VTT Technical Research Centre of Finland

Euro VI diesel city buses NOx emissions monitoring

Söderena, Petri; Kuutti, Hannu; Pellikka, Ari-Pekka

Published: 30/06/2021

Document Version
Publisher's final version

RESEARCH REPORT

VTT-R-00567-21

Euro VI diesel city buses NOx emissions monitoring

Authors: Petri Söderena, Hannu Kuutti, Ari-Pekka Pellikka

Confidentiality: Public

Report's title

Euro VI diesel city buses NOx emissions monitoring

Project steering group

City of Helsinki, HSL, HSY, Traficom, TØI and VTT

Project name	**Project number/Short name**
Euro VI diesel city buses on-road NO_x emissions monitoring	

Author(s)	**Pages**
Petri Söderena, Hannu Kuutti, Ari-Pekka Pellikka	47/

Keywords	**Report identification code**
Euro VI, diesel, NO_x emissions, PEMS, on-road, SEMS	VTT-R-00567-21

Summary

The on-road NO_x emissions monitoring project on Euro VI diesel city buses aimed at investigating the effect of aging on emissions performance of typical city buses. The project run between the years 2017-2020, and was jointly funded by the following partners: City of Helsinki, Helsinki Region Environmental Services HSY, Helsinki Region Transport, Traficom, TØI The Institute of Transport Economics and VTT Technical Research Centre of Finland.

Altogether four diesel city buses were chosen for the project. Those buses were driven during the project between 260 000 and 360 000 km depending on the bus. A comprehensive testing program included periodic (twice a year) chassis dynamometer and on-road PEMS testing campaigns. In addition, each of the buses were equipped with continuous NO_x concentration monitoring devices. Chassis dynamometer testing was performed with Braunschweig and WHVC cycles. On-road testing was done on two routes representing typical city bus operation at HSL traffic and on a route fulfilling Euro VI ISC requirement.

Regarding energy consumption, no effect of aging was observed. In addition, engine-out emission measurement during the project start and final measurement showed that engine-out NO_x emission decreased only 2.4 % - 9.3 % with buses A, C and D. These findings suggest that combustion- wise engines were not changed. However, depending on the bus, different degree of degradation in NO_x emissions control was observed. During the first measurements at project start, the buses showed NO_x emissions less than 0.3 g/kWh, but at the final measurements the emissions were increased even up to a level of 2.0 g/kWh. However, not all buses suffered degradation of emissions performance. Bus C had low NO_x emissions throughout the project both on chassis dynamometer and on-road. Especially in on-road testing high variation in NO_x emissions (between less than 0.1 g/kWh and 3.0 g/kWh) was observed depending on the test route, bus and time of testing. Continuous NO_x concentration monitoring showed that cold ambient temperature (below 0 °C) may increase the NO_x emissions by a factor of 2 - 4 compared to summer conditions. No change in PM, PN, CO or NMHC emission was measured during the project. The Euro VI EAT configuration for those emission components i.e. DOC (CO, NMHC) and DPF (PM, PN) seem to be rather robust against aging.

Confidentiality	Public

Espoo 30.6.2021

Written by	**Reviewed by**
DocuSigned by: Petri Söderena	DocuSigned by:
EDD0D5F0C3F3448...	B62B7DD57DE5452...
Petri Söderena,	Juhani Laurikko,
Research Team Leader	Principal Scientist

VTT's contact address

Distribution (customer and VTT)

Project partners and steering group, VTT and other distribution.

Preface

City of Helsinki, Helsinki Region Environmental Services HSY, Helsinki Region Transport, Traficom, TØI The Institute of Transport Economics and VTT Technical Research Centre of Finland executed a joint project for investigating the effect of aging and Nordic conditions on diesel Euro VI city buses NO_x emissions within the years 2017 - 2020. The project partners jointly funded the project.

Espoo 30.6.2021

Authors

Nomenclature

ASC	Ammonia Slip Catalyst
CD	Chassis Dynamometer
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EATS	Exhaust Aftertreatment System
EFM	Exhaust Flow Meter
FTIR	Fourier Transformation Infra-Red
GVW	Gross Vehicle Weight
HSL	Helsinki Region Transport
ISC	In-Service Conformity
lt.	Lightweight
OBD	On-Board Diagnostic
OEM	Original Equipment Manufacturer
PEMS	Portable Emission Measurement System
SCR	Selective Catalytic Reduction
WHSC	World Harmonized Steady Cycle
WHTC	World Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle

Contents

1. Introduction

Current Euro VI heavy-duty vehicles engines have sophisticated exhaust aftertreatment systems (EATS). Most common combination of emission reduction devices consists of DOC (Diesel Oxidation Catalyst), DPF (Diesel Particulate Filter), SCR (Selective Catalytic Reduction). In addition, many of the engine manufacturer use ASC (Ammonia Slip Catalyst) after the SCR for excess ammonia reduction. The EATS needs active monitoring and thermal management for maintaining the correct functionality and required emission reduction performance. Especially the SCR requires highly sophisticated control system with multiple sensors and control algorithms for enabling high NO_x reduction rates.

Euro VI legislation was phased in 2013. As a reform to previous Euro V legislation, it introduced multiple significant changes on top of the major reduction of some of the emission components like NO_x, to which some 77 % reduction in transient test cycle was implemented. The engine certification cycles were changed to new ones that represent better the actual use of the HD vehicles and cover wider engine operational area than the previous ones. In additional, off-cycle testing was introduced to control the emission levels in engine operation areas that are not directly controlled by the actual test cycles. Furthermore, a limit value for PN emission that practically forced to use particulate filters in diesel engines was launched. In addition. in-service Conformity (ISC) testing introduced on-road measurements for the vehicle performed with the PEMS (Portable Emission Measurement System) device on a vehicle category dependent test route periodically during the useful life period. First on-road in-use test should be done at the time of engine type-approval testing.

The official emission measurement during the type approval process of Euro VI heavy-duty vehicles incl. buses and trucks does not incorporate the vehicle. Instead of that, only the engine with the exhaust aftertreatment system is tested on the engine dynamometer. The measurement cycles used for Euro VI engines constitutes of two cycles, WHSC[1] (World Harmonized Steady Cycle) and WHTC[2] (World Harmonized Transient Cycle). The load profile of the official test cycles do not necessarily represent well the real-life load profiles and usage of the city buses. Especially this is the case at low ambient temperature during the winter conditions.

Since the introduction of the Euro VI legislation in 2013 it has been amended with multiple packages updating for example the requirements for OBD (On-Board Diagnostic) and ISC testing. Table 1 shows the main changes introduced with so-called Euro VI Steps. However, the actual limit values for emission constituents in engine dynamometer testing have not been changed. Currently Euro VI legislation is amended with Euro VI Step E legislation packages which introduced even more stringent requirements for ISC testing. It should be noted that before the Step E amendment the emission sampling in ISC on-road test did not start when the test started i.e. engine is started. For example during the Step B and C phase, the legislation allowed to postpone start the emission sampling until the engine cooling water reached 70 °C, but not later than 20 min from the test start.

[1] WHSC
[2] WHTC

Table 1: Summary of main topics of the amendments (Euro VI stage A-E) for the Euro VI ISC legislation [1].

Stage	Implementation Date		OCE/ISC Requirements				
	Type approval (new types/all vehicles)	Last date of registration	PEMS power threshold	Cold start included in PEMS	OCE NTE g/kWh	PEMS CO, HC, NMHC, CH_4 CF	PEMS PN CF
A	2013.01/2014.01	2015.08	20%	No	NOx 0.60 THC 0.22 CO 2.0 PM 0.016	1.50	-
B (CI)	2013.01/2014.01	2016.12					
B (PI)	2014.09/2015.09	2016.12					
C	2016.01/2017.01	2017.08					
D	2018.09/2019.09	2021.12	10%				
E	2020.09/2021.09	-		Yes			1.63[a]

[a] For PI engines and type 1A and 1B dual fuel engines in dual fuel mode, PN CF applies 2023.01/2024.01

The performance of the EATS is highly dependent of the temperature of the exhaust gas which is tightly proportional to the engine load profile and to the ambient air temperature (temperature of the intake air and cooling effect of the ambient air). Even though the EATS technology of the Euro VI buses is further developed from the Euro V buses, the thermal management of the EAT system is still challenging at low average engine loads, which is mostly the case in the city traffic.

The Euro VI emission standard includes currently so called RDE (Real Driving Emission) regulation that requires the emission levels enacted in the standard to be fulfilled also at real driving conditions measured with the PEMS (Portable Emission Measurement System) devices. However, there are boundary conditions for the RDE requirement, for example based on the ambient air temperature, and it is not required to be fulfilled at low ambient air temperatures, when “auxiliary emission control strategy” can be used for protecting purposes of engine and EAT device(s).

Especially the performance of the SCR system is extremely dependent of the exhaust gas temperature level and for good NOx conversion efficiencies about 200 - 220 °C exhaust gas temperature is needed. During normal operation in city traffic buses stop often which decreases effectively exhaust gas temperature level. Frequent stops and accelerations also increase soot loading on the DPF and thus DPF needs to be regenerated periodically more often. The DPF regeneration increases the fuel consumption.

Due to the issues above, field measurement of real driving emissions is still extremely important so that the real driving emissions of different type of buses can be monitored and evaluated on various routes, weather conditions and traffic volumes. In addition to various on-road conditions, the aging of the EATS is an important factor effecting on the emission reduction performance. EATS is facing throughout the usage different encumbrances originating from fuel, engine oil, engine wear and operational condition. These alone or together may reduce the effectiveness of the EATS greatly.

2. Objectives

During the years 2015 - 2016 VTT conducted first Euro VI city buses field emissions test project to determine and evaluate NO_x emissions on real driving conditions. Three buses were equipped with the Proventia Emission Control's PROCARE Drive NO_x concentration on-board continuous monitoring devices.

There were some problems with the buses itself and with the EATS monitoring devices. Consequently, usable measurement data was gathered with one of the buses only from 18 days, while the bus that functioned the best produced usable measurement data from 377 days. Nonetheless, it was possible to produce rough estimates of city buses NO_x emissions on real driving conditions below 0 °C, 0 °C…10 °C and above 10 °C temperature zones. It was possible only to define average NO_x conversion efficiencies and the mass-based NO_x emissions had to be estimated based on the emission rates measured on the chassis dynamometer.

Current project was a continuation to the former project conducted in 2015-2016. Based on the experiences and results of the former project it was well justified to conduct a multiyear project in which the emissions were also measured periodically on the vehicle chassis dynamometer. Additionally, to be able to define the mass based emissions on real driving conditions it was necessary to conduct PEMS measurements at various weather conditions. The PEMS equipment can also be used for verifying the NO_x emissions measured by the buses own EATS. Also this time buses were installed with Proventia PROCARE Drive NO_x concentration monitoring devices for bringing information from day-to-day operation.

The goal of the project was to define emissions of the Euro VI diesel buses, both as continuous and with four PEMS measurement campaigns, on different on-road conditions during a three-year period. Additionally, the objective was to monitor the emissions level development by periodic vehicle dynamometer measurements. The overall target was to gather emission data for every vehicle from at least 250 000 km of driving distance.

As a summary, the main objective was to provide new information for the participants and readers covering the Euro VI buses on-road emissions performance in city environment in different weather conditions.

The findings of the project can be thus utilized for example in development of bus traffic tendering process, development of use profile for reducing the emissions, utilize the results in emissions inventory calculations and understand the possibilities and shortcomings of the on-road measurements with PEMS device.

3. Test methods

The target in this project was especially in monitoring the change of NO_x emissions of four diesel city buses during the three years period. For this purpose, three different test methods were chosen. First, chassis dynamometer tests provide an accurate and repeatable method for assessing vehicle performance, i.e. energy consumption and powertrain functioning, as well as emissions measurements. Secondly, on-road testing with PEMS device in typical city buses operational environment provides as close as possible results from an in-use like environment. Finally, the continuous NO_x concentration monitoring provides a good addition by revealing the actual performance in day-to-day usage throughout the year.

For monitoring the development of the emission performance, it is crucial to have repeatable and accurate testing method. Thus, chassis dynamometer testing was included in the testing program as the base case. Exactly repeated test procedures in same testing conditions gave good base for critical analysis of the results and conclusions.

In addition to the chassis dynamometer testing, on-road tests with PEMS device were included in the testing program. The main motivation for the on-road testing was to identify the development of NO_x, CO, PN and CO_2 emissions in various typical city bus operational conditions occurring at HSL traffic and Nordic weather conditions, while the buses are accumulating more kilometers and the EATS is aging.

On-road testing has always disturbances due to the changing traffic situation and ambient conditions. Thus, it can be seen as a more “pass or fail” type of testing in relation to the emission limits. For this reason, the results of on-road testing were considered as upper and lower values that may occur in typical city bus operation. During the three years period of the project the testing generated a window in which the emissions may change during normal operation.

As the same buses were tested in the same testing routes multiple times during the project duration, the results gave good base for estimating the development of emissions performance due to the aging and possible deterioration of the EATS.

Continuous NO_x concentration monitoring fills-up the gaps that are not possible to identify with chassis dynamometer and on-road PEMS testing.

3.1 Buses monitored

Four typical Euro VI diesel city buses used in Finland in the traffic of HSL was selected for this three years monitoring project. Chosen buses represent the most common bus types and models used in HSL traffic. Buses were used by their respective operators in normal every day traffic. Two of them were identical models and had been taken in use at the same time. The model years of the buses were 2015 and 2016. At the start of the project in June 2017, the odometer readings were between ca. 90 000 to 197 000 km, depending of the bus. Table 2 summarizes the main details of the test buses.

In normal HSL traffic, bus operators are encouraged with incentives[3] to use renewable diesel (EN15940). This means that each of the buses were run during the project duration with different mixtures of normal EN590 diesel (summer and winter grade) sold in Finland, and renewable EN15940 diesel. Mixture may have changed between 0 - 100 % depending of the operator, and in which line the bus was used. Fuels used during the each test session are defined in the each individual sections 3.2 - 3.4.

[3] Incentive is called ”Environmental bonus”, which is based on annually organized tendering round.

Table 2: Test buses details.

Measure/Bus	Bus A	Bus B	Bus C	Bus D
Model year	2015	2015	2016	2016
Euro class	Euro VI	Euro VI	Euro VI	Euro VI
Chassis	three axle low entry	three axle low entry	two axle low entry	three axle low entry
Fuel	diesel	diesel	diesel	diesel
EATS	DOC+DPF+SCR	DOC+DPF+SCR	DOC+DPF+SCR	DOC+DPF+SCR
Odometer at start [km]	197 193	194 469	130 511	88 366

As said before, all buses served in normal day-to-day traffic. This mean that they were also undergoing normal service programs defined by the OEM (Original Equipment Manufacturer). Depending of the Euro VI engine manufacturer, the service programs includes different measures for maintaining the functionality and operational condition of EATS devices. This might mean a periodic change of DPF for a cleaned one, or periodic service of DPF and SCR regeneration. Despite the normal service and maintenance vehicle and engine parts renewal the only major breakdown occurred for bus C. The engine of bus C broke down at early days of 2018. Therefore, the engine was changed to a new one. However, the EATS was not renewed. Right after the bus was back in service, it was tested on the chassis dynamometer to check the emission level in comparison to earlier level.

3.2 Chassis dynamometer tests

Chassis dynamometer tests were conducted on the VTT heavy-duty vehicle chassis dynamometer (Figure 1). The dynamometer has a single roll with 2.5 m diameter, and it is capable for absorbing up to 300 kW continuous wheel power ratings, and simulating inertia from 2500 kg up to 60,000 kg of GVW (Gross Vehicle Weight). The chassis dynamometer facility is equipped with a full-flow dilution tunnel and a set of sample bags for emission measurement. Integrated emission analyzers can measure all regulated emission components and CO_2 emissions. In addition to the integrated emission analyzers, FTIR (Fourier Transformation Infra-Red) devices were used for N_2O and NH_3 emission measurements. Fuel consumption was measured with the gravimetric measurement device. Main information of the test-set up used during the project is shown in Table 3.

Figure 1: View of the HD chassis dynamometer. The CVS tunnel can be seen on the upper right corner of the figure.

Table 3 : Description of used devices on chassis dynamometer.

Device	**Information**
HD Chassis Dynamometer	Froude Consine Ltd, maximum power ± 300 kW (54–110 km/h)
Emission sampling and dilution system	Pierburg AG, CVS-12-WT, Maximum flow: 120 m3/min
Integrated emission analyzer system	Gaseous: AVL AMA i60 (THC, CH4, NOx, CO2, CO) PM: AVL PSS i60 PN: Butanol Condensation Particle Counter (bCPC) Airmodus A23
Fourier Transformation Infra-Red (FTIR)	Rowaco and Gasmet Cr-2000
Fuel scale	Sartorius Combics 1 CW1P1-60FE-I

Same test program and procedure was performed for each of the buses. Test program included so called zero measurements and periodically twice a year follow-up measurements during the project duration. Test cycles used for testing were WHVC[4] (World Harmonized Vehicle Cycle) and Braunschweig[5] test cycle. Below is presented the reasoning for choosing these test cycles. Tests were run with inertia that corresponds to a vehicle curb mass and half of the payload based on the unladen and maximum permissible weight of the bus. The test program is presented in Table 4. In case of detecting DPF regeneration or any other EAT related problem during the preconditioning or during the test cycle, the regeneration was tried to be brought to end by driving 80 km/h for a longer period of time. However, in some cases, the regeneration or active EAT heat control was not completely ended. Thus, the fuel consumption and emissions did not return to base level.

[4] WHVC
[5] Braunschweig

As described in the Introduction, there is no type approval test cycle on a chassis dynamometer for a complete HD vehicle, as for heavy-duty vehicles only the engine is tested during the type approval process. Euro VI engines are tested on two test cycles WHSC and WHTC during the type approval process.

However, the same data sets that were used for generating the WHTC (World Harmonized Transient Cycle) were used also for generating a chassis dynamometer test cycle WHVC. Thus, WHVC is replicating the WHTC on vehicle level on a chassis dynamometer. However, they are not identical, as depending on the simulated vehicle test load and the specific powertrain, the exact engine load and speed in respect to time might differ from that on the WHTC. During the project WHVC was run as WHTC in type approval process, meaning at first a cold start cycle followed by a hot started cycle. The result is then presented as an aggregated result with 14 % weighting factor for cold-started and 86 % weighting factor for hot-started cycle. Thus, WHVC gives the best possible comparison with the Euro VI certification cycle WHTC.

Table 4: Testing program on chassis dynamometer.

Test program	
Preconditioning	30 min driving at 80 km/h + Soak overnight
Zero measurements in June-July 2017	WHVC in cold-start conditions following a hot-start WHVC (cold cycle + 10 min pause + hot start cycle) Braunschweig cycle with fully warmed-up engine run three consecutive times (hot-start cycle + 10 min pause + hot-start cycle + 10 min pause + hot-start cycle) FTIR before and after the EATS
Follow-up measurements in November 2017 - January 2020	WHVC in cold-start conditions following hot-start WHVC (cold cycle + 10 min pause + hot-start cycle) Braunschweig cycle with fully warmed-up engine run three consecutive times (hot-start cycle + 10 min pause + hot-start cycle + 10 min pause + hot-start cycle) No FTIR measurements
Final measurements in May-June 2020	WHVC in cold-start conditions following hot-start WHVC (cold cycle + 10 min pause + hot start cycle) Braunschweig cycle with fully warmed-up engine run three consecutive times (hot-start cycle + 10 min pause + hot-start cycle + 10 min pause + hot-start cycle) FTIR before and after the EATS
Test fuel	Commercial EN590 diesel for summer and autumn use with the grade of ”-5/15” (lowest storage temperature -5 °C, lowest operability temperature -15 °C).

Braunschweig test cycle has been used for city buses performance and emissions testing at VTT since the HD chassis dynamometer was taken in use 2002. Since then, VTT and HSL has jointly built a database with annual projects covering Euro I - Euro VI diesel and CNG city buses energy consumption and emissions [2][3]. Currently the database covers performance results of 204 Euro I - Euro VI diesel and CNG city buses. Figure 2 shows the development of Euro VI city buses NO_x emissions as a function of mileage on hot-start Braunschweig cycle and on aggregated WHVC. As a main conclusion of the figure, we can see that the NO_x emission scatter increases as a function of mileage. With low-mileage buses NO_x emissions are low and within a small window. In case of high-mileage buses the scatter is highly fragmented. It should be noted that there are also low NO_x emission buses with high mileages.

Originally, Braunschweig test cycle was chosen as a base test cycle for city buses testing as it is in Europe widely used, and it describes well typical very cyclic driving occurring in city bus operation. For this project, Braunschweig cycle was chosen for the same reason and to maintain the comparability with the database. Figure 3 shows the speed traces for both Braunschweig and WHVC test cycles.

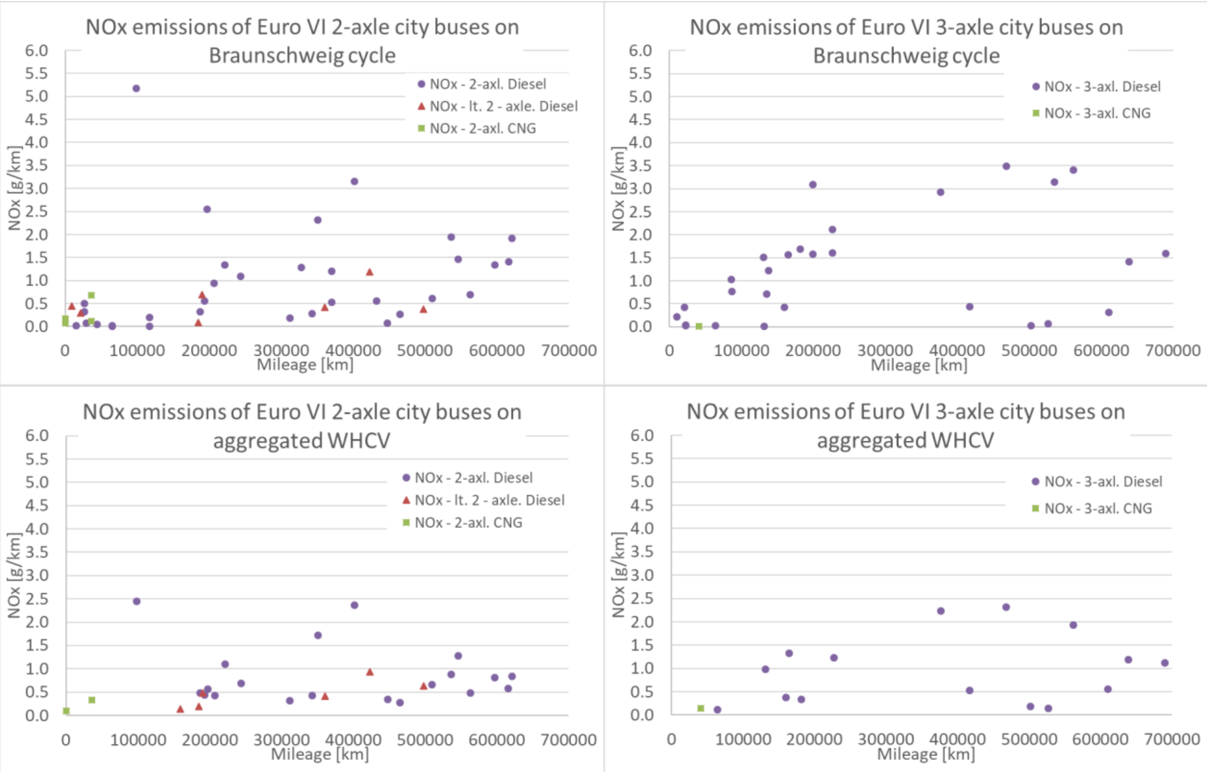

Figure 2: NO_x emissions of 2- and 3-axle Euro VI city buses in VTT city bus emissions performance database [3]. *Abbreviation lt. in figures mean lightweight.*

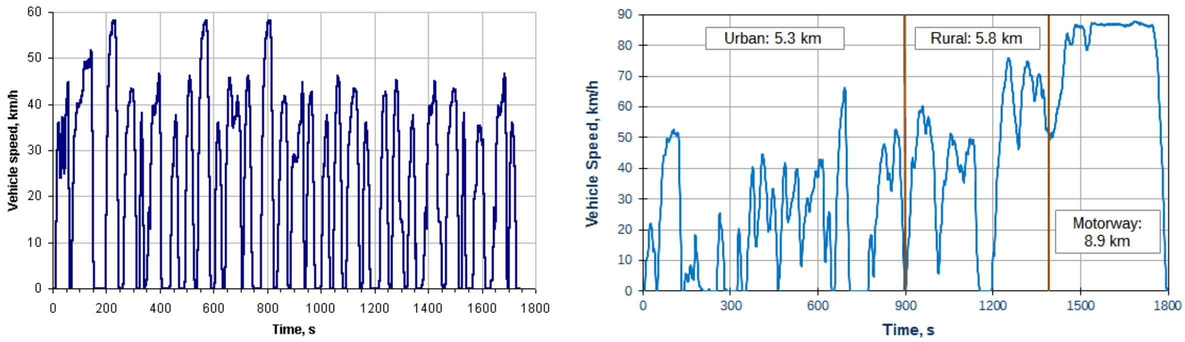

Figure 3: Test cycles used in chassis dynamometer testing. Braunschweig in left and WHVC in right.

For determining the gaseous emissions of CO, NO_x and NMHC, the exhaust mass flow was defined from the full-flow dilution tunnel and concentrations of the emissions from the bags were used. PN emissions were defined based on the CPC. PM emissions were collected on the filters in the measurement device (AVL PSS). The CO_2 emissions were calculated from the gravimetrically measured fuel consumption and the carbon intensity of the fuel, as this is a more accurate method than measuring CO_2 emissions directly from the sampled exhaust gas. The used carbon intensity (3,16 kg,$_{CO2}$/kg,$_{fuel}$) is based on the figures from the Joint Research Centre (JRC) of the European Commission [4].

Typically at VTT the “base” diesel fuel (EN590) for HD chassis dynamometer testing is delivered once a year. This means that the buses were tested with three different diesel batches. However, as the grade and the quality of the diesel is practically the same the difference between the different batches is negligible. Lower heating value and density were based on the analysis results provided by the diesel supplier. Table 5 shows typical characteristics of the EN590 diesel used in chassis dynamometer testing. Table shows also typical characteristics of EN15940 renewable diesel that the operators are using.

Table 5: Typical characteristics of the fuel used in the chassis dynamometer testing (EN590) and renewable diesel (EN15940) used by the operators.

Physical or chemical feature	Unit	VTT EN590 "base diesel" -5/-15	Renewable EN15940 diesel
Density	kg/m3	834	780
Cetane index	-	55,7	81,2
Lower heating value (LHV)	MJ/kg	43,02	43,66
Volumetric energy content	MJ/l	35,89	34,04
Cold filter plugging point (CFPP)	°C	-18	-43
Sulphur	mg/kg	5.6	< 1
Aromatics	%-w	17.7	0.2
95 % distillation point	°C	352	294

3.3 On-road PEMS tests

On-road PEMS tests were conducted with the VTT's PEMS devise. The main characteristics are shown in Table 6. The device can measure NO, NO_2, CO, CO_2 and PN emissions. The VTT's PEMS device can be used both in LD and HD vehicles. In this project, a 4-inch EFM (Exhaust Flow Meter) measurement tube was used, as it provides appropriate flow range.

Table 6: VTT PEMS device characteristics.

Feature	**Information**
PEMS device	AVL M.O.V.E GAS PEMS iS and PN PEMS
Exhaust flow meter:	AVL M.O.V.E EFM
Technology:	NO/ NO_2: UV (Ultraviolet light) CO/CO2: NDIR (Non-Dispersive Infrared) O_2: Electrochemical EFM: Differential pressure measurement
Measurement range:	NO/ NO_2: 0 - 5,000 ppm (NO) 0 - 2,500 ppm (NO_2) CO/ CO_2: 0 - 5 vol% (CO), 0 - 20 vol% (CO_2) PN: 23 nm - 200 nm EFM 4“ flow tube: 30 - 2140 kg/h @ 100 °C and 45 - 1600 kg/h @ 400 °C
Accuracy:	CO: 0 – 1,499 ppm: ± 30 ppm abs., 1,500 ppm – 49,999 ppm: ± 2% rel. CO_2: 0 – 9.99 vol.%: ± 0.1 vol.% abs., 10 - 20 vol.%: ± 2% rel. NO: 0 – 5,000 ppm: ± 0.2% FS or ± 2% rel. NO_2: 0 – 2,500 ppm: ± 0.2% FS or ± 2% rel. EFM: ±2.0% of reading or ±0.5% of full scale, whichever is greater

In the first on-road test campaign, the PEMS device was installed at the back of the buses on a bespoke rack, but afterwards the device was installed inside the bus. Figure 4 shows the typical installation of the PEMS device used through the project.

PEMS testing was performed on three different routes. The main characteristics are shown in Table 7.

Figure 4: Exemplary installation of the PEMS device. Emissions analyzers inside the bus and EFM installed at the back of the bus.Speed profile and location on a map are shown in Figure 5 and Figure 6. Two of them describing typical operation in HSL traffic. Third route was fulfilling the requirements of the Euro VI ISC testing. First typical HSL traffic route was following one

of the trunk lines[6], called Jokeri-line, from west part of the Helsinki metropolitan area to eastside of the city. In actual testing, the route was measured as two separate tests. One starting at Westend and ending at Eastend. The second starting at Eastend and ending at Westend. Before heading to the second part of the test, there was a 10 min pause to mimic the actual driving of the line. After the project was started in 2017 heavy road construction works were started on the Jokeri-line. In the future, the bus traffic in Jokeri-line will be replaced with trams. The railway construction work caused special arrangements for the bus route from 2018 onwards.

The other typical HSL traffic route was mainly following the HSL line 552 with some modifications to capture more city center driving.

For practical reasons the fuel in the tank was used in on-road testing, a the fuel change for the city bus tank requires high effort. In addition, it was known based on the earlier published research that the effect of HVO on engine-out NO_x emissions is at maximum around -10 % [5][6]. Due to the above details, it was reasoned that the fuel change do not provide enough benefit compared to required resources.

On the valid ISC route, the PEMS results were calculated based on the Euro VI C requirements. Thus, results include the data points starting after the engine cooling water has reached 70 °C, or test has lasted 20 min, whichever comes first. In other test routes, all the data points were included in data processing i.e. results include data from engine start to engine shut down.

Figure 4: Exemplary installation of the PEMS device. Emissions analyzers inside the bus and EFM installed at the back of the bus.

[6] HSL trunk line 550

Table 7: Main characteristics of the test routes

Feature	Westend - Eastend (WE-EE)	Eastend - Westend (EE-WE)	HD City	Euro VI ISC
Distance [km]	28	28	40	110
Duration [min]	67	67	ca. 100	ca. 180
Avg. speed [km/h]	29	29	23	39
Stopping at bus stops	Every second	Every second	Every second	none
Loading [kg]	Buses A, B and D: ca. 5000 Bus C: ca. 2500	Buses A, B and D: ca. 5000 Bus C: ca. 2500	Buses A, B and D: ca. 5000 Bus C: ca. 2500	Buses A, B and D: ca. 5000 Bus C: ca. 2500
Test condition:	Warm start	Warm start	Warm start	Cold start
Test data processing:	Whole test with no specific weighting etc.	Whole test with no specific weighting etc.	Whole test with no specific weighting etc.	According to ISC procedure
Test fuel	Fuel in tank	Fuel in tank	Fuel in tank	Fuel in tank

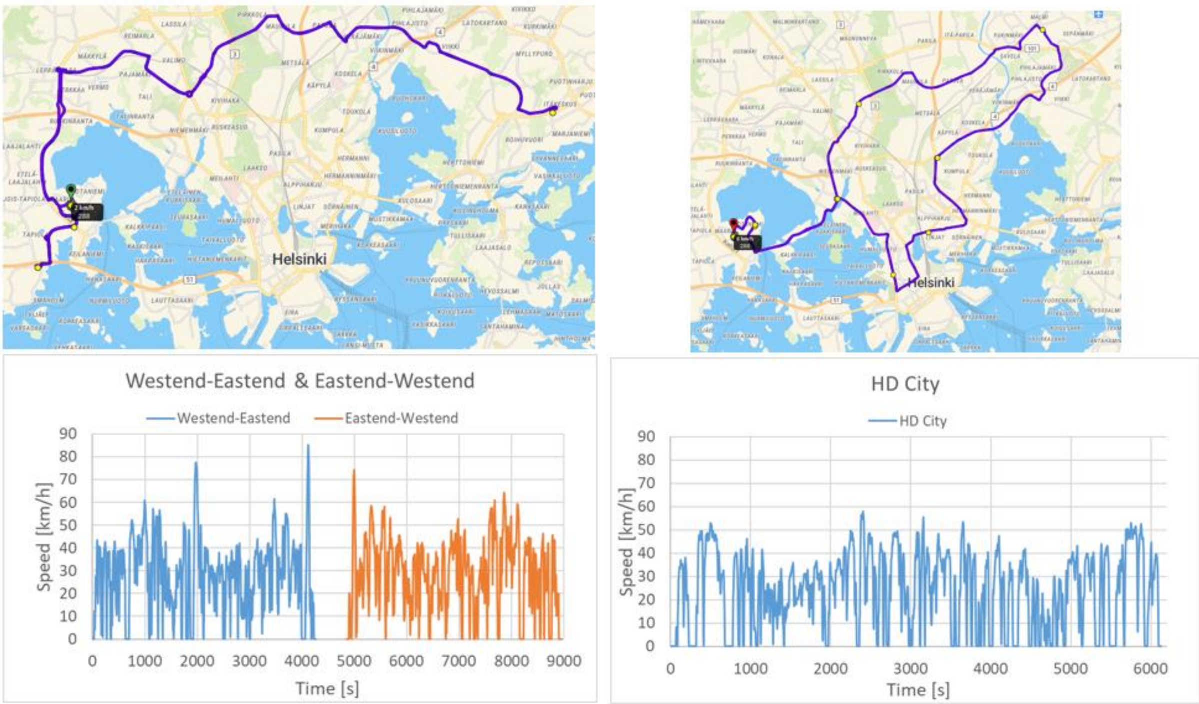

Figure 5: Route and speed profile of the test routes Westend-Eastend and HD City.

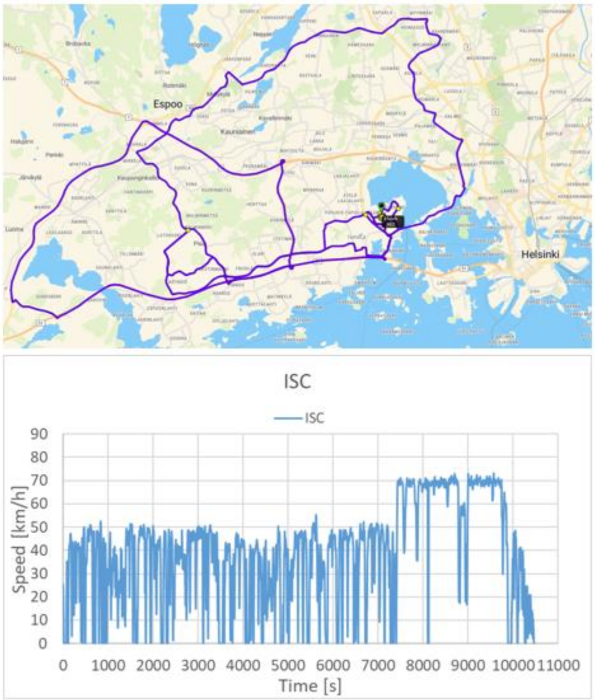

Figure 6: Route and speed profile of the valid ISC test route.

3.4 On-road NO_x monitoring

Each of the buses were equipped with the Proventia Procare Drive[7] NO_x concentration monitoring systems. The system includes the following sensors and devices:

- NO_x sensors, pre- and post-EAT
- Pressure sensor, pre-EAT
- Temperature sensor, pre-EAT
- Control unit
- GPS and GSM antenna

The system utilizes typical heavy-duty NO_x, pressure and temperature sensors. NO_x sensor is capable for measuring the NO, NO_2 concentration and excess oxygen percentage. Systems were installed prior the first chassis dynamometer tests. During the project, there were multiple technical problems with the devices, and because of that, data was data missing time-to-time. This is discussed more detailed in section 4.3.1.

In the analysis, results only from days where total operational time exceed 2 hours were included. The reasoning for this decision was that typically city buses are operated throughout the day even up to 18 hours. Thus, operation under 2 hour does not represent typical use and in many cases was actually transfer driving (maintenance etc.).

[7] Proventia Procare Drive

4. Results

In this paragraph, the results are presented starting from the chassis dynamometer (CD) and following with on-road PEMS and NO_x concentration monitoring. For the chassis dynamometer and PEMS results, first the cycle (CD) and route (PEMS) average results are presented and then more detailed results. Figure 7 shows the overall mileage per bus driven during the project and the testing program. Total mileage driven with each of the buses was following:

- Bus A: 356 000 km
- Bus B: 318 000 km
- Bus C: 264 000 km (218 000 km with new engine)
- Bus D: 257 000 km

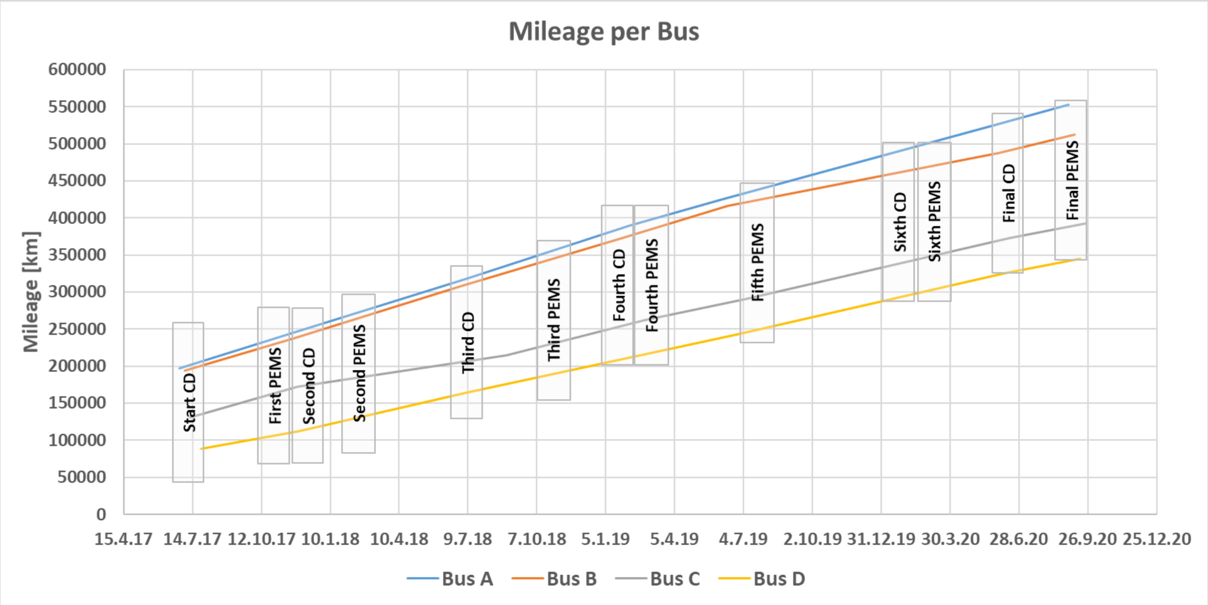

Figure 7: Accumulated mileage during the project and testing program with each tested bus.

4.1 Chassis dynamometer results

In this chapter, results on Braunschweig and WHVC cycles are presented. On Braunschweig cycle results are shown as average result of the two consecutive hot start test cycles. In case of WHVC, both cold-start and hot-start emission results are presented. Energy consumption on WHVC is shown from the hot-start cycle as it represent better the efficiency of the bus. In both cycles, emissions are expressed in grams per km (g/km) and in grams per kWh of engine work (g/kWh). An estimated powertrain (engine crankshaft to driven wheels) efficiency of 75 % was used to calculate the engine work from the work done on chassis dynamometer rolls. For estimating the global warming potential (GWP) of N_2O emissions greenhouse gas (GHG) equivalence emissions factor of 298 was used[7][8][9][8].

Figure 8 to Figure 15 show the results on hot.start Braunschweig cycle. Figure 8 and Figure 9 show the CO_2 emissions and energy consumption. NO_x, PM, and PN emissions are shown in Figure 10 to Figure 13, including the engine-out and tailpipe NO_x emissions and conversion efficiency at the first and final tests are shown in Figure 13. CO and NMHC emissions are shown in Figure 14. Both results of Braunschweig and WHVC are shown in the same figures. Figure 15 shows the direct N_2O and GHG equivalent emissions.

Results on WHVC cycle are shown in Figure 16 to Figure 20. CO_2 emissions and energy consumption are shown in Figure 16 and Figure 17. NO_x, PM and PN emissions are shown in Figure 18 to Figure 21.

In general, results show that each of the bus performed differently. Some more consistently than others. Bus A had consistent energy consumption in every test, whereas buses C and D had more deviations between the test times.

During the first test in 2017 bus B executed an active DPF regeneration, and had exceptionally high NO_x emissions. Despite the multiple attempts to finalize regeneration by driving constant speed of 80 km/h for long period, the increased NO_x emission did not return to typical Euro VI level. Actually, based on the on-road monitoring, the elevated NO_x emissions lasted approx. 45 days as can be noticed in Figure 33.

[8] Depending of the source the GWP of N_2O emissions varies between 265 - 310.

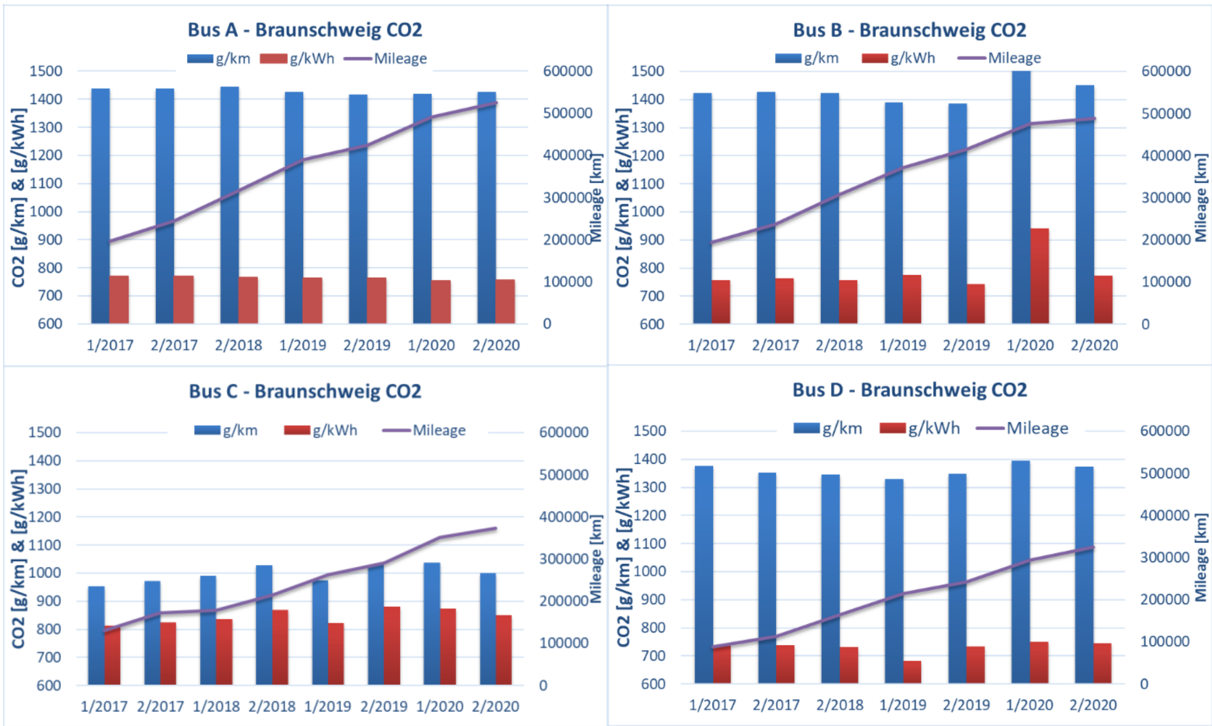

Figure 8: CO_2 emissions on hot start Braunschweig cycle.

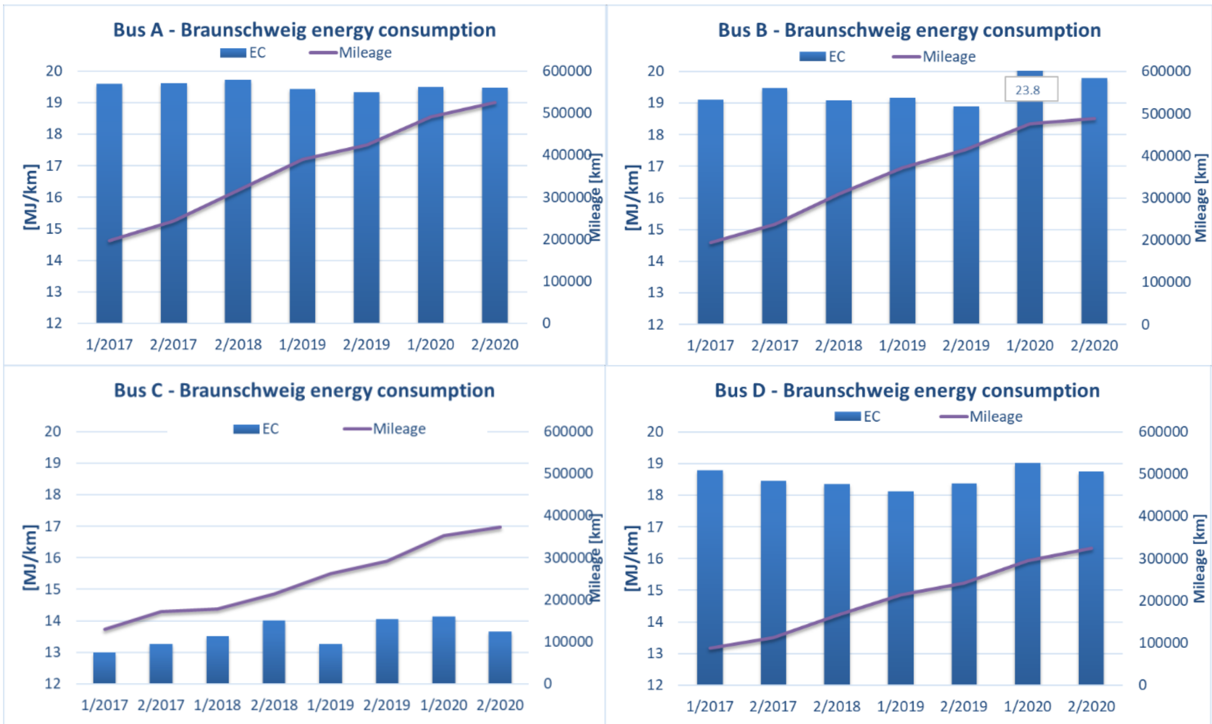

Figure 9: Energy consumption on hot-start Braunschweig cycle.

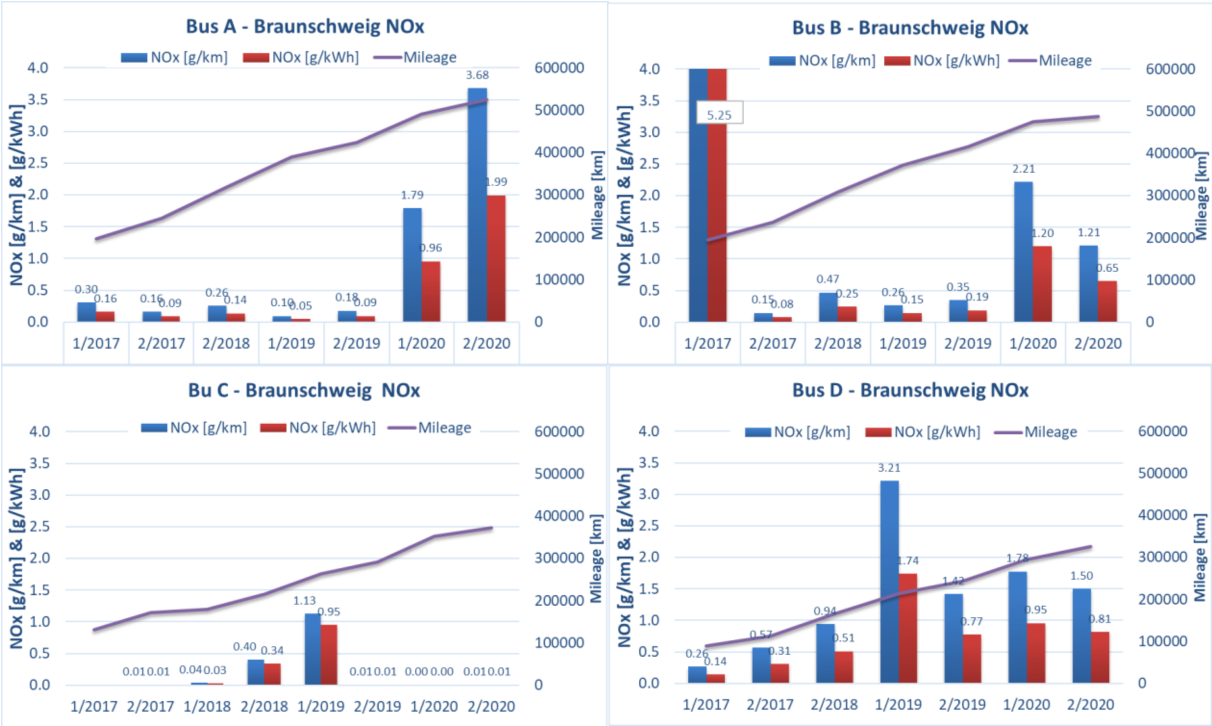

Figure 10: NO_x emissions on hot-start Braunschweig cycle. Euro VI limit value on WHTC is 0.46 g/kWh.

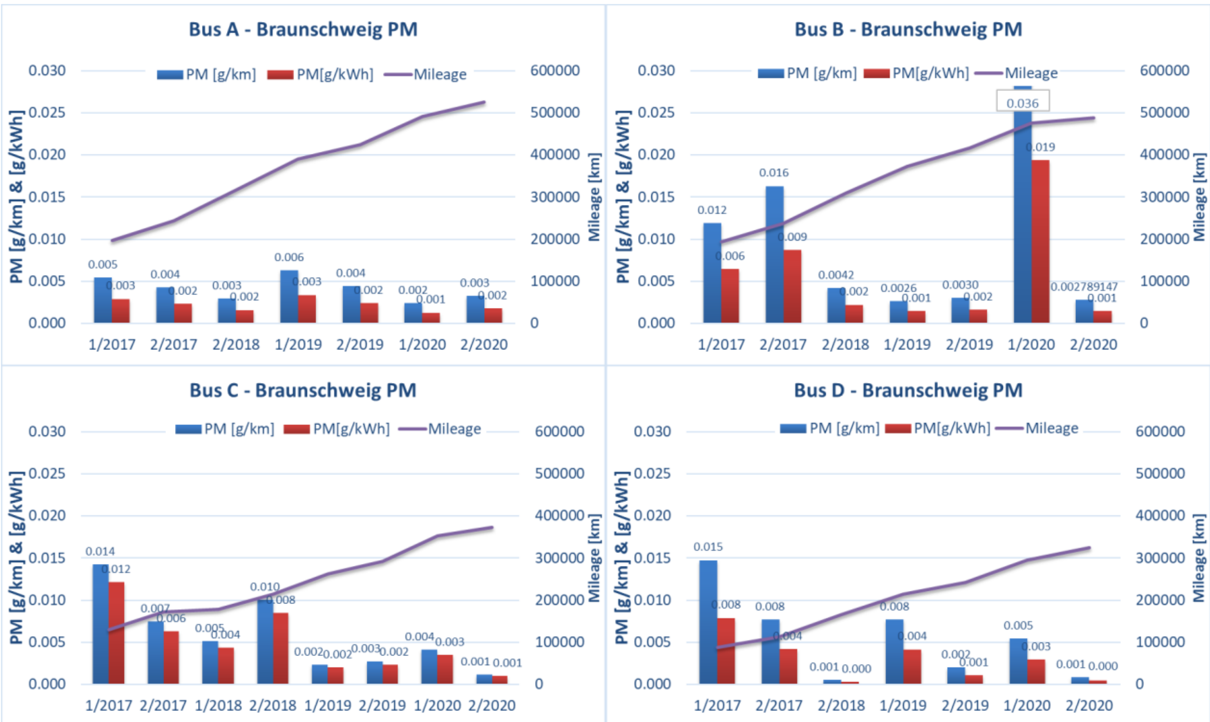

Figure 11: PM emissions on hot-start Braunschweig cycle. Euro VI limit value on WHTC is 0.01 g/kWh.

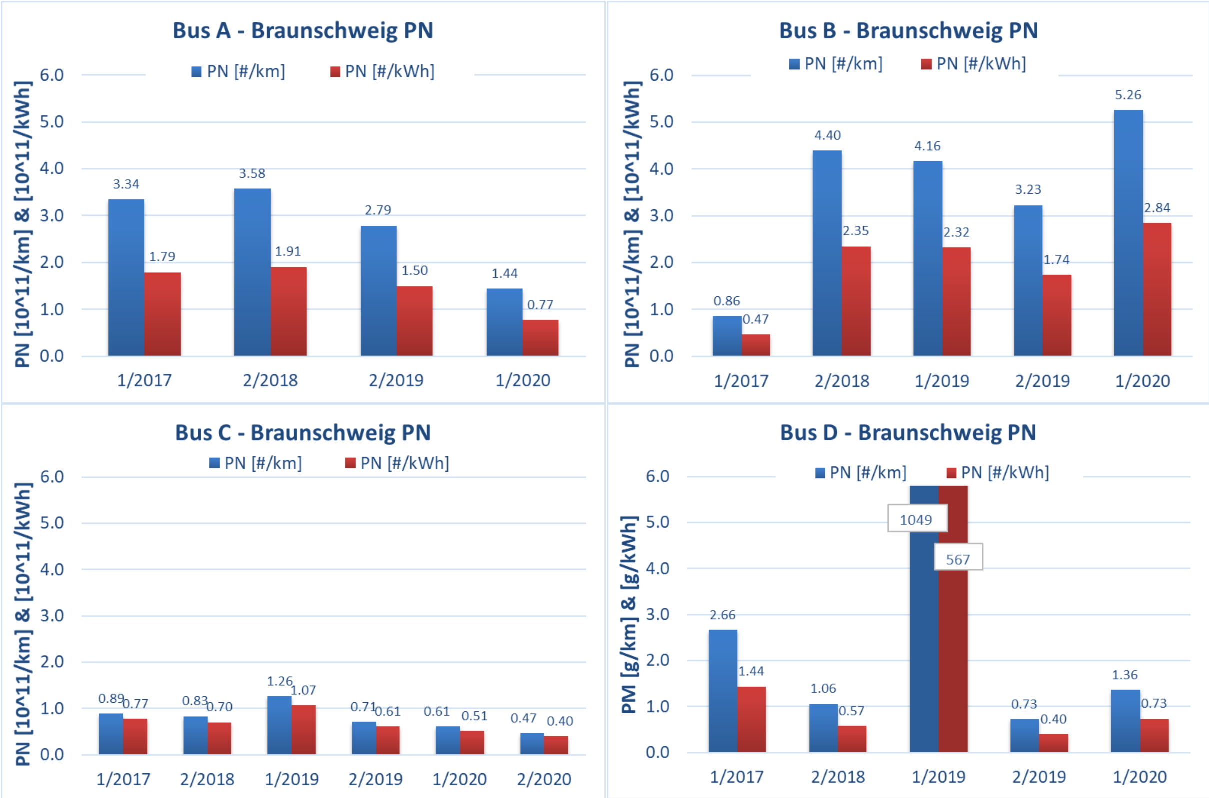

Figure 12: PN emissions on hot start Braunschweig cycle. Euro VI limit value on WHTC is 6x10^11/kWh.

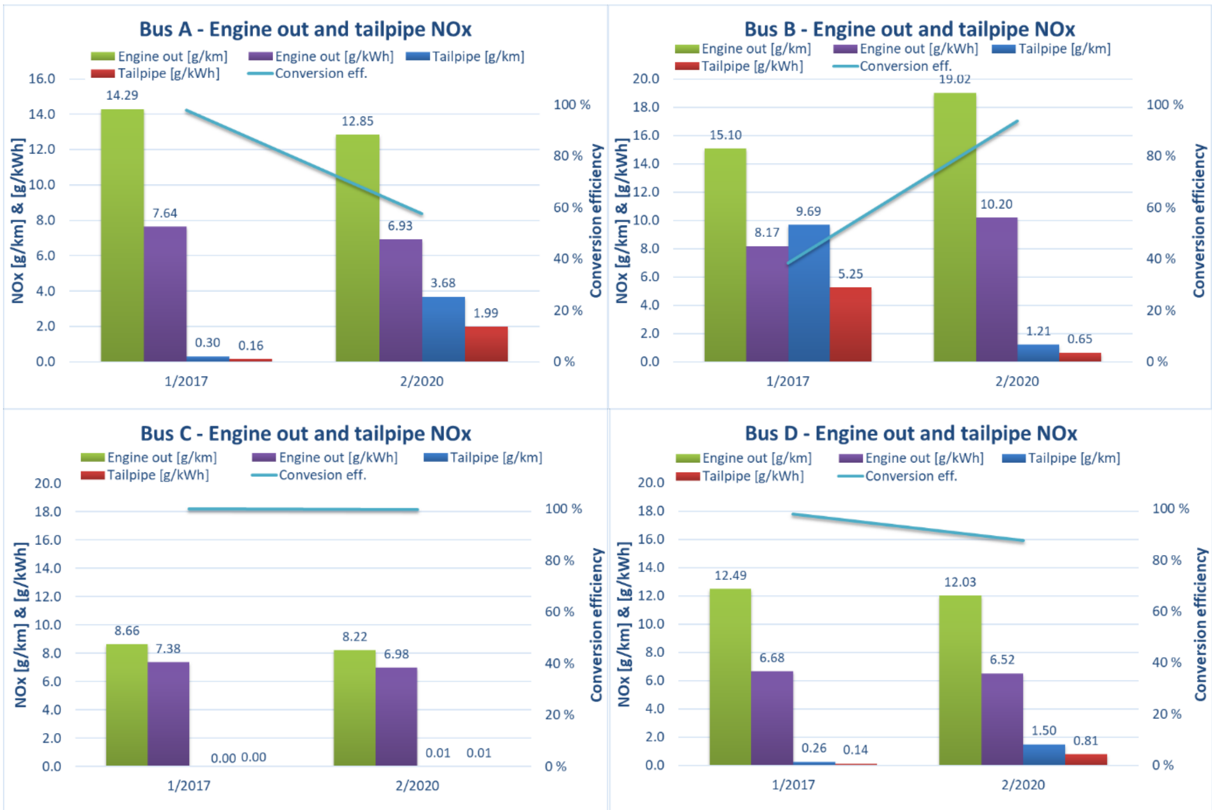

Figure 13: Engine out, tailpipe NO_x emissions and NO_x conversion efficiency on hot-start Braunschweig cycle. Results from the first and last chassis dynamometer test.

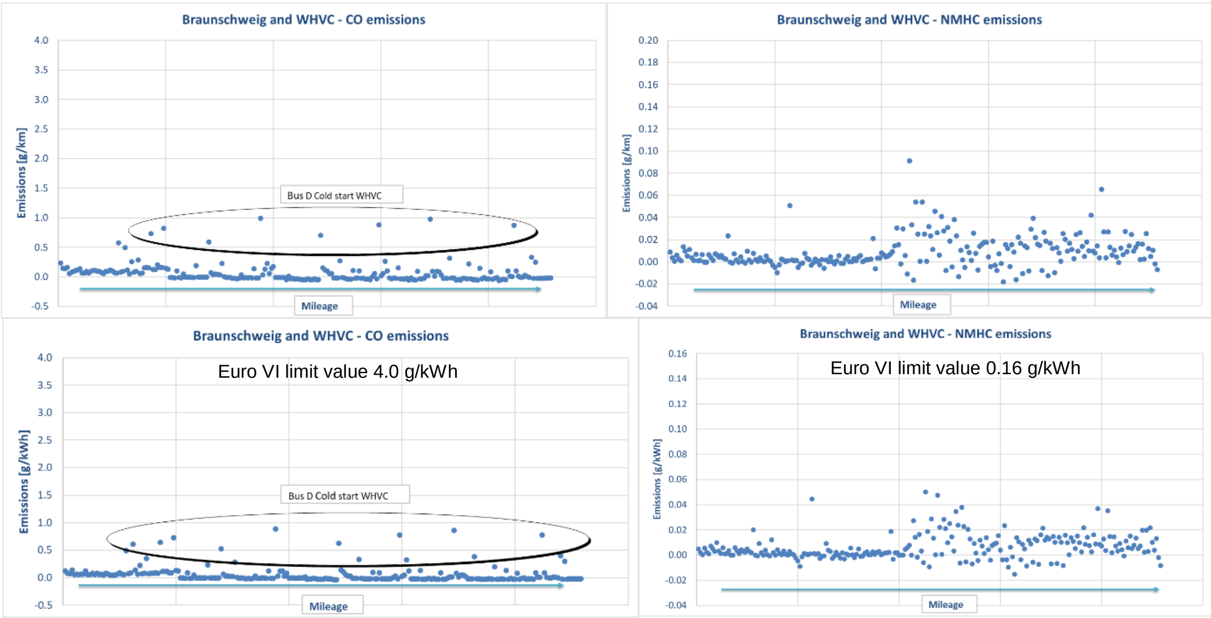

Figure 14: CO and NMHC emissions on hot-start Braunschweig cycle and cold and hot-start WHVC.

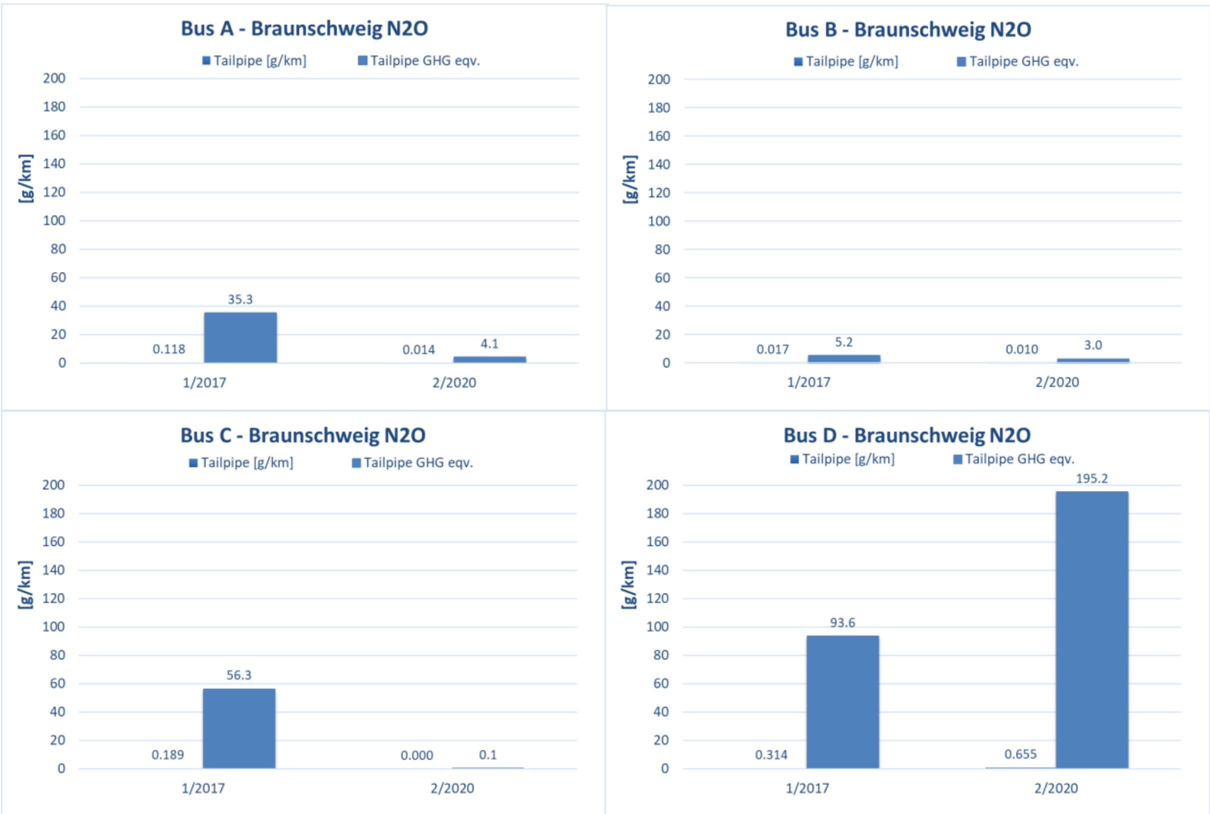

Figure 15: N_2O emissions on hot start Braunschweig cycle in the first and last chassis dynamometer test.

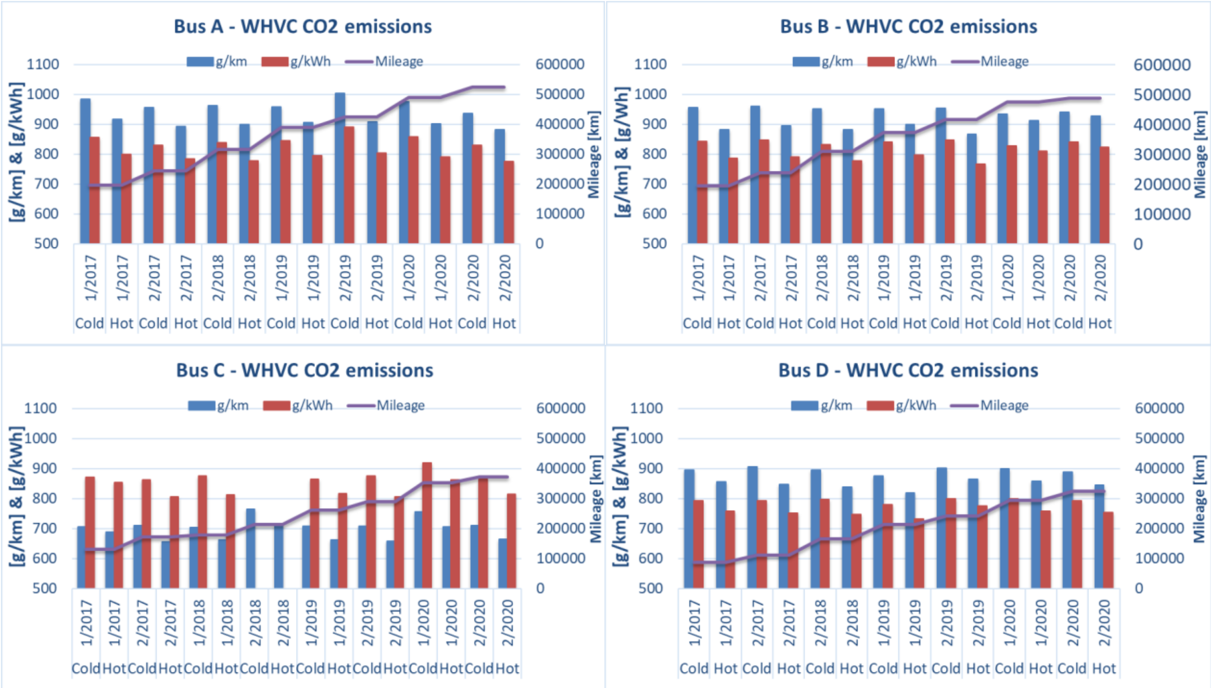

Figure 16: CO_2 emissions on cold and hot-start WHVC.

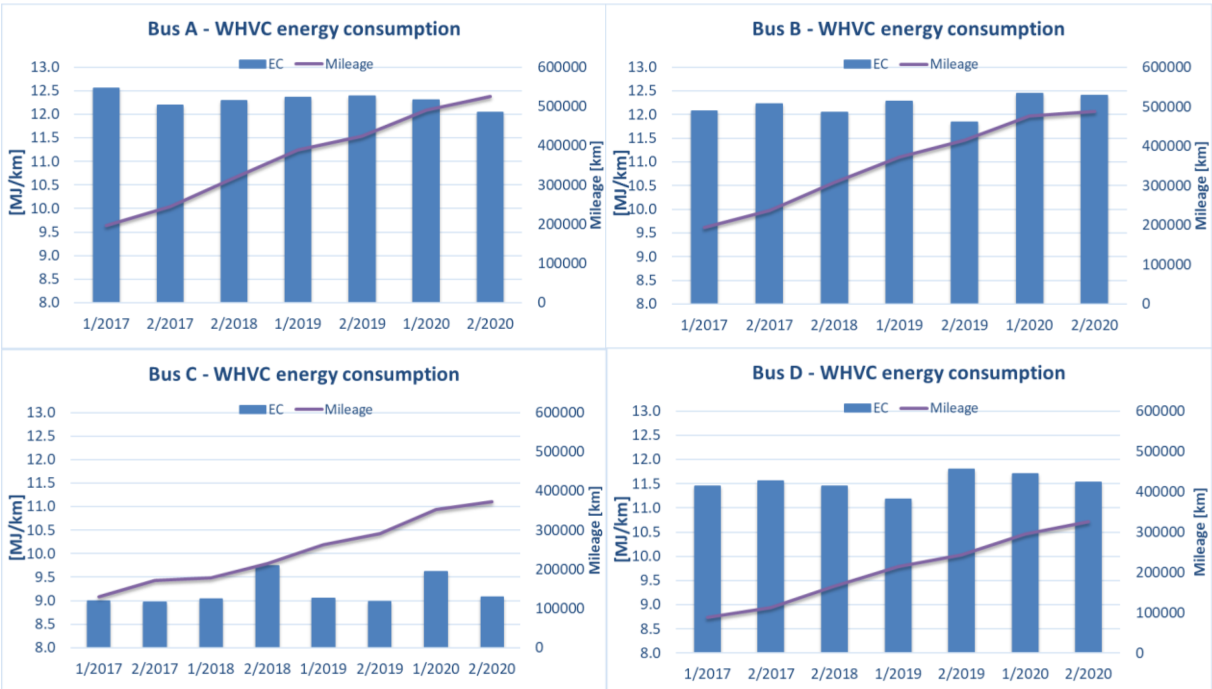

Figure 17: Energy consumption on hot-start WHVC.

Figure 18: Aggregated (cold + hot cycle) NO_x emissions on WHVC. Euro VI limit value on WHTC is 0.46 g/kWh.

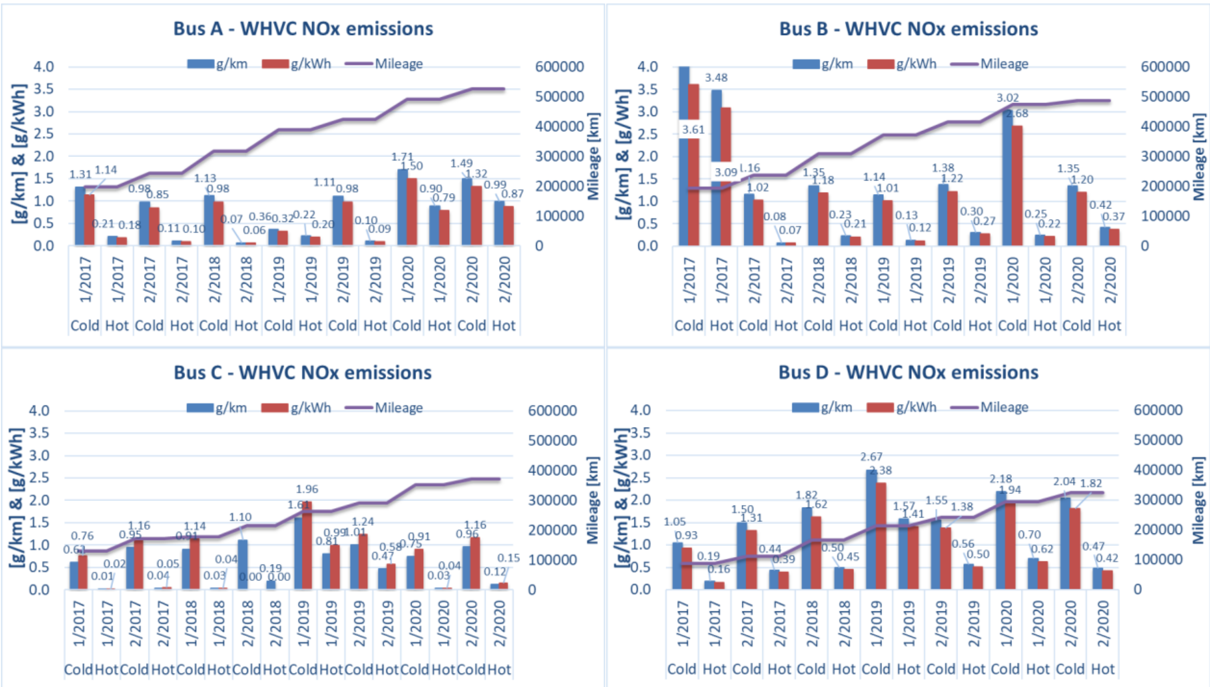

Figure 19: NO_x emissions on cold and hot start WHVC. Euro VI limit value on WHTC is 0.46 g/kWh.

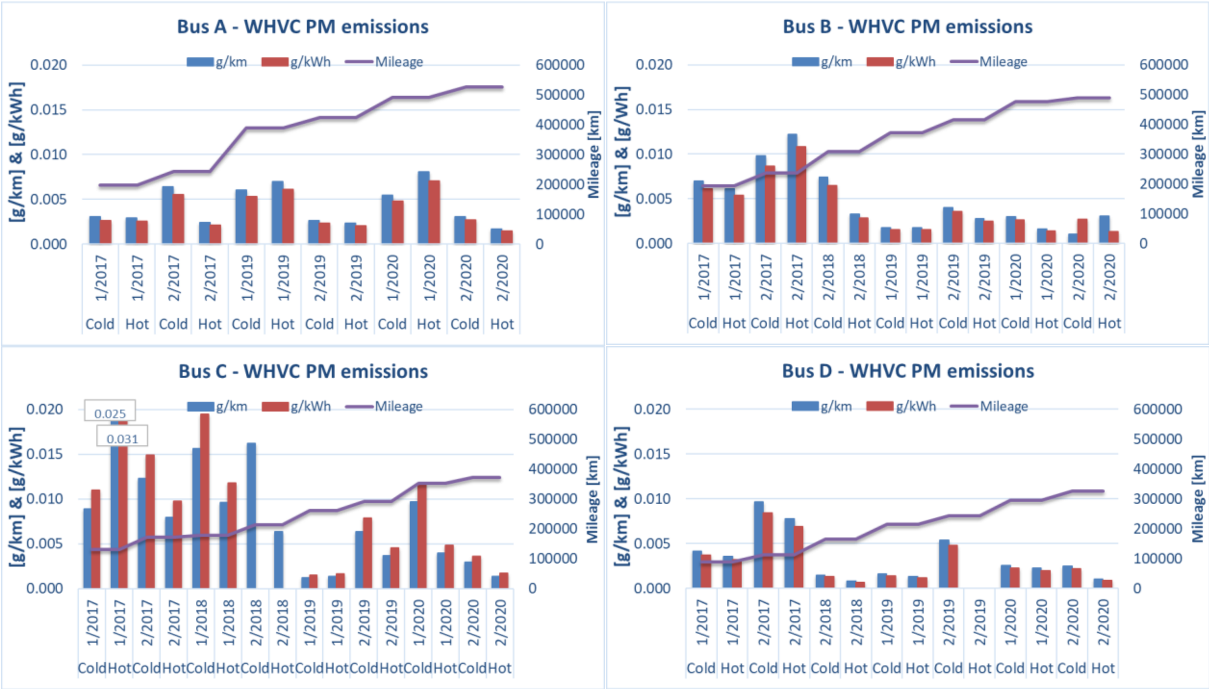

Figure 20: PM emissions on cold and hot start WHVC. Euro VI limit value on WHTC is 0.01 g/kWh.

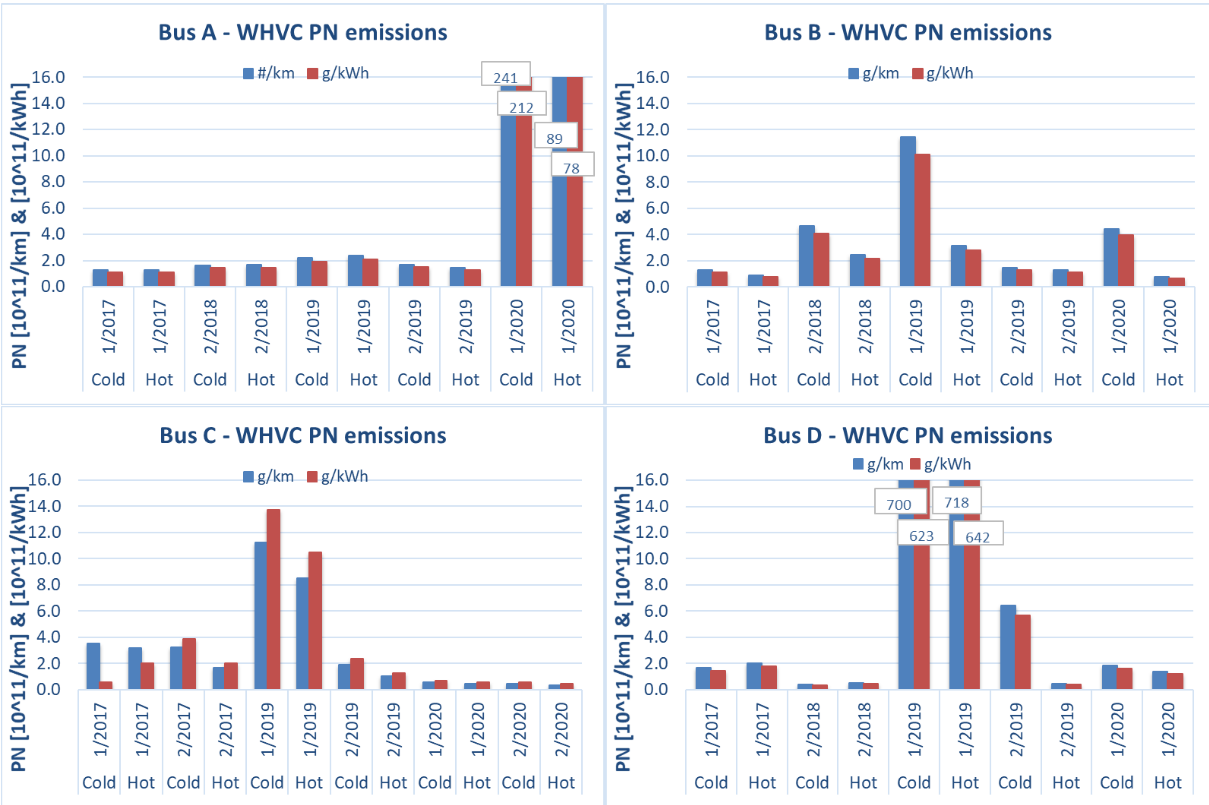

Figure 21: PN emissions on cold and hot start WHVC. Euro VI limit value on WHTC is 6x10^11/kWh.

4.1.1 Discussion

Energy consumption and CO_2 emissions

Regarding energy consumption and CO_2 emissions, there is no apparent clear trend, neither increase nor reduction (Figure 8, Figure 9, Figure 16, Figure 17). In general, buses A and B have been performing most constantly on both test cycles. However, both buses have had one (bus A) and two (Bus B) times clearly higher CO_2 emissions and energy consumption compared to average performance. Bus C have performed constantly on hot start WHVC except the tests in 2/2018 and 1/2019. On Braunschweig, it has had more deviation on performance between the test occasions. If we neglect the best and the worst results from each of the buses, they have performed quite similarly.

The interesting finding is that the active DPF regeneration that was identified during some preparation cycles before actual test sessions did have an effect mostly on NO_x emissions and in some cases also on PN emissions, but not on energy consumption and CO_2 emissions. For example, bus B had high NO_x emissions in tests 1/2017, but this did not have an effect on energy consumption. The same was observed with bus C and D in tests 1/2019.

The only exception was observed with bus B on both test cycles in 1/2020 and 2/2020, where the active regeneration was not able to completely finish during the preparation. Thus, high emissions and energy consumption was measured in actual test cycles. Especially this can be seen on Braunschweig cycle in 1/2020.

Overall, based on the results the driving mileage between 260 000 - 360 000 km during the project depending of the bus do not show increase in fuel consumption and thus change in powertrain efficiency. It should be noted that bus C had engine failure at the beginning of year 2018 and the engine was replaced with a new one. With the new engine bus C drove around 218 000 km.

NO_x, PM and PN emissions

In general, signs of deterioration of emission performance can be identified with buses A, B and D (Figure 10 and Figure 19). Buses B and D show most evident increasing trend in NO_x emissions. Bus C NO_x emissions performance has not changed during the project almost at all.

Bus A NO_x emissions show interesting trend. Between the tests 1/2017 to 2/2019 they show decreasing trend on both test cycles. However, in the two last tests (1/2020 and 2/2020) the emissions increased significantly on both test cycles. Before the tests in 2020, NO_x emissions were below 0.31 g/km in hot-start conditions on both Braunschweig and WHVC. However, at the test in January 2020 and June 2020, NO_x emissions were 1.7 g/km and 3.7 g/km on Braunschweig and 0.9 g/km and 1.0 g/km on hot-start WHVC. In engine work basis, the emissions were in the last two tests on WHVC roughly double compared to Euro VI limit value of 0.46 g/kWh. Similar trend was observed in on-road testing, as is discussed in section 4.2.1 covering the results of on-road testing.

On both test cycles, PM emissions were well below the Euro VI limit value 0.01 g/kWh (Figure 11 and Figure 20). During the tests before 2020, PN emissions were also clearly below the Euro VI limit value of 6x10^11/kWh (Figure 12 and Figure 21). In test 1/2020, PN emissions were on WHVC exceptionally high up to 35 times the limit value. The reason for high NO_x and PN emissions during measurements in 2020 was active regeneration that took place before the test cycles during the preparation phase. However, based on the energy consumption the regeneration was not active during the actual test cycles. This suggest that for some reason the engine control unit did not return right away to normal operation mode after the active regeneration was finished.

Bus B performed active regeneration during the project start test in 2017. Even though the regeneration itself was possible to finish by driving 80 km/h longer period of time (over 30 min), in couple of separate occasions the NO_x emissions did not revert to typical Euro VI level. Actually, after the testing on chassis dynamometer was over, the high NO_x emission mode continued altogether 45 days in the normal daily operations of the bus (see Figure 33). The system returned in normal condition only after the bus went into scheduled maintenance. The same phenomenon was observed with bus A in tests in 2020.

If the first tests are disregarded (probably system malfunctioning), the NO_x emissions of bus B showed slight increasing trend on Braunschweig cycle until the two last tests (1/2020 and 2/2020) in which the emissions increased clearly in comparison to previous results. On WHVC, NO_x emissions have increased steadily since the second tests in 2017. On Braunschweig cycle in 1/2020 tests, NO_x emissions were roughly 2.2 g/km and 1.2 g/kWh and in 2/2021 1.2 g/km and 0.65 g/kWh. On WHVC, there was no observed dramatic increase in NO_x emissions.

Interestingly PM emissions showed increasing trend in tests performed in 2017, but after that they have decreased on low level. PN emissions have been on a low level except the cold-start WHVC test in 1/2019.

Bus C showed most constant performance in NO_x, PM and PN emissions. However, high NO_x emissions, around 1 g/km and 1 g/kWh, occurred on both test cycles in 1/2019 tests. Energy consumption wise, high NO_x emissions did not have effect, i.e. there was no evidence that regeneration was activated.

PM emissions have actually decreased throughout the project, and have been well below the Euro VI limit value. In addition, the PN emissions have been on a low level throughout the project.

Bus D has showed steady increasing trend in NO_x emissions on both test cycles throughout the project. In project first tests 1/2017, NO_x emissions were 0.26 g/km and 0.14 g/kWh on Braunschweig cycle and 0.27 g/kWh on aggregated WHVC. In project final tests in 2020, emissions were 1.5 g/km and 0.81 g/kWh on Braunschweig and 0.62 g/kWh on aggregated WHVC. This mean around 480 % increase on Braunschweig and 130 % on WHVC.

PM emissions have showed fluctuation. However, emissions have been clearly under the Euro VI limit value. PN emissions have been mostly well under the Euro VI limit value. Only in tests in 1/2019, PN emissions were remarkably high, even above 6.0x10^13 [#/km]. The reason was probably the active regeneration that took place during the preparation cycle.

NO_x conversion efficiency and engine out NO_x emissions

Regarding the NO_x conversion efficiency of the buses A and D in Figure 13, we can see that the reason for increased NO_x emissions is the decreased NO_x conversion efficiency. Both buses had around 98 % conversion efficiency at project start.

For bus A, the reduction efficiency was as low as 58 % at the project final tests. This evidently led to high emission, as shown above. In project final tests for the bus D, the conversion efficiency was around 88 % that corresponds also well with the increased tailpipe NO_x emissions. With bus C, the conversion efficiency has stayed on similar level as in the project start, above 99 %.

Engine-out emissions have stayed rather constant with buses A, C and D. This would suggest that no major changes have occurred in combustion that would have effect on engine performance and engine-out NO_x emissions. Actually, the unchanged fuel consumption and CO_2 emissions also supports this conclusion.

In case of bus B, the comparison is rather difficult, as the bus was suffering from malfunctioning during the project start tests in 2017. It can only be said that the NO_x conversion efficiency has increased close to 95 % level in the project final test in 2020, but that is less than what bus A (same model as bus B) had at project start tests in 2017.

CO, NMHC and N_2O emissions

In general, CO and NMHC emissions have been on a low level, well below the Euro VI limit values 4.0 g/kWh for CO and 0.16 g/kWh for HC on WHTC (Figure 14). However, the behavior of bus D has been different compared to other buses. It has showed clearly higher CO emissions on cold-start WHVC in comparison to others. Even the emissions have been higher compared to other buses (up to 1 g/kWh). However, the emissions have been clearly under the Euro VI limit values.

Even though N_2O emissions are not regulated in Euro VI legislation, they have extremely high impact on GHG emissions, as the global warming potential (GWP) of N_2O is around 298 times the GWP of CO_2. Depending on the SCR chemistry and exhaust temperature there might be favorable conditions for N_2O formation in the EAT. N_2O emissions were investigated in this project during the first tests in 2017 and final tests in 2020 (Figure 15). Results show that buses A and C had 35 g/km and 56 g/km GHG equivalent N_2O emissions in project start test, but practically zero in the final tests. Bus B had practically close to zero emissions in both test occasions. Bus D had the highest GHG equivalent N_2O emissions, 94 g/km in the project first tests, and 195 g/km in project final tests. These are remarkably high emissions, if compared to actual CO_2 emissions, which were around 1370 g/km. Thus, they add from 7 % to 15 % the total CO_2 equivalent emissions.

4.2 On-road PEMS results

On-road PEMS results from three different test routes are presented in Figure 22 to Figure 32.

Figure 22 to Figure 24 show the route average CO_2, NO_x and PN emissions in grams per km and grams per kWh (engine power) basis. Accumulated mileage at the time of testing are shown with blue dashed lines in kilometers divided by 10 000, i.e. 40 means 400 000 km. Ambient temperature is shown with dashed red line.

Instantaneous NO_x emissions are shown in Figure 25 to Figure 32. Figures show the instantaneous results of each on-road test in grams per km and grams per kWh (engine basis).

In general, the NO_x emissions of each of the bus varies heavily depending on test time and route. Based on the instantaneous NO_x emissions the buses can be divided in two groups: Buses A and B and buses C and D. Buses A and B emissions change more during the driving, whereas buses C and D NO_x emissions decreases asymptotically toward bus and route specific fixed value. The main outcome from the on-road test results is actually the range in which the NO_x emissions may vary depending on the bus and operation (route etc.).

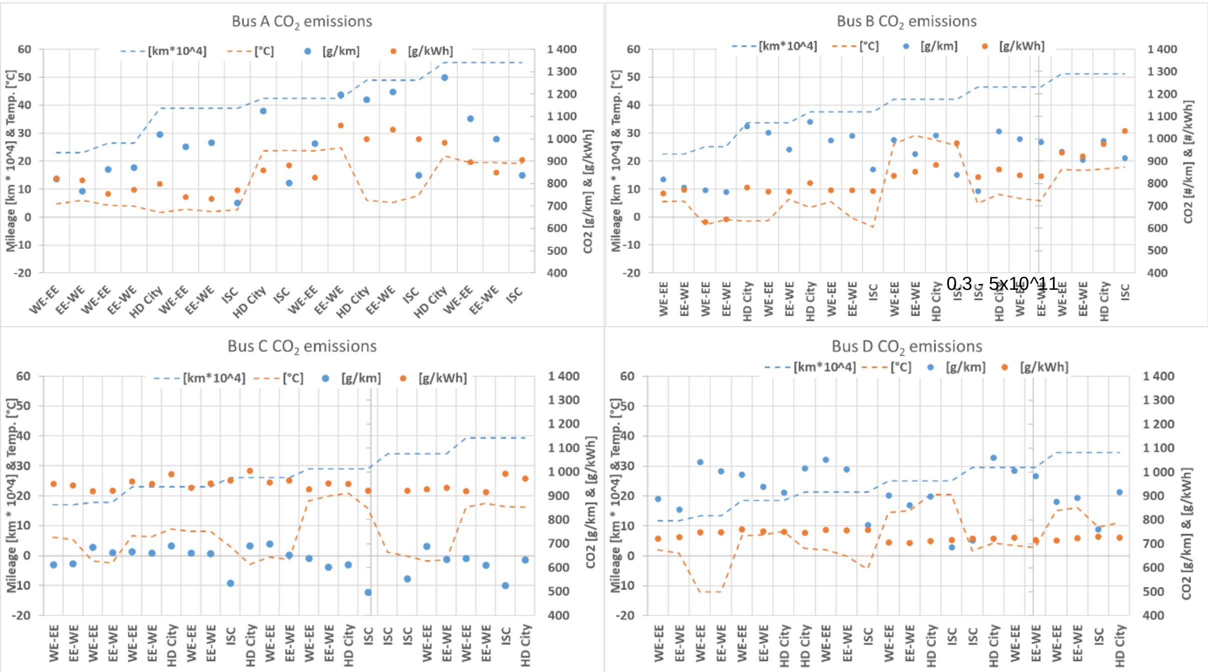

Figure 22: Route average CO2 emissions in on-road PEMS testing.

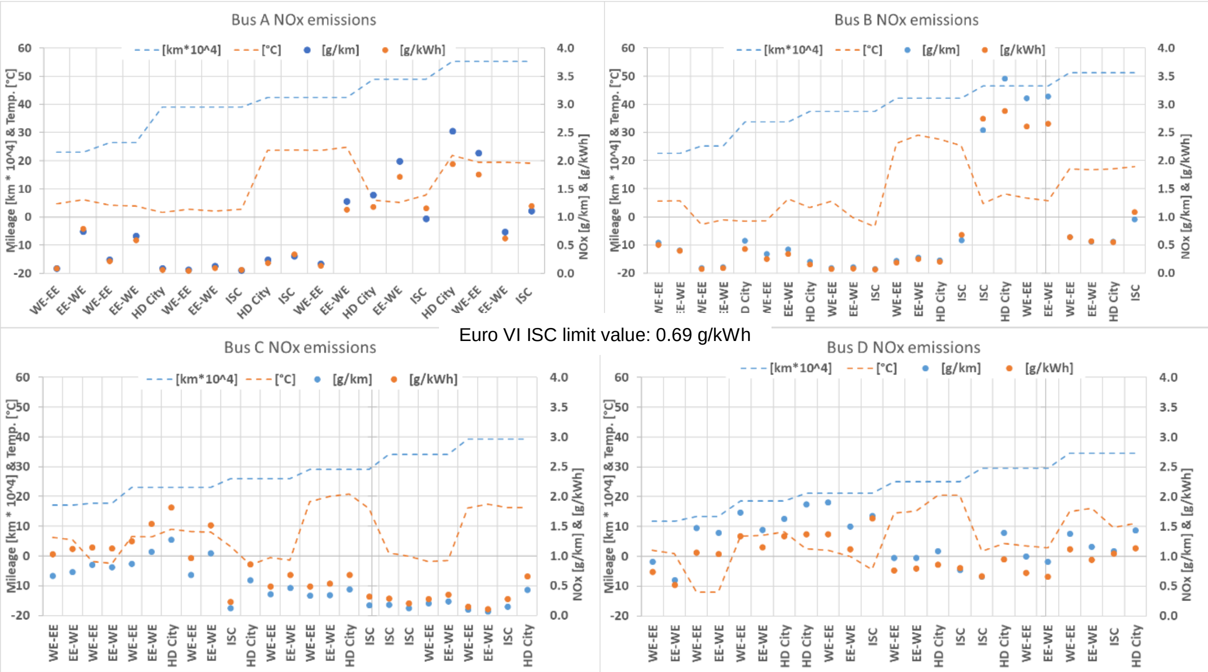

Figure 23: Route average NO_x emissions in on-road PEMS testing.

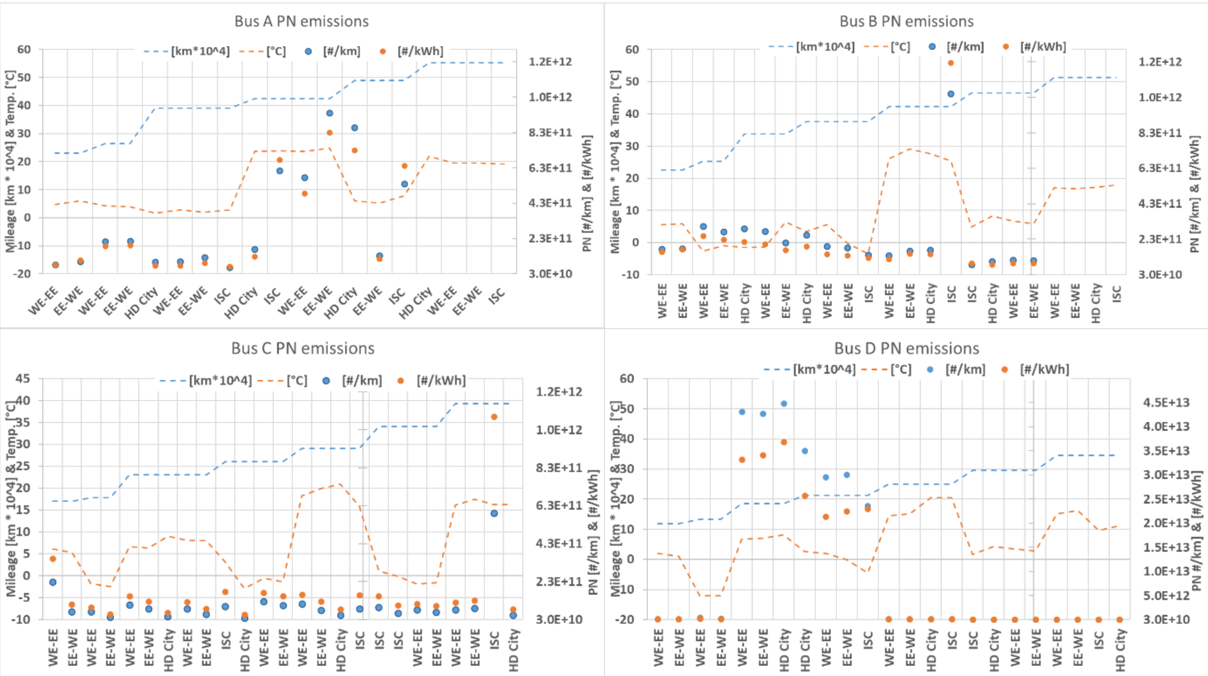

Figure 24: Route average PN emissions in on-road PEMS testing.

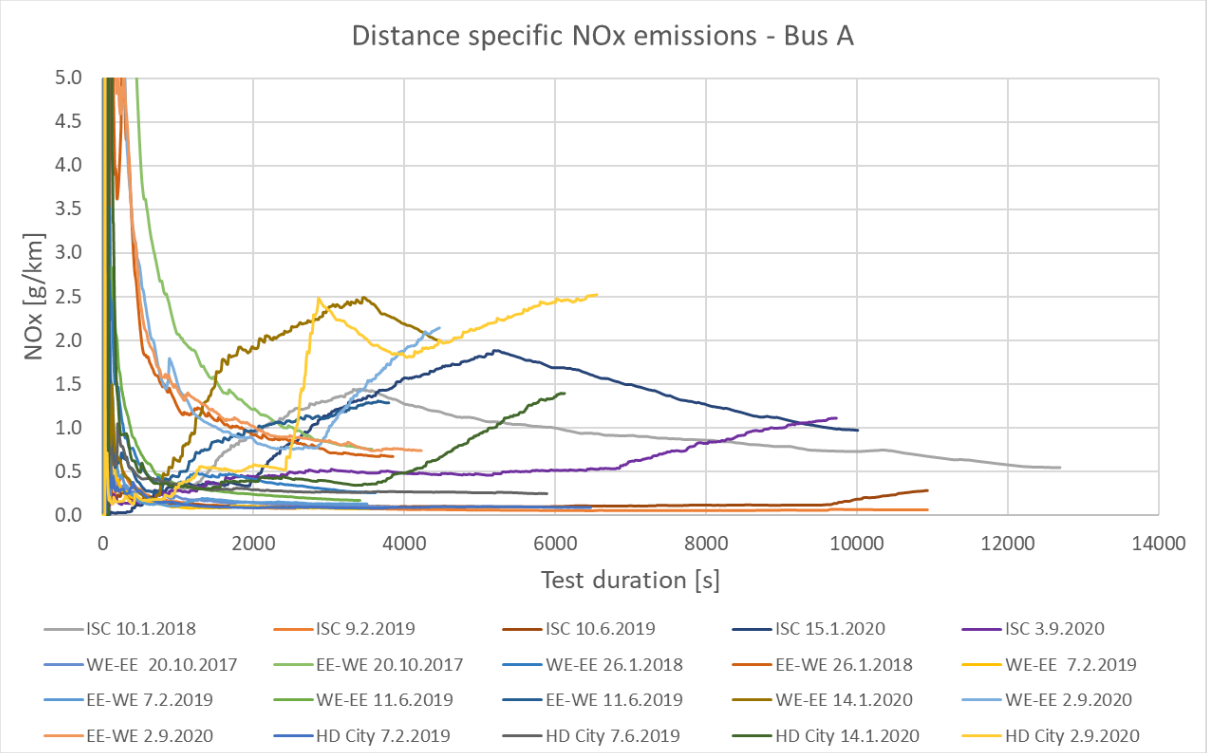

Figure 25: Instantaneous distance specific NO_x emissions for bus A.

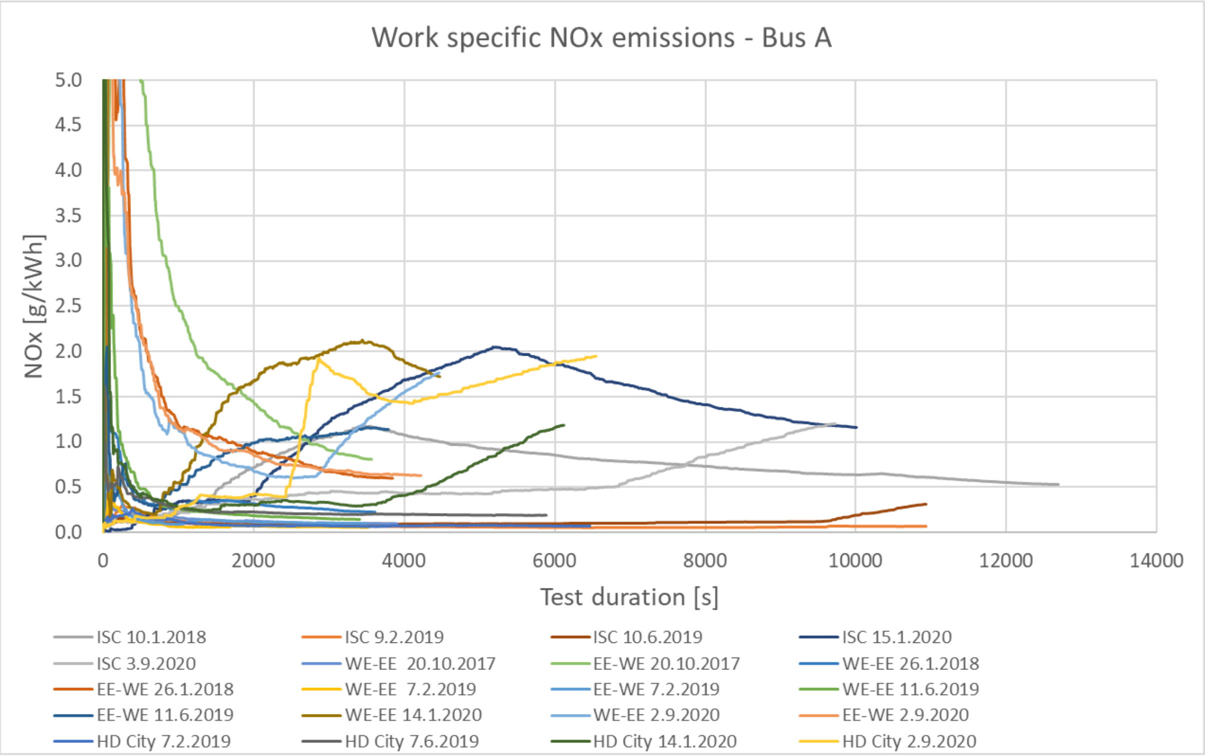

Figure 26: Instantaneous work specific NO_x emissions for bus A.

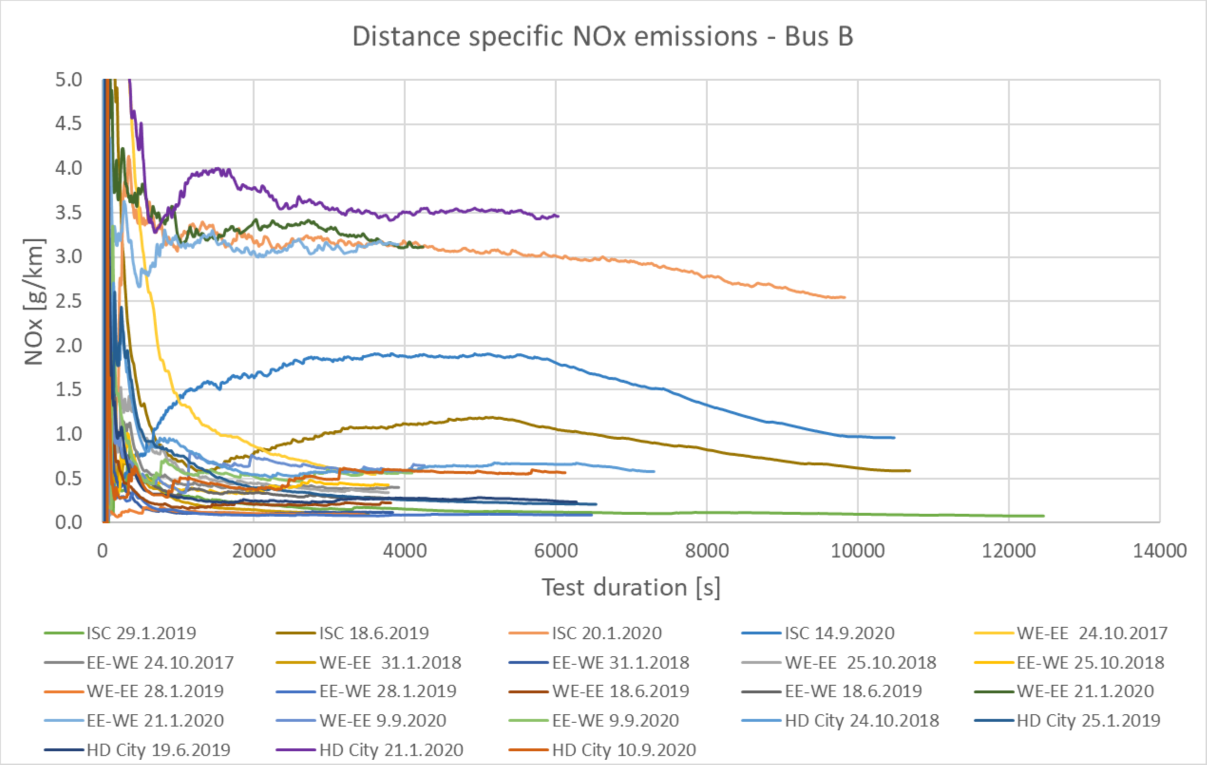

Figure 27: Instantaneous distance specific NO_x emissions for bus B.

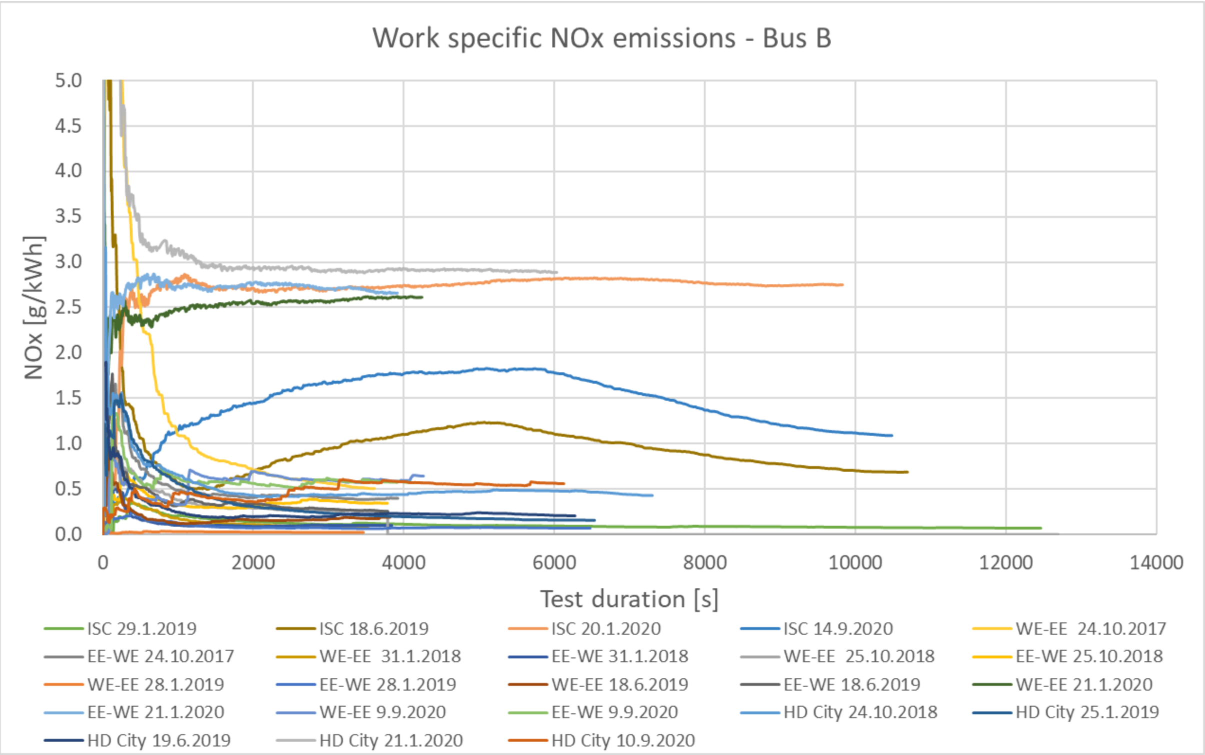

Figure 28: Instantaneous work specific NO_x emissions for bus B.

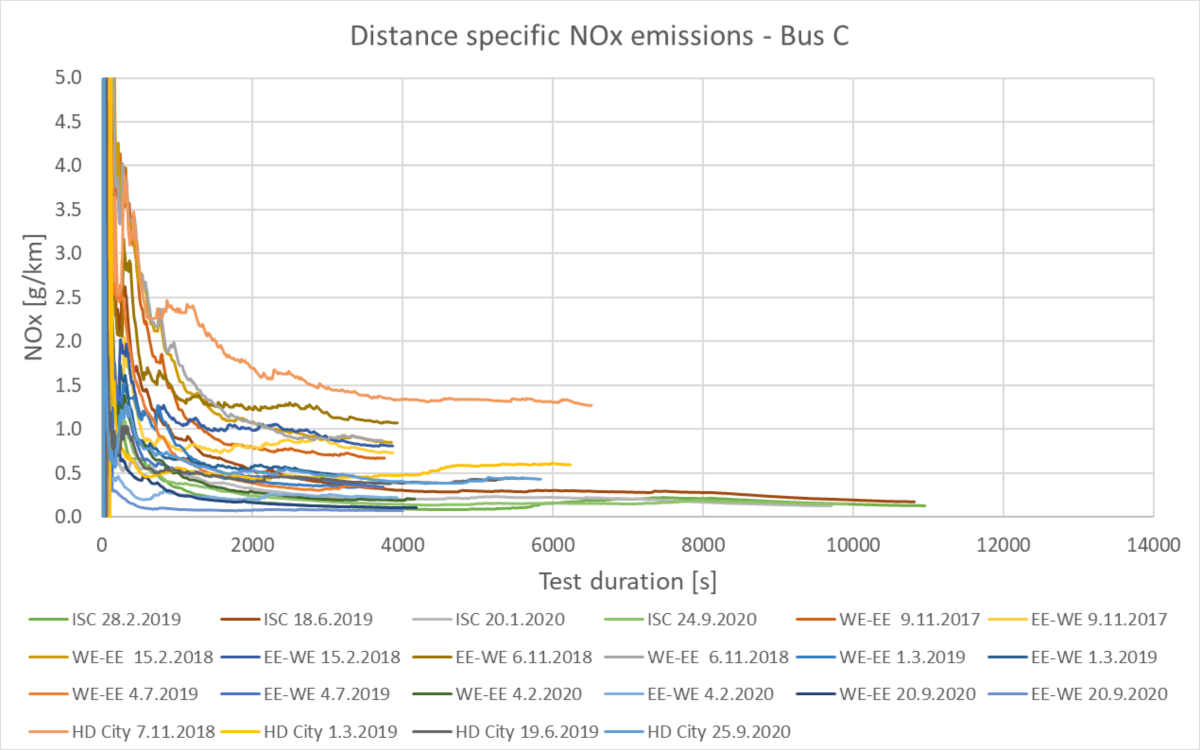

Figure 29: Instantaneous distance specific NO_x emissions for bus C.

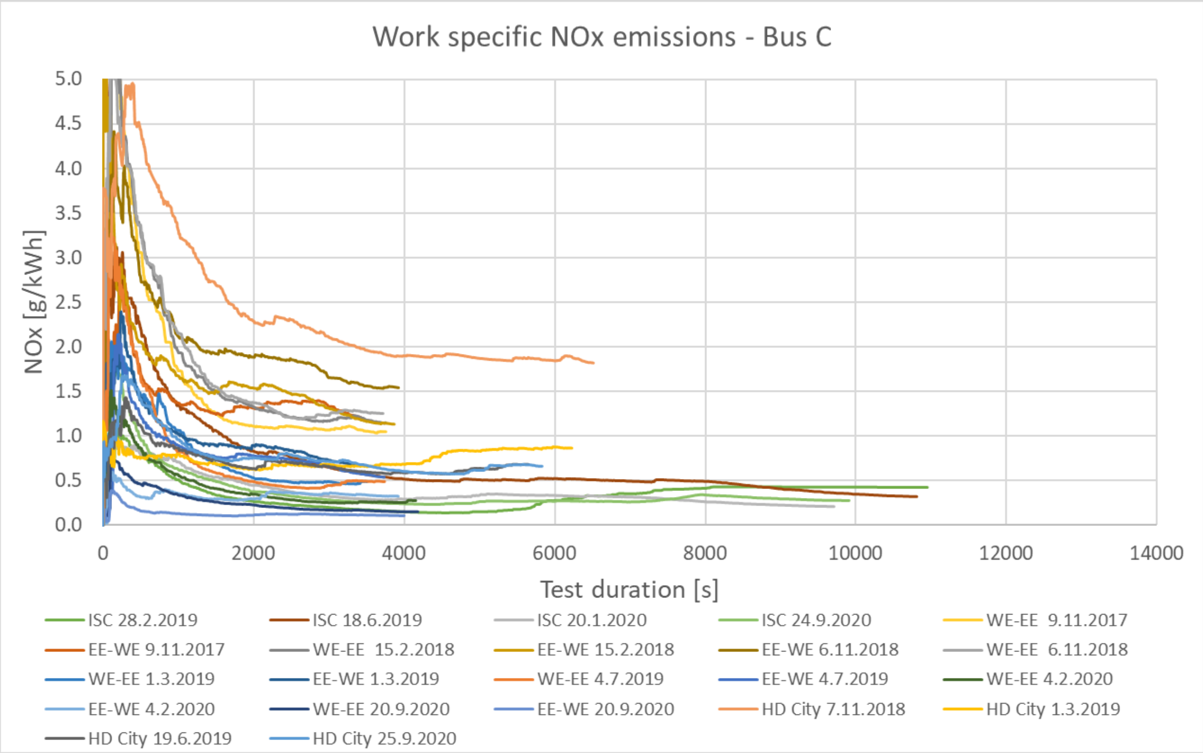

Figure 30: Instantaneous work specific NO_x emissions for bus C.

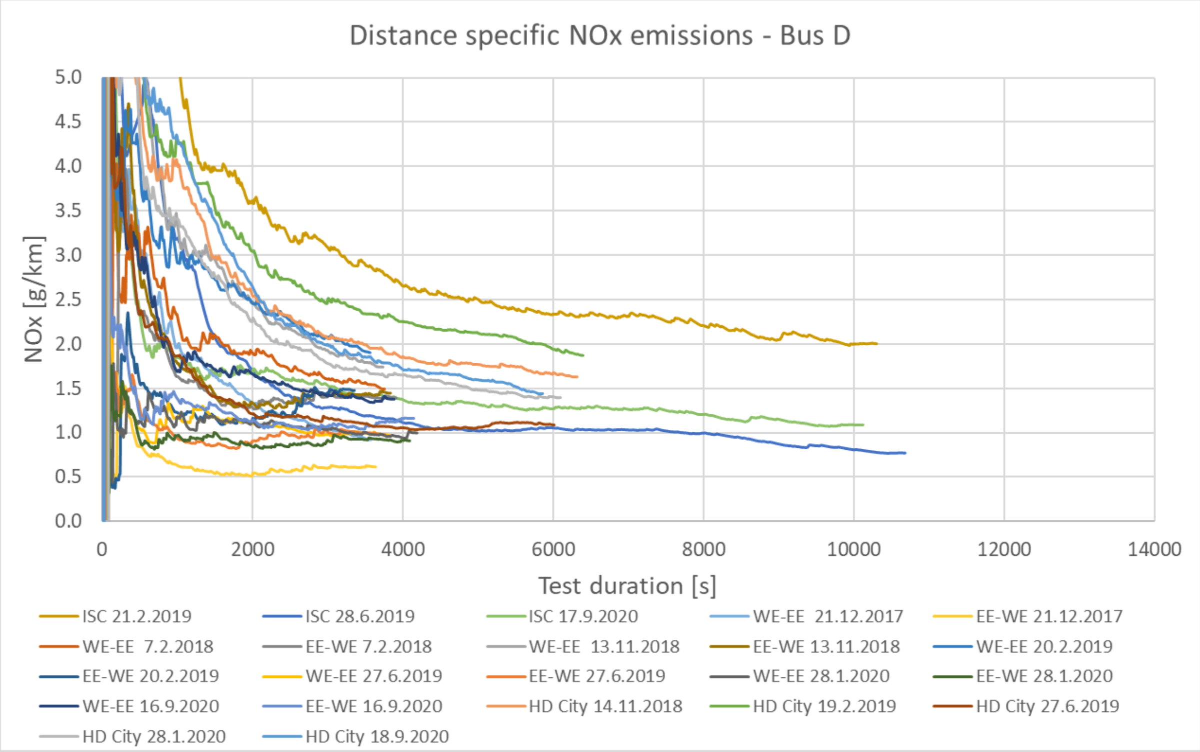

Figure 31: Instantaneous distance specific NO_x emissions for bus D

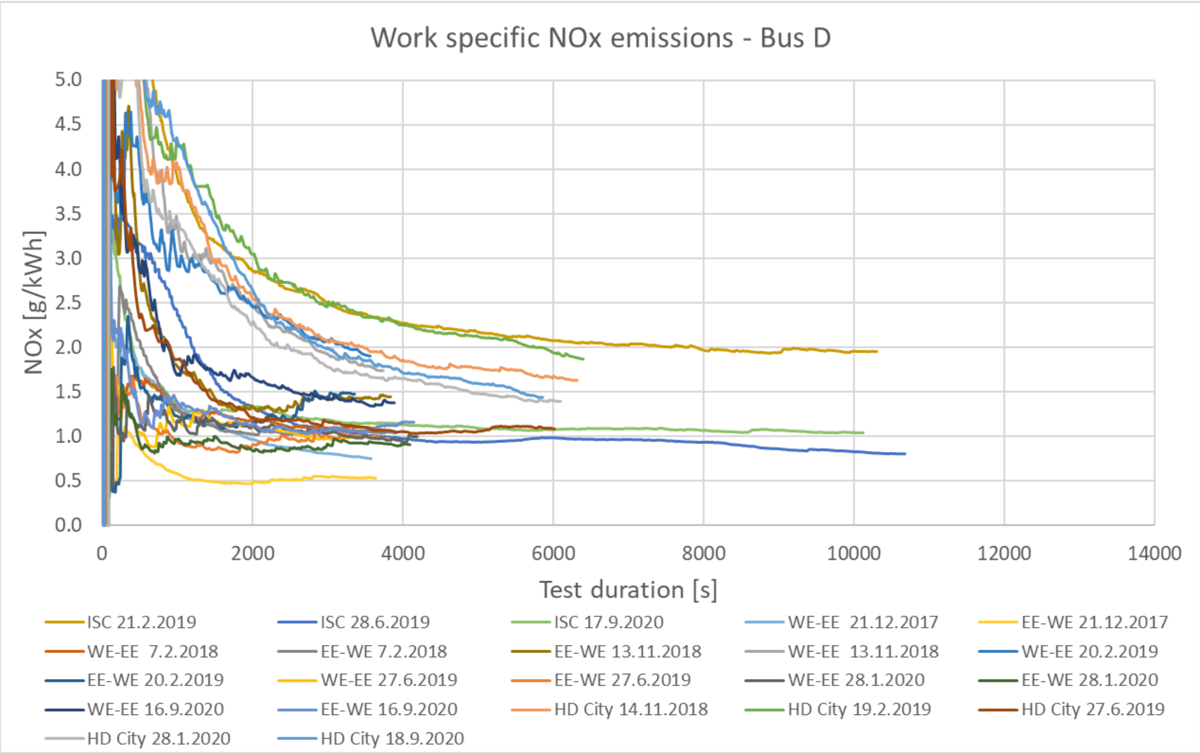

Figure 32: Instantaneous work specific NO_x emissions for bus D.

4.2.1 Discussion

As explained in the section 3.3, the Jokeri-line was affected by tramway construction work during the project. This meant that the driving arrangements on the route was changing during the project, which have of course some effect on the comparability.

CO_2 emissions

Overall, the CO_2 emissions were changing quite a lot depending on the bus (Figure 22). Bus A had the highest variation in CO_2 emissions both on kilometer and engine work basis. Bus B had almost as much variation as bus A. Buses C and D performed rather constantly throughout the project especially on engine work basis, which could indicate that the powertrain reproduced itself rather well i.e. no significant active regeneration during the testing. Regarding the effect of ambient temperature, only the bus D shows some indication for elevated CO_2 emissions. During the tests, when the ambient temperature has been close to 0 °C or below, there were also higher CO_2 emissions.

Average NO_x and PN emissions

Euro VI legislation allows 1.5 times higher NO_x emissions (0.69 g/kWh) in the in-service conformity (ISC) testing compared to engine dynamometer test WHTC (0.46 g/kWh). The latest Euro VI amendment (so called Euro VI step E) took place in 2020 and included also a limit value for the PN emissions in ISC testing. The buses within this project were type approved under the Euro VI step A and B regulation. Thus, they are not regulated with respect to PN emissions in on-road testing.

Results in Figure 23 show that buses A and B were performing well and had NO_x emissions clearly under the limit value before the tests in 2020. Similarly as in the chassis dynamometer, in 2020 the NO_x emissions increased remarkably. For bus A, NO_x emissions varied in 2020 tests between 0.63 g/kWh and 1.95 g/kWh (0.75 g/km and 2.5 g/km) depending on the test route. For bus B, NO_x emissions varied in 2020 tests between 0.57 g/kWh and 2.89 g/kWh (1.0 g/km and 3.5 g/km) depending on the test route.

In case of bus C, the NO_x emissions showed similar trend as in chassis dynamometer testing on Braunschweig. The emissions even decreased from the project start test to final test. During the test in 2017 - 2018, NO_x emissions were above 1 g/kWh (0.7 g/km) and even up to 1.8 g/kWh (1.3 g/km). However, during the tests in 2019 - 2020 NO_x emissions decreased below level of 0.7 g/kWh and were in some routes even down to 0.1 g/kWh.

Bus D showed similar trend as in chassis dynamometer testing. NO_x emissions have been increasing throughout the project. During the whole project, the emissions have been changing between 0.5 g/kWh and 1.5 g/kWh with slight increasing trend depending on the test route and time. Interestingly the lowest ambient temperature around -12 °C during the tests in 1/2018 (February) did not cause higher NO_x emissions than in tests in warmer environment afterwards.

Results in Figure 24 show that buses A, B and C had PN emissions mostly well below the type approval limit value of 6×10^{11} [#/kWh]. Bus A PN emissions varied between 4.9 to 8.3×10^{11} [#/kWh] in test 2/2019 and 1/2020. Also, the bus D had in general low PN emissions, but during the tests in 2/2018 - 1/2019 PN emissions were remarkably high, ranging from 2.1 to 3.7×10^{13} [#/kWh]. This translates to 35 to 62 times higher emissions compared to the type approval limit value of 6×10^{11} [#/kWh]. PN and NO_x emissions in those tests (2/2018-1/2019) suggest that some degree of regeneration was active during the testing, which, however, do not show that clearly in CO_2 emissions.

Time-resolved NO_x emissions in Figure 25 to Figure 32 show how each bus have performed as a function of time during the testing. The main information in the figures is the behavior and the range in which the emissions had varied. NO_x emissions are remarkably high right after the start but decreases sharply as the SCR heats up and start to reduce NO_x emissions. When functioning properly, buses A and B seem to reach low cumulative emissions (under 0.5 g/kWh) before 750 seconds. However, both of them show high variation in the performance, and during many tests, NO_x emissions start to increase, as the test continues due to active DPF regeneration or heat mode applied to EAT system. Results in 1/2020 for bus B indicate that the EAT has been malfunctioning in every on-road test route during the three-day test period. Malfunction in EAT did cause rather high emissions between 2.5 to 3.5 g/km and 2.5 to 2.9 g/kWh. As described in previous chapter, the high NO_x emissions were observed also in the chassis dynamometer testing in 1/2020. Dyno testing took place before the on-road testing.

More specifically, the results indicate that the NO_x emissions of bus A have varied between less than 0.1 g/kWh and 2.0 g/kWh (less than 0.1 g/km to 2.5 g/km). With bus B the NO_x emissions have varied between less than 0.1 g/kWh and 3.0 g/kWh (less than 0.1 g/km to 3.5 g/km).

In case of buses C and D, we can see that they have performed more consistently. However, depending on the bus the specific emission level was different. As seen in chassis dynamometer tests, bus C performs mostly well, having NO_x emissions under 0.7 g/kWh. The poor performance in tests in 2/2018 can be well seen in the time resolved results (Figure 29 and Figure 30). The NO_x emissions varied between 1.0 g/kWh and 1.8 g/kWh. Bus D performed worst of all the tested buses, as it did also in chassis dynamometer tests. Its average NO_x emission level was the highest and it took most time to stabilize the emission level to its specific level. NO_x emissions of bus D have varied between 0.5 g/kWh and 2.0 g/kWh (0.6 g/km to 2.0 g/km)

As a summary of the on-road testing, we can see that NO_x emission performance can vary significantly during normal operation, from less than 0.1 g/kWh to 3.0 g/kWh. Testing was done in routes those mimic typical HSL traffic. Because the testing was spread out over a long period of time, we can assume that those high emission results that occurred during the project were not just coincidences, but represented typical emissions behavior of Euro VI diesel buses. In addition, we can conclude that aging of the EAT system may affect differently on the bus emissions performance. For buses A and B, the NO_x emissions seem to have increased sharply after the year 2019. Higher mileage seems not to have affected yet on the NO_x emissions performance of the bus C. In case of the bus D, instead of stepwise increase in NO_x emissions, a slight continuous increase was encountered. Regarding the PN emissions, it seems that the DPF technology used in modern Euro VI diesel buses does work rather constantly, and reduce PN emissions to a low level.

4.3 On-road NO_x concentration monitoring

On-road NO_x concentration monitoring results are shown in Figure 33 to Figure 35. Results are expressed in concentration (ppm).

Figure 33 shows the development of the daily average tailpipe NO_x concentration throughout the project. In the same figure, also the ambient temperature is shown. In Figure 34, the daily average NO_x concentrations are divided into 15-ppm bins based on the occurrence, i.e. number of days the specific concentrations have occurred. Figure 35 shows the average NO_x conversion efficiency and tailpipe concentration over the whole three year period.

In total, the data gathered during the project varied between 427 days to 815 days depending on the bus. Below are the exact days for each of the bus when the data was successfully gathered:

- Bus A: 649 days
- Bus B: 427 days
- Bus C: 599 days
- Bus D: 815 days

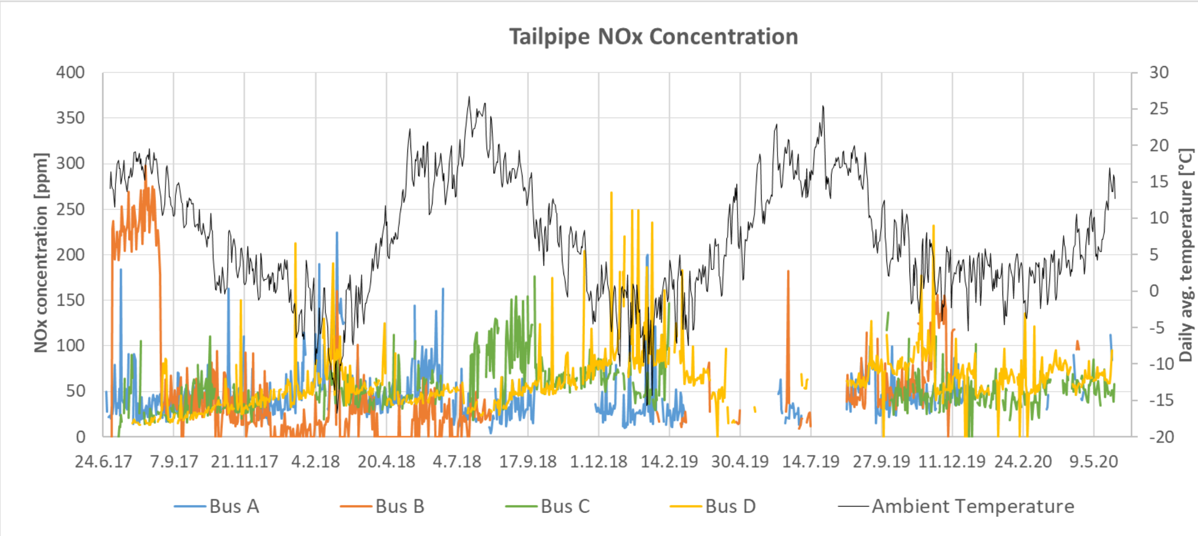

Figure 33: Average tailpipe NO_x concentration during the project.

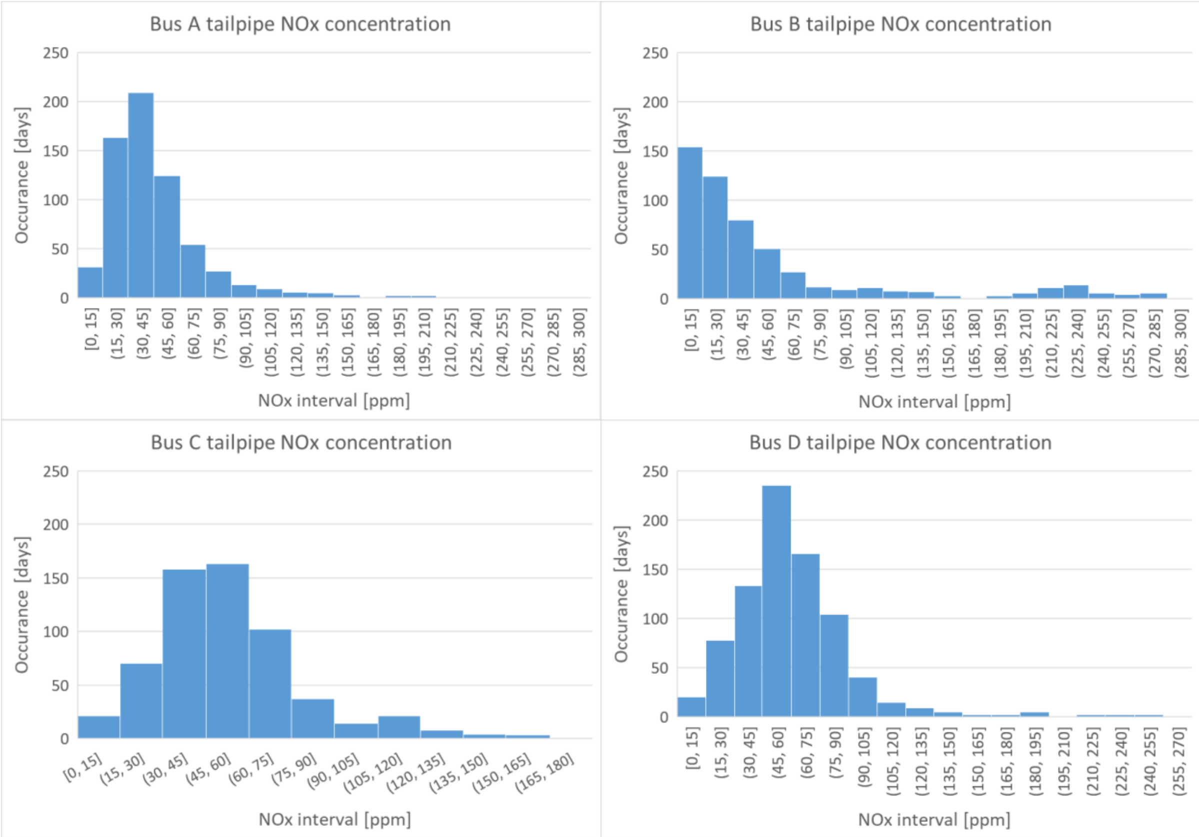

Figure 34: NO_x concentration occurrence during the project.

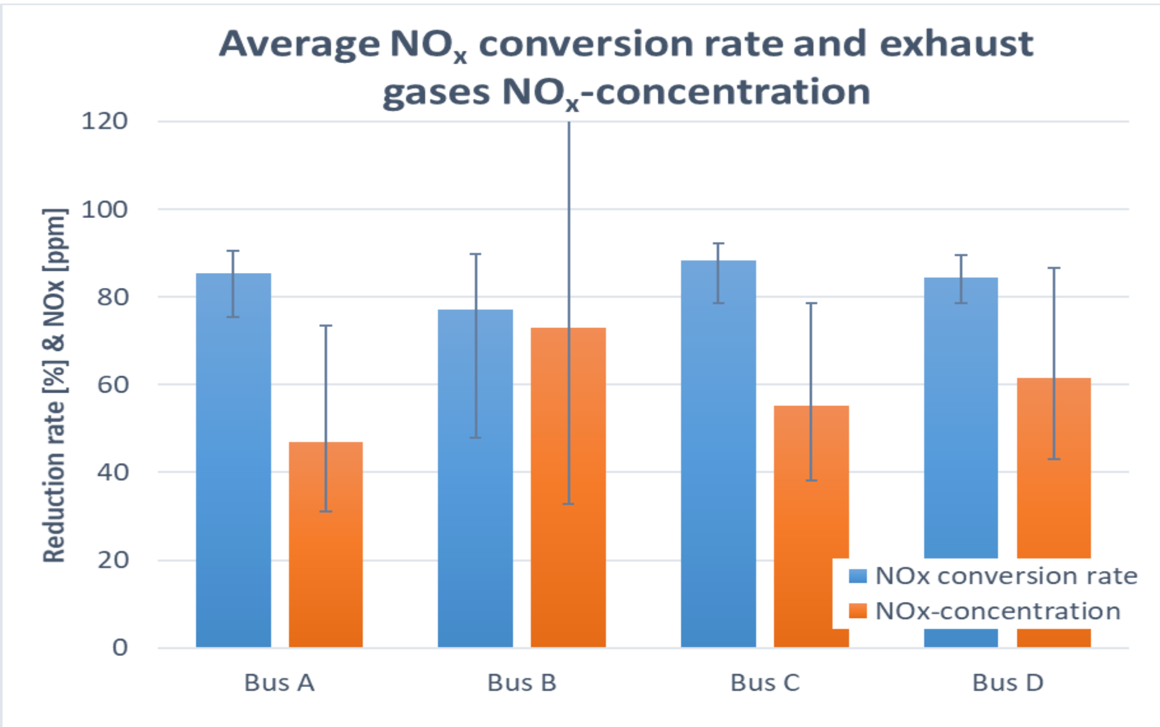

Figure 35: Average tailpipe NO_x concentration and NO_x conversion efficiency during the project. Error bars indicate the average of the values over and below the average value.

4.3.1 Discussion

During the project, challenges were faced concerning the on-road monitoring systems. Depending on the bus, the system was more or less vulnerable for malfunctioning. The most common cause for malfunctioning was crashing of the CAN-network due to a damaged pressure sensor. In the ProCare Drive system pressure and NO_x sensors are connected in the same CAN-network and if one of the sensor is damaged, the whole network crashes. Also the NO_x sensors, especially the pre-EAT, had to be renewed multiple times during the project. With buses A and B, the control unit was also replaced.

However, despite the technical problems the continuous on-road monitoring provided valuable information regarding the actual performance in day-to-day use in different ambient conditions that are impossible to capture with PEMS or chassis dynamometer testing.

Figure 36 in Appendix A shows the trip average NO_x concentrations and total exhaust gas mass flows. If we combine these results with the trip average results in Figure 23, we are able to make an estimation between the NO_x concentration and emissions in grams per kilometer. Below are shown the estimations derived as described above:

Bus A: 50 ppm correspond around 1 g/kWh
Bus B: 50 ppm correspond around 1 g/kWh
Bus C: 40 ppm correspond around 1 g/kWh
Bus D: 45 ppm correspond around 1 g/kWh

Figure 33 shows the daily average NO_x concentration for each of the bus. In general, depending on the bus we can see that the cold winter period (ambient temperature below 0 °C) increases the concentration level up to 2 - 4 times higher level compared to summer period.

We can see that the bus A has had in average NO_x concentration just below 50 ppm's, as is shown in Figure 35. By using the above presented estimation this would mean that on average bus A has had NO_x emissions slightly below 1 g/kWh during the project. Furthermore, during the winter 2017-2018, the concentration level increased up to 150 ppm that would correspond around 2-3 g/kWh NO_x emissions. From Figure 34, we can see that most of the time the concentration varied between 30 ppm to 45 ppm. Altogether, the concentration was below 60 ppm's above 530 days that corresponds around 82 % of the total time data gathered.

In case of bus B, we can see the malfunctioning lasting for 45 days in the beginning of the project. The malfunctioning did not end until the bus went into scheduled maintenance. After that, it had low emissions until the year 2019. Average concentration level was high for the bus B, because of the high level in the beginning of the project. However, as can be seen in Figure 34, NO_x concentration was mostly below 30 ppm that would correspond to NO_x emissions well below 1.0 g/kWh. Altogether, the concentration level was below 60 ppm for above 400 days that corresponds to around 95 % of total time the data was gathered.

Bus C have performed most constantly in chassis dynamometer and on-road PEMS testing. This outcome is supported also by the continuous NO_x monitoring. On average, the NO_x concentration has been around 50 ppm and there was no clear increase due to aging seen. With the presented estimation, around 50 ppm concentration would indicate above 1.0 g/kWh NO_x emissions. This would be actually contradictory with the chassis dynamometer and PEMS tests taken in years 2019-2020, as in those tests the results were at low level.

The results of bus D supports well the findings in chassis dynamometer and on-road testing. The NO_x emissions have increased continuously throughout the project. At the start of the project, the concentration level was around 30 ppm and at the end of the monitoring period concentration level was around 70 ppm. Therefore, the increase has been approx. 130 %. Based on the estimation presented above, the corresponding NO_x emissions would be 0.3 g/kWh - 0.5 g/kWh and 1.5 g/kWh - 2.0 g/kWh. The average concentration level was around

60 ppm that would correspond with slightly over 1.0 g/kWh NO_x emissions. These are well in line with the findings in chassis dynamometer and on-road testing. During the winter 2018-2019, the NO_x concentration increased up to 100 ppm and in the coldest days even up to 200 ppm. With the above presented estimation, these would correspond around 2.0 g/kWh and 4.0 - 5.0 g/kWh NO_x emissions.

As a summary, we can say that the on-road monitoring results amend and support the findings from chassis dynamometer and on-road PEMS testing. Based on the findings, it seems that the NO_x emissions evidently increase, when the ambient temperature decreases below 0 °C. In addition, the continuous monitoring supports the findings that depending on the SCR system, the aging translates in decrease of reduction performance of the SCR system on NO_x emissions.

5. Summary and conclusions

City of Helsinki, HSL, HSY, Traficom, TØI and VTT jointly funded during the years 2017-2020 a research project for diesel Euro VI buses on-road monitoring. Actual research activates was performed by VTT. The main target of the project was to investigate the effect of vehicle aging and the influence of typical Nordic weather conditions on NO_x emissions. The information gathered within the project can be utilized for example in emission inventories, development of public transport tendering schemes and development of city transport services.

Four typical diesel buses used by the HSL operators was selected for this monitoring project. Buses served throughout the project normally in the operator's fleet. Thus, no special actions were taken for the monitored buses. During the project, the buses were investigated with three types of testing: Periodic (twice a year) chassis dynamometer and on-road PEMS tests and continuous NO_x concentration monitoring. One drawback during the project period was relatively warm winters. Only in the first winter 2017 – 2018 there was a period of time when the ambient temperature dropped below 0 °C for a longer period. During following two winters, the ambient temperature in Helsinki was clearly warmer than typically.

Each of the buses were tested seven times on the chassis dynamometer on Braunschweig and WHVC cycles. Respectively, the buses were tested seven times also in on-road conditions with PEMS device in four different routes altogether close to 20 times. During the project buses were driven from 260 000 to 360 000 kilometers, depending on the bus. Data for continuous NO_x concentration monitoring was gathered 427 to 815 days, depending on the bus.

Regarding energy consumption, the chassis dynamometer tests showed that the mileage did not affect the tested Euro VI buses powertrains efficiency. Two of the buses (A and B) were driven in total over 500 000 km after the project, and showed still similar energy consumption and CO_2 emissions in the project final tests as they had in the first tests. Similar result was observed with the buses C and D. In addition, there was not seen any significant change in engine-out emissions between the project start and final measurement. On the other hand, for buses A, C and D from 2.4 % to 9.3 % reduction in engine-out NO_x emissions was measured. These findings highlight the fact that the change in tailpipe emissions is caused by the change of EAT system reduction efficiency.

Chassis dynamometer and on-road tests showed that depending on the bus the aging affect differently on tailpipe emissions. The most evident increase in NO_x emissions was observed with bus D. Its emissions increased rather constantly throughout the project. On Braunschweig from 0.14 g/kWh to 0.81 g/kWh. Respectively, on WHVC from 0.27 g/kWh to 0.62 g/kWh. In on-road tests, similar increasing trend was observed. In the project start measurements, NO_x emissions were around 0.75 g/kWh and in the final around 1.25 g/kWh. These correspond to a conformity factor between 1.35 to 2.72 in comparison to WHTC emission limit value of 0.46 g/kWh.

Buses A and B showed also clear indication of decrease in NO_x reduction efficiency. They were performing well before the last year having NO_x emissions well under 0.4 g/kWh on chassis dynamometer. However, NO_x emissions increased sharply in the two test campaigns done in 2020. Within the final tests bus A had NO_x emissions around 2.0 g/kWh on Braunschweig and 0.93 g/kWh on WHVC. Respectively, bus B had NO_x emissions around 0.65 g/kWh on Braunschweig and 0.49 g/kWh on WHVC. These correspond to a conformity factor between 1.07 to 4.35 in comparison to WHTC emission limit value of 0.46 g/kWh.

The bus C was exception. It showed no change in NO_x emissions reduction performance during the project. It produced constantly low emissions, apart from a couple of proven EAT regeneration, throughout the project both in chassis dynamometer and on-road tests.

Regarding PM, PN, CO and NMHC emissions, the Euro VI EAT systems seem to work well even after high mileage. In general, the trend in PM emissions was decreasing apart from occasionally higher PM emissions and below the Euro VI limit value. Similarly, the PN emissions were mostly well below the Euro VI limit value. However, during the active DPF regeneration mode PN emission might increase sharply even up to 100 times over the limit value. Testing showed that the DOC takes effectively care of CO and NMHC emissions, and the vehicle mileage does not affect the reduction performance.

N_2O emissions were investigated with the FTIR on chassis dynamometer during the project start and final measurements. Buses A and C showed low N_2O emissions in the first tests and slightly elevated in the final. However, as the N_2O is extremely strong greenhouse gas, the CO_2 equivalent GHG emissions can be significant. For bus B, the CO_2 equivalent GHG emissions were in the final tests around 35 g/km and for bus C around 56 g/km. Bus D emitted clearly more N_2O and the corresponding CO_2 equivalent GHG emissions were in the first test around 94 g/km and in the final around 195 g/km. The latter correspond around 15 % of direct combustion-based CO_2 emissions of the bus D.

In general, on-road testing and continuous NO_x monitoring showed that the NO_x emission reduction performance vary significantly from day-to-day. As the vehicle’s driving mileage increases the scatter increases even more. Based on the bus and the results gathered during the project the NO_x emissions may vary between close to zero and up to 3.0 g/kWh (3.5 g/km). Especially active DPF regeneration occurring time-to-time can lead to high emissions, Furthermore, the regeneration event may last for a long period, as was observed with buses A and B. This finding supports also well the results in the VTT’s city buses emission database.

Cold ambient temperature (below 0 °C) effects on the buses emission reduction performance clearly. During the on-road NO_x monitoring increase in NO_x concentration between 2 - 4 times higher level compared to summer conditions was observed.

As a summary, the project showed that the aging affects differently on buses NO_x emissions reduction performance. The reduction performance of some buses can be greatly reduced, but other’s stays the same. This indicates that even though Euro VI legislation managed to reduce emissions in actual usage, it is highly important also to monitor Euro VI vehicles emissions performance as vehicles are driven more.

References

[1] DieselNet, "Emission standards: Heavy-Duty Truck and Bus Engines." [Online]. Available: https://dieselnet.com/standards/eu/hd.php.

[2] P. Söderena, N.-O. Nylund, and R. Mäkinen, "City bus performance evaluation," 2019.

[3] P. Söderena, "Rakebus 2020 -projektin vuosiraportti," 2020.

[4] European Comission Joint Research Centre, "WELL-TO-TANK Appendix 4 - Version 4a Description , results and input data per pathway FUELS AND POWERTRAINS IN THE EUROPEAN CONTEXT," 2014.

[5] N. O. Nylund *et al.*, "Optimized usage of NExBTL renewable diesel fuel OPTIBIO," 2011.

[6] H. Aatola, M. Larmi, T. Sarjovaara, and S. Mikkonen, "Hydrotreated vegetable Oil (HVO) as a renewable diesel fuel: Trade-off between NOx, particulate emission, and fuel consumption of a heavy duty engine," *SAE Int. J. Engines*, vol. 1, no. 1, pp. 1251–1262, 2009.

[7] United States Environmental Protection Agency, "Greenhouse Gas Emissions." [Online]. Available: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

[8] United Nations Climate Change, "Global Warming Potentials (IPCC Second Assessment Report)." [Online]. Available: https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials.

[9] R.K. Pachauri and L.A. Meyer, "IPCC, 2014: Climate Change 2014: Synthesis Report.," 2014.

Appendix A

Trip average tailpipe NO_x concentration and total exhaust gas mass is presented in Figure 36

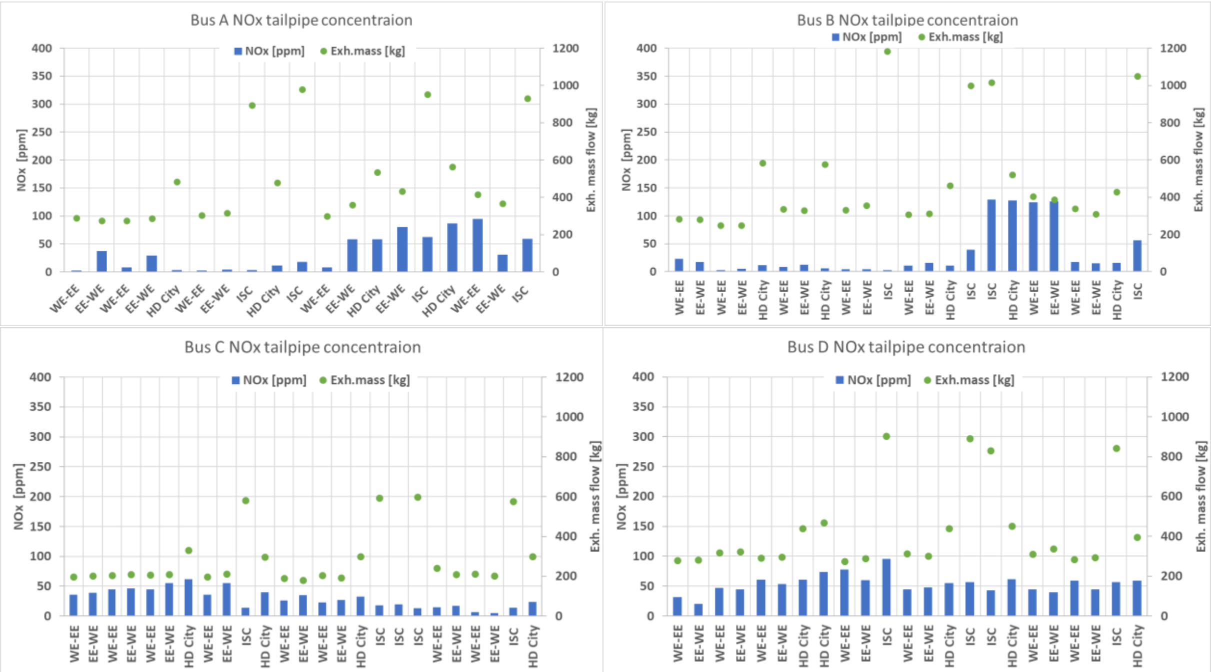

Figure 36: Trip average tailpipe NO_x concentration and total exhaust gas mass.