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An in depth analysis of post-processing methods on heavy duty Euro VI exhaust emissions

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beyond the obvious

Report's title

An in depth analysis of post-processing methods on heavy duty Euro VI exhaust emissions

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Order reference

132214

Project name

In-Use Testing of Euro VI-D/E Buses

Project number/Short name

HDB ISC

Summary

The purpose of the project was to study the true on-road emission performance of current Euro VI buses (step D) in various test conditions. The main goal of this project was to demonstrate the effect of different test routes and post-processing criteria in respect of current bus engine and emission after treatment (EAT) technologies. The emission results were analysed using the regular Euro VI step D and step E parameters and by utilizing a new Euro VII method suggested to the EU by the CLOVE consortium. Three routes were selected for the project, one Euro VI ISC compliant test route, one route representing a typical city bus trip and one route based on the CARB LLC (low load NOx test) test cycle specifically designed for this study. The outcome of all emission analyses were compared against one and other in order to determine the capability of current HD emission aftertreatment technologies and to distinguish factors that would require improvements in respect of suggested future legislative emission limits.

Despite performing relatively well within the current Euro VI ISC parameters, the greatest challenges for current HDVs were found related to SCR-systems and NOx reduction. The poorest NOx performance was found during cold starts and in low load conditions due to lack of proper SCR thermal control. Furthermore, introduction of currently unregulated gaseous emissions, N_2O and NH_3 were both found exceeding the Euro VII limits suggested by the CLOVE consortium. These results indicate that further EATS optimization and development of more efficient catalysts are needed if Euro VII is deployed. On contrary, the CO, HC and PN results suggests that current DOCs are relatively efficient in various conditions and that Euro VI DPFs are relatively effective even for reducing PN_{10} emissions.

The analysed test results indicate two main findings:

- Extending the MAW analysis to include cold starts has a relatively small effect on the average MAW-based emission results, but the deployment of 100th percentile MAW and 3x WHTC budget limit with will set high demands for future aftertreatment systems. Especially maintaining a sufficient SCR-temperature in low load conditions was found to play a significant role for further NOx-reduction.
- Current Euro VI engine technologies & EATS are generally not directly fully compatible with suggested, Euro VII emission requirements. However, the results indicate that for some components, such as CO, HC and PN10, the tested Euro VI vehicles/technology could potentially fulfil some of the CLOVE consortium suggested Euro VII emission limits.

Espoo 7.7.2022

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Contents

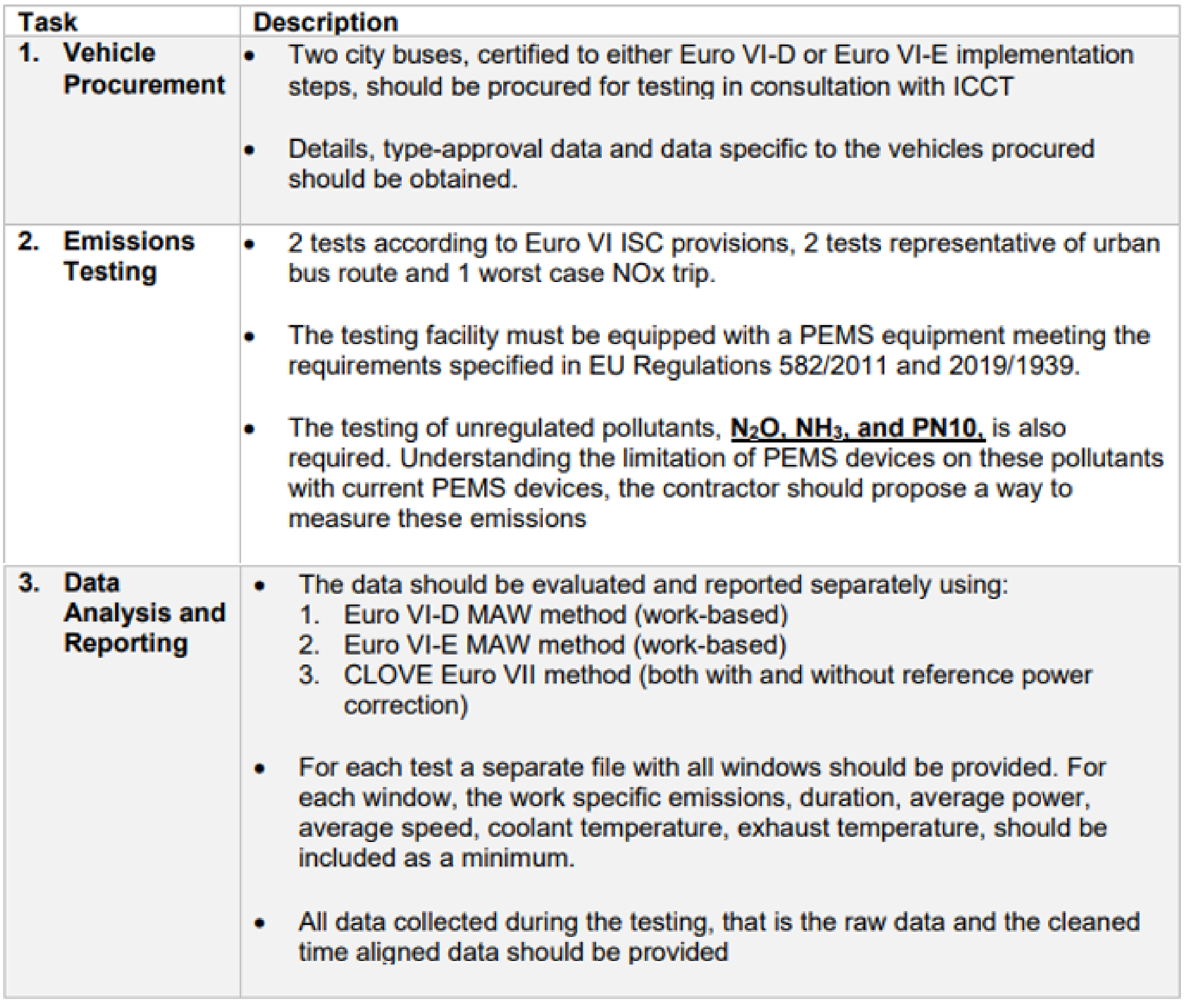
Acronyms/Abbreviations

ASC	Ammonia slip catalyst
CF	Conformity factor
CLOVE	Consortium for ultra low vehicle emissions
DOC	Diesel oxidation catalyst
EAT	Engine after treatment
EATS	Engine aftertreatment system
ECU	Engine control unit
EGR	Exhaust gas recirculation
EGT	Exhaust gas temperature
HD	Heavy duty
ISC	In service conformity
MAW	Moving average window
OBD	On-board diagnostics
OEC	Off-cycle testing
PEMS	Portable emissions measurement system
SCR	Selective catalytic reduction
WHTC	World Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle
WW	Work window

1. Project background, scope and objectives

The purpose of the project was to study the on-road emission performance of current Euro VI buses (- D or E) and to demonstrate the effect of different test routes and post-processing criteria in respect of current bus engine and emission after treatment (EAT) technologies. Furthermore, one of the main objects was to improve the understanding of how the current powertrains reflect on different emission legislation amendments and beyond that, as several scenarios of the upcoming Euro VII has already been suggested. The project was therefore set up so that the conducted tests would also cover different driving conditions outside of the current ISC regulation including scenarios that were known being challenging for the current state-of-the-art engine after treatment systems (EATS). During the project, two typical Euro VI-D city buses were studied using three different test routes. In order to improve the understanding of the possible supplementary measurements for future legislation, the measurements also covered the common non-regulated emissions, NH_3, N_2O and PN_{10}. The main elements of the project are described in Table 1-1.

Table 1-1 Project tasks and description

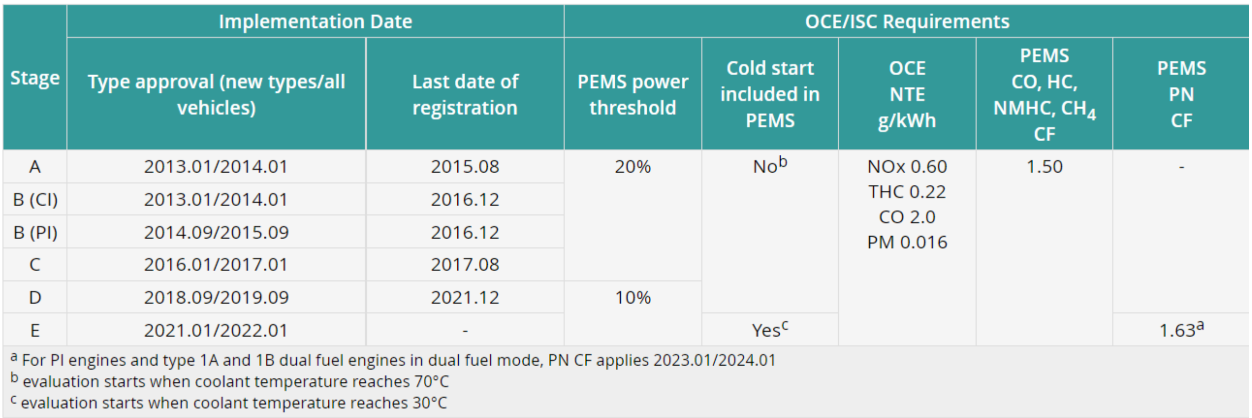


Task	**Description**
1. Vehicle Procurement	• Two city buses, certified to either Euro VI-D or Euro VI-E implementation steps, should be procured for testing in consultation with ICCT • Details, type-approval data and data specific to the vehicles procured should be obtained.
2. Emissions Testing	• 2 tests according to Euro VI ISC provisions, 2 tests representative of urban bus route and 1 worst case NOx trip. • The testing facility must be equipped with a PEMS equipment meeting the requirements specified in EU Regulations 582/2011 and 2019/1939. • The testing of unregulated pollutants, **N_2O, NH_3, and PN10,** is also required. Understanding the limitation of PEMS devices on these pollutants with current PEMS devices, the contractor should propose a way to measure these emissions
3. Data Analysis and Reporting	• The data should be evaluated and reported separately using: 1. Euro VI-D MAW method (work-based) 2. Euro VI-E MAW method (work-based) 3. CLOVE Euro VII method (both with and without reference power correction) • For each test a separate file with all windows should be provided. For each window, the work specific emissions, duration, average power, average speed, coolant temperature, exhaust temperature, should be included as a minimum. • All data collected during the testing, that is the raw data and the cleaned time aligned data should be provided

2. Current ISC protocol and evolution of future emission standards

Current heavy duty engines are type- approved by engine tests in both steady state and transient conditions. The current regulation (Euro VI) requires the the engine manufacturers to fulfill the type- approved emissions also in off-cycle conditions (OCE). The OCE emission testing includes so called in-service conformity (ISC) testing on real drive environments. The ISC tests are conducted on road using a portable emission measurement system (PEMS) device, that is installed temporarily to the test vehicle, thus enabling emission measurements in actual on road conditions. The latest stage of the ISC prodedure (Euro VI step E) has been effective for vehicles type-approved as Euro VI since 2021, and the procedure has been developed throughout the existense of the Euro VI regulation since 2013. The most significant differences between these stages are basically a stricter post-processing methods, meaning that the engine manufacturers have had the need to comply with these changes accordingly. The most significant changes throughout the regulation development has been inclusion of cold start emissions, lowered PEMS power threshold and addition of PN measurements. A more extensive description of the different stages are desctribed in Table 2-1. In the Euro VI ISC step D stage, the following emission components are measured: CO_2, CO, HC (HC + NMHC, CH_4). Later, a separate PN_{23} limit was set for the Euro VI Step E ISC protocol (*Table 2-2*). As the heavy duty engines are origianlly type-approved in an engine dynamometer environment using two specific engine test cycles, a steady state test, world harmonized stationaly cycle (WHSC) and a corresponding transient test cycle, world harmonized test cycle (WHTC), no chassis dynamometer tests are required. Nevertheless, the ISC PEMS test procedure was implemented for Euro VI in order to test the emissions performance on a complete chassis with corresponding limits for the the exhaust emissions allowed to exceed the WHTC limits with a conformity factor defined in the EU regulation (Table 2-1). The conformity factors were deployed in order to enable a conformity boundary covering the uncertainties affected by the on road PEMS measurements. Furthermore, the exhaust emissions in an ISC test are not allowed to exeeded the limits for the 90 percentile of the test cycle. As the dynamometer tests are described as work specific emissions (g/kWh), the relation between the ISC results are analyzed as WHTC-bound work or CO_2- windows monitored using the ECU data acquired from the vehicle OBD. Currently in an ISC test, a vehicle must perform work atleast of an equivalent of 4 times the work performed in the type approval test using the WHTC cycle, but not exceed an equivalent of 8 x WHTC work. The engine work is then divided into work or CO_2 based windows (moving average windows, MAW), that include the average emissions for each window fulfilled.

Table 2-1 The different OEC/ISC stages throughout the existence of the Euro VI regulation[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[b]	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	2021.01/2022.01	-		Yes[c]			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
[b] evaluation starts when coolant temperature reaches 70°C
[c] evaluation starts when coolant temperature reaches 30°C

Table 2-2 The emission limits for EURO VI regulation in engine testing (WHTC) and for the ISC tests

Stage	Date	Test	CO	NMHC	CH4a	NOx	PMb	PN
			g/kWh					1/kWh
Euro VI	2013.01	WHTC	4	0.16	0.5	0.46	0.01	6.00E+11
Euro VI	2018.09	ISC D*	6	0.24	0.75	0.69	▨	▨
Euro VI	2021.01	ISC E**	6	0.24	0.75	0.69	▨	9.78E+11

*evaluation starts when coolant temperature reaches 70°C

**evaluation starts when coolant temperature reaches 30°C

As the EU commission is still developing the limits for regulatory emissions, further extensions are expected to take effect latest by the time Euro VII is introduced. The exact limits and requirements are yet to be announced, but enlightened suggestions regarding the amendments have been widely been discussed all over Europe. The CLOVE consortium (*Consortium for ultra Low Vehicle Emissions*) consisting of several European research facilities (VTT among is among other partners[2]), has been collaborating with the EU commission to provide with recommendations regarding Euro VII regulation. The CLOVE consortium has been suggesting some possible Euro VII scenarios that are based on scientific proof[3]. This proposal include that new, currently unregulated, emission components should be introduced: N_2O, NH_3 and substituting PN_{23} with a PN_{10} limit. Furthermore, even stricter limits for the existing emissions are to be launched together with even stringent qualification of the post-processing data. This would possibly also include a scenario where all measured work windows in the MAW method would be accounted for and incorporated in the result post-processing, hence including cold start emissions beginning from the moment the engine is initially started. Also, the CLOVE Euro VII proposal contains a suggestion that a minimum work would no longer be required over the test trip to fulfil the test parameter/criteria (Euro VI has a minimum work requirement of 4x WHTC work). Instead, the analytical method would be divided based on the total engine work over the test trip with the criteria 3x WHTC work. A tests settling below the 3x WHTC criteria would be evaluated with a separate emission budget limit (g/test) together with a 100th percentile MAW limit of all MAWs over the compete test, meanwhile tests exceeding 3x WHTC work would be evaluated with a 100th percentile limit of all MAWs and a 90th percentile limit for the hot MAWs (Table 2-3). It should be noted that the suggestion assumes that the evaluation of hot MAWs start after 1x WHTC work is reached. The assessment of low load tests would be analysed by deploying a reference power correction for those MAWs that fall below 0.1 x P rated (Table 2-4). The latest suggested CLOVE Euro VII emission limits are shown in Table 2-5 (supplemented in 26.4.2021[4]) and the changes in test condition parameters are show in Table 2-6. The two primary HDV technology scenarios studied by the CLOVE consortium are: HD2 (optimised diesel with cc SRC) and HD3 (optimised diesel with cc SCR and pre heating of EATS), hence separate limits have been suggested in respect of their achievable emission performance.

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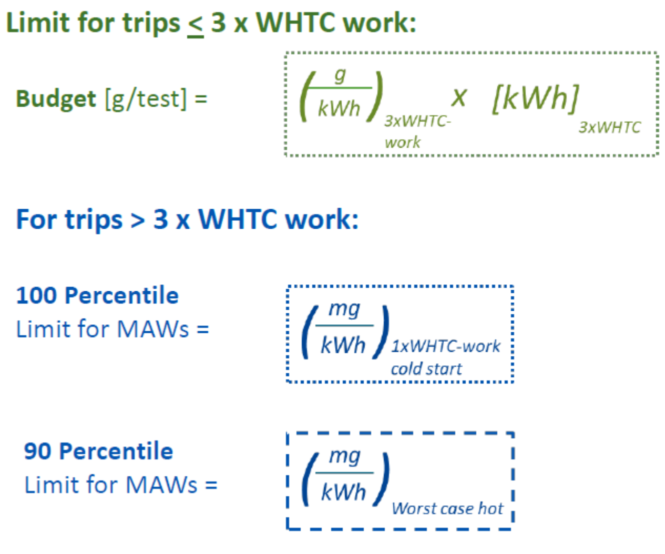
[1] www.dieselnet.com/standards/eu/hd.php
[2] CLOVE consortium partners: LAT, Emisia, FEV, Ricardo, TNO, TU Graz and VTT
[3] Scenarios for HDVsSummary Emission Limits and Test Conditions
https://circabc.europa.eu/sd/a/b706ffba-f863-4d23-809d-20d9f18ecba4/AGVE
[4] Supplements to the Scenarios for HDVs Emission Limits and Test Conditions
https://circabc.europa.eu/w/browse/f57c2059-ef63-4baf-b793-015e46f70421

Table 2-3 The limit values determining the analysis method based on total trip work



Limit for trips ≤ 3 x WHTC work:

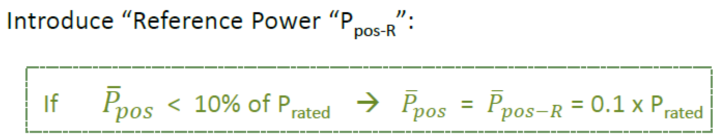
Budget [g/test] = $\left(\frac{g}{kWh}\right)_{3xWHTC\text{-}work} \; x \; [kWh]_{3xWHTC}$

For trips > 3 x WHTC work:

100 Percentile
Limit for MAWs = $\left(\frac{mg}{kWh}\right)_{1xWHTC\text{-}work\ cold\ start}$

90 Percentile
Limit for MAWs = $\left(\frac{mg}{kWh}\right)_{Worst\ case\ hot}$

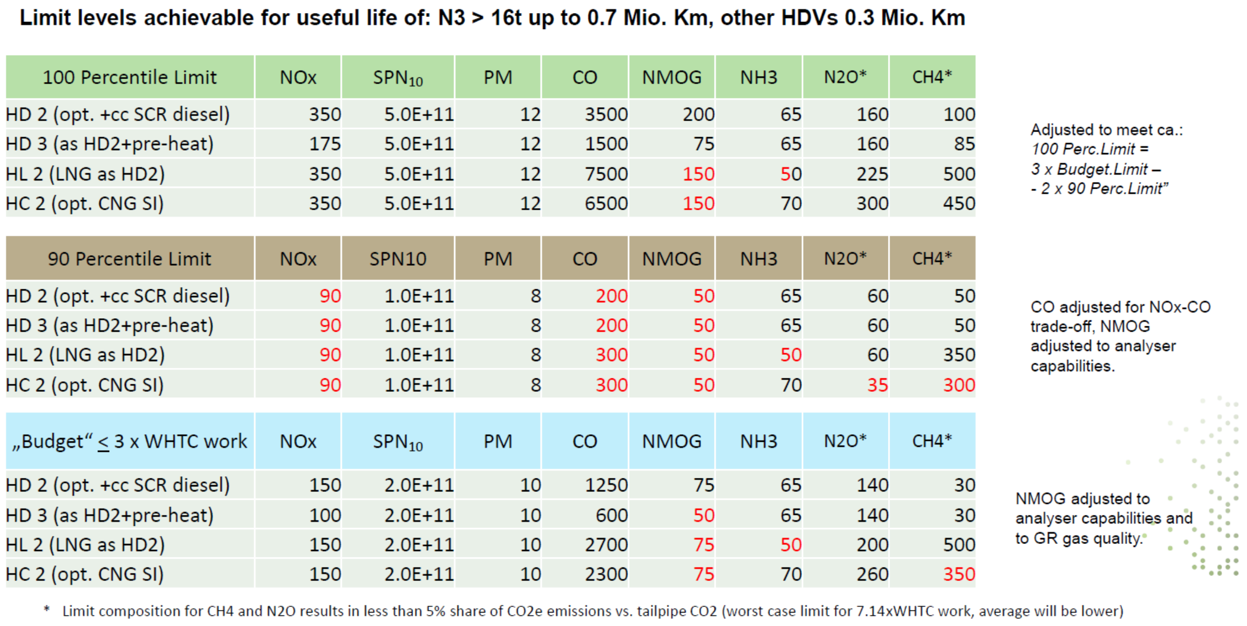
Table 2-4 Implementation of reference power correction suggested for Euro VII by CLOVE[4]



Introduce “Reference Power “$P_{pos\text{-}R}$”:

If $\bar{P}_{pos} <$ 10% of P_{rated} → $\bar{P}_{pos} = \bar{P}_{pos-R} = 0.1 \text{ x } P_{rated}$

Table 2-5 An overview of the emission limits (expressed in mg/kWh) for Euro VII suggested by the CLOVE consortium depending on test condition (Engine work criteria < 3x WHVC <)[4]



Limit levels achievable for useful life of: N3 > 16t up to 0.7 Mio. Km, other HDVs 0.3 Mio. Km

100 Percentile Limit	NOx	SPN_{10}	PM	CO	NMOG	NH3	N2O*	CH4*
HD 2 (opt. +cc SCR diesel)	350	5.0E+11	12	3500	200	65	160	100
HD 3 (as HD2+pre-heat)	175	5.0E+11	12	1500	75	65	160	85
HL 2 (LNG as HD2)	350	5.0E+11	12	7500	150	50	225	500
HC 2 (opt. CNG SI)	350	5.0E+11	12	6500	150	70	300	450

Adjusted to meet ca.:
100 Perc.Limit =
3 x Budget.Limit –
- 2 x 90 Perc.Limit”

90 Percentile Limit	NOx	SPN10	PM	CO	NMOG	NH3	N2O*	CH4*
HD 2 (opt. +cc SCR diesel)	90	1.0E+11	8	200	50	65	60	50
HD 3 (as HD2+pre-heat)	90	1.0E+11	8	200	50	65	60	50
HL 2 (LNG as HD2)	90	1.0E+11	8	300	50	50	60	350
HC 2 (opt. CNG SI)	90	1.0E+11	8	300	50	70	35	300

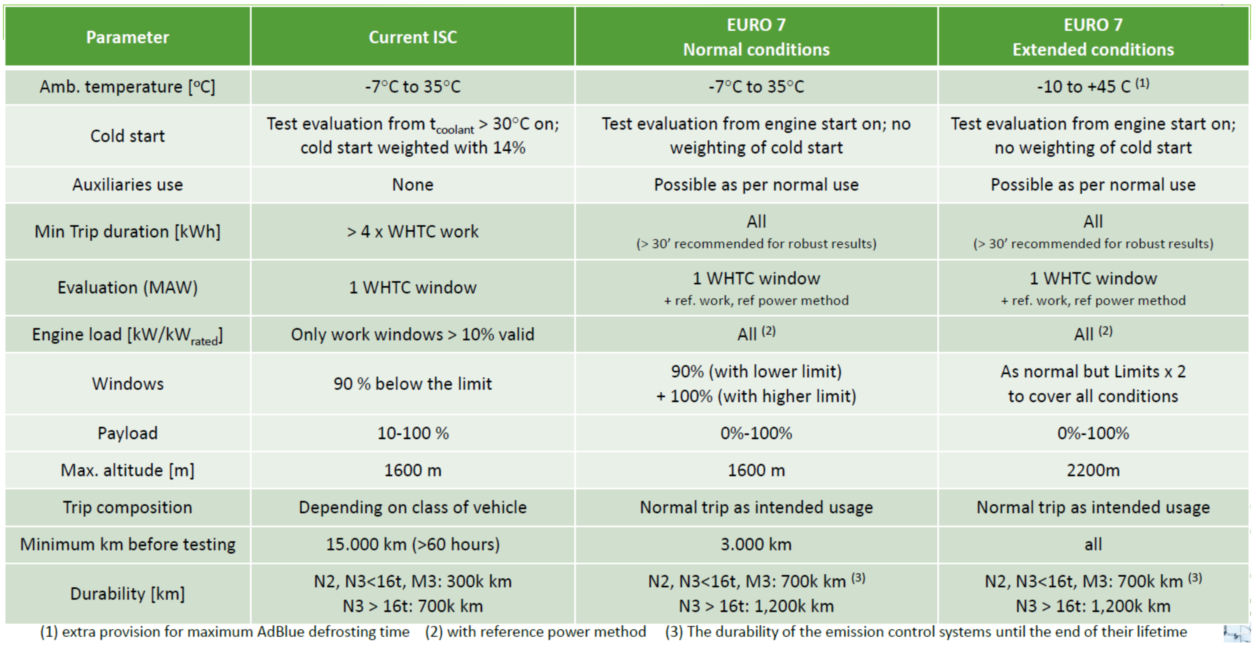
CO adjusted for NOx-CO trade-off, NMOG adjusted to analyser capabilities.

„Budget“ ≤ 3 x WHTC work	NOx	SPN_{10}	PM	CO	NMOG	NH3	N2O*	CH4*
HD 2 (opt. +cc SCR diesel)	150	2.0E+11	10	1250	75	65	140	30
HD 3 (as HD2+pre-heat)	100	2.0E+11	10	600	50	65	140	30
HL 2 (LNG as HD2)	150	2.0E+11	10	2700	75	50	200	500
HC 2 (opt. CNG SI)	150	2.0E+11	10	2300	75	70	260	350

NMOG adjusted to analyser capabilities and to GR gas quality.

* Limit composition for CH4 and N2O results in less than 5% share of CO2e emissions vs. tailpipe CO2 (worst case limit for 7.14xWHTC work, average will be lower)

Table 2-6 Testing conditions of the suggested Euro VII ISC tests compared to current regulation[4]



Parameter	Current ISC	EURO 7 Normal conditions	EURO 7 Extended conditions
Amb. temperature [ºC]	-7°C to 35°C	-7°C to 35°C	-10 to +45 C (1)
Cold start	Test evaluation from $t_{coolant}$ > 30°C on; cold start weighted with 14%	Test evaluation from engine start on; no weighting of cold start	Test evaluation from engine start on; no weighting of cold start
Auxiliaries use	None	Possible as per normal use	Possible as per normal use
Min Trip duration [kWh]	> 4 x WHTC work	All (> 30' recommended for robust results)	All (> 30' recommended for robust results)
Evaluation (MAW)	1 WHTC window	1 WHTC window + ref. work, ref power method	1 WHTC window + ref. work, ref power method
Engine load [kW/kW_{rated}]	Only work windows > 10% valid	All (2)	All (2)
Windows	90 % below the limit	90% (with lower limit) + 100% (with higher limit)	As normal but Limits x 2 to cover all conditions
Payload	10-100 %	0%-100%	0%-100%
Max. altitude [m]	1600 m	1600 m	2200m
Trip composition	Depending on class of vehicle	Normal trip as intended usage	Normal trip as intended usage
Minimum km before testing	15.000 km (>60 hours)	3.000 km	all
Durability [km]	N2, N3<16t, M3: 300k km N3 > 16t: 700k km	N2, N3<16t, M3: 700k km (3) N3 > 16t: 1,200k km	N2, N3<16t, M3: 700k km (3) N3 > 16t: 1,200k km

(1) extra provision for maximum AdBlue defrosting time (2) with reference power method (3) The durability of the emission control systems until the end of their lifetime

3. Project methodology

3.1 Project execution

The projects tests were executed using two heavy-duty city buses operating in the Helsinki region. Both individuals were type-approved according to the Euro VI step D regulation. In order to cover all necessary emission components targeted in the study, the vehicles were equipped with a standard, commercial PEMS device combined with a laboratory-grade CPC10 PN measurement device and a FTIR-gas analyser. The FTIR was used for monitoring N_2O, NH_3 and hydrocarbon emissions. The test load for both vehicles was kept as low as possible, as the most challenging conditions were tried be imitated for best distinguishability of emission causing factors. Especially low load conditions are typically challenging for vehicles EATS, as the thermal management and catalyst light off properties play a vital role in emission reduction.

3.1.1 Test matrix and test cycles

The project included testing of the two selected vehicles using three different test routes. The routes were chosen so that they would cover a wide range of typical driving conditions within and outside of the requirements defined in the ISC regulation. The test routes were requested by the ICCT following

- 2 ISC tests, compliant with EU Regulations 2011/582, 2016/1718 including PN measurement and cold-start 2019/1939 provisions.

- 2 urban bus route tests, these tests shall aim to replicate the typical city bus application, including frequent stops with adequate duration, in rush hour traffic, and with a representative distance and duration.

- Low load NOx test: The test route shall be designed based on the California Air Resources Board (CARB) low load cycle.

Based on these criteria, VTT implemented both new and existing test routes to fulfil the route requirements. VTT has long experience regarding city bus testing, hence a city bus (VTT HD-City) and an ISC route has been created at the time when VTT procured their PEMS unit. However, the low load NO_x test based on the CARB LLC test cycle[5] was separately created solely for this project. The low load NO_x test was developed using the central parameters from the LLC test cycle, implementing these values for creating a real world route. The central parameters of the VTT high NO_x cycle compared to CARB LLC test parameters are shown in Table 3-1. Examples of measured GPS- and speed data for each cycle are shown in Figure 3-1, Figure 3-2 and Figure 3-3. To ensure a high repeatability by preventing bystanders to board the vehicle during the performed tests, the doors were kept shut in all conditions when visiting bus stops.

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[5] www.dieselnet.com

Table 3-1 Main specifications of CARB LLC and VTT low load NOx test cycle

LLC driving cycle	**CARB LLC**	**VTT low load NOx test**
Total distance (km)	25.3	30.0
Time (s)	5505	5860
Idle time (s)	2171	2290
Average speed (km/h)	16.53	18.40
Average driving speed (km/h)	27.29	30.2
Maximum speed (km/h)	82.8	82.3

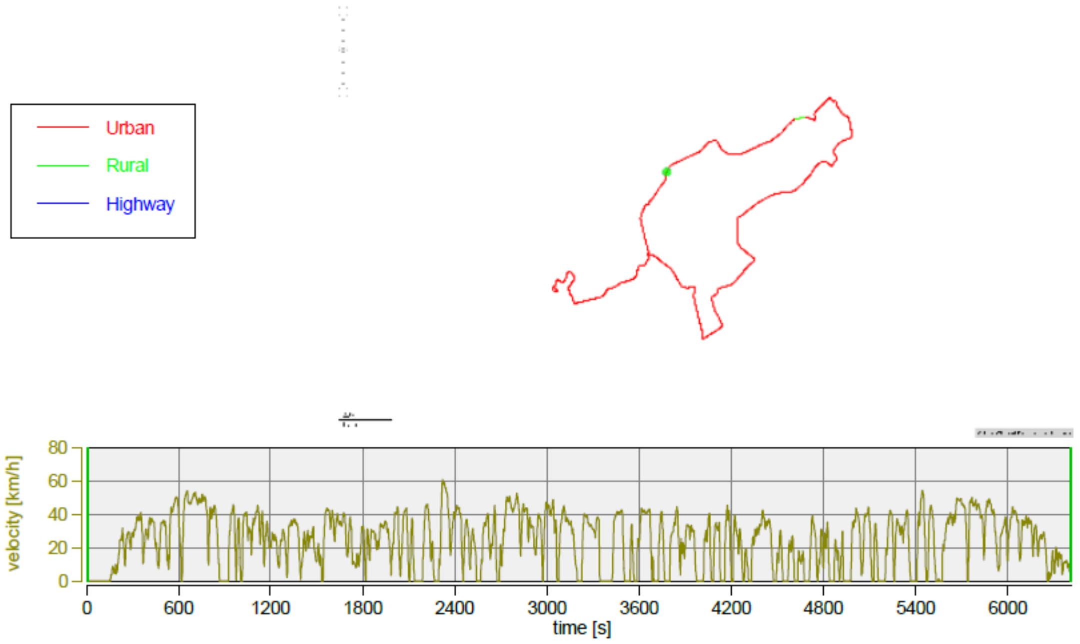


Figure 3-1 VTT HD City in Helsinki

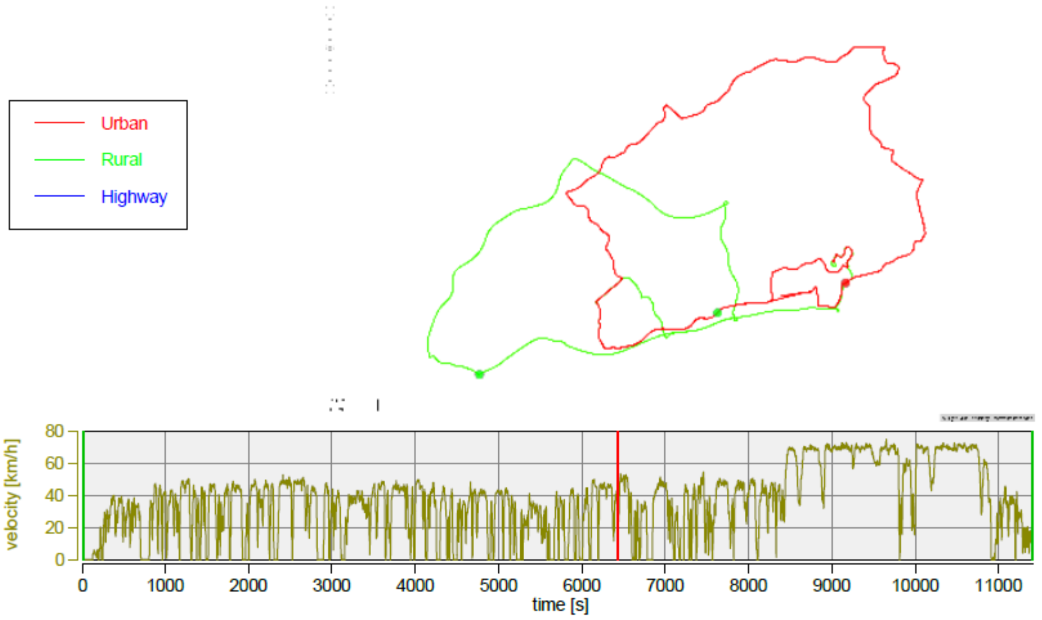


Figure 3-2 HD-ISC Espoo test route

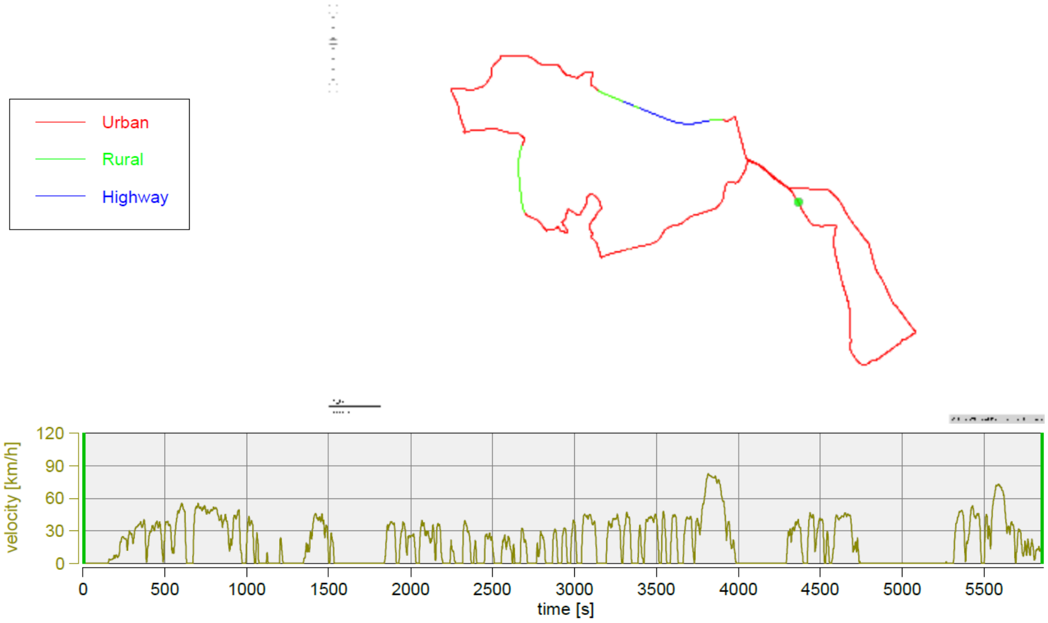


Figure 3-3 VTT High NOx cycle

3.1.2 Data collection

The requested data that was needed to be collected in this project was mainly based on the ISC regulation. Furthermore, in order to be able to analyse the alleged upcoming supplements for Euro VII, additional test parameters, such as N_2O, NH_3 and PN_{10} was added to the data collection. The collected data is expressed in the list below:

- Time
- Ambient temperature, pressure, and humidity
- Vehicle speed
- Engine speed
- Engine power
- Engine load (as a percentage of max torque at that engine speed)
- Engine coolant temperature
- Temperature upstream DPF (for one vehicle only)
- Temperature downstream SCR (collected from the exhaust mass flow meter EFM)
- Exhaust mass flow
- CO_2 tailpipe emissions (concentration and mass flow)
- CO tailpipe emissions (concentration and mass flow)
- HC tailpipe emissions (concentration and mass flow)
- NO tailpipe emissions (concentration and mass flow)
- NO_2 tailpipe emissions (concentration and mass flow)
- NO_x engine-out emissions (concentration and mass flow)
- PN (>23 nm) tailpipe emissions (concentration and mass flow)
- PN (>10 nm) tailpipe emissions (concentration and mass flow)
- N_2O tailpipe emissions (concentration and mass flow)
- NH_3 tailpipe emissions (concentration and mass flow)
- Fuel consumption (as broadcasted in the CAN bus)
- All other available broadcasted OBD channels need to be recorded

3.2 Data analysis and post-processing

3.2.1 A general overview of the post process methods

In order to form a wider understanding of the emission performance for the tested vehicles, the emission results were analysed using two principles: as a trip based emissions related to total trip work and as by using the work based averaging window principle. The collected data was gathered and processed together in a excel-based calculation program specifically designed for producing both trip based and work window results using the moving averaging window (MAW) method for following parameters:

- Engine work, kWh
- Engine power, % and kW
- Engine coolant, °C
- Vehicle speed, km/h
- CO_2, g/kWh
- CO, g/kWh
- NO_x, g/kWh
- N_2O, g/kWh
- NH_3, g/kWh
- HC, g/kWh
- PN_{23}, #/kWh
- PN_{10}, #/kWh

The emission masses were calculated by using the component concentration and the reading acquired from the PEMS EFM (@0 °C). The trip based measurements were calculated as the cumulative result over the complete cycle and the trip work specific results calculated by dividing the cumulative emissions with the total trip work, thus forming one value for each emission component over the complete trip [g/kWh]. The work window (WW) MAW calculations were processed with two principles: Euro VI ISC method described in COMMISSION REGULATION (EU) No 582/2011 and using the suggested CLOVE Euro VII method described in chapter 2. The work based MAW method is described in more detail in chapter *3.2.2 Work based MAW-calculations*.

As the current Euro VI and proposed CLOVE Euro VII methods use different criteria for which MAWs are included in the final analysis, the influence of test criteria for the MAWs were further analysed by dividing the processing into two main topics:

1. Assessment of the influence of MAW evaluation criteria between Euro VI and CLOVE Euro VII
    a. In respect of all included MAWs defined per method by comparing: average MAW results over the total trip, 90th percentile of all MAWs and 100th percentile of all calculated MAWs
2. Studying the emission performance of the two tested vehicles in respect of the suggested CLOVE Euro VII method using the criteria described in chapter 2:

    - For tests below 3x WHTC work: Emission budget limit + 100th percentile of all MAW limits
    - For tests above 3x WHTC work: Emission budget limit + 100th percentile of all MAWs limits + 90th percentile of how MAWs

3.2.2 Work based MAW-calculations

The exhaust emissions in the current HDV ISC regulation (and in the CLOVE Euro VII proposal) are analysed by dividing the cumulative trip emissions from the ISC-test into sub-sets determined by engine specific reference work or CO_2 mass. The reference work/CO_2 mass for a specific engine is defined in the type approval test conducted in laboratory conditions (transient engine dynamometer test, WHTC). The length of each sub-set is equivalent to reference work/CO_2 and corresponding cumulative emissions for each sub-set are divided by the reference work/CO_2 value (Figure 3-4). One sub-set is calculated for each increment in time that is equal to the data sampling period, forming a moving average of the complete test (Figure 3-5). The cumulative work for the test is collected from the instantaneous OBD work during the test trip and the emissions are calculated using the PEMS concentration and EFM mass flow.

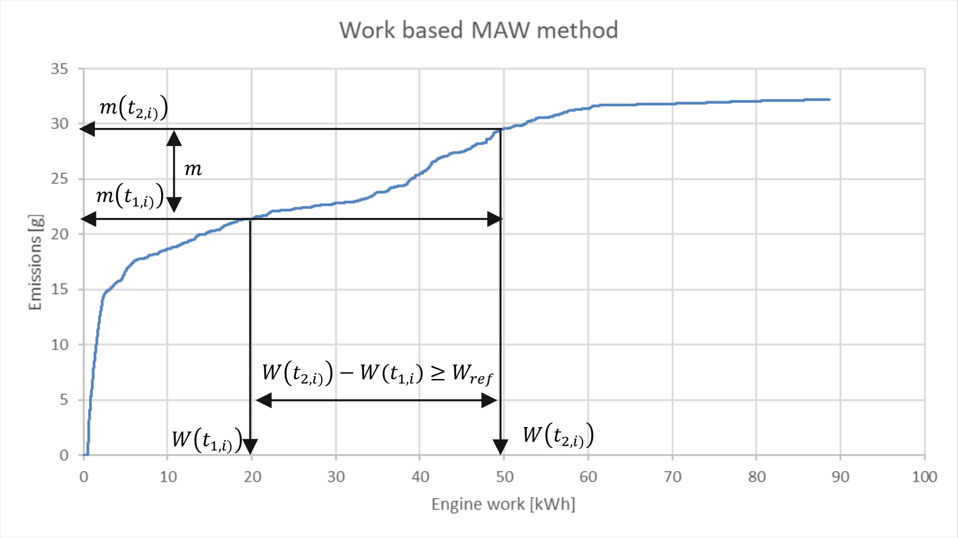


Figure 3-4 Example of emissions calculation with the work based MAW method

$$W(t_{2,i}) - W(t_{1,i}) \geq W_{ref}$$

where:

- $W(t_{j,i})$ is the engine work [kWh] measured between the start and time $t_{j,i}$
- W_{ref} is the engine reference work from WHTC [kWh]

and the specific emissions e [g/kWh] or [#/kWh] are calculated for each window and each pollutant following:

$$e = \frac{m}{W(t_{2,i}) - W(t_{1,i})}$$

where:

- m is the change in emissions (per component) over the given window [mg/window] or [#/window]

Emission values from each work window express the equivalent of exhaust emissions caused

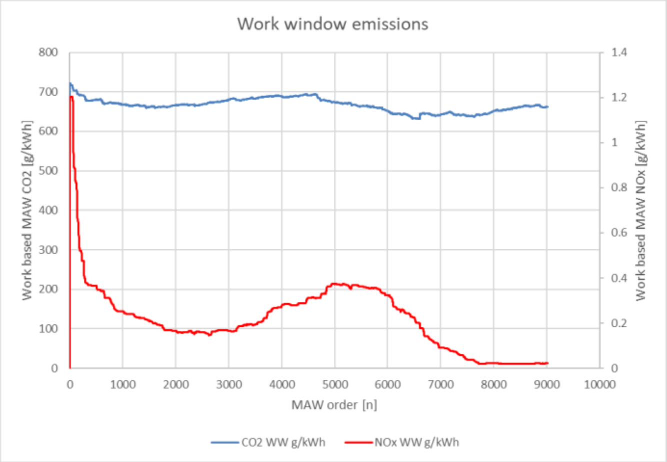


Figure 3-5 An example of CO_2 and NO_x work based MAW emissions over an ISC test

3.3 Test vehicles

3.3.1 Vehicle 1

Vehicle 1 (Figure 3-4) represented a lighter, two axle Euro VI city bus operating in the Helsinki metropolitan region. The vehicle was equipped with a common bus engine with an engine displacement of 6.7 l. As a typical Euro VI-D vehicle, the EATS consisted of a diesel oxidation catalyst (DOC), diesel particulate filter (DPF), a selective catalytic reduction (SCR) system and an ammonia slip catalyst (ASC). Due to its light structure, the load with all measuring equipment, driver and equipment operator the bus load was scaled at 18.3 % of the maximum payload. The reference work for the vehicle 1 was calculated based on the engine torque curve and WHTC parameters. No WHTC reference work was available or procurable despite the requests made for the vehicle importer. The vehicle specifications are described in more detail in Table 3-2 and the interpolated torque curve in Figure 3-5.

Figure 3-6 An overview of vehicle 1

Table 3-2 Vehicle 1 specifications

Vehicle 1			**Vehicle mass (scaled)**		**Load mass (scaled)**
Vehicle info			**Empty**	**Loaded (with meas. equipment)**	**kg**
Make	VDL	Left front	1525	1570	45
Model	Citea LLE Euro	Right front	1605	1540	-65
Engine	B6.7E6D250B	Left rear	3315	3790	475
Emission class	Euro VI D	Right rear	3190	3555	365
WHTC work, estimated (kWh)	17.5	Driver + operator	0	150	150
Trip at the start of the tests (km)	157934	**total**	**9635**	**10605**	**970**
EC type approval number	e13*2007/46*1312*08			**Load [%]**	**18.3**
Unladen weight	9570				
GVW	14870				
Max load capacity	5300				

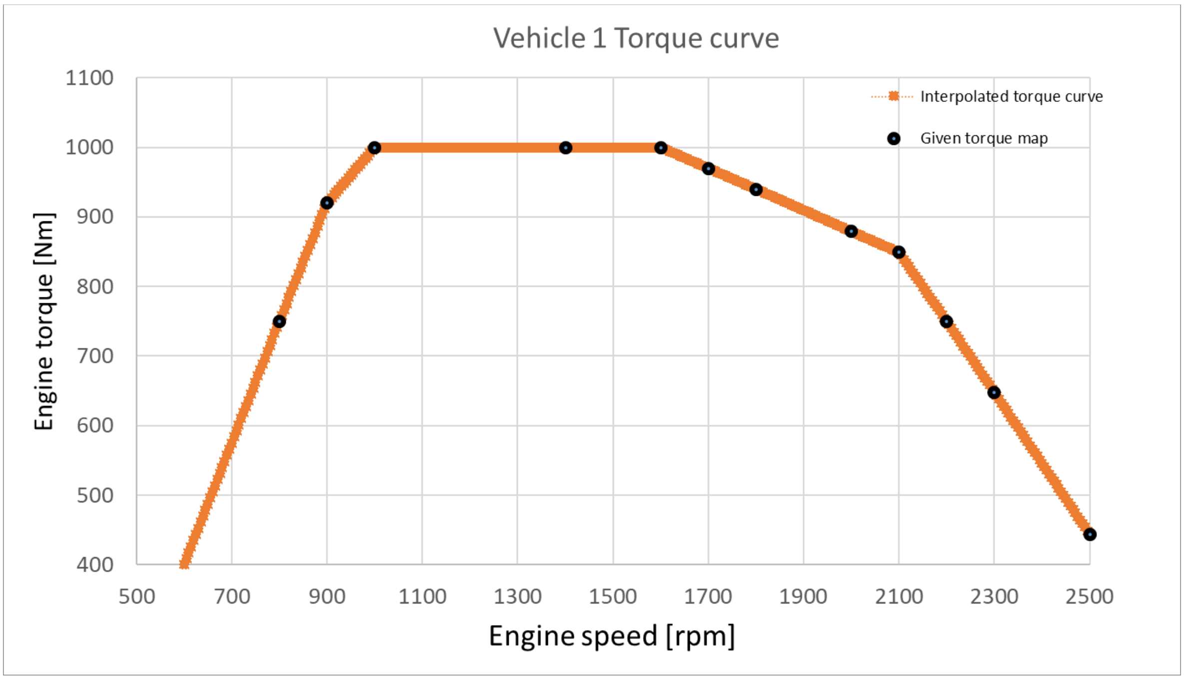


Figure 3-7 Vehicle 1 torque points and interpolated torque qurve

3.3.2 Vehicle 2

Vehicle 2 (Figure 3-6) represented a heavier, three axle Euro VI city bus operating in the Helsinki metropolitan region. The vehicle was equipped bigger 9.3 l diesel engine typically used in lighter heavy-duty trucks. As vehicle 2 was a Euro VI-D vehicle, the EAT-system consisted of a DOC, DPF a SCR-system and an ASC-system. With all measurement equipment, an operator and a driver, the loading was scaled as 11 %. The reference work for the vehicle 2 was calculated based on the engine torque curve and WHTC- parameters. No WHTC reference work was available or procurable despite the requests made for the vehicle importer. The vehicle specifications are described in more detail in Table 3-3 and the interpolated torque curve in Figure 3-7.

Figure 3-8 An overview of vehicle 2

Table 3-3 Vehicle 2 specifications

Vehicle 2			**Vehicle mass (weighted)**		**Load mass (weighted)**
Vehicle info			**Empty**	**Loaded (measu equipment)**	
Make	Scania	Left front	2245	2205	-40
Model	Citywide	Right front	2145	2150	5
Engine	DC9	Left rear 1	3310	3680	370
Emission class	Euro VI D	Right rear 1	3555	3805	250
WHTC work, estimated (kWh)	23.65	Left rear 2	1965	2145	180
Trip at the start of the tests (km)	214811	Right rear 2	2130	2310	180
EC type approval number	e4*595/2009*2018/932D*0010*06	Driver + operator	0	150	150
Unladen weight	15013	total	15350	16445	1095
GVW	24600			**Load [%]**	**11.42**
Max load capacity	9587				

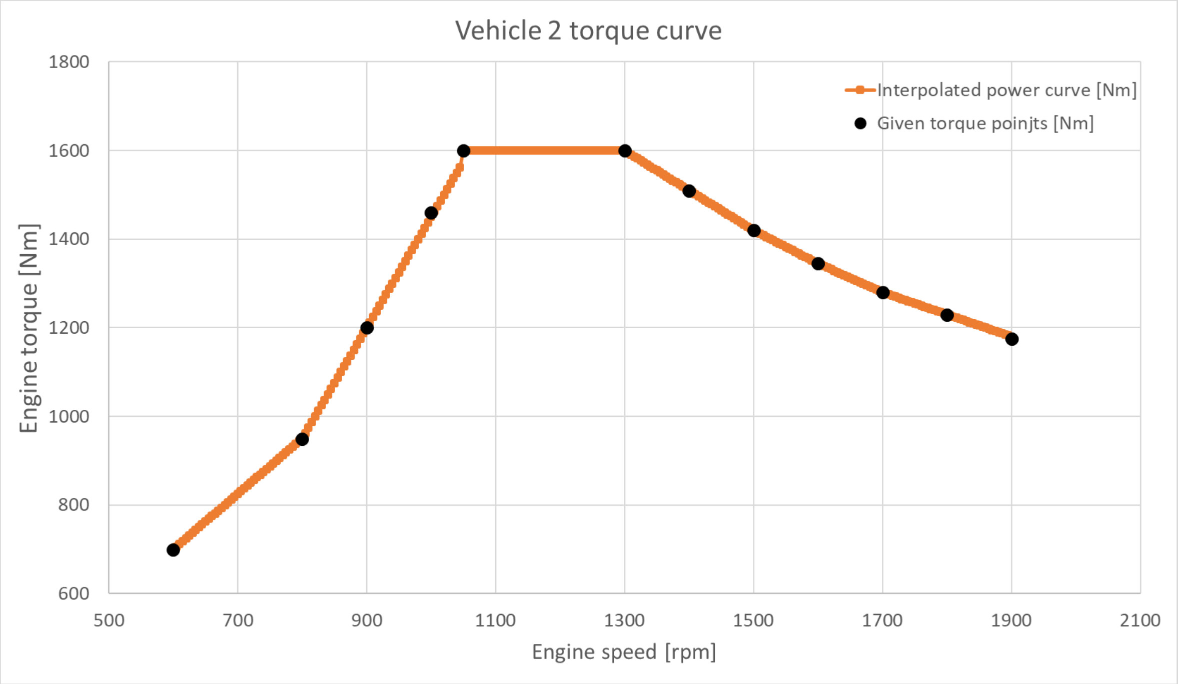


Figure 3-9 Vehicle 2 torque points and interpolated torque curve

3.4 Measurement devices and test layout

In order to protect the equipment from various weather conditions, all installations (apart from gasoline driven generators and the exhaust mass flow meter, EFM) were installed inside the vehicle cabin (Figure 3-8, Figure 3-9 and Figure 3-12). The dilution air for the PN analyser was supplied by an external air compressor (Figure 3-10) and the dilution air was pre-dried and filtered before being introduced to the DEED-diluter (Figure 3-11). The EFM was installed directly after the OEM tail pipe on a mounting bracket with the two generators installed on top of the structure (Figure 3-13). In order to prevent sample condensation, all extractive lines for FTIR, PEMS and CPC were heat controlled with a temperature set point of 180 °C. All measuring equipment were pretested according to the instructions given by the device manufacturer prior to every tests.

Figure 3-10 PEMS-installation in vehicle 2

Figure 3-11 FTIR-installation in vehicle 2

Figure 3-12 Air compressor for CPC dilution air

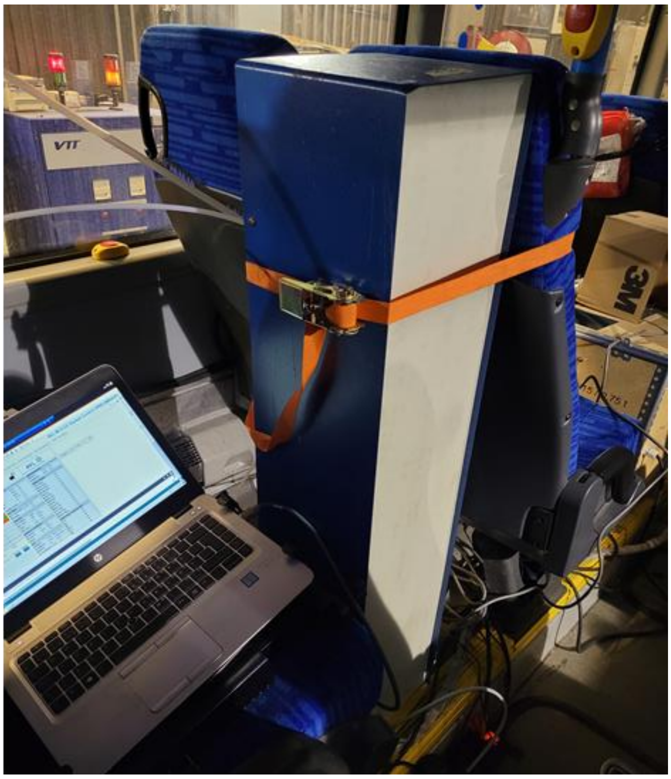


Figure 3-13 Compressed air HC-remover in vehicle 2

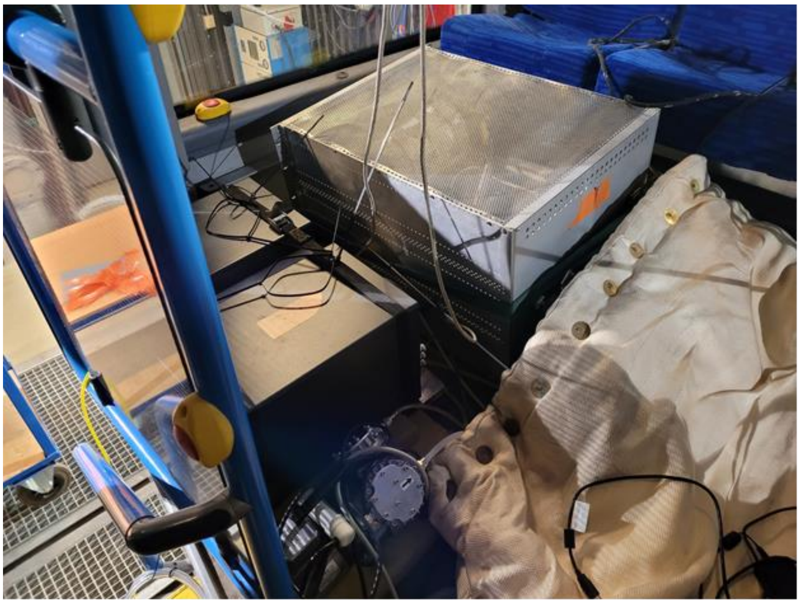


Figure 3-14 2x CPC and DEED diluter assembly in vehicle 2

Figure 3-15 Generator assembly in vehicle 2 for supplying electric power for the measurement equipment

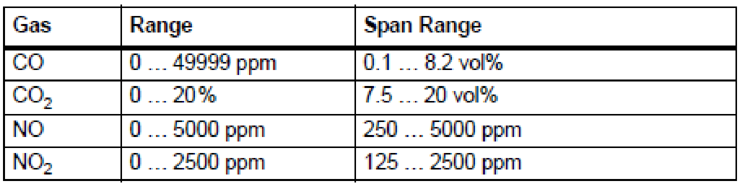
3.5 Emissions analysers and other measurement equipment

The emission analysers used in this project consisted of:

- AVL PEMS device
    - AVL Gas PEMS
    - AVL PN23 analyser
    - AVL PEMS control unit
    - AVL PEMS EFM
- Airmodus A20 CPC
- Airmodus A23 CPC (later added with vehicle 2)
- A&D BOB-1000FT

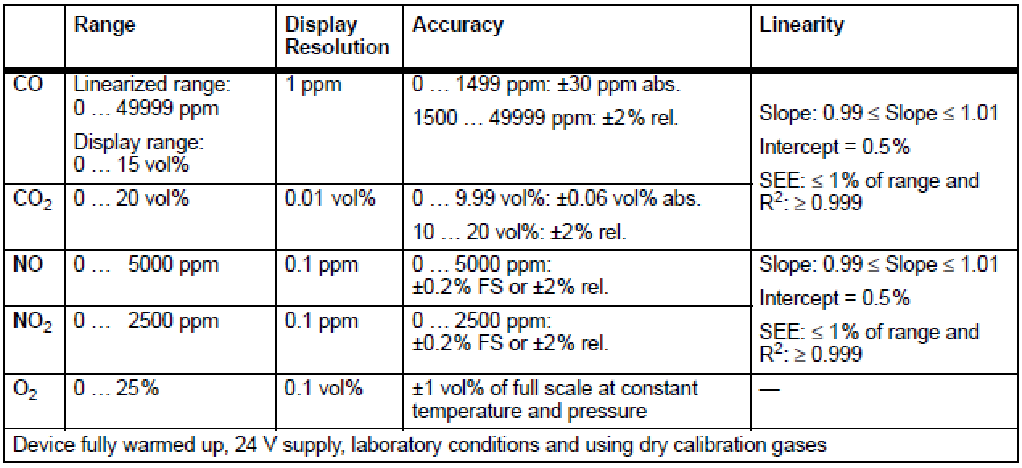
The main specifications for the AVL PEMS device are presented in Table 3-4, Table 3-5, Table 3-6 and Table 3-7. The main specifications of the FTIR are presented in Table 3-8, Table 3-9 and the CPC specifications are shown in Table 3-10.

Table 3-4 AVL gas PEMS measurement and span gas ranges



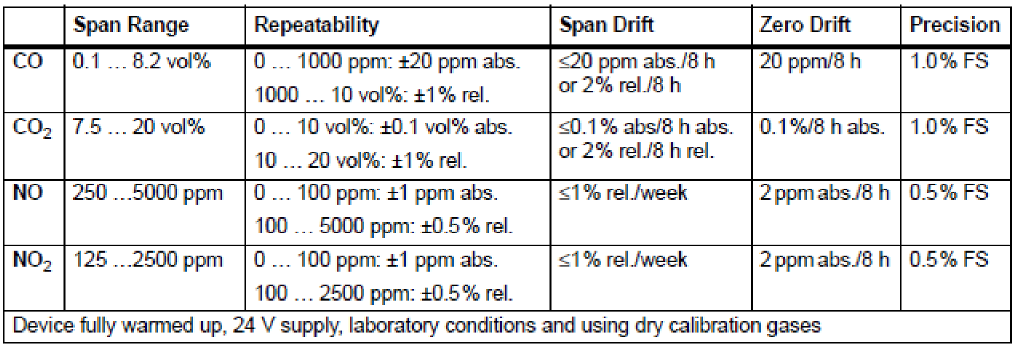
Gas	Range	Span Range
CO	0 … 49999 ppm	0.1 … 8.2 vol%
CO_2	0 … 20%	7.5 … 20 vol%
NO	0 … 5000 ppm	250 … 5000 ppm
NO_2	0 … 2500 ppm	125 … 2500 ppm

Table 3-5 AVL gas PEMS resolution, accuracy and linearity specifications



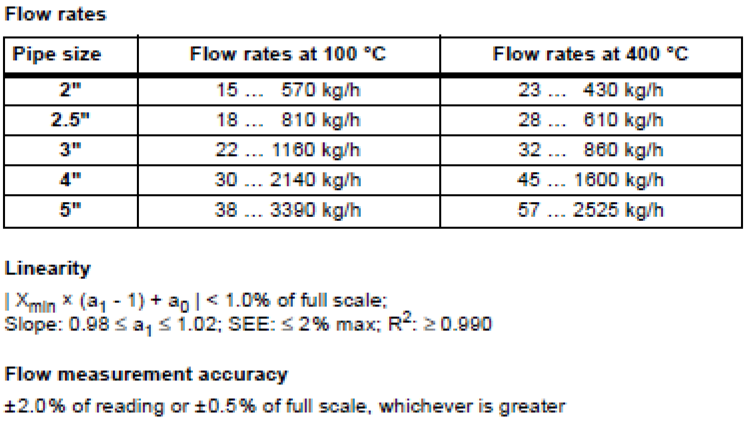
	Range	Display Resolution	Accuracy	Linearity
CO	Linearized range: 0 … 49999 ppm Display range: 0 … 15 vol%	1 ppm	0 … 1499 ppm: ±30 ppm abs. 1500 … 49999 ppm: ±2% rel.	Slope: 0.99 ≤ Slope ≤ 1.01 Intercept = 0.5% SEE: ≤ 1% of range and R^2: ≥ 0.999
CO_2	0 … 20 vol%	0.01 vol%	0 … 9.99 vol%: ±0.06 vol% abs. 10 … 20 vol%: ±2% rel.	
NO	0 … 5000 ppm	0.1 ppm	0 … 5000 ppm: ±0.2% FS or ±2% rel.	Slope: 0.99 ≤ Slope ≤ 1.01 Intercept = 0.5% SEE: ≤ 1% of range and R^2: ≥ 0.999
NO_2	0 … 2500 ppm	0.1 ppm	0 … 2500 ppm: ±0.2% FS or ±2% rel.	
O_2	0 … 25%	0.1 vol%	±1 vol% of full scale at constant temperature and pressure	—
Device fully warmed up, 24 V supply, laboratory conditions and using dry calibration gases				

Table 3-6 AVL gas PEMS repeatability and uncertainty



	Span Range	Repeatability	Span Drift	Zero Drift	Precision
CO	0.1 … 8.2 vol%	0 … 1000 ppm: ±20 ppm abs. 1000 … 10 vol%: ±1% rel.	≤20 ppm abs./8 h or 2% rel./8 h	20 ppm/8 h	1.0% FS
CO_2	7.5 … 20 vol%	0 … 10 vol%: ±0.1 vol% abs. 10 … 20 vol%: ±1% rel.	≤0.1% abs/8 h abs. or 2% rel./8 h rel.	0.1%/8 h abs.	1.0% FS
NO	250 …5000 ppm	0 … 100 ppm: ±1 ppm abs. 100 … 5000 ppm: ±0.5% rel.	≤1% rel./week	2 ppm abs./8 h	0.5% FS
NO_2	125 …2500 ppm	0 … 100 ppm: ±1 ppm abs. 100 … 2500 ppm: ±0.5% rel.	≤1% rel./week	2 ppm abs./8 h	0.5% FS
Device fully warmed up, 24 V supply, laboratory conditions and using dry calibration gases					

Table 3-7 AVL EFM specifications



Flow rates

Pipe size	Flow rates at 100 °C	Flow rates at 400 °C
2"	15 … 570 kg/h	23 … 430 kg/h
2.5"	18 … 810 kg/h	28 … 610 kg/h
3"	22 … 1160 kg/h	32 … 860 kg/h
4"	30 … 2140 kg/h	45 … 1600 kg/h
5"	38 … 3390 kg/h	57 … 2525 kg/h

Linearity

$| X_{min} \times (a_1 - 1) + a_0 | < 1.0\%$ of full scale;
Slope: $0.98 \leq a_1 \leq 1.02$; SEE: $\leq 2\%$ max; R^2: ≥ 0.990

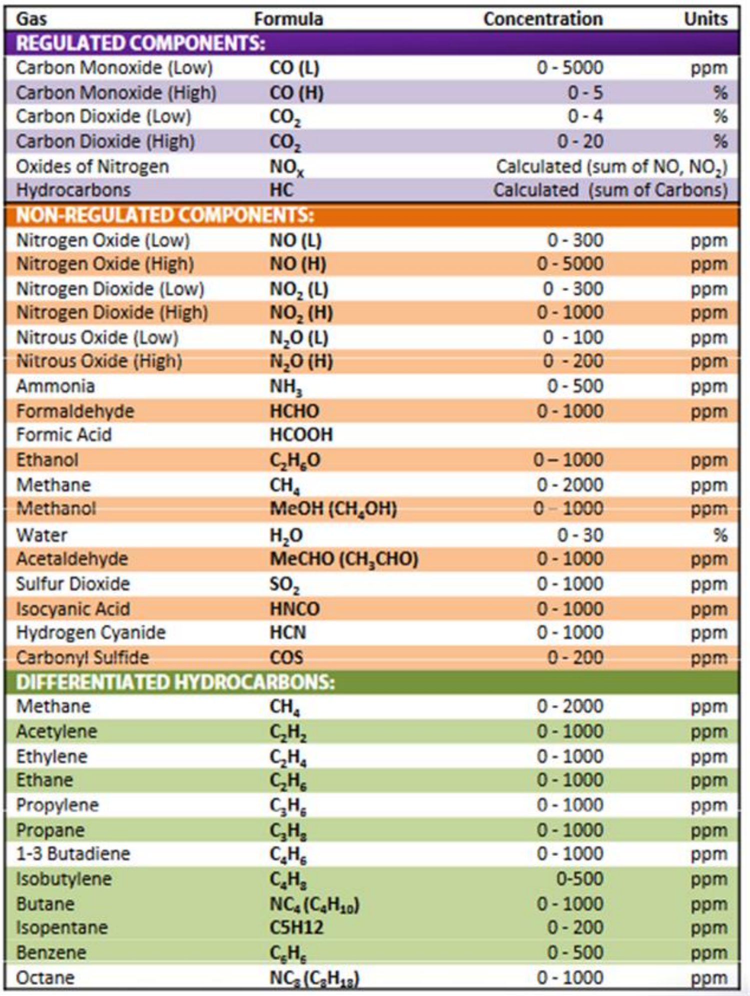
Flow measurement accuracy

±2.0% of reading or ±0.5% of full scale, whichever is greater

Table 3-8 FTIR (A&D BOB-1000FT) device specifications and system performance

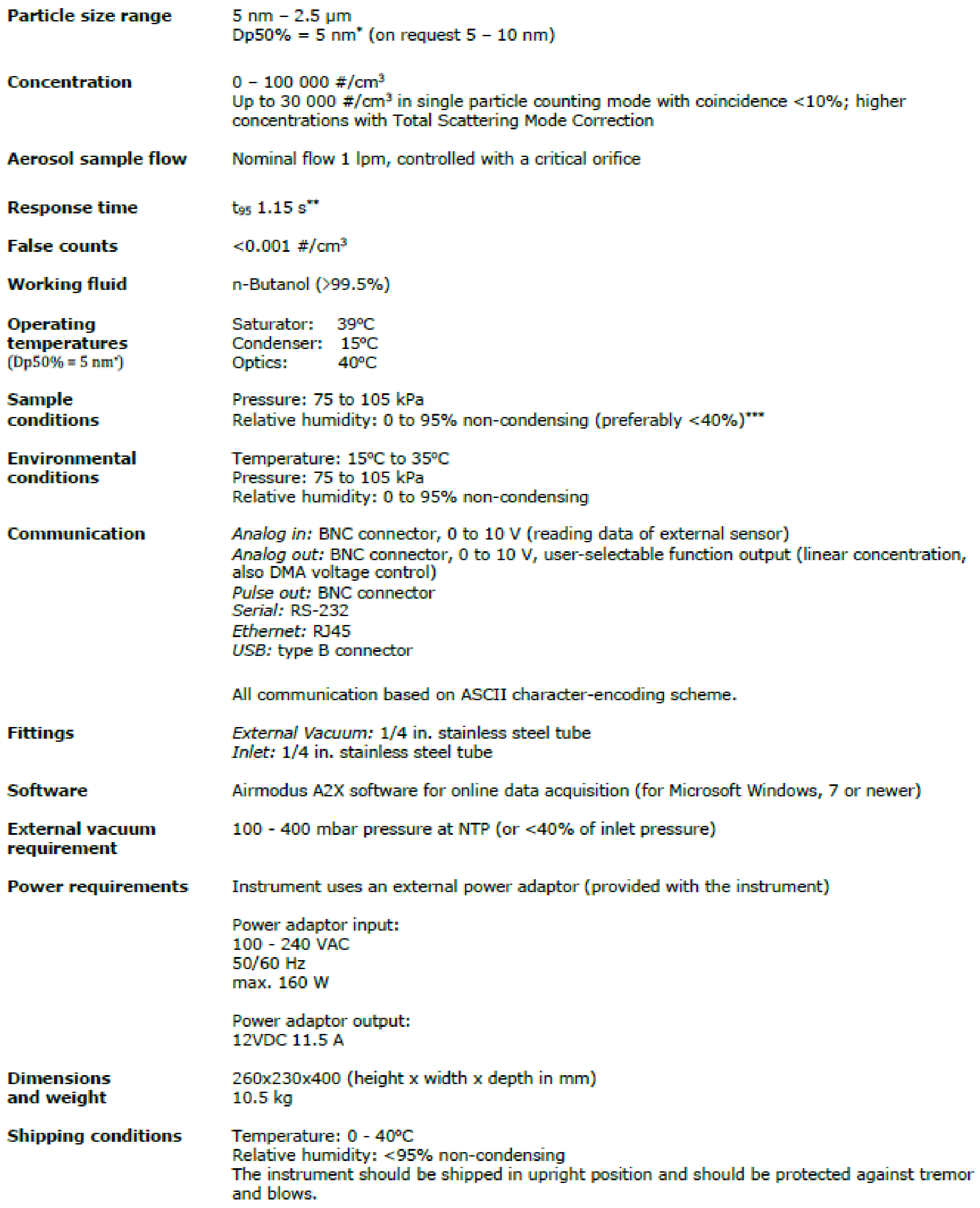
FTIR SPECTROMETER SPECIFICATIONS	
Measuring Method	FTIR
Measuring Component	24 Components standard, up to 30 optional
Application	Gasoline/Diesel Direct
Dimensions	Approximately 482(W) x 645(D) x 391(H)mm
Weight	Approximately 40 kg
Operating Conditions	5-40°C, Relative Humidity 80% (non-condensing)
Sampling Frequency	1 Hz and 5 Hz (selectable)
Absorbance Spectrum	500-5000 cm-1
Spectral Resolution	0.5 cm-1
Optical Path Length	5.1 m
Gas Cell Volume	200 ml
Gas Cell Temperature	191°C
Detector Cooling Method	MCT Liquid Nitrogen, 50 ml/h
SYSTEM PERFORMANCE	
Response Time (T10-T90)	1.5 -2.0 sec
Zero Drift	1.0% F.S./4 hrs=(±5°C)
Span Drift	1.0% F.S./4 hrs=(±5°C)
Repeatability	2.0% F.S.

Table 3-9 FTIR (A&D BOB-1000FT) emissions components concentration bands



Gas	Formula	Concentration	Units
REGULATED COMPONENTS:			
Carbon Monoxide (Low)	CO (L)	0 - 5000	ppm
Carbon Monoxide (High)	CO (H)	0 - 5	%
Carbon Dioxide (Low)	CO_2	0 - 4	%
Carbon Dioxide (High)	CO_2	0 - 20	%
Oxides of Nitrogen	NO_x	Calculated (sum of NO, NO_2)	
Hydrocarbons	HC	Calculated (sum of Carbons)	
NON-REGULATED COMPONENTS:			
Nitrogen Oxide (Low)	NO (L)	0 - 300	ppm
Nitrogen Oxide (High)	NO (H)	0 - 5000	ppm
Nitrogen Dioxide (Low)	NO_2 (L)	0 - 300	ppm
Nitrogen Dioxide (High)	NO_2 (H)	0 - 1000	ppm
Nitrous Oxide (Low)	N_2O (L)	0 - 100	ppm
Nitrous Oxide (High)	N_2O (H)	0 - 200	ppm
Ammonia	NH_3	0 - 500	ppm
Formaldehyde	HCHO	0 - 1000	ppm
Formic Acid	HCOOH		
Ethanol	C_2H_6O	0 – 1000	ppm
Methane	CH_4	0 - 2000	ppm
Methanol	MeOH (CH_4OH)	0 – 1000	ppm
Water	H_2O	0 - 30	%
Acetaldehyde	MeCHO (CH_3CHO)	0 - 1000	ppm
Sulfur Dioxide	SO_2	0 - 1000	ppm
Isocyanic Acid	HNCO	0 - 1000	ppm
Hydrogen Cyanide	HCN	0 - 1000	ppm
Carbonyl Sulfide	COS	0 - 200	ppm
DIFFERENTIATED HYDROCARBONS:			
Methane	CH_4	0 - 2000	ppm
Acetylene	C_2H_2	0 - 1000	ppm
Ethylene	C_2H_4	0 - 1000	ppm
Ethane	C_2H_6	0 - 1000	ppm
Propylene	C_3H_6	0 - 1000	ppm
Propane	C_3H_8	0 - 1000	ppm
1-3 Butadiene	C_4H_6	0 - 1000	ppm
Isobutylene	C_4H_8	0-500	ppm
Butane	NC_4 (C_4H_{10})	0 - 1000	ppm
Isopentane	C5H12	0 - 200	ppm
Benzene	C_6H_6	0 - 500	ppm
Octane	NC_8 (C_8H_{18})	0 - 1000	ppm

Table 3-10 CPC PN (Airmodus A20) specifications



Particle size range	5 nm – 2.5 µm Dp50% = 5 nm* (on request 5 – 10 nm)
Concentration	0 – 100 000 #/cm^3 Up to 30 000 #/cm^3 in single particle counting mode with coincidence <10%; higher concentrations with Total Scattering Mode Correction
Aerosol sample flow	Nominal flow 1 lpm, controlled with a critical orifice
Response time	t_{95} 1.15 s**
False counts	<0.001 #/cm^3
Working fluid	n-Butanol (>99.5%)
Operating temperatures (Dp50% = 5 nm*)	Saturator: 39°C Condenser: 15°C Optics: 40°C
Sample conditions	Pressure: 75 to 105 kPa Relative humidity: 0 to 95% non-condensing (preferably <40%)***
Environmental conditions	Temperature: 15°C to 35°C Pressure: 75 to 105 kPa Relative humidity: 0 to 95% non-condensing
Communication	*Analog in:* BNC connector, 0 to 10 V (reading data of external sensor) *Analog out:* BNC connector, 0 to 10 V, user-selectable function output (linear concentration, also DMA voltage control) *Pulse out:* BNC connector *Serial:* RS-232 *Ethernet:* RJ45 *USB:* type B connector All communication based on ASCII character-encoding scheme.
Fittings	*External Vacuum:* 1/4 in. stainless steel tube *Inlet:* 1/4 in. stainless steel tube
Software	Airmodus A2X software for online data acquisition (for Microsoft Windows, 7 or newer)
External vacuum requirement	100 - 400 mbar pressure at NTP (or <40% of inlet pressure)
Power requirements	Instrument uses an external power adaptor (provided with the instrument) Power adaptor input: 100 - 240 VAC 50/60 Hz max. 160 W Power adaptor output: 12VDC 11.5 A
Dimensions and weight	260x230x400 (height x width x depth in mm) 10.5 kg
Shipping conditions	Temperature: 0 - 40°C Relative humidity: <95% non-condensing The instrument should be shipped in upright position and should be protected against tremor and blows.

3.6 Conclusive test schedule and final test summary

The initial test plan included five on-road tests in total (per vehicle) performed in typical Nordic conditions during the winter period. During the project, the test matrix was supplemented with two additional on road tests (one additional VTT Low Load NOx for vehicle 1 and one additional ISC test for vehicle 2) and one chassis dynamometer tests (WHVC) conducted for vehicle 2. The supplemented on road tests were added due to equipment and vehicle malfunction, meanwhile the WHVC was added for comparing the PEMS-configuration with laboratory grade emissions measurement equipment and a CVS. The final test schedule departed from the original test plan following:

For vehicle 1

- 2x VTT HD City
- 2x ISC
- 2x VTT low load NO_x test
    - one additional was performed due to partial loss in FTIR-data

For vehicle 2

- WHVC performed on the VTT heavy duty chassis dynamometer
    - Based on findings related to PEMS PN_{23} vs CPC PN_{10}, VTT made additional testing on dyno to compare the results with laboratory instruments and CVS
- 2x VTT HD City
- 3x ISC
    - one additional tests due was performed due to vehicle malfunction (error code, backpressure sensor)
- 1x VTT low load NO_x test

As the temperature in the Nordic countries are somewhat unpredictable, the ambient temperature was fluctuating from test to test between -12 ˚C to ca. +4 ˚C. The exact predominant ambient test temperatures are described further in detail in chapter 3.7.

3.7 Test validation

As the characteristics of the test routes and conditions varied between test types, the given tests may be sorted as Euro VI ISC compatible and ISC non-compatible tests. The limits for fulfilling the minimum work in a valid Euro VI ISC test is > 4 x WHTC (and upper limit 8x WHTC) work. The allowed ambient temperature parameters are between -7°C to 38°C for Euro VI step D and -7°C to 35 °C for Euro VI step E. Furthermore, the Euro VI ISC regulation does not naturally allow any error codes to activate during the trip.

Due to the usage of applied test instruments, the test data was checked after each test, and the continuity and quality of each instrument was inspected. The main purpose for this was to assure the quality of data validation.

The tests conducted that are presented in this report were validated accordingly based on the above mentioned criteria. If any these ISC boundary parameters were not met, the tests were classified as non-ISC compatible tests, but were nevertheless considered as valid tests for the analysis as long as no instrument or vehicle malfunction occurred. In case of any critical instrument data was missing, the validity of the test was separately evaluated and rerun based on the problem severity and relevance, thus retests were performed if necessary. Furthermore, in case of vehicle error, the predominant problem was immediately addressed followed by an additional test repetition. The test validation for each test are shown in Table 3-11.

Due to the geolocation of the test site and season of testing (winter time), the predominant ambient conditions were fairly low for all tests. Two tests were performed outside current Euro VI ISC and CLOVE Euro VII parameters, below - 10 ˚C conditions (vehicle 1, Low load NOx tests), but these were still considered as valid tests as these conditions were seen as an interesting case of study in respect of EATS behaviour in extremely cold conditions.

For vehicle 2, error codes indicating vehicle malfunction appeared on the first ISC test attempt. The problem was examined and the vehicle was immediately addressed by returning the vehicle for service and inspection. During service, the problem was found to be related to the EATS DPF pressure sensor, which was replaced by the service provider. The conducted service also included a forced service regeneration. After the service had taken place, no error codes were found on the second ISC test. The failed ISC test is presented in this report as “ISC #F” (e.g. in Table 3-11).

Furthermore, due to challenges with power supply, FTIR shutdown was experienced in four test presented in Table 3-11. This issue was also tackled by performing a retest if possible (and if not one valid test of given test type had fulfilled the instrument validity criteria. E.g. for vehicle 1, the Low Load NOx test was repeated once as some FTIR data was missing on the first test attempt and only one test repetition for the given test cycle was planned.

Table 3-11 Test conditions and trip validation against Euro VI ISC and CLOVE Euro VII parameters

			Test validation			
Vehicle 1	**WHTC work**	**WHTC work equicvalent**	**Test temperature**	**Euro VI ISC work criteria fulfilled**	**ISC ambient criteria**	**Vehicle & test instruments**
Euro VI step D boudaries	**> 70.0**	**> 4x WHTC work**	**-7 ˚C to 38 ˚C**			
Euro VI step E boundaries	**> 70.0**	**> 4x WHTC work**	**-7 ˚C to 35 ˚C**			
CLOVE Euro VII	**All**	**All**	**-7 ˚C to 35 ˚C**			
VTT HD City #1	40.5	2.3	2.2	No	Ok	Vehicle +Test instruments Ok
VTT HD City #2	40.5	2.3	3.7	No	Ok	Vehicle +Test instruments Ok
ISC #1	88.6	5.1	3.6	Yes	Ok	Vehicle +Test instruments Ok
ISC #2	91.5	5.2	1.4	Yes	Ok	Vehicle Ok, cold start FTIR data missing
LowLoad NOx test #1	32.8	1.9	-10.1	No	Below extended conditions	Vehicle Ok, cold start FTIR data missing
LowLoad NOx test #2	36.3	2.1	-12.1	No	Below extended conditions	Vehicle +Test instruments Ok

			Test validation			
Vehicle 2	**WHTC work equivalent**	**WHTC work equivalent**	**Test temperature**	**Euro VI ISC work criteria fulfilled**	**ISC ambient criteria**	**Test assesment (Euro VI)**
Euro VI step D boudaries	**> 94.6**	**> 4x WHTC work**	**-7 ˚C to 38 ˚C**			
Euro VI step E boundaries	**> 94.6**	**> 4x WHTC work**	**-7 ˚C to 35 ˚C**			
CLOVE Euro VII	**All**	**All**	**-7 ˚C to 35 ˚C**			
VTT HD City #1	54.5	2.3	2.5	No	Ok	Vehicle +Test instruments Ok
VTT HD City #2	51.9	2.2	-0.2	No	Ok	Vehicle +Test instruments Ok
ISC #F	124.4	5.3	1.0	Yes	Ok	Vehicle malfunction, urea injection shutoff, Test instruments Ok
ISC #1	116.2	4.9	-2.9	Yes	Ok	Vehicle +Test instruments Ok
ISC #2	115.3	4.9	-3.9	Yes	Ok	Irregular vehicle begaviour + cold start FTIR data missing
LowLoad NOx test	36.3	1.5	3.7	No	Ok	Vehicle +Test instruments Ok

4. Results

The test results acquired from the executed heavy-duty on-road tests may be divided in different results types depending on the used post-processing and analysing method. Generally, trip based emissions (either expressed as total mass of emissions or work specific trip emissions) describes the absolute vehicular emissions calculated as an average value from the second-by-second emissions over the total test conducted, including cold start conditions. However, the current ISC-regulation accounts for emission results obtained as work or CO_2 based reference windows calculated using the MAW method, hence describing the comparable results that would be obtained from the dynamometer based type approval. The main focus of this commission was to evaluate the on road measurement according to work based MAW method. However, in order to cover the vehicular emissions as broad as possible, this report cover both work specific trip emissions, as well as vehicle emission performance evaluation using the work based MAW method.

4.1 Results in respect of Euro VI ISC regulation

For those tests fulfilling the ISC criteria (four tests in total), the vehicles were initially validated in respect to their type approved requirements (COMMISSION REGULATION (EU) 2018/932 Euro VI D) using the corresponding ISC conformity factors (CF). The ISC results in respect of CO, THC, NO_x and PN (PN23) including corresponding CFs are shown in Table 4-1. As PN is excluded from the Euro VI ISC criteria, a CF limit of 1 was set for analysing the particulate filtering efficiency. The main purpose of the Euro VI ISC analysis was to ensure that the vehicles meet the standards given and no irrational engine or EATS behaviour would take place.

Based on the results displayed in Table 4-1, vehicle 1 passed the two ISC tests with relatively safe margins in respect of the required CFs. However, this was not the case for vehicle 2, as the second ISC test exceeded NO_x CF limits by 6.42, hence did not pass the second ISC test. The reason for the significant increase in NOx is assessed in the later part of this report. Nevertheless, the NO_x and PN results indicate that vehicle 1 produce significantly less PN, meanwhile vehicle 2 has a superior NO_x reduction capability at its best (190 mg/kWh vs 785 mg/kWh), i.e. when the system works appropriately.

Table 4-1 The results acquired from the ISC-criteria fulfilling tests

Euro VI ISC, work based conformity factors					
Test vehicle	**Test**	**CO**	**THC**	**NOx**	**PN**
Euro VI D CF limit		1.5	1.5	1.5	NA
Vehicle 1	**ISC #1**	0.00	0.11	0.75	0.24
	ISC #2	0.00	0.05	0.82	0.34
Vehicle 2	**ISC #1**	0.00	0.06	0.19	1.01
	ISC #2	0.00	0.17	6.42	0.99

4.2 Euro VI emissions and vehicle performance and EAT characteristics

This chapter describes the emission performance for both test vehicles expressed as work-specific emissions over the total trip from the start to stop of the test cycle. The work specific emissions were calculated from the cumulative emissions over the trip and divided by the cumulative work gathered from the vehicle OBD. The analysis describes therefore the average emission characteristics that the vehicle produces over the given test cycle as the absolute mass of the measured exhaust emission components in relation to total trip work and does not account for any MAW-calculations. The work specific emissions does neither exclude of the emissions outside ISC-boundaries or regulative calculation methods. The trip emissions were used for comparing the overall EATS-performance of the two tested vehicles, so that the fundamental differences in fuel consumption and exhaust emissions characteristics could be potentially examined. Table 4-2 expresses the work specific trip emissions for vehicle 1, meanwhile Table 4-3 the equivalent results for vehicle 2.

Table 4-2 Work specific trip emissions for vehicle 1

Vehicle 1	Amb. Temp avg	Engine work trip	CO2	CO	NO	NO2	NOx	N2O	NH3	HC	PN23	PN10
Test type	°C	kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	#/kWh	#/kWh
HD CITY #1	2.2	40.5	698.8	0.02	0.50	0.09	0.60	0.16	0.06	0.01	8.5E+11	3.6E+11
HD CITY #2	3.7	40.5	704.3	0.02	0.53	0.10	0.63	0.17	0.06	0.01	4.6E+11	2.0E+11
ISC #1	3.6	88.6	672.1	0.01	0.28	0.08	0.36	0.17	0.07	0.02	2.0E+11	1.6E+11
ISC #2	1.4	91.5	673.9	0.01	0.28	0.06	0.35	0.17	0.00	0.01	3.1E+11	2.9E+11
HighNOx #1*	-10.1	32.8	729.8	0.04	2.13	1.03	3.15	0.81	0.04	0.01	9.4E+11	4.7E+11
HighNOx #2	-12.1	36.3	747.0	0.02	2.43	1.26	3.69	0.10	0.11	0.04	5.9E+11	2.2E+11

Table 4-3 Work specific trip emissions for vehicle 2

Vehicle 2	Amb. Temp avg	Engine work trip	CO2	CO	NO	NO2	NOx	N2O	NH3	HC	PN23	CPC PN23	CPC PN10
Test type	°C	kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	#/kWh	#/kWh	#/kWh
HD CITY #1	2.5	54.53	829.9	0.05	0.57	0.25	0.80	0.08	0.01	0.03	3.5E+11	1.5E+11	2.6E+11
HD CITY #2	-0.2	51.93	863.6	0.05	0.39	0.16	0.55	0.15	0.04	0.04	4.0E+11	1.3E+11	2.4E+11
ISC #F*	1.0	124.39	809.6	0.02	2.10	0.88	2.98	0.08	0.01	0.03	7.2E+11	3.0E+11	4.5E+11
ISC #1	-2.9	116.16	813.1	0.02	0.27	0.12	0.40	0.13	0.03	0.02	4.7E+11	1.5E+11	2.8E+11
ISC #2	-3.9	115.27	818.8	0.05	1.05	0.60	1.64	0.08	0.02	0.29	4.4E+11	1.4E+11	2.8E+11
LowLoad NOx test	3.7	36.30	934.7	0.08	0.93	0.52	1.45	0.12	0.00	0.02	3.6E+11	1.5E+11	2.4E+11

***test invalid due to vehicle malfunction**

Figure 4-1 shows the average engine power expressed as a relative to maximum power performed by the test vehicles in the conducted tests and Figure 4-2 shows the total work done by the vehicles in respective tests. Generally, vehicle 1 relative power and total work were found somewhat lower compared to vehicle 2 (apart from the Low Load NO$_x$ test). Therefore, it could be expected that the exhaust gas temperature (EGT) and engine load would be less favourable for vehicle 1 EAT working conditions. However, no direct comparison between the upstream EATS EGT could be performed, as this parameter was not measured for vehicle 1. Also, the total work performed by the vehicles are significantly less in the HD city and Low Load NO$_x$ tests compared to the ISC test (ISC based work was ca. 5 times WHTC work), hence would therefore fail to meet the criteria of current ISC regulation.

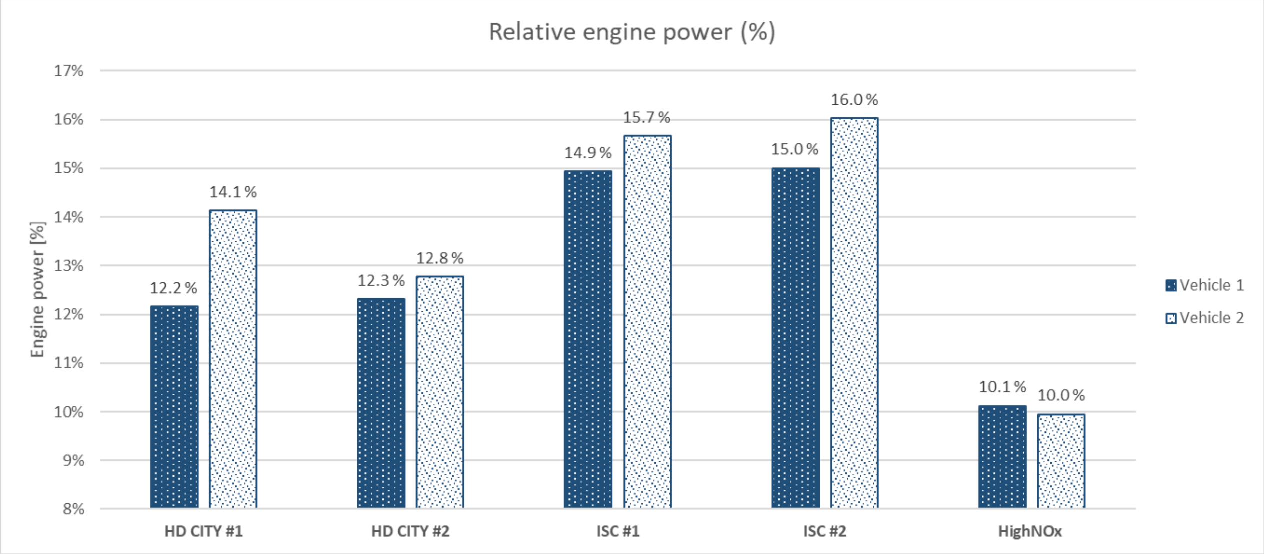


Figure 4-1 The effect on relative engine power (%) for different test routes and vehicles

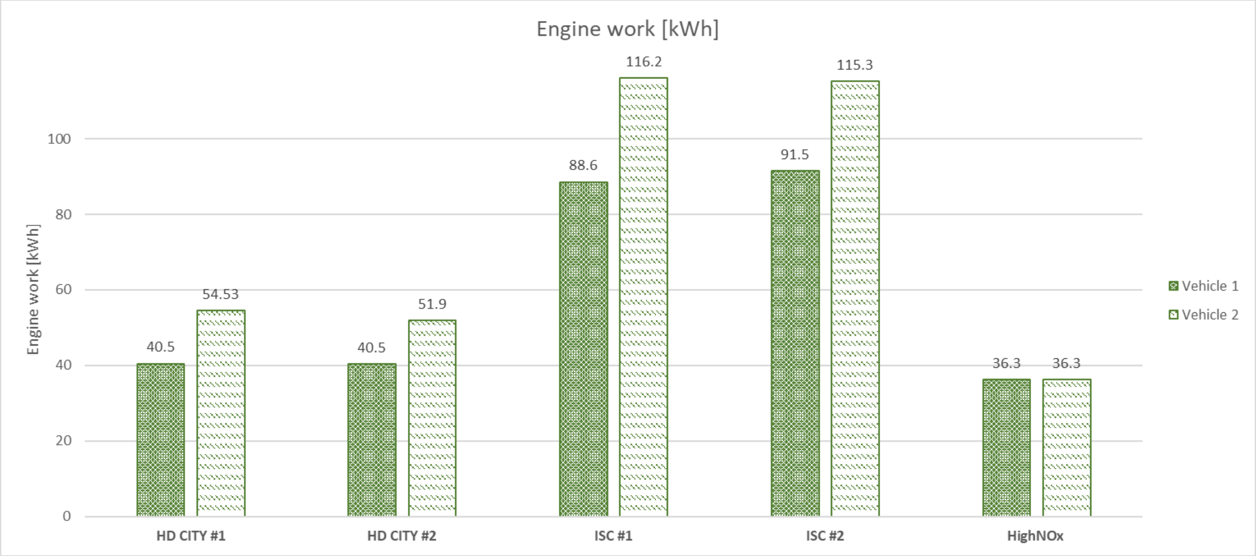


Figure 4-2 Total engine work for different test routes and vehicles

The exhaust emissions measured over the total tests were somewhat different between vehicle 1 and vehicle 2. As a result of the differences in average trip power, Vehicle 1 produced CO_2 emissions in the range of 670 to 750 g/kWh, meanwhile vehicle 2 produced significantly higher values, between 813 - 935 g/kWh (Figure 4-3). CO emission were found approximately double for vehicle 2, albeit the outcome for both were considered relatively low (Figure 4-4). No significant difference in hydrocarbon emissions could be found, apart from the second ISC tests conducted with vehicle 2 (Figure 4-5). Also, the NO_x outcome for both vehicles were similar in the conducted HD-City and ISC tests (again apart from the second ISC test with vehicle 2), between 0.35 to 0.36 g/kWh for vehicle 1 in ISC, and 0.6 to 0.63 g/kWh in HD-City respectively and 0.4 g/kWh in the “passed” ISC test (ISC #1) for vehicle 2, and ca. 0.55 to 0.8 g/kWh in the HD-City tests (Figure 4-6). The second ISC test for vehicle 2 resulted in a significant increase in NO_x, but the definitive root cause for this phenomena could not completely understood, as the phenomena was occurring without many other typical, supportive signs of regeneration or signs of active errors (no active error codes on the dashboard taking place). The spontaneous increase in NOx emissions may clearly be seen by comparing the cumulative NO$_x$ results of the two ISC tests shown in Figure 4-7, with the NO$_x$ emissions rapidly rising during the ISC #2 test after ca. 3x WHTC work. Somewhat higher upstream EAT temperature traces was noted for ISC #2 compared to ISC #1 from the start of the given time frame (Figure 4-8), albeit the difference was seen as relatively mild, thus not supporting a typical behaviour for active regeneration. Comparing the upstream EGTs with the data acquired from the failed ISC test (ISC #F), the traces remain similar or below to the case with a clear vehicle error (limp mode). Also, no distinguishable difference could be noted in the cumulative PN trace that would indicate an active regeneration, nor any other abnormal particulate trace could be distinguished like seen from the PN trace for the failed “ISC #F” test (Figure 4-9). Lastly, a rapid increase in CO and HC emissions was found starting from the beginning of the ISC #2 test (Figure 4-10), but the relation between CO and HC emissions, upstream EAT and tail pipe EGT prior to the rapid NO$_x$ increase was minimal. It should also be noted that prior to the two ISC test presented in this analysis, a forced regeneration was performed on the vehicle due to service protocols, thus an active regeneration after some hours of operation would not be expected within the given time frame. Due to these reasons, the ISC test #2 was validated and treated as a normal ISC, but seen as a “failed ISC test” due to the high NO$_x$ result.

The Low Load NO$_x$ test clearly produced challenges for the NO$_x$ control for both vehicles, albeit this effect was more dominant for vehicle 1. The Low Load NO$_x$ tests produced ca. 3.7 g/kWh for vehicle 1, meanwhile vehicle 2 produced 1.45 g/kWh of NO$_x$ emissions. Both vehicles produced relatively comparable N_2O emissions, 0.1 to 0.17 g/kWh for vehicle 1, with vehicle 2 producing slightly lower 0.08 (concentrations close or below detection limit) to 0.15 g/kWh for vehicle 2 (Figure 4-9). The NH_3 production was in general lower for vehicle 2, but both vehicles producing less than 0.11 g/kWh in all conditions. Correspondingly, the average recorded NH_3 concentration for vehicle 1 was between 10.9 - 18.6 ppm (Figure 4-14), meanwhile the average NH_3 emission concentration for vehicle 2 was between > 0 - 5.7 ppm (Figure 4-15). Some inconsistency was found between PN$_{10}$ and PN$_{23}$ emission for both vehicles, but producing generally PN emissions below $6*10^{11}$ g/kWh (Figure 4-16 and Figure 4-17). The inconsistency of the PN results are studied further in depth later in this report.

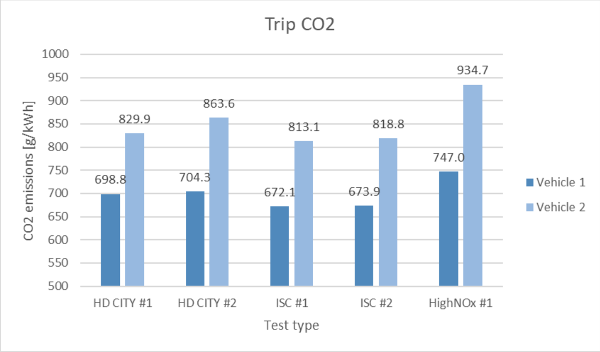


Figure 4-3 CO$_2$ trip emissions for both vehicles

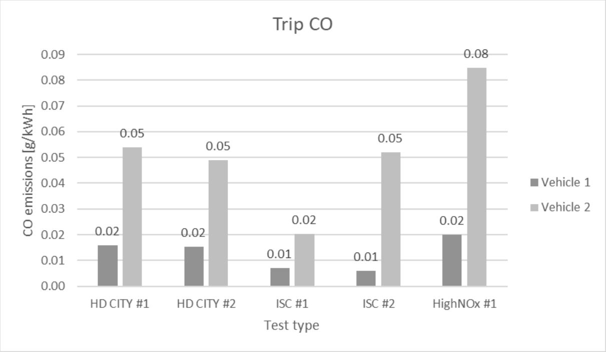


Figure 4-4 CO trip emissions for both vehicles

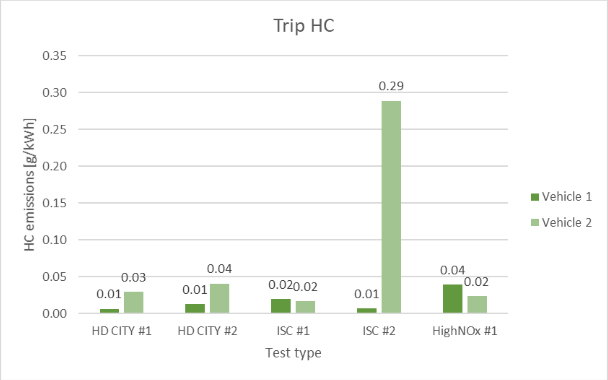


Figure 4-5 HC trip emissions for both vehicles

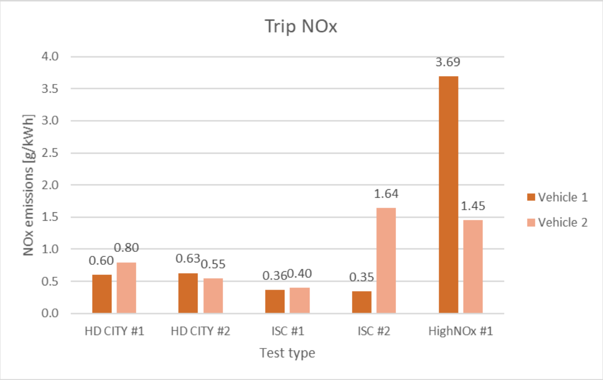


Figure 4-6 NO$_x$ trip emissions for both vehicles

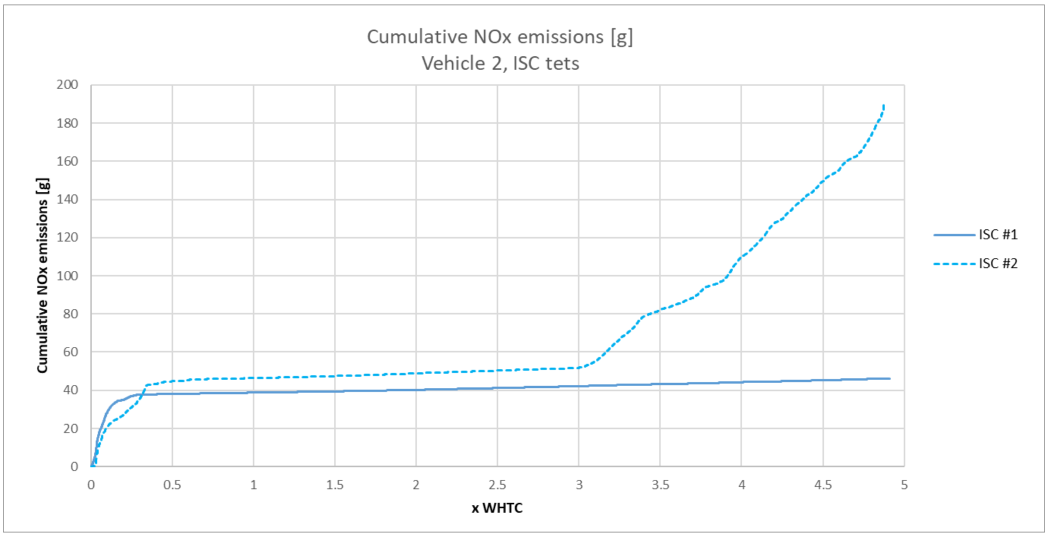


Figure 4-7 Cumulative NO$_x$ trace for the two ISC tests performed with vehicle 2

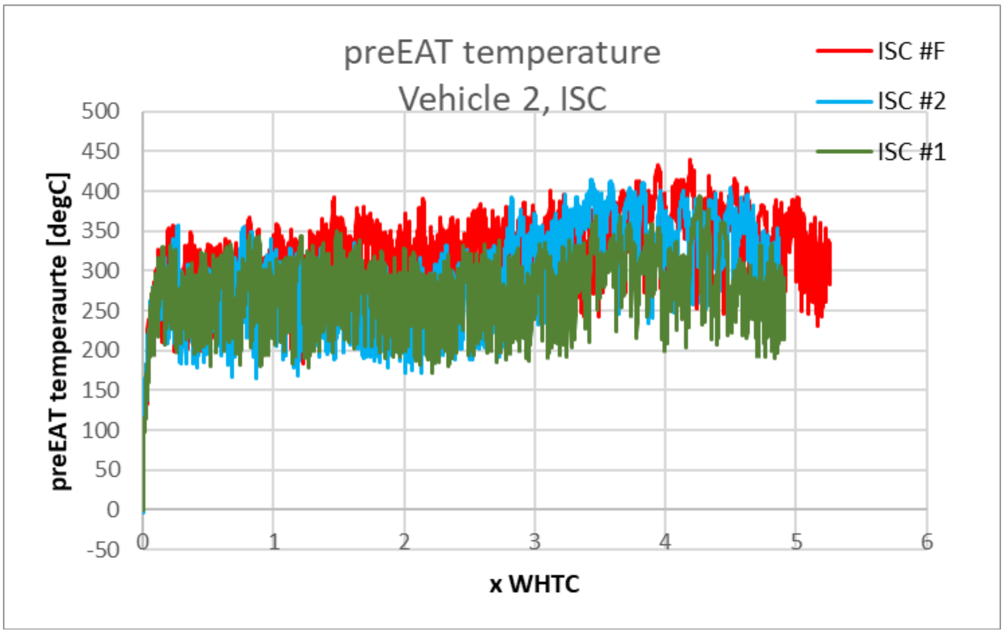


Figure 4-8 upstream (pre)EAT traces for all three ISC tests conducted with vehicle 2

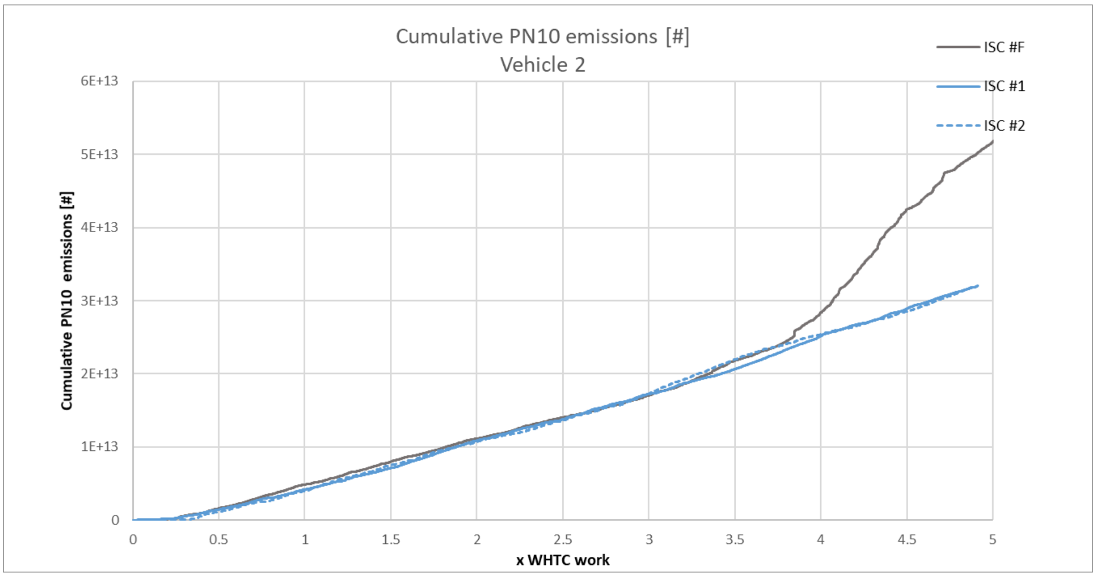


Figure 4-9 Cumulative PN results for vehicle 2, including all three ISC tests conducted.

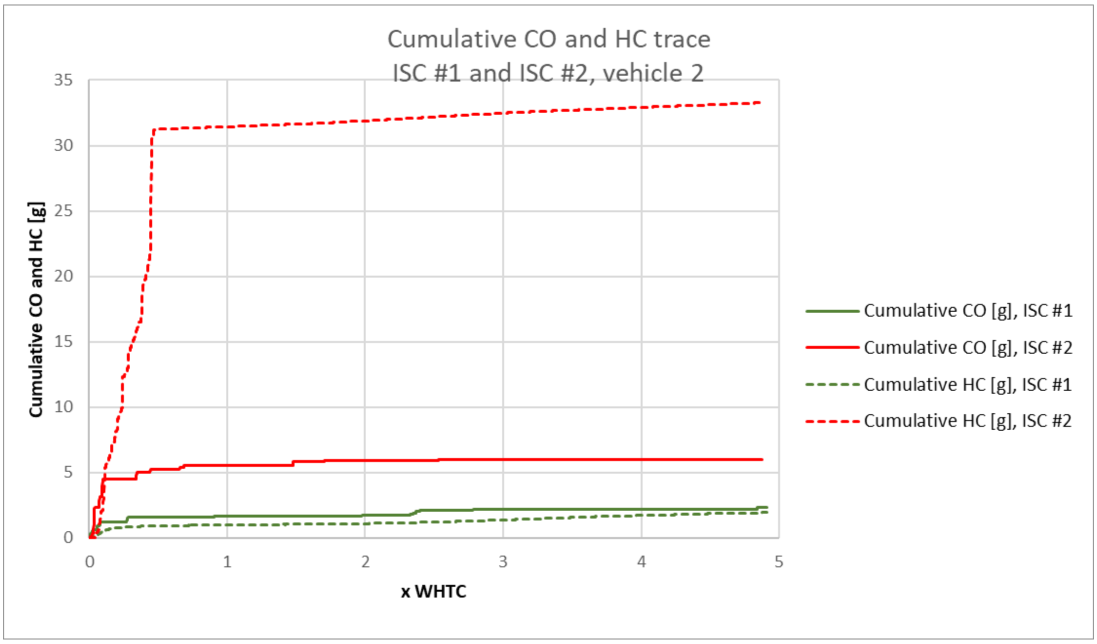


Figure 4-10 Cumulative CO and HC trace for ISC #1 and ISC #2 test conducted with vehicle 2

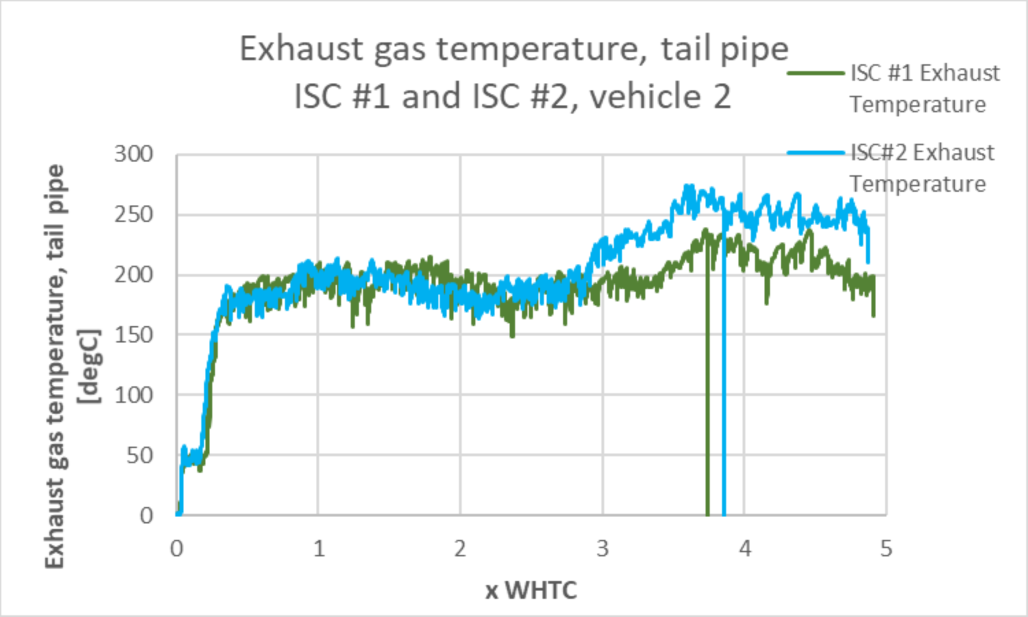
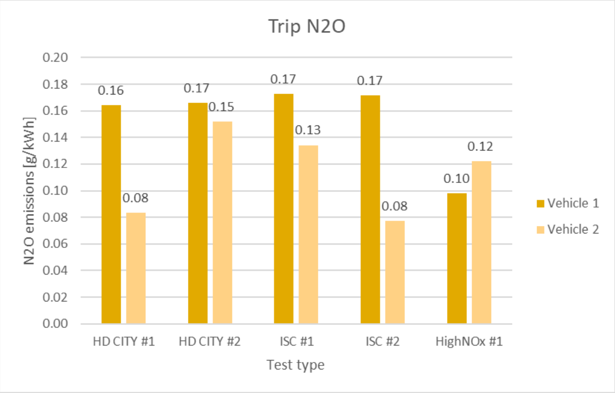


Figure 4-11 Tailpipe EGT traces for the two analysed ISC tests conducted with vehicle 2



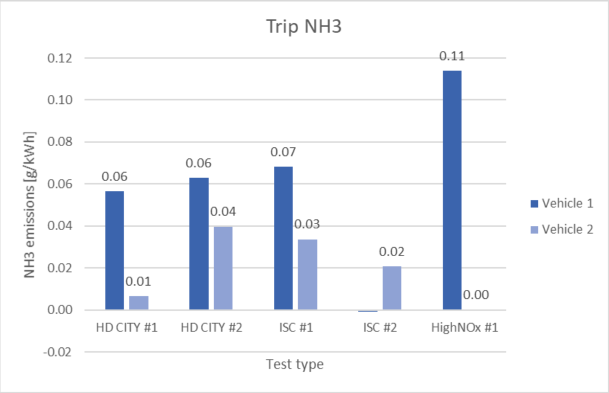


Figure 4-12 N_2O trip emissions *Figure 4-13 NH_3 trip emissions for both*
vehicles
for both vehicles

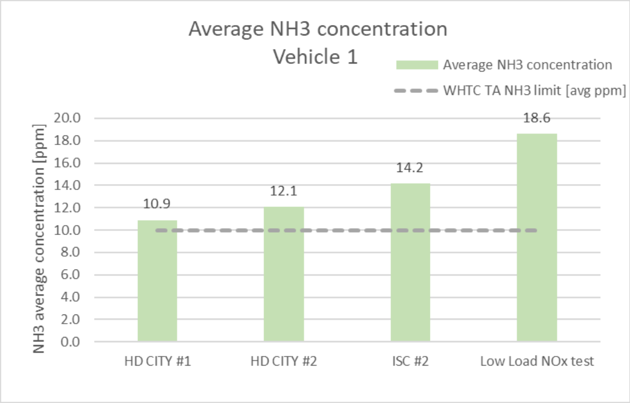


Figure 4-14 Average NH$_3$ concentration for vehicle 1

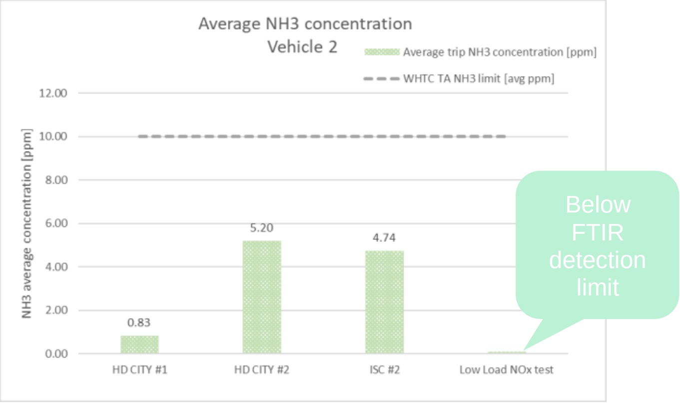


Figure 4-15 Average NH$_3$ concentration for vehicle 2

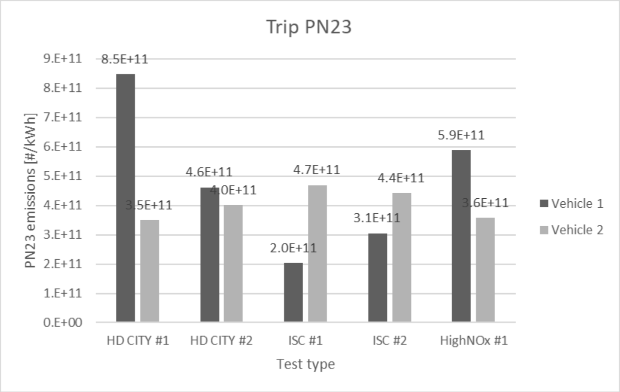


Figure 4-16 PN$_{23}$ trip emissions for both vehicles measured with PEMS

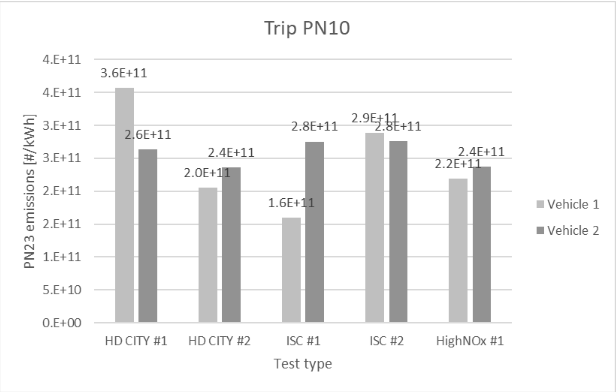


Figure 4-17 PN$_{10}$ trip emissions for both vehicles

4.3 Effect of testing conditions on total MAW- based results

This chapter describes the effect of different parameters that influence the MAW based analysis in respect of both Euro VI and CLOVE Euro VII boundaries. The work based emissions calculated with different MAW parameters (Euro VI D, E and CLOVE Euro VII, CLOVE Euro VII *reference P corrected*) demonstrates the influence of different analytical variables (such as boundary parameters shown in chapter 2, Table 2-6) in respect of legislative HDV emissions, but also indicates the relation between engine load, thermal management and test condition that influence the emission analysis of HDVs. The current parameters for the ISC-criteria are set so that the most challenging conditions (such as cold start emissions or low power conditions) for current Euro VI EATS-technologies are generally excluded from the ISC-test analysis. The cold start threshold for the coolant temperature used in Euro VI step D analysis starts when the coolant is > 70 ˚C and > 30 ˚C for Euro VI step E respectively. If the conditions are not met within 900s after the start of the test, the analysis begins in any case with coolant state at the given time (900 s). For the proposed CLOVE Euro VII analysis, the evaluation starts from the moment the engine is started, with no exclusions of any coolant temperature conditions. Furthermore, the criteria for the minimum payload and test route (balance between different driving speeds and stand still time) are crucial for the predominant exhaust temperature, hence thermal management of the EATS, as the emission reduction is highly dependent on the thermal state and catalyst operating threshold temperatures. The allowed payload in the Euro VI regulation is between 10 to 100 %, meanwhile the Euro VII proposal by the CLOVE consortium includes all payload conditions.

This section describes the emission characteristics for both vehicles in respect of test route and data post-processing method. The figures presented in this paragraph are presented both as average WW of all included MAWs and as 90th percentile of the average calculated work based MAWs over all valid window according to the parameter criteria defined by each analysis method (Euro VI and Euro VII MAW criteria).

4.3.1 Assessment of CLOVE Euro VII parameters on current Euro VI approved vehicle regulated emissions - Vehicle 1

The general overview of the post processed results may be categorized based on valid data evaluation. E.g. Figure 4-18 expresses the average and minimum relative engine power over all work windows for each test type and calculation method. On basis of Figure 4-18, we may conclude two clear phenomenon: 1. Due to the nature of the engine load in relation to test type, minimum work window power in the given tests falls below the criteria for Clove Euro VII reference power correction only during the low load NOx test. Therefore no ref P corrections are needed for the HD City results nor to the ISC data. 2. Also, no valid work windows for the VTT low load NO_x test cycle were found to produce any MAW data in terms of Euro VI legislation, therefore no analysis for neither step D or step E could be made. Because of these findings, the rest of the emission analysis for vehicle 1 exclude these above mentioned cycles (Euro VI step D and E in low load NO_x tests) that include no further usable information, and all results described as Clove Euro VII are treated as:

ref P uncorrected = ref P corrected

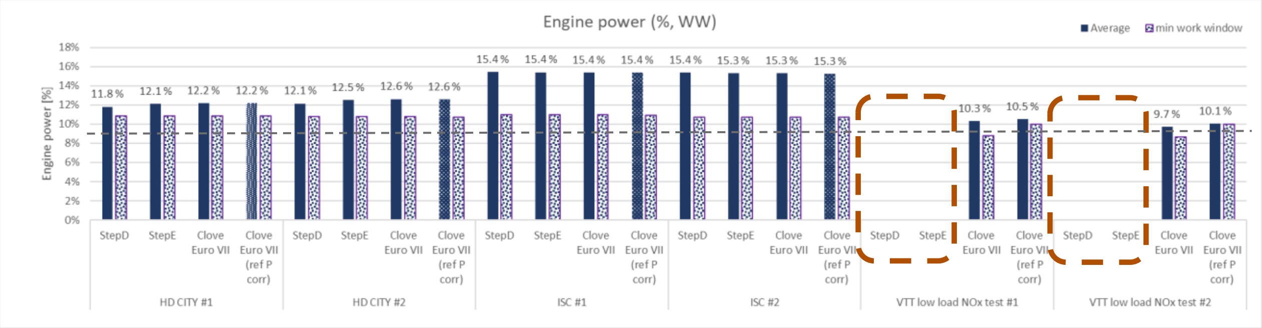


Figure 4-18 Average and minimum engine power (work window) calculated from the work based MAW:s

The WW results for CO_2 emissions are presented in Figure 4-19. Relative small changes between the post processing methods may be found between the cases Euro VI step D, E and Clove Euro VII criteria. The CO_2 results in these tests vary between 685 - 687 g/kWh for HD-city and 665 - 670 g/kWh for the ISC tests. Also, the influence of test condition (driving environment) on CO_2 emissions are well demonstrated by comparing two best vs worst case scenarios: Vehicle 1 produces CO_2 emissions in a valid ISC tests with Euro VI step D processing ca. 664 g/kWh, meanwhile in low driving speeds with long stop periods (processed with CLOVE Euro VII method), the CO_2 emissions increase for the Low Load NO_x test up to 760 g/kWh.

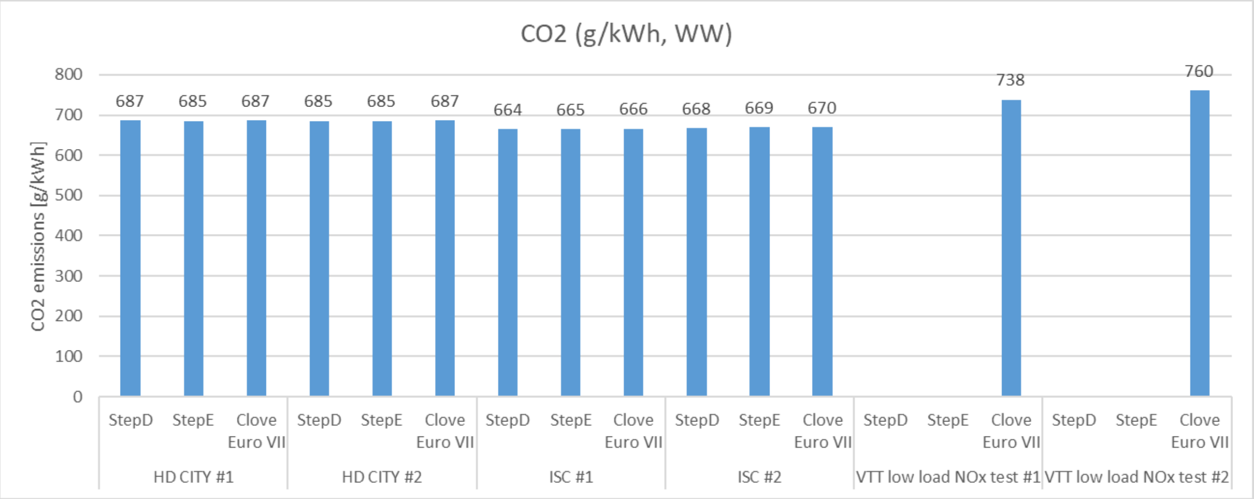


Figure 4-19 Average valid work window CO_2 results obtained from vehicle 1 in respect of test type and post processing method

For all tests conducted with vehicle 1, the CO emissions were found extremely low, especially for the conducted HD-City or ISC-conditions. However, the low loads and long idle period causes slightly increased CO emissions in the Low Load NO_x tests with the CLOVE Euro VII processing methods (Figure 4-20). Nevertheless, it should be noted that the CO emissions even in these conditions are relatively low, indicating that the DOC used in this particular vehicle is operating satisfactory in various, even challenging conditions. The variation between all CO results for all WWs included and for the 90th percentile were also almost equally low, indicating that the CO emission variation is reasonably small. Similarly, the highly efficient DOC operation may be confirmed from the THC emissions, which were correspondingly remarkably low in all tests throughout all test conditions, despite some increase in the Low Load NO_x test was seen. Therefore, no issues fulfilling even stricter CO or THC regulation is expected to raise issues even with current EAT-technologies in future development of legislation.

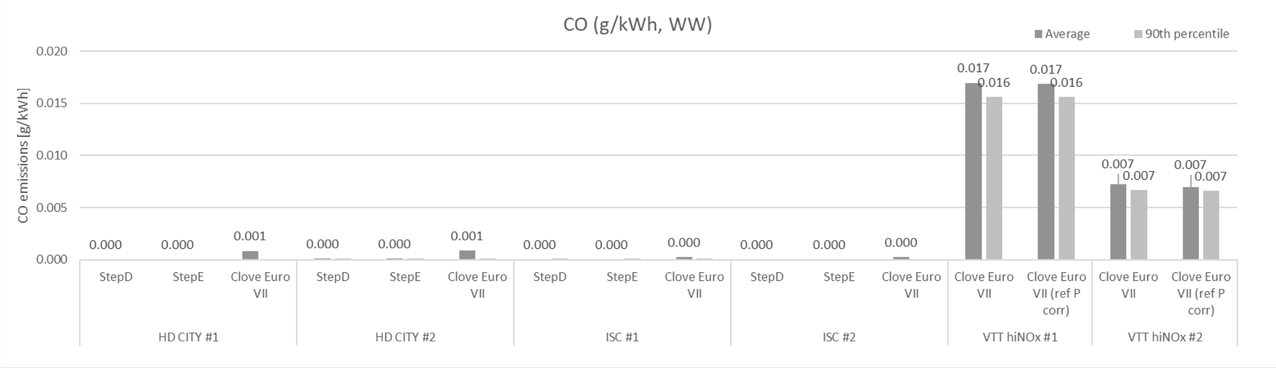


Figure 4-20 Average valid work window CO results obtained from vehicle 1 in respect of test type and post processing method

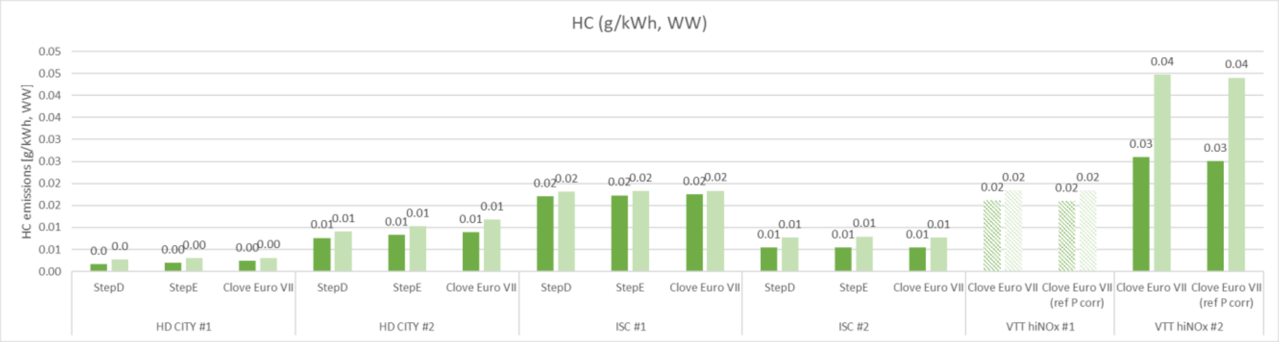


Figure 4-21 Average valid work window HC results obtained from vehicle 1 in respect of test type and post processing method (results marked with striped bars are excluded from the analysis due to partly missing data)

The WW NO_x emissions, both evaluated by total average MAW or 90th percentile turned out low with the 90th percentile NO_x emissions passing the Euro VI regulative limit (0.46 x 1.5 = 0.69 g/kWh) for all post processing methods for the HD-city and ISC tests. However, the conducted tests indicate clearly that the conditions in the Low Load NO_x tests turned out challenging for SCR-system, as the low driving speeds and long idle periods promote cold catalyst temperatures as the NO_x conversion efficiency decrease significantly below thermochemical boundaries and outside the designed operation conditions. The Low Load NO_x test resulted in NO_x emissions in average 3 to 3.2 g/kWh meanwhile with the ref power correction, NO_x emissions rose up to between 4.2 to 5.8 g/kWh.

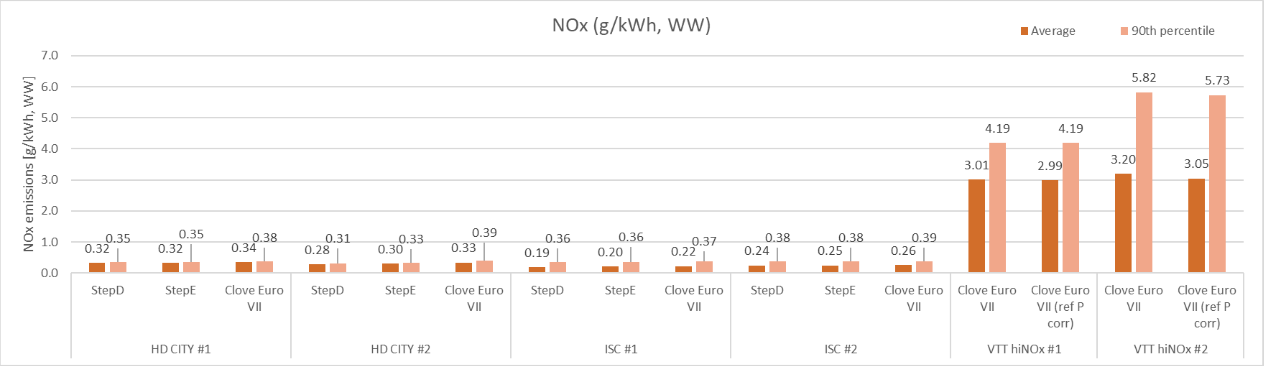


Figure 4-22 Average valid work window NO_x results obtained from vehicle 1 in respect of test type and post processing method

The PN_{23} WW emissions were found below the current limits (with the CF for PN23 of 1.63) for all HD-city and ISC tests conducted (Figure 4-23). Like for the NO_x trend, a remarkable increase in PN_{23} emissions were found for both Low Load NO_x cases. The PN_{23} results were especially above the boundaries for the 90th percentile of the test quantities, exceeding the current Euro VI limits for both power corrected and uncorrected results. The reason for the increase for the 90th percentile are the rapid load changes caused in urban conditions where sudden accelerations cause rapid fluctuations in the engine load, thus air-fuel ratio.

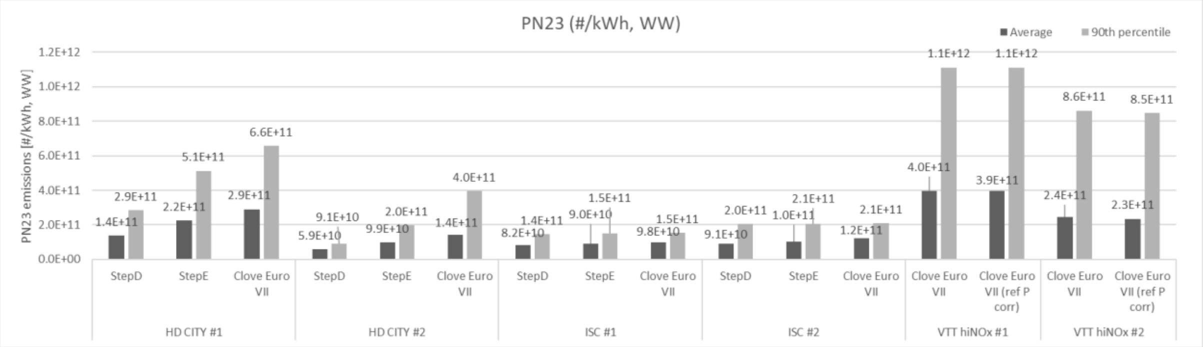


Figure 4-23 Average valid work window PN_{23} results for PEMS PN obtained from vehicle 1 in respect of test type and post processing method

4.3.2 Impacts of CLOVE Euro VII parameters on current Euro VI approved vehicle unregulated emissions - Vehicle 1

By monitoring the currently unregulated Euro VI emissions, N_2O, NH_3 and PN_{10}, the applicability and compliance of current EAT-technologies for upcoming supplements in emission regulations may be analysed. Especially certain catalyst materials, rate of charging and catalyst control strategies (such as SCR and urea injection efficiency) are parameters that affect N_2O and NH_3 formation. Also, the filtering efficiency of a DPF is typically bound to various parameters that are optimized for current particle size criteria, without causing excess losses in backpressure, deterioration and DPF life span.

The production of N_2O emissions for vehicle 1 were found surprisingly even throughout all test conditions (Figure 4-24). All WW results, average and 90th percentile in respect to all analysed WWs were monitored between 0.11 - 0.2 g/kWh. Also, NH_3 emissions were typically low for all HD-city and ISC tests. However, with the HiNOx tests the NH_3 emissions were roughly doubled, expectedly being caused by poorer SCR performance as the catalyst temperatures decrease with low load conditions (Figure 4-22).

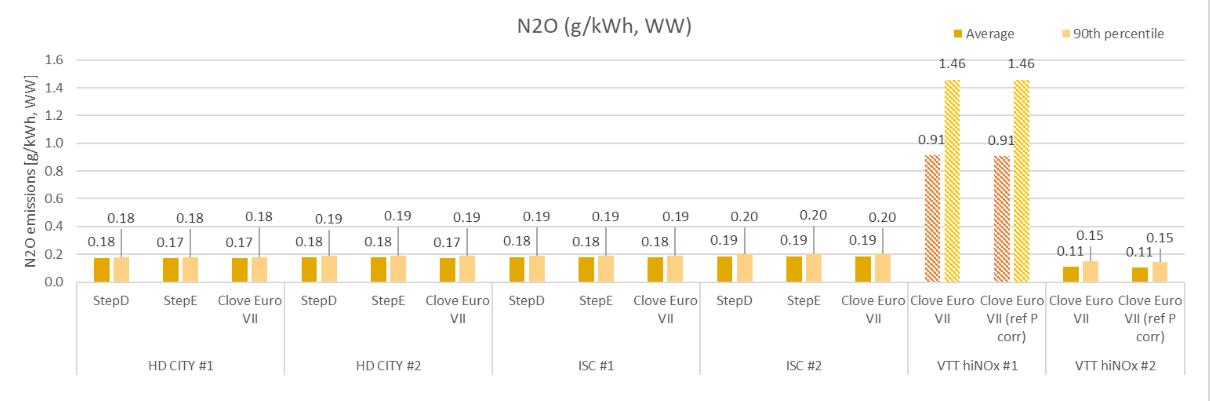


Figure 4-24 Average valid work window N_2O results obtained from vehicle 1 in respect of test type and post processing method (results marked with striped bars are excluded from the analysis due to partly missing data)

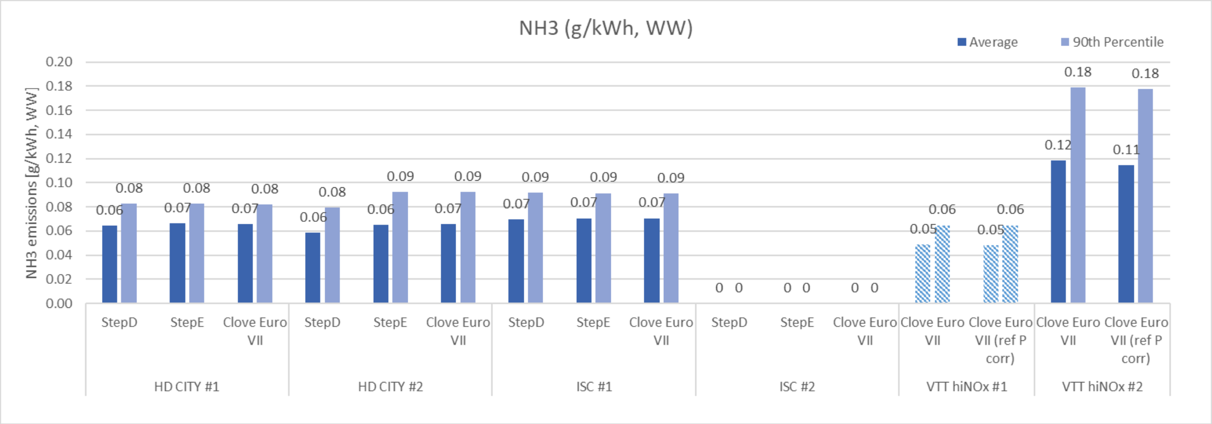


Figure 4-25 Average valid work window NH_3 results obtained from vehicle 1 in respect of test type and post processing method

The PN_{10} emissions remain throughout the total average WW results below $3*10^{11}$ #/kWh, with no significant trend distinguishable between the performed tests. However, the 90th percentile results of the WWs indicate that high variation within the WWs take place from test to test, with highest values obtained in ISC #2. A deeper analysis indicate that high, sudden increase in cumulative particulate number explain the incoherency in the 90th percentile PN_{10} results (Figure 4-24). Furthermore, it should at this point be noted that the PN_{10} results were found generally lower than the PN_{23} outcome, suggesting that the results between PEMS PN device and CPC PN were contradictory, as PN_{10} results account for larger quantities of particles than PN_{23} (Figure 4-25). Both the rapid increase in PN_{10} and the incoherency between the PN_{10} and PN_{23} results were found to be caused by sensitivity differences for the PN devices due to 1: Higher signal noise for PN_{23} measurements, especially in the beginning of the tests were found, ca 0 - 2000 s (Figure 4-26) and 2: due to higher sensitivity of the CPC PN_{10} device, detecting and reacting more strongly on single, rapid PN changes in particulate emissions (Figure 4-27). E.g. some of the spikes in PN were suspected to be caused by vehicle vibration or shocks caused by the vehicle hitting curbs or potholes while driving through construction sites, but due to the frequent appearance, other cause (such as natural PN peaks originated from the EAT) were not possible to be ruled out. Because of these findings, VTT decided to study the phenomenon more deeply, a second CPC measuring PN_{23} was installed on vehicle 2. Furthermore, in order to be able to compare the CPC PN_{23} and PEMS PN device, a chassis dynamometer test (1x WHVC) was decided to be executed prior to further testing. The results from the WHVC-test is described in chapter 4.3.

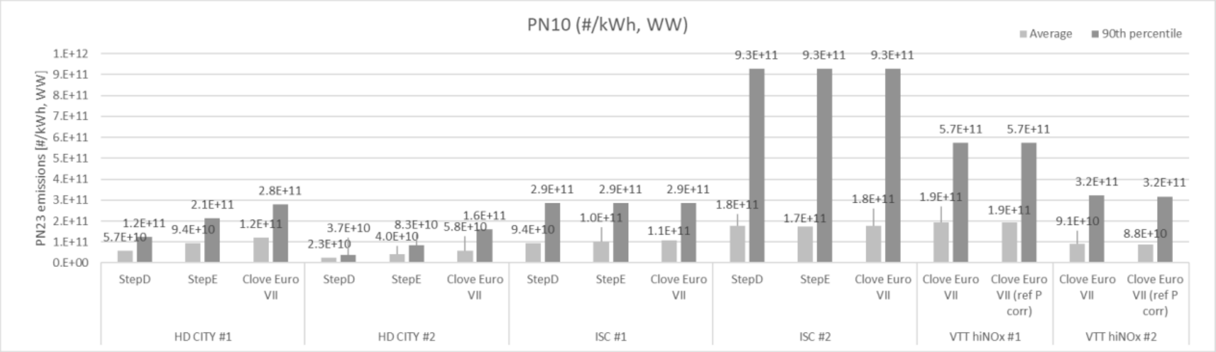


Figure 4-26 Average valid work window PN_{10} results obtained from vehicle 1 in respect of test type and post processing method

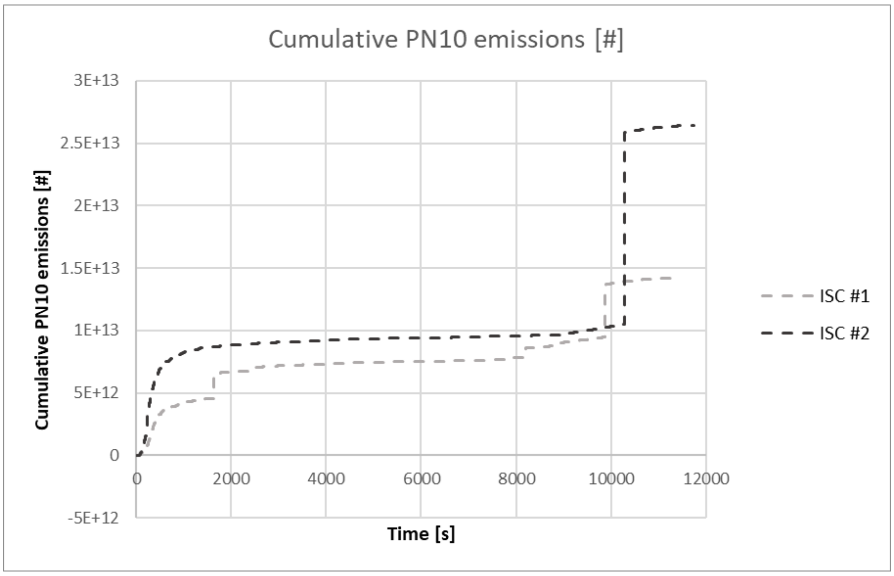


Figure 4-27 Cumulative PN_{10} emissions in two ISC tests

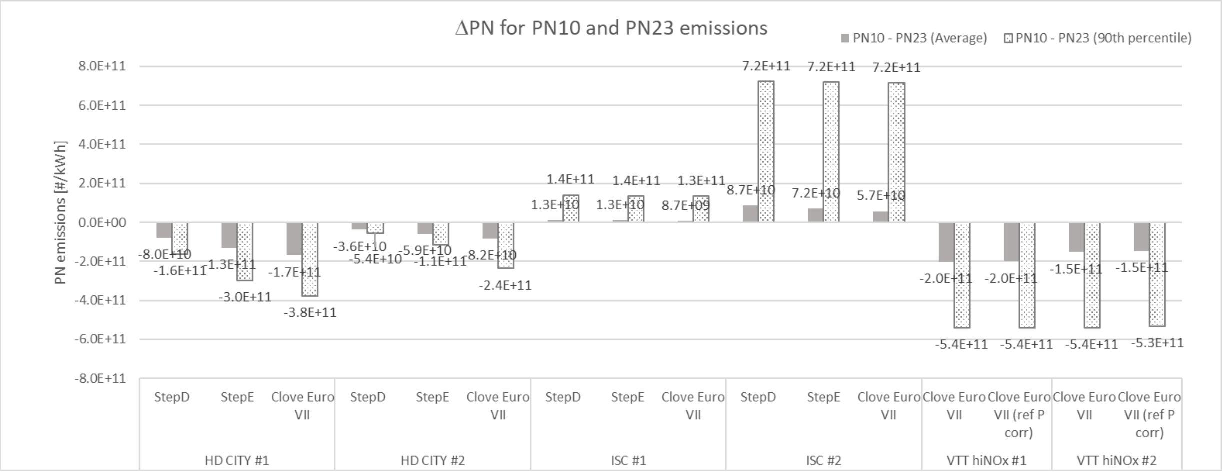


Figure 4-28 Difference in PN emissions between PN10 (CPC) and PN23 (PEMS)

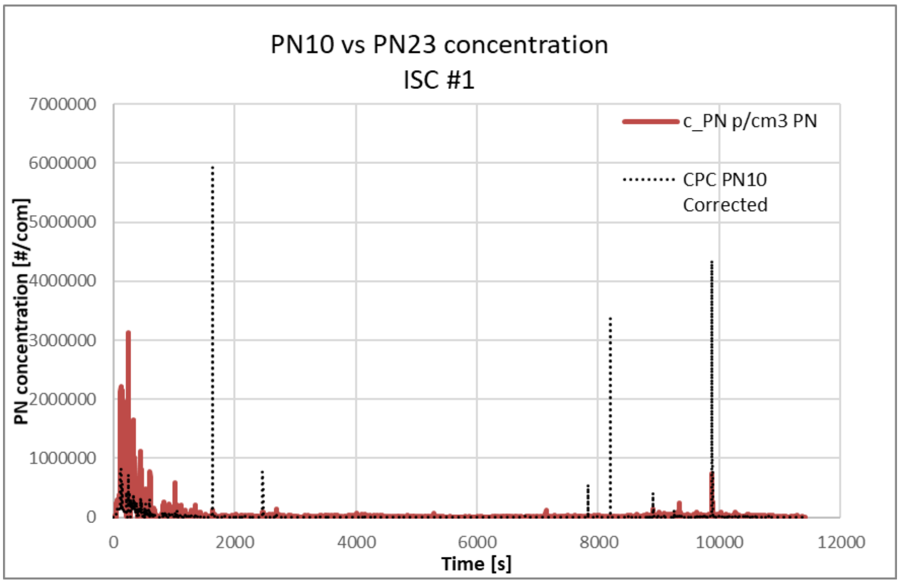


Figure 4-29 Example of PN_{10} vs PN_{23} concentration, ISC #1

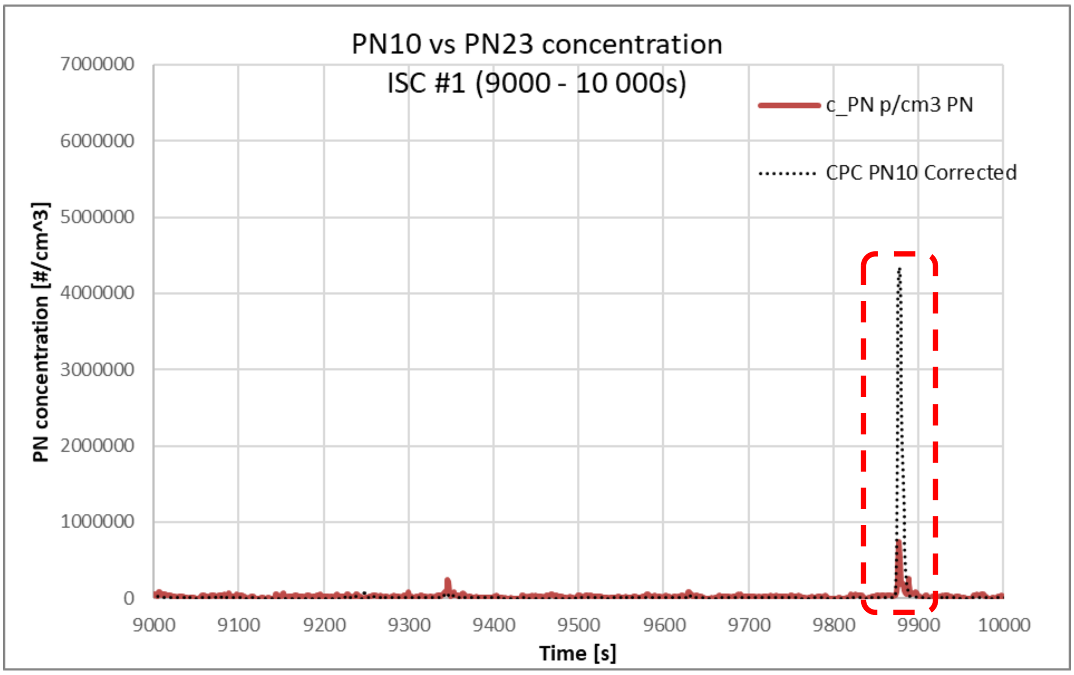


Figure 4-30 A sample of the ISC #1 test between 9000 - 10 000 s

4.3.3 Assessment of CLOVE Euro VII parameters on current Euro VI approved vehicle regulated emissions - Vehicle 2

The evaluation of the calculation methods for vehicle 2 were made equally to vehicle 1, based on the total trip work and work window validity. CLOVE Euro VII reference power corrections were calculated if necessary. The minimum relative WW power was found above the CLOVE Euro VII ref P correction boundary, apart from the VTT Low Load NO_x test. Figure 4-28 indicates that the average WW power was highest for the ISC tests, meanwhile VTT Low Load NO_x caused lowest. However, despite not fulfilling ISC-criteria, sufficient valid work windows were found for all given tests so that the MAW results could be calculated. Because no ref P correction was needed for HD-City tests nor the ISCs, these results were excluded from this report.

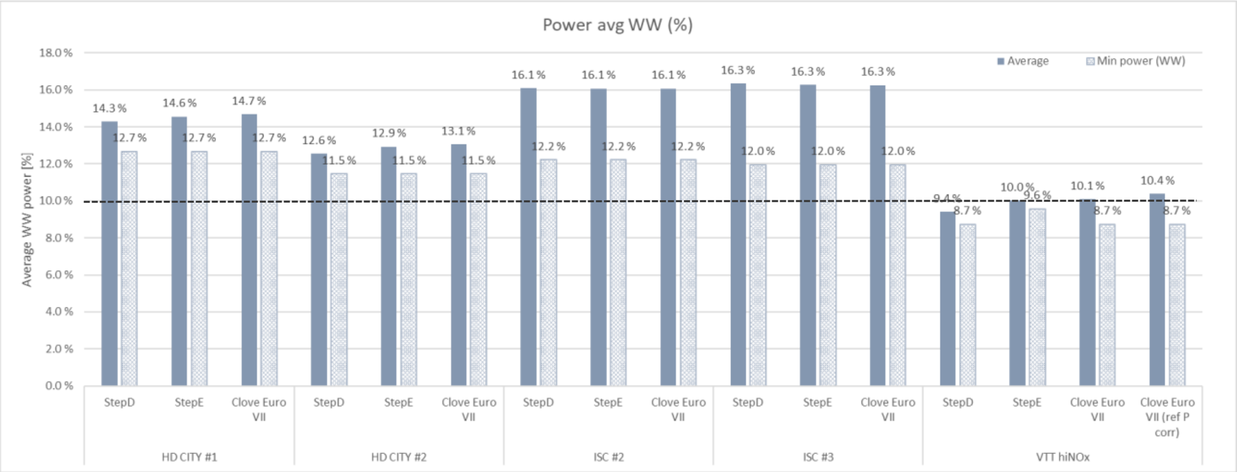


Figure 4-31 Average and minimum work window engine power calculated from the work based MAW:s

The trend of the average CO_2 emissions for the average WWs were opposite to the average relative power figure, with the vehicle producing highest CO_2 emission in the VTT Low Load NO_x cycle and correspondingly lowest for the ISC-tests. The vehicle produced CO_2 emissions in the range of 804 to 936 g/kWh depending on test and evaluation method.

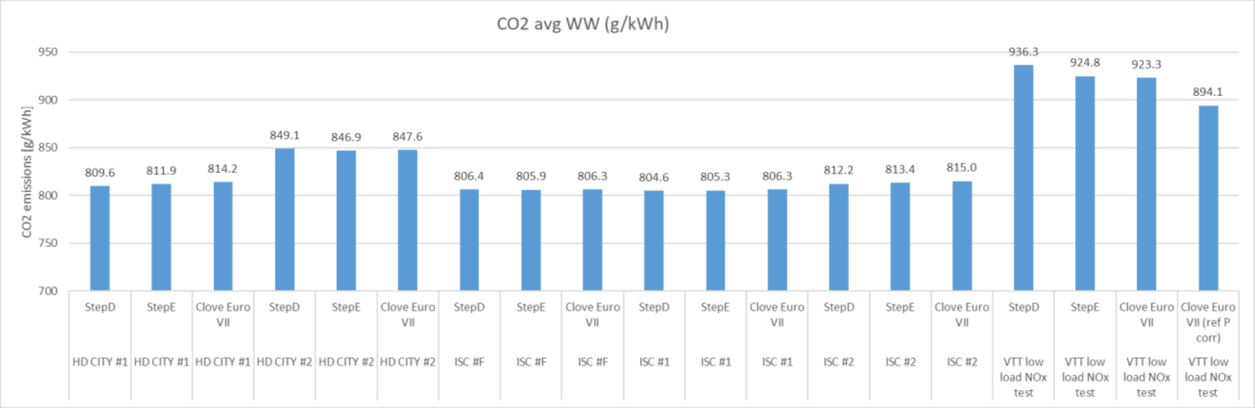


Figure 4-32 Average valid work window CO_2 results obtained from vehicle 2 in respect of test type and post processing method

Like for vehicle 1, CO and HC 90th percentile emissions were found low and well below Euro VI requirements in all test conditions. The difference between total average WW s and 90th percentile results were also found relatively low. For HD-city and ISC-tests, CO results were between 4 to 22 mg/kWh in average, and for 90th percentile up to 25 mg/kWh respectively (Figure 4-30). HC-emissions were found in the range of 10 - 70 mg/kWh in average WWs, and for 90th percentile typically below 40 mg/kWh (Figure 4-31). Due to its nature with long idle times, VTT Low Load NO_x cycle proved to cause highest CO emissions, with an average for WWs between 47 to 51 mg/kWh and for the 90th percentile, between 54 to 58 mg/kWh. During ISC #2, it was suspected that some catalyst thermal management occurred, as the HC emissions were somewhat higher compared to the other tests. Based on these tests, it may be concluded that current DOC technologies are typically very effective and are able to oxidize CO and hydrocarbons effectively even in challenging conditions.

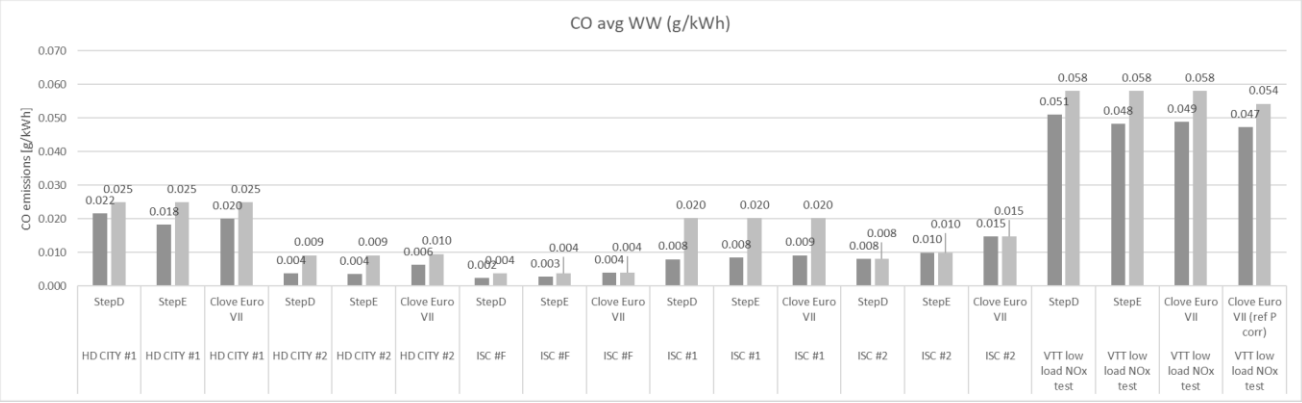


Figure 4-33 Average and 90th percentile of the valid work window CO results obtained from vehicle 2 in respect of test type and post processing method

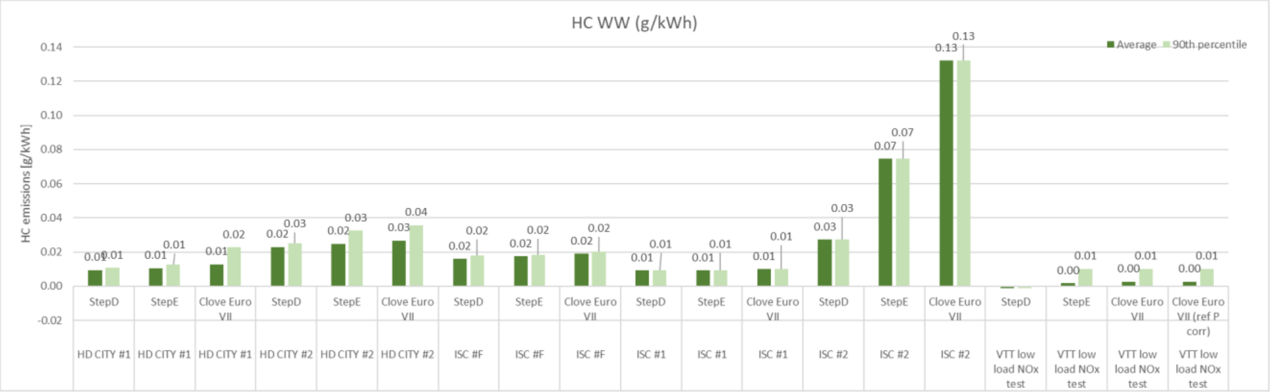


Figure 4-34 Average and 90th percentile of the valid work window HC results obtained from vehicle 2 in respect of test type and post processing method

The NO_x emissions for vehicle 2 were found somewhat two-folded. For the two HD-City tests and for the initial ISC, the NO_x emissions were remarkably low (< 0.1 g/kWh), with the NO_x emissions in the VTT High NO_x also passing the current regulative limit with the CF-factor accounted (ca. 0.69 g/kWh). On the other hand, the second ISC test produced oddly high NO_x emissions, ca. 1 g/kWh as described in chapter 4.2, thus no evidence of otherwise abnormal behaviour for the vehicle operation was found. However, PN emissions indicate that no clear sign of regeneration took place either (Figure 4-33). Also, if the vehicle would have been in a permanent limp/faulty mode, similar trends in the following test, VTT Low Load NO_x would have been seen. VTT suspects that during the second ISC test, the vehicle launched some kind of a passive, thermal control mode for the managing the EATS, thus no evidence of a failed test could be noted.

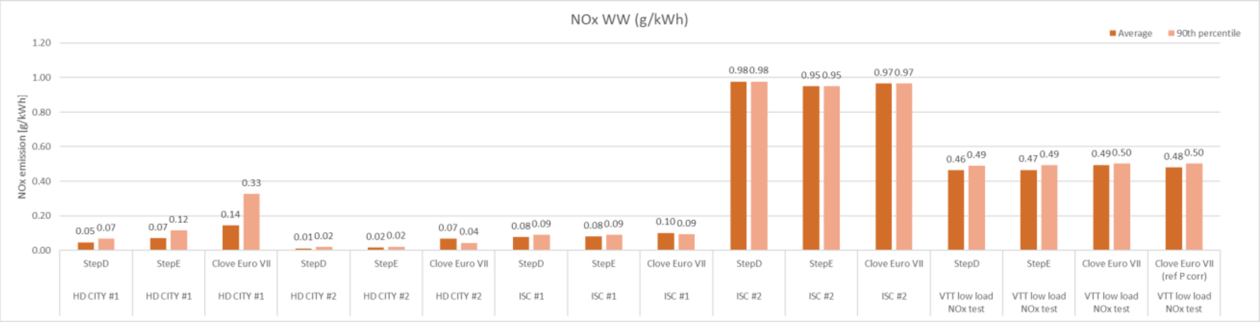


Figure 4-35 Average and 90th percentile of the valid work window NO_x results obtained from vehicle 2 in respect of test type and post processing method

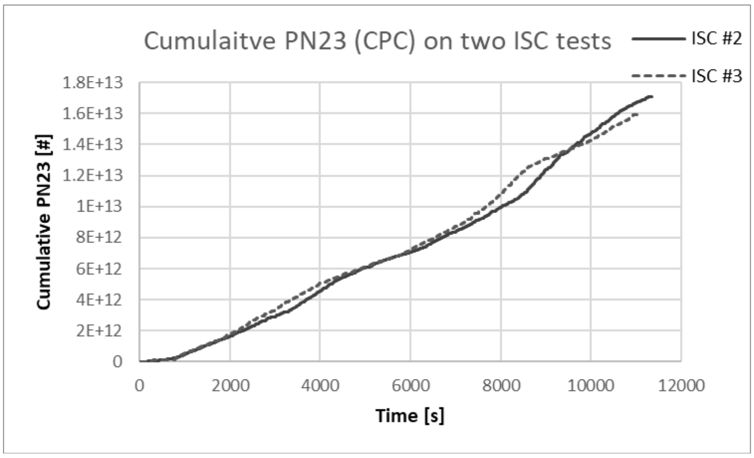


Figure 4-36 Cumulative PN_{23} for two ISC tests

The PN_{23} emissions measured by PEMS PN and the additional CPC (PN_{23}) indicate similarly to the results obtained with vehicle 1, that the PN_{23} results acquired with PEMS PN device are somewhat higher compared to corresponding emissions measured using a CPC (Figure 4-34). However, the PN emissions measured with both devices suggests that the PN_{23}-emissions are well below the Euro VI emissions in all test conditions. Opposite to vehicle 1, vehicle 2 seems to produce more particulate emissions in the tests with higher average power/work and vice versa. The average WW PN_{23} emissions measured with PEMS PN device was between $2.3*10^{11}$ #/kWh meanwhile equal results measured with CPC were below $1.6*10^{11}$ #/kWh in all tests.

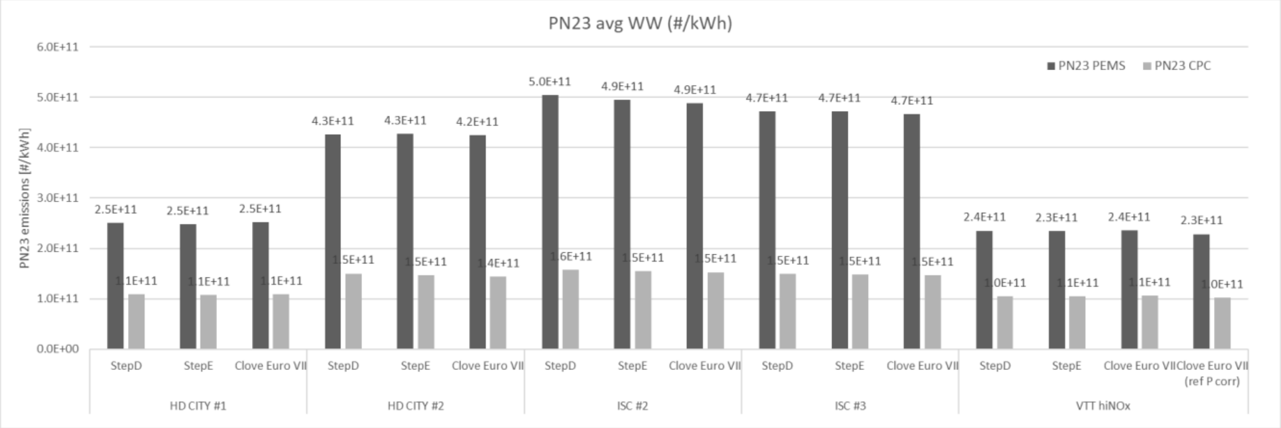


Figure 4-37 Average valid work window PN_{23} results with both CPC and PEMS PN obtained from vehicle 2 in respect of test type and post processing method

4.3.4 Assessment of CLOVE Euro VII parameters on current Euro VI approved vehicle unregulated emissions - Vehicle 2

The N_2O emissions were found less stable for vehicle 2 compared to those results acquired from vehicle 1. The N_2O emissions emitted by vehicle 2 calculated with WW MAW method were found in the region of 80 mg/kWh to 160 mg/kWh in average, with the highest N_2O emissions caused in one of the HD-City tests (Figure 4-35). Lowest N_2O emissions were found for the ISC #2 test, the test with the abnormal NOx behaviour. The NH_3 emissions caused by vehicle 2 were in the region of 10 - 50 mg/kWh over average WWs. The NH_3 behaviour was found somewhat irregular with relatively large variation between test repetitions. Interestingly for the low load NO_x tests, virtually no NH_3 was produced, as the average NH_3 emissions remain somewhere on the region of 0.2 mg/kWh.

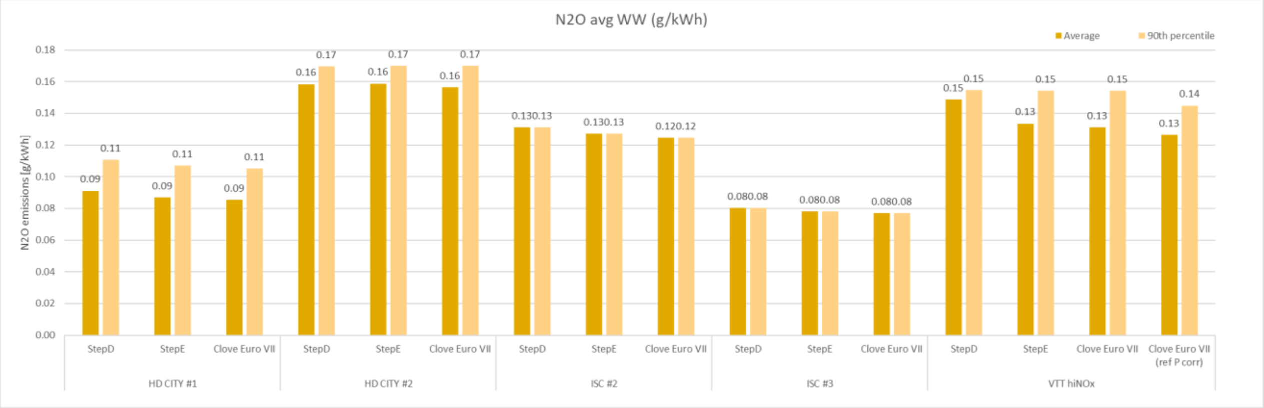


Figure 4-38 Average valid work window N_2O results obtained from vehicle 2 in respect of test type and post processing method

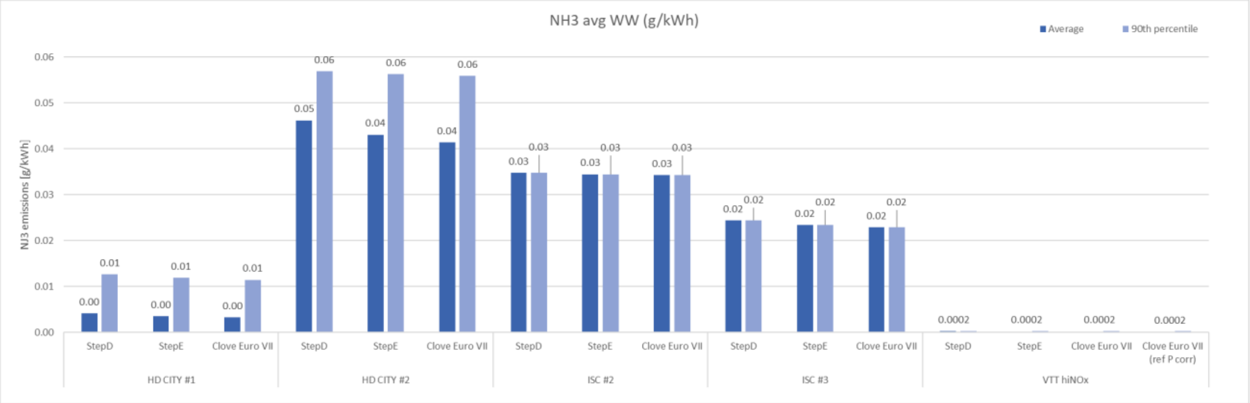


Figure 4-39 Average valid work window NH_3 results obtained from vehicle 2 in respect of test type and post processing method

Average WW PN_{10} emissions caused by vehicle 2 were in line with the CPC PN_{23} results, causing somewhat higher results compared to CPC PN_{23}. Also, the difference between average WW results and 90th percentile remain relatively low. The PN_{10} results turned out highest in the two ISC-tests, ca $2.9*10^{11}$ #/kWh, meanwhile lowest in the VTT Low Load NOx test, ca. $2*10^{11}$ #/kWh. This means that if the CLOVE Euro VII limits would remain in the boundaries of scenario A ($4*10^{11}$

#/kWh), not further improvements for particulate reduction would be needed to be made for similar technologies that has been applied for vehicle 2.

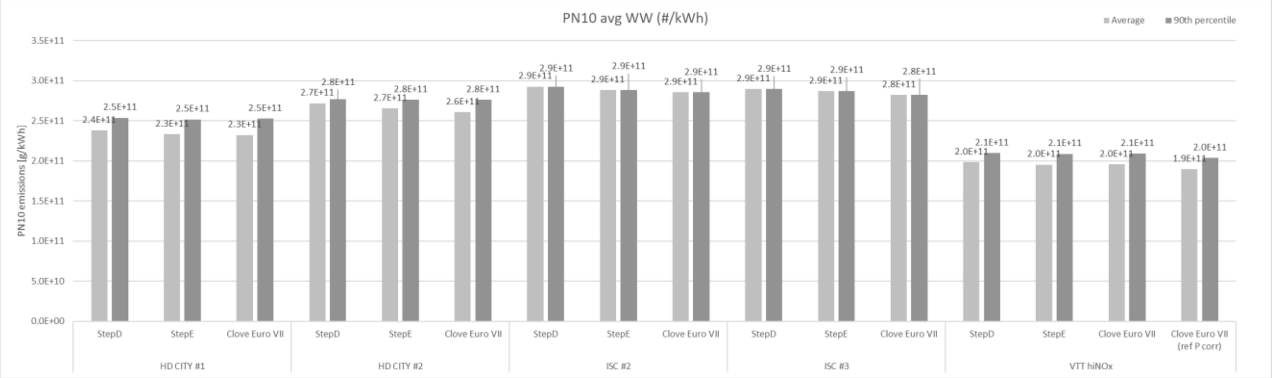


Figure 4-40 Average valid work window PN_{10} results obtained from vehicle 2 in respect of test type and post processing method

4.3.5 A summary of the effect regarding calculation method on HD-emissions

The regulatory boundaries and analytical parameters may significantly affect the emission outcome, may yet set requirements for further thermal control or optimization the vehicle EATS. The main difference between Euro VI stepD and stepE are the start of analysis in respect of engine coolant. Euro VI stepD includes the analysis of all WW that takes place after coolant has reached 70 °C, meanwhile step E correspondingly accounts for valid WWs when the coolant is above 30 °C. Also, Euro VI results exclude WWs that fall below the 10% power threshold. Based on the CLOVE consortium suggested scenarios for Euro VII, all windows should be included from the start of the tests, regardless of coolant temperature and WW power. , and shows the different time related WW NO_x emissions and , and WW PN_{23} emissions in relation to different analytical parameters, Euro VI step D, step E and CLOVE Euro VII. Based on the tests conducted in this project, the difference between step D and step E are for NO_x emissions rather insignificant, as the SCR light off takes place before the temperature reaches and urea injection, hence NOx reduction starts prior, or around the coolant temperature reaches both boundary conditions. However, this is not the case for CLOVE Euro VII analysis, as this would account for all WWs since the start of the tests. This effect is clearly seen in the WW NO_x emissions, as the pre SCR light off emissions are seen as a high peak in all cases. Interestingly, due to its short period in relation to total test time, the WWs between CLOVE Euro VII and current Euro VI step E effect the end result very little. E.g. in HD-City, the change in NO_x emissions are ca. 20 mg/kWh and in ISC, the effect is even smaller, ~10 mg/kWh.

Correspondingly, a similar effect is seen in the particulate emissions, as highest PN are formed in the early part of the test, and because cold start emissions require fuel enrichment, less efficient combustion occur and more particulate are formed. On the other hand, the effect of start boundaries are greater for PN emissions compared to NO_x, as the WW PN emissions less dependent of any active filtering threshold, rather upstream DPF particulate emissions and filter loading.

For the tests conducted in this project, CLOVE reference power correction has a relatively small effect, mostly due to the relatively high base load characteristics (typically above power correction threshold, apart from the Low Load NO_x cycle). Nevertheless, when applied, the correction effect on NO_x results is some 4 to 5 %, and for PN ca. 3 %.

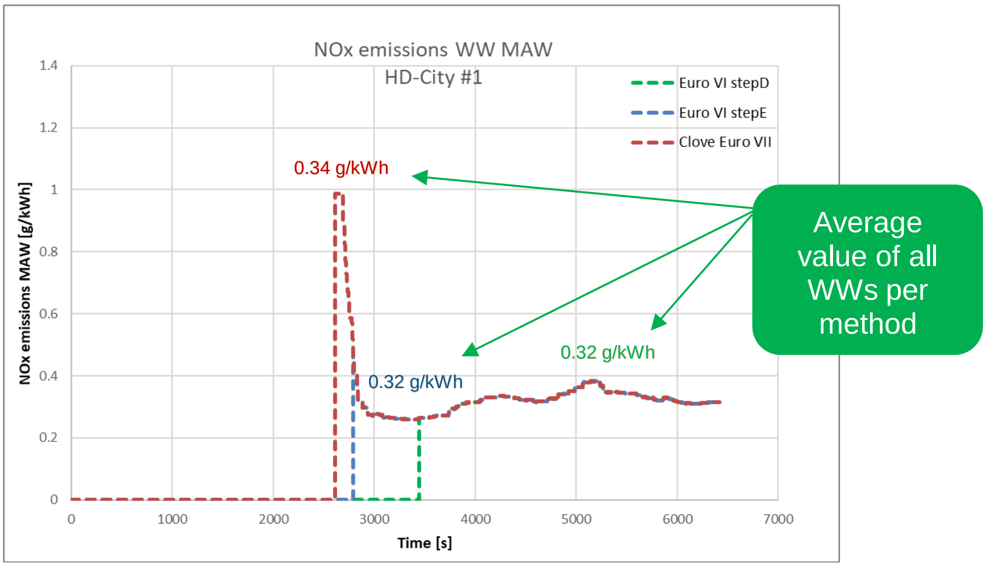


Figure 4-41 Effect of analytical method on NO_x emissions in HD-City for vehicle 1

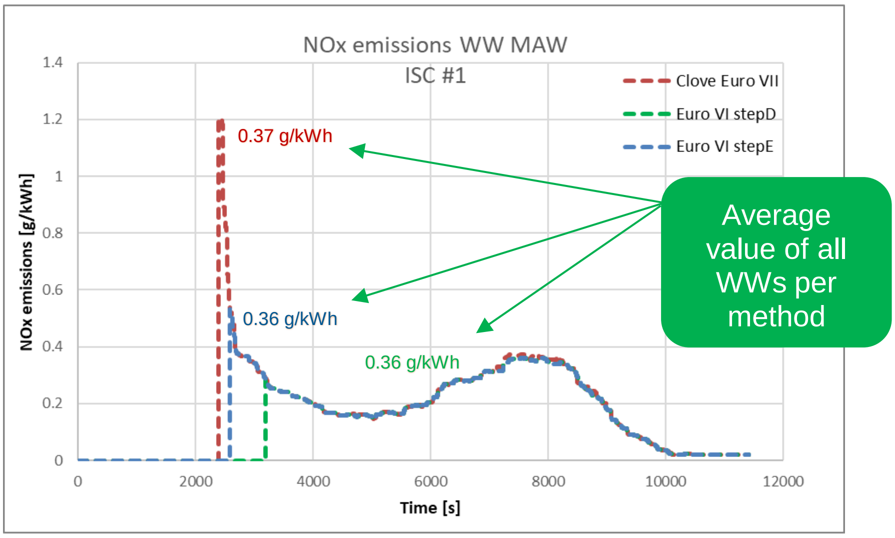


Figure 4-42 Effect of analytical method on NO_x emissions in an ISC test for vehicle 1

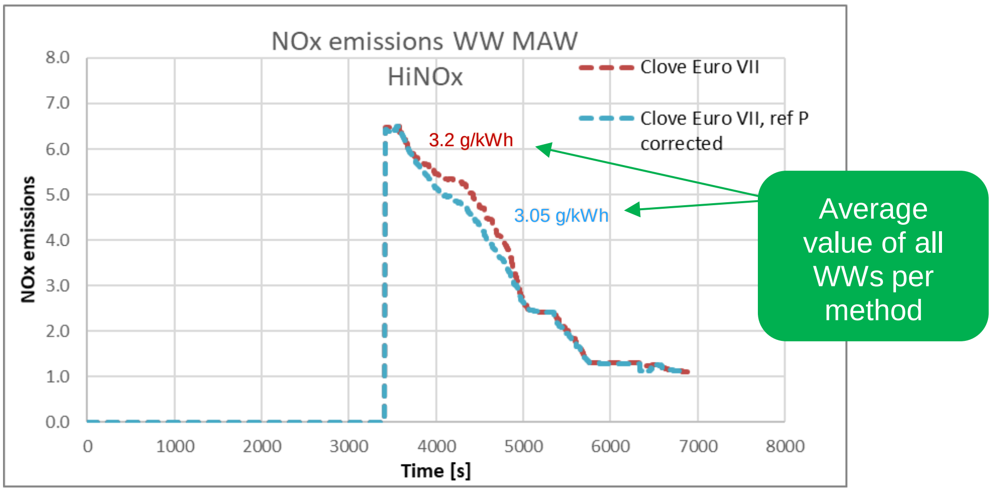


Figure 4-43 Effect of analytical method on NO_x emissions in the VTT Low Load NO_x test for vehicle 1

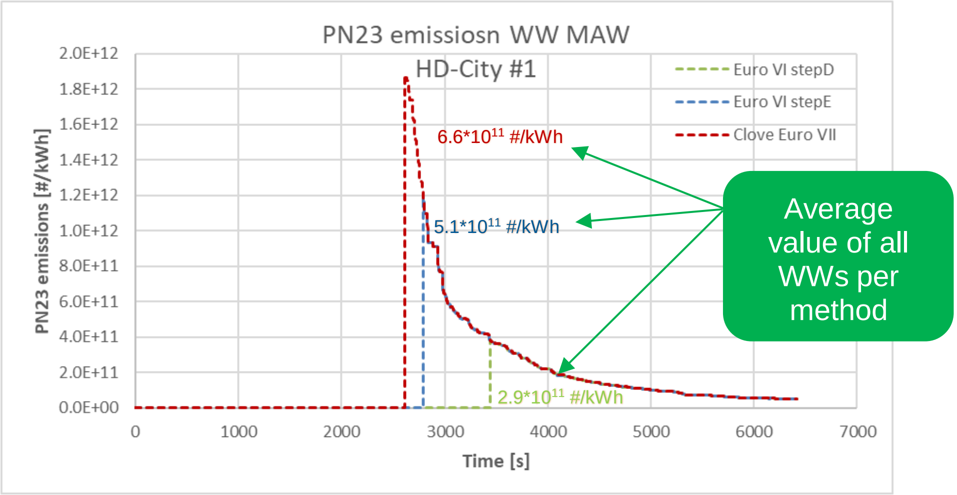


Figure 4-44 Effect of analytical method on PN_{23} emissions in the HD-city test for vehicle 1

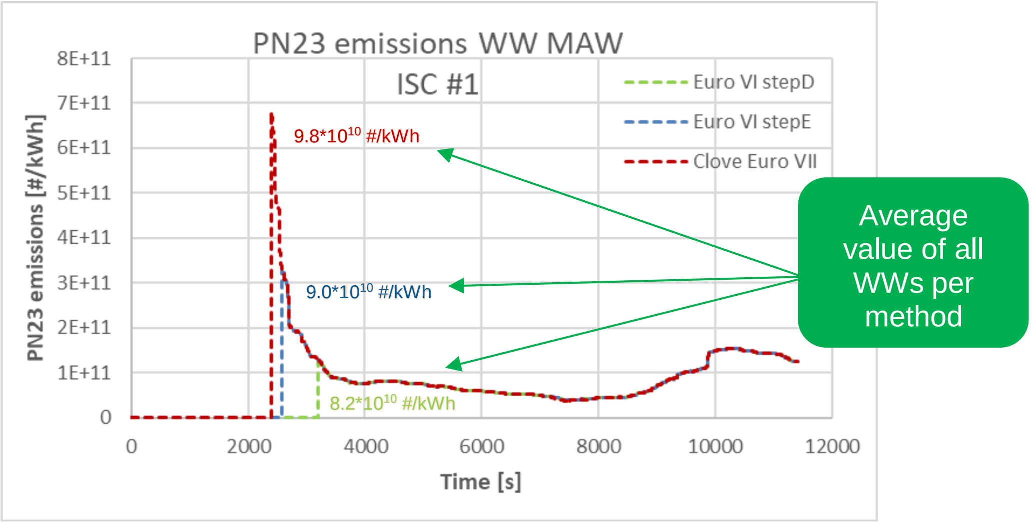


Figure 4-45 Effect of analytical method on PN_{23} emissions in one ISC test for vehicle 1

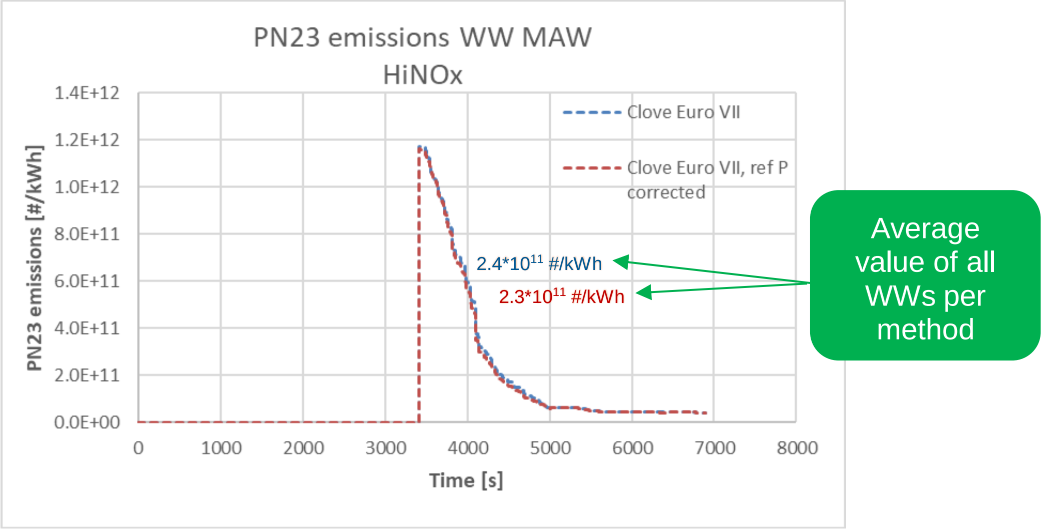


Figure 4-46 Effect of analytical method on PN_{23} emissions in VTT Low Load NO_x for vehicle 1

5. CLOVE Euro VII analysis

This chapter describes the analysed emission results in respect of the proposed CLOVE Euro VII methods and its emission limits. The performed tests were initially categorized in terms of trip WHTC work criteria and processed accordingly to the suggested post processing procedures. Prior to the final analysis, the tests were therefore divided into categories based on the 3x WHTC limit, and then further analysed either by the suggested emission budget (for trips below ≤ 3x WHTC work), 90th percentile hot MAW and 100th percentile MAW limits.

5.1 Emission analysed with CLOVE Euro VII method, Vehicle 1

5.1.1 Test limits and application of CLOVE EURO VII analysis

In order to assess the vehicle emission performance according to the suggested CLOVE Euro VII method, all tests performed in this project were initially categorized based on the trip work with the 3x WHTC criteria, shown for vehicle 1 in Figure 5-1 and for vehicle 2 in Figure 5-2. Depending on the total trip work, the results were then processed for each cycle determined accordingly using the suggested procedure presented by the CLOVE consortium following:

1. *For tests with trip work ≤ 3x WHTC: 3x WHTC budget + 100th percentile MAW limit were calculated*
2. *For tests with trip work > 3x WHTC: 3x WHTC budge + 100th percentile MAW + 90th percentile hot MAW limits were calculated*

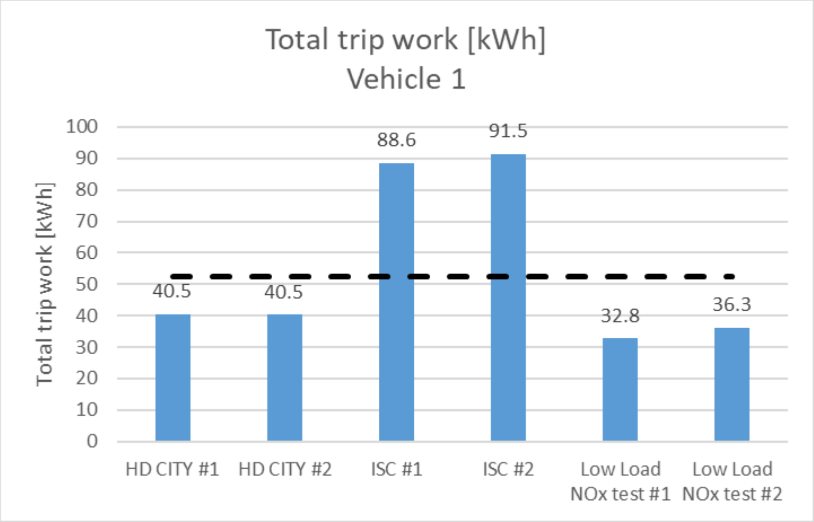


Figure 5-1 Trip work for the five tests conducted for vehicle 1

Based on the trip results, following evaluation methods were used for vehicle 1:

- HDC #1 → < 3x WHTC budget + 100th percentile
- HDC #2 → < 3x WHTC + 100th percentile
- ISC #1 → < 3x WHTC + 100th percentile + 90th percentile
- ISC #2 → < 3x WHTC + 100th percentile + 90th percentile
- Low Load NOx #1 → < 3x WHTC + 100th percentile + ref_P_corr
- Low Load NOx #2 → < 3x WHTC + 100th percentile + ref_P_corr

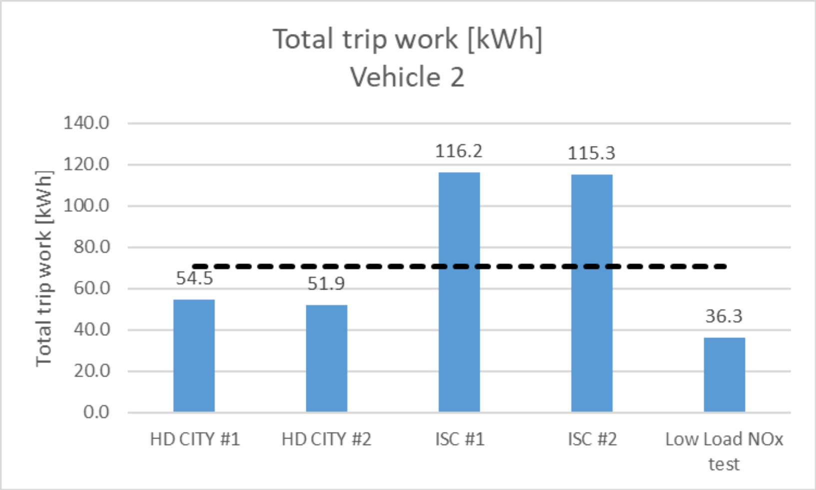


Figure 5-2 Trip work for the five tests conducted for vehicle 2

Based on the trip results, following evaluation methods were used for vehicle 2:

- HDC #1 → < 3x WHTC + 100th percentile
- HDC #2 → < 3x WHTC + 100th percentile
- ISC #1 → < 3x WHTC + 100th percentile + 90th percentile
- ISC #2 → < 3x WHTC + 100th percentile + 90th percentile
- Low Load NOx #1 → < 3x WHTC + 100th percentile + ref_P_corr
- Low Load NOx #2 → < 3x WHTC + 100th percentile + ref_P_corr

The final results calculated with the CLOVE Euro VII method are presented for vehicle 1 in Table 5-1and for vehicle 2 in Table 5-2. Cells marked in the table with red are expressing emission values exceeding the proposed CLOVE Euro VII limit, while cells marked with green represents a value passing the suggested emission boundaries. Results calculated from each test were compared against two future HD-scenarios and their respective limits defined by the CLOVE consortium: HD2 (optimised diesel with cc SRC) and HD3 (optimised diesel with cc SCR and pre heating of EATS, described in more detail in chapter 2).

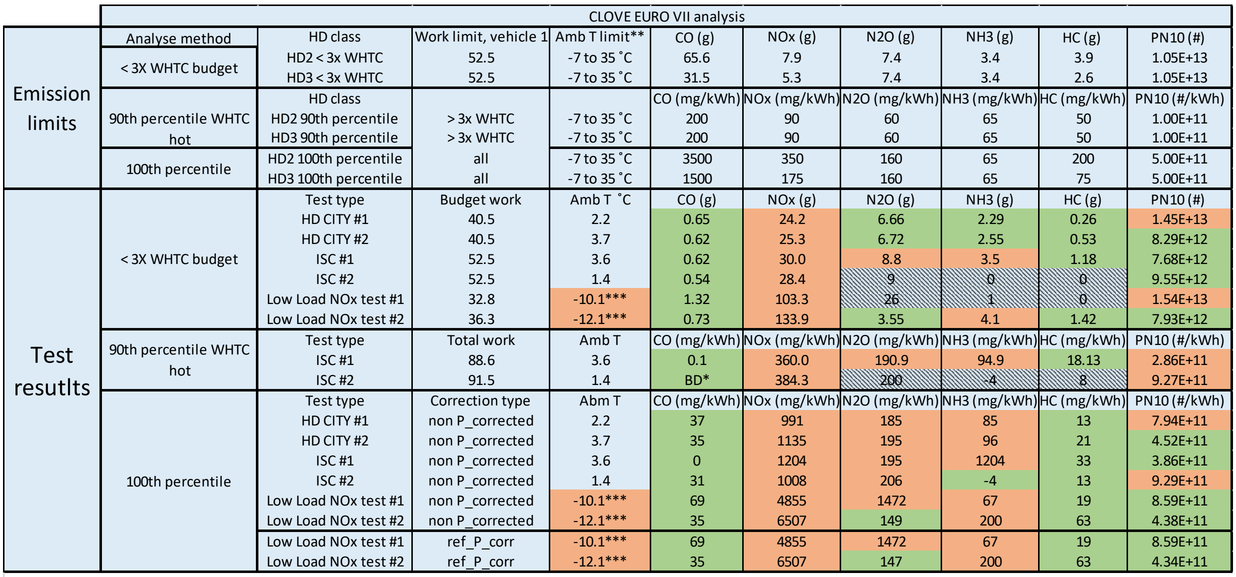
The results indicate that both vehicle 1 and vehicle 2 pass the suggested Euro VII limits for CO and HC relatively easily, as the efficiency of current DOCs are sufficient even for further regulations. The only exception is the second ISC test performed with vehicle 2, which were noted to behave abnormally during the test. The root cause for the behaviour could not explicitly be identified, yet it was suspected that a EATS thermal management, some stage of regeneration or a soft error in the EATS occurred.

The greatest challenges with current EATS technologies in respect of potential future legislation are clearly related to the NO_x reduction capability during the cold start/engine warmup periods and low load conditions. This can be seen both from the cumulative and MAW based NOx emissions, as the 3x WHTC budget limit and 100th percentile MAW limit exceed far beyond the suggested CLOVE Euro VII limits (Table 5-1 and Table 5-2). Figure 5-3 and Figure 5-4 illustrates corresponding cumulative NO_x emissions in relation to WHTC work and the proposed 3x WHTC NO_x budget limit for both vehicles. NOx emissions clearly rise above their respective 3x WHTC budget limits already by 0.1 x WHTC work is fulfilled in all test conditions, i.e. during the cold start and engine warmup phase. Typically, the formation of NO_x emissions rapidly decrease immediately after SCR light-off temperature (often around 250 °C) is reached and urea injection in enabled. Examples of upstream EATS temperature in respect of cumulative NO_x for vehicle 2 are shown in Figure 5-5 and Figure 5-6. Interestingly, vehicle 2 seems less sensitive to test conditions with lower loads and longer idle times (low load NO_x test) compared to vehicle 1, as the NO_x emissions steadily increase for vehicle 1 in the low load NO_x tests. The NO_x emissions emitted during the warm up periods are correspondingly reflected to the CLOVE Euro VII 100th percentile MAW WW results (Figure 5-8 and Figure 5-9), and the 100th percentile emissions exceeds both HD2 and HD3 NO_x limits by a remarkable magnitude. The 90th percentile hot MAWs results indicate that a higher SCR efficiency for further NO_x reduction in hot conditions would also be needed for reaching the proposed 90 mg/kWh hot MAW WW limit, as only one of the four tests (ISC #1, vehicle 2) met the proposed requirements. Nevertheless, the 1st ISC tests performed with vehicle 2 suggests that the 90th percentile is barely reachable with current Euro VI EATS performance, with a 90th percentile MAW WW result of 89.9 mg/kWh.

The CLOVE Euro VII based results suggest also that vehicle 1 is more prone to produce NH_3 and N_2O emissions, therefore not passing a single test simultaneously with given methods (≤ 3x WHTC, 90th percentile and 100th percentile) and using the corresponding CLOVE Euro VII NH3 and N_2O limits. However, vehicle 2 manages to pass simultaneously the ≤ 3x WHTC budget (Figure 5-11 and Figure 5-13) and 100th percentile limit for NH_3 and N_2O in two HD city tests and the low load NO_x test. Despite the success regarding these conditions, vehicle 2 fails the 90th percentile hot MAW and 100th MAW limits ISC conditions.

The PN(10) results are on the other hand somewhat two folded, and as relatively significant variation in the PN results were found for both vehicles between test to test. Meanwhile the 100th percentile limits are mostly met with both vehicles the PN emissions repeatedly fail to pass the limits in respect the given 90th percentile hot MAW limit. The ≤ 3x WHTC budget results also supports the finding that fairly large variation in particulate formation exists for current Euro VI vehicles between cycle to cycle. E.g. the PN10 limits are exceeded for both vehicles in their initial HD city tests, meanwhile the second repetition pass the suggested emission limits. A similar phenomenon was seen for vehicle 1 ≤ 3x WHTC budget (PN) emissions which fail to pass on the first attempt, but pass on the following. The cumulative PN figures also indicates that the characteristics of PN formation is somewhat different between the two tested individuals, as vehicle 1 produce more PN10 during the warmup phase (Figure 5-14), meanwhile vehicle 2 PN formation is more or less linear (Figure 5-15).

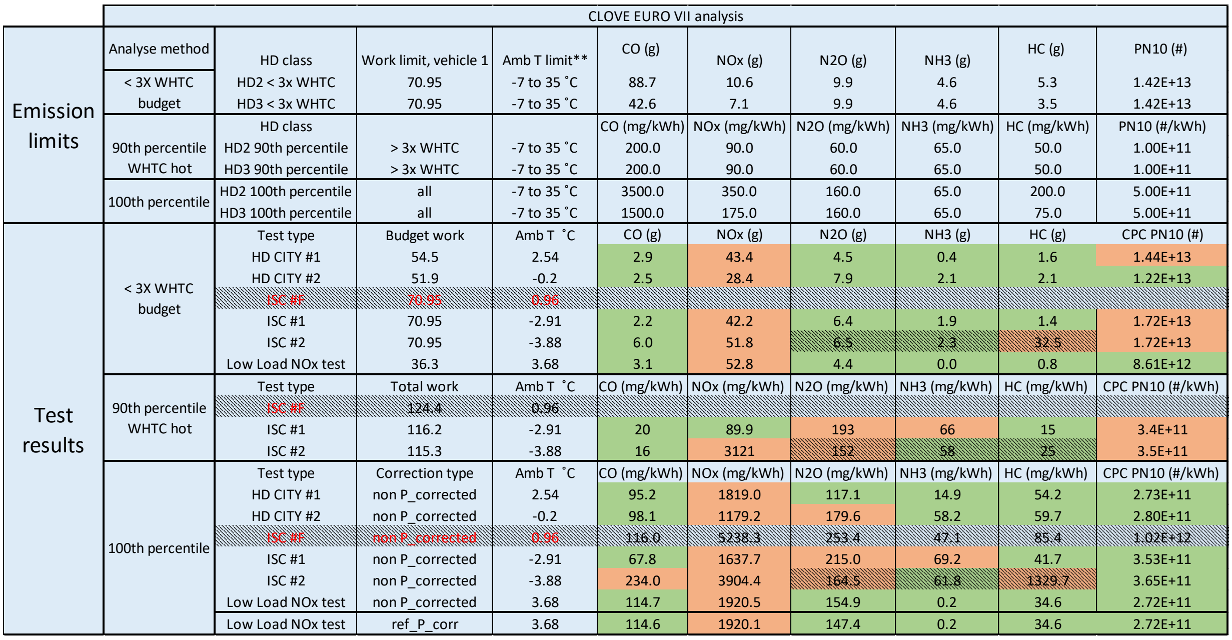
Table 5-1 The calculated tes,t results for vehicle 1 assessed using the CLOVE Euro VII method



		CLOVE EURO VII analysis								
Emission limits	Analyse method	HD class	Work limit, vehicle 1	Amb T limit**	CO (g)	NOx (g)	N2O (g)	NH3 (g)	HC (g)	PN10 (#)
	< 3X WHTC budget	HD2 < 3x WHTC	52.5	-7 to 35 ˚C	65.6	7.9	7.4	3.4	3.9	1.05E+13
		HD3 < 3x WHTC	52.5	-7 to 35 ˚C	31.5	5.3	7.4	3.4	2.6	1.05E+13
	90th percentile WHTC hot	HD class			CO (mg/kWh)	NOx (mg/kWh)	N2O (mg/kWh)	NH3 (mg/kWh)	HC (mg/kWh)	PN10 (#/kWh)
		HD2 90th percentile	> 3x WHTC	-7 to 35 ˚C	200	90	60	65	50	1.00E+11
		HD3 90th percentile	> 3x WHTC	-7 to 35 ˚C	200	90	60	65	50	1.00E+11
	100th percentile	HD2 100th percentile	all	-7 to 35 ˚C	3500	350	160	65	200	5.00E+11
		HD3 100th percentile	all	-7 to 35 ˚C	1500	175	160	65	75	5.00E+11
Test resutlts	< 3X WHTC budget	Test type	Budget work	Amb T ˚C	CO (g)	NOx (g)	N2O (g)	NH3 (g)	HC (g)	PN10 (#)
		HD CITY #1	40.5	2.2	0.65	24.2	6.66	2.29	0.26	1.45E+13
		HD CITY #2	40.5	3.7	0.62	25.3	6.72	2.55	0.53	8.29E+12
		ISC #1	52.5	3.6	0.62	30.0	8.8	3.5	1.18	7.68E+12
		ISC #2	52.5	1.4	0.54	28.4	9	0	0	9.55E+12
		Low Load NOx test #1	32.8	-10.1***	1.32	103.3	26	1	0	1.54E+13
		Low Load NOx test #2	36.3	-12.1***	0.73	133.9	3.55	4.1	1.42	7.93E+12
	90th percentile WHTC hot	Test type	Total work	Amb T	CO (mg/kWh)	NOx (mg/kWh)	N2O (mg/kWh)	NH3 (mg/kWh)	HC (mg/kWh)	PN10 (#/kWh)
		ISC #1	88.6	3.6	0.1	360.0	190.9	94.9	18.13	2.86E+11
		ISC #2	91.5	1.4	BD*	384.3	200	-4	8	9.27E+11
	100th percentile	Test type	Correction type	Abm T	CO (mg/kWh)	NOx (mg/kWh)	N2O (mg/kWh)	NH3 (mg/kWh)	HC (mg/kWh)	PN10 (#/kWh)
		HD CITY #1	non P_corrected	2.2	37	991	185	85	13	7.94E+11
		HD CITY #2	non P_corrected	3.7	35	1135	195	96	21	4.52E+11
		ISC #1	non P_corrected	3.6	0	1204	195	1204	33	3.86E+11
		ISC #2	non P_corrected	1.4	31	1008	206	-4	13	9.29E+11
		Low Load NOx test #1	non P_corrected	-10.1***	69	4855	1472	67	19	8.59E+11
		Low Load NOx test #2	non P_corrected	-12.1***	35	6507	149	200	63	4.38E+11
		Low Load NOx test #1	ref_P_corr	-10.1***	69	4855	1472	67	19	8.59E+11
		Low Load NOx test #2	ref_P_corr	-12.1***	35	6507	147	200	63	4.34E+11

*Below detection limit **extended conditions: -10 to 45 ˚C ***extended conditions exceeded, emission limits x2

Table 5-2 The calculated test results for vehicle 2 assessed using the CLOVE Euro VII method



		CLOVE EURO VII analysis								
Emission limits	Analyse method	HD class	Work limit, vehicle 1	Amb T limit**	CO (g)	NOx (g)	N2O (g)	NH3 (g)	HC (g)	PN10 (#)
	< 3X WHTC budget	HD2 < 3x WHTC	70.95	-7 to 35 ˚C	88.7	10.6	9.9	4.6	5.3	1.42E+13
		HD3 < 3x WHTC	70.95	-7 to 35 ˚C	42.6	7.1	9.9	4.6	3.5	1.42E+13
	90th percentile WHTC hot	HD class			CO (mg/kWh)	NOx (mg/kWh)	N2O (mg/kWh)	NH3 (mg/kWh)	HC (mg/kWh)	PN10 (#/kWh)
		HD2 90th percentile	> 3x WHTC	-7 to 35 ˚C	200.0	90.0	60.0	65.0	50.0	1.00E+11
		HD3 90th percentile	> 3x WHTC	-7 to 35 ˚C	200.0	90.0	60.0	65.0	50.0	1.00E+11
	100th percentile	HD2 100th percentile	all	-7 to 35 ˚C	3500.0	350.0	160.0	65.0	200.0	5.00E+11
		HD3 100th percentile	all	-7 to 35 ˚C	1500.0	175.0	160.0	65.0	75.0	5.00E+11
Test results	< 3X WHTC budget	Test type	Budget work	Amb T ˚C	CO (g)	NOx (g)	N2O (g)	NH3 (g)	HC (g)	CPC PN10 (#)
		HD CITY #1	54.5	2.54	2.9	43.4	4.5	0.4	1.6	1.44E+13
		HD CITY #2	51.9	-0.2	2.5	28.4	7.9	2.1	2.1	1.22E+13
		ISC #F	70.95	0.96						
		ISC #1	70.95	-2.91	2.2	42.2	6.4	1.9	1.4	1.72E+13
		ISC #2	70.95	-3.88	6.0	51.8	6.5	2.3	32.5	1.72E+13
		Low Load NOx test	36.3	3.68	3.1	52.8	4.4	0.0	0.8	8.61E+12
	90th percentile WHTC hot	Test type	Total work	Amb T ˚C	CO (mg/kWh)	NOx (mg/kWh)	N2O (mg/kWh)	NH3 (mg/kWh)	HC (mg/kWh)	CPC PN10 (#/kWh)
		ISC #F	124.4	0.96						
		ISC #1	116.2	-2.91	20	89.9	193	66	15	3.4E+11
		ISC #2	115.3	-3.88	16	3121	152	58	25	3.5E+11
	100th percentile	Test type	Correction type	Amb T ˚C	CO (mg/kWh)	NOx (mg/kWh)	N2O (mg/kWh)	NH3 (mg/kWh)	HC (mg/kWh)	CPC PN10 (#/kWh)
		HD CITY #1	non P_corrected	2.54	95.2	1819.0	117.1	14.9	54.2	2.73E+11
		HD CITY #2	non P_corrected	-0.2	98.1	1179.2	179.6	58.2	59.7	2.80E+11
		ISC #F	non P_corrected	0.96	116.0	5238.3	253.4	47.1	85.4	1.02E+12
		ISC #1	non P_corrected	-2.91	67.8	1637.7	215.0	69.2	41.7	3.53E+11
		ISC #2	non P_corrected	-3.88	234.0	3904.4	164.5	61.8	1329.7	3.65E+11
		Low Load NOx test	non P_corrected	3.68	114.7	1920.5	154.9	0.2	34.6	2.72E+11
		Low Load NOx test	ref_P_corr	3.68	114.6	1920.1	147.4	0.2	34.6	2.72E+11

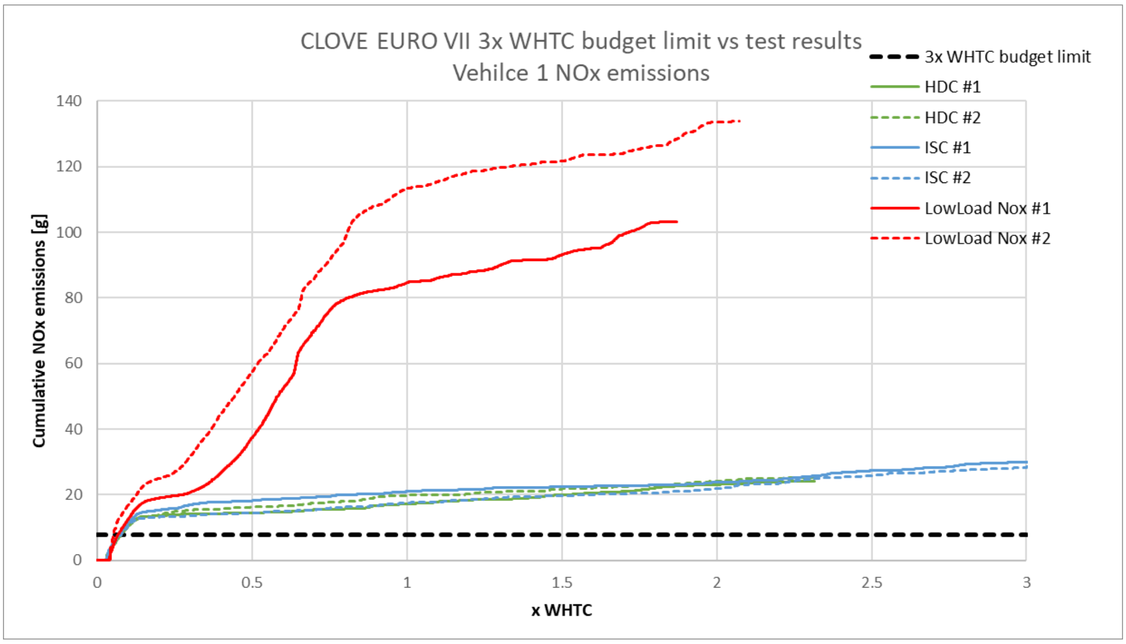


Figure 5-3 Cumulative NO$_x$ emissions for vehicle 1 in relation to trip work and suggested CLOVE Euro VII < 3x WHTC budget limit

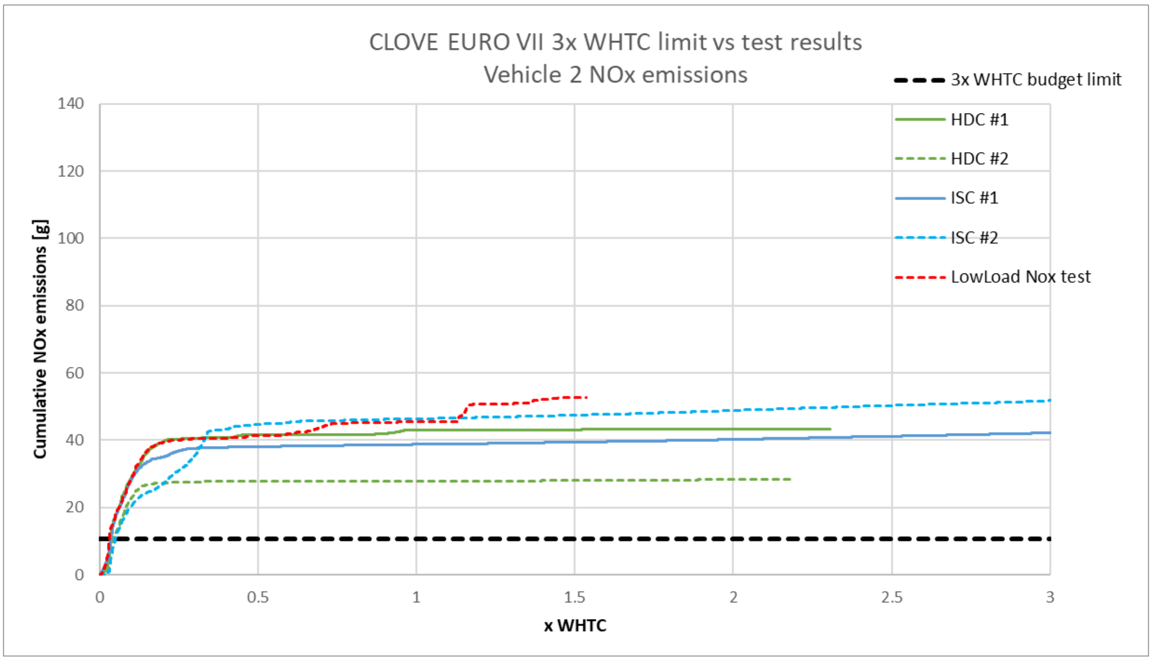


Figure 5-4 Cumulative NO$_x$ emissions for vehicle 2 in relation to trip work and suggested CLOVE Euro VII < 3x WHTC budget limit

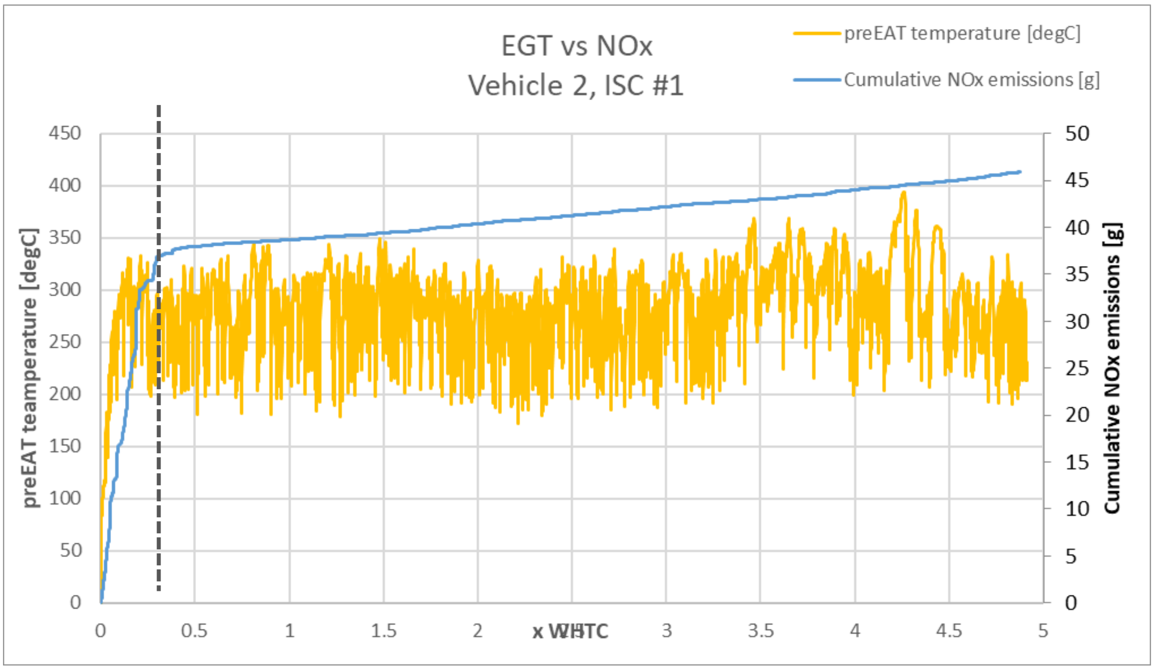


Figure 5-5 Cumulative NO_x vs EGT for vehicle 2 indicating the SCR light-off conditions in ISC #1 test

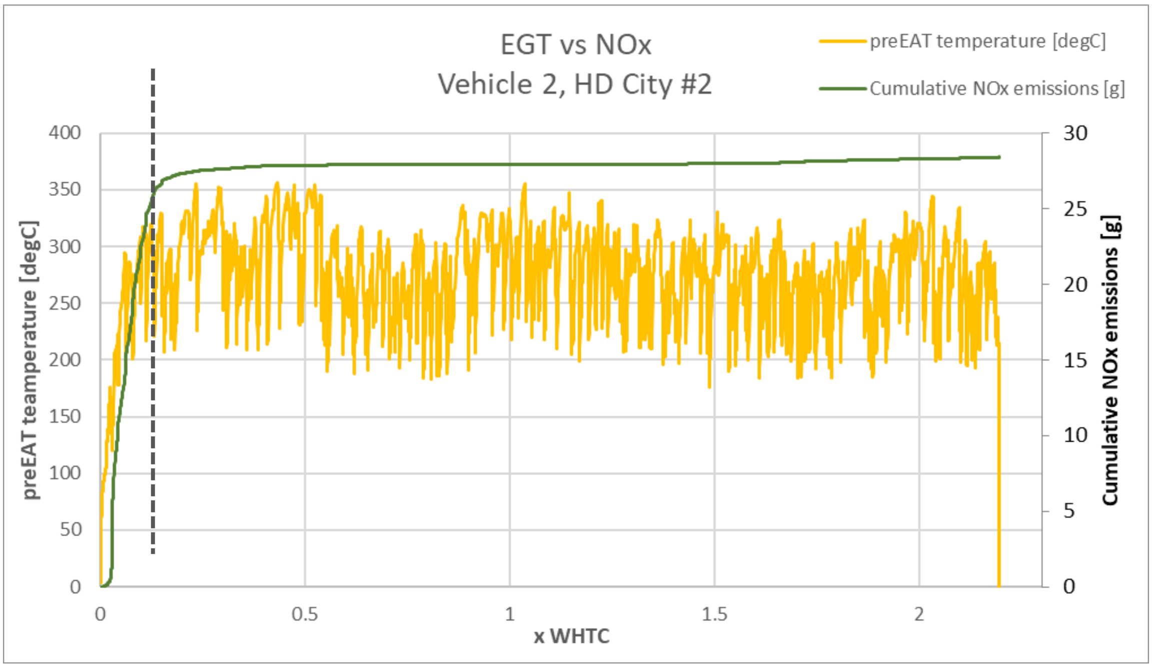


Figure 5-6 Cumulative NO_x vs EGT for vehicle 2 indicating the SCR light-off conditions in HD City #2 test

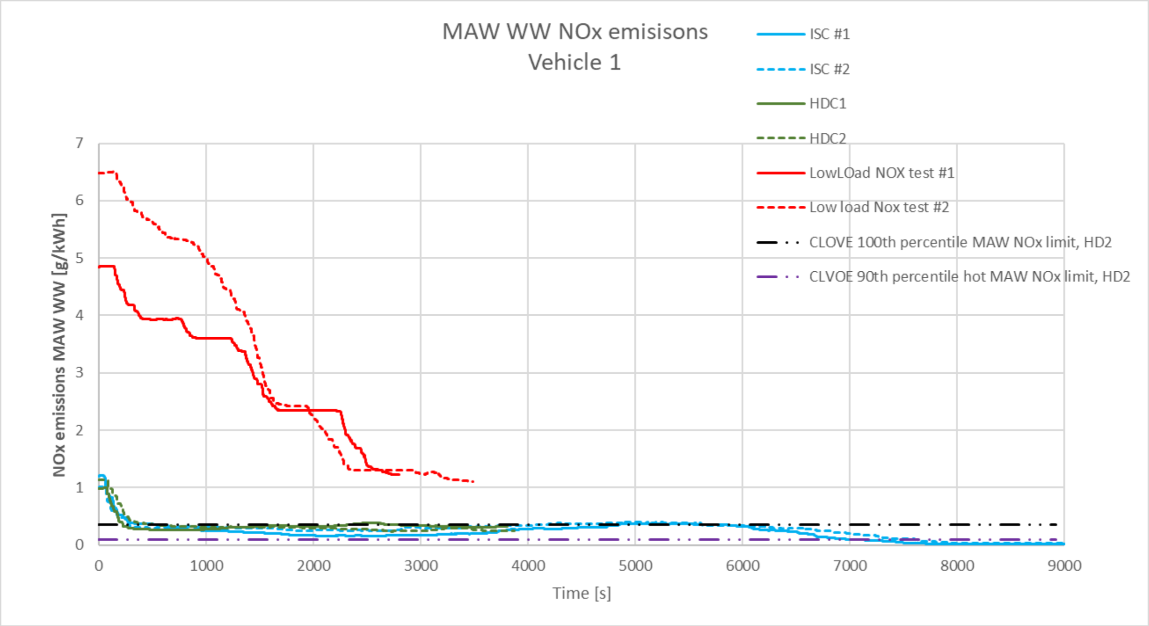


Figure 5-7 Vehicle 1 MAW WW NOx emissions in respect of the suggested CLOVE EURO VII 100th percentile MAW and 90th percentile hot MAW HD2 limits

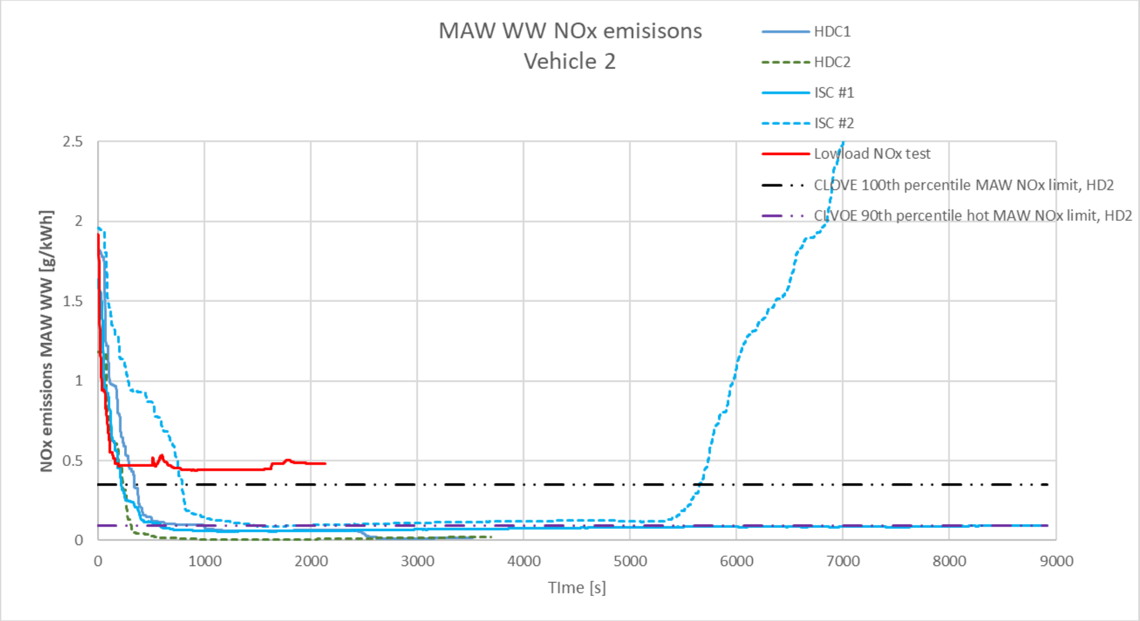


Figure 5-8 Vehicle 2 MAW WW NOx emissions in respect of the suggested CLOVE EURO VII 100th percentile MAW and 90th percentile hot MAW HD2 limits

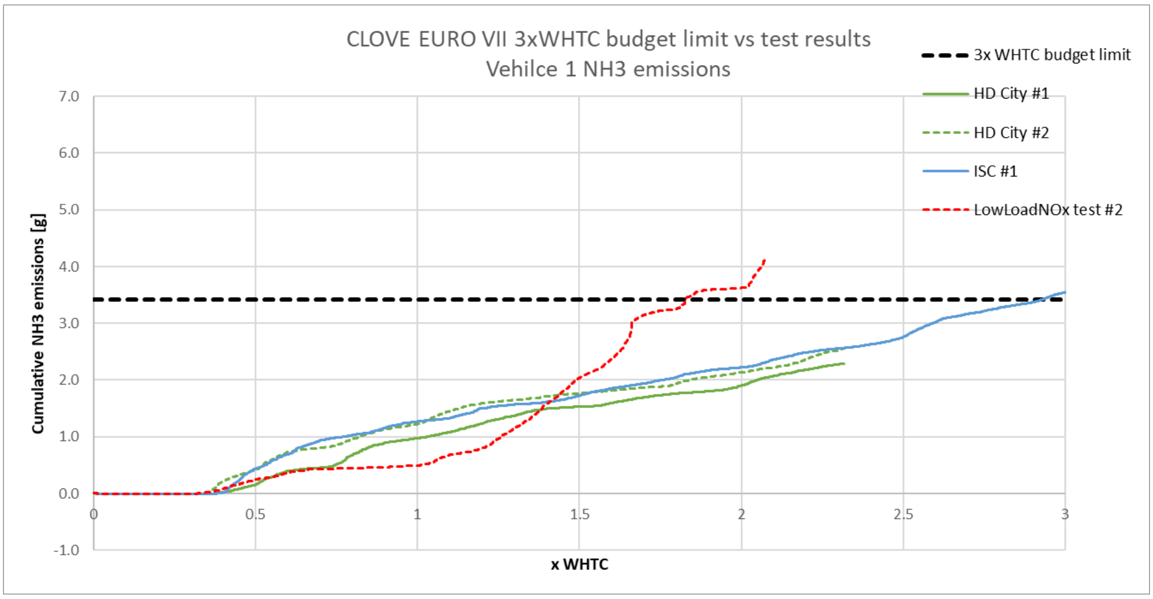


Figure 5-9 Cumulative NH_3 emissions for vehicle 1 in relation to trip work and suggested CLOVE Euro VII < 3x WHTC budget limit

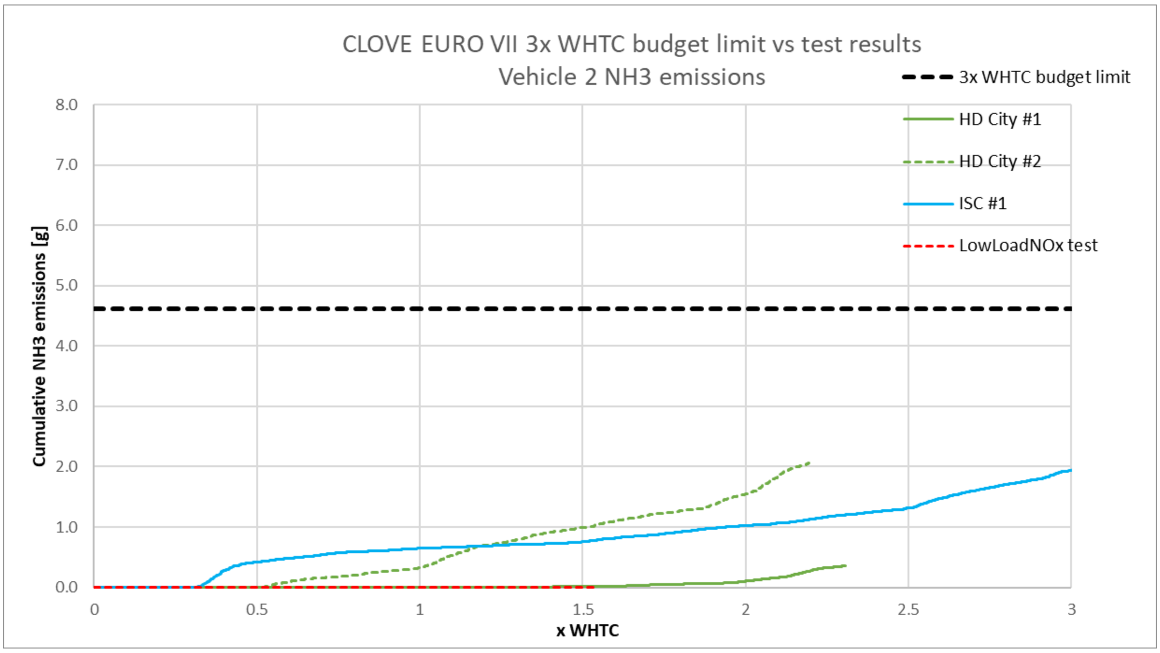


Figure 5-10 Cumulative NH_3 emissions for vehicle 2 in relation to trip work and suggested CLOVE Euro VII < 3x WHTC budget limit

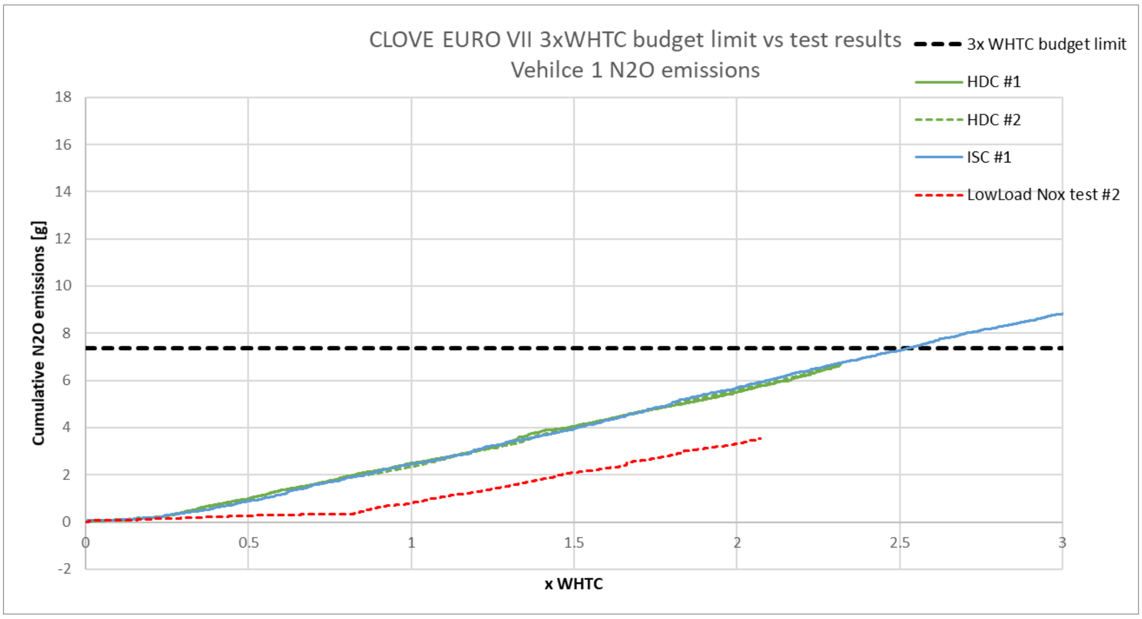


Figure 5-11 Cumulative N_2O emissions for vehicle 1 in relation to trip work and suggested CLOVE Euro VII < 3x WHTC budget limit

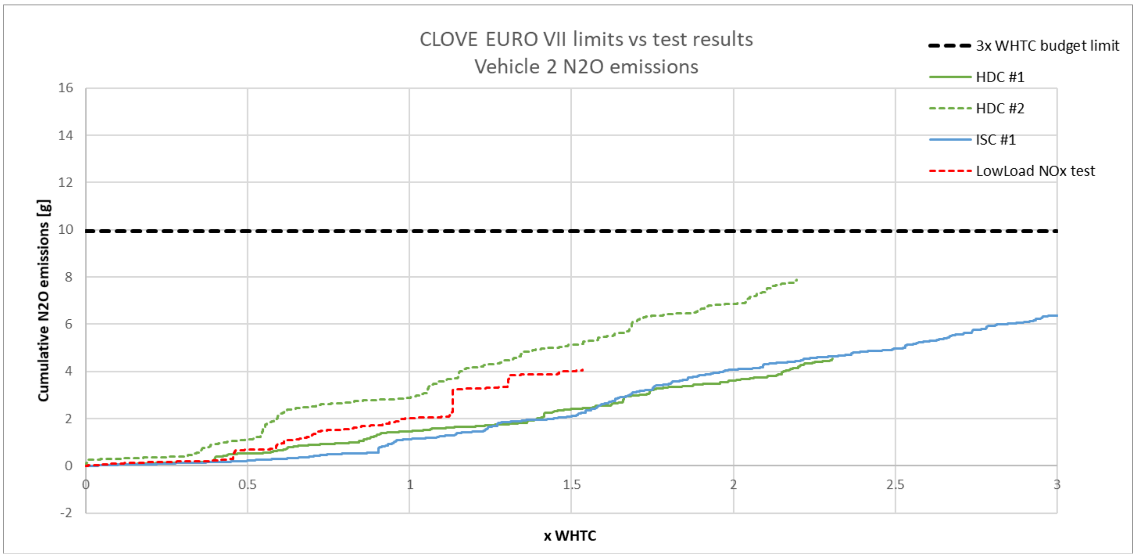


Figure 5-12 Cumulative N_2O emissions for vehicle 2 in relation to trip work and suggested CLOVE Euro VII < 3x WHTC budget limit

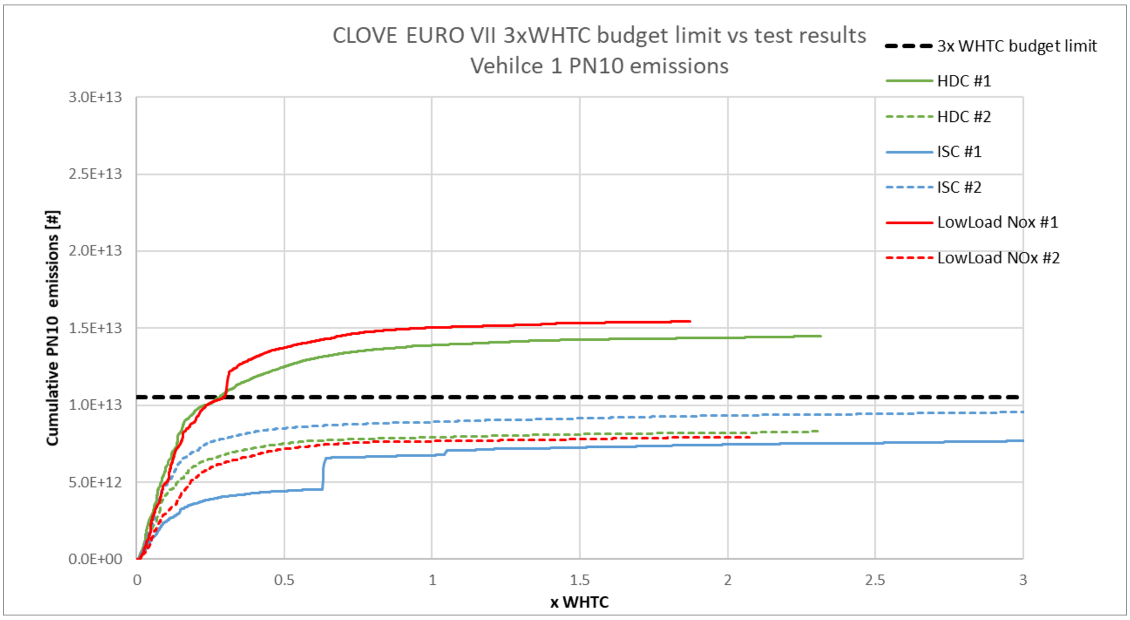


Figure 5-13 Cumulative PN10 emissions for vehicle 1 in relation to trip work and suggested CLOVE Euro VII < 3x WHTC budget limit

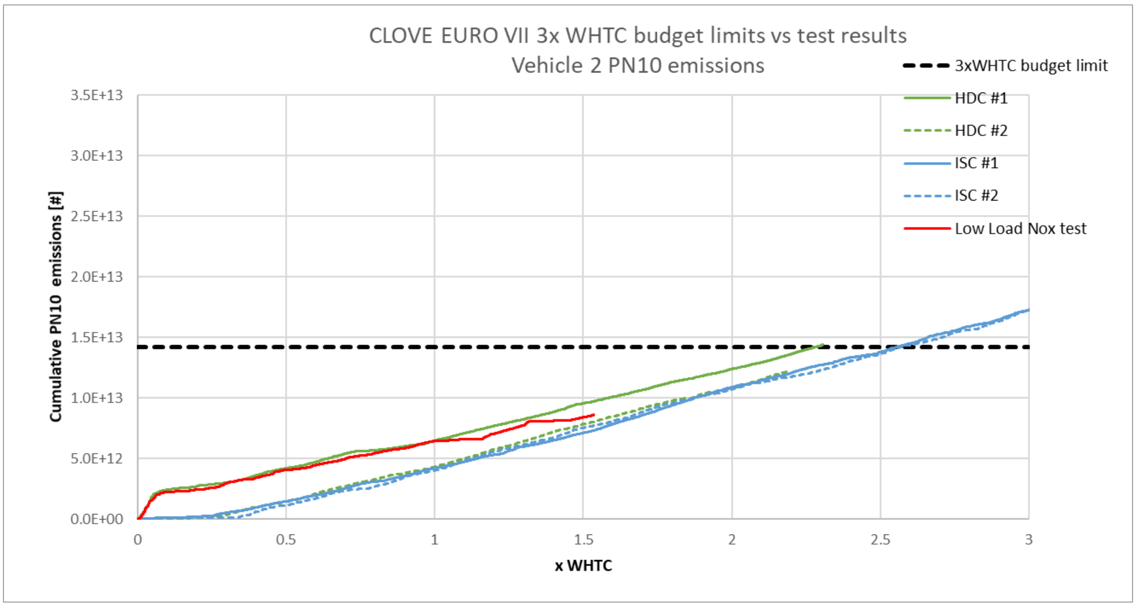


Figure 5-14 Cumulative PN10 emissions for vehicle 2 in relation to trip work and suggested CLOVE Euro VII < 3x WHTC budget limit

5.2 PN-PEMS and CPC-PN measurement correlation

5.2.1 PN trends for PEMS PN_{23} in on road conditions

During the measurements conducted in this project, it was found that clear inconsistency between CPC (PN_{10}) and PEMS PN (PN_{23}) measurements took place throughout all conducted tests (Figure 5-3). Typically, the results acquired with PEMS PN_{23} were higher to the PN_{10} emissions. Because of this, an additional CPC measuring PN_{23} was added to vehicle 2 measurement configuration. Furthermore, one WHVC laboratory test was conducted on the VTT HD chassis dynamometer to validate the vehicle installed entity.

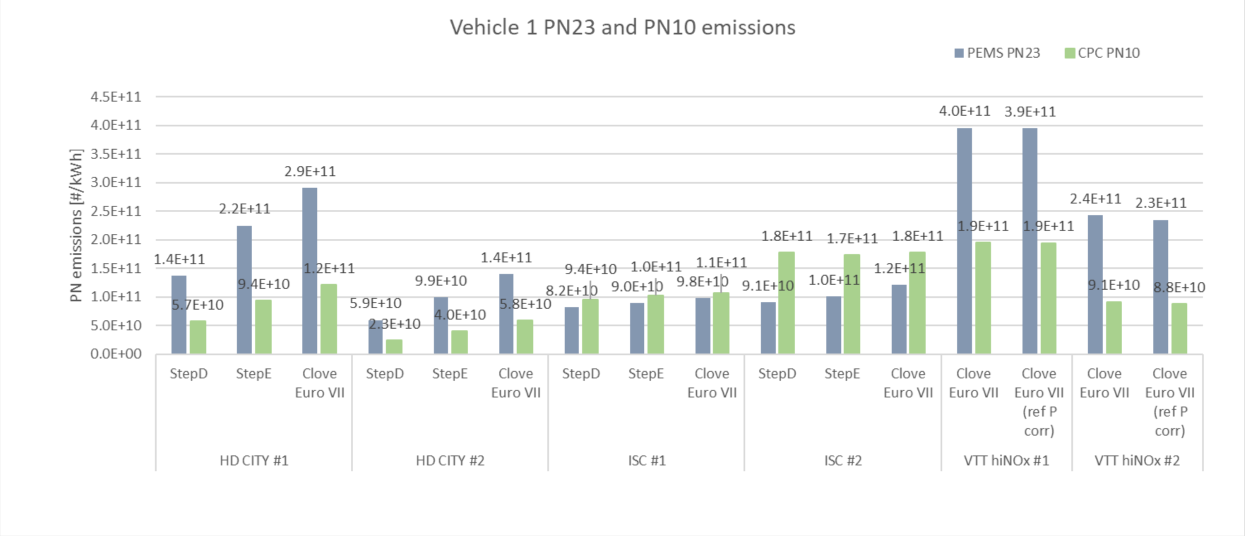


Figure 5-15 PN10 and PN23 emissions with vehicle 1

The CPC PN_{23} and PEMS PN_{23} results from the on road tests are shown in Figure 5-4. Although the pattern of the two results acquired from the two devices seem similar, a significant shift in the end result occur, with the PEMS PN device resulting in significantly higher PN emissions. Table 5-3 shows the emission results captured acquired in WHVC-test cycle, executed in VTT HD-laboratory. Based on these results, gaseous PEMS results are reasonably well in line with the CVS-based outcome. However, based on the CVS comparison, the PEMS PN is more than 250 % greater compared to the CVS results, meanwhile the additional CPC PN_{23}-device installed in vehicle 2, produced only less than 10 % higher results than CVS-based CPC. The fundamental cause for this was investigated by both examining raw and cumulative results, and based on these, following conclusions were made: heavy distortion occur for the PEMS PN emission signal, especially in cases where the concentrations change rapidly, causing a bias in the PEMS based calculation (Figure 5-5). This cause a bias in PN emissions with a significant increase in cumulative PN emissions seen in Figure 5-6. Based on these findings, VTT suggests that PN results acquired by CPCs used in this project are significantly more reliable compared to results declared based on PEMS results. It should be worthwhile to mention, that VTT use the same individual regularly with other projects (most often LD-vehicle measurements), and a similar trend of uncertainty has been noted. However, the PEMS PN results have seldom exceeded the boundaries of CVS validation with over 50%, as set as a requirement by the light duty RDE regulation (EU 1151/2017). Based on these notifications, it would be suggested that if further amendments in any regulation would take place, improvements in current PN measurement devices should take place. The uncertainty of current commercial PEMS PN devices are widely acknowledged, hence typically high measurement uncertainties are still tolerated.

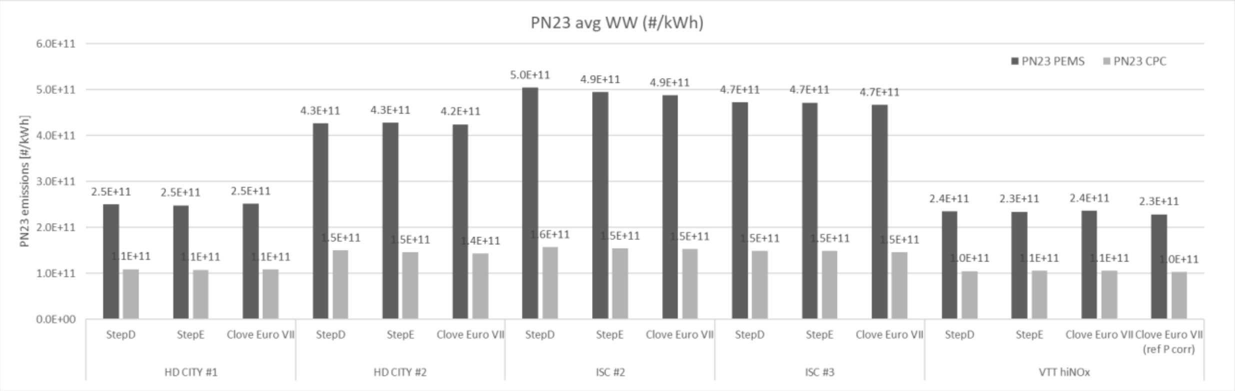


Figure 5-16 CPC PN_{23} vs PEMS PN_{23} results with acquired from vehicle 2

Table 5-3 Emission results in WHVC measured with CVS, PEMS (gas and PN) and CPC23 installed in vehicle 2

WHVC	CO2 [g/kWh]	CO [mg/kWh]	HC [mg/kWh]	CH4 [mg/kWh]	NMHC [mg/kWh]	NOx [mg/kWh]	PN23 [10^11/kWh]
Dyno	1182.10	0.42	0.07	0.00	0.07	2.97	1.70
PEMS	1245.19	0.37				2.94	4.30
CPC PN23 vehicle							1.85
CVS vs PEMS	105 %	89 %				99 %	253 %
CVS vs CPC PN23 vehicle							9 %

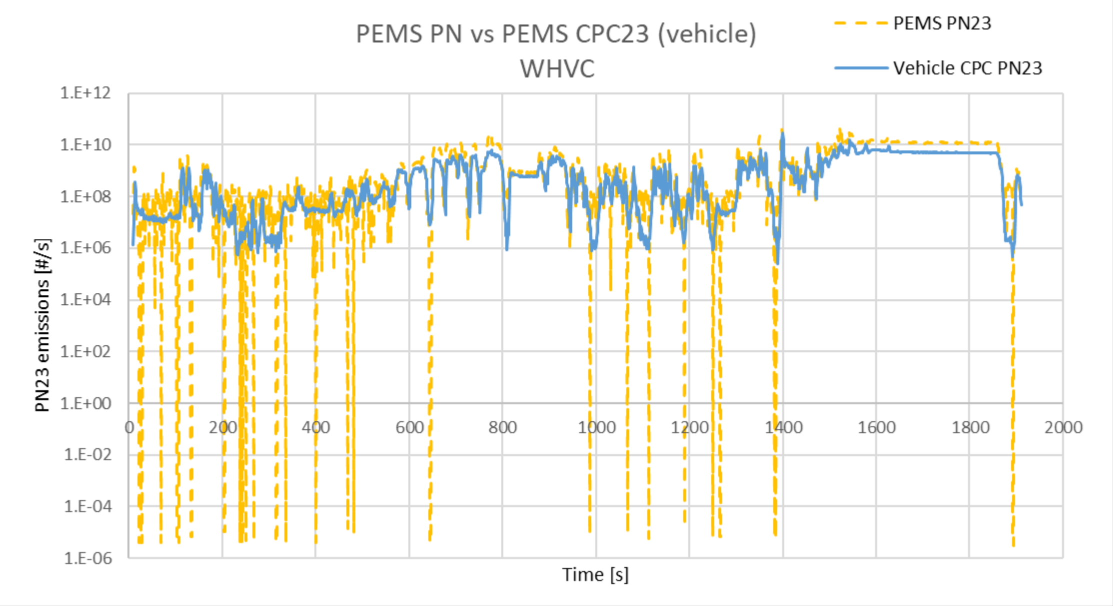


Figure 5-17 PEMS PN vs CPC PN23 emissions, #/s (on a logarithmic scale), captured in WHVC for vehicle 2

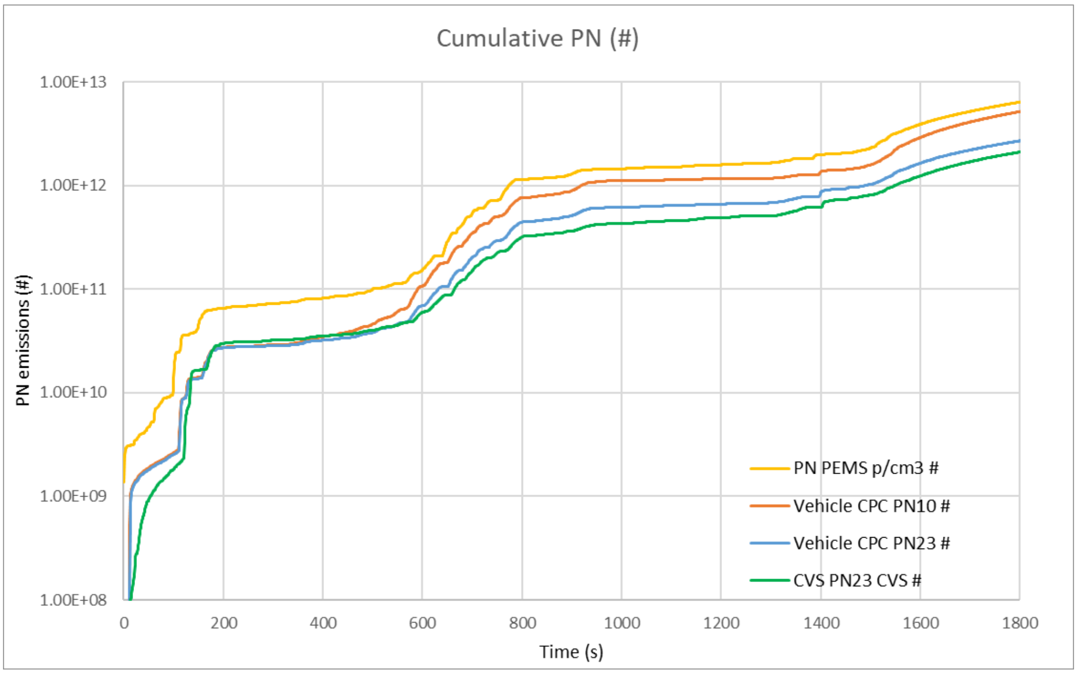


Figure 5-18 Cumulative PN emissions from CVS CPC, CPC PN_{10}, CPC PN_{23} and PEMS PN_{23} in WHVC test cycle

6. Conclusions and summary

The project results may be concluded by categorizing the project themes following:

- Compatibility and status of current technologies (Euro VI) for future emissions regulations, such as suggested Euro VII limits
- Effect of analysing methods on emission outcome on current and future heavy-duty fleet
- Implementation of unregulated emissions in future emission regulation
    - Targeted components N_2O, NH_3 and PN_{10}

The tested Euro VI step D vehicles performed relatively well within and even outside the ISC-boundaries using Euro VI ISC parameters. Generally, both tested vehicles pass the current Euro VI requirements in terms of CO, HC, NO_x and PN_{23}. The CO and HC emissions were found generally low for both test vehicles as the current DOCs in use seem being able to operate well in various conditions. The NO_x average WW NOx emissions for vehicle 1 were found consistent over all HD-city and ISC-tests with all calculation methods. Likewise, with the Euro VI parameters the NO_x performance was found generally good for vehicle 2, but some inconsistency was found in one ISC test due to suspected SCR-system related failure causing rapid increase in NO_x emissions. However, low load conditions and e.g. long idle periods were found most challenging for current SCR-systems, as the lack of proper SCR-thermal control decrease the SCR-temperature below the required operating range. These conditions were found to increase the NO_x emissions significantly, as the NO_x-reduction efficiency is highly dependent on the catalyst temperature. The reduction of particulate emissions (PN_{23} and PN_{10}) was found for both vehicles generally good in all conditions as the DPF-systems are less temperature dependent compared to e.g. SCR-systems.

The Euro VII method suggested by CLOVE introduce stricter requirements on currently regulated emissions together with an introduction of new emission components, NH_3 and N_2O. The suggestion also expands the particle size limit from PN_{23} to PN_{10}. Furthermore, the suggested Euro VII method would emphasize cold start emissions in form of a 100th percentile MAW limit and would take into account all MAWs beginning from the initial moment of engine start. Introduction of a separate emission budget would take place for trips below 3x WHTC work. These new boundaries would set high standards for future HDV engine and EATS performance, as the EATS would need to be working within the proper operational temperature in all conditions. The tests conducted with two Euro VI Step D HDVs demonstrates that the greatest challenges for future emission regulation are related to SCR-systems and NO_x-reduction requirements. With the Euro VII method, none of the tests conducted passed the suggested Euro VII NO_x limits. The results indicate that despite being efficient within the boundaries of current regulation, the thermal control of current SCR-systems are rather insufficient to cover all conditions. These include engine cold starts and low load conditions. These conditions were found to contribute most of the NO_x emissions for each test trip. The main reason for the poor performance in these conditions were concluded to be a results of the SCR-systems being outside their required operational temperatures. Additionally, both vehicles as such seem to have too high N_2O emissions, if CLOVE suggested Euro VII limits would be implemented. The typical N_2O emissions were in the region of 0.1 to 0.2 g/kWh for vehicle 1 and 0.08 to 0.17 g/kWh for vehicle 2, as the suggested limit would be either 0.02 or 0.05 g/kWh. Similarly, the NH_3 emissions are currently on the edge of passing the Euro VII limits, depending on deployed CF and further EATS optimization. Judging by the given results, minor improvements would be required to improve the SCR efficiency for decreasing NO_x, N_2O and NH_3 emissions.

The PN_{23} results were found somewhat contradictory, suspected being a results of the high measurement uncertainty of the PEMS PN device. The correlation between PEMS PN and all included CPCs were found somewhat poor. Despite this, all tests indicate that current Euro VI buses use highly efficient DPFs, as average WW PN_{10} emissions were in many cases lower than the suggested CLOVE Euro VII limits.

The current DOC catalysts seem to work well under various conditions, as the CO and HC emissions remain low in all tests. Based on the tests conducted in this project CO emissions are likely to pass CLOVE Euro VII requirements with current DOC-applications. However, this is necessary not directly the case for HC, as it would depend on deployed CF-factors and other parameters accounting for permissible uncertainty.

The ref P correction accounted for the CLOVE Euro VII analysis were found for both vehicles minor, but the effect could be greater in cases where the average WW power would be lower than the those obtained in the tests conducted in this project.