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# Monitoring Euro 6 diesel passenger cars $NO_x$ emissions for one year in various ambient conditions with PEMS and $NO_x$ sensors


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## Abstract

In this study, the $NO_x$ emissions of four Euro 6 diesel passenger cars ranging from Euro 6 b to Euro 6 d-TEMP in different ambient conditions and driving routes were investigated with a Portable Emissions Measurement System (PEMS) and continuous $NO_x$ concentration monitoring device. A model was also generated for translating $NO_x$ concentration values into a gram basis. The results suggest that there is a marked difference in $NO_x$ emissions based on the Euro 6 step for the car is type approved. The study showed that the conformity factor for $NO_x$ emissions on a route in a city environment ("City route") changed from 0.65 to 5.2 depending on the Euro 6 step and car. Surprisingly, a Euro 6 b car equipped with Selective Catalytic Reduction SCR system and updated engine control unit (ECU) software for lower tailpipe $NO_x$ emissions provided lower average $NO_x$ emissions than a Euro 6 d-TEMP diesel car equipped with dual lean-$NO_x$ traps. Results for the City route also showed that the road infrastructure (crossroads and speed limitations) can have a noticeable effect on promoting driving that leads to higher $NO_x$ emissions even with a Euro 6 d-TEMP car. Estimations of $NO_x$ emissions with modelling based on continuous $NO_x$ concentration monitoring suggested that Euro 6 b diesel cars can provide $NO_x$ emissions close to the current RDE legislation. In addition, the modelling suggested that the Euro 6 b car with updated ECU software and the Euro 6 d-TEMP diesel car are capable of extremely low daily average $NO_x$ emissions, even close to 20 mg/km, in normal daily usage. Nevertheless, the monitoring results and model also suggest that cold ambient temperature has a high effect on the $NO_x$ emissions reduction performance of these vehicles, occasionally increasing their daily average emissions to as high as 900 mg/km.

Keywords:

On-road emissions
On-road monitoring
City driving
Cold temperature
$NO_x$ emissions modelling

## 1. Introduction

Although limit values for nitrogen oxides in type approval have declined over the past decades, many European cities still fail to meet the levels of air pollution set by the European Union air quality standards (European Environment Agency, 2019; Degraeuwe et al., 2017). EU legislation has adapted to this challenge and introduced a new type approval framework: a new test cycle (WLTC) that is supposed to reflect more realistic driving situations than the New European driving Cycle (NEDC) that was until recently used in chassis dynamometer testing in type approval and additionally on-road testing so called real-driving emissions (RDE) testing, which is measured with portable emission measurement (PEMS) device.

RDE requirements were first introduced in RDE 1 package (European Commission, 2016) and successive regulatory packages with RDE 4 (European Commission, 2018) being the latest one. RDE 4 is applicable to all new vehicle types since September 1$^{st}$ 2017 and to all new vehicles since September 1st 2018. During the phasing-in of the RDE regulation (2017–2019) a temporary conformity factor of 2.1 for $NO_x$ tailpipe emissions was possible to apply upon the request of the manufacturer. Vehicles type approved within this time frame are called Euro 6 d-TEMP vehicles. In RDE4, a conformity factor of 1.43 for $NO_x$ emissions is applicable for all new types and all new vehicles from January 1st 2020 and January 1st 2021, respectively. “Pre-RDE” vehicles i.e. vehicles type approved as Euro 6 b or Euro 6 c were not required to fulfil on-road testing limits. They were also measured on NEDC test cycle whereas Euro 6 d-TEMP onwards vehicles are tested according to WLTP.

Some recent studies (Triantafyllopoulos ym., 2018) indicate that with the current state-of-the-art technology the $NO_x$ emissions limits in current EU legislation can be fulfilled, and there are already diesel passenger cars on the market that comply with the current Real Driving Emissions (RDE) legislation (Suarez-Bertoa ym., 2019). At the same time, other studies show that driving conditions outside RDE conditions are challenging with respect to $NO_x$ emissions even for the Euro 6d-TEMP and Euro 6d diesel passenger cars and especially for the early Euro 6 diesel (Euro 6b-c) passenger cars (O'Driscoll et al., 2018; Suarez-Bertoa et al., 2019; Triantafyllopoulos et al., 2019).

Failure of passenger cars to comply with emission regulation limit values, especially in city environments, has led to the establishment of low-emission zones in numerous European cities; 200 such zones were in place by 2016, and numbers continue to grow rapidly (Hooftman ym., 2018). Other cities (e.g. Oslo) have introduced diesel vehicle bans on days with high $NO_x$ levels. Studies performed on chassis dynamometer in a cold ambient temperature have revealed that the $NO_x$ emissions of Euro 6 diesel passenger cars are also sensitive to cold temperatures and there is a clear increasing trend in $NO_x$ emissions as the temperature decreases (Juhani Laurikko, 2016; Ko et al., 2017; Suarez-Bertoa and Astorga, 2018; Weber et al., 2019). The trend is highly dependent on the vehicles' Euro 6 step and the aftertreatment technology used.

Recent study on-road by using the remote sensing technology in normal daily traffic is well in line with these findings. The sensitivity depends indeed of the Euro class and the aftertreatment technology used. In the study (Grange ym., 2019) was found that pre-Euro 6 diesel passenger cars emitted roughly 1.7 times more fuel specific $NO_x$ emissions relative to fuel mass at 0 °C compared to 20 °C ambient temperature. In the case of Euro 6 diesel passenger cars, the factor was found to be roughly 1.8 for cars equipped with LNT (Lean $NO_x$ Trap) and roughly 2 for cars with SCR (Selective Catalytic Reduction). Although, the cars equipped with SCR emitted roughly 1.5 times less $NO_x$ than cars with LNT.

As a one-time test, PEMS measurement reveals the on-road emissions performance of the tested vehicle only in the specific test situation, and therefore does not reveal emissions characteristics in wider use cases and ambient conditions. The $NO_x$ emissions may vary widely depending on the driving behavior and route parameters. In the studies (Gallus ym., 2017), (Varella ym., 2019) was found that the $NO_x$ emissions may increase up to 55 % between normal and aggressive driving and even up to 115 % in case of 5 % step in road grade.

In a recent study by (Bishop et al. 2019), models for emissions factors was generated for estimating the fuel economy and $NO_x$ emissions of passenger cars. These emissions factors can be used for fleet-level emissions estimation in different driving conditions. The fleet-level models are not suitable tools for $NO_x$ emissions performance evaluation of specific diesel passenger cars in different driving and ambient conditions. On the other hand, multiple PEMS measurement campaigns covering a wide spectrum of conditions are resource-intensive and, despite the wide testing conditions, might not ultimately reveal all use cases and ambient conditions that the vehicles encounter in real-world usage.

The objective of this study was to combine PEMS measurement with continuous NOx concentration monitoring of four different Euro 6 diesel passenger cars for a one year monitoring period. There are many studies in which the on-road emissions of passenger cars in different driving conditions and driver behaviors are investigated. However, PEMS measurement, as discussed above, is always reflecting the situation (traffic etc,) at time and effected by the ambient conditions at given time. This study shows the variation in day-to-day $NO_x$ emissions of four different Euro 6 diesel passenger cars during a one year period, in addition to the PEMS measurement. For PEMS measurement, three different driving routes were used. An RDE route was used for comparison purposes. A highway route served as a reference in rural and highway conditions. In this study, the “City route” was the main focus as this represents the conditions in which most cars are used on a daily basis. The monitor device was installed on four cars to measure $NO_x$ concentration during typical winter and summer temperatures in the Nordic countries. Furthermore, this study shows the possibilities that modelling of $NO_x$ emissions based on concentration values obtained from a monitor device attached to the car could provide for revealing $NO_x$ emissions in a wide range of real use cases.

# 2. Methods

## 2.1 Test vehicles

Four diesel vehicles were selected for the experiment. Depending on the vehicle, the monitoring period varied from approximately six months to one year. The chosen vehicles represent medium size and common family-size cars used in Finland (see Table 1) for key data). Cars A and B are the same model, but different year of manufacture. Car A was manufactured in 2015 before so called “Dieselgate” which was a result of firstly in 2014 reported discrepancy between the laboratory and on-road $NO_x$ emissions (Thompson ym., 2014) and the Car B was manufactured after it in 2017. Car A and B has the same base engine. Engine of the Car B is a new version of it and it has four kilowatts more peak power compared to Car A. Car B uses five gear transmission instead of 6 gear that is used in Car A. In the recent study (Grange ym., 2020), pre- and post “Dieselgate” passenger cars was investigated based on the remote sensing data and emissions modelling. The study suggested that $NO_x$ emissions varied between -36.2 % …93.2 % depending on the manufacturer and type approval category (M1 or N1).

Cars A to C have been type approved following the NEDC procedure and fulfil Euro 6 b certification requirements. Car D is type approved for the Euro 6 d-TEMP regulation, and is thus tested according to the WLTP as well as the RDE procedure. This is also the main difference between the Cars A to C and Car D. Cars A to C are developed for NEDC procedure in which the test cycle covers only a relative narrow area of the engine operational map and there was no on-road testing requirement. Respectively, the Car D is developed under the WLTP and RDE testing requirement which covers wider spectrum of engine operational map and thus should force for lower emissions in different driving situations even though the legislative limit values are the same in type approval testing.

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

Cars A-C were equipped with a manual gearbox, Car D with an automatic gearbox. All cars were front wheel driven. All of the cars were used as a company car for daily employee trips. During the PEMS measurements the EN590 standard diesel was used (see Table 2 for properties). In normal daily operation, the cars were refueled with the following diesel fuels available in Finland: EN590 diesel (summer and winter grades), EN15940 diesel, and WWFC 5 diesel. No specific guidance was given regarding the fuels to be used.

During the monitoring phase, Car C received an engine control unit (ECU) software update by the original equipment manufacturer (OEM). The update was aimed at achieving lower $NO_x$ emissions as a part of the OEM's recall campaign. The OEM stated that the update should exclusively target $NO_x$ emissions, while leaving other emission values unchanged. The dynamometer results (both NEDC and WLTP) can be examined in detail in (Söderena et al., 2019).

*Table 1: Key data for the cars investigated in this study. The ECU of Car C was updated during the project by the public campaign of the OEM.*

| Id. | Description | Euro | Engine | Gearbox | EAT | Mileage at start | $CO_2$ emission |
|---|---|---|---|---|---|---|---|
| Car A | Class C family car MY2015 | Euro 6 b | 1.5-2.0 TDI | M6 | DOC+DPF+LNT | 73500 km | 90 g/km @ NEDC |
| Car B | Class C family car MY2017 | Euro 6 b | 1.5-2.0 TDI | M5 | DOC+DPF+LNT | 24800 km | 106 g/km @ NEDC |
| Car C | Class C family car MY 2014 | Euro 6 b | 1.5-2.0 TDI | M6 | DPF+SCR (new software updated) | 59100 km | 109 g/km @ NEDC |
| Car D | Class C hatchback MY 2018 | Euro 6 d-temp | 1.5-2.0 TDI | AT8 | DOC+DPF+2xLNT | 2000 km | 112 g/km @ WLTP |

*Table 2: Diesel fuel used during the PEMS measurements.*

| Fuel/ Property | EN590 diesel |
|---|---|
| Density [kg/m$^3$] | 834.3 |
| Carbon content [w-%] | 86.3 |
| Hydrogen content [w-%] | 13.7 |
| AROM-DI+TRI [vol-%] | 1.5 |
| LVH [MJ/kg] | 43.02 |
| Cetane number [-] | 55.7 |

## 2.2 PEMS measurements

Measurements were performed on three on-road routes. One fulfilling the requirements of Euro 6d-TEMP RDE testing (VTT RDE), one representing normal city driving in Helsinki (City route) and one representing rural and motorway driving (VTT Highway). (Söderena et al., 2019) shows example speed profiles of each test route during the winter speed limit period. VTT RDE was performed as a cold start test with the vehicles kept overnight indoors at approximately 20 °C, whereas the City route and VTT Highway were tested as warm-start tests. During each test, the cars were driven normally following the traffic stream. Table 4 shows the key data on the test routes. The test route speed profiles can be found in (Söderena et al., 2019).

A commercial AVL PEMS device was used in all tests. The PEMS device was attached to the towing hook with a special mounting bracket. Table 3 below shows the key parameters of the device, and Figure 1 shows an example installation. PEMS device includes also PN PEMS, but in this study the PN emissions are not covered. Results of PN emissions and comparison of PEMS device against laboratory measurement device can be found in (Söderena et al., 2019).

*Table 3: Key parameters of the AVL PEMS device used for passenger car measurements*

| Device | Information measured |
|---|---|
| AVL MOVE Gas PEMS iS | CO, $CO_2$, NO, $NO_2$ emissions |
| AVL MOVE PN PEMS | PN emissions |
| AVL MOVE EFM 2.5” | Exhaust gas mass flow |
| GPS | Longitude, altitude, speed and acceleration |
| Weather station | Ambient temperature, pressure and relative humidity |

| | |
|---|---|
| OBD logger (integrated in PEMS device) | OBD information (engine speed, engine load, cooling water temp. etc..) |

*Figure 1: Portable emission measurement (PEMS) device installed on a test car.*

*Table 4: Key parameters of the on-road City route, which focused in city environment.*

| Test route / variable | City route |
|---|---|
| Test fuel | VTT EN590 diesel |
| Cold/warm start | warm start |
| Route mileage [km] | 40 |
| Trip share (urban/rural/highway) [%] | ~90/~10/~0 |
| Altitude difference, max - min [m] | 45 m |
| Maximum speed | ~80 km/h |
| Stop duration [% of trip] | ~24 % |
| Avg. speed | ~26 km/h |
| Avg. pos. acceleration | ~0.4 m/s$^2$ |

### 2.2.1 Data analysis

Each test trip was measured once if no clear reason for repetition was found. Engine malfunctioning or an accident or abnormal congestion on the road was kept as a reason for repetition. During the measurement of the City route no such situation occurred meaning that the data shown in this paper covers result from one repetition per measurement campaign i.e. summer and winter. Post processing of the measurement data was performed according to RDE 3 package Euro 6 legislation. The moving average window method was used for trip validity checking and normalization. Nevertheless, no data was excluded from the analysis and the results are shown as measured by each individual measurement device.

## 2.3 Continuous on-road $NO_x$ monitoring

Conventional on-road and chassis dynamometer tests provide information only on vehicle performance during the specific, one-time measurement event. We decided, therefore, to equip cars with continuous $NO_x$ concentration monitoring devices. With continuous monitoring it is possible to generate a broader picture of car $NO_x$ tailpipe concentration under different ambient conditions throughout the year.

Each car was equipped with a tailpipe $NO_x$ concentration monitoring device. In addition, Car C was equipped with an engine-out $NO_x$ concentration sensor. The installed monitoring system contains the following sensors:

- GPS sensor for determination of location, speed and mileage
- $NO_x$ sensor for determination of engine-out (possible only for Car C) and tailpipe $NO_x$ concentration
- Temperature sensor for determination of exhaust gas temperature (EGT) before (Car C) or after EAT (Cars A, B and D)

The $NO_x$ sensor used is a commercial sensor (produced by Continental) widely used in heavy-duty applications. The sensor has a light-off temperature of roughly 200 °C, which means that $NO_x$ concentration before the sensor reaches the light-off temperature are not measured. Therefore, for example, vehicle cold start concentrations and short trips were not detected. The measurement data was stored in a cloud server. The sensor cannot distinguish between $NO_2$ and NO, but the overall concentration result is presented as $NO_x$. A comparison of sensor against PEMS device $NO_x$ measurement is presented in Figure 3 in supporting information. It shows that the ppm values measured with the sensor and the PEMS device are rather well in line with each other. The sensor overshoot some highest peaks in comparison to PEMS device, but in general it gives a good basis for long period monitoring purposes.

### 2.3.1 Estimation of on-road $NO_x$ emissions

There are multiple models for vehicle fleet-level emissions and fuel consumption modelling, such as COPERT (Ntziachristos ym., 2008), HBEFA (Keller ym., 2017) and VERSIT+ (Smit ym., 2007). The US Environmental Protection Agency (EPA) developed one of the very first such models, MOVES, which is used for light- and heavy-duty vehicle fleet emissions modelling (U.S. Environmental Protection Agency, 2015a; 2015b). The models model vehicle fleet-level emissions using different parameters such as vehicle type, model year, traffic conditions, fuel type, speed, emissions factors, etc. In our study, however, the aim was to estimate the on-road emissions of specific cars in various ambient conditions. In the study (O'Driscoll ym., 2016) was found that comparison between vast number of PEMS measurements and COPERT speed dependent $NO_x$ emissions factors showed on average 1.6 times higher emissions for PEMS results. For estimating the day-to-day $NO_x$ emissions of each car involved in the project it was found that the models mentioned above were not suitable and a new semi-empirical model for this purpose was developed.

As the $NO_x$ concentration monitoring device did not contain a sensor for exhaust gas mass flow determination, it was not possible to present the continuous $NO_x$ data directly on a gram basis. To overcome this lack, a mathematical model was introduced to estimate the exhaust gas mass flow and further to estimate the $NO_x$ concentration results on a gram basis.

The model developed was intended for estimation purposes only, to present high ppm peaks during cold winter days on a gram basis. It was well understood that such a model cannot be capable of exact estimations, especially in dynamic conditions. The highest uncertainty relates to the fact that diesel engines can operate at the same vehicle speed with different exhaust gas oxygen content depending on the engine operation point, i.e. engine speed and load. There are multiple situations in which this can happen, such as acceleration, deceleration, downhill or uphill cruising, heat modes, or regeneration of exhaust after a treatment device, and difference in gear selection depending on the driver and gross weight of the vehicle.

The diesel process is described as a lean mixture diffusion combustion in which the engine operates with excess air factor. This means that by the end of combustion in each working cycle not all oxygen is consumed, i.e. the exhaust contains oxygen. Typically, the oxygen content is inversely proportional to engine loading and it varies depending on the engine speed.

During normal driving on a road without gradient at constant speed, the required power for moving the vehicle is constant. It was assumed that in this situation a vehicle with an automatic gearbox uses a specific gear, which means a specific engine speed and loading, thus constant exhaust gas oxygen content and mass flow. Similarly, with vehicles equipped with manual gearboxes this is the case when assuming that gear selection at a certain speed is independent of the driver.

The introduced mathematical model for exhaust gas mass flow estimation is based on the basic relations mentioned above of the diesel engine combustion process and required vehicle driving power. The relation can be expressed as follows:

$$\dot{m}_{exh.gas} \sim f(v, O_{2,exh.gas}),$$

where $v$ is vehicle speed and $O_{2,exh.gas}$ is oxygen content in the exhaust gas. In model building, the input data for vehicle speed and oxygen content were measured by the continuous monitoring device. Speed was defined based on the GPS value. The oxygen content was measured with the $NO_x$ sensor.

Exhaust gas mass flow, vehicle speed and oxygen content measurement data from the City route, VTT Highway and VTT RDE routes were used for model training. The best fit for the model was achieved by interpolation using the nearest data points for the values to be estimated. An individual model was generated for each car. The generated models were validated with a set of car-specific on-road measurements with the PEMS device, which was not used for the model training. As described in section 2.3 the used $NO_x$ sensor is not capable of distinguishing between $NO_2$ and NO concentrations. As a result, it was assumed in the mass-based calculations that the total $NO_x$ concentration was composed purely of $NO_2$. No humidity correction was used as there was no on-board humidity measurement device installed in the cars. Table 5 shows the model goodness and differences between the modelled and measured exhaust mass flow and $NO_x$ value in grams. As can be seen from the table, the model gave an adequate match with the cumulative emissions compared to measured results for the purpose of indicating emission levels on a gram basis. The modelled exhaust mass flow was surprisingly close to the measured values in the validation runs. The difference in modelled cumulative $NO_x$ emissions compared to the validation data sets varied between - 23.4% … 22.0% depending on the car.

*Table 5: Model validation results versus PEMS measurements.*

| Car | Model goodness, R2 [-] | Diff. In exh. Mass flow [%] | Diff. In cum. $NO_x$ [%] |
|---|---|---|---|
| Car A | 0.69 | 4.9 | -4.0 |
| Car B | 0.55 | -3.1 | 22.0 |
| Car C | 0.60* | 5.4* | -23.4* |
| Car D | 0.70* | 3.3* | -13.2* |

* Avg. Value of 3 validation routes

## 2.4 Ambient conditions and test environment

The experimental period covered 6 to 12 months in total depending on the car. During the monitoring period the cars were in normal company use, covering daily trips from a couple of kilometers to hundreds of kilometers.

On-road measurements were carried out in two different measurement campaigns. One depicting driving in warm weather, with ambient temperature above 10 °C, and the other depicting driving in winter conditions, with ambient temperature below 10 °C. The intention originally was to perform measurements in ambient temperature conditions under 0 °C, but unfortunately by the time of the winter measurement campaign, the ambient temperature was approx. 10 °C above normal temperature levels in southern Finland. The PEMS measurements for cars A and B were conducted in early autumn 2018 and in March 2019. Cars C and D were tested in March-April 2019 and in April-May 2019.

During the monitoring period the cars used normal diesel fuels available at Finnish fuel stations, covering EN590, EN15940 and winter grade diesel fuels.

# 3. Results and discussion

This paper presents the results of the City route and continuous on-road monitoring. Results from the chassis dynamometer and PEMS results on the VTT RDE and VTT Highway routes are presented in (Söderena et al., 2019).

## 3.1 Route average $NO_x$-emissions

The overall results in Figure 2 illustrate well the development in City route driving during the Euro 6 regulation from Euro 6 b to Euro 6 d-TEMP. Euro 6 b Car A had $NO_x$ emissions of 350 mg/km during summer and 417 mg/km during winter conditions, whereas Euro 6 d-TEMP Car D had $NO_x$ emissions of 81 mg/km during summer and 70 mg/km during winter conditions. Car C, which was originally Euro 6 b type approved but updated during the project for lower tailpipe $NO_x$ emissions with new ECU software by the original equipment manufacturer, performed well in City route driving conditions. During both measurement campaigns it had average $NO_x$ emissions of around 50 mg/km. Thus, results suggest that the lower ambient temperature level around 7 °C during the winter measurement compared to around 17 °C during the summer measurement do not have effect on the $NO_x$ reduction performance of the SCR used in the Car C. In the other words, result suggest that after the ECU update the SCR-system used in Car C seems to work rather well at least above around 7 °C ambient temperatures. Similar trend is presented also in section 3.3 in which the results of continuous $NO_x$-monitor is presented. Car B, which was a similar model to Car A but two years younger with an updated engine and different transmission explained in the section 2.1, performed slightly better than Car A and had $NO_x$ emissions of approx. 257 mg/km. Nevertheless, Car B performed much better on the RDE and Highway routes with average $NO_x$ emissions of 140 mg/km and 130 mg/km, respectively (Söderena et al., 2019). Car C and Car D had $NO_x$ emissions with a conformity factor (CF) of approx. 0.65 for Car C and approx. 0.95 for Car D. These are below the Euro 6 type approval limit of 80 mg/km. Car A had a CF of 4.3 in summer and 5.2 in winter conditions. Car B had a CF of 3.2 in summer and winter conditions. The results are discussed in more detail in section 3.2.

In this study, no substantial differences in PEMS measurements due to temperature were found. The temperature varied from 0.9 to 18.5 °C between winter and summer, respectively. Only Car A had approx. 20% higher $NO_x$ emissions in winter.

In a study by Triantafyllopoulos et al. (2019), on-road tests were performed for three Euro 6 b passenger diesel cars on a Euro 6 RDE specifications compliant route and had CFs for $NO_x$ emissions ranging from 5 to 16. Suarez-Bertoa et al. (2019) performed on-road tests on a city-motorway route for Euro 6 b and Euro 6 d-TEMP diesel passenger cars. They reported for three Euro 6 b diesel cars $NO_x$ emissions ranging from 141 mg/km to 673 mg/km. Similarly, for three Euro 6 d-TEMP diesel cars they reported $NO_x$ emissions ranging from 19 mg/km to 89 mg/km. Their findings are similar in range to those of the present study.

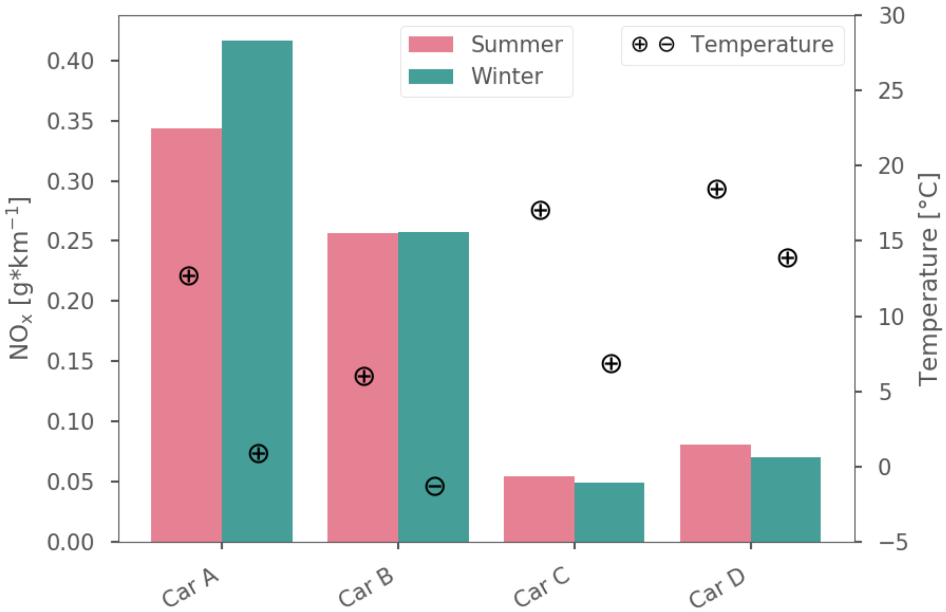


*Figure 2: Average $NO_x$ emissions in [g*s$^{-1}$] (left axis) on the City route, measured by the portable emission measurement (PEMS) device. The daily average temperature in [°C] is represented by a marker with plus and minus signs for positive and negative temperatures, respectively (right axis). For each car, the left bar represents the measurement result in summer conditions, whereas the right bar represents the result in winter conditions, respectively.*

## 3.2 Second-by-second $NO_x$-emission as a function of acceleration and speed

Figure 3 presents second-by-second $NO_x$ emissions during the winter measurement campaign as a function of acceleration and speed for the City route. Car A had high $NO_x$ emissions at high acceleration through all driving speed zones. Between the speed zones of approx. 30 km/h to 50 km/h Car A had high $NO_x$ emissions also at low acceleration values. Car B produced much lower $NO_x$ values during low acceleration, with the highest $NO_x$ emissions produced during higher accelerations between the 20 km/h to 50 km/h speed zones. For Cars A and B this indicates that their LNT for $NO_x$ emissions reduction is sensitive to transient situations with high acceleration values and thus high engine power. Car C exhibits low emission values throughout the whole acceleration-speed map, indicating that the SCR and emissions reduction strategy works well over the engine map used in normal city driving conditions. The highest emissions for Car D occur at relatively low accelerations and speeds around 40 km/h, although a couple of higher $NO_x$ peaks did occur at higher speeds and accelerations.

Overall, these results suggest that driving dynamics have a high effect on $NO_x$ emissions as each car had the highest instantaneous $NO_x$ emissions during the high acceleration. Although, in case of Car C the $NO_x$ peaks were in absolute basis much lower compared to other cars. During the measurement, there was no specific intension to drive dynamically, i.e., the driving dynamic was a consequence of traffic flow.

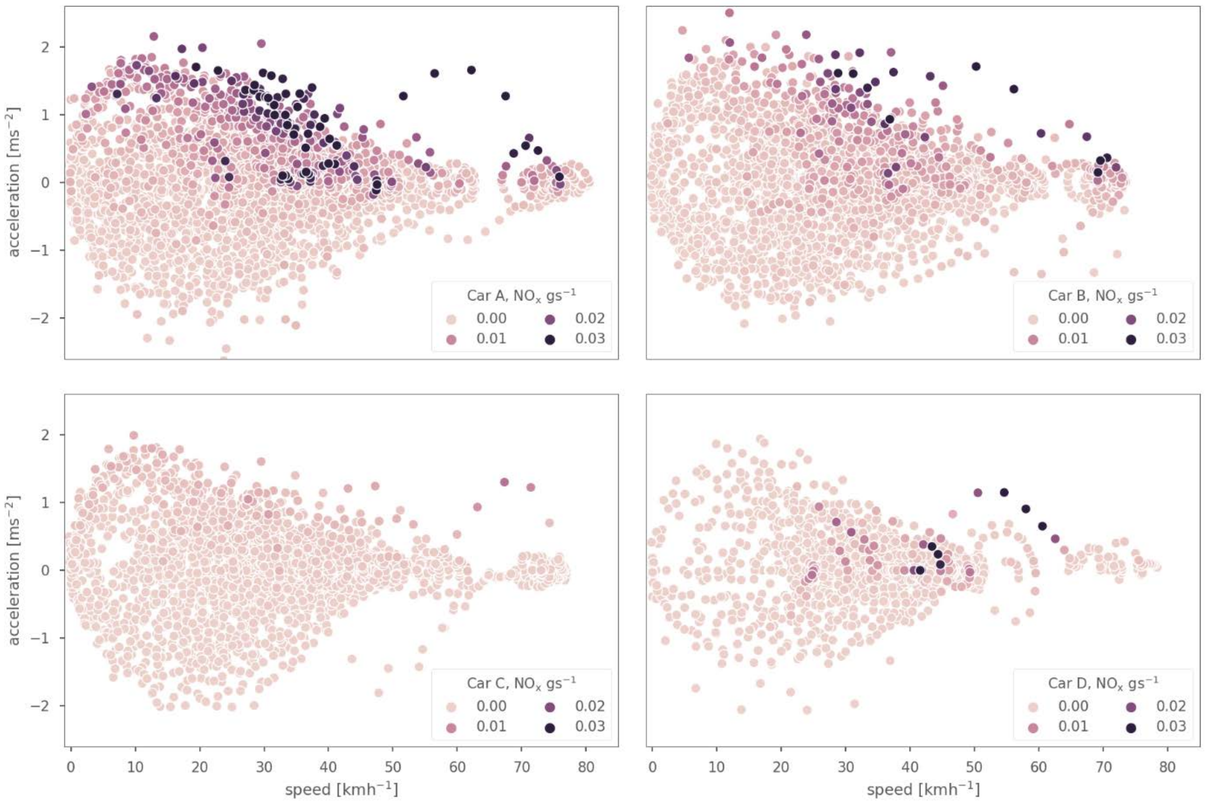


*Figure 3: Instantaneous $NO_x$ emission in [$g*s^{-1}$], for all four cars on the city-route, measured by the portable emission measurement (PEMS) device. The data are shown depending on speed in [$kmh^{-1}$] and acceleration [$ms^{-2}$]. The colour scale is normalized over all graphs.*

Figure 4 maps $NO_x$ emissions during the winter measurement campaign. Each car had its highest emission peak at the northernmost point of the route. At that point there are traffic lights followed by a 90° turn to left and an acceleration lane onto an 80 km/h road. This resulted in acceleration from 0 km/h to 80 km/h within a relatively short time. Emissions of Car A were spread rather constantly across the test route with multiple high peaks, the highest peak being at the northernmost corner. Car B had fewer peaks, which likely resulted in the slightly lower average result than Car A, as shown in Figure 2. Car C had no high peaks of the magnitude recorded by Cars A and B, and most of its emissions occurred at the beginning of the test as seen from the cumulative emissions in Figure 1 in the appendix. The behavior of Car D was interesting. It had slightly higher average emissions compared to Car C, but extremely low emissions during the route except for the start of the test and the high acceleration section at the northernmost point. Car D did produce six higher $NO_x$ emissions peaks, which had high effect on its cumulative emissions. The heaviest peak occurred approx. 150 s after the start of the route. From the data it was possible to identify that Car D regenerated its LNT system for approx. 20 s, duration which its cumulative $NO_x$ emissions increased by 1 g. This accounts for almost 40% of its total emissions. This can be seen in Figure 4 as the excess oxygen content drops to zero for a longer period of time.

Overall, the map clearly shows the development in $NO_x$ emissions from the early Euro 6 b to Euro 6 d-TEMP car. The Euro 6 d-TEMP car (Car D) emitted almost no $NO_x$ emissions for most of the route, whereas Car A produced $NO_x$ emissions steadily over the route and high peaks in some locations where higher accelerations occurred.

These findings point towards some important consequences for city planning: even though we might have fleets of low-emission vehicles in the future, there might still be “hotspots” of high emission levels due to high acceleration from traffic lights or steep changes in speed zones, etc.

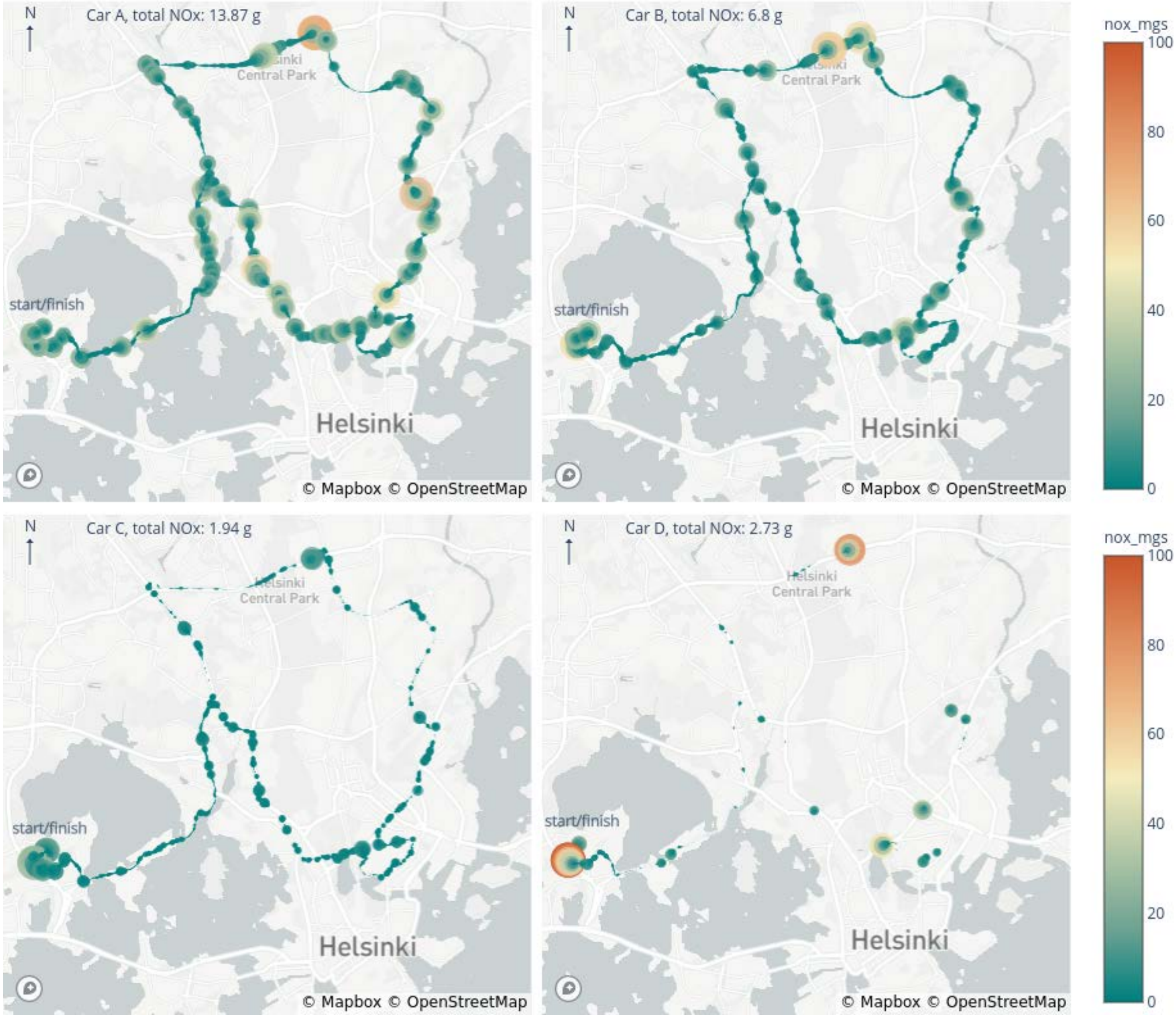


*Figure 4: Localization of $NO_x$ emissions during the City route in the winter campaign, for all four cars, measured by the portable emission measurement (PEMS) device. The size and colour of the markers correspond to the emissions in [mg*s$^{-1}$]. The colour range is normalized over the four maps.*

## 3.3 Continuous on-road $NO_x$ monitoring

Daily average tailpipe $NO_x$ concentration and temperature during the monitoring period are shown in Figure 5. Figure 6 shows a boxplot of all of the data and the daily average values. It should be noted that these values do not include cold start emissions, as the $NO_x$ sensor is only operational after the EAT reaches its light-off temperature. Therefore, the cold start contribution is not seen.

Car A had on average rather constant $NO_x$ emissions during the monitoring period, with concentration level varying between 60…110 ppm. During the coldest period in January to February 2019 there were only couple of high peaks in daily average results. This suggests that the $NO_x$ reduction system (ECU software and LNT) works somewhat independently of the ambient temperature. The median value was approx. 80 ppm and the mean value 90 ppm. Car B had a concentration level mostly between 30…60 ppm and the concentration changed least of the four cars tested. Its median value was approx. 45 ppm, and mean approx. 55 ppm. These results indicate that the $NO_x$ emissions reduction system of Car B also rather consistently performed independently of the ambient temperature.

It can be clearly seen from Figure 5 and Figure 6 that the update at the end of August 2018 in Car C ECU for lower tailpipe $NO_x$ emissions brought a real decrease in on-road $NO_x$ concentrations to a roughly 3 times lower level, i.e. a reduction in median concentration from approx. 150 ppm to 50 ppm. Figure 6 also reveals that the update might have affected the engine out $NO_x$ emissions level as the median was roughly 25 ppm lower than before the update. Nevertheless, no difference in fuel consumption was seen in the chassis dynamometer measurements before and after the ECU update (Söderena et al., 2019), which questions if the reduction of $NO_x$ concentration was really due to ECU software update or due to other unknown matters. Winter conditions greatly affected the performance of the SCR system. In Figure 5 we can see that the high concentration peaks cluster during the coldest period. On days when the ambient temperature dropped below -10 °C the daily average concentrations increased to 350 ppm.

The behavior of the Euro 6 d-TEMP Car D $NO_x$ concentrations throughout the monitoring period is interesting. As can be seen in Figure 5 and Figure 6, the daily median concentration value is the lowest of all the cars tested, but the medium value is close to Car B. This is due to the fact that Car D had randomly high daily average values during the winter period. This suggests that the $NO_x$ reduction performance of the dual-LNT system used in Car D was affected by the low ambient temperature during the winter period. Nevertheless, the monitoring period did not include data from the summer, which leaves room for uncertainty regarding this conclusion. All in all, Car D's $NO_x$ concentration was below 75 ppm 75% of the time and below 25 ppm 50% of the time.

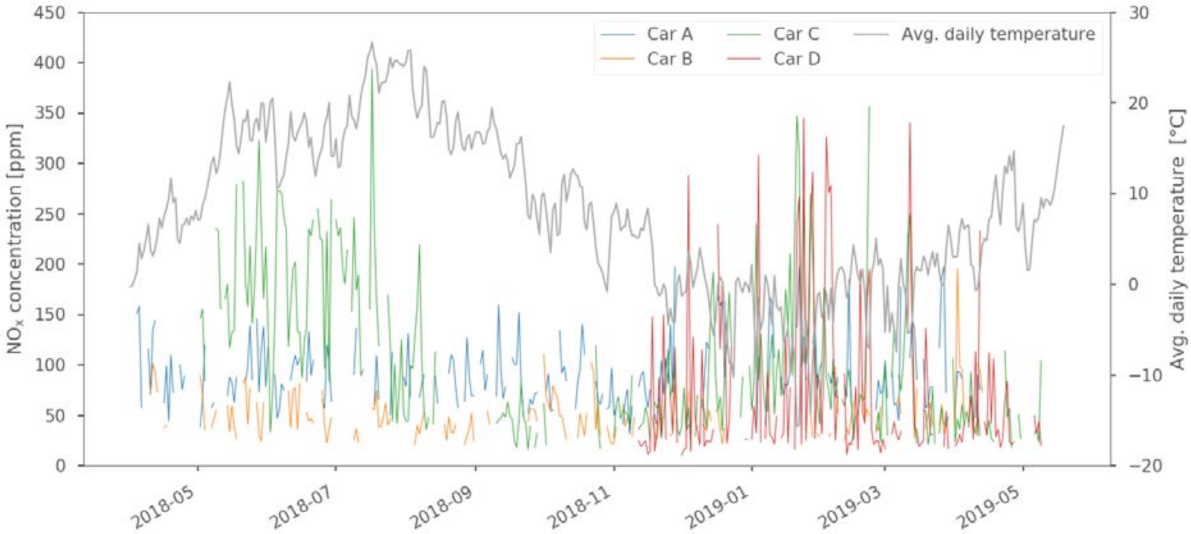


*Figure 5: Daily average tailpipe $NO_x$ concentration in [ppm] (left axis) for all four cars, measured by the continuous $NO_x$ sensor and temperature in [°C] (right axis) for all four cars during the monitoring period.*

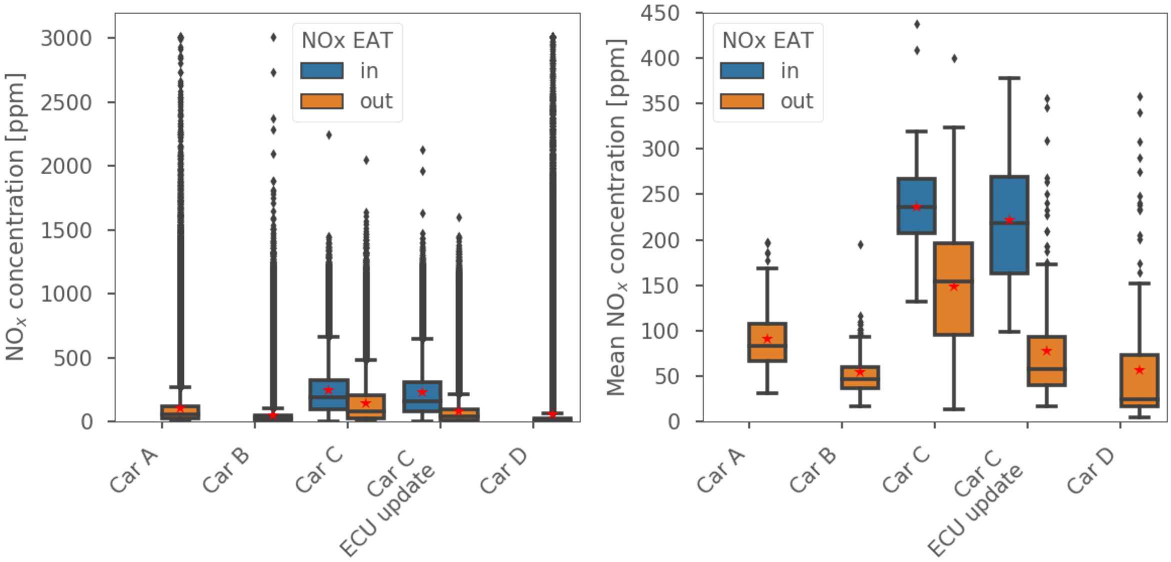


*Figure 6: Boxplot of all data points (left) and of daily average data (right) for the $NO_x$ concentration in [ppm], measured by the continuous $NO_x$ sensors in all cars. Car C is the only vehicle that has a $NO_x$ sensor installed before and after ("in"/"out", respectively) the exhaust aftertreatment (EAT) device. The data for Car C is also split into before and after it received an update of the engine control unit (ECU) software. The red stars mark the mean value for each dataset, the horizontal bar in the box marks the median value.*

The results of the modelled $NO_x$ emissions are shown in Figure 7, and Figure 8. We decided to present results from the five best and worst days to demonstrate the possible variation in emissions due to changes in $NO_x$ concentration levels. These are shown in Figure 7. and Figure 8 show the instantaneous $NO_x$ emissions derived from the highest and lowest daily average concentrations. As described below, the data logging system was not capable of recording the data before the $NO_x$ sensor reached the light-off temperature. This means that the mileages indicated in the Figure 7 callouts might differ from the real mileage. In addition, this might have a substantial effect on the results, especially for short trips such as some of the trips presented in Figure 7, as the cold start phase was not recorded.

Based on the model in Figure 7, the five lowest daily average concentrations for Car A translated into $NO_x$ emissions ranging from 50 mg/km…90 mg/km. During the worst five days the cumulative daily $NO_x$ emissions ranged from 152 mg/km… 373 mg/km. The instantaneous $NO_x$ concentration and emissions shown in Figure 2 in supporting information clarify the big differences in Car A's $NO_x$ emissions. The instantaneous $NO_x$ concentration was multiple times higher during the trip on 22.1.2019, especially during the first 180 s and from 1000 s to 1600 s after data logging started, which also translates as higher emissions on a gram basis. Low ambient temperature on the high emissions day seems not to correlate directly with the tailpipe exhaust gas temperature (EGT) profile. The EGT profile indicates that there might have occurred active DPF or LNT regeneration during the trip on 22.1.2019 starting at approx. 1400s after data logging started.

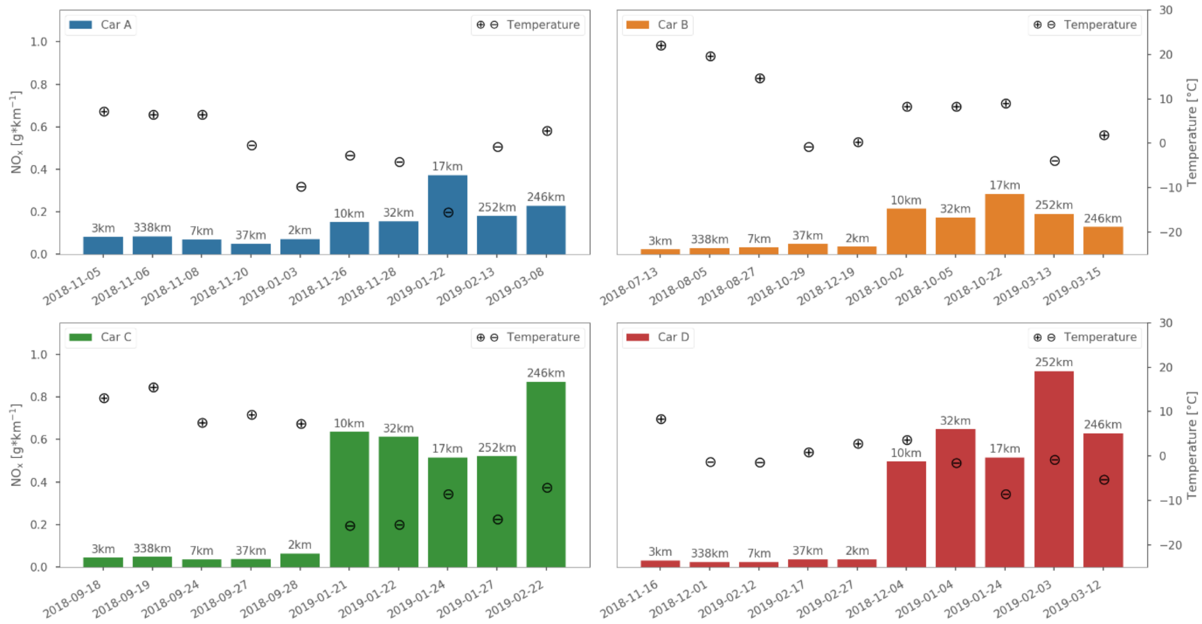


*Figure 7: Modelled trip average $NO_x$ emissions in [$gs^{-1}$] (left axis) for each car on the five days with highest and lowest $NO_x$-ppm-emission, respectively, as measured by the continuous $NO_x$ sensor and presented in Figure 5. Trip distance in kilometres [km] shown on top of each bar. The daily average temperature in [°C] is represented by a marker with plus and minus signs for positive and negative temperatures, respectively (right axis).*

For Car B, the five lowest daily average concentration days in Figure 7 translate into $NO_x$ emissions changing between 23 mg/km…48 mg/km. During days on which the daily average $NO_x$ concentration was the highest, Car B had $NO_x$ emissions ranging from 129 mg/km…284 mg/km. As seen in Figure 2 in supporting information, Car B performed well on day 13.7.2018, when its daily average concentration was the lowest. The model also predicted low $NO_x$ emissions of 23 mg/km for the trip. Also, it can be clearly seen that on day 22.10.2018, during which the daily average concentration was the highest, the instantaneous $NO_x$ concentration was high throughout the trip corresponding to high average $NO_x$ emissions of 284 mg/km. Also in this case, the EGT profile indicated that there might have occurred active regeneration of DPF or LNT because the temperature level is substantially higher than on day 13.7.2018, even though the driving speed was more cyclic and lower and the ambient temperature level was 13 °C lower.

The results shown in Figure 7 based on the model illustrate well the $NO_x$ emissions performance of Cars C and D shown in Figure 5. Both Cars were capable of low $NO_x$ concentrations (Figure 5 and Figure 6) on most days, but occasionally they generated extremely high concentrations. The model translated these accordingly as low or high emissions on a gram basis. Based on the model, the lowest daily average $NO_x$ emissions for Car C during the monitoring period changed from 37 mg/km…64 mg/km and for Car D from 23 mg/km…48 mg/km. Similarly, during the days on which the daily average $NO_x$ concentration was the highest, the model estimated for Car C a change in $NO_x$ emissions from 515 mg/km…871 mg/km and for Car D from 497 mg/km…922 mg/km. From Figure 8 we can see that during the best days both cars had extremely low $NO_x$ concentration levels and thus $NO_x$ emissions on a gram basis. For Car C, some $NO_x$ emission peaks can be identified during the accelerations, but these were still rather low. For both cars there was a huge difference in concentration levels between the best and worst days leading also to a huge difference in gram-based emissions. On days when the daily average concentrations were the highest, 22.2.2019 for Car C and 3.2.2019 for Car D, the modelled $NO_x$ emissions were also high. In the case of Car C, the ambient temperature was -7 °C on day 22.2.2019 and 25 °C on day 27.9.2018. The low temperature might have had an effect on the SCR performance. Most of the day the EGT was below 250 °C, although it was above 250 °C during the first third of the day. For Car D, there was no GPS signal for 650 s during day 3.2.2019. Nevertheless, this had no marked effect on the modelled $NO_x$ emissions since the model predicts exhaust mass flow and thus emissions close to zero at zero speed.

In case of Car A and B shown in Figure 2 in the supporting information the difference between the best and the worst day was also clearly evident. Although, the absolute levels in worst cases were not as high as with Cars C and D. For Car A, the ambient temperature was around - 16 °C during the worst day which might have had an effect. There can be identified couple of high periods in which the $NO_x$ emissions accumulated around 50 % of the total emissions during that driving mission. Also the EGT was clearly higher, indicating some sort of regeneration especially when the ambient temperature level is also considered. Car B showed during the worst day in average level similar $NO_x$ emissions as got with PEMS measurements shown in Figure 2. Increase in cumulative $NO_x$ emissions was rather constant throughout the driving mission. Interestingly also for Car B the EGT was noticeably higher during the worst emission day even though the average speed was lower. This could indicate some level regeneration of DPF when considering also the speed profile.

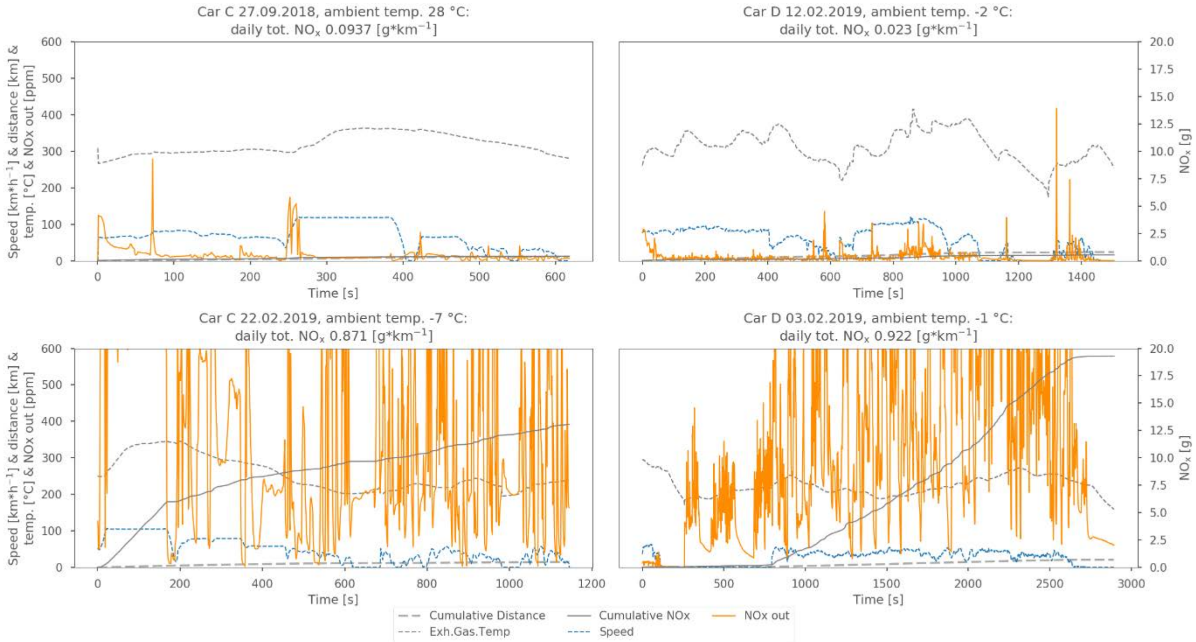


*Figure 8: Cumulative daily mileage in [km] and modelled cumulative $NO_x$ in [g*km$^{-1}$] for Car C and D during the days with the lowest (upper row) and highest (lower row) distance based $NO_x$ emissions as presented in Figure 7. Distance, speed, exhaust gas temperature and $NO_x$ out are measured values (all on left axis) and cumulative $NO_x$ in [g] is modelled (right axis).*

## 4. Conclusions

The purpose of this study was to investigate the $NO_x$ emissions of four Euro 6 b to d-TEMP diesel passenger cars in an urban environment with a PEMS device. A parallel objective was to combine on-road PEMS measurements with continuous $NO_x$ concentration monitoring for a one-year monitoring period and demonstrate that even though PEMS measurement is clearly a step in the right direction in vehicle emissions surveillance, the of one-time PEMS measurement might leave a high amount of information hidden.

In the city environment there is a marked difference in $NO_x$ emissions between the Euro 6 step b and Euro 6 step d-TEMP cars. The dual-LNT step d-TEMP car was capable of a CF of 0.95, whereas the step b cars had a CF ranging from 3.2 to 5.2 depending on the car and time of testing. During the project, Car C’s ECU was updated for lower $NO_x$ emissions and it performed well on the City route with a CF of 0.65. These findings suggest that legislation has succeed in forcing the car industry to reduce on-road $NO_x$ emissions. It also indicates that there are reduction technologies available for even lower on-road $NO_x$ levels.

In addition, this study shows the importance of driving style on emissions, and that the city road network might have a substantial effect on $NO_x$ emissions. All of the cars produced high $NO_x$ peaks at a junction requiring acceleration from 0 km/h to 80 km/h over a short distance. This finding suggests that the city road network should be designed so that high accelerations are avoided. Future emission legislation could also include not-to-exceed values for momentary emission values, not only aggregated or averaged values, to reduce local emissions at heavy traffic junctions.
Monitoring of $NO_x$ concentrations over a long period of time for each of the cars showed that some EAT technologies might be sensitive to high $NO_x$ emissions in cold ambient conditions. The model developed for estimating $NO_x$ emissions on a gram basis showed that even with the Euro 6 d-TEMP car $NO_x$ emissions could be on a daily basis occasionally over 500 mg/km and even high as 900 mg/km. Similarly, the car equipped with SCR on a daily basis occasionally produced $NO_x$ emissions over 500 mg/km and even close to 900 mg/km. Nevertheless, in most cases the Euro 6 step d-TEMP and the ECU software updated Euro 6 b car with SCR were capable of providing $NO_x$ emissions below the current Euro 6 legislation limit of 80 mg/km and even as low as 23 mg/km…37 mg/km in everyday driving conditions.

The study demonstrated that further on-road monitoring studies even for Euro 6 step d-TEMP and step d diesel cars are justified to prove their real $NO_x$ emissions in different everyday driving conditions. The Study also shows that the modelling of $NO_x$ emissions based on the continuous $NO_x$ concentration monitoring data offers a good tool for investigating the day-to-day $NO_x$ emissions of modern diesel passenger cars.

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