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Joni Kemppainen

NOx EMISSION ANALYSIS OF RETROFITTED DIESEL-POWERED BUSES

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Joni Kemppainen
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ABSTRACT

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Author: Joni Kemppainen
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Proventia Oy is a medium sized international company focused on heavy-duty diesel engine emission control. The company designs and manufactures exhaust aftertreatment systems for OEM and retrofit purposes. They have been collecting data by using telematics from thousands of buses with retrofitted exhaust aftertreatment systems. The objective of this thesis was to find out how the surrounding conditions and vehicle's mechanical solutions affect the emissions and the operation of the retrofitted exhaust aftertreatment system in different bus models.

To understand the reasons behind the system operation in different conditions, the focused area in the background theory is the components of the aftertreatment system. Also, heavy-duty diesel emissions standards have been studied to clarify the reasons behind developing advanced exhaust aftertreatment systems. The material used in the background theory has been collected from various internet sources, including technical publications and websites of the manufacturers in the industry. Some book sources have also been used and the knowledge provided by the background study has been applied in the presenting and analyzing of the results.

The research was carried out by utilizing the data Proventia has collected. The data was combined with vehicle technical information which was mainly tabulated in separate Excel files. Excel's Power Query and Power Pivot add ins were the tools in the processing and analyzing of the data. As a result, emission readings and the aftertreatment system efficiencies for various bus models are presented and relations between various measures have been studied.

As a conclusion it can be stated that retrofitting buses is an efficient way to quickly reduce the emissions in highly crowded areas such as big cities. However, the proper function of the system requires a sufficiently high exhaust temperature which is affected by the operating conditions and the vehicle's mechanical solutions. Also, to keep the emissions low, the maintenance of the vehicle and exhaust aftertreatment system must not be neglected. The achieved results can be exploited to estimate the possible problems of the future retrofit targets and to conduct further research on the factors affecting the operation of the aftertreatment system.

Keywords: retrofit, bus, exhaust aftertreatment, emission control, analysis

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1 INTRODUCTION

This thesis is commissioned by Proventia Oy, a medium size international company focused on heavy-duty diesel engine emission control. The goal of this thesis work is to research how different factors, environmental or mechanical, affect the function of their retrofitted emission aftertreatment system. The purpose of the retrofit system is to reduce the emissions in exhaust gases and upgrade a vehicle to achieve the latest emission standards. The European emission standards are studied and opened for gaining a more accurate picture of the objective for a correctly working EAT (exhaust aftertreatment) system.

The studied data has been collected from vehicles which have been retrofitted with Proventia's EAT system. In the EAT system exhaust gases flow through DOC, DPF and SCR and achieved emission values will be collected from variable vehicle sensors. The used data in this thesis has been collected by a NO_x emissions monitoring system called PROCARE Drive. The system collects live data from the vehicles with the retrofitted EAT system and uploads the information online. In the theoretical part of this thesis is studied more deeply the function of different components in the EAT system.

The aim was on finding factors in different vehicle categories which cause EAT system to work inefficiently. Because of the large amount of collected data and the fact that the information has not been categorized in any clear order, emission readings had to be tabulated for more precise analysis. To find connections between actual emission readings and mechanical or environmental factors multiple vehicle characteristics had to be sorted out too. It was expected that studying the data would reveal some phenomena that affect the EAT system operation negatively.

2 DIESEL ENGINE EMISSIONS

Diesel engines like other internal combustion engines convert chemical energy that is bonded to the fuel to mechanical power. Diesel fuel constructs from carbon and hydrogen, and for the ideal thermodynamic equilibrium the complete combustion process would only generate CO_2 and H_2O. (DieselNet, 2012.) The approximate composition of the diesel exhaust fumes is shown below in figure 1.

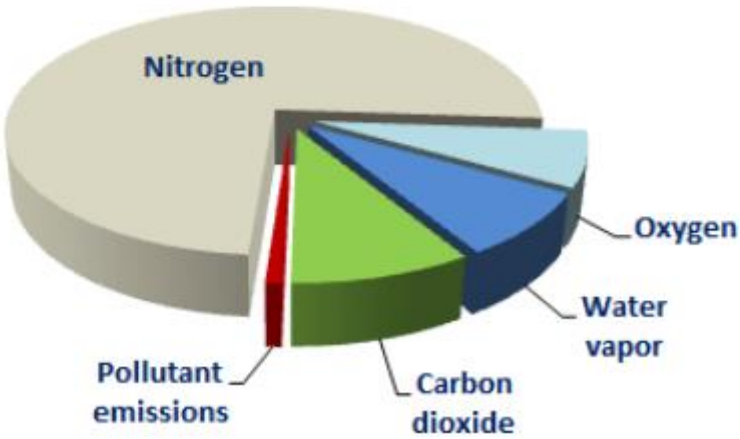

FIGURE 1. Approximate volumetric concentration of pollutant emissions in diesel exhaust gas (DieselNet, 2012)

Four main pollutant emissions (CO, Hydrocarbons (HC), NO_x and PM) are formed in the combustion process for various reasons. Incomplete combustion of diesel fuel generates CO (carbon monoxide) when the oxidation process has not occurred completely. Incomplete combustion can occur because of high air/fuel mixture ratio, poor fuel injection where diesel droplets are too large or insufficient turbulence in the combustion chamber. Hydrocarbons are unburned fuel and consequence of incomplete burning. These hydrocarbons occur mainly on light loads, when the air-fuel mixture is lean and the temperature near cylinder walls is too low. (The pollutant emissions of diesel-engines and exhaust aftertreatment systems, 2015.)

The particulate matter of diesel exhaust fumes mainly consists of soot and soluble organic components attached on the surface of soot particle. The soluble organic fraction of PM is mainly unburned fuel or lubricant oil, in addition some sulfates and moisture are present in the particles. (Handbook of Diesel Engines, 2010 p. 446-447.)

NO_x emissions are formed when engine uses oxygen in the intake air to burn the injected fuel in combustion chamber. Nitrogen in the intake air reacts with oxygen when the temperature in cylinder increases as a result of combustion process (The pollutant emissions of diesel-engines and exhaust aftertreatment systems, 2015.)

These four main pollutants are known to have negative impact on environment and human health causing respiratory deceases and polluting air, water and soil. Therefore, these harmful compounds have been restricted by emission standards which have been tightened considerably over the past decade. Emissions can be somewhat influenced by engine design and parameters, but to achieve the latest emission limits, modern EAT system is essential.

3 HEAVY-DUTY DIESEL EMISSION LEGISLATION AND TESTING PROCEDURES

Increased emissions and pollutants in air have led to more stringent emission standards. In order to meet the latest legislations manufacturers have been forced to make improvements in their vehicles by mounting exhaust gas aftertreatment systems to them. Another significant factor in reducing pollutants is to retrofit EAT systems in high-emitting vehicles. Retrofitted buses must be tested to approve the low emission adaptations.

3.1 European Emission Standards

European emission standards for new heavy-duty diesels are commonly referred to as Euro I...VI. The first, Euro I standards were introduced in 1992 and followed by the introduction of Euro II in 1996. Euro I and II were applicable to urban buses and truck engines but the bus standards were not mandatory. (DieselNet 2019, Emission Standards.) In the measuring of emissions, Euro I and II used ECE R49 testing cycle. It is a steady-state engine test cycle which is operated in 13 different speed and load conditions. (Delphi, Worldwide Emission Standards, 2016.) The emission limit values for Euro I and II standards are shown in Figure 2 below.

EURO I - Dir 88/77/EEC amended by Dir 91/542/EEC
Exhaust emissions of C.I. engines for vehicles > 25 km/h

Test Cycle	Emissions TA (1992) - FR (1993)	Unit	Engine Power (kW)	
			P ≤ 85 [1)]	P > 85 [1)]
ECE 49	CO	g/kWh	4,5 (4,9)	4,5 (4,9)
	HC		1,1 (1,23)	1,1 (1,23)
	NOx		8,0 (9,0)	8,0 (9,0)
	PM		0,612 (0,68)	0,36 (0,40)

1) In brackets: COP values

EURO II - Dir 88/77/EEC as amended by Dir 91/542/EEC and Dir 96/1/EEC

Test Cycle	Emissions TA (Oct 1995) - FR (Oct 1996)	Unit	Euro II - TA – FR [2)]
ECE R49-02	CO	g/kWh	4,0
	HC		1,1
	NOx		7,0
	PM		0,15 [1)]

1) 0,25 g/kWh for engines with a cylinder swept volume < 0,7 liters and rated power speed > 3.000 rpm and engine power < 85 kW until 30 Sep 97 forTA and 30 Sep 98 for FR
2) COP Limits =TA limits

FIGURE 2. Euro I and II emission limit values (Delphi, Worldwide Emission Standards, 2016)

Euro III standards were introduced in 2000 and the old test cycle was replaced by thee new engine testing cycles. The old ECE R49 testing cycle was replaced by the European Steady-State cycle (ESC). ESC is determined with 13 steady and 3 random speed and power modes which cover the typical operating range of diesel engines. In addition, European Transient Cycle (ETC) and European Load Response (ELR) testing cycles were included. The ELR is used to measure only diesel smoke. The ETC consists of a second-by-second sequence of transient mode which is divided in 3 parts:1/3 urban roads, 1/3 rural roads, 1/3 motorways. Each part is based on-road-type-specific patterns of heavy-duty engines installed in trucks and buses. At the same time voluntary, stricter emission limits for extra low emission vehicles, also known as enhanced environmentally friendly vehicles (EEV) were set. Emission limit values of Euro III standards are illustrated below in Figure 3. (Delphi, Worldwide Emission Standards, 2016.)

Limit Values - EURO III

Emissions TA: 10/2000 - FR: 10/2001	Unit	Euro III		Euro III - EEV	
		ESC/ELR	ETC	ESC/ELR	ETC
		Diesel only	Diesel / Gas	Diesel only	Diesel / Gas
CO	g/kWh	2,1	5,45	1,5	3,0
HC		0,66	-	0,25	-
NMHC		-	0,78	-	0,40
CH_4 [2]		-	1,6	-	0,65
NOx		5,0	5,0	2,0	2,0
PM		0,1/0,13 [1]	0,16/0,21 [1] [3]	0,02	0,02 [3]
Smoke	m^{-1}	0,8	-	0,15	-

1) For engines having a swept volume of less than 0,75 dm^3 per cylinder and a rated power speed of more than 3.000 min-1
2) For natural gas engines only
3) Not applicable for gas engines - Euro III stage

FIGURE 3. Euro III and EEV emission limit values with new test cycles (Delphi, Worldwide Emission Standards, 2016)

Euro IV emission limits came into force 2005 first for new type approvals and for serial production vehicles one year later. In Euro IV all emission limits were notably lower than specified by Euro III, but the biggest reduction applied to particulates. Particulate matter limits were lowered approximately by 80%. When Euro V was introduced in 2008, only NO_x emission limits were more severe compared to Euro IV. Both Euro IV and V use previously mentioned ESC, ETC and ELR testing methods to measure emissions. (Automotive handbook, s. 550-551.) Euro IV and V emission limits shown in Figure 4.

Emissions TA: Oct05 - FR: Oct06	Unit	Euro IV		Euro IV - EEV	
		ESC/ELR Diesel only	ETC Diesel & Gas	ESC/ELR Diesel only	ETC Diesel & Gas
CO	g/kWh	1,5	4,0	1,5	3,0
HC		0,46	-	0,25	-
NMHC		-	0,55	-	0,40
CH_4 [1]		-	1,1	-	0,65
NOx		3,5	3,5	2,0	2,0
PM		0,02	0,03 [2]	0,02	0,02 [2]
Smoke	m^{-1}	0,5	-	0,15	-

Emissions TA: 01Oct08 - FR: 01Oct09	Unit	Euro V		Euro V - EEV	
		ESC/ELR Diesel Only	ETC Diesel & gas	ESC/ELR Diesel Only	ETC Diesel & gas
CO	g/kWh	1,5	4,0	1,5	3,0
HC		0,46	-	0,25	-
NMHC		-	0,55	-	0,40
CH_4 [1]		-	1,1	-	0,65
NOx		2,0	2,0	2,0	2,0
PM		0,02	0,03 [2]	0,02	0,02 [2]
Smoke	m^{-1}	0,5	-	0,15	-

[1] For natural gas engines only
[2] Not applicable for gas fuelled engines - Euro IV Stage

FIGURE 4. Euro IV and V emission limit values (Delphi, Worldwide Emission Standards, 2016)

Move from Euro V to Euro VI standards implemented a large reduction in the NO_x limits, which were reduced by 80% and particulate matter emission, which were reduced by more than 60% (Automotive handbook, p. 551). For the first time standards included particulate number (PN) limit too (The International Council on Clean Transportation, 2016). Euro VI also introduced new harmonized testing cycles. The World Harmonized Stationary Cycle (WHSC), which replaced the old ESC, is a steady-state cycle with several speed and power modes which cover the typical operating range of heavy-duty engines. The ETC test was replaced by the World Harmonized Transient Cycle (WHTC) which is a transient test with several motoring segments created to cover typical driving conditions. (Delphi, Worldwide Emission Standards, 2016.) Euro VI emission limits are presented in Figure 5.

	CO	THC	NMHC	CH4	NOx [1]	NH_3	PM Mass	PM [2] Number
	mg/kWh					ppm	mg/kWh	#/kWh
WHSC (C.I.)	1.500	130			400	10	10	$8{,}0 \times 10^{11}$
WHTC (C.I.)	4.000	160			460	10	10	$6{,}0 \times 10^{11}$
WHTC (P.I.)	4.000		160	500	460	10	10	[3]

C.I. Compression Ignition
P.I. Positive Ignition
WHSC, WHTC (see pages 2-3)

[1] Admissible level of NO_2 may be defined later
[2] Measurement procedure to be introduced at a later date
[3] Particle number limit and date of implementation not confirmed yet

FIGURE 5. Euro VI emission limit values with harmonized testing cycles (Delphi, Worldwide Emission Standards, 2016)

3.2 Testing Procedures

Low emission adaptations must be tested to meet the technical performance requirements. Buses must be tested at kerb weight plus driver weight and one quarter of the specified total passenger load using a weight of 68 kg per passenger, or half of the specified seated passenger load using a weight of 68 kg per passenger, whichever is judged by the technical service to be the worst case for effective performance of the retrofit system. (CVRC, 2019.)

Buses operating in the UK must be tested according to the LowCVP UK Bus (LUB Revised) cycle, which is shown in figure 6. To warm the vehicle up prior to testing, only the Outer-London phase shall be used. (CVRC, 2019.)

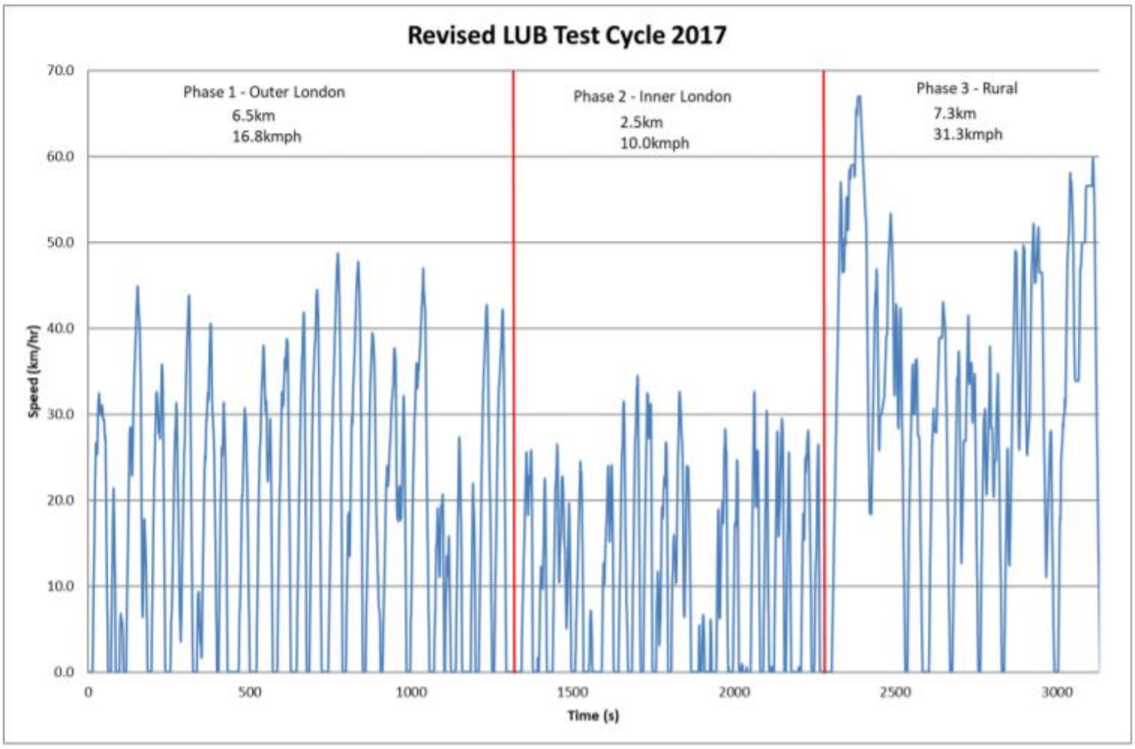

FIGURE 6. Revised LUB Test Cycle 2017 (CVRC, 2019)

Applying emission limits for the test cycle are presented in figure 7.

Exhaust emission parameter		**Maximum permitted limit**	**Reduction performance**
Primary emissions			
Mixed oxides of nitrogen	NOx	500mg/km	>80%
Nitrogen dioxide	NO_2	100mg/km	
Particulate matter (PM)	PM	10mg/km	
Number of particles (PN)	PN	6×10^{11}/km	
Secondary emissions			
Nitrous oxide/methane	N_2O/CH_4 (as CO_2e)	< 5% of CO_2	
Carbon dioxide	CO_2	< 1% increase	
Ammonia	NH_3	10ppm average 25ppm peak	
In service			
Mixed oxides of nitrogen	NOx		> 80% daily average

FIGURE 7. Emission limits applying to buses (CVRC, 2019)

Evaluation criteria for NO_x reduction systems with increased reduction performance for buses operating in Germany are different. The emissions are measured on-route with PEMS-testing and the emission limits are divided by a speed class (Federal gazette, 2018). Classified route related emissions can be seen from table 1.

TABLE 1. Classified route-related emissions

Speed class (km/h)	Speed range (km/h)	Limit (g/km)
10	7,5 - 12,5	7,5
15	> 12,5 - 17,5	5
20	> 17,5 - 22,5	4
25	> 22,5 - 27,5	3
30	> 27,5 - 32,5	2,5

In addition to the route-related emissions, The NO_x reduction efficiency must be >85% and the EAT system must include ammonia slip catalyst with minimum volume of 800ml per 100kW engine power (Federal gazette, 2018).

4 EMISSION CONTROL SYSTEMS IN VEHICLES

In modern emission control solutions engine's internal parameters and aftertreatment system are optimized to operate together. These aftertreatment systems use selective catalytic reduction (SCR) technology to decrease the amount of nitrogen oxides (NO_x) together with diesel oxidation catalysts (DOC) and diesel particulate filters (DPF) for oxidation of incomplete combustion products and reducing particle matter (Grigoratos, T. 2019).

4.1 In Cylinder Emission Control

Pollutant emissions that are formed in the combustion process can be somewhat controlled by engine design and internal parameters. Strategies to minimize engine-out emissions include developing engine geometries that improve combustion efficiency, improving fuel injection, air handling and exhaust gas recirculation technology.

By controlling fuel injection pressure, rate and timing, NO_x and PM emissions can be reduced. Increasing injection pressure leads to more complete fuel combustion, improved fuel economy and reduced PM emissions as a result of reduced size of fuel droplets and better mixing of fuel and air. Electronic control of injectors allows variable injection timing and metering. In conventional fuel injection systems that use only single injection for every engine cycle, timing of the fuel injection favors either NO_x or PM reduction. Early fuel injection increases combustion pressures and temperatures in cylinder, reduces PM and improves fuel efficiency but at the same time increases NO_x emissions. Delayed fuel injection leads to lower combustion temperatures followed by reduced NO_x emission but has a negative effect on increasing PM. To reach the desired trade-off between these pollutants, multiple injection strategy is needed. Electronically controlled high-pressure injection system i.e. common rail enables this kind of fuel injection and metering technique and allows to minimize the engine-out emissions. (ICCT, 2016. Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles.)

The air management system is in charge of the flow, pressure and temperature of the air entering the combustion chamber. More efficient combustion is achieved by using turbocharger to increase the pressure and density of the air entering the chamber. Instead of conventional turbo, variable geometry turbochargers (VGT) are often used because of their wider range of engine operating conditions. VGT also allows better control of the change in pressure between engine intake and output, which can be used to drive EGR flow, and provides the ability to raise exhaust temperatures to meet the needs of aftertreatment systems. (ICCT, 2016. Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles.)

Exhaust gas recirculation (EGR) system is commonly used method in diesel engines to reduce NO_x emissions. By recirculating part of the exhaust fumes back to the engine's cylinders, timing of the start of combustion is delayed and combustion is slowed down. This lowers peak combustion temperatures in cylinders and reduces NO_x formation (ICCT, 2016. Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles.) However, EGR can have a negative effect on fuel economy and PM emissions (DieselNet, 2019). Figure 8 describes the influence of different measures on emissions.

Measure	NOx	HC/CO	Soot	bsfc	Noise
Retarded start of injection	+	−	−	−	+
Exhaust gas recirculation	+	−	−	−	+
Cooled EGR	+	−	+	+	0
Supercharging	−	+	+	+	0
Intercooling	+	−	+	+	0
Pilot injection	0	+	−	0	+
Added post-injection	+	0	+	−	0
Injection pressure increase	0	+	+	+	0
Lower compression ratio	+	−	+	0	−

Symbols: +: reduction; −: increase; 0: no change

FIGURE 8. Various measures for the optimization of diesel engine combustion and their influence on different parameters (Handbook of Diesel Engines, 2010)

4.2 Exhaust Aftertreatment (EAT)

Emission limits have rapidly become stricter during the past decades. The exhaust aftertreatment system is designed to reduce the regulated emissions generated in the combustion process of engine. This means restricting the number of unburnt hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x) and particulate matter (PM) in the exhaust gases exiting tailpipe. In order to keep emissions at regulated levels, series of exhaust treatment components are needed to process these pollutants. (DeLand, S. Dudgeon, R. 2015.)

Proventia's EAT system consists of the actual emission aftertreatment components including the sensors where the information is collected and the user interface which allows monitoring of the actual emissions of urea injection system.

4.2.1 Diesel Oxidation Catalyst (DOC)

The diesel oxidation catalyst has been invented for reducing effectively hydrocarbon (HC) and carbon monoxide (CO) emissions as well as the soluble organic fraction of the particulate matter in exhaust gases. These soluble hydrocarbons desorb from the particle core with increasing temperature and oxidizing them in the DOC helps to reduce the particle mass. In the oxidizing reaction CO and HC are converted almost completely to CO_2 and H_2O. The oxidation catalytic converter oxidizes also nitric oxide (NO) into nitrogen dioxide (NO_2) which is important for the function of the downstream components DPF and SCR. (Automotive Handbook, p. 716.) The oxidation reaction of hydrocarbons, CO and NO is described below:

$$Hydrocarbons + O_2 \rightarrow CO_2 + H_2O \qquad \text{(Reaction 1)}$$
$$2CO + O_2 \rightarrow 2CO_2 \qquad \text{(Reaction 2)}$$
$$2NO + O_2 \rightarrow 2NO_2 \qquad \text{(Reaction 3)}$$

The catalyst is built on three main structures. Substrate consists ceramic or metallic carries, which can have structures to make flow more turbulent or it can have a filtering character. Catalyst reactions are surface reactions and therefore larger surface area is preferred. Surface area is increased by applying porous and refractory oxide layer to the substrate. This oxide layer is called washcoat and it operates as a carrier for noble metal catalyst. The oxygen needed in oxidation reaction is bonded to a washcoat and when reactants, such as hydrocarbons and carbon monoxide diffuse to the surface of catalyst, forms reaction products as shown above in reactions 1 and 2. DOC's operating principle is illustrated in figure 9 below.

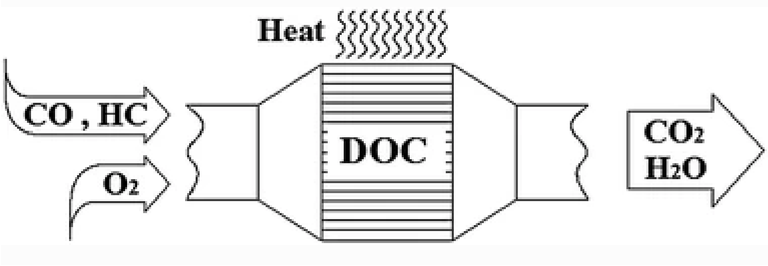

FIGURE 9. Diesel oxidation catalyst (The pollutant emissions from diesel-engines and exhaust aftertreatment systems, 2015)

However, the oxidation reactions can cause unwanted chemical compounds to generate. High sulfuric fuels contain sulfur which occurs as SO_2 compounds in the exhaust fumes and in the DOC's oxidizing reactions is oxidized to SO_3. SO_3 reacts with water and creates sulfates and sulfuric acid. These compounds can damage the downstream components, DPF and SCR and have harmful effects to human health and environment. (The pollutant emissions from diesel-engines and exhaust aftertreatment systems, 2015.)

4.2.2 Diesel Particulate Filter (DPF)

The diesel particulate filter is a device designed to remove particulate matter from the exhaust gas of a diesel engine. The structure of particulate filter is quite similar with the oxidation catalyst. It consists primarily of a ceramic honeycomb structure made from silicon carbide or cordierite with large number of parallel channels. There are closed particulate filters and open particulate filters, which filter only part of the exhaust fumes. These open particulate filters achieve filtration efficiency of 30-80% while wall-flow filters achieve filtration efficiency of over 90%. In closed filters, channels are closed off at each end with a ceramic plug to force the exhaust-gas flow through the porous walls of channels. As exhaust fumes flow through the filter, soot particles adhere to the ceramic walls. (Automotive Handbook, p. 719-720.) Operating principles for open and closed filters are shown in figure 10.

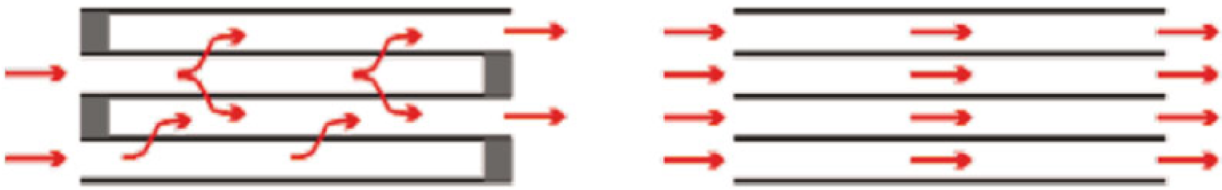

FIGURE 10. Operating principle of wall-flow (closed) filter and flow through (open) filter

The continuous flow of the soot would eventually block the filter; therefore, the collected particulates must be burnt off on a regular basis. This burning or oxidizing of the soot is called regeneration. Regeneration of the deposited soot requires temperature approximately 600 ºC or more to form nontoxic CO_2, which is highly rare in normal vehicle operation. Because of this the temperature of the exhaust gas must be increased actively by using retarded fuel injection or additive secondary injection. This type of soot burning is called active regeneration. Regeneration can also be done passively by oxidizing the soot with NO_2 which is generated in the oxidation reactions of DOC. Powerful oxidative properties of NO_2 allow the soot regeneration to occur such low temperatures as 250-400 ºC. (CTS Corp., Basics of DPF Operation.)

4.2.3 Selective Catalytic Reduction (SCR)

Function of SCR is based on the reducing agents' ability to selectively reduce nitrogen oxides (NO_x). AdBlue is commonly used reductant which is basically a solution made of urea and water. Reductant is injected to the exhaust stream before the SCR catalyst chamber. Before the actual catalytic reactions in the SCR chamber take place, the active compound, urea goes through couple of reactions to form ammonia. The first phase is called thermolysis reaction, where urea ($(NH_2)_2CO$) in the sprayed urea/water solution begins to melt and generates ammonia (NH_3) and isocyanic acid (HNCO) according to the reaction 4 below. (Automotive handbook, p. 717)

$$(NH_2)_2CO \rightarrow NH_3 + HNCO \qquad \text{(Reaction 4)}$$

The generated NH_3 takes part in the reactions of SCR catalyst, while the isocyanic acid is reacting with water and converted to ammonia and carbon dioxide in hydrolysis reaction described below (Reaction 5) (Automotive Handbook, p. 717).

$$HNCO + H_2O \rightarrow NH_3 + CO_2 \qquad \text{(Reaction 5)}$$

The efficiency of mentioned reactions to form ammonia is highly depending on the exhaust temperature, as thermolysis takes place in temperatures close to 150 ˚C (The pollutant emissions of diesel-engines and exhaust aftertreatment systems, 2015). The hydrolysis of the isocyanic acid in turn requires temperature of 250 ºC or above (Handbook of Diesel Engines, 2010).

As the exhaust gases and injected reductant enter to the catalyst chamber, number of chemical reactions occur where NO and NO_2 molecules are converted into diatomic nitrogen (N_2) and water (H_2O). Reactions 6 to 10 below express the SCR reactions. (DieselNet, 2005 Selective Catalyst Reduction.)

$6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O$ (Reaction 6)

$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$ (Reaction 7)

$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$ (Reaction 8)

$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$ (Reaction 9)

$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$ (Reaction 10)

The dominant reaction in the SCR system is described in reaction 7. By looking at the other reactions, one can see that NO_2 is involved in the reactions 8 to 10. Diesel SCR systems require the presence of NO_2 to allow NO_x conversion to happen in low temperatures, especially if major of the driving takes place in a heavily congested city where the driving speeds and exhaust temperatures stay low. Normally NO_2 concentration in diesel engine exhaust gas is low, therefore NO_2 levels are increased in an upstream oxidation catalyst to achieve the best possible efficiency. (DieselNet, 2005 Selective Catalyst Reduction.) Figure 11 illustrates a typical SCR system.

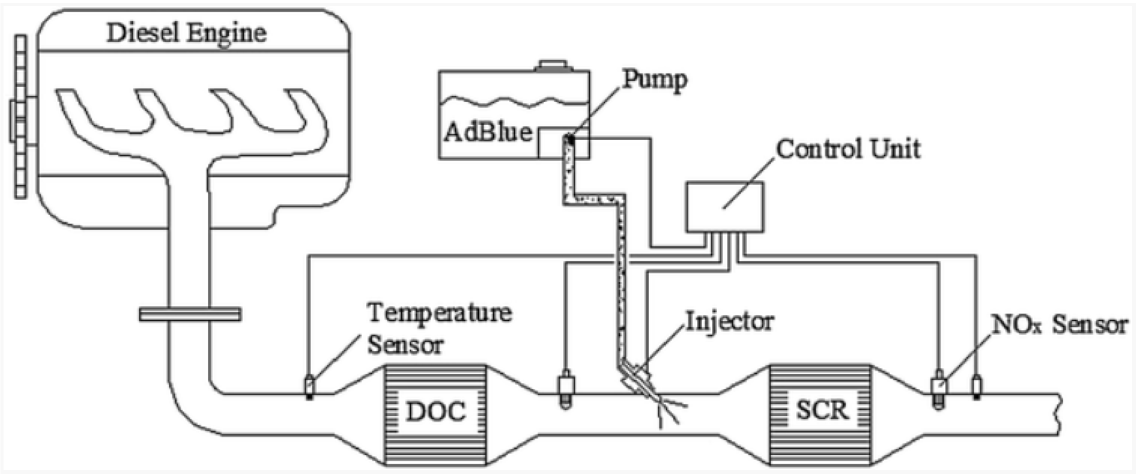

FIGURE 11. Typical SCR system with DOC (The pollutant emissions from diesel-engines and exhaust aftertreatment systems, 2015)

The best conversion efficiency is achieved about at 350 degrees of Celsius. In temperatures below 200 ˚C reacting ammonium can generate unwanted compounds (i.e. ammonium nitrate and cyanide acid) which can deposit to the exhaust pipe walls, possibly disable whole SCR system, and/or have negative health- and environmental effects. Because of this urea injection is often started after the exhaust temperature reaches 200 ˚C. (The pollutant emissions of diesel-engines and exhaust aftertreatment systems, 2015.)

4.2.4 Urea Mixing

Urea/water solution (AdBlue™) has an essential role in NO_x reduction. To achieve high efficiency of NO_x conversion, the amount of ammonium, which is generated in reactions 4 and 5, should be controlled as high as possible (The pollutant emissions of diesel-engines and exhaust aftertreatment systems, 2015). However, excessive urea dosing over time leads to exceeding the catalyst's adsorptive capacity and part of the ammonia leaves the SCR catalyst unconverted. This is called ammonia slip. The maximum NH_3 storage amount of the SCR is depending on its volume as the storage capacity is approximately 1 g/l. The adsorptive capacity is also depending on the temperature because only 10% of the low temperature value is retained at temperatures of 350 ºC and above. Although, short time over metering of AdBlue does not directly cause ammonia slip and the NO_x conversion can proceed with the stored NH_3 even at temperatures that are too low for a hydrolysis reaction, too rapid increase of temperatures may cause adsorbed NH_3 to desorb. (Handbook of Diesel Engines, 2010 p. 462-463.)

This NH_3 slip can be minimized by injecting precisely calculated amount of urea based on the required ammonia. The mass ratio of required AdBlue to reduced NO_x is 2 g_{AdBlue}/g_{NOx}. The metering ratio α is defined as the molar ratio of the metered NH_3 to the amount of NO_x within the exhaust gas. (Handbook of Diesel Engines, 2010 p. 462-463.) Theoretically, in optimal situation when there is no NH_3 slip or secondary reactions 100% of the emitted NO_x can be eliminated with metering ratio α = 1 (SAE international, 2007). The calculation for required urea is made based on the vehicle's sensor information. When the amount of emitted NOx in ppm and manifold air flow is known, the urea dosing amount for metering ratio α = 1 can be calculated.

To achieve the best possible NO_x reduction all the urea must be dissolved and converted to ammonia. This reaction can be enhanced by optimizing the injection and mixing with exhaust fumes. To minimize the injected urea droplet size, heavy duty diesel SCR systems often mix the urea with compressed air before it enters the injection nozzle. To enhance urea dissolution, separate mixing device might be used to mix the injected urea with exhaust gas. (DieselNet 2018, Urea Dosing and Injection Systems.)

Proventia's urea injection system includes urea container, urea dosing unit, urea lines and a dosing nozzle. Dosing unit is connected to the Procare device. Urea tank is connected to the dosing unit with two pipes, a urea suction pipe and a return pipe. Urea is dosed to the nozzle by using compressed air which is obtained from a vehicle's compressed air line by adding a T-connector to the line. The used air must be filtered before air and urea mixture is dosed to the nozzle to avoid contaminations. Nozzle, which is located before SCR catalyst, injects the mixture to the inlet channel.

4.3 Emission Monitoring & Data Collection

Emission monitoring in Proventia's EAT system has been implemented by using telematics. Telematics is a general term that refers to any device combining telecommunications and informatics. It includes controller, PROCARE Drive-unit which is connected to vehicle's CAN bus. The controller unit is equipped with GSM and GPS antennas to enable the place routing. Real time information about the back pressure, exhaust gas temperature, NO_x levels, AdBlue level and temperature and dosing rate is transmitted to the web service, where operators can monitor their fleet's emission readings. (Proventia, Procare Drive.)

To collect the needed information, variable sensors such as temperature, backpressure, NO_x and mass air flow sensors must be installed. Exhaust temperature is measured from the inlet side of the SCR. Exhaust gas pressure information is collected and transmitted to PROCARE Drive by using CAN bus pressure sensor which is connected to the pipe before DOC with flexible metal tube. In order to find out the NO_x reduction, two NO_x sensors must be installed. First one is connected to the inlet side of DOC to measure the number of NO_x in exhaust fumes before the EAT system and the second measures NO_x amount after the EAT system from outlet pipe of the SCR. MAF information is received from CAN or MAF sensor is installed to the pipe between air filter and turbocharger. (Proventia, NOxBUSTER installation manual.) Operating principle of Proventia's NOxBUSTER EAT system is shown in figure 12.

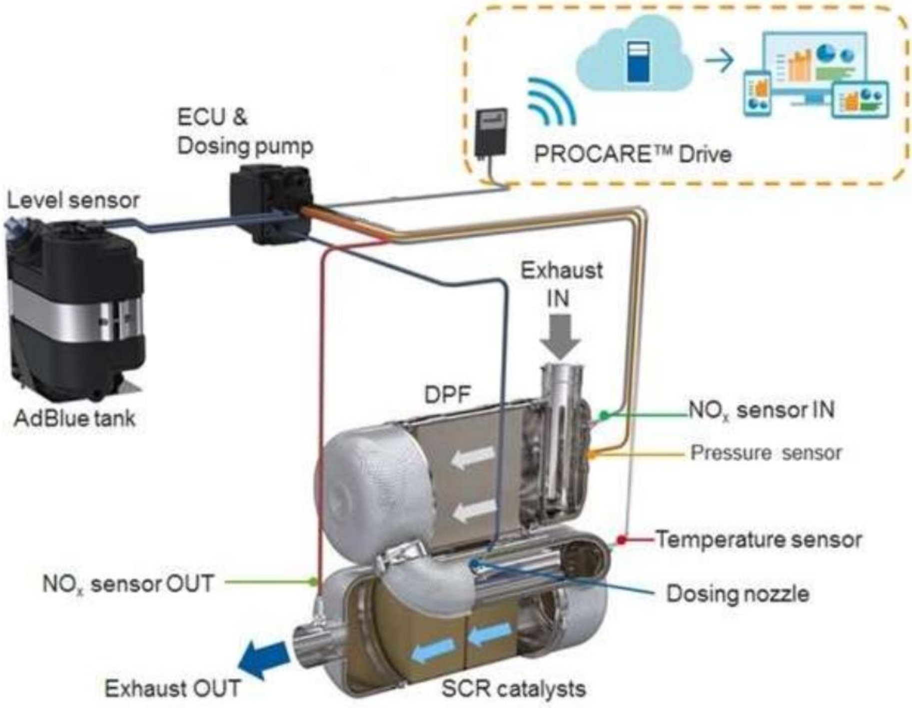

FIGURE 12. Operating principle of NOxBUSTER City system

5 DATA PROCESSING & RESEARCH METHODS

The work was started by thinking of measures that could be needed in analysing the achieved emission readings. After the planning was done, daily reports were exported from Procare drive. The exported files included daily values for about 2000 vehicles from start of 2019 to end of October 2019. Before the actual analysis could be started, the received data needed to be processed to a readable form because all the exported files were in Excel Comma format. The main tool in processing the data was Excel's Power Query add in. Power Query allowed to combine all the received data files in one and to format the data in clear order. Each row in the data shows daily averages for certain fleet numbers. Among other things the data included values for the NO_x in and out in ppm and mg/s, reduction efficiency, MAF, SCR inlet temperature and urea dosing amount.

To investigate the function of the retrofitted EAT system in different vehicles, the Procare data had to be combined with vehicle information. Power Query enabled combining the Procare data with vehicle information by matching fleet numbers from different excel files that included information such as chassis make and model.

Considering that there were hundreds of thousands of rows information, some incorrect or missing values were involved. To gain a picture of how the EAT system is working in different type of vehicles and what emission values have been achieved, rows which did not have data, or the values were inaccurate i.e. because of broken NO_x sensor were removed. The data export included columns which stated daily running time of the system and travelled distance. It was noticed that g/km emission readings were excessively high on rows where the running time was low or travelled distance was not recorded for some reason. To ensure that only data where the EAT system was running and the vehicle has been on route was included, rows where the running time was less than 3600 seconds, or the travelled distance was under 10000 meters were filtered out.

The data also included a column which stated the ignored rows of MAF and NO_x sensors. This value is increased if there is no signal detected from the sensors for some reasons. Rows where the ignored rows exceeded half of the counted rows value were filtered out. In some cases, the intake manifold pressure sensor was down and messed up the calculation of MAF causing values to get excessively high. Because of this, filtering in MAF values had to be done.

The data did not include daily average speeds and engine-out NO_x emissions in g/km and therefore, they had to be calculated in custom columns. The custom column calculations were comparatively easy to complete with Power Query. The speed was calculated by using the running time of EAT system and travelled distance. NO_x emissions from engine were calculated with emissions after the EAT system and reduction efficiency.

In the research, the aim was on finding factors that affect the NO_x emissions and reduction efficiency of the EAT system. To gain a large picture of the bus fleet the count of different type of buses and engines were sorted out. NO_x reduction efficiencies for all the manufacturers and bus models were presented to reveal the differences in EAT system operation between different models. Engine-out NO_x emissions for engine types were presented to analyse the correlations between the engine design and emissions.

The effects of operating conditions were studied by comparing the average operating speed to the emitted NO_x and exhaust temperatures. Also, the exhaust temperatures were compared to the ambient temperature on a monthly level. The comparisons between operating speed and emissions were made to see if the increase in speed has a significant effect on emissions. As the SCR temperature is a huge factor in the catalyst operation, it was hoped to see if the ambient temperature and operating speed affect the exhaust temperatures.

To see how the EAT system is operating in different exhaust temperatures, the NO_x reduction efficiency was compared with temperatures. Because the reduction efficiency is depending on the urea dosing amount, temperature’s effect on the urea injection was also studied. In addition, some influences of vehicles’ mechanical solution have been analysed.

6 RESULTS

When the data was processed in readable form, additional filtering in Pivot could be used to select the vehicles to be studied. In example, only vehicle models with over eight units would be included in studied data. As additional filtering was done, results were presented using data-based tables and graphs.

6.1 Vehicles & EAT System Efficiency

The studied data contained information from 266 articulated buses, 950 double-deckers and 457 solo buses with retrofit EAT system. Body types from different manufactures and count of buses is shown in table 2.

TABLE 2. Count of buses by body type & manufacturer

Body type	Manufacturer	Count, n	Total, n
Articulated	MAN	143	266
	Mercedes-Benz	123	
Double-decker	ADL	325	950
	Volvo	241	
	Wrightbus	301	
	VDL	83	
Solo	ADL	284	457
	MAN	60	
	Mercedes-Benz	81	
	Wrightbus	18	
	VDL	14	

Figure 13 illustrates the differences between body types.

FIGURE 13. Articulated (top), double-decker (middle) and solo/single-decker (bottom) bus bodies

Also, the engine types and properties for engines were defined. Properties and count of the buses by engine type is presented in table 3.

TABLE 3. Properties & population for engine types

Engine	Euro class	Count, n	Original EAT	EGR
Cummins ISBe 4,5	IV	90	SCR	-
	V	184	SCR	-
Cummins ISBe 6,7	IV	21	SCR	-
	V	308	SCR	-
OM906 hLA	V/EEV	31	SCR / SCR + DPF	-
OM457 hLA	V/EEV	162	SCR / SCR + DPF	-
Volvo D9	IV	3	SCR	-
	V	184	SCR	-
Volvo D5E/D5F	V	54	SCR	-
D2066 LUH	IV	52	PM-Kat	X
	V/EEV	123	CRT	X
D2866 LUH	III	8	EGR	X
	IV	3	PM-Kat	X

To see a wider picture about function of the EAT system, first it would be wise to compare the efficiency between different manufacturers and models. As seen in figure 14, clearly, the best efficiency is achieved within MAN and Mercedes-Benz.

Row Labels	Distinct Count of Fleet Number	Average of NOx reduction efficiency from ppm (%)
Volvo	242	81,3
Wrightbus	319	82,1
VDL	97	86,4
ADL	609	86,5
Mercedes-Benz	204	92,6
MAN	203	93,0
Grand Total	1674	86,3

FIGURE 14. Vehicle count and average NOx reduction efficiency by manufacturer

The filtering within models to show vehicles with eight units or more was chosen to include both Wrightbus Streetlite models. Efficiencies between different models are shown in figure 15.

Row Labels	Distinct Count of Fleet Number	Average of NOx reduction efficiency from ppm (%)
Volvo		
B5LH	54	79,7
B9TL	188	81,5
Wrightbus		
Streetlite DF	10	70,0
NRM	301	82,1
Streetlite WF	8	89,5
VDL		
Citea LLE-120	14	85,3
DB300	83	86,7
ADL		
Enviro 400H	79	73,5
Enviro 200	284	83,4
Enviro 400	246	91,5
Mercedes-Benz		
CITARO O530 OM457	16	86,6
CITARO O530 OM457 WO DPF	13	87,2
CITARO O530 G OM457 WO DPF	68	87,9
CITARO O530 OM906 W DPF	30	95,0
CITARO O530 OM457 W DPF	22	95,0
CITARO O530 G OM457 W DPF	55	95,2
MAN		
LION´S CITY NG323	24	83,1
LION´S CITY A21 D20 E4	10	89,8
LION´S CITY A40 D20 E5	11	92,3
LION´S CITY A23 D20 E5	61	92,8
LION´S CITY A23 D28 E3	8	93,6
LION´S CITY A21 D20 E5	50	93,9
LION´S CITY A23 D20 E4	39	94,8
Grand Total	1674	86,3

FIGURE 15. NOx reduction efficiency by vehicle model

6.2 NO_x Emissions & Reduction Efficiency

The recorded emission readings were initially studied on a large scale based on the original emission class and number of axles. Average NO_x emissions for 2-axle buses presented in Figure 16 and 3-axle buses in Figure 17.

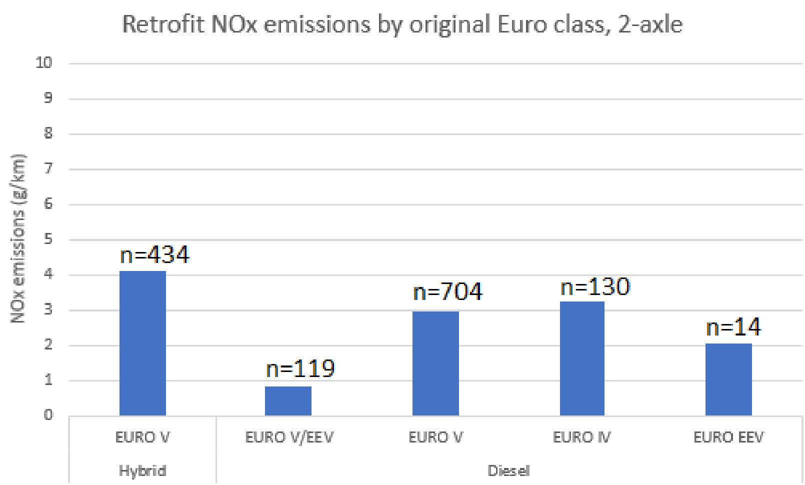

FIGURE 16. Achieved NOx emissions for 2-axle buses (Average of all buses)

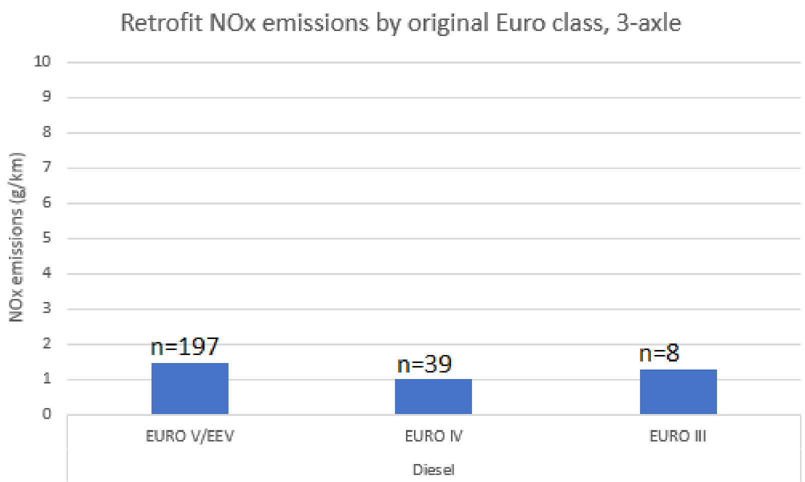

FIGURE 17. Achieved NOx emissions for 3-axle buses (Average of all buses)

Emissions for vehicles divided by body type are seen on figure 18.

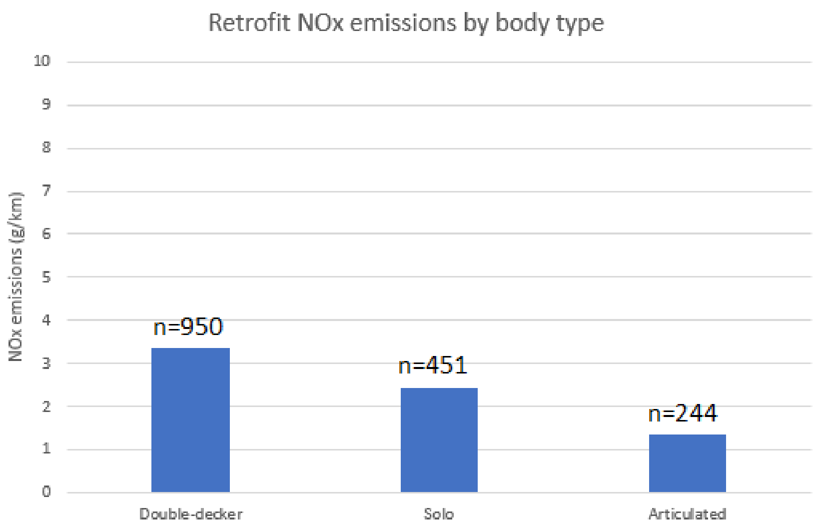

FIGURE 18. Achieved NOx emissions by body type

The average NO_x reduction efficiencies during the period from January to October were compared between the models with the best and the worst reduction efficiency. Figure 19, where n=count of included vehicles, reveals that the EAT in MAN and Mercedes buses functions in great efficiency about 95% while the bottom end is working with little over 80% efficiency. Figure also shows that the vehicles with worst efficiency are equipped with Cummins and Volvo engines, therefore closer inspection of engines' NO_x emissions and design is needed.

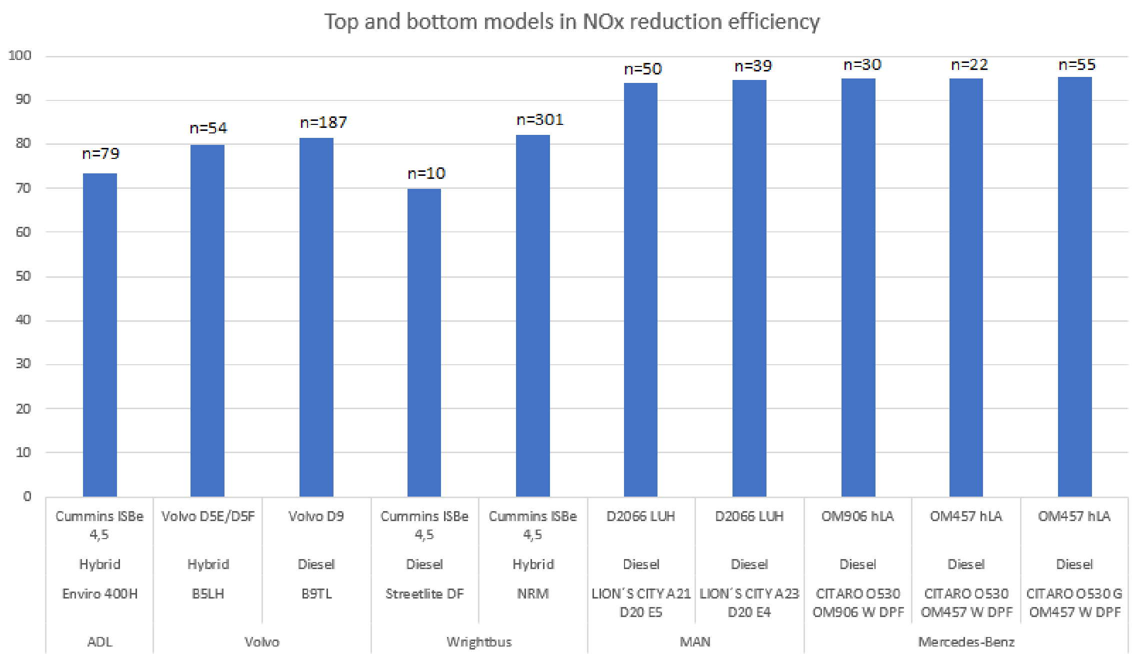

FIGURE 19. Top and bottom models in NOx reduction efficiency

As engine emissions were compared, Volvo and Cummins engines generated notably higher NO_x emissions in combustion process than the rest. Raw engine-out emissions by different engine types and count of buses are presented in figure 20 below.

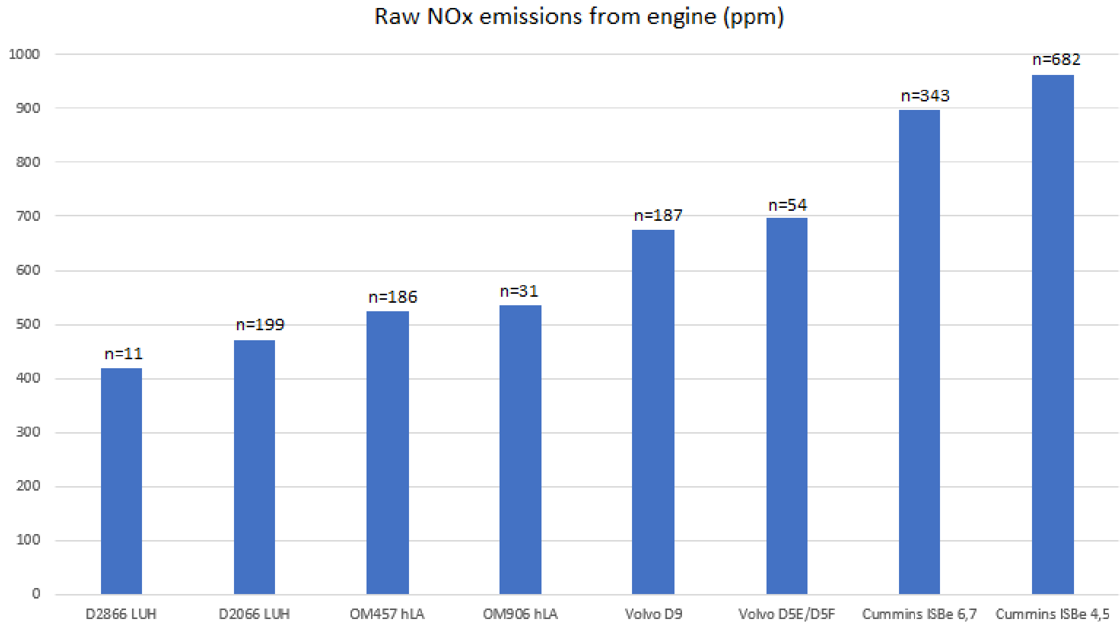

FIGURE 20. NOx emissions before EAT (engine out NOx)

Figure 21 represents the NO_x emissions within the vehicle models with the best and the worst reduction efficiencies on a four-month period from July to September. Orange beams indicate the raw engine-out NO_x emissions, grey beams show the tailpipe emissions after the EAT system and the blue line is reduction efficiency.

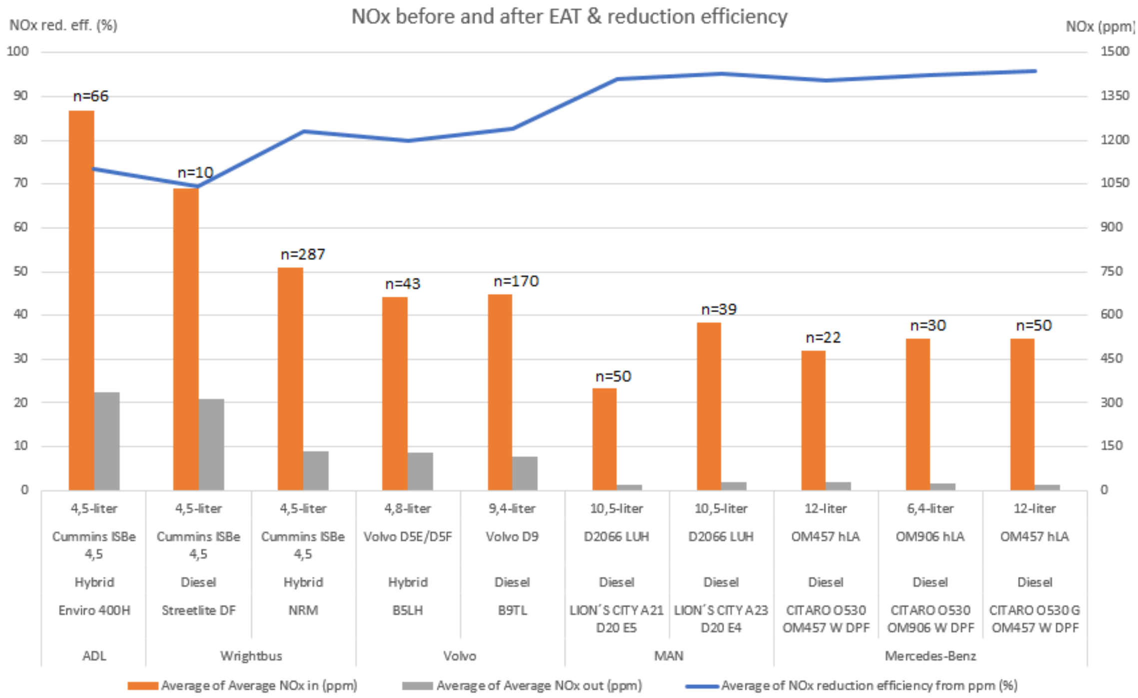

FIGURE 21. NOx emissions before and after EAT

Figure 21 shows that three out of five bottom models are hybrids, and there is significant difference in NO_x emissions between Enviro 400H and NRM, although both models use series hybrid technology and the same Cummins' engine.

To see a picture of emissions during driving, comparison of emissions over the travelled distance was done. NOx emissions in grams per kilometer for the same vehicle models are shown in the figure 22. Buses with Cummins, Volvo and Mercedes engines have been originally equipped with SCR catalyst.

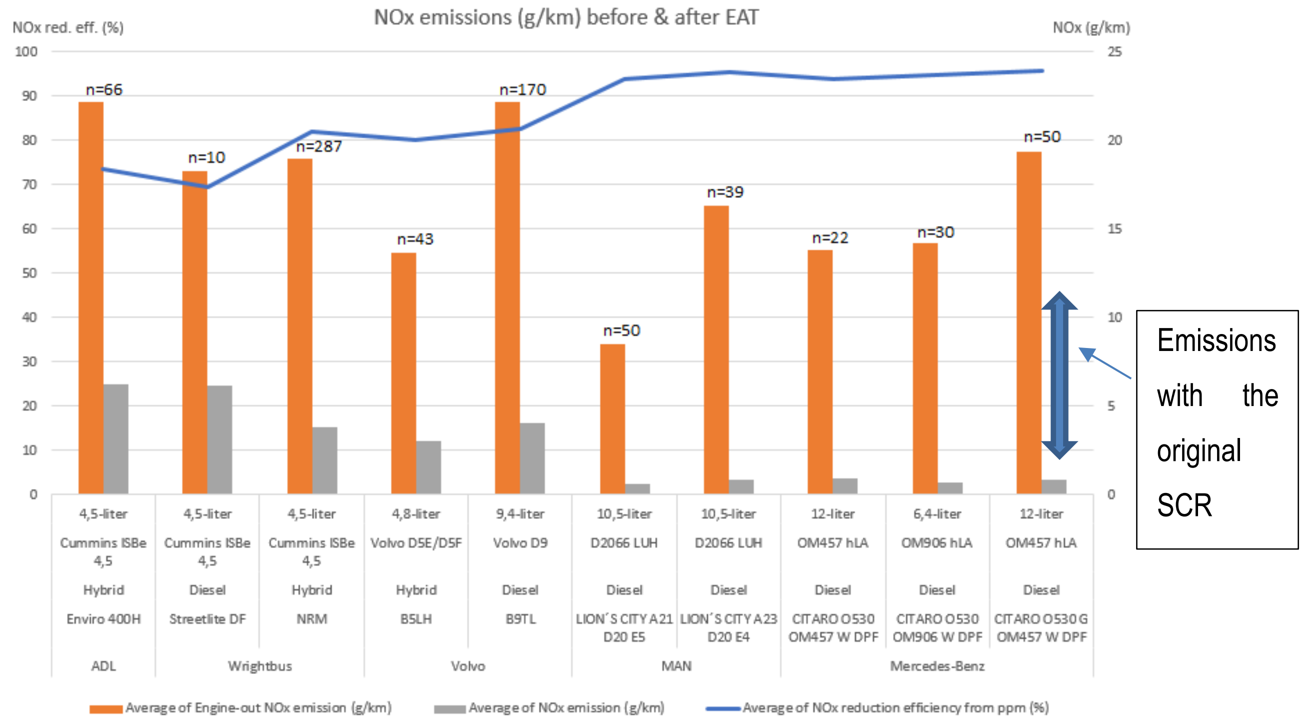

FIGURE 22. NOx emissions in grams per kilometer

The graph above shows average NO_x emissions in g/km before and after the EAT for different vehicles. Blue arrow on the right side of the picture represents the estimated scale of achieved emissions with the original SCR, in this case for buses with Cummins, Volvo and Mercedes engines. The estimation is based on research results, where various Euro III, IV, V and EEV buses were tested on Braunschweig, Helsinki2 and Helsinki3 test cycles (VTT Research Notes, 2007 & City bus performance evaluation, 2019). The researches were conducted by VTT Technical Research Centre of Finland, which is a state owned and controlled non-profit limited liability company. Comparing the emissions over the travelled distance reveals that the reduced amount of NO_x is nearly same between some models even the reduction efficiency and the emissions from tailpipe vary a lot. Figure 23 shows the average amount of reduced NO_x emissions in distance of one kilometer for these bus models.

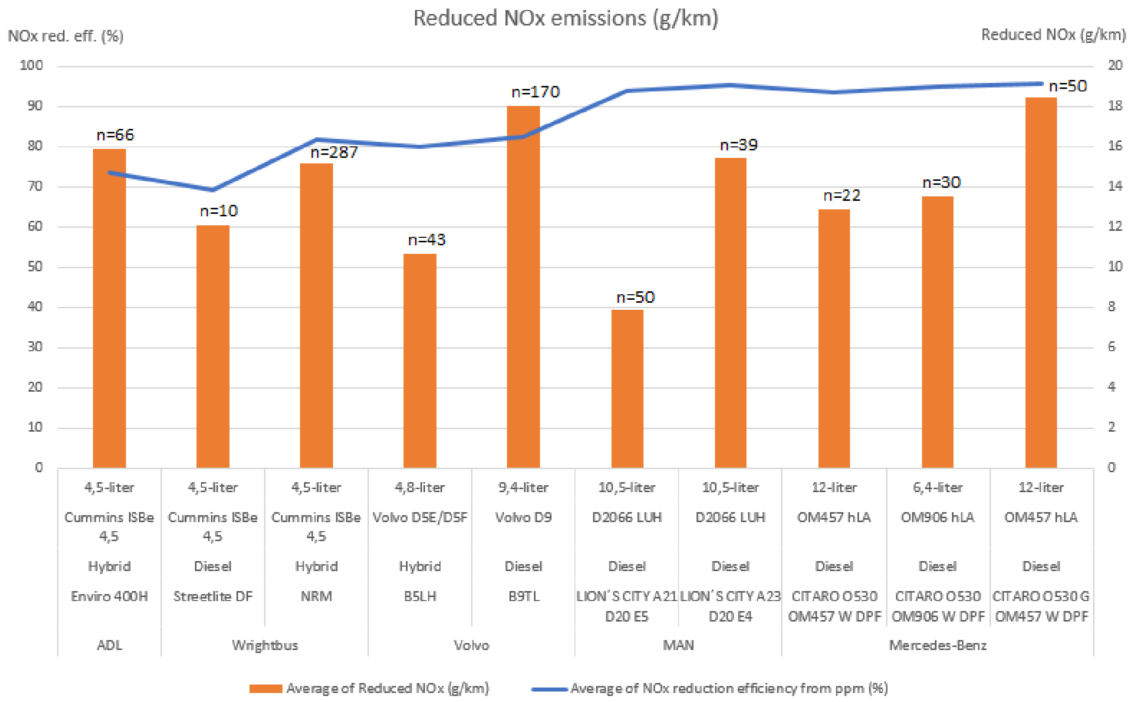

FIGURE 23. Reduced NOx emissions per kilometer

By looking at the reduced grams of NO_x per kilometer, it can be noted that the amounts between buses with best and worst NOx reduction efficiencies are quite similar. In example, Citaro O530 G and B9TL have both reached average reduction of slightly over 18 g/km even the reduction efficiency in Citaro is notably higher.

6.3 Driving Conditions

In addition to reduction efficiency, grams per kilometer emissions are influenced by engine size and driving conditions, especially speed. The average driving speed and emissions per kilometer within these vehicles can be seen in figure 24.

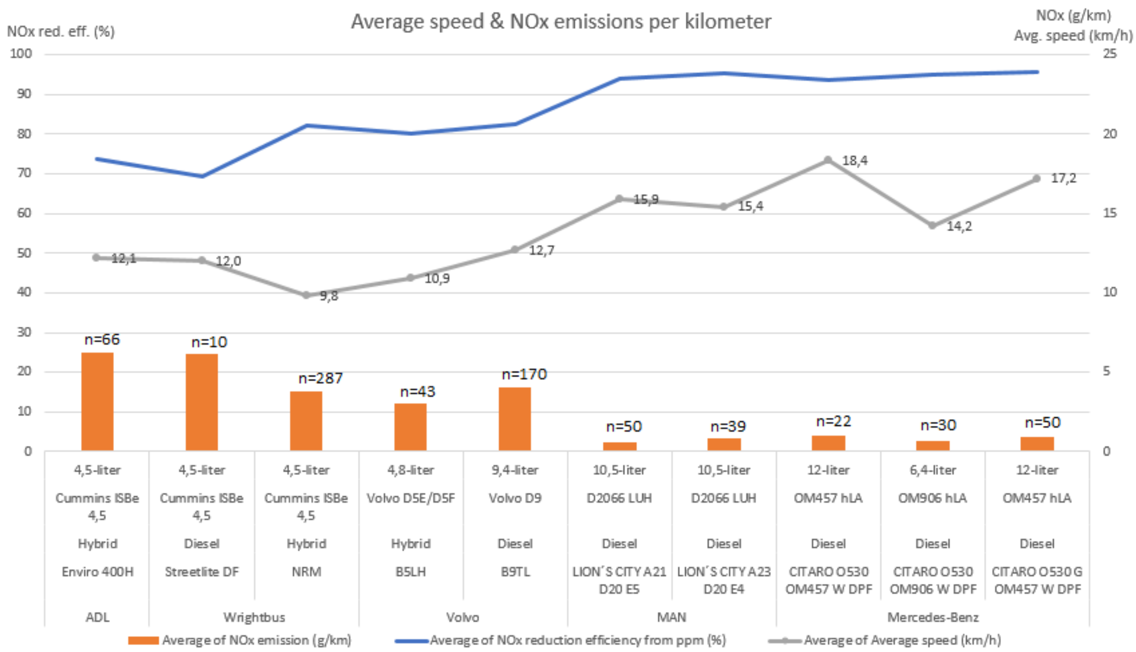

FIGURE 24. Average driving speeds and NOx emissions

By looking at the picture, it can be seen that vehicles with the smallest NO_x emissions have slightly higher average speed than vehicles with the largest emissions. To illustrate the effect of driving speed to emissions, individual vehicle's emissions relation to driving speed was studied.

When investigating the relation between single vehicles' driving speed and emissions, filtering from date was removed. This enabled the selection of a vehicle with the most amount of data for comparison. To see the influence of driving speed to NO_x emissions, daily values were sorted ascending by driving speed. Figures 25 and 26 visualize the relation between these measurements for ADL's Enviro 400H and Mercedes' Citaro O530 G. The selected examples of single vehicles have been chosen to match the single vehicle's average EAT system efficiency to the average efficiency of the group in question as close as possible.

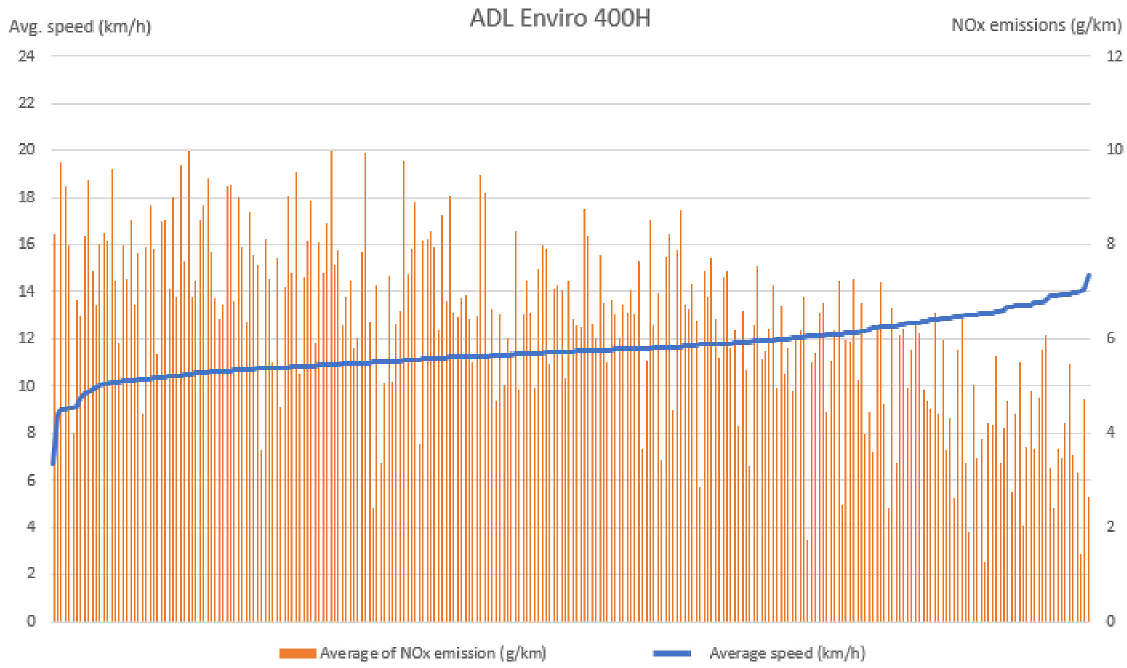

FIGURE 25. ADL Enviro 400H NOx emissions (g/km) related to speed

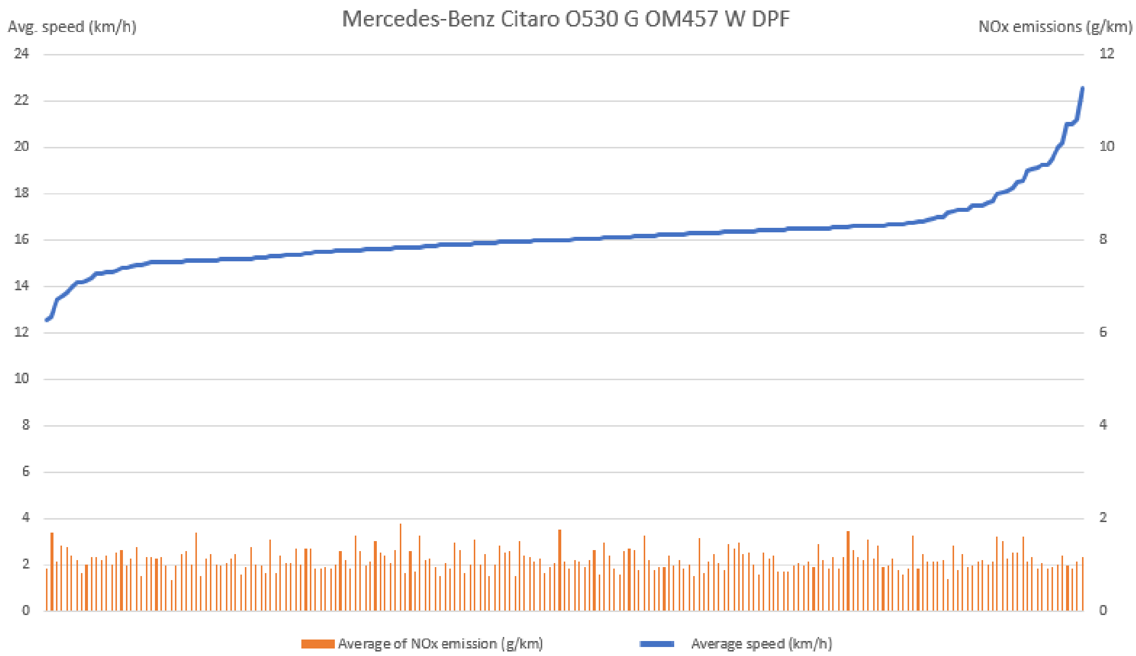

FIGURE 26. MB Citaro O530 G NOx emissions (g/km) related to speed

Figure 25 shows that operating the vehicle in higher speeds reduces the NO_x emissions per kilometer. In Mercedes, similar decrease of the emitted NO_x per kilometer cannot be noticed as the speed increases. The overall NO_x reduction efficiency in the investigated Citaro is about 95% while in the Enviro 400H it is about 75%. Also, must be noted that the operating speeds in Mercedes remain notably higher. In heavily congested cities, buses' average driving speeds stay very low and the emissions per kilometer are higher, therefore it is important that the EAT systems operate efficiently in this kind of conditions. From all the buses, Wrightbus New Routemasters have the lowest average speed because they operate in congested areas near the city center. Example of NRM below (Figure 27) shows that the average operating speeds mainly stay under 14 km/h while Mercedes Citaro O530 G's average speeds (Figure 26) remain above this and may reach up to 22 km/h.

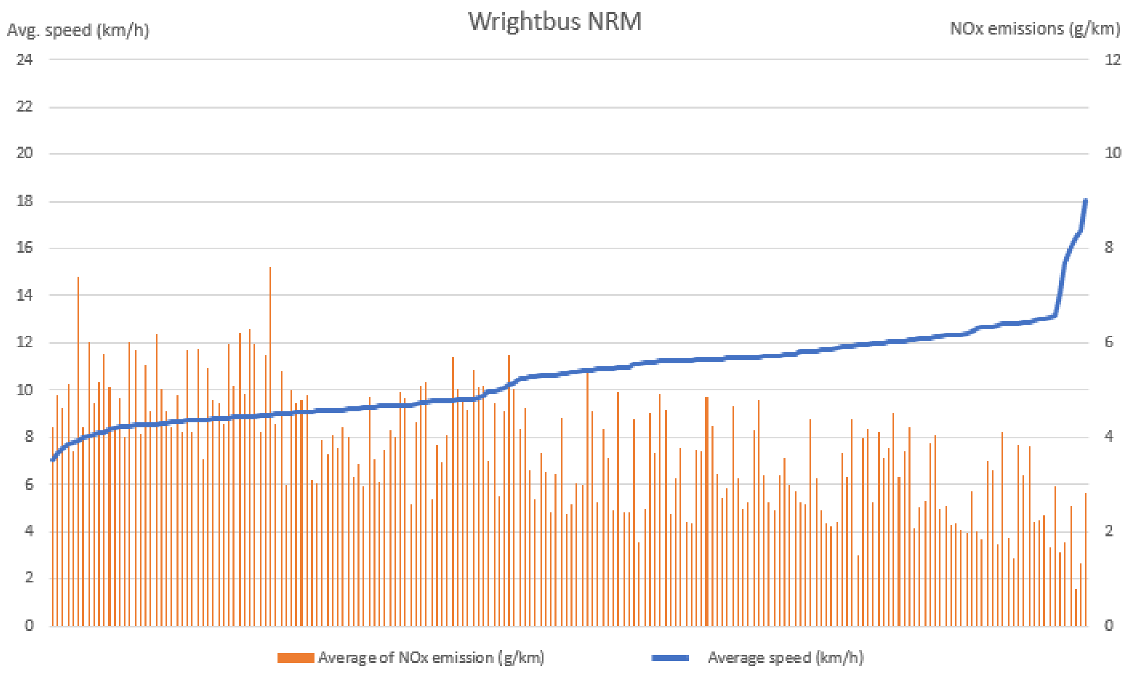

FIGURE 27. Wrightbus NRM NOx emissions (g/km) related to speed

As mentioned earlier in this document, exhaust temperature is a significant factor for operation of the aftertreatment system. The relation between operating speed and exhaust temperature was investigated in the same buses than the examples above. As the average speed increases a slightly rising trend is noticeable in temperatures within Enviro 400H and New Routemaster (Figures 28 & 29).

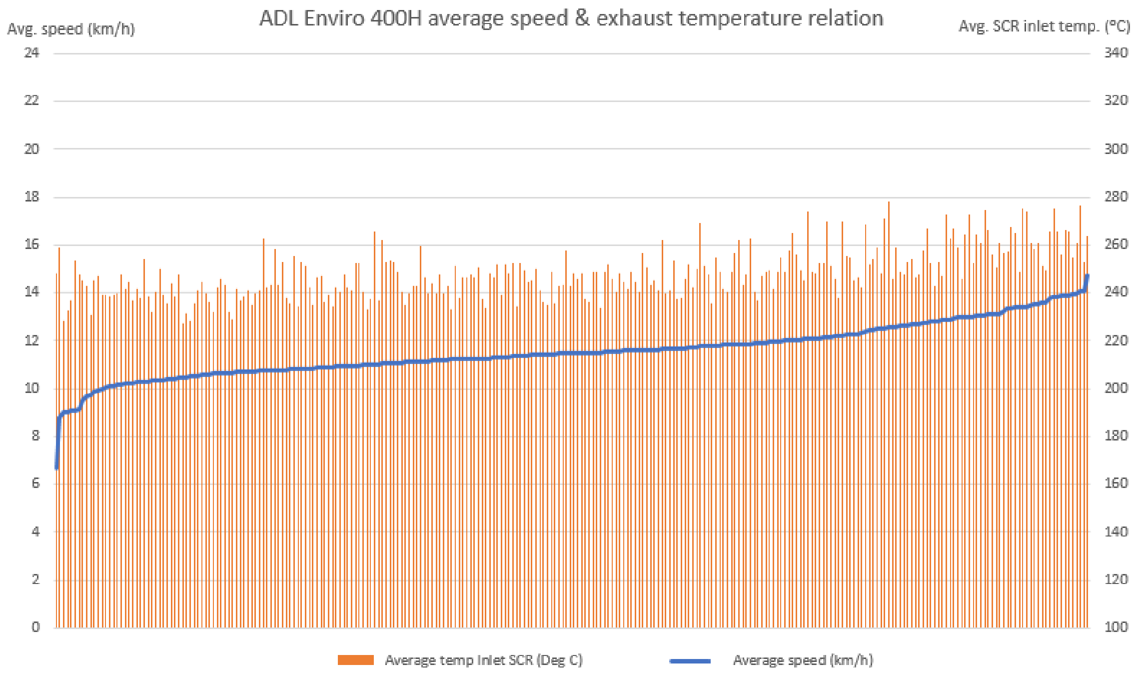

FIGURE 28. ADL Enviro 400H relation between driving speeds and exhaust temperatures

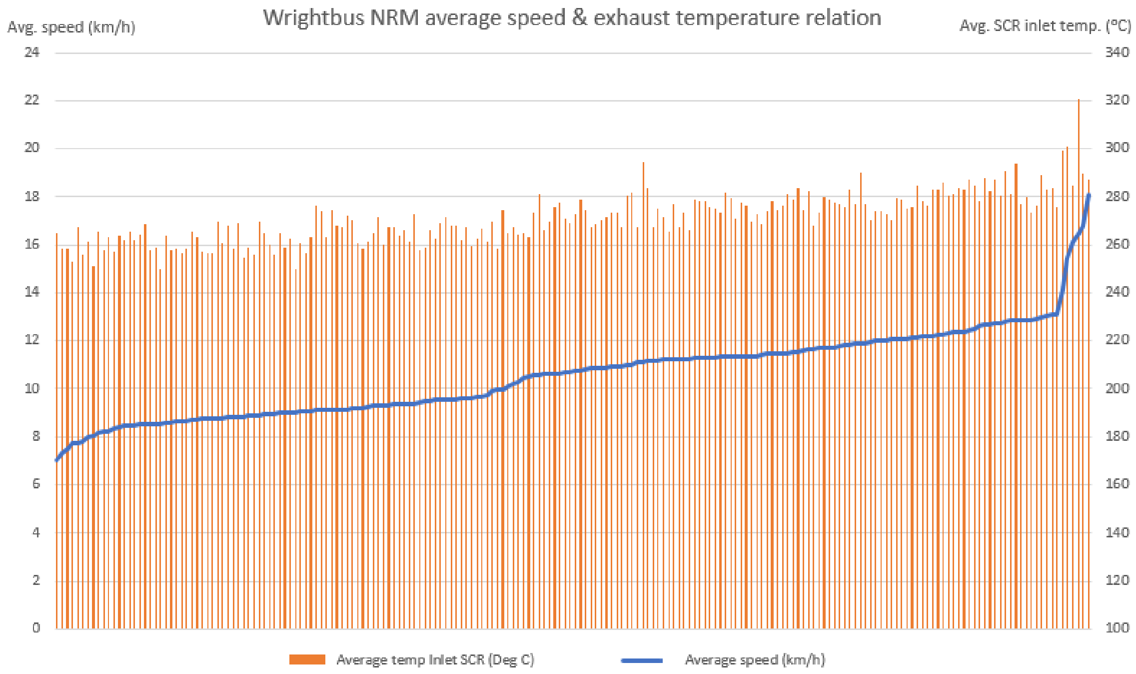

FIGURE 29. Wrightbus NRM relation between driving speeds and exhaust temperatures

In addition to articulated Citaro, average speed and temperatures were also studied in a solo Citaro which is equipped with the same OM457 engine. Figure 30 represents the behavior of exhaust temperatures with increasing speed for articulated Citaro O530 G and figure 31 for a solo bus Citaro O530.

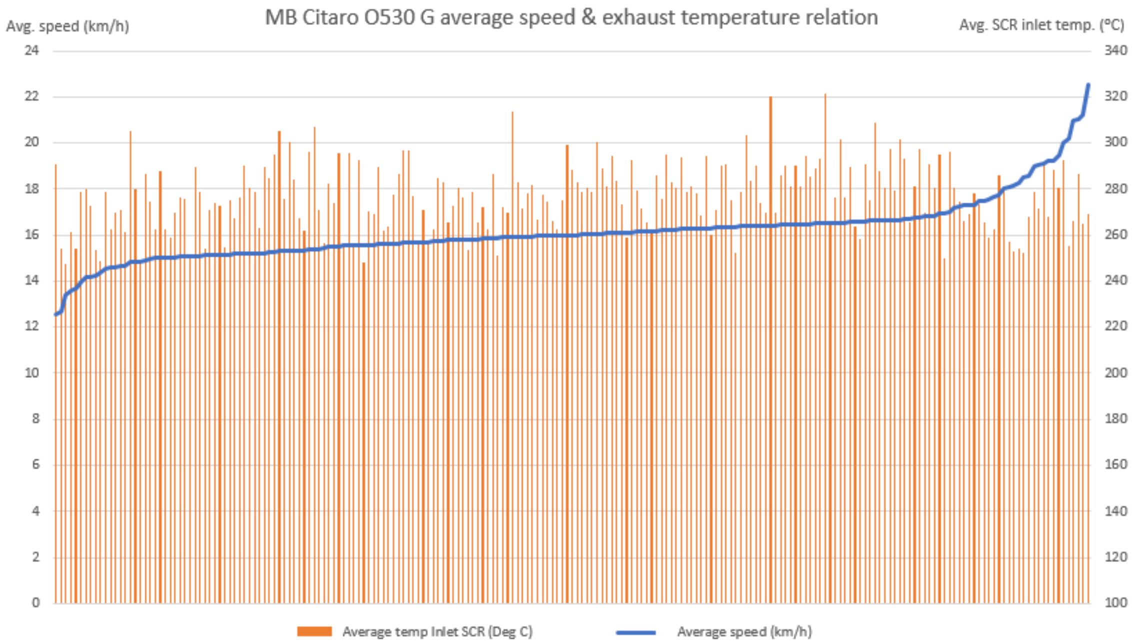

FIGURE 30. MB Citaro O530 G Average operating speeds & exhaust temperatures

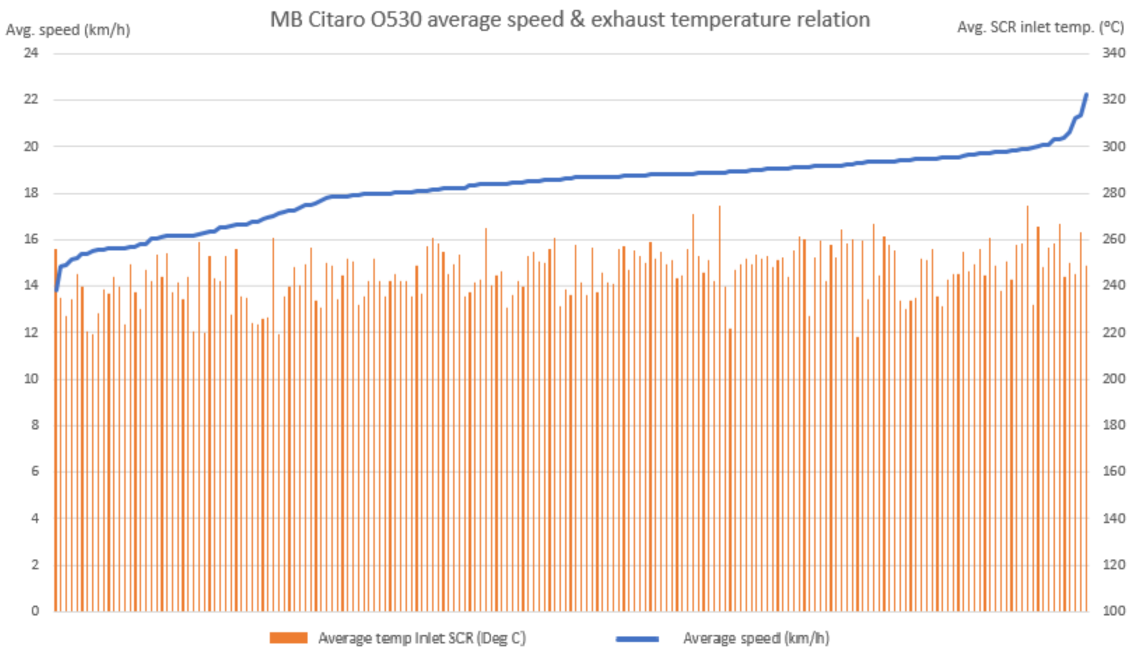

FIGURE 31. MB Citaro O530 average operating speeds & exhaust temperatures

Exhaust temperatures and ambient temperatures were observed in monthly averages within different bus types. A noticeable trend shows that exhaust temperatures remain higher during the summertime when the ambient temperature is also higher. This phenomenon was more notable in diesel-powered buses than in hybrid buses. Figure 32 shows the monthly average ambient temperatures and variation of exhaust temperatures for three different hybrid buses operating in London.

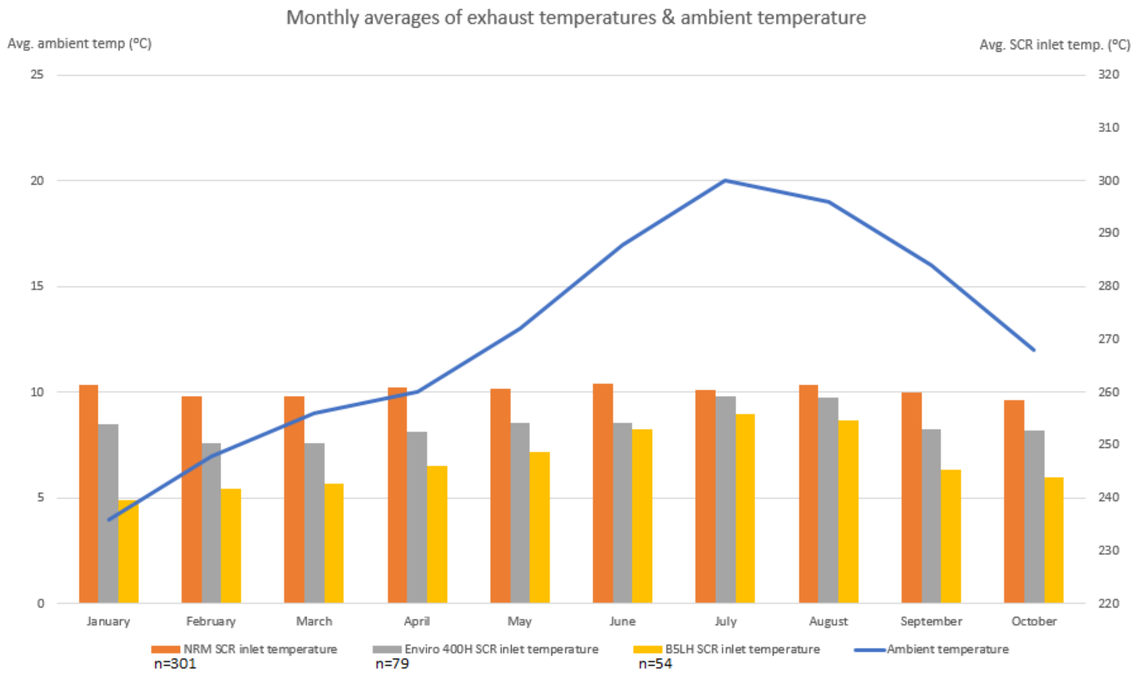

FIGURE 32. Exhaust temperature comparison between NRM, Enviro 400H & B5LH

The picture above shows that the ambient temperature variation has no significant effect in NRM's exhaust temperatures. There is not clear effect on Enviro 400H's exhaust temperatures either but in B5LH temperatures are slightly increasing towards the warmest month.

A similar comparison was made between three diesel-powered double decker buses that operate in London; Volvo B9TL, ADL Enviro 400 and VDL DB300. Volvo is using Volvo's 9,4-liter diesel engine and E400 and DB300 are both equipped with Cummins' ISBe 6,7-liter engine. Monthly exhaust temperature variations between these models can be seen in figure 33.

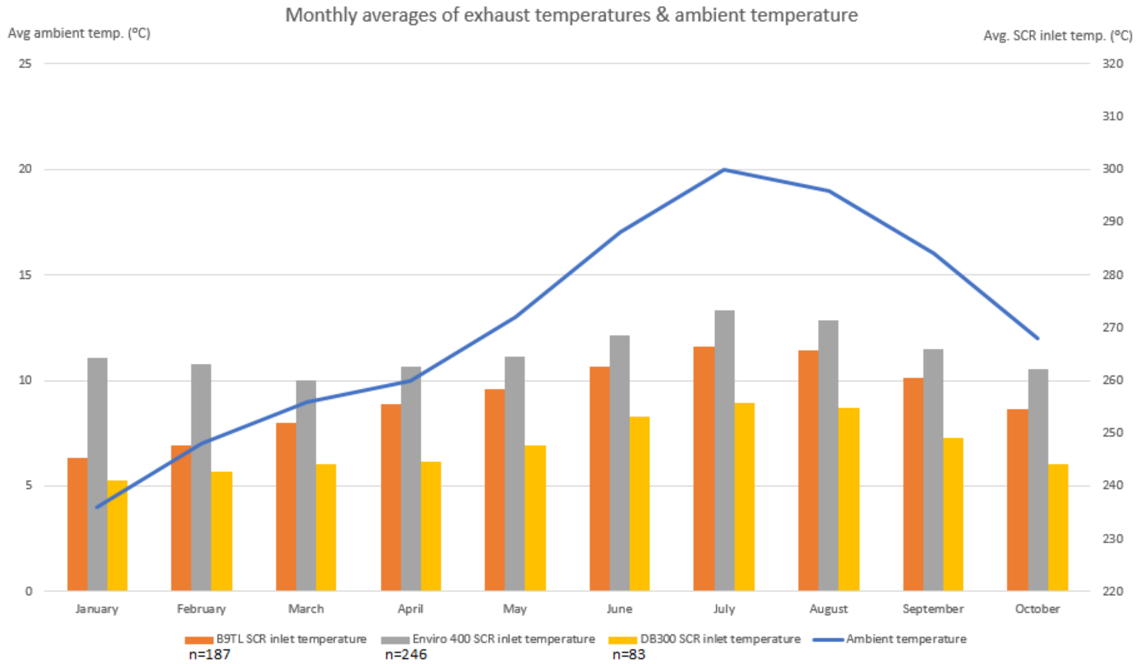

FIGURE 33. Exhaust temperature comparison between B9TL, Enviro 400 & DB300

The graph above shows that the exhaust temperatures remain higher in each bus during the warmest months. it can be also noted that temperature variations are slightly larger in B9TL than in Enviro 400 or DB300.

The effect of ambient temperature was also studied between two types of solo buses that operate in London. Mercedes Citaro is equipped with six-cylinder 6,4-litre OM609 engine and the slightly smaller ADL Enviro 200 is powered by four-cylinder 4,5-litre ISBe engine. Differences in the exhaust temperatures between these solo buses are shown in figure 34.

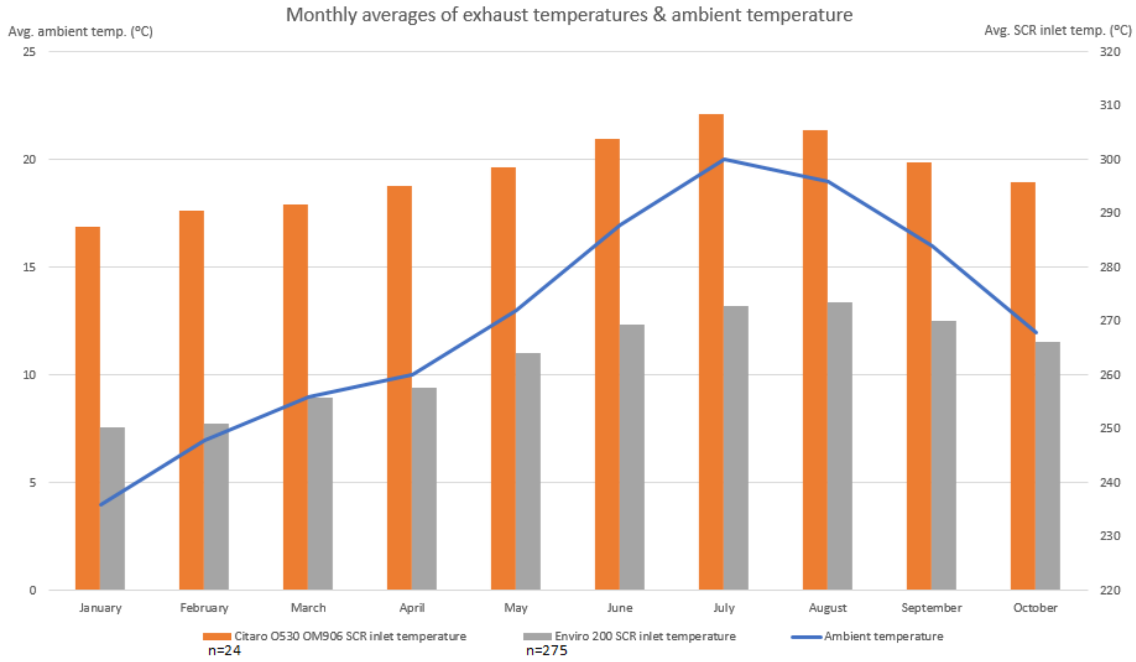

FIGURE 34. Exhaust temperature comparison between Citaro O530 OM906 & Enviro 200

Figure 34 reveals that, even the exhaust temperatures behave quite similar, Mercedes' temperatures remain much higher than ADL's through the reviewed period.

Figure 35 below represents the exhaust temperature behavior within four bus types operating in Aachen Germany.

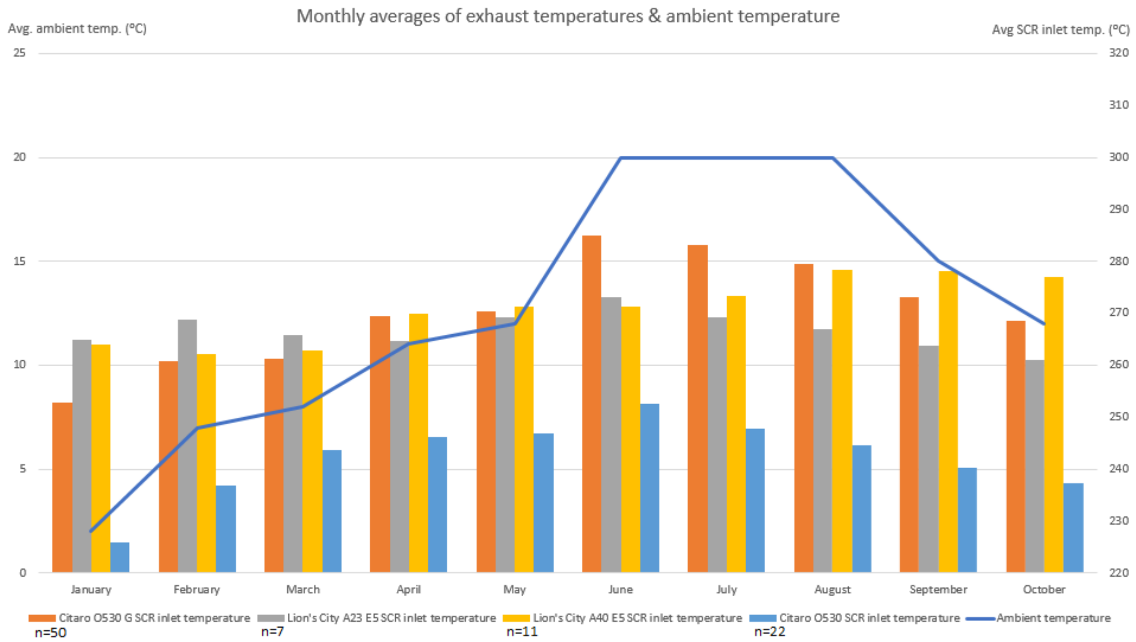

FIGURE 35. Exhaust temperature comparison between Citaro O530 G, O530, Lion's City A23 & A40

The EAT systems in all these bus models are operating in high, over 90% NO_x reduction efficiency. Both Mercedes' buses, Citaro O530 and O530 G are powered by 12-liter OM457 diesel engine while Lion's City A23 and A40 are both using smaller MAN's 10,5-liter D2066 LUH engine. By looking at the picture, it can be seen that exhaust temperatures in Mercedes' buses are correlating with ambient temperatures more than temperatures in MAN's buses. Also, it should be noted that temperatures in solo Citaros are staying notably lower than in articulated Citaro O530 G.

6.4 Exhaust Temperatures & Reduction Efficiency

The behavior of the EAT system when exhaust gas temperatures are increasing were compared between various bus models. The following graphics include the daily values for all the buses that had recorded data in period of 10 months from January to October. The n in the figure states the count of buses and the light blue on the background indicates the daily values of NO_x reduction efficiency with increasing average SCR temperatures, which is presented with the orange line. The dark blue trendline has been included in order to ease the interpretation. When comparing Enviro 400H and NRM, graphics reveal that exhaust temperatures remain slightly higher in NRM and the average reduction efficiency is about 80% when the average temperature is 250, while in the 400H the efficiency reaches 70% in the same temperature. The relation between NO_x reduction efficiency and exhaust temperatures between these models are shown in figures 36 and 37.

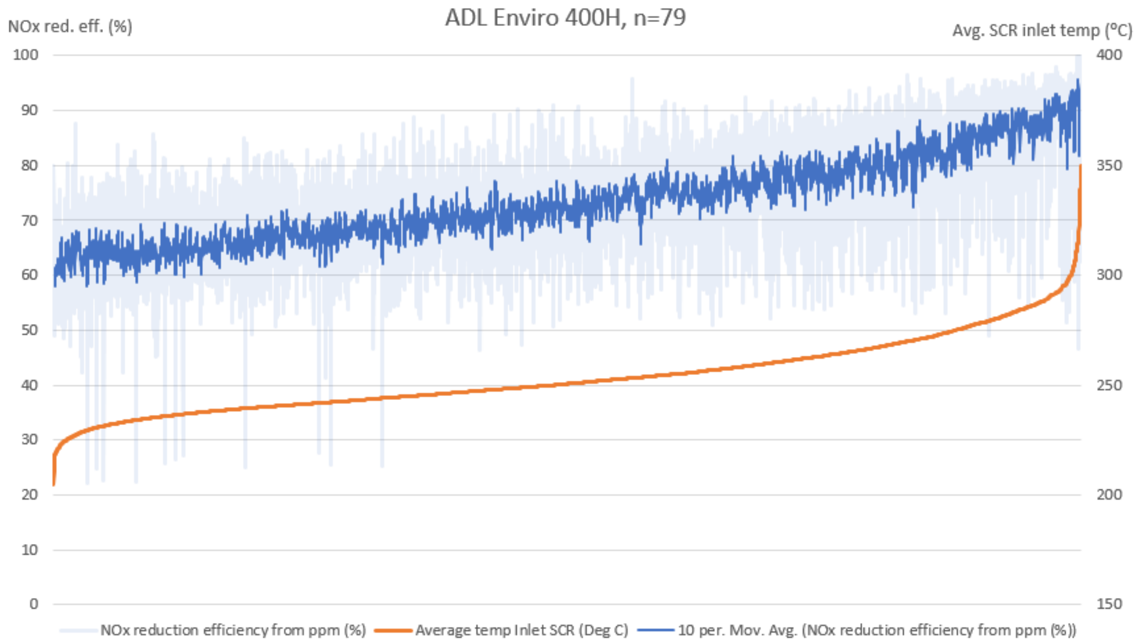

FIGURE 36. Enviro 400H NOx reduction efficiency related to exhaust temperature

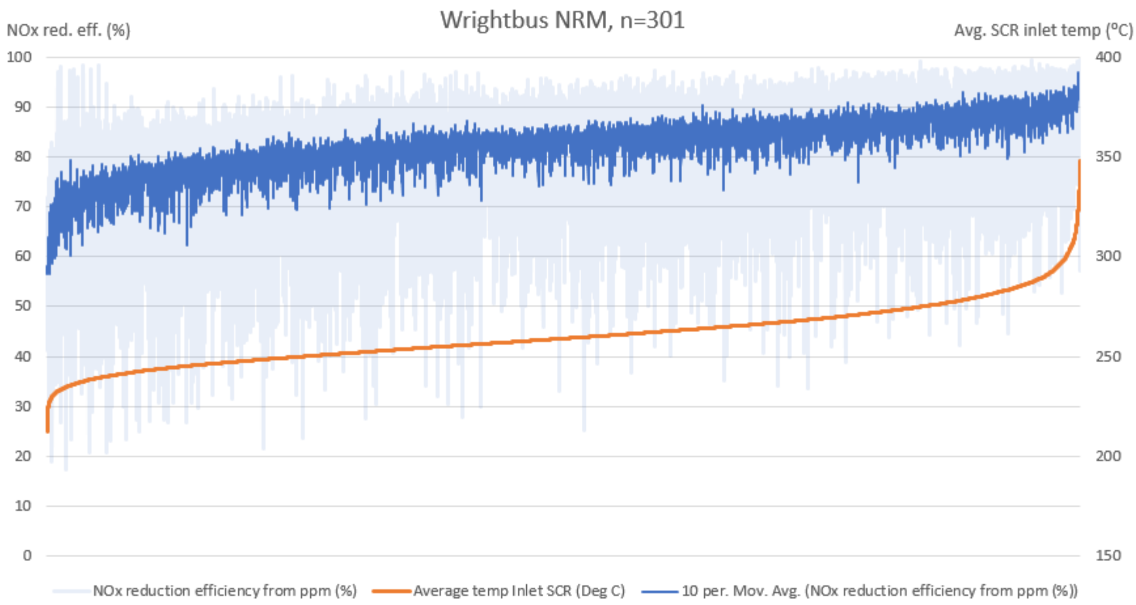

FIGURE 37. Wrightbus NRM NOx reduction efficiency related to exhaust temperature

In comparison ADL's Enviro 200 is also equipped with the same Cummins ISBe engine but without hybrid technology. The behavior of the EAT system is similar with Enviro 400H when temperatures increase, but the overall efficiency remains higher due to slightly higher exhaust temperatures. Enviro 200's EAT system efficiency related to exhaust gas temperatures is presented in figure 38.

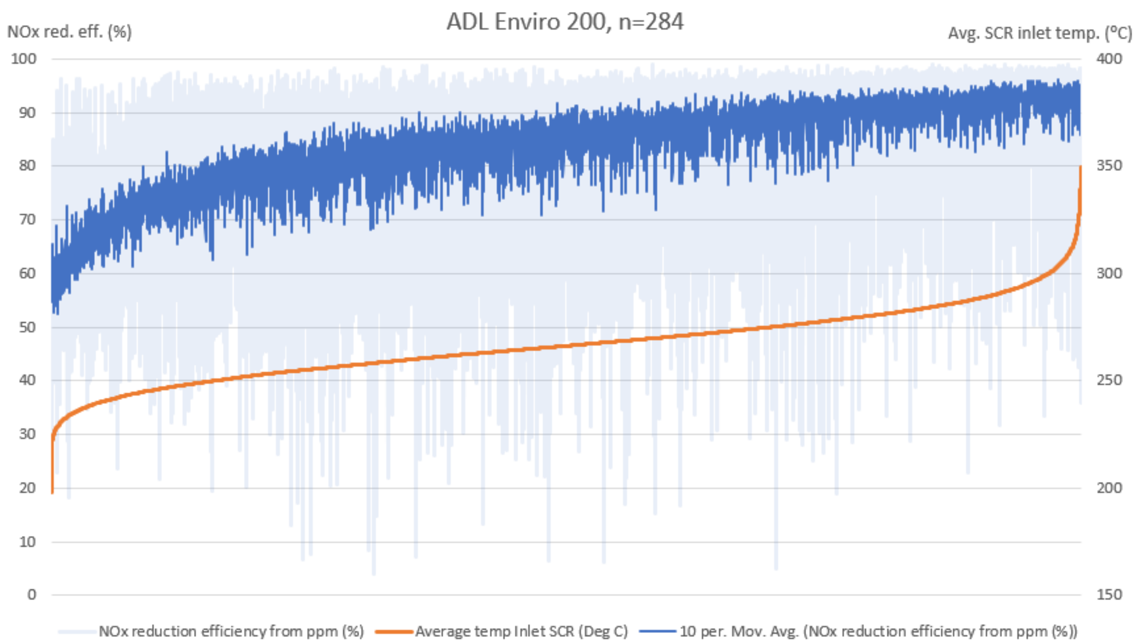

FIGURE 38. Enviro 200 NOx reduction efficiency related to exhaust temperature

When these models are compared with Mercedes Citaro O530 G or MAN Lion's City A21 can be seen that the EAT system efficiency in both these models remains constantly close to 90% or above and dramatic decreases in NO_x reduction does not occur even at low temperatures such as 230 ºC. The EAT system efficiencies for Mercedes Citaro O530 G and MAN Lion's City A21 are presented in figures 39 and 40.

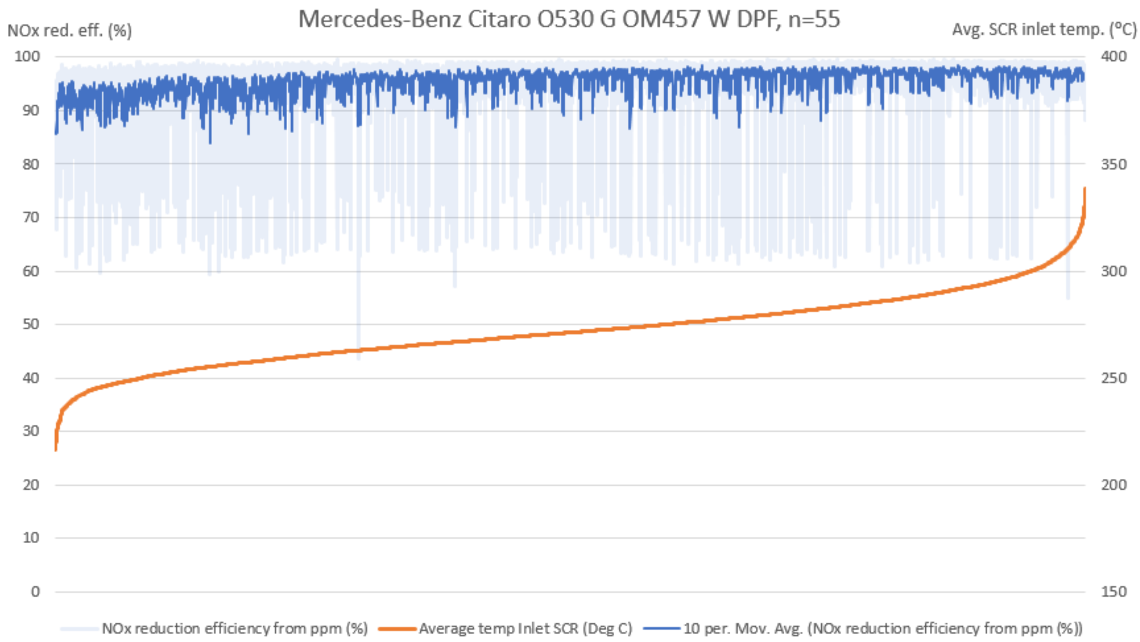

FIGURE 39. Citaro O530 G NOx reduction efficiency related to exhaust temperature

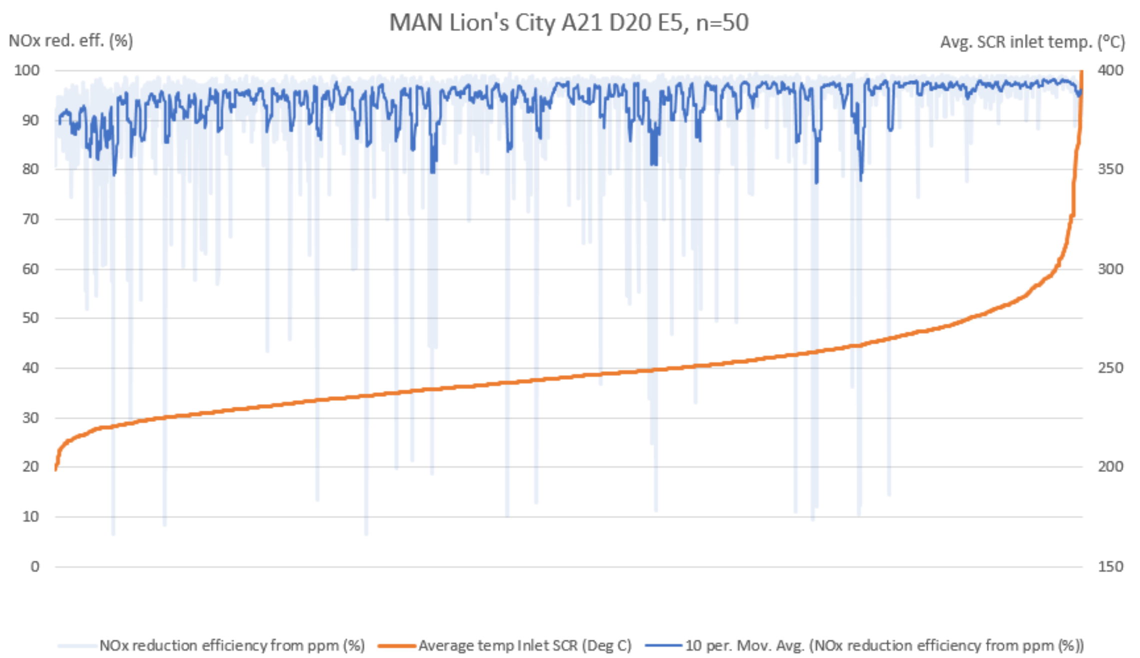

FIGURE 40. Lion's City A21 NOx reduction efficiency related to exhaust temperature

7 INFLUENCING FACTORS

In this chapter the processed data will be analyzed by taking account the aspects of the operating conditions and different mechanical factors. Reasons for the influence of different factors in retrofit EAT system operation are studied and explained by utilizing the background theory.

7.1 Engine Design & Parameters

In the study, reduction efficiency and emissions were investigated from vehicles with retrofitted EAT system. The results were compared between different engines and bus models with the best and the worst reduction efficiency. In comparison of the raw engine-out NO_x emissions was noticed that Cummins' engines generated clearly the largest amount of NO_x (ppm) in combustion process (Figure 20). Both Cummins' ISBe 4,5- and 6,7-liter engines emitted average of nearly 900 ppm of NO_x or above, while the second most emitting engines from Volvo had both little under 700 ppm average of NO_x. Averages of engine-out NO_x emissions in rest of the engines were between 400 and 550 ppm.

As figure 8 points out, there is number of correlations between emitted pollutants and engine design and operating parameters. To reach the emission limits, optimization of the engine combustion and the selected aftertreatment method must be done for the purpose of overall system design. Different manufacturers have chosen different kind of approach in the system design to reach the emission limits, which could explain the differences in the combustion process and raw NO_x emissions.

Table 3 shows that Cummins and Volvo have implemented the emission control by using SCR only as aftertreatment to achieve EURO IV and V levels. In this kind of solution without any particulate filters, combustion is optimized for minimum soot generation. Engine operating parameters i.e. EGR rate and/or injection timing can be utilized to change the ratio between NO_x and soot emissions, so called soot-NO_x trade-off. This could be one of the reasons for high NOx emissions of Cummins and Volvo engines.

MAN's engines generated the smallest amount of NO_x in the combustion process. This could be partly explained by the different parameters and aftertreatment solutions in the engines. All MAN engines are equipped with EGR, which reduces the NO_x generation due to lowered in-cylinder temperatures. MAN's EURO IV engines are also equipped with PM-Kat, which is basically an oxidizing catalyst and open particulate filter combined, where the catalyst oxidizes NO to NO_2, and the nitrogen dioxide is then used to oxidize the collected soot particles. This kind of aftertreatment method allows more PM emissions in combustion process than SCR system without any filtering components. EURO V/EEV engines from MAN are equipped with CRT™ (continuously regenerating trap), which requires ultra-low sulfur fuel and a certain minimum NOx/PM ratio for proper operation. CRT™ is a combination of DOC and DPF, where the particulates trapped in a wall-flow filter are continuously oxidized by NO_2 generated in upstream DOC.

7.2 Operating Conditions & Exhaust Temperature

The influence of driving conditions to EAT system operation was studied by comparing first the reduction efficiency to the NO_x emissions and average driving speeds. The comparison revealed that vehicles with the best reduction efficiency and the lowest NO_x emissions per kilometer were also operating on slightly higher average speeds (Figure 24). Closer inspection of three individual vehicles stated that increasing the driving speed decreases the emitted NO_x per kilometer. In case of the studied ADL Enviro 400H, emissions were reduced from average of 8 g/km to 4 g/km when the average speed was increased from 10 km/h to 15 km/h (see Figure 25). Figures 26 and 27 represent reduction in emissions in case of Citaro O530 G and NRM when average speed is increasing. The emissions for NRM were also decreased from 4 g/km to 2 g/km when the average operating speed increased from 8 km/h to 14 km/h. Similar decrease in Citaro O530 G was not noticed but the emissions remained constantly below 2 g/km because of great reduction efficiency. Although increasing operating speed has influence on the engine operation and thereby exhaust temperatures the air resistance has minimal effects even if the speed was increased from 10 km/h to 20 km/h. Therefore, reduction of emissions can mostly be explained by the fact that with only slight increase of the engine load, driving speed can be doubled and the relative fuel consumption remains lower.

The daily average speeds were compared with the average temperatures, and slight increase of the temperatures was noticed in case of Enviro 400H and NRM, when the average speeds were sorted ascending (Figures 28 & 29). Although the increase in temperatures seems very small, it can be substantial for the EAT system efficiency when taking account, that the temperature required for efficient hydrolysis reaction of urea is 250 ºC or above. Therefore, the operating speed can have negative influence on the EAT system efficiency. Especially heavily congested areas expose the EAT system to challenging conditions because buses are constantly accelerating, decelerating and standing still, which means there is possibility for excessive idling of the engine, and when the engine load stays low the exhaust temperatures might drop below the optimal level for efficient NO_x reduction. A similar comparison was made for one articulated Citaro and one solo Citaro but the increase in exhaust temperatures was not as clear (see Figures 30 & 31).

When the ambient temperatures were compared with the exhaust temperatures between various vehicle types, it was noticed that exhaust temperatures were correlating with ambient temperatures stronger in some bus models than others. The comparison was done between buses with similar features e.g. double decker buses that operate in the same city or buses with same engine. It was noticed that within the three hybrid buses, New Routemaster, Enviro 400H and B5LH, the biggest variation in the average temperatures between the coldest and the warmest month was recorded from Volvo B5LH buses. In case of E400H the exhaust temperatures were varying slightly but no clear correlation with ambient temperature is in sight, while the average temperatures in New Routemasters seem to remain close to 260 ºC regardless of the month and the ambient temperature (see Figure 32).

A similar comparison between diesel-powered double-decker buses and solo buses that operate in London is seen in figures 33 and 34. Pictures show that the average exhaust temperatures are increasing in these buses towards the warmest month. From the double-deckers most variation between the coldest and the warmest month is seen within Volvo B9TLs when the average SCR temperatures vary up to 20 ºC. Similar variation was noticed within Mercedes Citaro O530 solo buses.

Figure 35 shows the exhaust temperature variation between four different bus models operating in Aachen. The picture reveals that the average SCR temperatures in both Mercedes' buses behave similar but the average temperatures in articulated Citaro O530 G stay up to 30 ºC higher than in solo Citaro. Within the MAN's Lion's City A23 and slightly longer A40 buses the variation in average exhaust temperatures is notably smaller compared to the two Mercedes' models and there is no clear connection with the average ambient temperatures.

According to the graphs, the ambient temperature has quite big impact on the exhaust gas temperatures in the SCR chamber. The effect also seems to vary notably between different vehicle types. Proper insulation of the EAT system components is important factor to minimize heat losses and keep the SCR temperatures high enough for efficient NO_x reduction. Also, the placement of the SCR chamber has effect on how the catalyst reacts to the variations of ambient temperature.

7.3 Temperature Relation to NOx Reduction & Emissions

The study of the exhaust temperatures and the efficiency of the EAT system was carried out on various bus models by including recorded values from multiple buses to one graph. Few examples reveal, how big of an impact the SCR temperatures have on the NOx reduction efficiency when values were sorted ascending by average exhaust temperatures. Figures 36…40 represent the change of the reduction efficiency with increasing SCR temperatures within various bus types. By looking at the graph for Enviro 400H (figure 36) can be seen that 50 ºC increment in the average SCR temperatures from 250 to 300 increases the average reduction efficiency from 70% to 90%.

When studying the emissions and the reduction efficiency it can be noted that the variation in EAT system efficiency in typical Enviro 400H is very large. Increasing the reduction efficiency from 65% to 95% for Enviro 400H means drop in NO_x emissions from 10 g/km to below 2 g/km. If the daily average NO_x emissions could be kept in 2 g/km instead of 10 g/km would that mean 1.2 kg more of reduced NO_x on a daily operation if the driven distance would be 150km. The relation between NO_x reduction efficiency and emissions in typical Enviro 400H can be seen on figure 47.

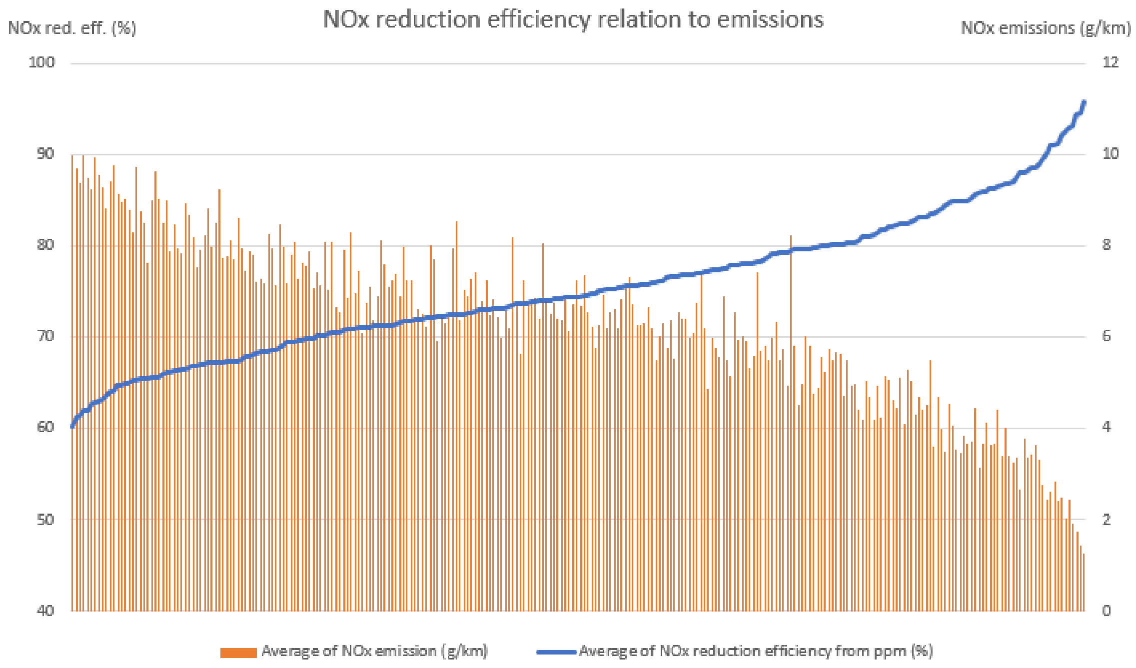

FIGURE 41. Impact of reduction efficiency to emissions in typical Enviro 400H

When viewing an average Mercedes-Benz Citaro O530 G when the reduction efficiency readings have been sorted ascending, it can be noted that the line follows closely the trendline that has been presented in figure 39. Figure 48 represents an example of typical Citaro O530 G and reveals that constant high efficiency of the EAT system keeps the emissions low under 2 g/km.

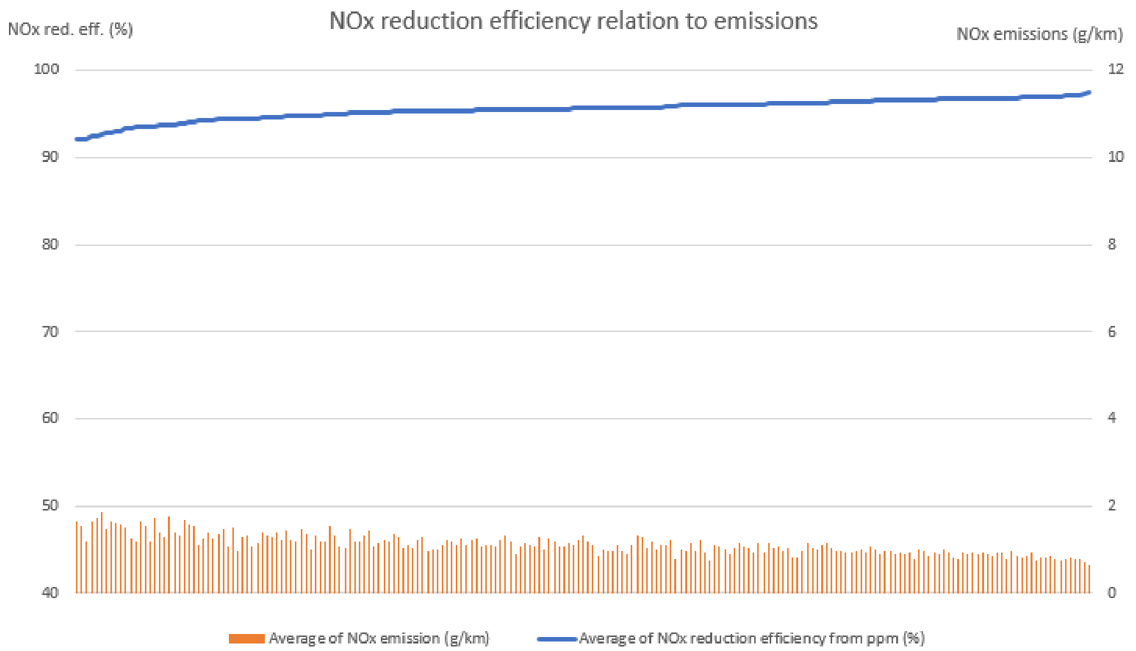

FIGURE 42. Impact of reduction efficiency on emissions in typical Citaro O530 G

7.4 Vehicle Design

A vehicle's overall design can influence the exhaust temperatures and emissions. For example, placing a large high-powered engine to a small bus can lead to a problem where exhaust temperatures stay too low for efficient NO_x reduction. Although the aftertreatment system is working with high efficiency in all three Mercedes buses in figure 49 below, the solo Citaro with 12-liter OM457 engine has notably lower exhaust temperatures than a similar bus with a smaller engine or heavier articulated Citaro G.

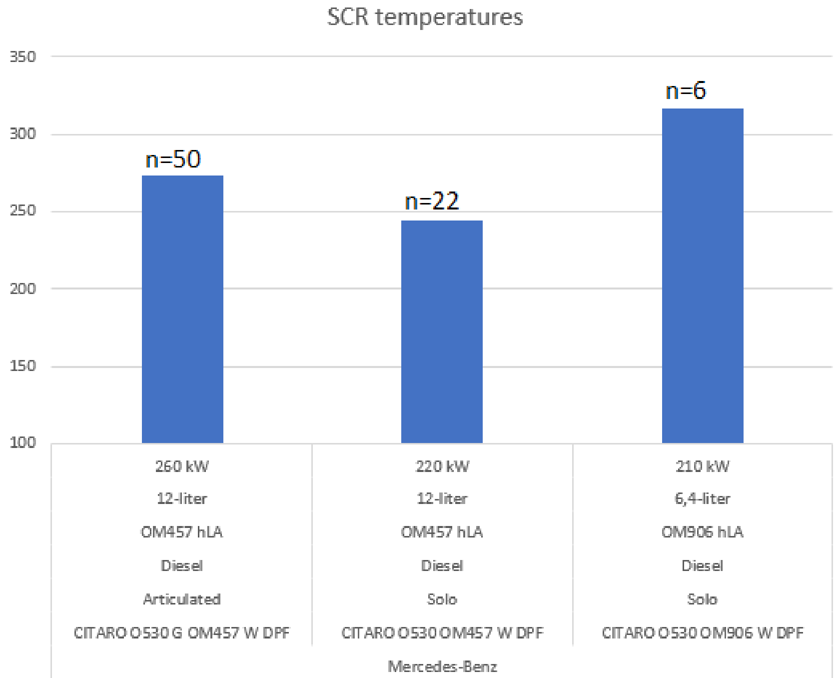

FIGURE 43. Difference between model variants

Four of the double-decker buses are comparable with the body model and the weights are close to each other's. VDL DB300, Volvo B5LH and B9TL are Wrightbus Gemini 1 ,2 or 3 bodied and Enviro 400 is bodied by ADL. The difference in the exhaust temperatures between these models is shown in figure 50.

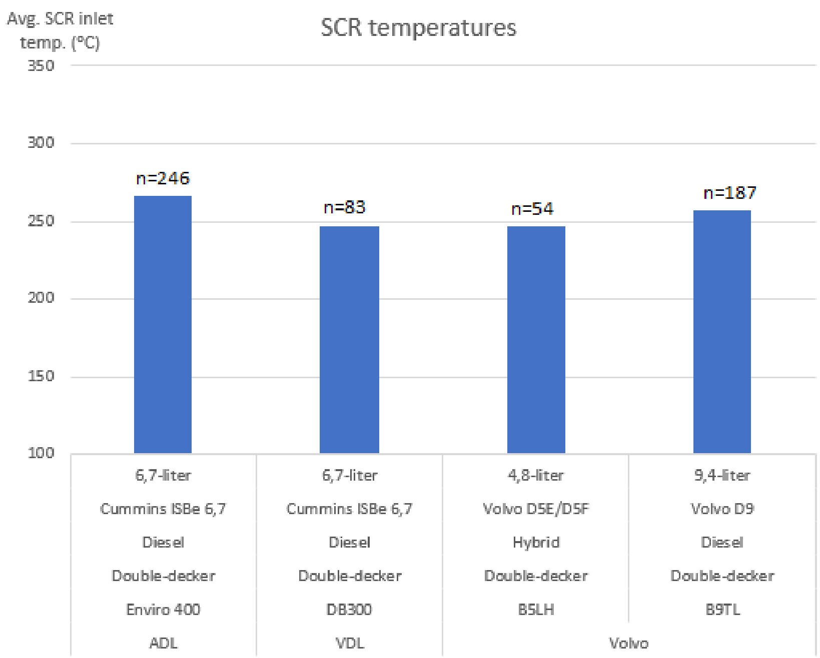

FIGURE 44. Difference between double-decker buses in London

In case of Wrightbus Streetlite WF and DF models the emissions and the SCR temperatures had notable differences. The difference in the bodywork is that the DF version is slightly longer and heavier and the door is in front of the front axle but in WF the door is behind the front axle. Both have been equipped with Cummins ISBe 4,5 engine but the maximum power in heavier DF version is only 119 kW while in WF version it is 160 kW. The difference between Streetlite DF and Streetlite WF is shown in figure 51 below.

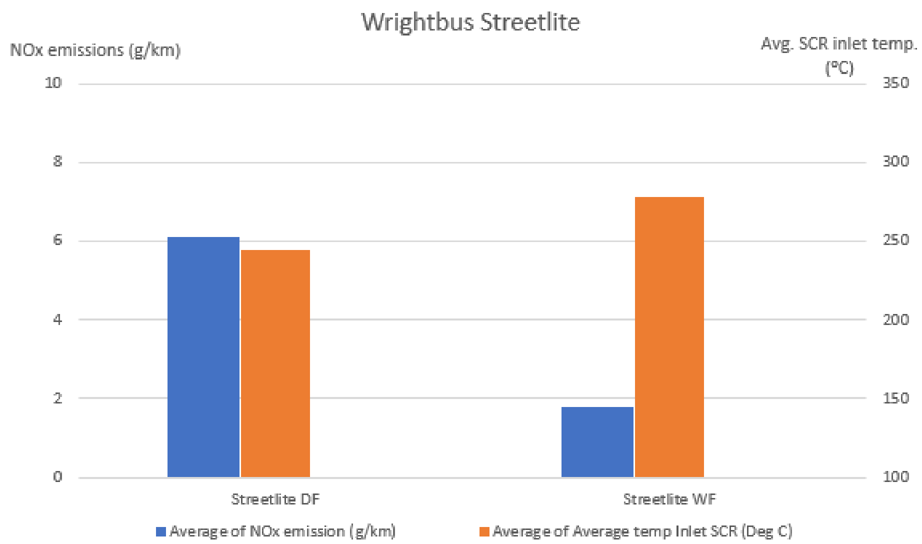

FIGURE 45. Difference in exhaust temperatures and emissions between Streetlite DF & WF models

In addition to engine size and body weight there are multiple other mechanical and technical factors that can affect the EAT system operation. For example, the length of the exhaust pipe between the engine and the SCR catalyst affect the temperature of exhaust gases entering the catalyst chamber. Also, different transmissions can affect the engine operation and emissions, and therefore the influence of transmission should be studied.

7.5 Impact of Maintenance

To ensure that the EAT system operates without problems, it must be serviced at regular intervals. Therefore, maintenance instructions will be provided to operators when the system is installed. Following the maintenance instructions is important to prevent any DPF blockages or deposits in the urea dosing nozzle, which could radically decrease the EAT system efficiency or in the worst case disable the whole system.

Although, Mercedes' engines are one of the cleanest engines within the studied population with generated engine-out NO_x emissions of slightly over 500 ppm, the amount of raw NO_x emissions in g/km is one of the highest in Citaro O530 G. Figure 52 shows the vehicles with the most amount of engine-out NO_x emissions in g/km. It can be noticed that all these buses generate nearly 20 g/km of NO_x or above in the combustion process. In the best cases this amount can be reduced with aftertreatment down to below 1 g/km.

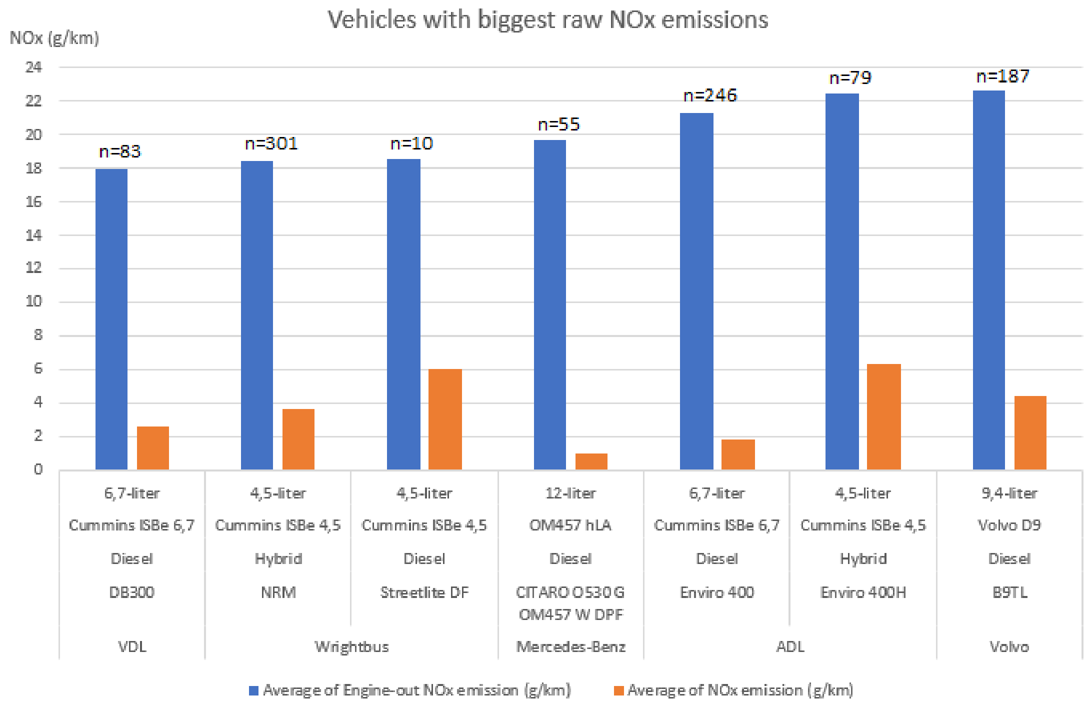

FIGURE 46. Vehicles with most engine-out NOx emissions

If the EAT system has not been serviced and the SCR fails due to a malfunction, or the emission control system has been made to inoperable, emissions from a faulty vehicle in operation could be multiple compared to a good one. The example below (Figure 53) represents a vehicle that has been operating with a faulty EAT system.

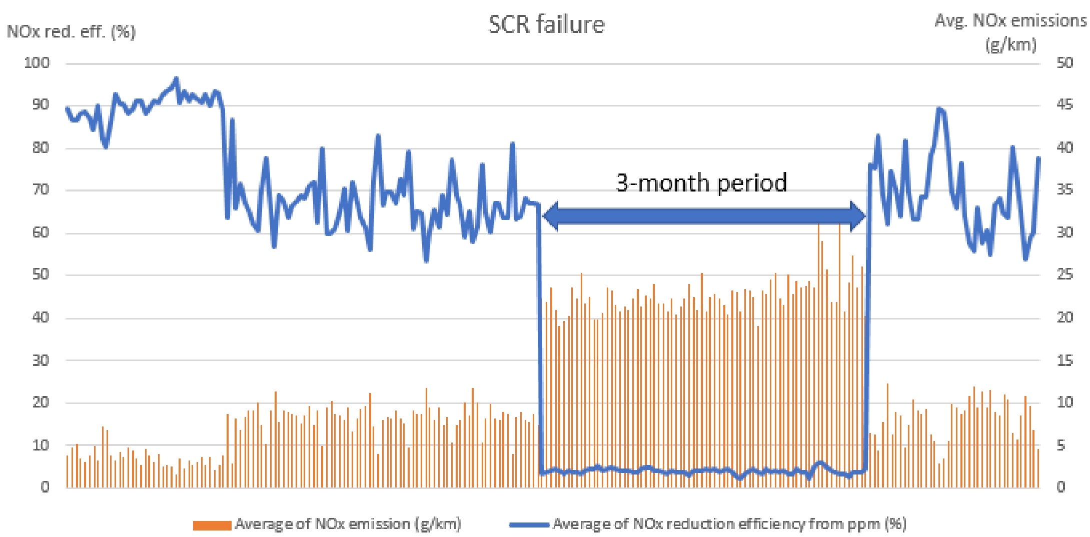

FIGURE 47. SCR failure

In a situation where the reduction efficiency has dropped to zero, the vehicle should have been taken for service. Instead it has been operated nearly three months with poor NO_x reduction and the emissions have been 20 g/km instead of 5 g/km. If the average distance driven each day has been 150 km the bus has been emitting 2.3 kg of extra NOx daily.

In addition to the poor maintenance, tampering the vehicle's EAT system has a similar effect. Tampering means removing, disconnecting, altering, bypassing or rendering ineffective any pollution control equipment installed in a motor vehicle. Tampering with a vehicle emissions control system is illegal and can negatively affect the vehicle performance and contribute to air pollution. The example in figure 54 represents the effect of a tampered vehicle.

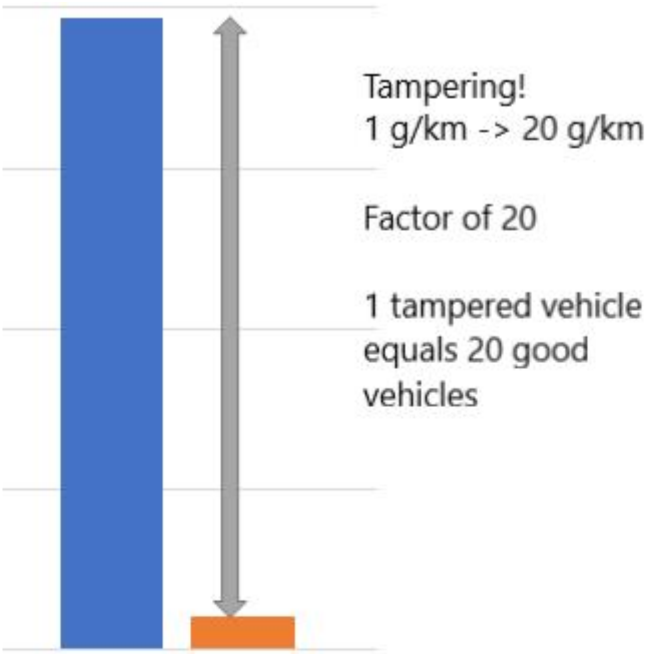

FIGURE 48. Tampering effect

As the figure shows, emissions from one faulty or tampered vehicle can equal 20 good vehicles. In the worst case this factor can be even larger, and therefore it is necessary to eliminate these vehicles from traffic and polluting the environment.

7.6 Technical Challenges

Designing an EAT system for retrofit purposes includes multiple technical challenges due to challenging operating conditions and limited space. In crowded cities the average operating speeds remain low, possibly under 10 km/h and include multiple stops in short period of time. As a result of this, the exhaust temperatures might drop below the optimal level for NO_x reduction, and therefore the EAT system must be designed to operate on a wide temperature scale. Reducing thermal losses from exhaust to aftertreatment components fastens the light-off from cold start and improves the SCR efficiency. Optimizing the urea mixing and flow characteristics allows injecting more urea solution at minimal mixing length and to reach sufficient NO_x reduction with reasonable catalyst size and minimum ammonia slip.

Designing the aftertreatment for the engine is very important because both have effect on each other. If the engine-out NO_x emissions are very high and especially if the engine does not have EGR, the SCR efficiency must exceed 95%. High engine-out emissions also require more reagent to eliminate generated NO_x emissions which in turn leads to a need of a larger SCR element. Together the low exhaust temperatures and high engine-out NO_x emissions create high requirements for the EAT system design and because of limited space, some compromises may be needed. In addition to the challenges in the EAT system design, the system must pass the required tests before approval.

8 CONCLUSIONS

The research data included information on over 1500 buses which have been equipped with Proventia's retrofit EAT system. The goal of this study was to find various factors that affect the operation of the EAT system and to get a clear picture of which vehicles the system is operating with great efficiency or if there are problems with certain models.

As a result of this study, different manufacturers' model-specific NO_x emissions in g/km and reduction efficiency with Proventia's EAT system have been resolved. Comparisons were done within vehicle models with the best and the worst NO_x reduction efficiency to address the reasons behind different behavior in the EAT system operation and emissions. Engine-specific NO_x emissions in ppm were presented for gaining a better picture of the relationship between engine design and emission control solution.

From all the vehicles, buses with Cummins' and Volvo's engines were the most emitting ones and had the lowest NO_x reduction efficiency. The highest emissions were recorded from ADL Enviro 400H and Wrightbus Streetlite DF which both had average NO_x emissions of over 6 g/km and reduction efficiency of approximately 70%. The best results were achieved in MAN's and Mercedes' buses where the average reduction efficiency was about 95% and the average emissions were approximately 1 g/km.

The emissions and EAT system efficiency are affected by multiple different conditions and technical factors. Operating conditions such as driving speed and ambient temperature both have influence on the exhaust temperatures which is a huge factor in EAT system operation. In addition, if the engine-out NO_x and reduction efficiency remain constant, operating speed has direct influence by increasing the g/km emissions when the speed is decreasing.

Exhaust temperatures are also influenced by the vehicle mass. With heavy body the load of the engine is increased when compared to a bus with a similar engine but lighter body. The same phenomenon can be noticed in buses with same body but equipped with different size and power engine. High-powered large engine moves the body with a lighter load and thereby, the exhaust temperatures stay lower. In case of Streetlite DF and WF was noticed that exhaust temperatures were notably higher in WF version, which was equipped with more powerful engine than DF version.

The used engine in both models is Cummins' ISBe 4,5, which means that there could be differences in engine control or some other mechanical differences, that affect the exhaust temperatures.

The NO_x reduction is directly comparable to the amount of injected urea since the required AdBlue amount is determined by the emitted engine-out NO_x. Because of this the earlier mentioned temperature has a huge impact on the EAT system efficiency as the required temperature for complete hydrolysis of urea is 250 ºC. In addition to temperature, dosing capacity is affected by engine size and design and by the EAT system design.

Retrofitting is efficient way to reduce NO_x emissions quickly in highly congested cities with lots of buses. Crowded cities also create very challenging operation conditions, and therefore it is important that the operators ensure the proper maintenance of the buses and do not release vehicles with faulty EAT system to traffic. Although, there are multiple factors that must be considered in retrofitting buses, by interpreting the presented data, it is fair to say that the retrofitted EAT system allows significant reduction in the NO_x emissions within the studied vehicle fleet. Also, the reduction efficiencies remain high when no defects occur.

9 DISCUSSION

The goal of this thesis was to find out how different factors, environmental and mechanical, influence the operation of the retrofitted EAT system by studying and analyzing the collected data. Processing and analyzing the research data was implemented by using Excel and its Power Query and Power Pivot add ins. As a result, the achieved emission readings and EAT system efficiencies were presented and relations between various measures were studied within different vehicle models.

Since the author of the thesis was not familiar with the use of Power Query and Power Pivot at the beginning of the work, some time was spent in learning the use of these programs and processing the data. The time spent for this could have been used to search more specific technical information for different bus models or to study and analyze the achieved results. Because of this, some stages of the analysis remained somewhat limited. Regardless of some difficulties, the achieved results of this research give a wide picture of the factors that affect the operation of the exhaust aftertreatment system and both, environmental and mechanical sides have been studied as widely as possible within the time available.

Considering that the aim was on studying the results from buses where the EAT system is working correctly, some data had to be filtered. Filtering of the data was attempted to carry out so that as much data as possible was kept for the analysis. Therefore, the filtering was made mostly on the columns which were not calculated values. Despite this, some values that should have been included in the data might have been removed, and some incorrect values might have remained in the data. But, since the sampling in vehicles was large, single deviations did not stand out from the crowd and the results can be considered quite accurate. Also, in the examples where data from an only one vehicle was included, the example was chosen to match the average of the whole group.

The largest error in the data was most likely in the average speeds since they had to be calculated and the travelled distance was recorded in part of the buses by the odometer and in another part by the GPS. Also, the values of the ignored rows varied. Although there might be some error in the average speeds, they give a well descriptive picture of the effects of the average operating speeds of the buses.

Since the air pollution has been a frequently discussed topic for a while, the subject of this thesis is very topical and interesting. In addition, as a thesis it provided a great deal of interesting information about the operation of the exhaust aftertreatment system and the background factors. During the progress of this work, the operating principles of different components became clearer and it was interesting to notice how much the aftertreatment system is dependable on the exhaust temperatures. Although the original deadline for the completion of this thesis was slightly exceeded, the author is quite satisfied with the work since the results match the objective reasonably well.

As a further development, part of the research could be expanded to a wider study that includes more ambient conditions such as atmospheric pressure and rainfall together with a wider temperature scale. The research could be carried out by driving predetermined routes on various days in different seasons and the results would be logged in as second by second data. Also, the mechanical factors could be studied more closely, for example the effect of transmission on emissions. The research should be conducted with a sufficient population of basically identical vehicles but equipped with a different transmission.

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