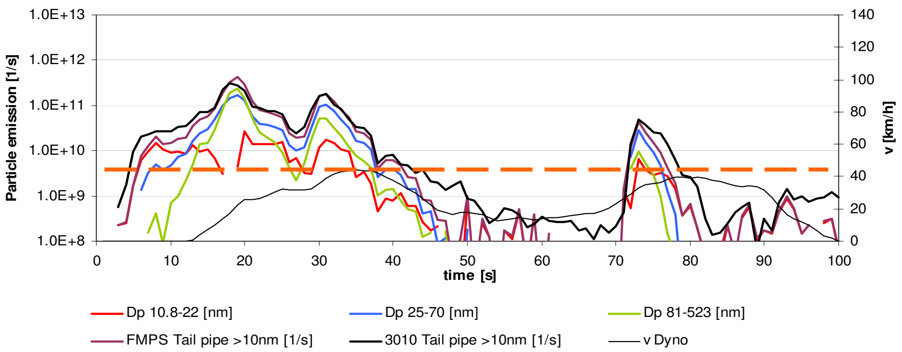


Figure 32: WLTC 23°C cycle, MPI gasoline engine, particle number emissions measured with a CPC3010, and a FMPS separated in three size classes.

WLTC -7°C cold start, DI vehicle No. 1

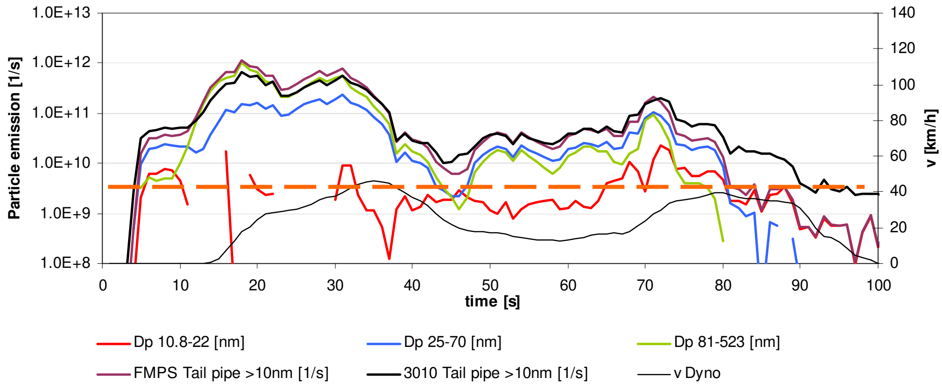


Figure 33: WLTC -7°C cycle, DI gasoline engine, particle number emissions measured with a CPC3010, and an FMPS separated in three size classes.

WLTC -7°C cold start, MPI vehicle No. 5

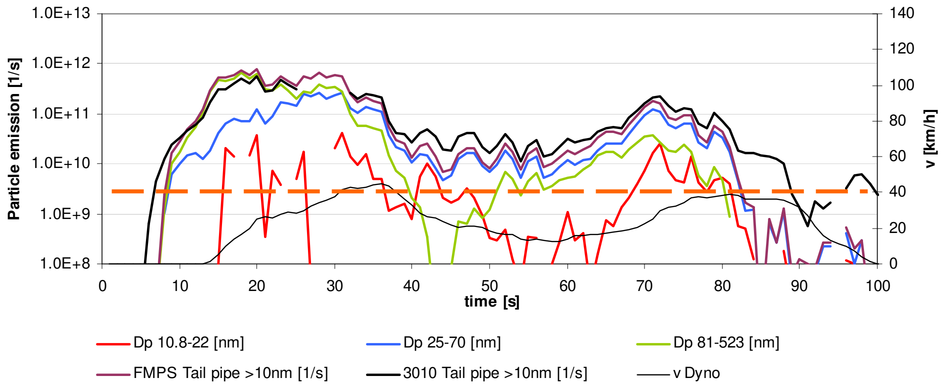


Figure 34: WLTC -7°C cycle, MPI gasoline engine, particle number emissions measured with a CPC3010, and an FMPS separated in three size classes.

3.2 Particle Number emission (PN) diesel vehicles

3.2.1 Aftertreatment system comparison

The bar charts below compare the particle number emission of diesel vehicles equipped with different exhaust aftertreatment systems.

Red bars indicate the particle emissions of the two vehicles equipped with a Diesel Oxidation Catalyst (DOC) and a Diesel Particle Filter (DPF).

Blue bars indicate the particle emissions of the three vehicles equipped with a Diesel Oxidation Catalyst (DOC) a Diesel Particle Filter (DPF) and a Selective Reduction Catalyst (SCR).

Green bars indicate the particle emissions of the one vehicle equipped with a Diesel Oxidation Catalyst (DOC) NOx Storage Catalyst (NSC) and a Diesel Particle Filter (DPF).

The emissions are sampled at different exhaust tube positions with different dilution systems and particle counter measuring ranges (indicated as Tail pipe>10nm, CVS>10nm, CVS>23nm). However, only two vehicles have been measured with the CVS>10nm. Therefore this measuring position was omitted in average values.

Particle emissions change drastically (increase) during an active DPF regeneration. In addition, increased particles numbers are emitted for the first approx. 15 minutes after the regeneration during particle cake build-up inside the DPF channels. Therefore in all following results of average particle emissions, cycles where active DPF regenerations could be identified have been excluded. A separate discussion of particle emissions during active regeneration has been added.

Summary of the main findings

Taking into account only the particles larger than 23nm:

- All diesel vehicles had particle number emissions at the NEDC cycle below the Euro 6b limit (Fig. 35).
- The particle emissions of all diesel vehicles are more than 10 times lower than the Euro 6b limit (Fig. 35).
- The average Euro 6 diesel vehicle emits 1.9×10^{10} 1/km particles at the NEDC cycle including the cold start at 23°C (Fig. 35).
- During the CADC, (higher loads, no cold start) the average diesel Euro 6 vehicle emits 3.1 times higher particle numbers than during the NEDC (lower loads with cold start).

Comparison of particle emissions of the different exhaust aftertreatment systems:

- The DOC/NSC/DPF equipped vehicle had clearly the highest particle emissions in all measured cycles (Fig. 35-36). It should though be kept in mind that only one vehicle, equipped with such a system, was available and measured.
- The DOC/DPF (no additional NOx aftertreatment device) vehicles had the lowest particle number emissions (Fig. 35-36).
- The particle emissions differences among the 3 measured DOC/DPF/SCR vehicles have been significant and much higher than the differences among the DOC/DPF vehicles (Fig. 35, 36).
- During the NEDC the DOC/NSC/DPF vehicle emitted 12.8 times more particles than the average DOC/DPF (Fig. 35). During the higher load CADC cycle (without cold start) the DOC/NSC/DPF vehicle emitted 3000 times more particles than the average DOC/DPF vehicle (Fig. 36).

- During the NEDC the average DOC/DPF/SCR vehicle emitted 2.4 times more particles than the average DOC/DPF (Fig. 35). During the higher load CADC cycle (without cold start) the average DOC/DPF/SCR vehicle emitted 125 times more particles than the average DOC/DPF vehicle (Fig. 36).

Comparison of the particle number emissions counting particles >10nm

- At the tailpipe all particles bigger than 10nm counted during the NEDC cycle have been in average 1.3 times higher than particles bigger than 23nm counted at the CVS.
- The corresponding particle number ratio during the CADC cycle (higher loads without cold start), i.e. particles > 10nm measured at the tailpipe to particles >23nm measured at the CVS was 3.1

The IUFC cycle is a three times repetition of identical cycle parts and therefore ideal for evaluating the effect of the cold start:

- During cold start, particularly during the first part of the IUFC start testing cycle particle emissions of DOC/DPF were almost three orders of magnitude higher than during the second repetition (Figs 37, 38).
- Particle emissions of DOC/DPF/SCR vehicles were also higher during the first IUFC part in respect to the second, but only by a factor of roughly 100 (Figs 37, 38).
- In contrast, the DOC/NSC/DPF vehicle had only a modest increase (factor of 2) of particle emissions during the first IUFC part (Figs 37, 38).
- Particle emissions decreased for a factor of roughly 4 between the second and the third IUFC repetition for the DOC/DPF vehicles (Figs 37, 38).
- DOC/DPF/SCR vehicles did not show any change in particles between the second and third IUFC repletion indicating the shortest warm-up time (Figs 37, 38).
- Particle emissions decreased for a factor of roughly 2 between the second and the third IUFC repetition for the DOC/NSC/DPF vehicle (Figs 37, 38).
- The described behaviour of all vehicles and associated ratios was very similar regardless the starting temperature of the IUFC (-7C and 23C, Figs 38 and 37).

NEDC diesel, cold start

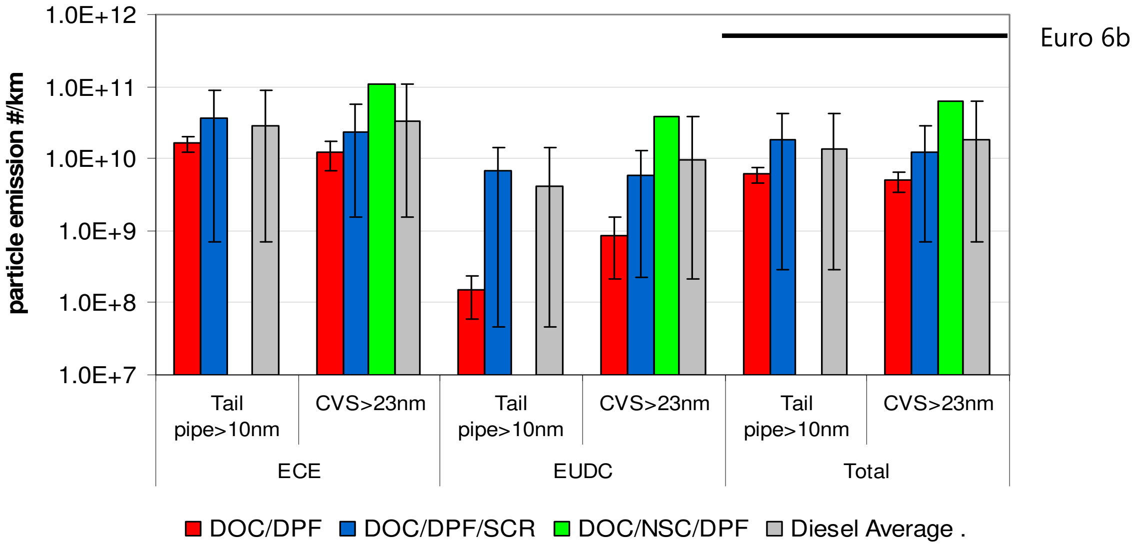


Figure 35: NEDC cycle phase (ECE, EUDC) and total cycle average emissions with minimum and maximum indication.

CADC diesel, warm start

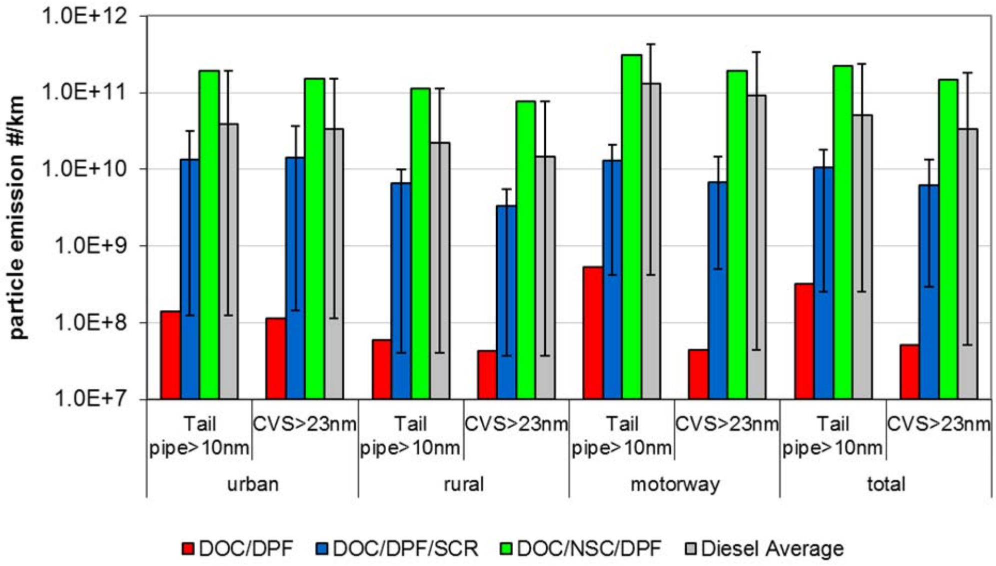


Figure 36: CADC cycle phase (urban, rural, motorway) and total cycle average emissions with minimum and maximum indication.

IUFC diesel, cold start

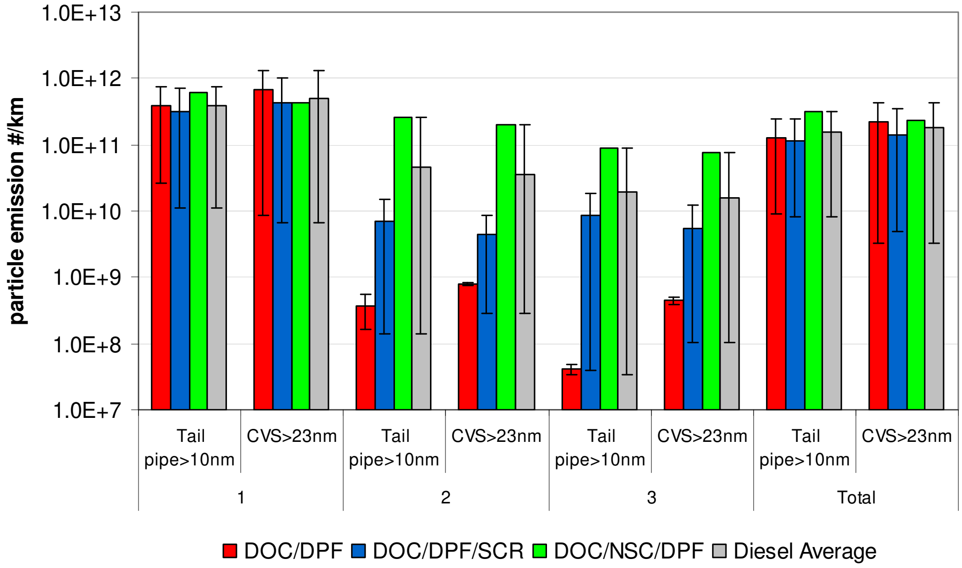


Figure 37: IUFC cycle phase (1, 2, 3) and total cycle average emissions with minimum and maximum indication.

IUFC -7°C diesel, cold start

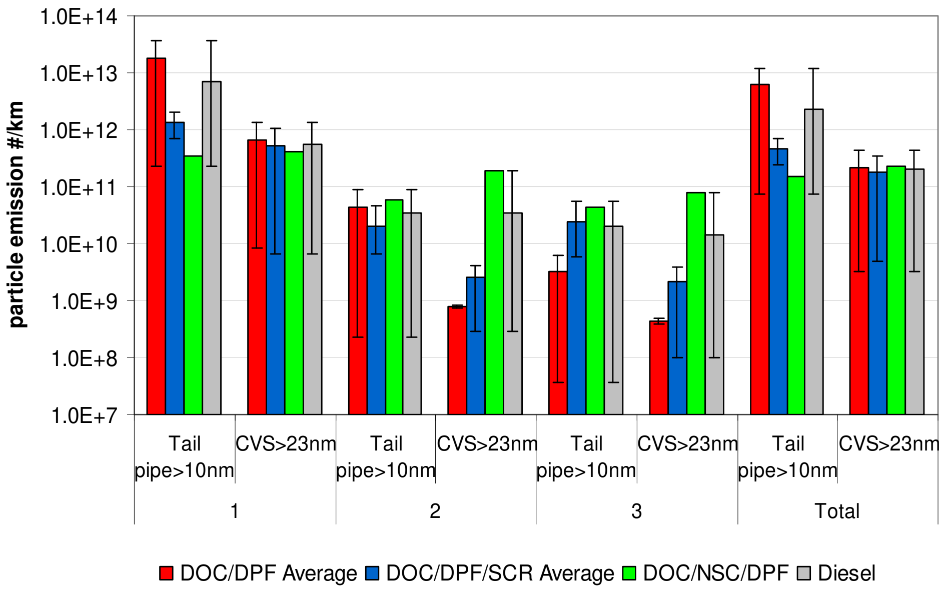


Figure 38: IUFC cycle phase (1, 2, 3) and total cycle average emissions with minimum and maximum indication.

3.2.2 Particle number emissions during and after DPF active regeneration

From time to time the ECU of the engine introduces the process of active DPF regeneration. During active DPF regeneration the engine is running intermittently with rich ($\lambda<1$) and lean conditions ($\lambda>1$), the air flow is constricted by a throttle in order to increase the exhaust temperature as well as to increase the unburnt hydrocarbons at the engine exhaust. These unburnt hydrocarbons oxidize in the DOC. The combined effect is the increase of the temperature upstream the DPF in order to reach roughly 600°C where the soot stored in the DPF burns. It is known from previous investigations (also from our lab) that during regeneration as well as directly after (having a quite empty DPF) the particle emissions increase.

It is difficult to study systematically the phenomenon when no access in the ECU is available and thus no possibilities to predict a coming regeneration or to trigger one. During the measurements performed in the present work a limited number of active DPF regenerations occurred. The cycles involving those have not been used in the results of the previous chapter. On the other hand, the measurements during and directly after active DPF regenerations have been used to assess the effect of active DPF regeneration on the particle emissions of the vehicle in question. It should be kept in mind that active regenerations are necessary roughly every 1000km and require roughly 20 minutes, these characteristics strongly depending on driving loads and style.

<u>Summary of the main findings</u>

- There was one NEDC cycle started directly after active DPF regeneration, i.e. with a clean DPF. Here vehicle 6 (DOC/DPF/SCR) had almost two orders of magnitude higher particle number emissions in respect to the emissions with a normally loaded filter (Fig. 39). In this cycle, the Euro 6b limit has been exceeded
- A further active DPF regeneration happened during the BAB part of an L2 cycle. In this cycle the particle emission was one order of magnitude higher than all other vehicles (Fig. 40).
- The following cycle, which was deliberately started for assessing the particle emissions with a freshly regenerated DPF had also one order of magnitude higher particles (Fig. 41).
- The increased particle number emissions caused by an active DPF regeneration was measured at very similar, if not identical, values by all systems (tailpipe > 10nm, CVS > 23nm) (Figs 39, 40, 41). Thus, the amount of small particles (below 23nm) during active regeneration is very small.
- Similar particle emission increase was detected with a further vehicle during a CADC cycle where also an active regeneration occurred (Fig 42).
- The influence of particle number emissions during active DPF regeneration in the overall particle emission depends from the occurrence frequency of such regenerations. Using the results measured in this study and assuming a limited number (1-6) of active DPF regenerations every 1000km, the weighted particle emission average increases by a factor of 4, should only one active regeneration occur every 1000km. Should 6 active regenerations occur every 1000km then the particle emissions increase by a factor of 20.
- Using the worst case (i.e. 6 active regenerations every 1000km) the DOC-DPF as well as the DOC-DPF-SCR vehicles are below the Euro 6b limit with a good safety margin. The DOC-NSC-DPF vehicle will be at the Euro 6b limit. Active DPF regenerations, however, are less frequently needed in DOC-NSC-DPF systems.

NEDC diesel, cold start

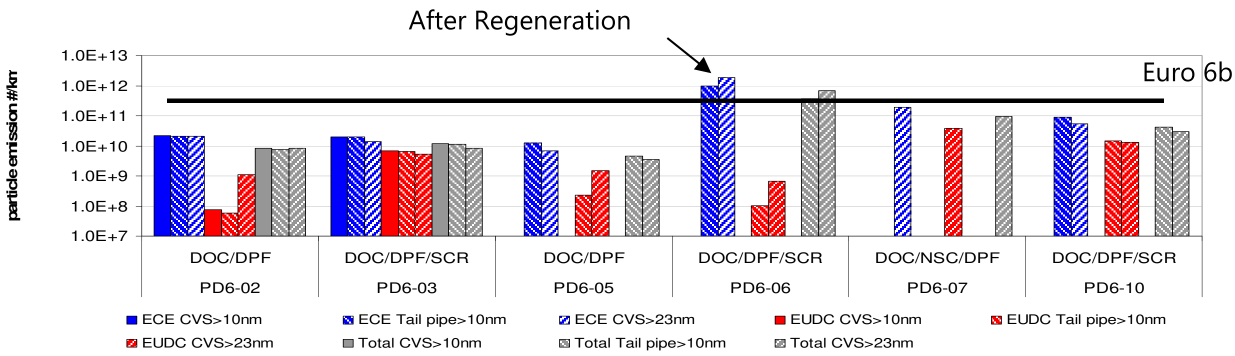


Figure 39: NEDC cycle phase emission, ECE (blue), EUDC (red) and total cycle average emission (grey).

L2 diesel, warm start

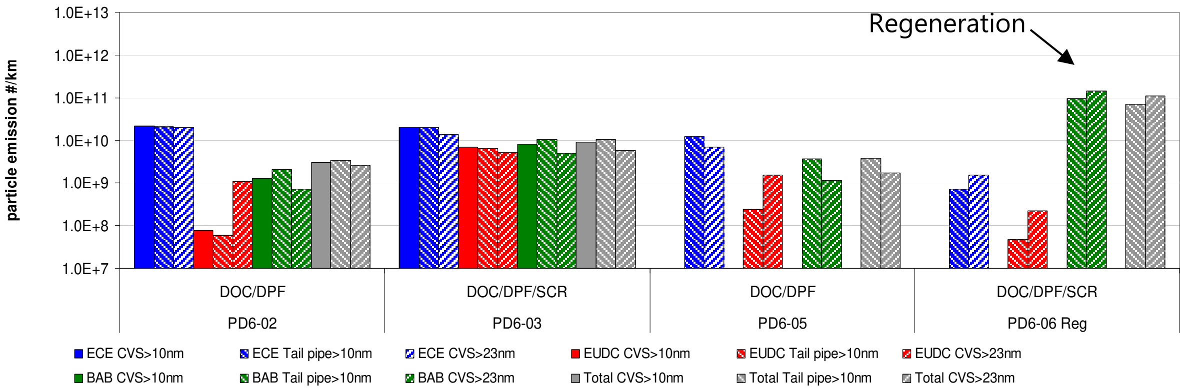


Figure 40: L2 cycle phase emission, ECE (blue), EUDC (red), BAB (green) and total cycle average emission (grey).

L2 diesel, regeneration at BAB phase and next cycle start of vehicle No. 6

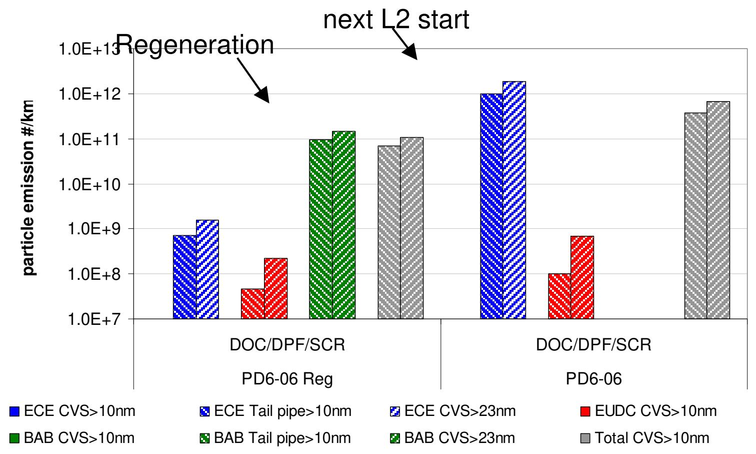


Figure 41: L2 cycle phase emission, ECE (blue), EUDC (red), BAB (green) and total cycle average emission (grey).

CADC diesel, warm start

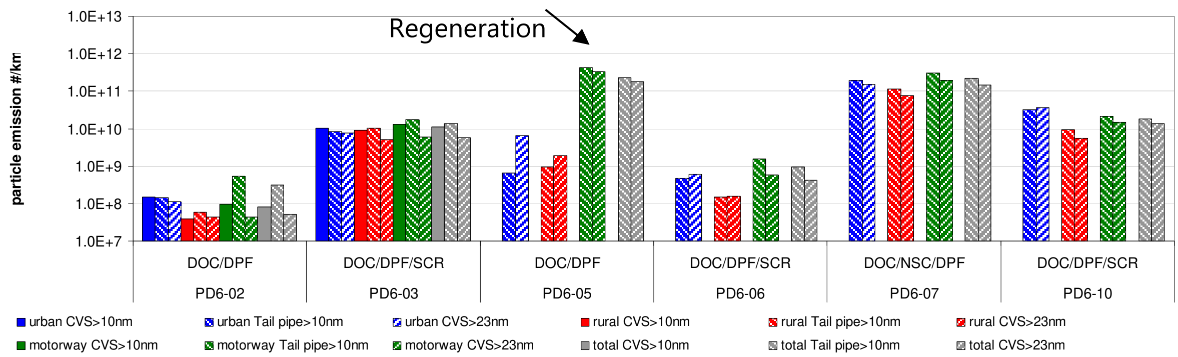


Figure 42: CADC cycle phase emission, urban (blue), rural (red), motorway (green) and total cycle average emission (grey).

3.2.3 Characteristics of the vehicle particle emissions and the measurement technology

In the following diagrams of selected vehicles the particle emissions >10nm at the tail pipe are red, at the CVS dark blue and the particle emissions >23nm at the CVS clear blue.

Remarks to the following graphs:

- The three vehicles, vehicle 2 (DOC-DPF), 3 (DOC-DPF-SCR) and 6 (DOC-DPF-SCR), have particle emissions measured by the three measurement systems which are practically identical in the ECE cycle. This shows that there are very low, if any, small particles below 23nm (Figs 43, 44, 45) emitted.
- Vehicle 2 (DOC-DPF) (Fig. 43) had a short significant emission peak in the beginning of the cycle followed by low emissions. Vehicle 3 (DOC-DPF-SCR), (Fig. 44) had constantly higher emissions without a peak and vehicle 6 (DOC-DPF-SCR) (Fig 45) had a low start emission peak followed by low emissions.
- The three vehicles (2, 3 and 6) show also different behaviour in the 2nd half of the L2 cycle.
    - Vehicle 2 (DOC-DPF) has, in general, very low values and some peaks of the particle measured by the tailpipe system (>10nm). These peaks are not detected by the CVS (>23nm) system and they appear only attenuated at the CVS (>10nm). Also a CVS storage/release effect is evident at the cycle end (Fig. 46).
    - Vehicle 3 (DOC-DPF-SCR) show PN(tailpipe>10nm)>PN(CVS>10nm)>PN(CVS>23nm). This is evidence for some small particle emission. Strong accelerations lead to higher small particle emissions, (Fig 47).
    - Vehicle 6 (DOC-DPF-SCR) had an active regeneration in the last cycle part strongly increasing particle emissions. The results confirm the observations of the former section, having no, or very low amount of sub 23nm during regeneration, (Fig 48).
- Figure 49 and 50 show the IUFC cold start of vehicle 3 (DOC-DPF-SCR) at normal and -7°C temperature. At -7°C a large emission start peak was formed. Both figures indicate no sub-23nm particle emissions, given that all PN measuring systems show similar values.
- Figure 51 and 52 show the first part of the WLTC cycle of Vehicle 7 (DOC/NSC/DPF) at 23°C and -7°C respectively. Figs 53 and 54 the second half of the WLTC cycle. Throughout the cycles there is some significant difference between the >10nm and the >23nm particle number showing some small particle emission. The differences among the two temperatures are not significant, apart from idling phases (specifically denoted in the figs). During idling the particle emissions at 23°C are very low. At -7°C however, they are significantly more.

L2 (ECE) Vehicle no. 2, diesel, DOC-DPF, cold start

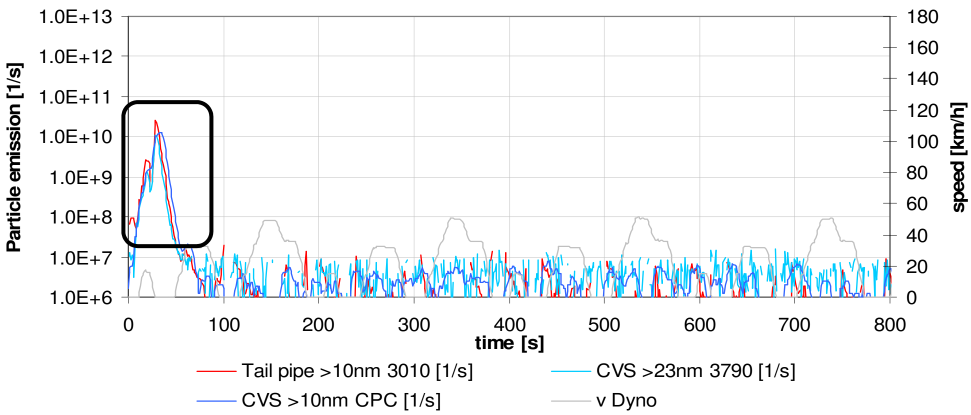


Figure 43: L2 (ECE) cycle, particle number emission and vehicle speed (grey).

L2 (ECE) Vehicle no. 3, diesel, DOC-DPF-SCR, cold start

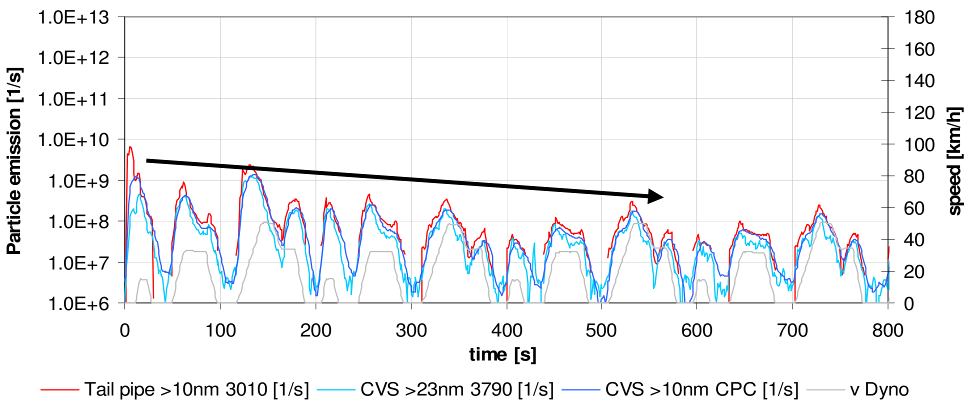


Figure 44: L2 (ECE) cycle, particle number emission and vehicle speed (grey).

L2 (ECE) Vehicle no. 6, DOC-DPF-SCR, cold start

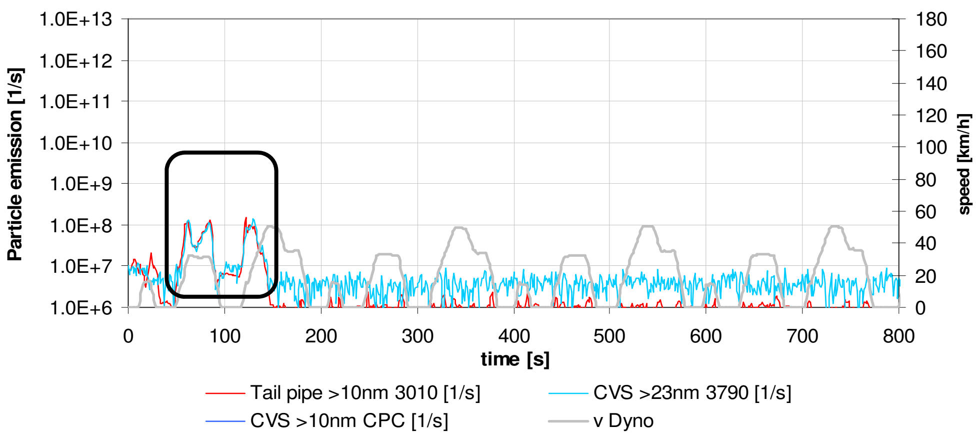


Figure 45: L2 (ECE) cycle, particle number emission and vehicle speed (grey).

L2 (EUDC+BAB) Vehicle no. 2, diesel, DOC-DPF, cold start

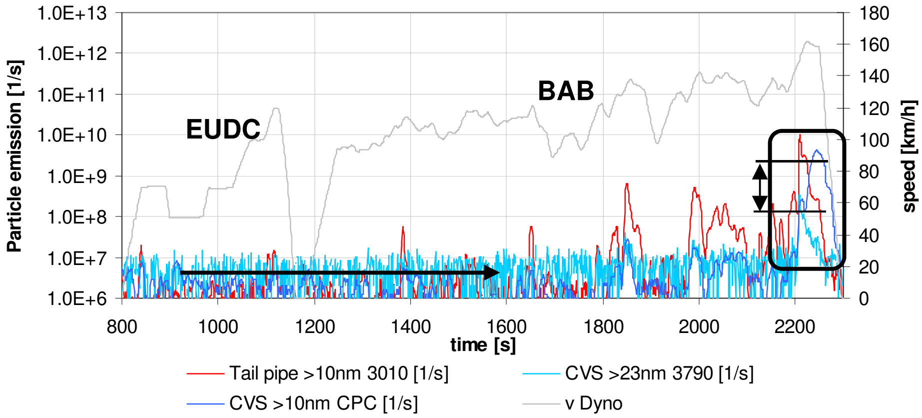


Figure 46: L2 (EUDC, BAB) cycle, particle number emission and vehicle speed (grey).

L2 (EUDC+BAB) Vehicle no. 3, diesel, DOC-DPF-SCR, cold start

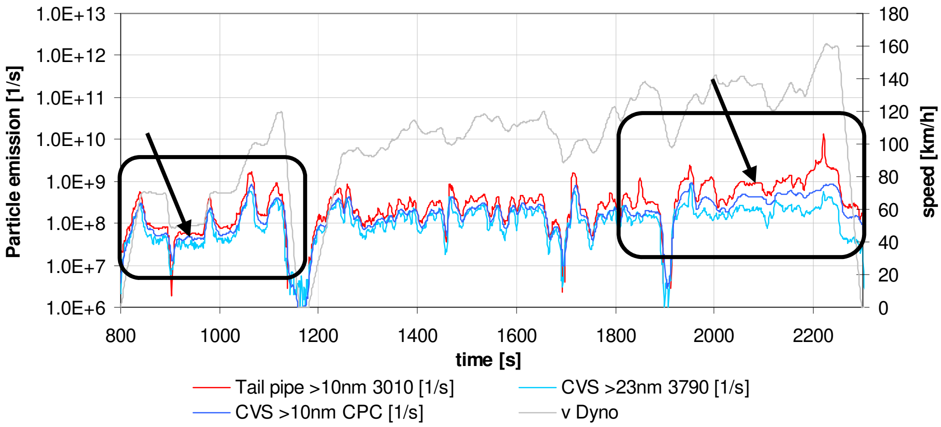


Figure 47: L2 (EUDC, BAB) cycle, particle number emission and vehicle speed (grey).

L2 (EUDC+BAB) Vehicle no. 6, DOC-DPF-SCR, cold start

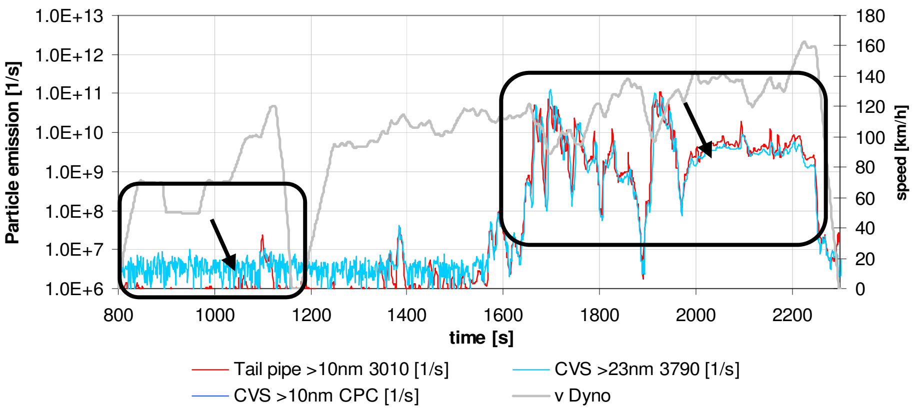


Figure 48: L2 (EUDC, BAB) cycle, particle number emission and vehicle speed (grey).

IUFC Vehicle no. 3, diesel, DOC-DPF-SCR, cold start

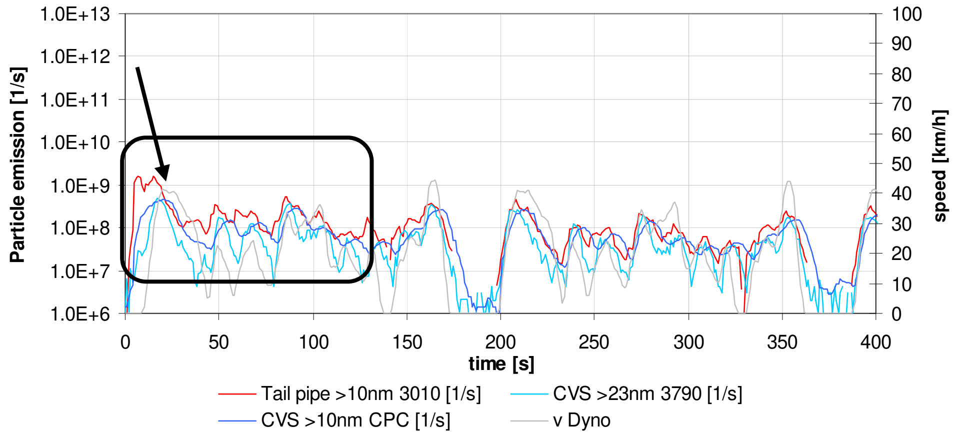


Figure 49: IUFC cycle, particle number emission and vehicle speed (grey).

IUFC -7°C Vehicle no. 3, diesel, DOC-DPF-SCR, cold start

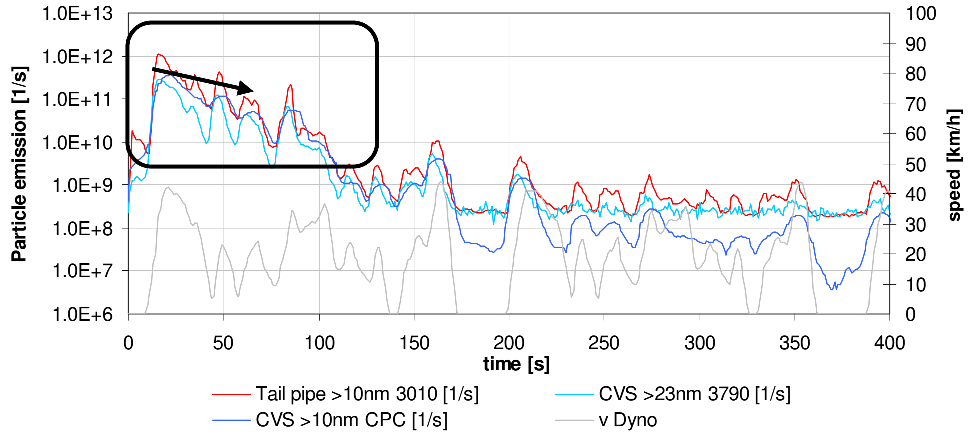


Figure 50: IUFC cycle at -7°C condition, particle number emission and vehicle speed (grey).

WLTC Vehicle no. 7, DOC-NSC-DPF, cold start

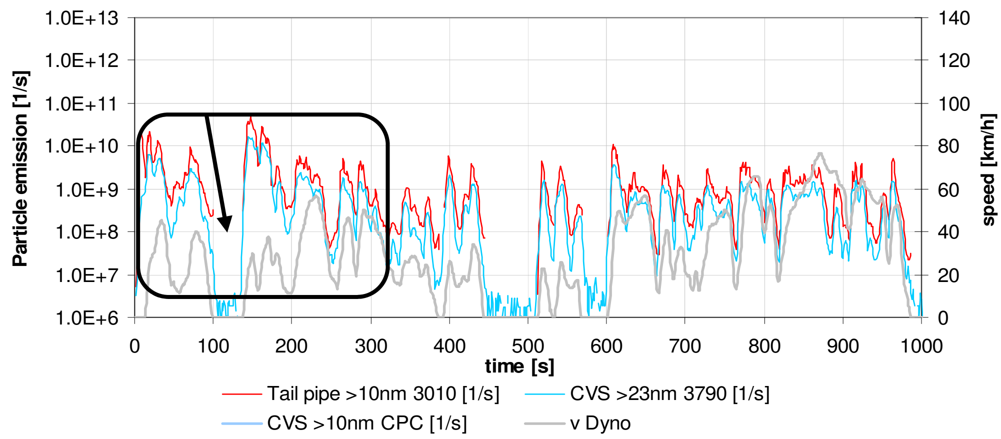


Figure 51: WLTC cycle, particle number emission and vehicle speed (grey).

WLTC -7°C Vehicle no. 7, DOC-NSC-DPF, cold start

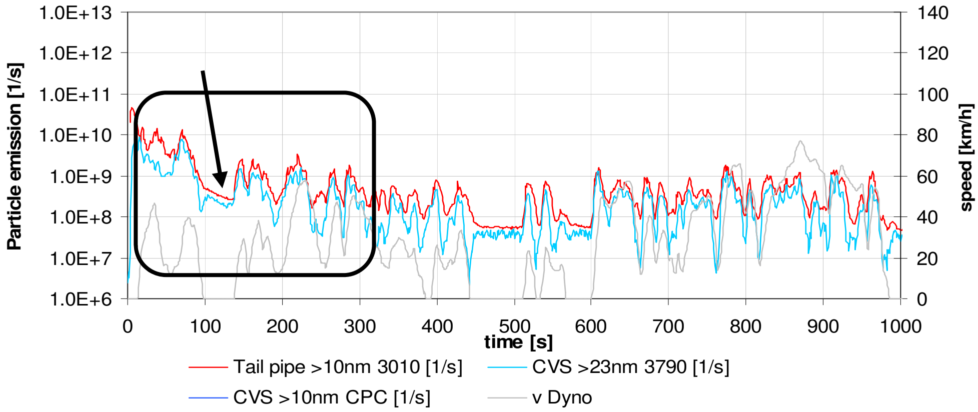


Figure 52: WLTC cycle at -7°C condition, particle number emission and vehicle speed (grey).

WLTC Vehicle no. 7, DOC-NSC-DPF, cold start

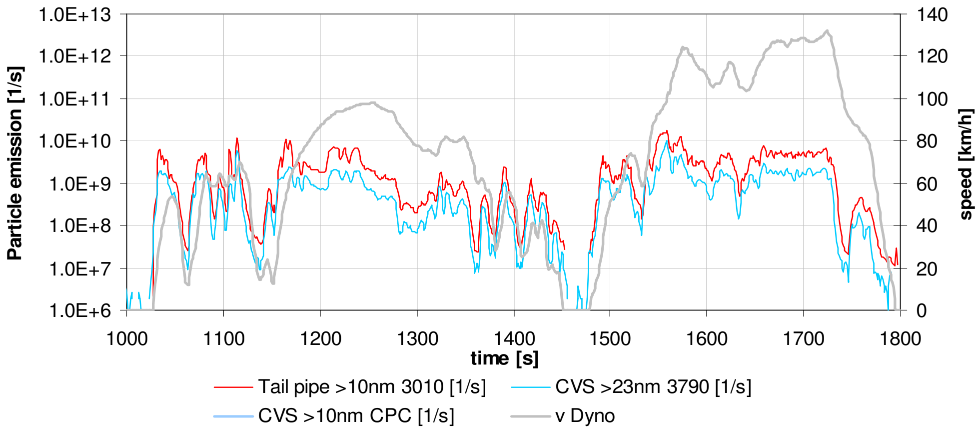


Figure 53: WLTC cycle, particle number emission and vehicle speed (grey).

WLTC -7°C Vehicle no. 7, DOC-NSC-DPF, cold start

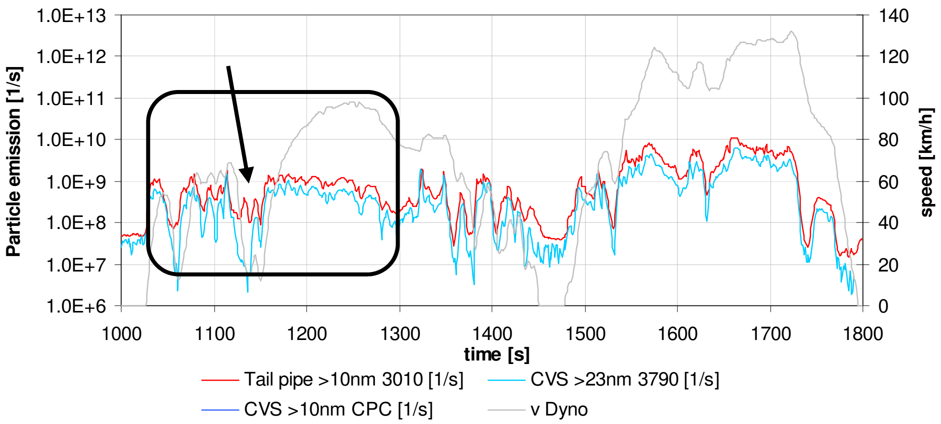


Figure 54: WLTC cycle, particle number emission and vehicle speed (grey).

3.2.4 Particle emissions in size ranges, of a DOC-DPF and two DOC-DPF- SCR vehicles

In the following diagrams particle number emissions of three diesel vehicles are presented. The black lines indicate the total particle number >10nm measured with a CPC 3010, the purple line indicates the computed total particle number >10nm measured with a TSI FMPS and the additional graphs (red, blue, green) indicate computed particle number concentrations of selected particle size ranges as measured by the FMPS.

The FMPS detection limit is reached at about a particle number concentration of $6*10^8$ $1/cm^3$ (orange dashed line in the graphs). As a confirmation of the accuracy of our measurements we regard that, above the detection limit, the trends of the CPC (black line) and the total of the FMPS (purple line) are similar, if not equal.

The main insights, confirming already described results can be summarized as follows:

- The DOC-DPF vehicle has PN emissions only during cold start, (Figs 55, 56). The contribution of the smallest particles to the overall result is rather modest.
- The DOC-DPF-SCR vehicle (no 3), Figs 57 and 58, shows significant particle emissions mainly in the first part of the NEDC cycle. Here the size class of the smallest particles is a significant fraction. In the second half of the NEDC cycle particle emissions are very low.
- The second DOC-DPF-SCR vehicle (no 6) had a rather low small particles quantity (Fig 59). At about 1650s an active DPF regeneration was initiated (Fig. 60). During this regeneration particle emissions increased while the mid and large size class are predominant.
- In a subsequent started cycle (Fig 61), with a clean DPF, particle emissions have been high, with the mid and the large size class being predominant.

NEDC Vehicle no. 2, DOC-DPF, cold start, first 200s

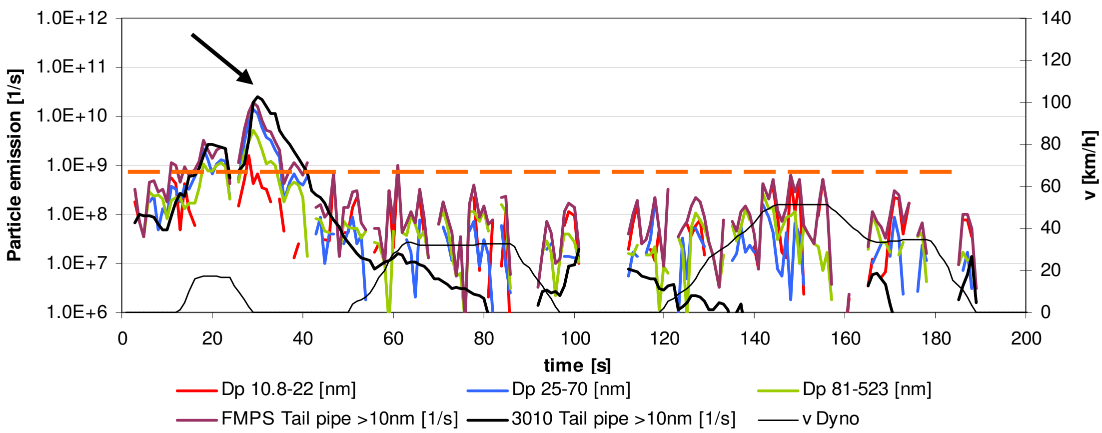


Figure 55: NEDC cycle, particle number emission and vehicle speed (grey).

NEDC Vehicle no. 2, DOC-DPF, cold start, EUDC phase

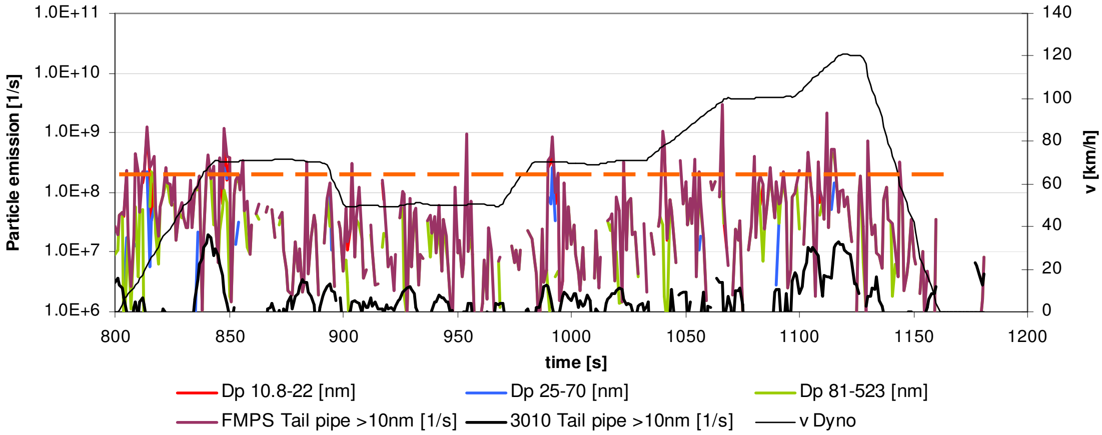


Figure 56: NEDC cycle, particle number emission and vehicle speed (grey).

NEDC Vehicle no. 3, DOC-DPF-SCR, cold start, first 200s

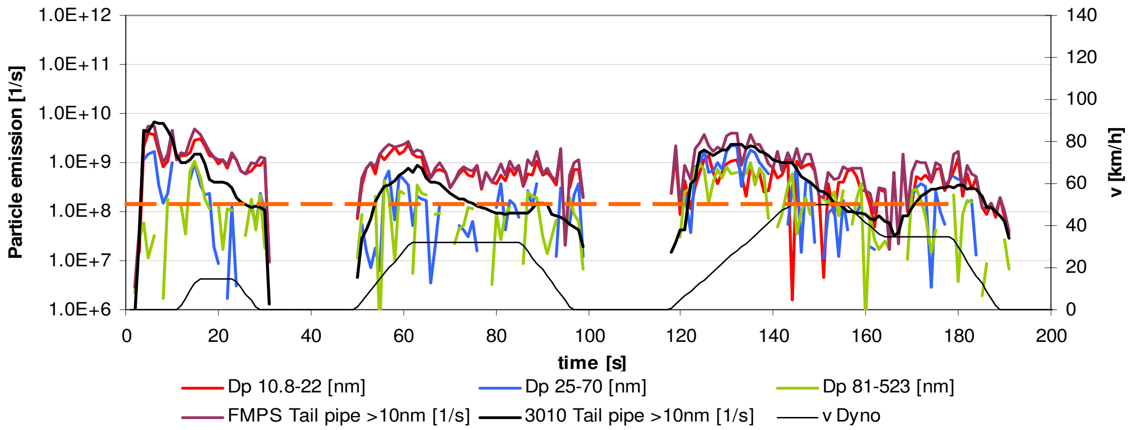


Figure 57: WLTC cycle, particle number emission and vehicle speed (grey).

NEDC Vehicle no. 3, DOC-DPF-SCR, cold start, EUDC phase

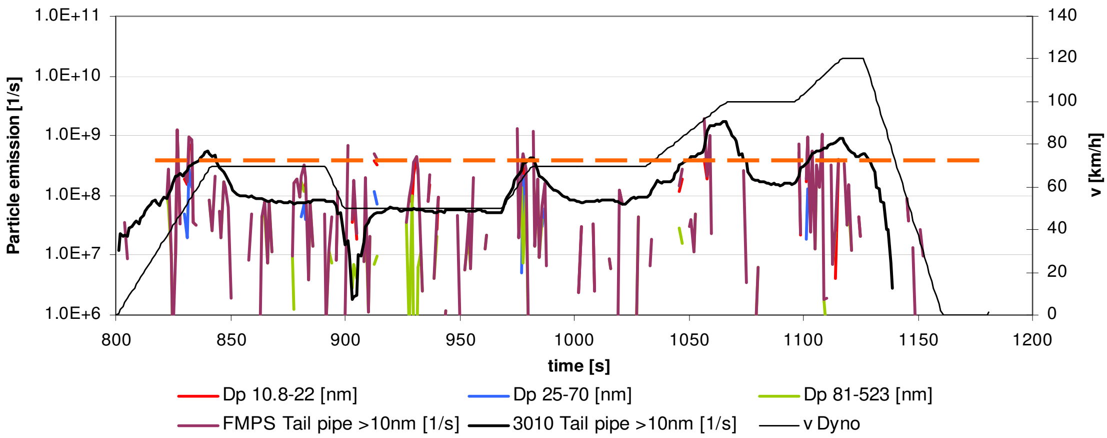


Figure 58: WLTC cycle, particle number emission and vehicle speed (grey).

NEDC Vehicle no. 6, DOC-DPF-SCR, cold start (ECE)

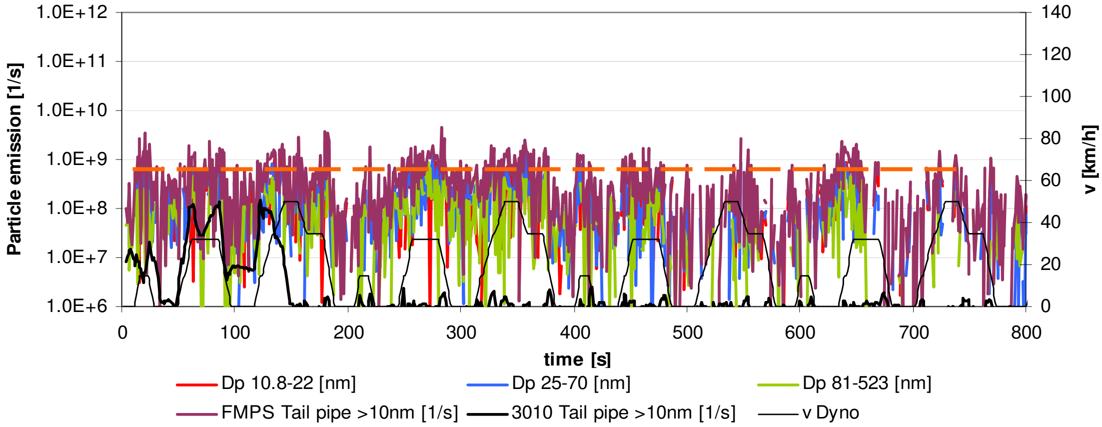


Figure 59: WLTC cycle, particle number emission and vehicle speed (grey).

BAB Vehicle no. 6, DOC-DPF-SCR, regeneration during BAB phase

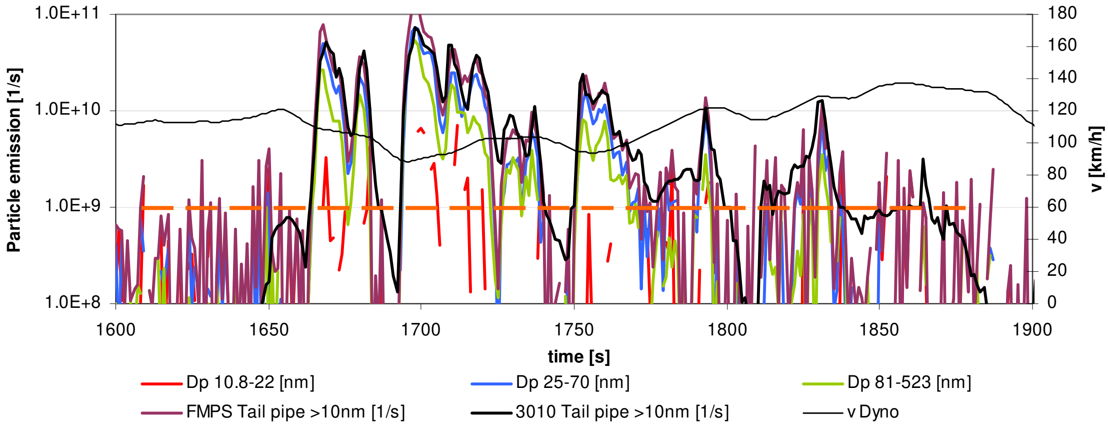


Figure 60: WLTC cycle, particle number emission and vehicle speed (grey).

NEDC cold start Vehicle no. 6, DOC-DPF-SCR, start after regeneration

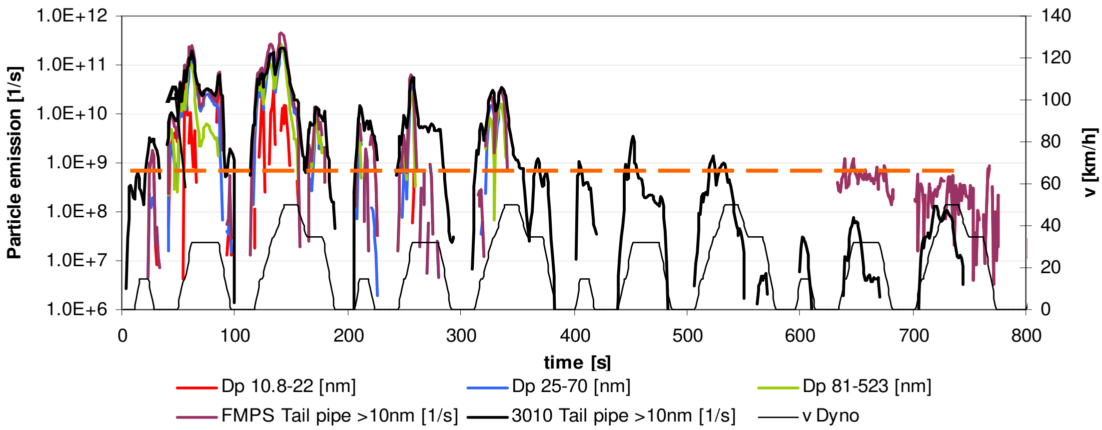


Figure 61: WLTC cycle, particle number emission and vehicle speed (grey).

3.3 Particle Number emission of a Compressed Natural Gas vehicle and comparisons

One CNG, Compressed Natural Gas, vehicle has also been measured. This vehicle had stoichiometric premixed combustion, was spark ignited and was equipped with a Three Way Catalyst. From the point of view of the combustion mode and exhaust aftertreatment system, this vehicle was similar to gasoline vehicles.

The main insights can be summarized as follows:

Taking into account all particles larger than >23nm (Fig. 62):

- In the NEDC cycle the lowest particle numbers have been emitted by the Diesel DOC/DPF vehicles.
- The Diesel DOC/DPF/SCR vehicles emitted in average 2.5 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The CNG vehicle emitted in average 5 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The Diesel DOC/NSC/DPF emitted in average 13 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The gasoline MPI emitted in average 110 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The gasoline DI emitted in average 105 times more particles (in respect to the Diesel DOC/DPF vehicles)

The relations have been similar for particles larger than >10nm (Fig 63). There is though only one striking difference to the particles larger than 23nm:

- The gasoline MPI emitted in average 60 times more particles
- The gasoline DI emitted in average 65 times more particles

in respect to the DOC/DPF diesels. This rather shows that gasolines and diesels are more similar in their emission behaviour in the smallest particle range, i.e. those between 10nm and 23nm.

In the particle number emissions of Diesel vehicles the effect of the active DPF regeneration has to be taken into account. As described in section 3.2.2 active regenerations of the DPF result in increased particle number emissions during and directly after regeneration before a new soot cake is build up. For the assessment of the influence of active regenerations in the overall particle emission characteristics a reasonable active regeneration frequency has to be assumed. Active regenerations are more frequent should the vehicles be used predominantly in city driving modes and less frequent should the vehicles be used predominantly in highway driving. We considered 3 active regenerations per 1000km as a reasonable average assumption. Based on this assumption and using the increased particle emissions as measured and described in section 3.2.2 the conclusion is

- Active DPF regenerations lead to an increase of the average particle number emissions per km of the Diesel vehicles by a factor of 10.

As already described the cold start leads to an increase of the particle emissions in particular for the Diesel DOC/DPF as well as for the MPI gasoline vehicles. The comparison of the particulate emissions during the CADC cycle with no cold start provides the relevant comparisons, Figs 64, 65. Following conclusions can be summarized concerning the particle emissions, >23nm during the CADC cycle, Fig 64:

- In the CADC cycle the lowest particle numbers have been emitted by the Diesel DOC/DPF vehicles.
- The Diesel DOC/DPF/SCR vehicles emitted in average 120 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The CNG vehicle emitted in average 150 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The Diesel DOC/NSC/DPF emitted in average 3000 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The gasoline MPI emitted in average 7000 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The gasoline DI emitted in average 26000 times more particles (in respect to the Diesel DOC/DPF vehicles)
- Active DPF regenerations lead to an increase of the average particle number emissions of the Diesel vehicles by a factor of 10.

Considering all particles, i.e. >10nm the differences to the lowest particle emitters, the Diesel DOC/DPFs were significantly lower, Fig. 65:

- The Diesel DOC/DPF/SCR vehicles emitted in average 30 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The CNG vehicle emitted in average 100 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The Diesel DOC/NSC/DPF emitted in average 700 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The gasoline MPI emitted in average 1000 times more particles (in respect to the Diesel DOC/DPF vehicles)
- The gasoline DI emitted in average 2500 times more particles (in respect to the Diesel DOC/DPF vehicles)

Again this shows that when smallest particles are also counted, the differences among the different combustion modes and fuels decrease.

The particularities of the cold start have been studied by using the IUFC cycle, consisting of 3 consequent repetitions of the identical mainly low load cycle. The IUFC cycle has been performed with all vehicles at two temperatures, 23°C and -7°C. The results are shown in Figs 66-69. Main results can be summarized, Figs 66 and 67, as follows:

In the first repetition of the IUFC cycle at 23°C:

- The lowest particle numbers have been emitted by the CNG vehicle.
- The Diesel DOC/DPF vehicles emitted some 12 times more particles (in respect to the CNG vehicle)
- The Diesel DOC/DPF/SCR vehicles emitted 8 times more particles, (in respect to the CNG vehicle)
- The Diesel DOC/NSC/DPF emitted 10 times more particles (in respect to the CNG vehicle)
- The gasoline MPI emitted in average 40 times more particles (in respect to the CNG vehicle)
- The gasoline DI emitted in average 40 times more particles (in respect to the CNG vehicle)
- All these trends were identical when comparing also particles >10nm, comparison of Figs. 66 and 67.

In the first repetition of the IUFC cycle at -7°C the above mentioned trends at 23°C have been practically the same Figs (68, 69). Only

- The Diesel DOC/DPF vehicles emitted 30 times more particles >10nm in respect to those >23nm

Following the first repetition of the IUFC the subsequent two repetitions had as a result the warming up of the engines and aftertreatment systems. This lead to decreasing particle emissions, the Diesel DOC/DPF vehicles exhibiting the steepest decrease. This changed the relations among the particles of the different vehicle classes, though not fundamentally. For the entire IUFC cycle the main findings can be summarized as follows:

- The lowest particle numbers have been emitted by the CNG vehicle.
- The Diesel DOC/DPF vehicles emitted some 4 times more particles (in respect to the CNG vehicle)
- The Diesel DOC/DPF/SCR vehicles emitted 3 times more particles, (in respect to the CNG vehicle)
- The Diesel DOC/NSC/DPF emitted 6 times more particles (in respect to the CNG vehicle)
- The gasoline MPI emitted in average 20 times more particles (in respect to the CNG vehicle)
- The gasoline DI emitted in average 22 times more particles (in respect to the CNG vehicle)
- All these trends were identical when comparing also particles >10nm, comparison of Figs. 66 and 67.

Also in the entire IUFC cycle at -7°C the above mentioned trends at 23°C have been practically the same Figs (68, 69). Only

- the Diesel DOC/DPF vehicles emitted 30 times more particles >10nm in respect to those >23nm

NEDC, cold start, 23°C

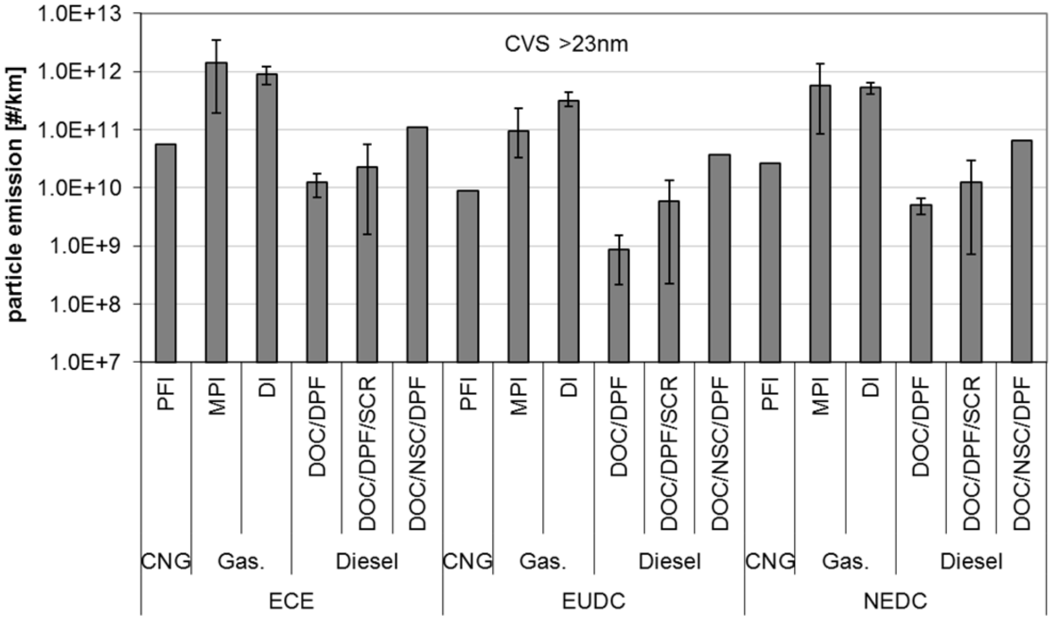


Figure 62: Particle emission overview of all powertrain technologies investigated in this study at the NEDC cycle measuring all particles at the CVS >23nm, in the Diesels no active regeneration has been accounted for.

NEDC, cold start, 23°C

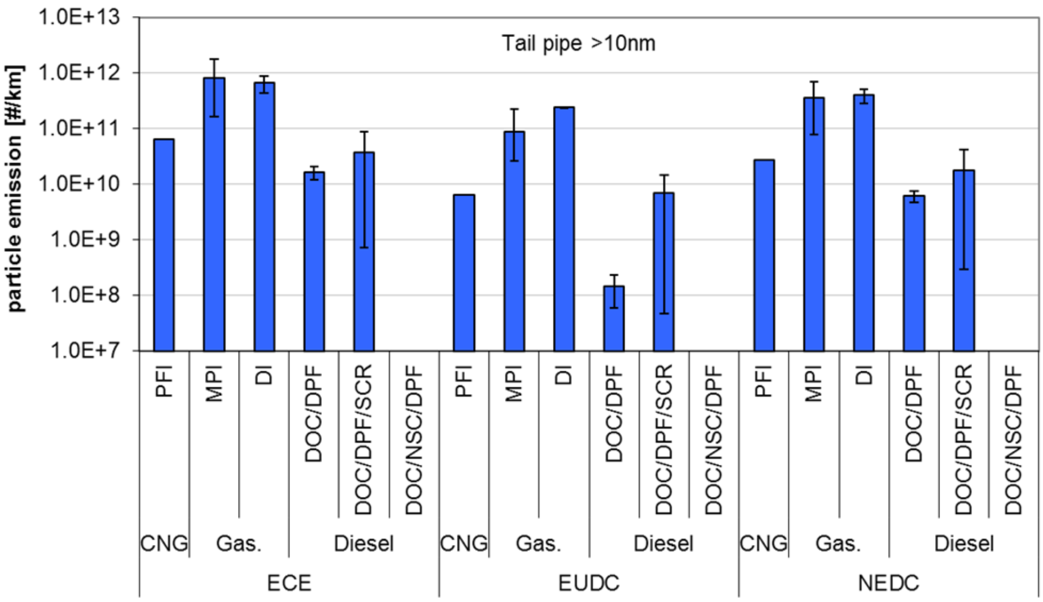


Figure 63: Particle emission overview of all powertrain technologies investigated in this study at the NEDC cycle measuring all particles at the tail pipe >10nm, in the Diesels no active regeneration has been accounted for.

CADC, warm start

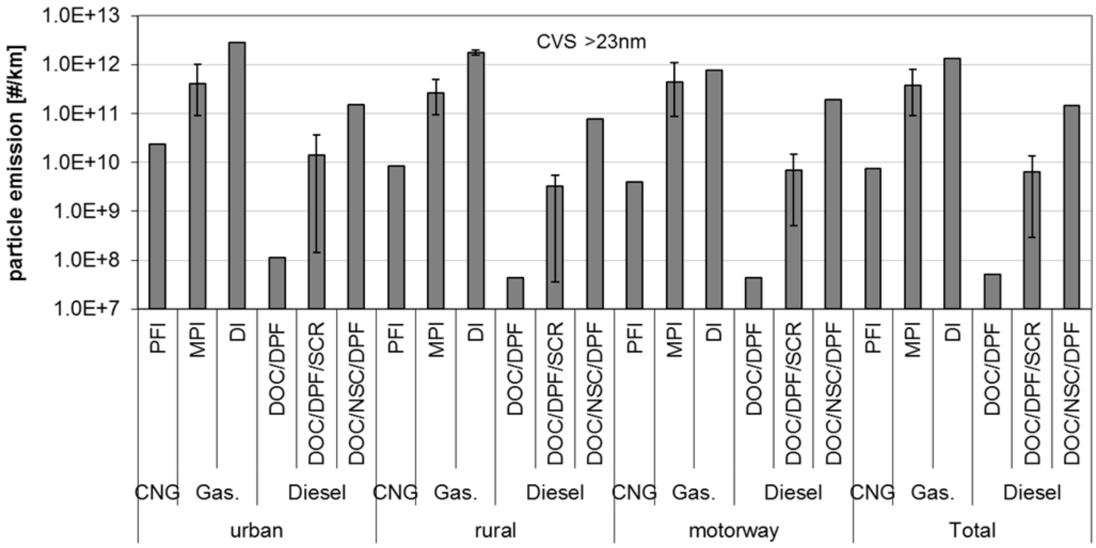


Figure 64: Particle emission overview of all powertrain technologies investigated in this study at the CADC cycle measuring all particles at the CVS >23nm, in the Diesels no active regeneration has been accounted for.

CADC, warm start

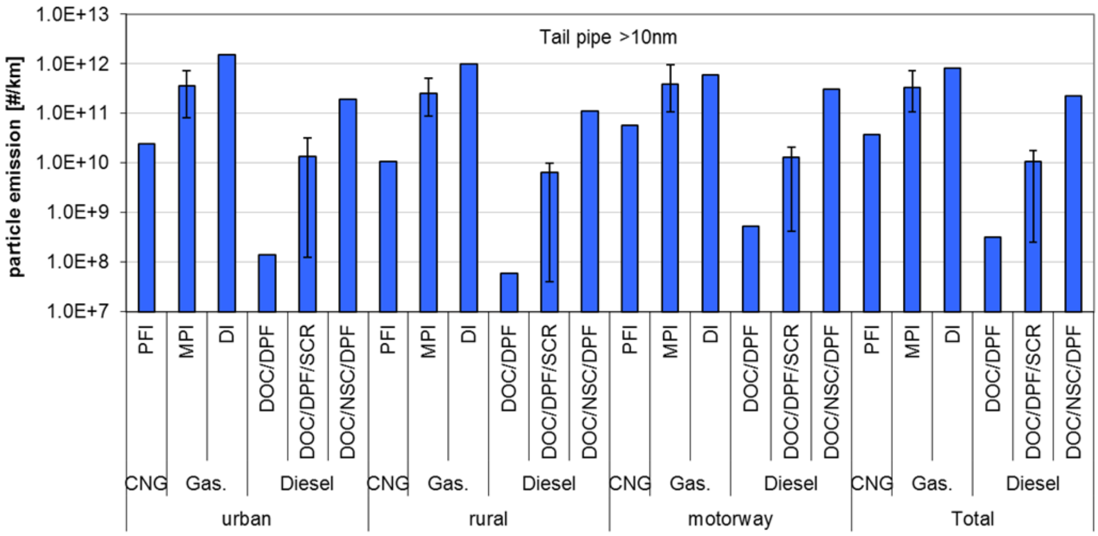


Figure 65: Particle emission overview of all powertrain technologies investigated in this study at the CADC cycle measuring all particles at the CVS >10nm, in the Diesels no active regeneration has been accounted for.

IUFC, cold start, 23°C

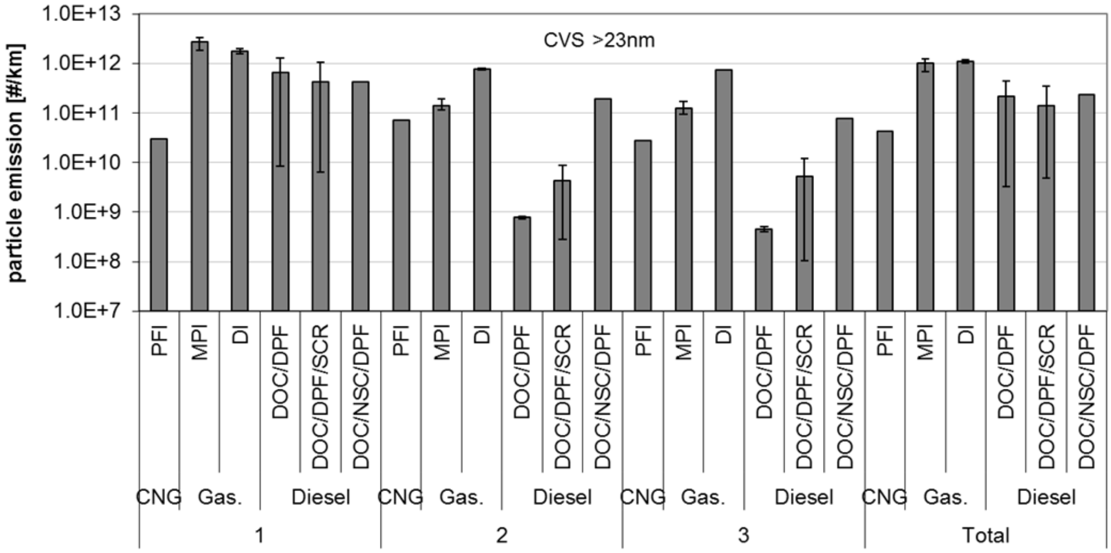


Figure 66: Particle emission overview of all powertrain technologies investigated in this study at the IUFC cycle at 23°C measuring all particles at the CVS >23nm, in the Diesels no active regeneration has been accounted for.

IUFC, cold start, 23°C

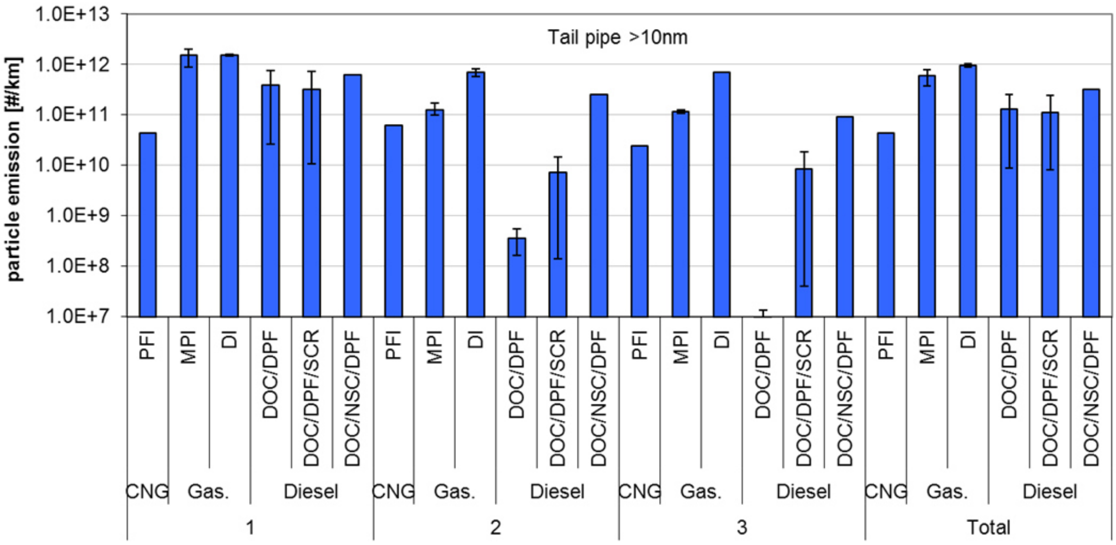
- 

Figure 67: Particle emission overview of all powertrain technologies investigated in this study at the IUFC cycle at 23°C measuring all particles at the CVS >23nm, in the Diesels no active regeneration has been accounted for.

IUFC, cold start, -7°C

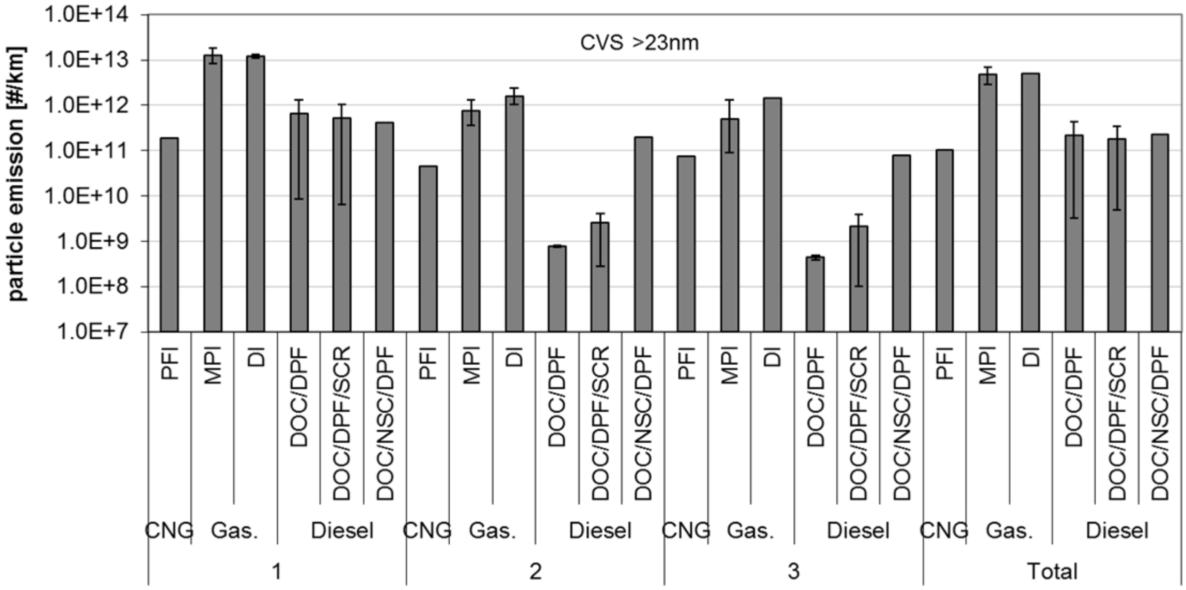


Figure 68: Particle emission overview of all powertrain technologies investigated in this study at the IUFC cycle at -7°C measuring all particles at the CVS >23nm, in the Diesels no active regeneration has been accounted for.

IUFC, cold start, -7°C

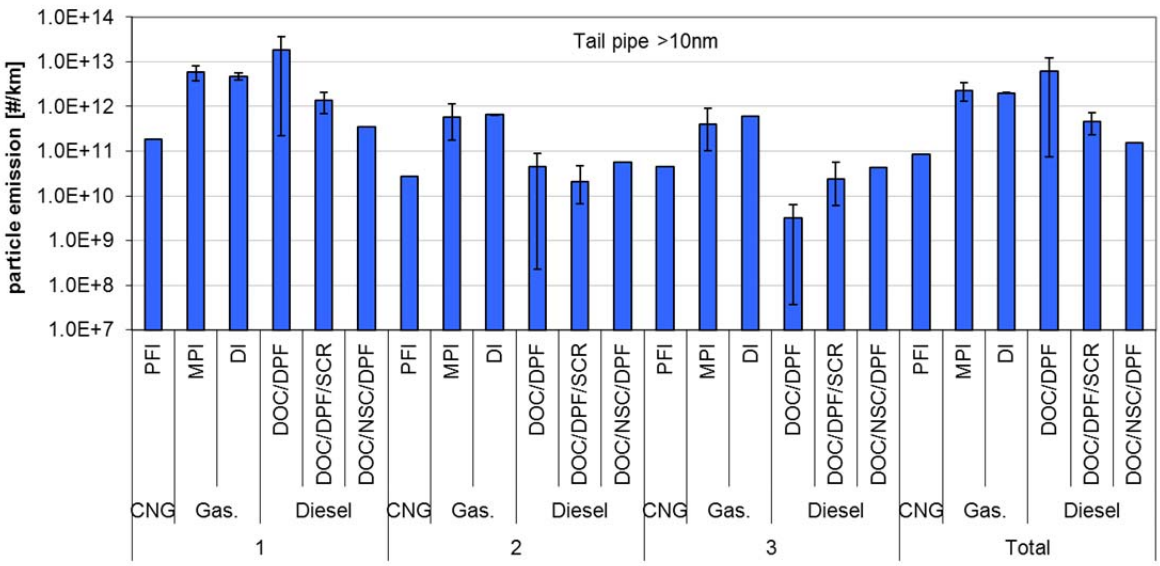


Figure 69: Particle emission overview of all powertrain technologies investigated in this study at the IUFC cycle at -7°C measuring all particles at the CVS >23nm, in the Diesels no active regeneration has been accounted for.

4. References

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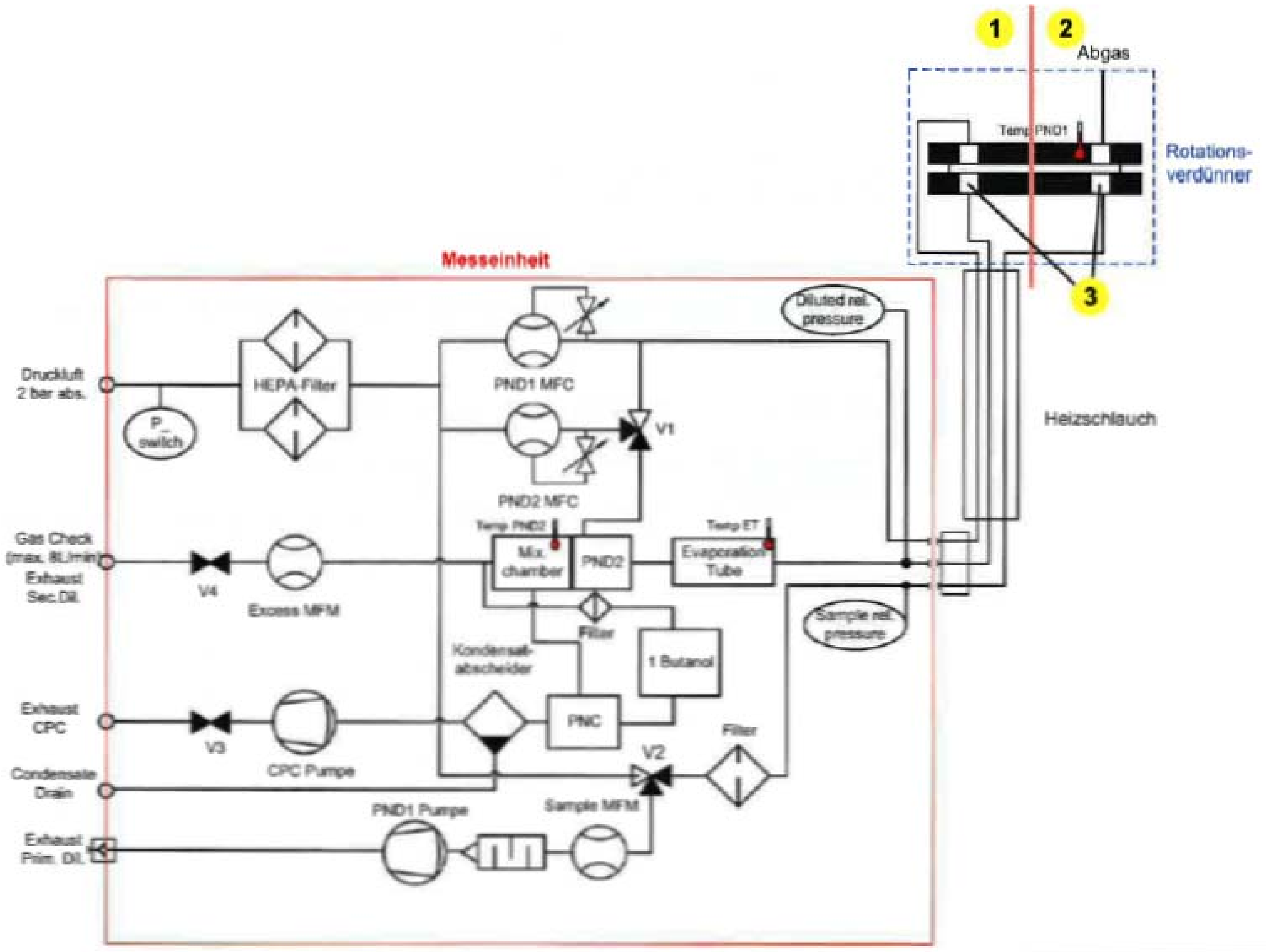
5. Appendix

5.1 Appendix 1, APC setup



5.2 Appendix 2, Used VPR dilution factors

Table 5: VPR Dilution Factor, gasoline vehicles

		PB6-01	PB6-02	PB6-03	PB6-04	PB6-05	PB6-06
NEDC	TP >10nm	2100	2100	2100	2100	2100	2100
	CVS >10nm	-	1000	1000	1000	2334	2334
	CVS >23nm	1350	1350	1350	1350	1350	1350
CADC	TP >10nm	2100	2100	2100	2100	2100	2100
	CVS >10nm	-	1000	1000	1000	1000	1000
	CVS >23nm	1350	1350	1350	1350	1350	1350
ERMES	TP >10nm	2100	2100	2100	2100	2100	2100
	CVS >10nm	-	1000	1000	1000	-	1000
	CVS >23nm	1350	1350	1350	1350	1350	1350
IUFC	TP >10nm	2100	2100	2100	2100	2100	2100
	CVS >10nm	-	1000	1000	1000	2334	1000
	CVS >23nm	1350	1350	1350	1350	1350	1350
IUFC -7°	TP >10nm	2100	2100	2100	2100	2100	2100
	CVS >10nm	-	1000	1000	1000	2334	1000
	CVS >23nm	1350	1350	1350	1350	1350	1350
WLTC	TP >10nm	2100	2100	2100	2100	2100	2100
	CVS >10nm	-	1000	1000	1000	2334	1000
	CVS >23nm	1350	1350	1350	1350	1350	1350
WLTC -7°	TP >10nm	2100	2100	2100	2100	2100	2100
	CVS >10nm	-	1000	1000	1000	2334	1000
	CVS >23nm	1350	1350	1350	1350	1350	1350

Table 6: VPR Dilution Factor, diesel vehicles

		PD6-02	PD6-03	PD6-05	PD6-06	PD6-07	PD6-10
L2	TP >10nm	205	205	205	205	2100	2100
	CVS >10nm	250	250	-	-	-	-
	CVS >23nm	145	145	145	145	145	145
CADC	TP >10nm	205	205	205	205	2100	2100
	CVS >10nm	250	500	-	-	-	-
	CVS >23nm	145	145	145	145	145	145
IUFC	TP >10nm	205	205	205	205	2100	2100
	CVS >10nm	250	250	-	-	-	-
	CVS >23nm	145	145	145	145	145	145
IUFC -7°	TP >10nm	2100	2100	205	2100	2100	2100
	CVS >10nm	1000	1000	-	-	-	-
	CVS >23nm	1350	1350	145	1350	145	145
WLTC	TP >10nm					2100	2100
	CVS >10nm					-	-
	CVS >23nm					145	145
WLTC -7°	TP >10nm					2100	2100
	CVS >10nm					-	-
	CVS >23nm					145	145

5.3 Appendix 3, Emissions comparison of each vehicle per cycle, supplementary material

The following bar charts compare the particle number emission of each vehicle per cycle. The colours blue, red and green indicate the separate cycle phases and the gray bars represent the total cycle emissions. The different sample points (tail pipe and CVS) and the different counting size ranges (>10nm and >23nm) are distinguished with different bar patterns. The dilution factor set (DF) of every measurement is indicated in

table 5 below.

NEDC gasoline, cold start

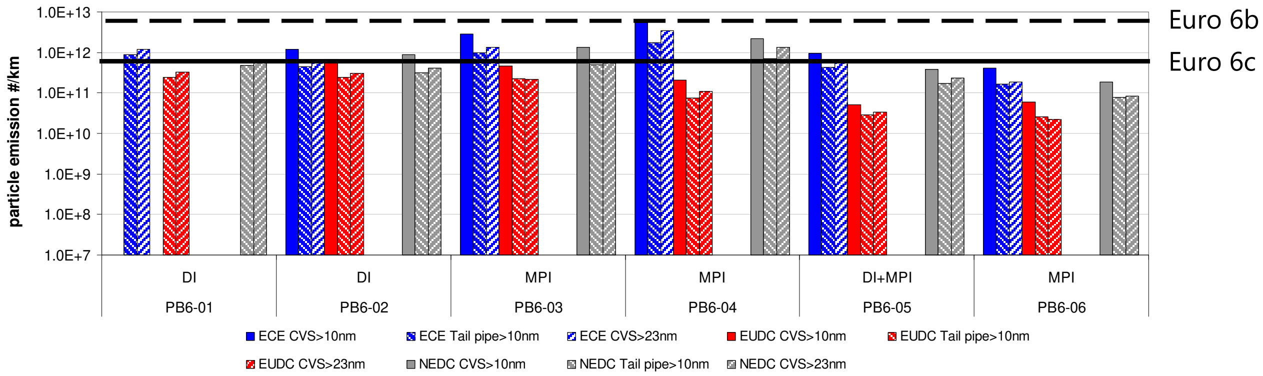


Figure A6.3-1: NEDC cycle phase emission, ECE (blue), EUDC (red) and total cycle average emission (grey).

CADC gasoline, warm start

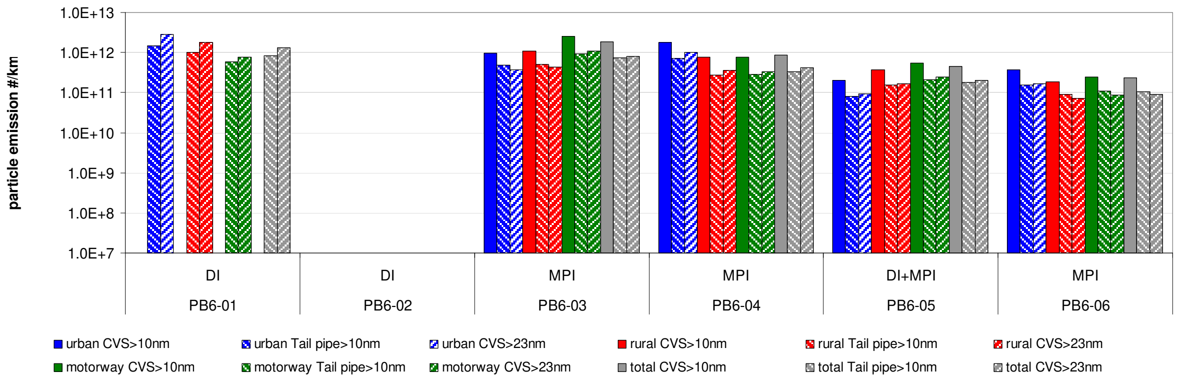


Figure A6.3-2: CADC cycle phase emission, urban (blue), rural (red), motorway (green) and total cycle average emission (grey).

ERMES gasoline, warm start

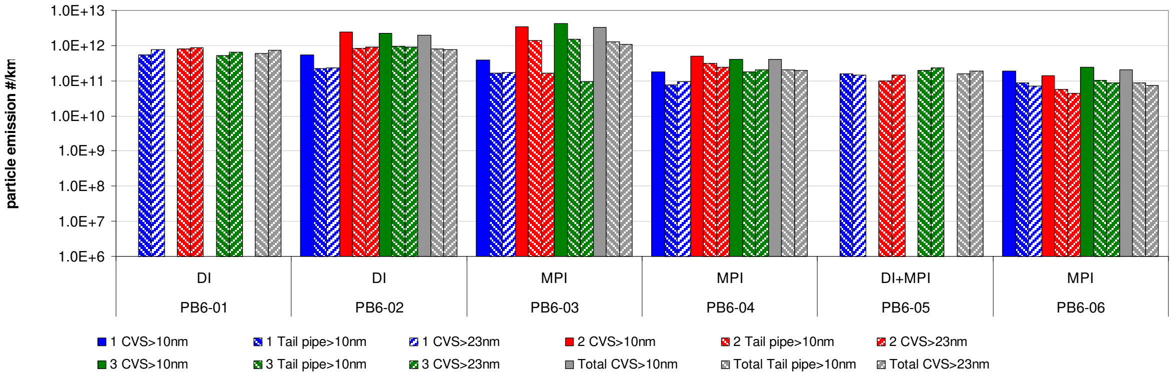


Figure A6.3-3: ERMES cycle phase emission, first phase (blue), second phase (red), third phase (green) and total cycle average emission (grey).

IUFC gasoline, cold start

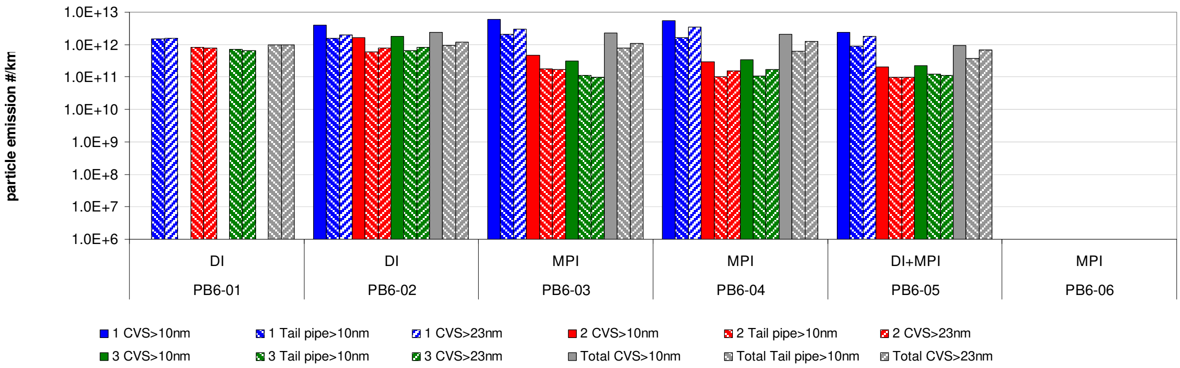


Figure A6.3-4: IUFC cycle phase emission, first phase (blue), second phase (red), third phase (green) and total cycle average emission (grey).

IUFC -7°C gasoline, cold start

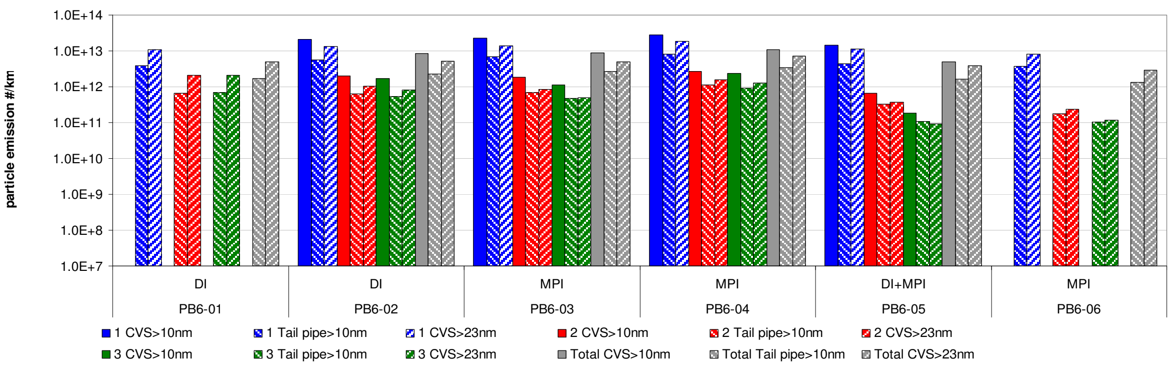


Figure A6.3-5: IUFC cycle phase emission at -7°C condition, first phase (blue), second phase (red), third phase (green) and total cycle average emission (grey).

WLTC gasoline, cold start

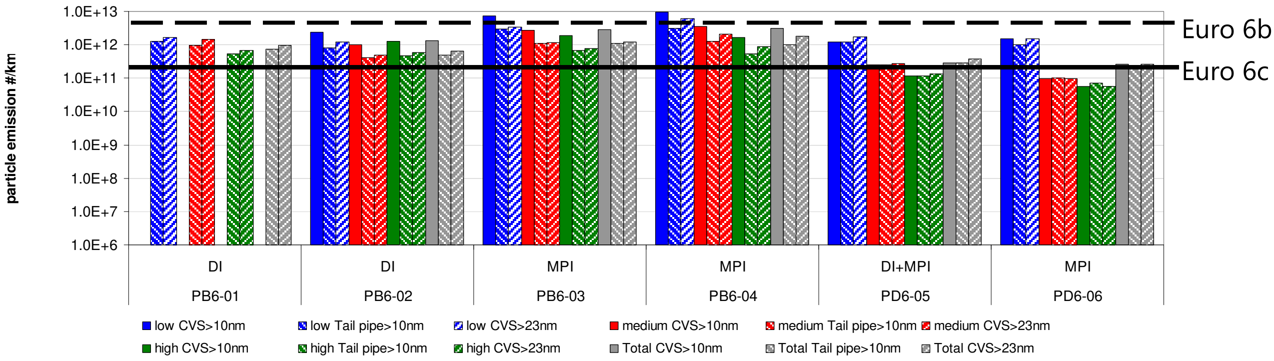


Figure A6.3-6: WLTC cycle phase emission, low phase (blue), medium phase (red), high phase (green) and total cycle average emission (grey).

WLTC -7°C gasoline, cold start

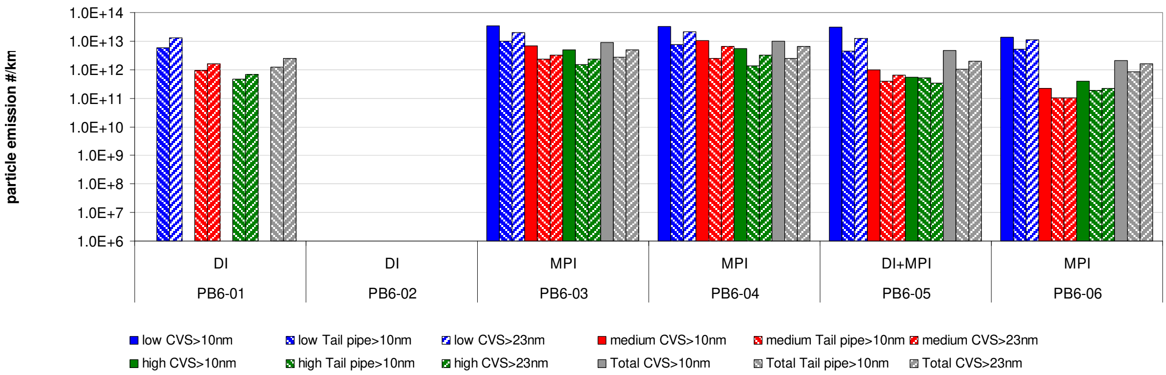


Figure A6.3-7: WLTC cycle phase emission at -7°C condition, low phase (blue), medium phase (red), high phase (green) and total cycle average emission (grey).

IUFC diesel, cold start

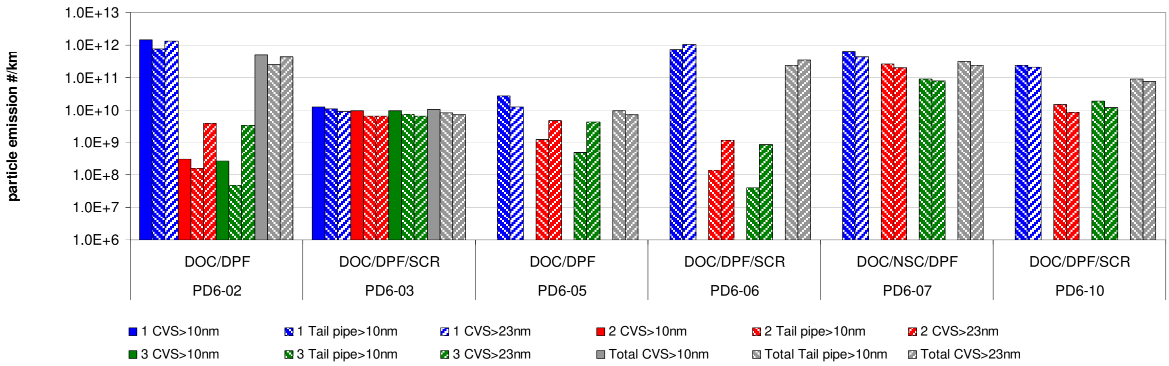


Figure A6.3-8: IUFC cycle phase emission, first phase (blue), second phase (red), third phase (green) and total cycle average emission (grey).

IUFC -7°C diesel, cold start

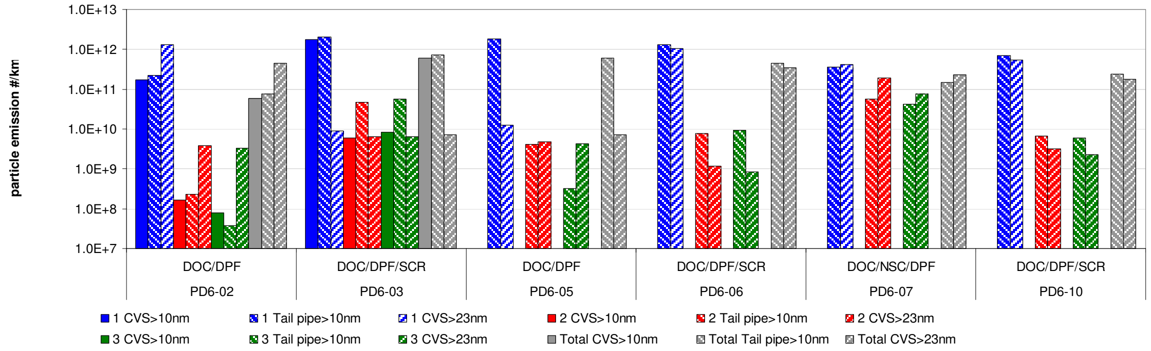


Figure A6.3-9: IUFC cycle phase emission at -7°C condition, first phase (blue), second phase (red), third phase (green) and total cycle average emission (grey).

5.4 Appendix 4, particle emission results

Gasoline and CNG

NEDC		PB6-01 DI [1/km]	PB6-02 DI [1/km]	PB6-03 MPI [1/km]	PB6-04 MPI [1/km]	PB6-05 DI+MPI [1/km]	PB6-06 MPI [1/km]	PG6-99 CNG [1/km]
ECE	CVS>10nm		1.18E+12	2.87E+12	5.51E+12	9.46E+11	4.07E+11	
	Tail pipe>10nm	8.89E+11	4.39E+11	9.69E+11	1.77E+12	4.26E+11	1.64E+11	6.42E+10
	CVS>23nm	1.19E+12	5.88E+11	1.34E+12	3.43E+12	5.69E+11	1.89E+11	5.53E+10
EUDC	CVS>10nm		6.83E+11	4.66E+11	2.05E+11	5.19E+10	6.05E+10	
	Tail pipe>10nm	2.43E+11	2.38E+11	2.26E+11	7.48E+10	2.89E+10	2.63E+10	6.57E+9
	CVS>23nm	3.27E+11	3.09E+11	2.16E+11	1.07E+11	3.41E+10	2.25E+10	8.69E+9
NEDC	CVS>10nm		8.65E+11	1.35E+12	2.16E+12	3.82E+11	1.88E+11	
	Tail pipe>10nm	4.81E+11	3.13E+11	4.99E+11	6.99E+11	1.75E+11	7.70E+10	2.78E+10
	CVS>23nm	6.44E+11	4.12E+11	6.30E+11	1.33E+12	2.31E+11	8.39E+10	2.59E+10

CADC		PB6-01 DI [1/km]	PB6-02 DI [1/km]	PB6-03 MPI [1/km]	PB6-04 MPI [1/km]	PB6-05 DI+MPI [1/km]	PB6-06 MPI [1/km]	PG6-99 CNG [1/km]
urban	CVS>10nm			9.75E+11	1.82E+12	2.02E+11	3.74E+11	
	Tail pipe>10nm	1.50E+12		4.91E+11	7.19E+11	8.18E+10	1.56E+11	2.40E+10
	CVS>23nm	2.86E+12		3.78E+11	1.01E+12	9.21E+10	1.70E+11	2.41E+10
rural	CVS>10nm			1.08E+12	7.75E+11	3.69E+11	1.90E+11	
	Tail pipe>10nm	1.01E+12		5.04E+11	2.77E+11	1.55E+11	8.97E+10	1.06E+10
	CVS>23nm	1.77E+12		4.42E+11	3.58E+11	1.67E+11	7.19E+10	8.33E+9
motorway	CVS>10nm			2.52E+12	7.75E+11	5.45E+11	2.40E+11	
	Tail pipe>10nm	5.89E+11		9.37E+11	2.87E+11	2.08E+11	1.08E+11	3.71E+10
	CVS>23nm	7.61E+11		1.10E+12	3.38E+11	2.47E+11	8.84E+10	7.51E+9
total	CVS>10nm			1.85E+12	8.77E+11	4.48E+11	2.35E+11	
	Tail pipe>10nm	8.29E+11		7.37E+11	3.26E+11	1.77E+11	1.06E+11	3.71E+10
	CVS>23nm	1.33E+12		7.93E+11	4.11E+11	2.03E+11	9.05E+10	7.51E+9

ERMES		**PB6-01 DI**	**PB6-02 DI**	**PB6-03 MPI**	**PB6-04 MPI**	**PB6-05 DI+MPI**	**PB6-06 MPI**
		[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]
1	CVS>10nm		5.58E+11	3.94E+11	1.76E+11		1.89E+11
	Tail pipe>10nm	5.41E+11	2.19E+11	1.68E+11	7.52E+10	1.55E+11	8.53E+10
	CVS>23nm	7.74E+11	2.30E+11	1.69E+11	9.48E+10	1.42E+11	7.13E+10
2	CVS>10nm		2.42E+12	3.43E+12	5.10E+11		1.39E+11
	Tail pipe>10nm	7.86E+11	8.51E+11	1.40E+12	3.17E+11	9.74E+10	5.63E+10
	CVS>23nm	8.83E+11	8.95E+11	1.67E+11	2.44E+11	1.44E+11	4.46E+10
3	CVS>10nm		2.22E+12	4.22E+12	4.04E+11		2.45E+11
	Tail pipe>10nm	5.17E+11	9.34E+11	1.54E+12	1.79E+11	1.99E+11	1.04E+11
	CVS>23nm	6.40E+11	8.97E+11	9.60E+10	2.06E+11	2.33E+11	8.83E+10
Total	CVS>10nm		2.00E+12	3.33E+12	3.99E+11		2.03E+11
	Tail pipe>10nm	6.04E+11	7.89E+11	1.27E+12	2.04E+11	1.60E+11	8.60E+10
	CVS>23nm	7.37E+11	7.85E+11	1.10E+12	1.99E+11	1.91E+11	7.20E+10

IUFC		**PB6-01 DI**	**PB6-02 DI**	**PB6-03 MPI**	**PB6-04 MPI**	**PB6-05 DI+MPI**	**PB6-06 MPI**	**PG6-99 CNG**
		[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]
1	CVS>10nm		3.91E+12	6.06E+12	5.56E+12	2.42E+12		
	Tail pipe>10nm	1.48E+12	1.56E+12	2.04E+12	1.65E+12	8.98E+11		1.83E+11
	CVS>23nm	1.54E+12	1.96E+12	3.04E+12	3.40E+12	1.84E+12		1.90E+11
2	CVS>10nm		1.63E+12	4.65E+11	3.00E+11	2.00E+11		
	Tail pipe>10nm	8.08E+11	5.85E+11	1.74E+11	1.00E+11	9.96E+10		2.77E+10
	CVS>23nm	7.95E+11	7.68E+11	1.67E+11	1.56E+11	9.86E+10		4.47E+10
3	CVS>10nm		1.76E+12	3.06E+11	3.34E+11	2.20E+11		
	Tail pipe>10nm	7.14E+11	6.57E+11	1.14E+11	1.06E+11	1.24E+11		8.50E+10
	CVS>23nm	6.65E+11	8.03E+11	9.60E+10	1.70E+11	1.13E+11		1.03E+11
Total	CVS>10nm		2.43E+12	2.28E+12	2.06E+12	9.48E+11		
	Tail pipe>10nm	1.00E+12	9.32E+11	7.76E+11	6.16E+11	3.74E+11		8.50E+10
	CVS>23nm	1.00E+12	1.17E+12	1.10E+12	1.24E+12	6.85E+11		1.03E+11

IUFC -7°C		**PB6-01 DI**	**PB6-02 DI**	**PB6-03 MPI**	**PB6-04 MPI**	**PB6-05 DI+MPI**	**PB6-06 MPI**	**PG6-99 CNG**
		[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]
1	CVS>10nm		2.14E+13	2.31E+13	2.81E+13	1.44E+13		
	Tail pipe>10nm	3.83E+12	5.69E+12	6.89E+12	8.14E+12	4.48E+12	3.72E+12	4.30E+10
	CVS>23nm	1.10E+13	1.34E+13	1.37E+13	1.83E+13	1.12E+13	8.28E+12	3.05E+10
2	CVS>10nm		2.03E+12	1.88E+12	2.73E+12	6.54E+11		
	Tail pipe>10nm	6.65E+11	6.43E+11	6.90E+11	1.12E+12	3.28E+11	1.79E+11	6.25E+10
	CVS>23nm	2.07E+12	1.04E+12	8.56E+11	1.58E+12	3.66E+11	2.33E+11	7.14E+10
3	CVS>10nm		1.68E+12	1.14E+12	2.33E+12	1.86E+11		
	Tail pipe>10nm	6.82E+11	5.33E+11	4.86E+11	9.11E+11	1.08E+11	1.05E+11	4.33E+10
	CVS>23nm	2.09E+12	8.26E+11	5.05E+11	1.31E+12	9.02E+10	1.18E+11	4.30E+10
Total	CVS>10nm		8.37E+12	8.68E+12	1.11E+13	5.06E+12		
	Tail pipe>10nm	1.72E+12	2.29E+12	2.68E+12	3.39E+12	1.63E+12	1.34E+12	4.33E+10
	CVS>23nm	5.03E+12	5.09E+12	5.02E+12	7.06E+12	3.86E+12	2.88E+12	4.30E+10

WLTC		**PB6-01 DI**	**PB6-02 DI**	**PB6-03 MPI**	**PB6-04 MPI**	**PB6-05 DI+MPI**	**PB6-06 MPI**	**PG6-99 CNG**
		[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]
low	CVS>10nm		2.35E+12	7.22E+12	9.53E+12	1.20E+12	1.51E+12	
	Tail pipe>10nm	1.27E+12	7.86E+11	3.03E+12	3.08E+12	1.20E+12	9.92E+11	3.46E+10
	CVS>23nm	1.68E+12	1.19E+12	3.38E+12	6.04E+12	1.76E+12	1.51E+12	4.87E+10
medium	CVS>10nm		9.99E+11	2.73E+12	3.56E+12	2.44E+11	9.58E+10	
	Tail pipe>10nm	9.75E+11	4.03E+11	1.11E+12	1.26E+12	2.44E+11	1.01E+11	2.64E+9
	CVS>23nm	1.46E+12	4.88E+11	1.13E+12	2.11E+12	2.78E+11	9.58E+10	7.89E+9
high	CVS>10nm		1.25E+12	1.90E+12	1.62E+12	1.14E+11	5.55E+10	
	Tail pipe>10nm	5.37E+11	4.69E+11	6.73E+11	5.30E+11	1.14E+11	7.17E+10	6.83E+9
	CVS>23nm	6.86E+11	5.95E+11	7.84E+11	8.71E+11	1.34E+11	5.55E+10	1.15E+10
Total	CVS>10nm		1.34E+12	2.78E+12	3.08E+12	2.84E+11	2.59E+11	
	Tail pipe>10nm	7.23E+11	4.98E+11	1.08E+12	1.02E+12	2.84E+11	2.01E+11	6.83E+9
	CVS>23nm	9.77E+11	6.53E+11	1.20E+12	1.82E+12	3.79E+11	2.59E+11	1.15E+10

WLTC -7°C		**PB6-01 DI**	**PB6-02 DI**	**PB6-03 MPI**	**PB6-04 MPI**	**PB6-05 DI+MPI**	**PB6-06 MPI**	**PG6-99 CNG**
		[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]
low	CVS>10nm			3.41E+13	3.25E+13	3.10E+13	1.36E+13	
	Tail pipe>10nm	5.69E+12		9.91E+12	7.54E+12	4.42E+12	5.15E+12	2.30E+11
	CVS>23nm	1.30E+13		2.01E+13	2.15E+13	1.24E+13	1.11E+13	2.18E+11
medium	CVS>10nm			6.67E+12	1.06E+13	1.00E+12	2.22E+11	
	Tail pipe>10nm	9.41E+11		2.32E+12	2.51E+12	4.04E+11	1.01E+11	3.05E+9
	CVS>23nm	1.57E+12		3.29E+12	6.64E+12	6.26E+11	1.06E+11	5.00E+9
high	CVS>10nm			4.85E+12	5.62E+12	5.40E+11	3.99E+11	
	Tail pipe>10nm	4.53E+11		1.49E+12	1.37E+12	5.28E+11	1.87E+11	3.43E+10
	CVS>23nm	6.74E+11		2.28E+12	3.14E+12	3.30E+11	2.23E+11	3.41E+10
Total	CVS>10nm			9.09E+12	1.02E+13	4.67E+12	2.11E+12	
	Tail pipe>10nm	1.25E+12		2.77E+12	2.42E+12	1.02E+12	8.28E+11	3.43E+10
	CVS>23nm	2.50E+12		4.84E+12	6.30E+12	1.99E+12	1.64E+12	3.41E+10

Diesel

L2		PD6-02 DOC/DPF [1/km]	PD6-03 DOC/DPF/SCR [1/km]	PD6-05 DOC/DPF [1/km]	PD6-06 Reg DOC/DPF/SCR [1/km]	PD6-06 DOC/DPF/SCR [1/km]	PD6-07 DOC/NSC/DPF [1/km]	PD6-10 DOC/DPF/SCR [1/km]
ECE	CVS>10nm	2.20E+10	2.01E+10					
	Tail pipe>10nm	2.06E+10	1.99E+10	1.22E+10	7.17E+08	1.00E+12		8.96E+10
	CVS>23nm	2.04E+10	1.39E+10	6.87E+09	1.56E+09	1.85E+12	1.92E+11	5.57E+10
EUDC	CVS>10nm	7.75E+07	6.90E+09					
	Tail pipe>10nm	5.98E+07	6.41E+09	2.36E+08	4.67E+07	1.01E+08		1.44E+10
	CVS>23nm	1.08E+09	5.19E+09	1.52E+09	2.23E+08	6.74E+08	3.75E+10	1.32E+10
BAB	CVS>10nm	1.27E+09	8.19E+09					
	Tail pipe>10nm	2.05E+09	1.05E+10	3.62E+09	9.34E+10			
	CVS>23nm	7.29E+08	5.05E+09	1.12E+09	1.45E+11			
Total	CVS>10nm	3.02E+09	9.08E+09					
	Tail pipe>10nm	3.46E+09	1.07E+10	3.87E+09	6.99E+10	3.69E+11		
	CVS>23nm	2.62E+09	5.89E+09	1.71E+09	1.09E+11	6.81E+11		

NEDC		PD6-02 DOC/DPF [1/km]	PD6-03 DOC/DPF/SCR [1/km]	PD6-05 DOC/DPF [1/km]	PD6-06 Reg DOC/DPF/SCR [1/km]	PD6-06 DOC/DPF/SCR [1/km]	PD6-07 DOC/NSC/DPF [1/km]	PD6-10 DOC/DPF/SCR [1/km]
ECE	CVS>10nm	2.20E+10	2.01E+10					
	Tail pipe>10nm	2.06E+10	1.99E+10	1.22E+10	7.17E+08	1.00E+12		8.96E+10
	CVS>23nm	2.04E+10	1.39E+10	6.87E+09	1.56E+09	1.85E+12	1.92E+11	5.57E+10
EUDC	CVS>10nm	7.75E+07	6.90E+09					
	Tail pipe>10nm	5.98E+07	6.41E+09	2.36E+08	4.67E+07	1.01E+08		1.44E+10
	CVS>23nm	1.08E+09	5.19E+09	1.52E+09	2.23E+08	6.74E+08	3.75E+10	1.32E+10
Total	CVS>10nm	8.18E+09	1.18E+10					
	Tail pipe>10nm	7.64E+09	1.14E+10	4.63E+09	2.94E+08	3.69E+11		4.24E+10
	CVS>23nm	8.20E+09	8.39E+09	3.47E+09	7.16E+08	6.81E+11	9.47E+10	2.90E+10

after regeneration

CADC		PD6-02 DOC/DPF [1/km]	PD6-03 DOC/DPF/SCR [1/km]	PD6-05 DOC/DPF [1/km]	PD6-06 DOC/DPF/SCR [1/km]	PD6-07 DOC/NSC/DPF [1/km]	PD6-10 DOC/DPF/SCR [1/km]
urban	CVS>10nm	1.47E+08	1.02E+10				
	Tail pipe>10nm	1.41E+08	8.30E+09	6.68E+08	4.68E+08	1.94E+11	3.18E+10
	CVS>23nm	1.13E+08	7.53E+09	6.60E+09	5.93E+08	1.55E+11	3.71E+10
rural	CVS>10nm	3.90E+07	8.86E+09				
	Tail pipe>10nm	5.90E+07	1.01E+10	9.38E+08	1.49E+08	1.13E+11	9.53E+09
	CVS>23nm	4.32E+07	5.18E+09	1.90E+09	1.58E+08	7.75E+10	5.55E+09
motorway	CVS>10nm	9.52E+07	1.29E+10				
	Tail pipe>10nm	5.26E+08	1.73E+10	4.34E+11	1.55E+09	3.06E+11	2.11E+10
	CVS>23nm	4.41E+07	5.91E+09	3.35E+11	5.71E+08	1.95E+11	1.47E+10
total	CVS>10nm	8.00E+07	1.12E+10				
	Tail pipe>10nm	3.19E+08	1.38E+10	2.34E+11	9.36E+08	2.25E+11	1.80E+10
	CVS>23nm	5.06E+07	5.80E+09	1.82E+11	4.24E+08	1.48E+11	1.36E+10

IUFC		**PD6-02**	**PD6-03**	**PD6-05**	**PD6-06**	**PD6-07**	**PD6-10**
		DOC/DPF	**DOC/DPF/SCR**	**DOC/DPF**	**DOC/DPF/SCR**	**DOC/NSC/DPF**	**DOC/DPF/SCR**
		[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]
1	CVS>10nm	1.46E+12	1.25E+10				
	Tail pipe>10nm	7.45E+11	1.09E+10	2.71E+10	7.17E+11	6.13E+11	2.34E+11
	CVS>23nm	1.32E+12	8.89E+09	1.26E+10	1.04E+12	4.24E+11	2.05E+11
2	CVS>10nm	3.05E+08	9.33E+09				
	Tail pipe>10nm	1.62E+08	6.51E+09	1.20E+09	1.41E+08	2.56E+11	1.48E+10
	CVS>23nm	3.83E+09	6.36E+09	4.77E+09	1.17E+09	1.96E+11	8.64E+09
3	CVS>10nm	2.67E+08	9.37E+09				
	Tail pipe>10nm	4.83E+07	7.28E+09	4.80E+08	3.98E+07	9.01E+10	1.83E+10
	CVS>23nm	3.36E+09	6.34E+09	4.35E+09	8.32E+08	7.74E+10	1.20E+10
Total	CVS>10nm	4.87E+11	1.04E+10				
	Tail pipe>10nm	2.49E+11	8.23E+09	9.56E+09	2.40E+11	3.20E+11	8.89E+10
	CVS>23nm	4.42E+11	7.19E+09	7.22E+09	3.50E+11	2.33E+11	7.52E+10

IUFC -7°C		**PD6-02**	**PD6-03**	**PD6-05**	**PD6-06**	**PD6-07**	**PD6-10**
		DOC/DPF	DOC/DPF/SCR	DOC/DPF	DOC/DPF/SCR	DOC/NSC/DPF	DOC/DPF/SCR
		[1/km]	[1/km]	[1/km]	[1/km]	[1/km]	[1/km]
1	CVS>10nm	1.74E+11	1.77E+12				
	Tail pipe>10nm	2.25E+11	2.05E+12	1.83E+12	1.33E+12	3.54E+11	6.92E+11
	CVS>23nm	1.32E+12	8.89E+09	1.26E+10	1.04E+12	4.24E+11	5.33E+11
2	CVS>10nm	1.69E+08	5.98E+09				
	Tail pipe>10nm	2.27E+08	4.78E+10	4.07E+09	7.83E+09	5.75E+10	6.70E+09
	CVS>23nm	3.83E+09	6.36E+09	4.77E+09	1.17E+09	1.96E+11	3.21E+09
3	CVS>10nm	8.02E+07	8.46E+09				
	Tail pipe>10nm	3.75E+07	5.59E+10	3.25E+08	9.38E+09	4.28E+10	5.98E+09
	CVS>23nm	3.36E+09	6.34E+09	4.35E+09	8.32E+08	7.74E+10	2.29E+09
Total	CVS>10nm	5.80E+10	5.93E+11				
	Tail pipe>10nm	7.50E+10	7.17E+11	6.09E+11	4.49E+11	1.51E+11	2.35E+11
	CVS>23nm	4.42E+11	7.19E+09	7.22E+09	3.50E+11	2.33E+11	1.80E+11

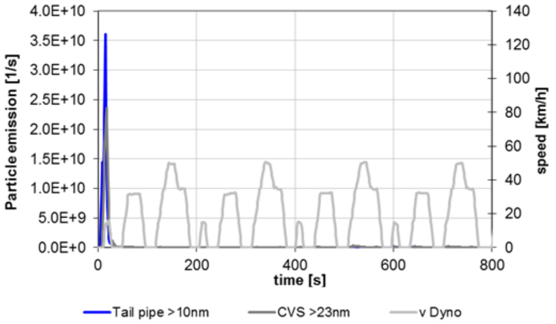
WLTC		**PD6-07**	**PD6-10**
		DOC/NSC/DPF	**DOC/DPF/SCR**
		[1/km]	[1/km]
low	CVS>10nm		
	Tail pipe>10nm	4.64E+11	1.47E+11
	CVS>23nm	1.93E+11	8.77E+10
medium	CVS>10nm		
	Tail pipe>10nm	9.62E+10	1.24E+10
	CVS>23nm	4.19E+10	1.30E+10
high	CVS>10nm		
	Tail pipe>10nm	1.14E+11	1.49E+10
	CVS>23nm	4.22E+10	9.46E+09
Total	CVS>10nm		
	Tail pipe>10nm	1.57E+11	3.21E+10
	CVS>23nm	6.23E+10	2.07E+10

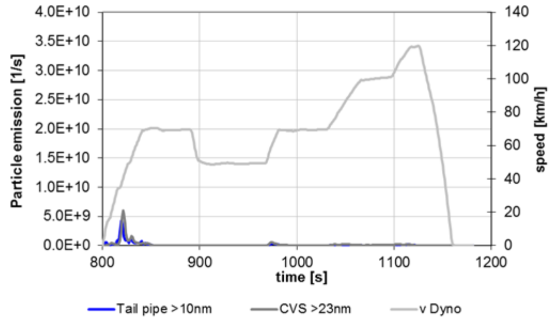
WLTC -7°C		PD6-07	PD6-10
		DOC/DPF/SCR	DOC/DPF/SCR
		[1/km]	[1/km]
low	CVS>10nm		
	Tail pipe>10nm	3.87E+11	1.99E+11
	CVS>23nm	1.19E+11	1.28E+11
medium	CVS>10nm		
	Tail pipe>10nm	3.52E+10	2.48E+09
	CVS>23nm	2.09E+10	2.53E+09
high	CVS>10nm		
	Tail pipe>10nm	7.17E+10	4.72E+09
	CVS>23nm	3.85E+10	4.12E+09
Total	CVS>10nm		
	Tail pipe>10nm	1.06E+11	3.01E+10
	CVS>23nm	4.56E+10	2.03E+10

ERMES		**PD6-07**
		DOC/DPF/SCR
		[1/km]
1	CVS>10nm	
	Tail pipe>10nm	1.53E+10
	CVS>23nm	6.57E+10
2	CVS>10nm	
	Tail pipe>10nm	7.62E+10
	CVS>23nm	2.02E+11
3	CVS>10nm	
	Tail pipe>10nm	7.83E+10
	CVS>23nm	1.22E+11
Total	CVS>10nm	
	Tail pipe>10nm	6.71E+10
	CVS>23nm	1.37E+11

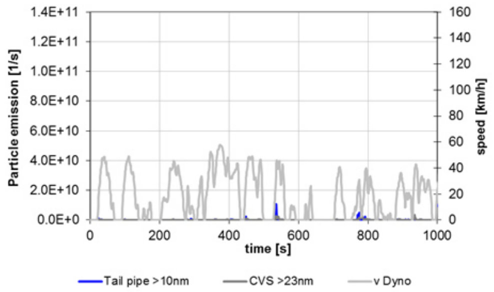
5.5 Appendix 5, particle emission profiles of the CNG vehicle

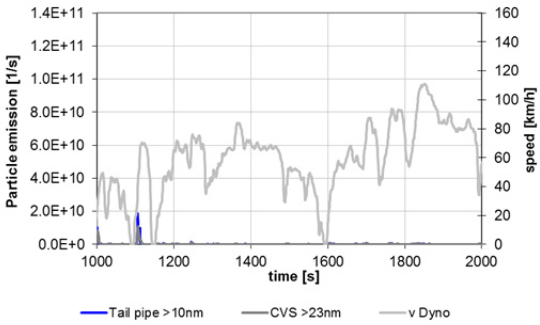
NEDC CNG, cold start

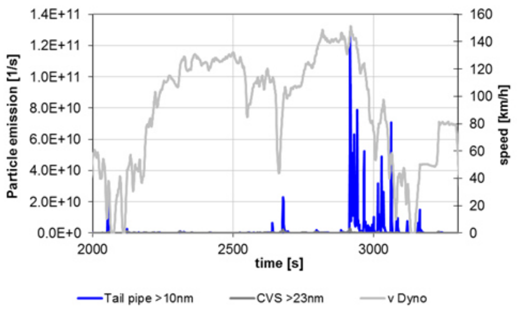




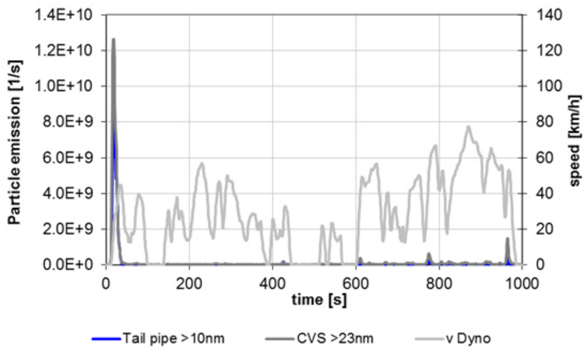
CADC CNG, warm start

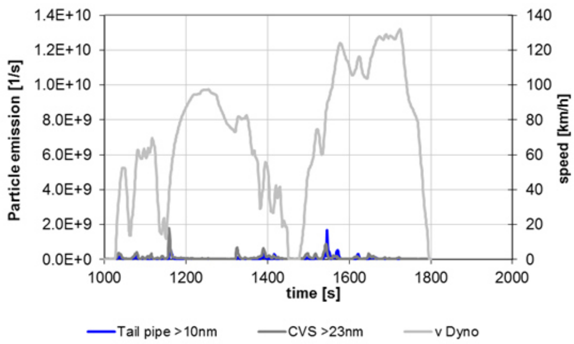




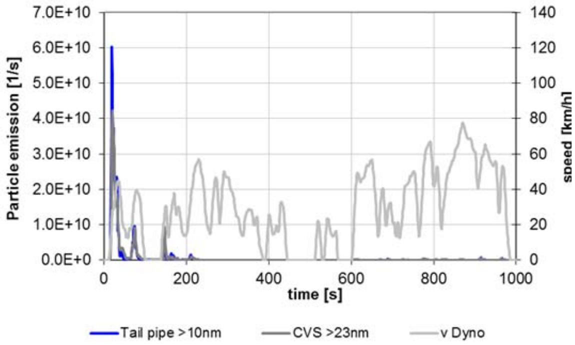


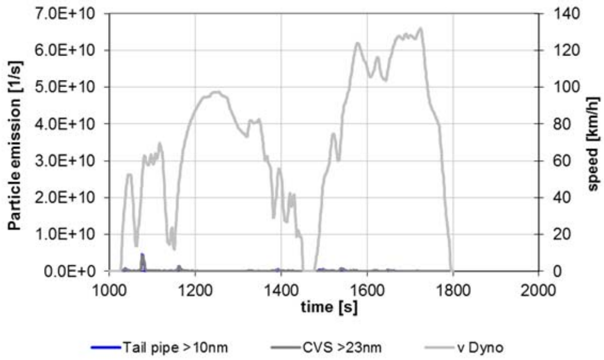
WLTC CNG, cold start, 23°C



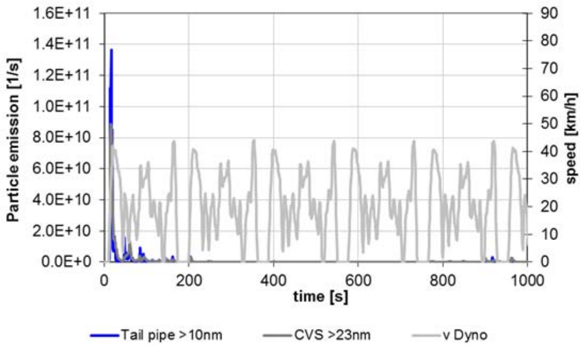


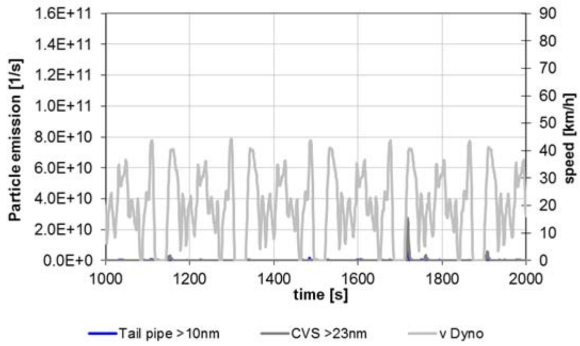
WLTC CNG, cold start, -7°C

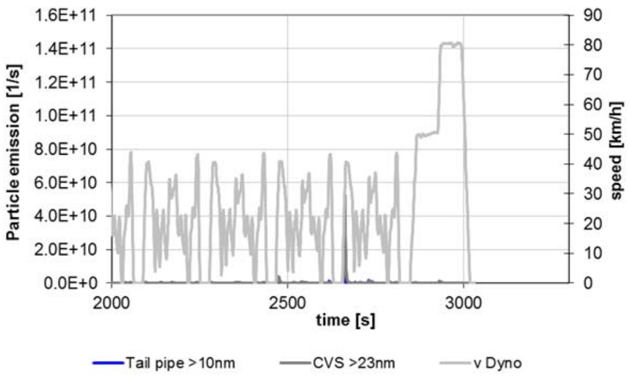




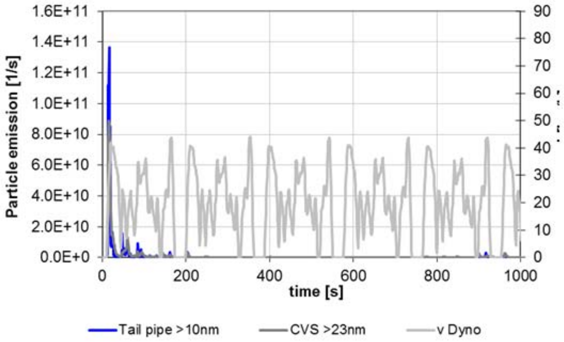
IUFC CNG, cold start, 23°C

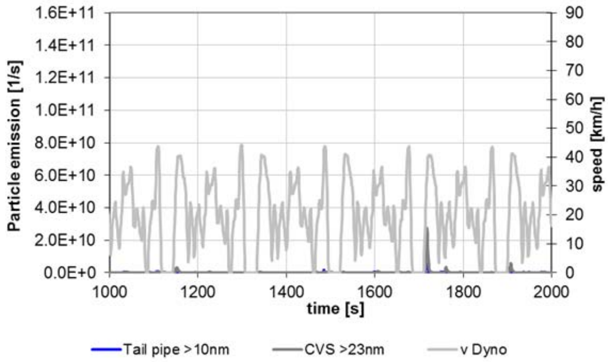


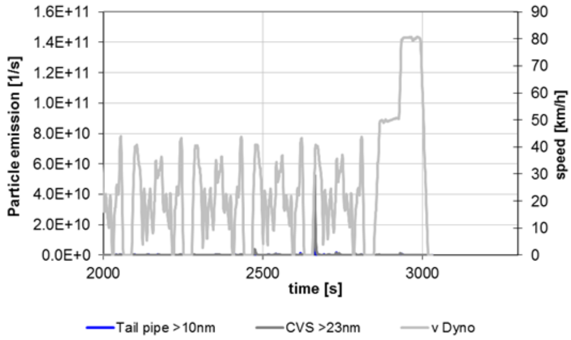




IUFC CNG, cold start, -7°C







Appendix VI – Full report from United States

Report

Real Driving Emissions and Fuel Consumption

Authors

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Supported by

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Project Manager: Kevin Stork

October 30, 2019

Argonne National Laboratory
Lemont, IL
United States

Background

Argonne National Laboratory's Center for Transportation Research is a collection of multi-disciplinary researchers using cutting edge analytical tools and experimental facilities to address challenges such as fuel efficiency, emissions, durability, petroleum dependence, interoperability, compatibility and codes/standards compliance and harmonization. The group undertaking this study comprise of engineers and technicians with over 10-20 years chassis dynamometer testing experience.

Argonne's chassis dynamometer laboratory has tested, analyzed and provided critical benchmark vehicle data for the US Department of Energy since the late 1990s and has pioneered new test procedures for electric, hybrid, and plug-in hybrid electric vehicles with SAE International standards committees.

US DOE and Argonne's interest in "real driving emissions" for the IEA is to learn more about on-road testing and understand the uncertainties and comparability to standard chassis dynamometer test results.

Description of Test Program

Argonne's test program looks at emissions and fuel consumption for a couple advanced technology vehicles using RDE testing concepts. Argonne has a number of test vehicles available for study that have extra instrumentation and decoded data bus parameters relevant to powertrain operational insights. The particular focus of the work was to examine the sensitivity of driving style and its relationship to emissions results. Routes were developed for different driving types, but also within those routes, driver style (level of aggressiveness) was varied in the tests. Driving statistics were calculated for all the tests so that correlations could be made and variances quantified.

Basic Drive Cycles

The three fundamental drive cycles for RDE testing are urban artery and highway. For each of these we developed short and manageable drives on or near Argonne campus that were roughly 30 minutes in duration. For repeatability, each test starts and ends at the same location. The routes are overlaid on a map in Figure 1 below.

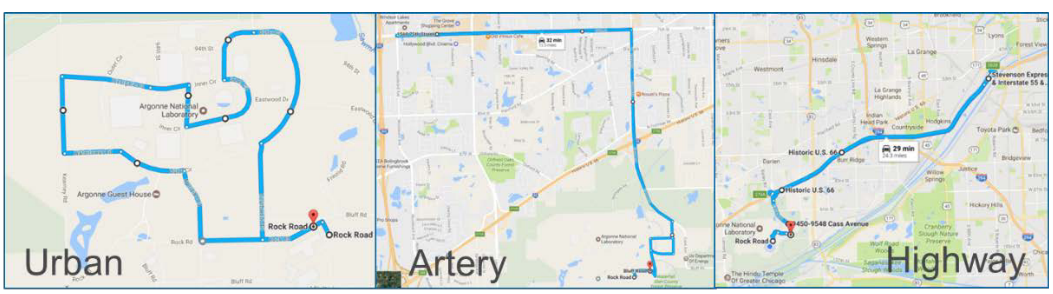

Figure 1: Three basic drive routes in Argonne RDE testing

Table 1 lists some of fundamental properties for the Urban, Artery, and Highway test routes. The drive routes were roughly the same duration, so as the speed increases, the distance and idle time decreases.

Table 1: RDE Drive Route Properties

Route	Distance [km]	Idle %	Stops / km	Average Spd [kph]
Urban	7	10-20	5.5	36.5
Artery	22-23	12-28	2.2	50
Highway	39-43	5-10	0.8	70

Whereas dynamometer drive cycles are defined in time-speed schedules, RDE cycles are better shown in distance-speed traces. Figure 2 shows the driving speed and distance from test data for each of the three drive routes. Note that in urban driving the stops occur at the same location, whereas in artery driving, vehicle congestion and stoplights creates less predictable stops and stop locations.

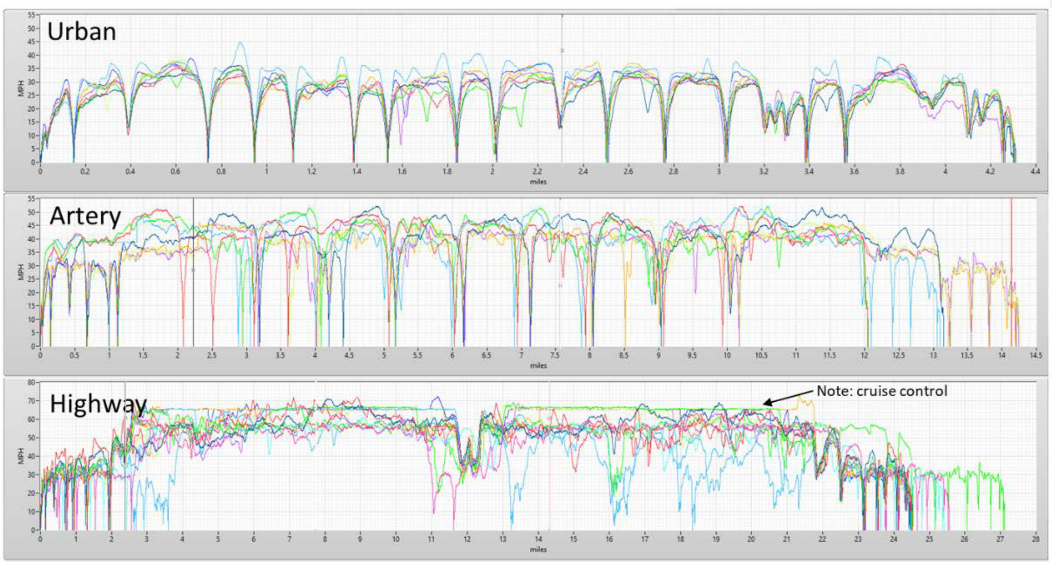

Figure 2: RDE cycles in distance-speed traces

Route Driving Statistics

There were a few key characteristics that were calculated for the tests to help explain variations in results among tests along the same routes. These differences are due to both traffic conditions and drive aggressiveness. The first is Relative Positive Acceleration (RPA), the second is the aerodynamic speed, and the third is amount of time the accelerator pedal is above 40%. The expressions for each calculation are shown below.

- RPA $= \sum(\Delta t \ * (v * a_{pos})) \ / \ \sum d$
- Aerodynamic Speed = $mean \sqrt{V^2}$
- Time above 40% = $\sum \Delta t_{>40\%} \ / \ \sum \Delta t_{all}$

The RDE tests along with EPA drive cycles were expressed on a two dimensional plot defining their respective transient aggressiveness (RPA) and aerodynamic speed (Root(runV^2)). Patterns emerge as seen in Figure 3.

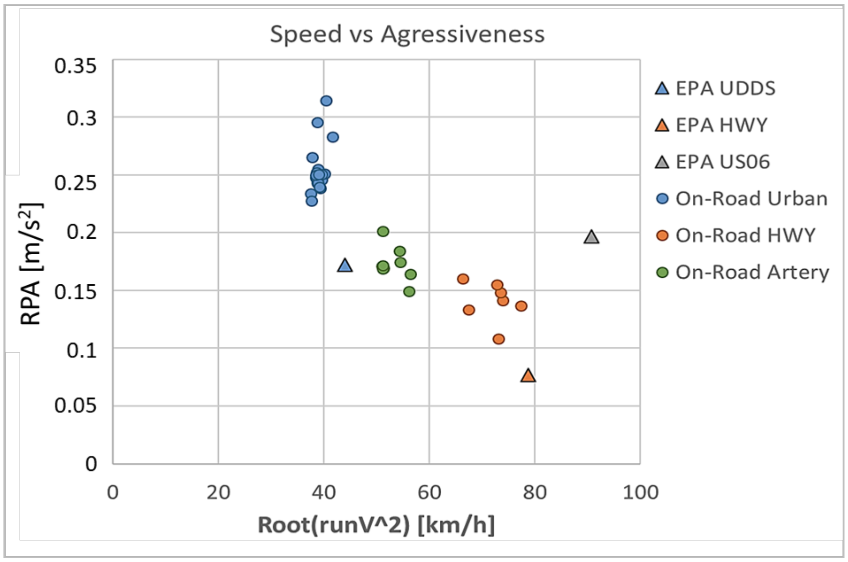

Figure 3: Driven test and EPA Drive Cycle Characteristics (aero speed and RPA)

The accelerator pedal > 40% proxy for aggressiveness is less helpful that RPA for some driving, note the the UDDS and HWY cycles are driven with 0% time above 40% pedal position (see Figure 4).

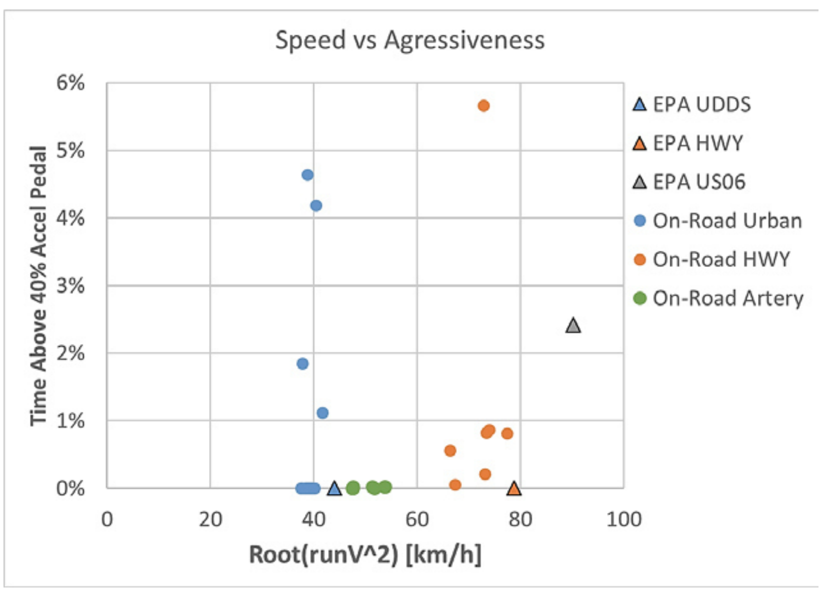

Figure 4: Driven test and EPA Drive Cycle Characteristics (aero speed and time > 40% pedal)

Argonne RDE Cycles vs EPA Dynamometer Drive Cycles

Before looking at the results and comparing RDE to chassis dynamometer emissions, let us look at the differences in the drive cycle statistics. Argonne's Urban RDE cycle is compared to the EPA UDDS cycle and the Highway RDE to the US EPA Highway cycle. These are shown in Figure 5and Figure 6.

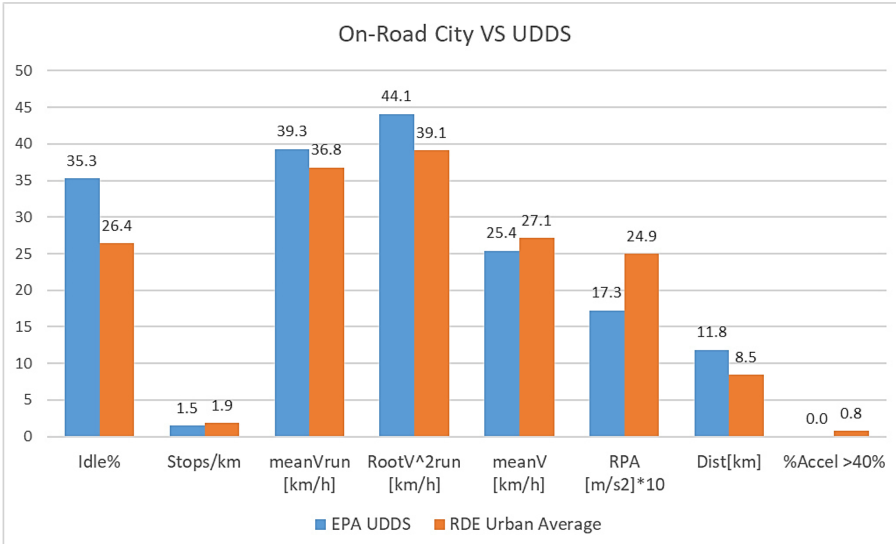

Figure 5: Argonne Urban RDE vs EPA UDDS Cycle

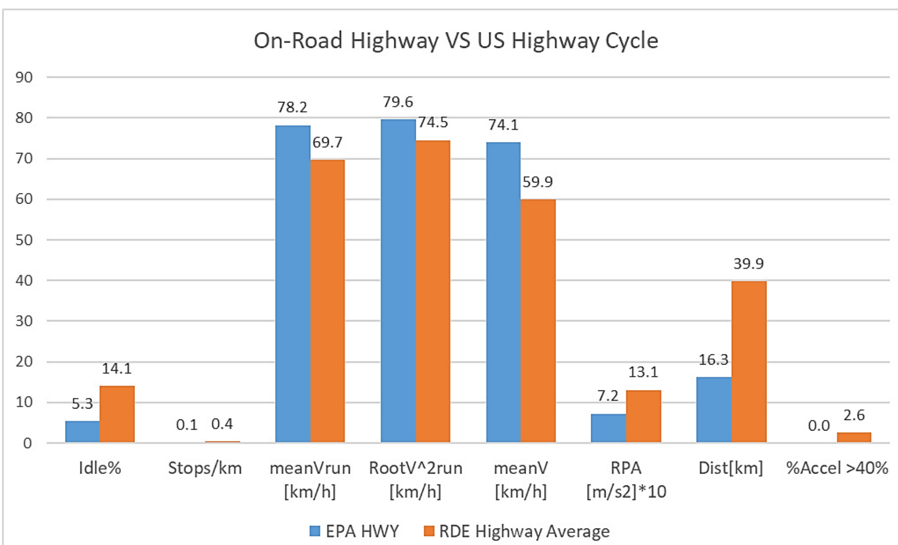

Figure 6: Argonne Highway RDE vs EPA Highway Cycle

Test Vehicles

Two vehicles were selected because of their advanced new powertrain technology and the questions that exist about how the powertrain performs in real driving conditions.

<u>Mazda CX-9</u>: Downsized turbocharged engines are efficient and clean during operating conditions found in certification testing. But do these benefits extend into real world operating conditions in terms of fuel efficiency and criteria pollutants? The Mazda CX-9 has a 186 kW 4-cylinder, 2.5L turbocharged direct injection engine. It is downsized compared to comparable vehicles that use v-6 engines with 3.3 to 3.6L of displacement. A downsized engine spends more time at higher brake specific torque output compared to larger displacement engines. The RDE testing is looking for a possible threshold where the efficiency gains may diminish or the emissions levels increase dramatically. See the installation of the RDE measurement system in Figure 7 below.

Figure 7: Mazda CX-9 Test Vehicle with RDE Equipment Installed

Previous dynamometer testing specifically investigated the transition to high CO emissions with steady state testing. The standard drive cycle operating regimes were superimposed on the ANL-generated CO engine emissions map for analysis. See Figure 8 below.

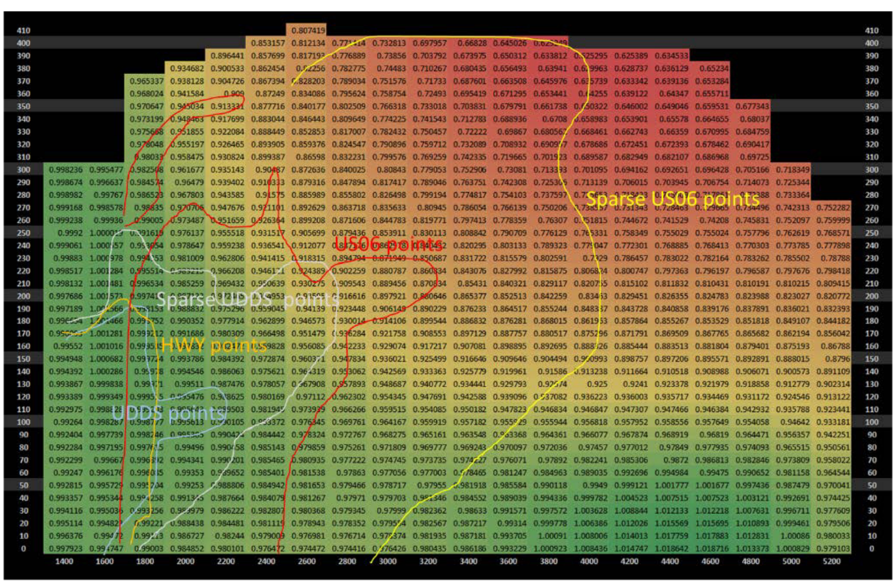

Figure 8: CO grams/second Emissions Map for CX-9 from Chassis Dynamometer Testing

Honda Accord PHEV: PHEVs have the potential to save dramatic amounts of fuel as long as the engine is supplanted by electric energy during driving. PHEV designs vary in the power capability of the electric drive system and the engine is used to assist the electric drive in more aggressive driving conditions. Argonne studied the electric drive capability of the Accord PHEV on the chassis dynamometer and found the electric drive zone, the orange points in Figure 9 below.

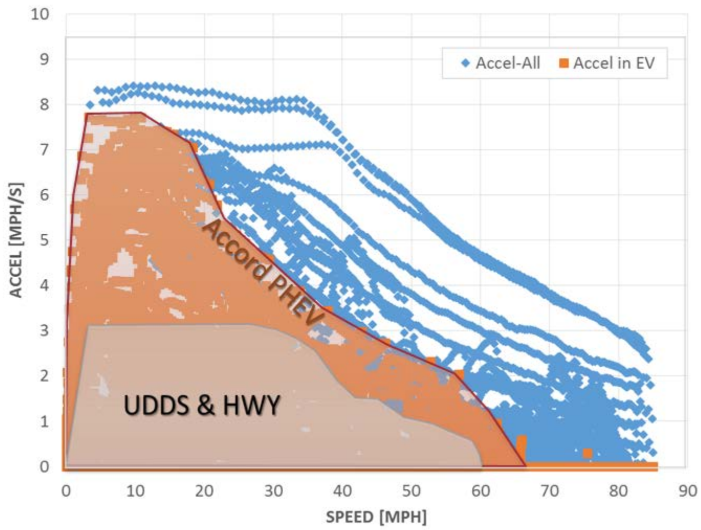

Figure 9: Zone of Electric Drive Capability in the Accord PHEV

Notice that the UDDS and Highway cycles fits comfortably within the Accord PHEV all-electric capability. At low speeds nearly all driving is expected to drive electrically, but one typically drives at higher at high speeds than this on the highway . Above 65 MPH (104 km/h), the vehicle must use the engine for propulsion. Just how much engine operation and associated emissions was the aim of the RDE testing. The vehicle with the RDE system installed is shown below in Figure 10.

Figure 10: RDE Installed on the Accord PHEV Test Vehicle

Fuel Used

The fuel was standard pump fuel from Argonne's central refueling station. We worked with the fuel supply manager to make sure all of our testing was done from the same batch of fuel. A sample was pulled for analysis, the results shown in Table 2.

Table 2: Fuel Analysis

Individual Parameters	
Analytical Method: ASTM D4052 [A]	
API Gravity at 15.56°C	61.6 °API
Density at 15.56°C	0.7322 g/mL
Spec. Grav. at 15.56°C/15.56°C	0.7329
Analytical Method: ASTM D240 [A]	
Gross Heating Value (BTU/lb)	19355 BTU/lb
Gross Heating Value (MJ/kg)	45.021 MJ/kg
Net Heating Value (BTU/lb)	18002 BTU/lb
Net Heating Value(MJ/kg)	41.874 MJ/kg

Instrumentation

<u>RDE System</u>: Argonne used a 2006 model SEMTECH-DS with a heated line and a flow sensor with a 2 inch diameter tube (see Figure 11 below with photos of the equipment). Found were some incompatibility issues between the exhaust measurement system and the test vehicle. A surge device was installed that helped this issue, but did not eliminate it for all vehicles. Ultimately, we were satisfied with the performance of the sensor on the test vehicles in this report and did not experience measurement issues.

Figure 11: SEMTECH RDE System Used in Study

<u>Data Acquisition</u>: The instrumentation installed on the test vehicles were very helpful for analysis of all our vehicle testing results. The data bus for both vehicles was decoded and logged with a system by Intrepid Control Systems of Madison Heights Michigan, USA. The hardware we have can acquire and log broadcast CAN data and scan tool data along with analog sensor data. The overall setup (see Figure 12)

includes both the SEMTECH and the Vehicle Spy software running concurrently and merged later in post-processing.

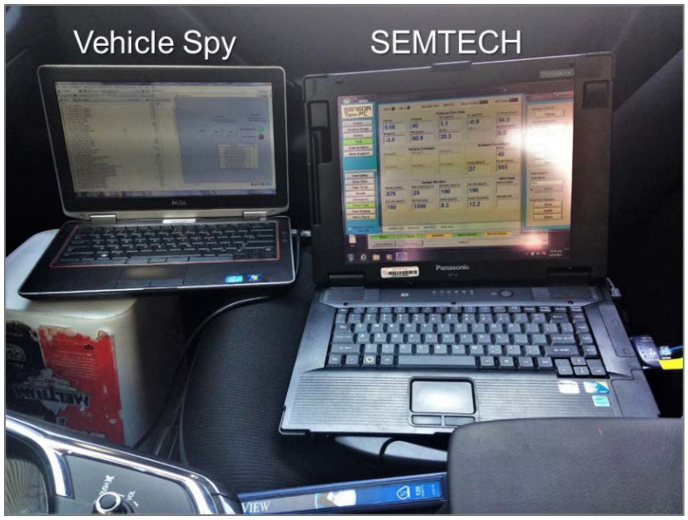

Figure 12: In-Vehicle Data Acquisition Setup

To ensure data quality the fuel consumption as reported by the SEMTECH system for both vehicles were validated with another measurement. The Accord PHEV had an in-line direct fuel measurement sensor (see Figure 13). A math model computing fuel flow rate was generated for the CX-9 based upon engine RPM, injector pulse width and fuel flow rate collected from earlier chassis dynamometer testing. Both of these fuel flow results showed a good match to the SEMTECH results thus giving us confidence in the entire emissions measurement system (including accurate exhaust flow measurements).

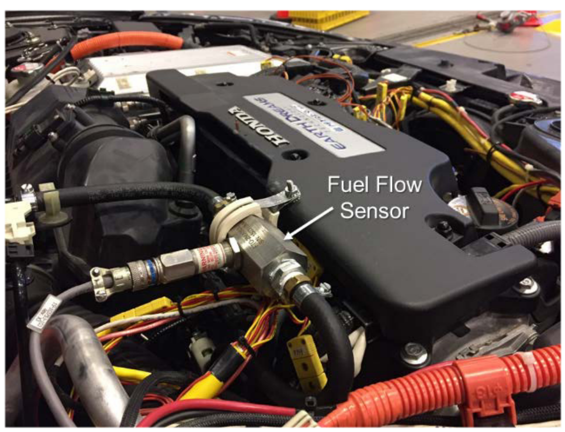

Figure 13: Honda Accord PHEV with in-line direct fuel measurement sensor

Another extra data signal was direct measurement of axle torque of the Accord PHEV while driving. This allows comparison of the driving style in terms of total wheel energy characteristics of transients. Two sensors are permanently mounted to the axle half-shafts and send analog signals to the data acquisition system. A photo of the axle sensor is shown in Figure 14 below.

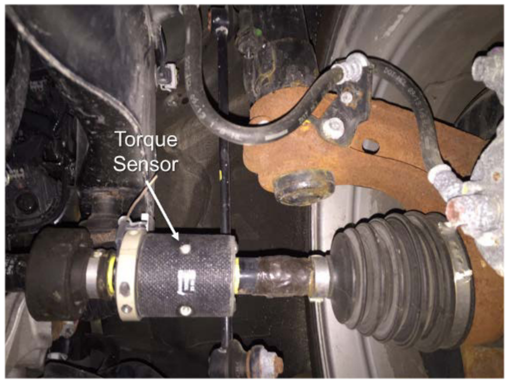

Figure 14: Honda Accord PHEV with axle torque sensor

Test Results: CX-9

The emissions results were analyzed along many driving style characteristics but aggressiveness parameters were the only ones that showed some correlation with criteria and CO2 emissions. Thus, results are expressed here in the context of aggressiveness. The two aggressiveness metrics referenced earlier are RPA and percentage of time above 40% accelerator pedal position (%Accel>40%).

City RDE and UDDS Dynamometer Results

For the UDDS cycle the results are shown in Figure 15 below. In orange are the results from chassis dynamometer tests and in blue are the RDE results. Note that the spread in RPA for the RDE tests, but for UDDS cycle tests, the RPA is nearly identical. The >40% accelerator pedal metric is zero for the mild UDDS cycle. RDE emissions are generally higher but there exists considerable overlap.

There are no trends for NOx and THC but for CO emissions, there is a strong trend with aggressiveness. Analysis of the RDE testing and other dynamometer testing, show that CO emissions will spike during high torque commands. A trend is seen in the RPA vs CO emissions plot, but a stronger correlation is seen in the 40% Accel pedal metric. CO emissions are very sensitive to high pedal positions, CO emissions increased by an order of magnitude in the data set we acquired.

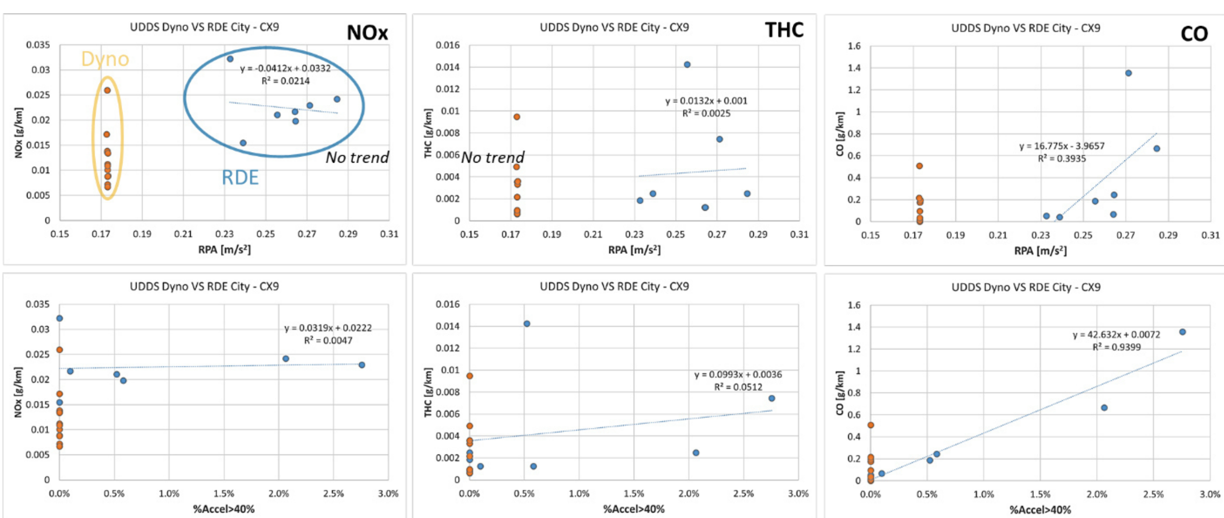

Figure 15: Criteria Pollutants for City RDE and Dynamometer UDDS Tests

CO2 emissions (fuel consumption) also show some correlation with aggressiveness as seen in Figure 16. Whereas there is some overlap in criteria emissions between dynamometer testing the UDDS cycle and city RDE, there is no overlap in CO2 emissions. The RDE CO2 results are 20% to 40% higher. This is likely traced to the significant difference in driving style. The RDE city driving has roughly 35% to 68% higher RPA values than the EPA UDDS cycle. Also interesting is the inverse relationship between both aggressiveness metrics and CO2 emissions. This means that more acceleration events provides better fuel efficiency. This could be a combination of aggressive decel fuel cutoff and improved engine efficiency under load compared to cruise. Isolating the exact would require some further analysis of the various data streams (and perhaps additional tests).

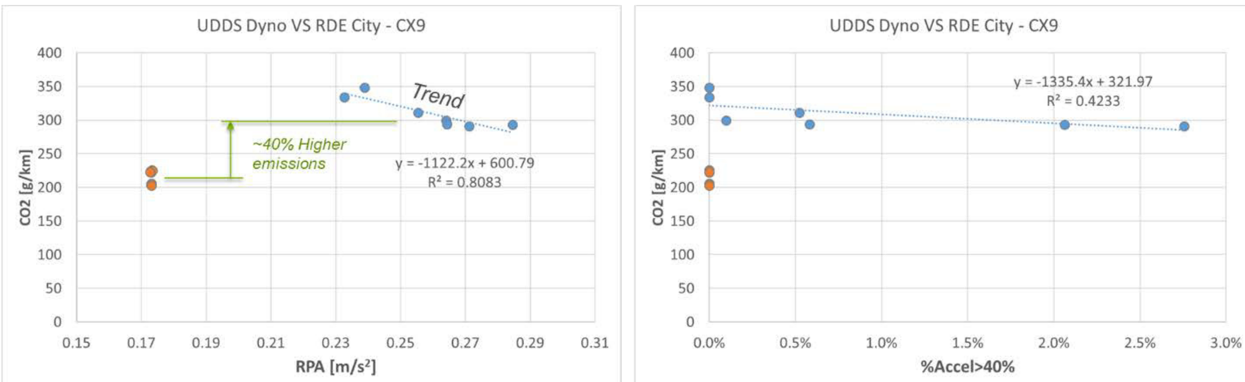

Figure 16: CO2 Emissions for City RDE and Dynamometer UDDS Tests

Highway RDE and HWFET Dynamometer Results

The criteria emissions results of the highway RDE and HWFET tests are found in Figure 17. There is a considerable spread in the emissions results from RDE testing. Like the UDDS tests, the NOx results are only slightly higher in the RDE testing. THC and CO emissions are much higher in the RDE tests. For highway RDE testing the correlation of >40% accel pedal is a good predictor for higher THC and CO emissions. This is likely related to the number and frequency of enrichment events On the highway RDE, RPA does not seem to help predict higher emissions.

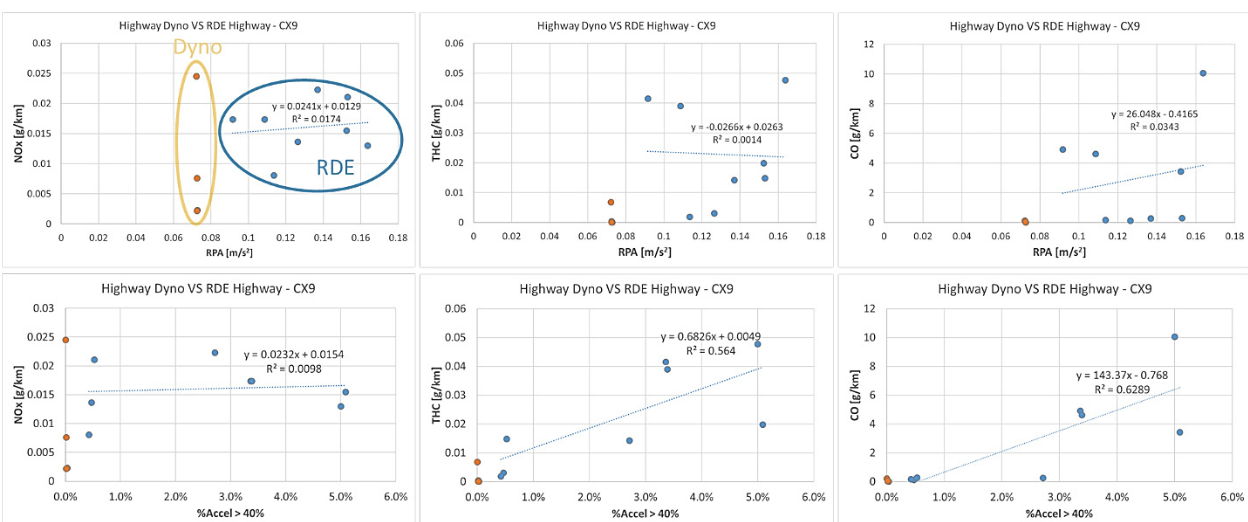

Figure 17: Criteria Pollutants for Highway RDE and Dynamometer HWFET Tests

The CO2 emissions results of the highway RDE and HWFET tests are found in Figure 18. The spread in CO2 emissions from RDE testing is relatively small. Moreover, there seems to be little correlation in CO2 with the two aggressiveness metrics. The CO2 emission are roughly 25% higher in RDE testing.

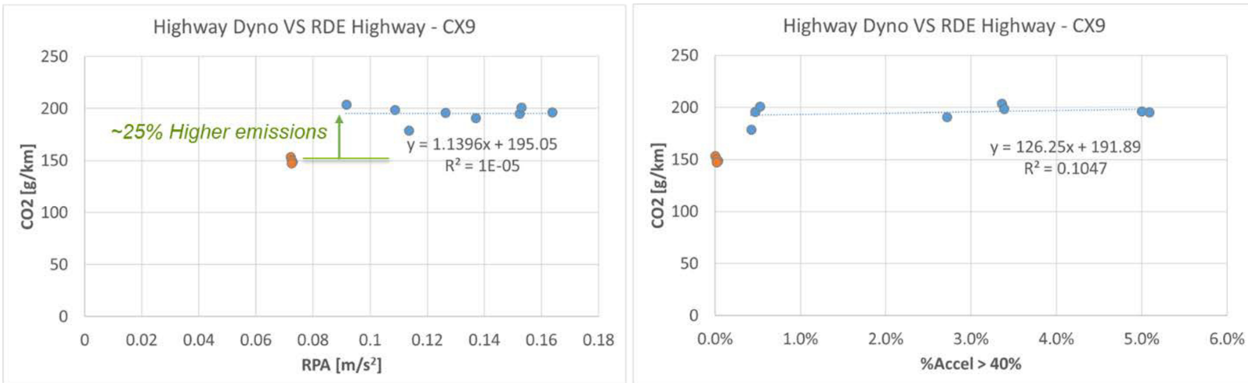

Figure 18: CO2 Emissions for Highway RDE and Dynamometer HWFET Tests

Test Results: Honda Accord PHEV

Whereas in the CX-9 the focus was on emissions and aggressive driving style, the focus of analysis for the Accord PHEV is the differences between charge-sustaining (CS) and charge-depleting (CD) operation. The tests analyzed in this section are from sets of three city drive cycles driven back-to-back. One set was begun with a full charge and the other was in CS operation at the start of the day.

Charge-Sustaining Results

The criteria and CO2 emissions results of the urban RDE tests are found in Figure 19. As with most vehicles (including hybrids), most of the criteria emissions come from the first test cycle, in chassis dynamometer vernacular, this is the “cold-start” test. THC emissions are a cold-start phenomenon and measureable emissions were only detected in the first cycle. NOx was detected in the first and third cycles. CO emissions were detected in all three cycles, but at very low levels. CO2 emissions were highest in the first cycle and fell as the vehicle warmed up.

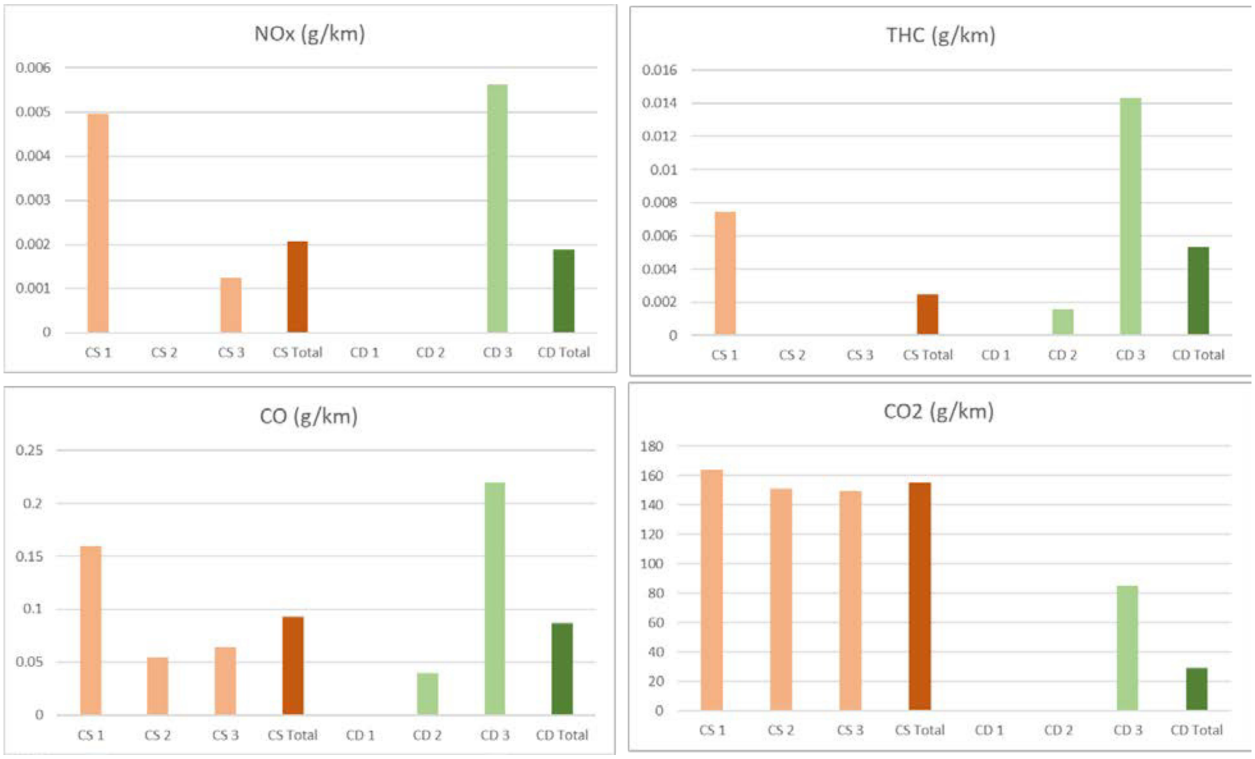

Figure 19: Criteria and CO2 emissions results of the urban RDE

Charge-Depleting Results

Figure 20 shows the emissions, vehicle operation and battery state-of-charge for the back-to-back urban RDE cycles.

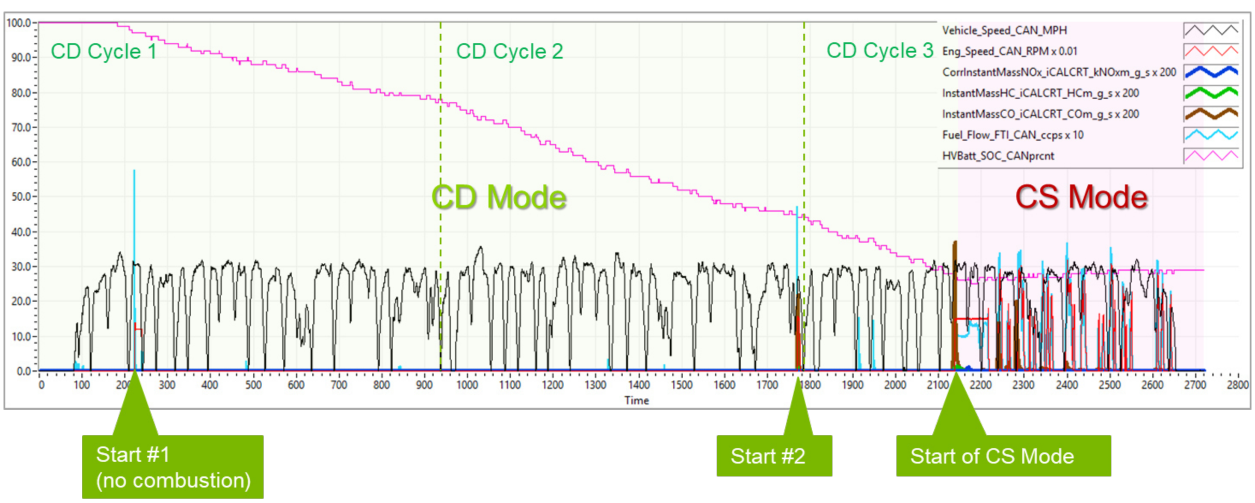

Figure 20: Emissions, vehicle operation and battery state-of-charge for the back-to-back urban RDE cycles

The Accord PHEV is a blended design that will engage the engine in CD mode if the driver demands are beyond the electric capability. Sometimes the engine assist is a quite short event and could even cause more criteria emissions than driving in CS mode. The engine start event in the first cycle appears not to contain any combustion. The engine is seen to be rotating for a few seconds and the fuel sensor detects an impulse spike. However, this could just be evidence of the fuel pump coming up to pressure but there is no evidence of the engine firing. In the second engine start, emissions were detected, but the engine was quickly shut down again. Without continued operation, the next engine start will essentially be yet another “cold-start” event with more emissions. Indeed looking back at Figure 20, engine start emissions appears to be the reason the criteria emissions total from all three cycles are no better in CD mode than in the CS mode – even though there was a considerable amount of electric driving in the CD cycles. These results highlight that criteria emissions are a concern for both CD and CS. Just because there is significant electric driving, does not mean that emissions are proportionally lower in CD mode because of less engine use.

The CO2 emissions follow what is expected considering that electricity is being used almost exclusively in the first two depleting cycles and then half-way through the thrid cycle, CS mode is invoked and net energy is taken from the liquid fuel.

Recommendations for RDE Testing PHEVs

With over 20 years of experience dynamometer testing PHEVs, Argonne has received many questions from engineers tasked with performing on-road testing for PHEVs. One major magazine that tests vehicles on its own test routes was looking to perform their testing by driving a “representative distance” that was beyond the range of the vehicle They were to take the total average of the whole trip (both CD and CS operation) for the final results. The obvious problem with this approach was realized when the next generation of that model vehicle came out with a range that was beyond the original test distance chosen earlier. If they repeated the same test as the earlier generation, the results would only consist of CD operation. To avoid these problems, one could follow the method presented in SAE paper 2012-01-1194, “Design of an On-Road PHEV Fuel Economy Testing Methodology with Built-In Utility Factor Distance Weighting.” This test method developed by Argonne for the EcoCar university student vehicle competition to provide built-in weighting of the CD and CS modes by driving 3 different distances that were chosen to mimic the results from a “Utility Factor” (UF) approach. See standards SAE J1711 and SAE J2948 for more information about the Utility Factor.

Driving three separate RDE tests may be too burdensome for RDE testing. One possible alternative would be to run the typical 90 minute test twice, once in CS mode and once starting from a full charge. The two results can be averaged together or considered separately. This may seem like a crude approach but the math actually works out to provide roughly similar trends in weighting to the more precise UF approach. Assuming that the average speed of a 90 minute test with a combination of urban, artery and highway driving is 68 km/h, this equates to a test distance of 102 km. In Figure 21, the standard fleet UF curve is compared to the weighting of CS vs CD mode with the average of two 102 km tests with the CD test having a combination of CD and CS that would vary depending upon a vehicle’s range. Whereas the plot is not an exact match, it does provide results that do not significantly depart from the UF for vehicles assuming the CD range is under 90 km.

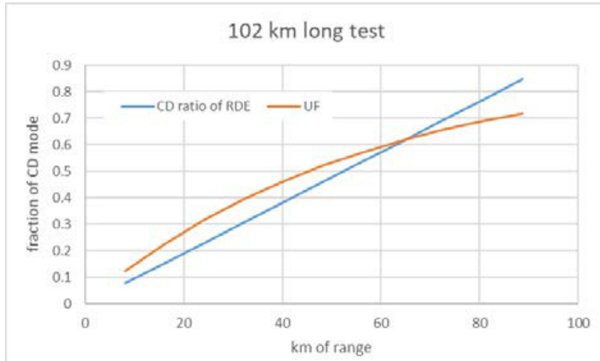

Figure 21: Comparison of standard fleet UF curve to the weighting of CS vs CD mode

Summary

Regarding the testing aspects of the program here are a few summery points:

- Utilizing extensive CAN bus vehicle data was useful in analysis and investigating some of the variabilities
- Our emissions equipment is old and perhaps more success is possible with newer equipment
- Some cycles could not be directly compared to other because of unanticipated construction projects. But perhaps this is part of the uncontrollable aspects of the "on-road testing" process.

The Mazda CX-9 vehicle emissions results can be summarized in the following points:

- Emissions were on average higher (30-100% higher than dyno data)
- This model vehicle can emit very high CO when driven aggressively
- THC emissions were sometimes high, but not "gross polluting"

The Mazda CX-9 vehicle emissions results can be summarized in the following points:

- Emissions were not much related to driving style, more to how and how often the engine starts
- Blended CD operation created short-lived engine-on events that produced considerable emissions for the small amount of overall energy provided by the engine.
- Criteria pollutant emissions similar for both CD and CS mode in our 3-cycle city test, even though CD operation was comprised of considerable amounts of "EV driving"
- However, overall emissions are still very low in both CD and CS mode

Final Remarks

Obviously, to use RDE instead of, or in addition to, established chassis dynamometer methods, there must be compelling reasons. Some of these reasons are listed here:

- A PEMS unit is cheaper to buy and operate than an entire chassis dyno lab
- Other aspects of the real road environments are included
  - Hills
  - Road surface
  - Turns
  - Wind / Crosswind
- RDE driver in traffic differs from dyno driver following speed schedule

  - Driver accel pedal travel characteristics vs reacting to real traffic flow
  - Argonne currently investigating this with respect to autonomous driving, future testing include a dyno driver reacting to traffic instead of using a speed schedule

Laboratory capabilities similar to RDE test aspects:

- All relevant on-road variations can be replicated in laboratory
  - Temperature, solar heat load
  - Increased road load: road conditions, weather, hills (grade changes)
  - Aggressiveness, high-speed
- Cycle diversity (finding “cycle-beaters”) can be added to dyno testing process
  - Speed drive cycles could be randomized or generated by stochastic models

On the one hand, the “realistic environment” of RDE testing is its biggest limitation in the context of a standard test. Many uncontrollable and unpredictable variations are injected into the testing process. Test results are only good as a metric of comparison if control in variability is possible in the testing process. Some of the concerns about RDE are listed here:

- Not everyone has the same roadways so no two tests from two organizations can be compared exactly.
- Weather changes from day to day and most of the globe has dramatic seasonal changes for which corrections would be hard to make.
- Other variations injected into the testing process may never be known.

In conclusion, finding manufacturers that are actively cheating the test by recognizing that a dynamometer is being used may be the only unique strength of on-road testing. If GPS and/or the inertia sensors show no movement, the vehicle can detect that a test may be underway. All other factors a dynamometer lab can mimic with road load management and an environmental chamber are well suited to find “real-world” repeatable results. However, the results would be invalid if the vehicle senses it is being tested and changes its operation as a result.

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