Atmospheric Environment 206 (2019) 208–217

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Comparison of regulated emission factors of Euro 6 LDV in Nordic temperatures and cold start conditions: Diesel- and gasoline direct-injection

Christian Weber*, Ingrid Sundvor, Erik Figenbaum

Institute of Transport Economics, Gaustadalléen 21, 0349, Oslo, Norway

ARTICLE INFO

Keywords:
Low temperature emissions
NO_x
CO_2
GDI
PM
PN

ABSTRACT

Local air pollution in Norwegian wintertime is characterized by an increase in NO_2 concentrations, due to poor dispersion and increased vehicle emissions. The focus of this study is therefore the characterisation of exhaust vehicle emissions in cold ambient temperatures. Euro 6 Gasoline Direct Injection (GDI) cars and diesel cars were tested in the laboratory in cold temperatures, including with cold start of the engine. Results show high emissions of CO_2, PM and NO_x. For the first time, we report also elevated NO_x values for GDI vehicles. Further measurements are required to investigate whether these results are the beginning of a new trend of high NO_x emissions from GDIs, or if these results represent singular events, but it may indicate that further NO_x traps or catalysts are required for these vehicles. Understanding the relationship of cold ambient temperatures and vehicle emissions is also particularly important for air quality dispersion modelling, which do not currently account for emission temperature dependence.

1. Introduction

Local air pollution is a persistent problem all over Europe (Air quality in Europe, 2017, 2017). In Norway, air pollution is mainly noticeable during wintertime due to poorer dispersion conditions. These occasional episodes with long-lasting temperature inversions create a build-up of pollution (Ødegaard et al., 2010), which may lead to violations of air quality regulations. Winter conditions also pose an additional challenge for air quality, since vehicle starts in ambient temperatures ('cold starts') cause increased exhaust emissions from internal combustion engine vehicles at low temperatures. Norway follows European Union (EU) legislation on vehicle emissions, through which few exhaust components (hydrocarbons and CO) have been specifically regulated for emission in cold temperatures.

The knowledge basis for estimating the extra cold temperature emission contribution for NO_x and particulate matter (PM), as well as particulate number (PN), has hence been limited (Dardiotis et al., 2013). In order to fill this gap, the Institute of Transport Economics has since 2011 investigated emissions, with a special focus on NO_x and PM, of Euro 6 passenger cars (Hagman and Amundsen, 2013; Weber et al., 2015; Weber and Amundsen, 2016). The Euro 6 category is especially important to investigate as several measures (such as low emission zones and scrapping regimes) target an accelerated renewal of the fleet, and rely on lower emissions for increasing Euro standards. Good knowledge of the emissions of newer vehicles is hence important to predict future air quality and ensure the selection of the most effective mitigation measures.

This paper presents the results of an exploratory laboratory study of emissions from 8 diesel and 6 gasoline Euro 6 passenger cars (light duty vehicles, LDVs), focusing on the effect of ambient temperature during cold starts of the engine. Driving cycles were chosen that represent more realistic urban driving conditions than the New European Driving Cycle (NEDC). The study adds valuable information to the body of literature reporting cold start emissions of Euro 6 vehicles in cold temperature. Section 2 provides an overview of existing knowledge on the topic. Section 3 presents the measurement program and the rationale for the selection of test conditions and vehicles. Results are presented in Section 4, the discussion in Section 5 and the conclusion in Section 6.

2. Existing knowledge

The Institute of Transport Economics (Transportøkonomisk institutt, TØI) has since 2011 investigated emissions from light- and heavy duty vehicles under realistic driving conditions (Hagman et al., 2011; Hagman and Amundsen, 2013; Weber et al., 2015; Weber and Amundsen, 2016). These investigations were initiated by the Norwegian Public Roads Administration to find out why the air quality in Norwegian cities did not improve even though stricter EU emission

* Corresponding author.
E-mail address: christian.weber@toi.no (C. Weber).

https://doi.org/10.1016/j.atmosenv.2019.02.031
Received 23 August 2018; Received in revised form 19 February 2019; Accepted 21 February 2019
Available online 05 March 2019

Table 1
Key data for the vehicles investigated. ”Odom.” stands for odometer, M/A refer to manual and automatic gear shift, respectively.

Name	Fuel type	Model year	Cylinder displacement (L)	Engine power (kW)	odom. (km)	Curb weight (kg)	Gear- box	Emission control
DA 2012	Diesel	2012	2.2	110	5821	1571	M	EGR + DPF
DB 2013	Diesel	2013	2.1	125	17081	1525	A	SCR + DPF
DC 2013	Diesel	2013	2.2	129	6537	1597	A	EGR + DPF
DD 2013	Diesel	2013	2.0	135	13409	1429	A	SCR + DPF
DE 2014	Diesel	2014	2.0	140	465	1635	A	LNT + DPF
DF 2014	Diesel	2014	2.1	125	17158	1570	A	SCR + DPF
DG 2015	Diesel	2015	2	110	16781	1490	M	SCR + DPF
DH 2015	Diesel	2015	1.5	81	4660	1492	M	LNT + DPF
PA 2014	Petrol	2014	2.0	180	2782	1583	A	TWC
PB 2014	Petrol	2014	1.1	96	16101	1375	M	TWC
PC 2014	Petrol	2014	1.6	115	10386	1395	M	TWC
PD 2015	Petrol	2015	1.2	85	1851	1436	M	TWC
PE 2016	Petrol	2016	1.2	85	4955	1300	A	TWC
PF 2016	Petrol	2016	1.4	110	9020	1292	A	TWC

regulations had been introduced. Heavy duty vehicles with Euro VI engines have in these investigations been shown to have very low emissions of both particulate matter and NO_x . In contrast, huge gaps between type approval values and actual NO_x emissions were discovered for Euro 6 diesel passenger vehicles under more realistic driving cycles, especially in cold temperatures (-7 °C).

After the so called ”diesel scandal” was revealed by the California Air Resources Board (CARB) and the International Council for Clean Transportation (ICCT), national governments all across Europe started additional fleet measurements of diesel vehicles (see e.g. (BMVI; Overview of reports measu; The UK Department for Transport)). Several problematic issues were highlighted, but the common base of these studies was high NO_x emission levels in real traffic conditions, across all vehicle brands, when compared to laboratory measurement results. Most of these studies were designed for regulatory purposes and to reveal ”defeat devices” that tune the car to give low emissions during the type approval tests, and not to create best estimates of emissions for normal usage of the car under different conditions.

The effects of cold engine starts on emissions, and causes for these changes (including non-optimal temperatures in the engine, lubricant and catalyst) have been previously discussed in the literature (Roberts et al., 2014; Weilenmann et al., 2009). The largest increase in emissions because of the cold start is traditionally seen for CO and HC pollutants, particularly for gasoline vehicles, leading to their regulation. As emission limits in vehicles have decreased, the extra emissions associated with cold starts seem not to have decreased in the same manner, making their contribution increasingly significant (Weilenmann et al., 2009). Changes in engine control strategies and exhaust after-treatment systems in newer diesel vehicles, as well as in gasoline direct-injection (GDI) vehicles, might also lead to the need for a broader focus with regards to a temperature dependence. In addition, emissions of other components may become more relevant when discussing cold starts and the effects of cold ambient temperatures (Suarez-Bertoa and Astorga, 2018).

Relatively few studies are available of emission measurements from Euro 6 vehicles, especially regarding the effects of cold ambient temperatures and cold starts. Dardiotis et al. investigated emissions from five diesel- and eight gasoline vehicles in NEDC, at ambient temperatures of $+23$, and -7 °C with cold starts (Dardiotis et al., 2013). Only one diesel vehicle was Euro 6 compliant. All gasoline vehicles were Euro 5, but three GDIs were included. Results showed increased NO_x emissions for the diesel vehicles at cold temperatures. Over the cycle, the emission patterns for the Euro 5 vehicles were similar at the two temperatures. Although some variation was experienced between vehicles, there were higher emissions at -7 °C, and the Euro 6 vehicle with selective catalytic reduction (SCR) had the highest relative difference in emissions when comparing hot to cold temperatures. The vehicle also had higher emissions in the first part (the urban driving cycle, UDC) of the NEDC compared to the extra-urban driving cycle (EUDC) part which was quite low. The authors explain these results by good functioning of the SCR during the EUDC in cold temperature. When looking only at the UDC at -7 °C the Euro 6 vehicle had similar NO_x emission level as the earlier models. For the gasoline vehicles the emissions showed more variation in the trend, but at least one vehicle had higher NO_x emissions at low temperature.

The impact of cold temperature has also recently been investigated by Suarez-Bertoa et al., who performed emission measurements on five diesel- and gasoline vehicles (Suarez-Bertoa and Astorga, 2018). Both the Worldwide harmonized Light vehicles Test Cycles (WLTC) and the New European Driving Cycle NEDC were used. The authors found that whilst in WLTC at $+23$ °C, vehicles complied with the limit values set in the Euro 6 standard with the exception of NO_x from the diesel vehicles, which was significantly elevated. In cold temperatures (-7 °C), average emission factors for NO_x increased (compared to $+23$ °C) by a factor of 3.4. The results were explained by malfunctioning of the SCR for three of the vehicles, as the increases were due to higher emissions through the entire test cycle. The authors also emphasize that further comparisons are not possible because of the lack of reported measurements of SCR equipped Euro 6 vehicles at cold temperatures.

2.1. Measurements

The measurement program consisted of 8 diesel and 6 gasoline passenger vehicles. The vehicles were chosen according to availability in the market, and were acquired directly from the importer, from rental companies or from private owners. All the cars had a relatively low mileage (between 2000 and 17000 km, see Table 1) and were tested in the same year they were registered in. The year in the sample name thus refers to both the testing- and the model year. All petrol cars have a GDI engine and a three-way catalyst. The diesel cars have a diesel direct-injection engine (DI) and are equipped with a diesel particle filter (DPF). The NO_x control technology varies from exhaust gas recirculation (EGR), lean nitrogen traps (LNT) to systems with selective catalytic reduction (SCR). All vehicles are type approved by the Euro 6b emission standard, but the model year varies from 2012 to 2016. Note that the gasoline cars in our sample, in accordance with the European sales average (EEA, 2017), are smaller and lighter than the diesel cars (about 1300–1400 kg and 1400–1600 kg for gasoline and diesel cars, respectively.). However, an exception is for vehicles PD 2015 and DD 2013, which have curb weights of 1436 and 1429 kg, respectively (see Table 1).

Measurements were conducted at the emission laboratory of the VTT Technical Research Centre of Finland (VTT) in Helsinki. The chassis dynamometer is placed in a climate chamber, and test temperatures were maintained at either $+23$ or -7 °C. These temperatures were chosen in order to comply with existing literature (e.g. (Suarez-

Bertoa and Astorga, 2018; Dardiotis et al., 2013)) and the test for CO and total hydrocarbon emissions (THC) (gasoline vehicles) in the type approval regulation (EPRegulation (EC) No 715/2007, 2007). A winter temperature of −7 °C is also very common in Nordic regions. The cold start measurements were performed after the vehicles had resided in the climate chamber over night. The vehicles were tested as is, i.e. with the equipment they had originally been delivered with, and they had been used in real traffic directly previous to testing. The vehicles were measured with the summer tires that the vehicles were equipped with at the time of the tests. Tire pressure was set according to the user manuals, and the air conditioning in the cars was deactivated during testing. Inside temperature is set to 20 °C and the fan is set to the second lowest speed or about 2/5 of the maximum. If a vehicle was equipped with a specific "dyno test run" function to disable certain systems such as anti-lock brakes and electronic stability control while driving on dynamometer rollers, the function was activated prior to dynamometer test runs. Tests were run on a single-roller chassis dynamometer manufactured by Froude-Consine (UK), with 1 m roller diameter and 100 kW maximum power absorption. The vehicles were tested according to the test methods used in the EU type approval regulation for vehicles (NEDC (EPRegulation (EC) No 715/2007, 2007),). The road loads were set per vehicle, corresponding to the curb weight of each car according to the registration documents. The values are kept constant for all tests performed with the vehicle. Rolling resistance was set to so called "table values" which are based on vehicle reference weight and do not take into account different aerodynamic or rolling resistance characteristics of vehicles.

The study focused on measuring the regulated emission factors, PM, PN, NO_x, CO and hydrocarbons (HC). In addition, emission of CO_2 was measured. The exhaust gases were guided into a constant volume sampling system and collected in bags for analysis. Concentrations of regulated gaseous emission components (CO, HC, NO_x) were determined using an AVL AMA i60 emissions test bench. PM concentration was measured using an AVL Particle Sampling System, whilst PN was measured using an Airmodus A23 Butanol Condensation Particle Counter. The fuel consumption was calculated from the gaseous emissions using the carbon balance method. The gravimetric values for the measured species are converted to emission factors (g per km) by dividing with the driven distance in the cycle. Besides the type approval cycle (NEDC), Artemis Urban- and Helsinki City cycles are applied to reflect how vehicles are used in areas where local pollution is most problematic (city driving). The Artemis Urban cycle is part of the Common Artemis Driving Cycles that were developed in the Artemis project, aiming to be representative for the most common driving situations (urban, rural-road and motorway) (André, 2004). The cycle consists of a mix of congested and free-flow situations. The Helsinki City cycle is a proprietary real-world driving cycle developed by VTT to represent congested urban driving. Of the 14 vehicles, 8 were tested in the Artemis Urban cycle with a cold start of the vehicle. All 14 vehicles were tested in the Helsinki City cycle, with a warm start of the vehicle. This means that the cycle was driven directly after e.g. an Artemis Urban cycle. See Table 2 for an overview of the key parameters of the driving cycles, and Table 3 for an overview of the test matrix.

Most vehicles were measured twice in one cycle, temperature and start condition (see Table 3). The error bars shown in the figures in Section 4 show the half spread of results of two measurements. In some cases, only one measurement was recorded and hence no error bar is shown.

4. Results

This section presents the results of the measurements of the vehicles in the Helsinki City cycle with warm start of the engine, and of the Artemis Urban cycle with cold start of the engine. The results for the NEDC measurements are used for comparisons and analysis. The following bar diagrams include the values achieved in the type-approval test in the case of CO_2, and the type approval limit for light duty vehicles in the Euro 6 regulation. Note that this limit value strictly applies for the NEDC cycle in +23 °C measured according to the requirements and conditions of the EU emission regulation. It is shown here as a comparative background to the more realistic emissions measured from the Artemis Urban and Helsinki cycles. The results are summarized in Tables 4–6 int the appendix and will be presented in detail in the following.

4.1. CO_2

Fig. 1 shows the emission of CO_2 for the diesel- and gasoline cars, after cold start of the engine in the Artemis Urban cycle. Compared to the value reported for the type approval cycle, all vehicles have higher emission values in this more demanding cycle, especially at cold temperature (−7 °C). At +23 °C, the average CO_2 emission factor value of 231 g/km for the GDI cars is close to the average for the diesel cars (224 g/km). For the lower temperature, however, diesel cars have a higher average CO_2 emission factor value (306 g/km) than the GDI cars (276 g/km). The results for the Helsinki City cycle follow the same trends, see Fig. 2, but the values are on average lower as the cycle is less demanding and there is a warm start of the engine. The higher CO_2 emission values at −7 °C are (for most vehicles) due to the ambient temperature throughout the cycle, rather than being an effect from the cold start of the engine only. This is further discussed in subsection 5.2.

4.2. NO_x

Traditionally, since the introduction of the three-way-catalyst (TWC), petrol cars are regarded to have low NO_x emission under all driving cycles. For the GDI gasoline vehicles here and with a warm start of the engine, the results are inconclusive. Measurements in the Artemis urban cycle (performed for 4 of the 6 vehicles, compare Table 3) reveal that two vehicles (PE 2016 and PF 2016) had low NO_x emissions and two (PB 2014 and PD 2015) had higher NO_x emissions of about 0.2 g/km. This raises the average NO_x value for the four vehicles at +23 °C to 0.13 g/km, which is a factor 2.2 above the type approval limit.

The same two vehicles also have higher NO_x emissions in cold temperatures. This result seems not only to originate from the cold start of the engine, since the same vehicles also have high emissions of NO_x after a warm start of the engine in the Helsinki cycle, see Fig. 4. Vehicle PF 2016, which performed close to the limit value in the cold start measurements (Fig. 3), exhibits higher values in the Helsinki City cycle. Also for the warm start and Helsinki cycle the results are inconclusive. Here three vehicles PA 2014, PC 2014 and PE 2016 exhibit low values, the latter also in cold start conditions. Therefore, the high values are unlikely to result from GDI technology in general. To the best of our knowledge, this is the first time such high NO_x emissions from GDIs are reported in the literature.

The ambient temperature seems not to have the same recognizable

Table 2
Key parameters for the driving cycles applied in this study, compared to the type-approval cycle (NEDC).

	Engine state	Total length (m)	Duration (s)	Average speed (km/h)	Maximum speed (km/h)	Ratio of idling (%)
NEDC	cold	10931	1180	33	120	23
Helsinki	warm	7807	1380	20	61	30
Artemis Urban	cold	4470	920	18	58	3

Table 3
Measurement matrix showing the number of tests per vehicle and drive cycle, temperature and start condition.

Drive cycle	Temp. (°C)	Start condition	DA 2012	DB 2013	DC 2013	DD 2013	DE 2014	DF 2014	DG 2015	DH 2015	PA 2014	PB 2014	PC 2014	PD 2015	PE 2016	PF 2016
Artemis Urban	−7	cold	0	0	1	1	0	0	2	2	0	2	0	2	2	3
Artemis Urban	−7	warm	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Artemis Urban	+23	cold	0	0	1	1	0	0	2	2	0	2	0	2	2	2
Artemis Urban	+23	warm	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Helsinki City	−7	cold	0	1	2	2	0	0	0	0	0	0	0	0	0	0
Helsinki City	−7	warm	2	1	3	2	2	2	2	2	2	2	2	2	2	2
Helsinki City	+23	cold	1	1	2	2	0	0	0	0	0	0	0	0	0	0
Helsinki City	+23	warm	1	1	2	2	2	2	2	3	2	2	2	2	2	2
NEDC	−7	cold	1	2	1	1	3	2	2	2	2	2	2	3	2	2
NEDC	−7	warm	1	0	1	1	0	0	2	2	0	2	0	1	2	2
NEDC	+23	cold	1	2	3	1	2	2	2	2	2	2	2	2	2	2
NEDC	+23	warm	1	0	3	1	0	0	2	3	0	2	0	2	2	2

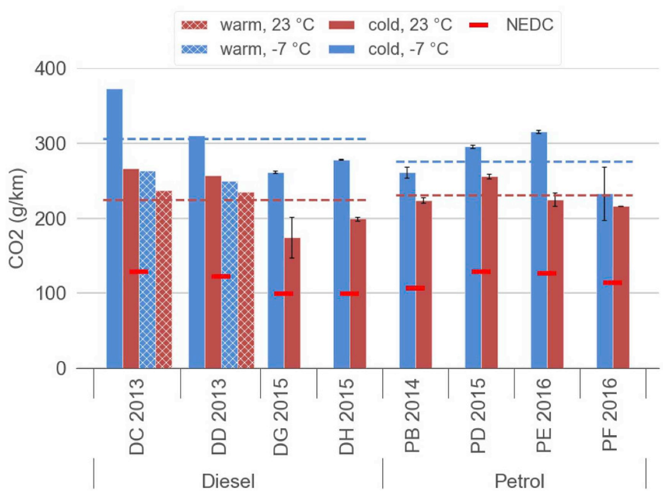

Fig. 1. CO_2 emission factors for LDV tested in the Artemis Urban cycle with a cold engine start. A warm engine start was performed in addition for vehicles DC 2013 and DD 2013. The dashed lines show the average values for diesel- and gasoline cars at −7 and +23 °C, respectively. The bar marker shows the value reported in the type-approval cycle.

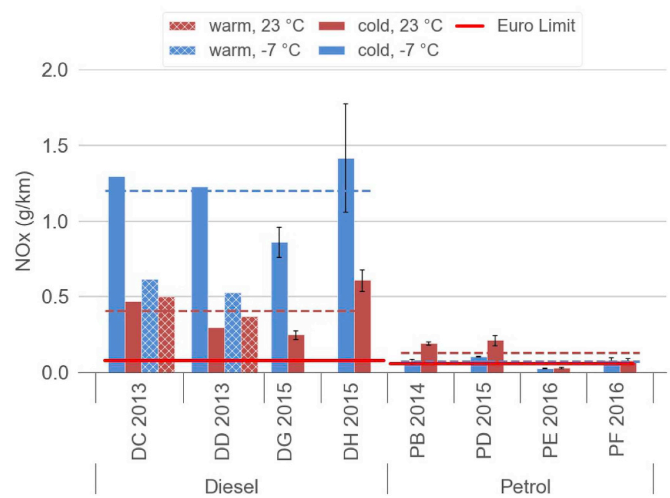

Fig. 3. NO_x emission factors for LDV tested in the Artemis Urban-cycle with a cold engine start. Warm engine start in addition for vehicles DC 2013 and DD 2013. The dashed lines show the average values for diesel- and gasoline cars at −7 and +23 °C, respectively. The full line shows the type-approval limit for Euro 6 (EPRegulation (EC) No 715/2007, 2007).

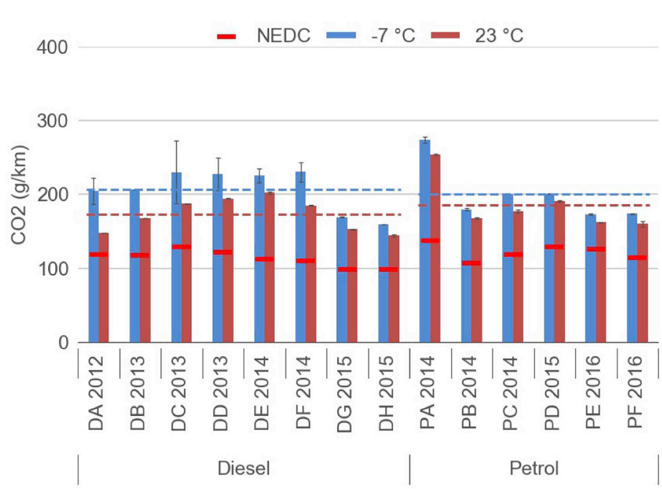

Fig. 2. CO_2 emission factors for LDV tested in the Helsinki City cycle with a warm engine start. The dashed lines show the average values for diesel- and gasoline cars at −7 and +23 °C, respectively. The bar marker shows the value reported in the type-approval cycle.

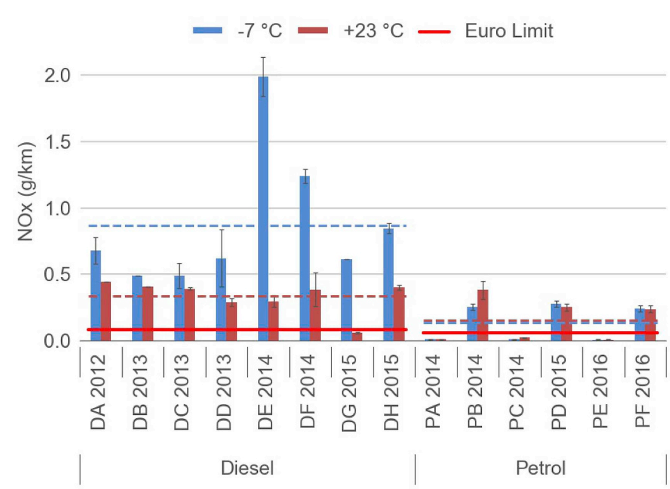

Fig. 4. NO_x emission factors for LDV tested in the Helsinki City-cycle with a warm engine start. The dashed lines show the average values for diesel- and gasoline cars at −7 and +23 °C, respectively. The full line shows the type-approval limit for Euro 6 (EPRegulation (EC) No 715/2007, 2007).

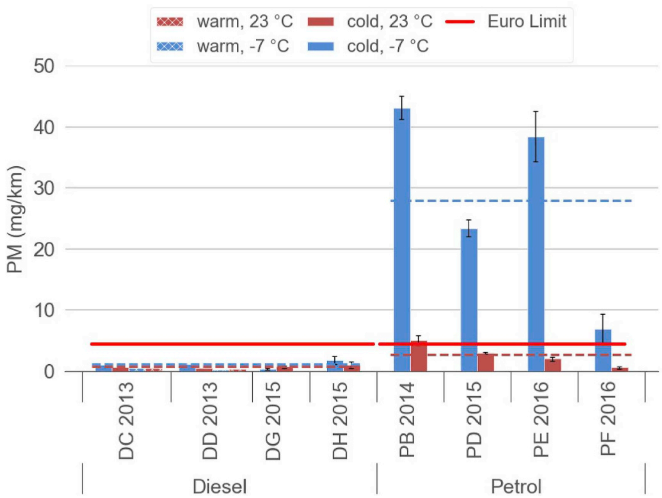

Fig. 5. PM emission factors for LDV tested in the Artemis Urban cycle with a cold engine start. Warm engine start in addition for vehicles DC 2013 and DD 2013. The dashed lines show the average values for diesel- and gasoline cars at −7 and +23 °C, respectively. The bar marker shows the value reported in the type-approval cycle.

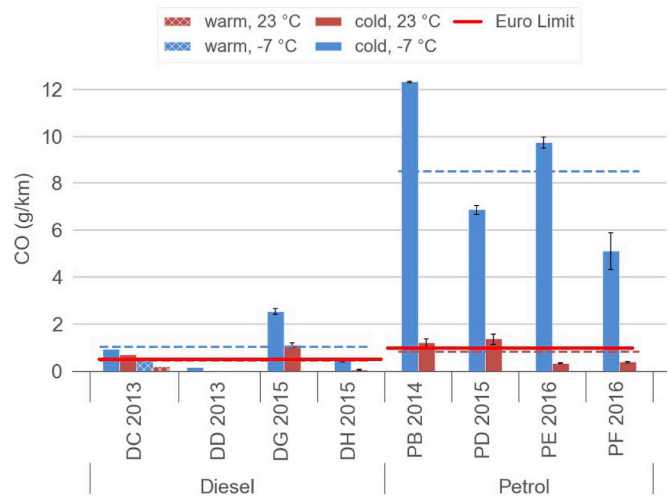

Fig. 7. CO emission factors for LDV tested in the Artemis Urban cycle with a cold engine start. Warm engine start in addition for vehicles DC 2013 and DD 2013. The dashed lines show the average values for diesel- and gasoline cars at −7 and +23 °C, respectively. The bar marker shows the value reported in the type-approval cycle.

effect on NO_x emission for the GDI vehicles as it has for the diesel vehicles; i.e. it appears that NO_x emission is higher at +23 °C than at −7 °C (vehicles PB 2014 and PD 2015). However, since the sample size and observed differences are small, it is not possible to conclude that this is a significant effect.

The absolute emissions in g/km are higher in the Helsinki city cycle (when compared to the Artemis Urban cycle) for PB 2014, PD 2015 and PE 2016, even though the cycle is longer than the Artemis Urban cycle (see Table 2). This will be further discussed in section 5.3.

4.3. PM and PN

The results for PM emissions in the Artemis Urban cycle with cold start of the engine are compiled in Fig. 5. Evidently, the DPF is efficiently reducing the emission of PM from the diesel engines to well below the type approval limit. This is valid for both temperatures tested. For the GDI cars, PM emissions are below the type approval limit in +23 °C, whilst at −7 °C, three of the vehicles have high levels of PM (averaging 28 mg/km).

The results for PN, see Fig. 6, confirm the differences as seen for PM emissions.

We find low PN values for the diesel vehicles under all conditions, whereas for the GDI vehicles there are substantial emissions at −7 °C. Note that at +23 °C, all vehicles comply with their current type approval limit. All GDI vehicles would, however, have exceeded the PN limit value which came in force in 2017 of $6{\cdot}10^{11}$#/km (EC. 692/2008, 2008). With a warm start of the engine in the Helsinki City cycle, emissions of both PM and PN were low and below the type approval limit (see Table 5, supporting information).

4.4. CO and THC

The emission of CO and THC were low for all vehicles in most measurements - except the cold starts of the GDI vehicles in the Artemis Urban cycles with a temperature of −7 °C (see Figs. 7 and 8, respectively). Here, the average emission factors were 8.5 g/km and 0.9 g/km, for CO and THC, respectively. The diesel vehicles DC 2013 and DG 2015

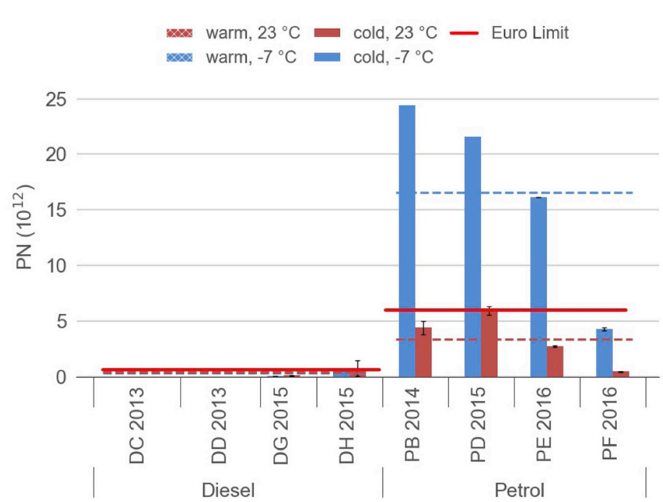

Fig. 6. Particulate number emission factors for LDV tested in the Artemis Urban cycle with a cold engine start. The dashed lines show the average values for diesel- and gasoline cars at −7 and +23 °C, respectively. The full line shows the type-approval limit for Euro 6 (EPRegulation (EC) No 715/2007, 2007).

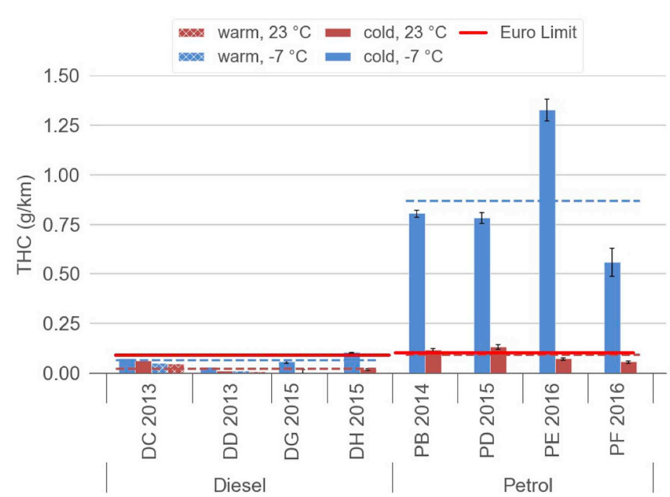

Fig. 8. THC emission factors for LDV tested in the Artemis Urban cycle with a cold engine start. The dashed lines show the average values for diesel- and gasoline cars at −7 and +23 °C, respectively. The full line shows the type-approval limit for Euro 6 (EPRegulation (EC) No 715/2007, 2007).

had increased CO emissions in the Artemis Urban cycle at −7 °C, however these were low compared to the emissions from the GDI vehicles. For both THC and CO some diesel vehicles had higher emissions than the GDIs in the Helsinki cycle with a warm start of the engine, but still in most cases an order of magnitude lower than the emissions from GDIs with a cold start (see Figs. 13 and 14, supporting information). The formation of secondary organic aerosols from emitted hydrocarbons (Gordon et al., 2014; Platt et al., 2014) makes discussions about the contribution of GDI vehicles to total PM pollution in ambient air (Suarez-Bertoa and Astorga, 2018) highly relevant when temperature dependence is also accounted for.

5. Discussion

5.1. Effects on particles

Figs. 5 and 6 suggest that the GDI technology increases the particle pollution from gasoline vehicles. The increase in PN during cold starts has been expected and extra regulation of particles from GDI is included in the EU type approval regulations (Raza et al., 1106). At +23 °C, all vehicles comply with the type approval limit. However, cold temperatures cause even larger increases for both PM and PN. The diesel vehicles keep low emission levels. Hence, the need for extra particle filters in the GDIs becomes evident. From the experience of use in diesel vehicles, a good effect also at low temperatures can be expected. No GDI vehicle in this study had a particle filter installed.

5.2. Effect on CO_2

Fig. 1 reveals that the outside (ambient) temperature has a larger influence on the levels of CO_2 emitted from diesel cars than from petrol cars. This can be explained by heavier engine blocks in the diesel cars, needing longer time to warm up. For cold starts at +23 °C, the measured CO_2 emission factor (g per km) relating to diesel vehicles is similar to that for petrol vehicles. It should be noted that on average, the diesel vehicles are heavier than the petrol vehicles, and therefore will need more energy to move the higher mass (see Table 1). All vehicles exhibit CO_2 emission factor values above the reported NEDC values (see bar marker in Fig. 1). These figures are not directly comparable to the numbers presented by Tietge et al., 2017a, 2017b, since they are not calculated on a fleet basis. However, they suggest a difference between values measured in independent laboratories (with more realistic cycles) and the values obtained using the type approval cycle for the homologation process.

The continuous data plots for CO_2 for the vehicles DC 2013 and DD 2013 reveal different engine control strategies in the different conditions (compare Fig. 9): For vehicle DD 2013 the CO_2 emission is increased compared to the other runs in the beginning of the cycle (e.g. at around 400 s), but consolidates towards the same levels later in the cycle (e.g. at around 700 s). For vehicle DC 2013, however, this consolidation occurs later and especially in idle sections of the cycle.

5.3. Effect on NO_x

Suarez-Bertoa and Astorga (2018) report NO_x emission values from GDI vehicles in the WLTC cycle ranging from 9 to 34 mg/km and from 7 to 82 mg/km at +23 and −7 °C, respectively. In the present study, in the Artemis Urban cycle with cold start of the engine, values are an order of magnitude higher ranging from 31 to 212 mg/km and from 27 to 107 mg/km at +23 and −7 °C (see Fig. 3). These findings strengthen the need for additional NO_x control systems in GDI vehicles. Although we attempt to shed light on the possible origins of the elevated NO_x emission levels observed in the present study, it should be noted that the vehicles are treated as "black boxes" since no insight into the engine control mechanisms is available. The discussion rather relies on interpretation of tailpipe emissions. In future regulations, a requirement to grant public insight into the engine control strategies might help to monitor emissions by independent institutions, also in real traffic.

The high NO_x levels for some vehicles are the result of engine control management strategies rather than cold start effects on the catalyst, as seen in the continuous NO_x data in Fig. 10.

Continuous measurements for vehicle PE 2016, which had low emissions in the bag results presented in Fig. 3, are shown in subfigure a). As expected, NO_x emission sharply rises when the engine is started. After about 50 s the TWC seems to have reached its operating temperature and the emission levels drop quickly. During the rest of the cycle, no further emissions are observed. This result suggests that the engine is operated in a stochiometric mode, providing just enough reagents for the TWC to operate efficiently.

Vehicle PD 2015, however, exhibits a completely different behaviour. As already seen in Fig. 3, NO_x emission levels were considerably higher, compared to vehicle PE 2015. In Fig. 10 b), the reason for this difference becomes clear: As for vehicle PE 2015, NO_x emission rises sharply a few seconds after the engine is started. After some seconds the

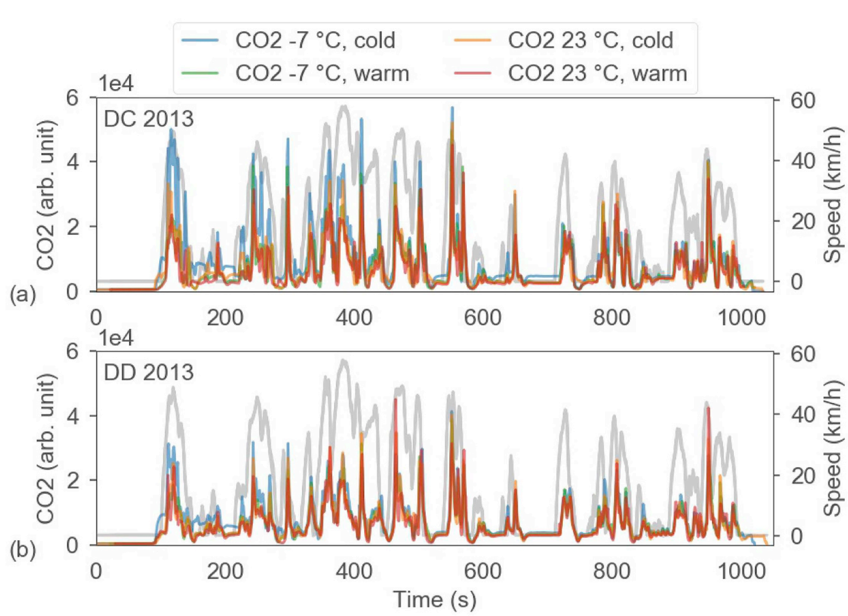

Fig. 9. Continuous data readings for the vehicles DC 2013 and DD 2013, for two runs at −7 and +23 °C in the Artemis Urban cycle with cold and warm starts of the engine. CO_2 emission is shown in arbitrary units, with the same scale used for comparability in figure a) and b). The grey line represents the speed profile (right axis). The continuous data are not corrected for variations in the exhaust mass flow. Therefore, the emission data can not be directly related to the speed profile, but should rather give an approximate orientation.

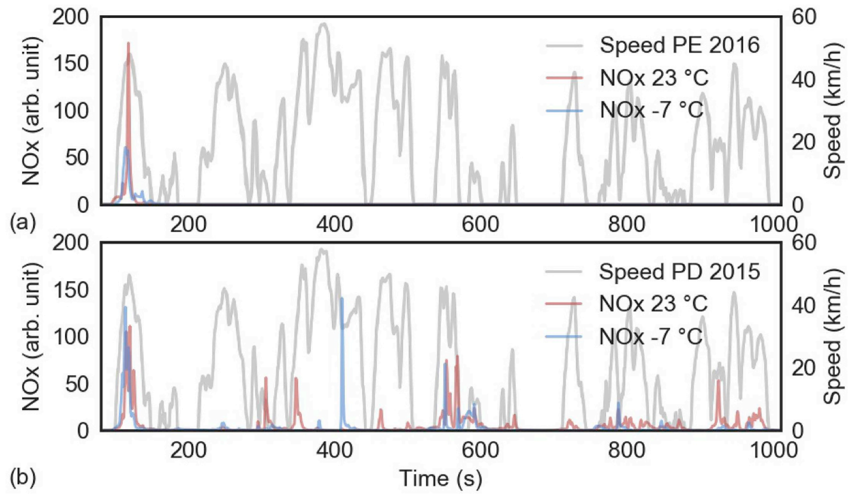

Fig. 10. Continuous data readings for the vehicles PE 2016 and PD 2015, for two runs at −7 and +23 °C in Artemis Urban cycle with cold start of the engine. NO_x emission is shown in arbitrary units, however same scale in figure a) and b). The continuous data are not corrected for variations in the exhaust mass flow. Therefore, the emission data can not be directly related to the speed profile, but should rather give an approximate orientation.

emission levels drop sharply, likely because of the TWC reaching optimal operation temperature. However, emission levels do not remain at zero level; sharp spikes arise throughout the cycle, most of them correlating with increased power demand in the driving cycle. It should be noted that the NO_x emission is detected later than the change in speed, so the speed- and NO_x curves in Fig. 10 are offset by about 10 s.

We hypothesise that this behaviour is caused by non-stochiometric engine control, i.e. the engine is operated in lean mode in order to fulfil the higher power demand. As already mentioned in section 4, the total NO_x emission is higher at +23 °C than at −7 °C, resulting from more NO_x emission events for the curves at +23 °C in Fig. 10.

With respect to the diesel vehicles, the measured NO_x emission levels in this study are more in line with e.g. results from Suarez-Bortoa and Astorga ((Suarez-Bertoa and Astorga, 2018)) with about 3 times more NO_x emissions at −7 °C than at +23 °C. We find that for some vehicles no clear effect of catalyst and engine warm up can be isolated, with sudden increases in concentration (spikes) distributed over the whole cycle, see Fig. 11. The spikes seem to be more frequent and higher in magnitude at −7 °C than in +23 °C. This situation is common for both vehicles shown in Fig. 11, which are equipped with different exhaust after treatment systems: SCR for vehicle DG 2015 (subfigure a)) and LNT for vehicle DH 2015 (subfigure b)). One interesting difference is notable: The NO_x emission measurement curve for vehicle DH 2015 has distinct and sharp spikes, which have earlier been attributed to LNT regeneration events, e.g. by Ko et al. (2017). However, since the NO_x levels before and after the LNT device were not measured, one can not conclusively pinpoint that the higher emissions originate from LNT regeneration exclusively. In any way, the continuous measurement data of NO_x emissions from the diesel vehicles (and some of the petrol vehicles) show that the vehicles fail to remove NO_x efficiently from the exhaust gasses. Reasons may include too low urea dosing (for the SCR systems), or too small a dimension of the catalyst system (for both the SCR and LNT systems) (see Fig. 12).

5.4. Cold start vs. warm start in different temperatures

For the two vehicles DC 2013 and DD 2013, measurements were performed during both warm- and cold starts (at temperatures of −7 and +23 °C), in the Artemis Urban cycle.

For CO_2, both cars show similar trends in the different conditions, and a cold start in +23 °C amounts for about the same emission as a warm start in −7 °C. Both conditions lead to higher emissions than in a warm start cycle in +23 °C. Emissions are highest for both cars in the cold start in the cold temperature, by a factor of 1.6 and 1.3, respectively, when compared to the warm start at ++23 °C.

For THC and CO, the results differ between the two cars. DD 2013 shows constant values for all conditions except the cold start at −7 °C. In contrast, the emissions for DC 2013 increase for the warm start when the temperature is lowered from +23 °C to −7 °C. The cold start condition results in higher emissions, which also increase with decreasing temperature. For THC, emissions increase by factors of 1.65 and 4.1 for car DC 2013 and DC 2013, respectively, when compared to the warm start at +23 °C. In comparison, the emissions for CO increase by factors of 4.5 and 20.8, respectively.

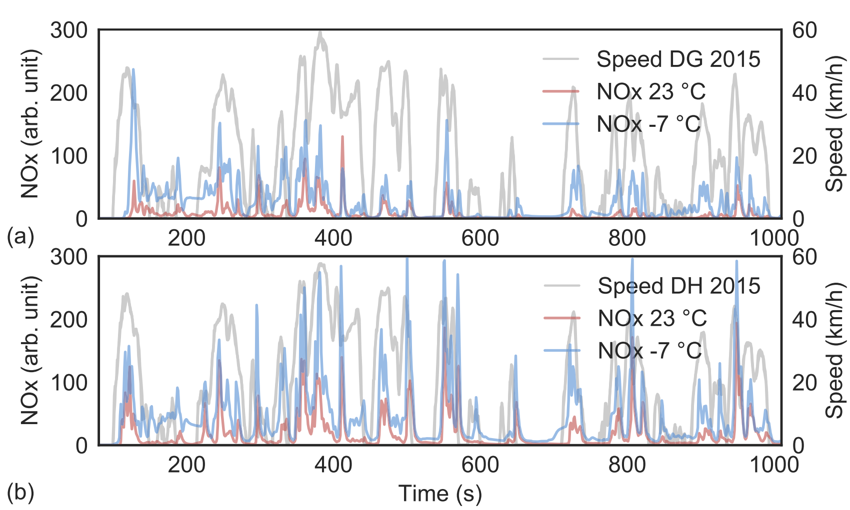

Fig. 11. Continuous data readings for the vehicles DG 2015 (SCR) and DH 2015 (LNT), for two runs at −7 and +23 °C in Artemis Urban cycle with cold start of the engine. NO_x emission is shown in arbitrary units, however same scale in figure a) and b). The continuous data are not corrected for variations in the exhaust mass flow. Therefore, the emission data can not be directly related to the speed profile, but should rather give an approximate orientation.

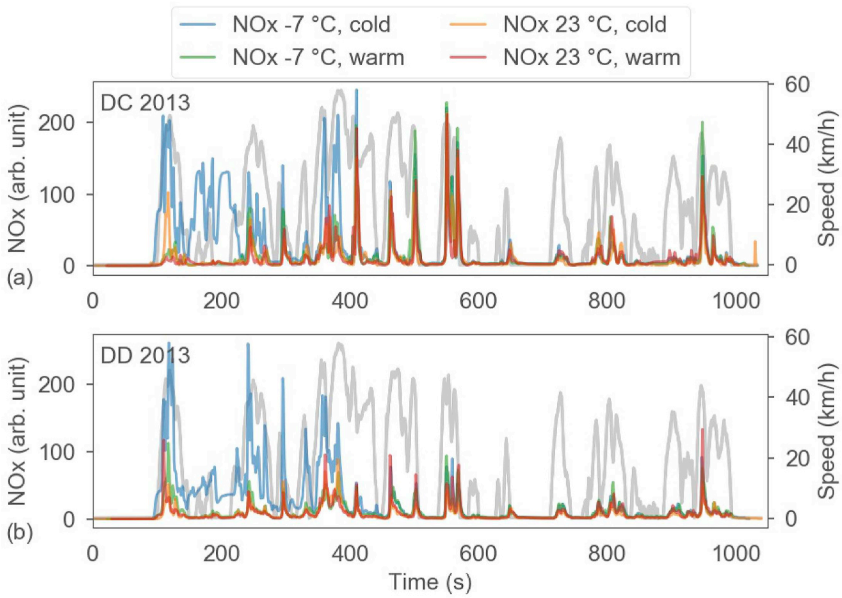

Fig. 12. Continuous data readings for the vehicles DC 2013 and DD 2013, tested in the Artemis Urban cycle with a cold and warm engine start, at −7 and +23 °C, respectively. NO_x emission is shown in arbitrary units, however same scale in figure a) and b). The continuous data are not corrected for variations in the exhaust mass flow. Therefore, the emission data can not be directly related to the speed profile, but shall rather give an approximate orientation.

The reason for this fundamentally different behaviour might lie in the exhaust treatment strategies: Car DC 2013 relies solely on EGR, whereas DD 2013 a diesel oxidation catalyst (DOC) in combination with a SCR system is applied.

For these two vehicles, additional cold start emissions at +23 °C cannot be seen for all components measured (see Figs. 1–8). CO_2 and PM emissions are higher for both vehicles in cold start conditions, while extra CO is only seen for one vehicle. In contrast, when looking at the cold temperature measurements extra cold start emissions become evident for all components. Plots of the continuous data readings also show that this difference, i.e. extra emissions, is visible at −7 °C until about 400 s into the cycle. The continuous readings for these two vehicles compared with the two shown in Fig. 11 are quite different. Where a change in the NO_x emissions is seen at about 400 s for the vehicles DC 2013 and DD 2013, this is not the case for DG 2015 and DH 2015.

Even if both DC 2013 and DG 2015 are equipped with a SCR system they behave differently. The time it takes to reach peak efficiency of exhaust after treatment systems is discussed in Roberts et al., 2014), who argue that as much as 1000 s might not be enough to detect these effects. We do, however, not have a plausible explanation for why we see such differences in these two otherwise rather similar vehicles. In the new real driving emissions (RDE) regulation the cold start period is defined as no longer than 5 min. This is 300 s, which is shorter than what at least measurements from vehicle DC 2013 and DD 2013 indicate is needed to reach full efficiency of the exhaust emission reduction equipment at cold temperatures.

5.5. Consequences for air quality management

The measurements of Euro 6 vehicles presented here indicate a strong dependence of vehicle exhaust emissions with ambient temperature. Diesel Euro 6 vehicles have much higher NO_x emissions than the type approval according to several studies, which is also confirmed here. At cold ambient temperatures the NO_x emissions increase even further, to 20–70 times higher than the value reported in type approval for the respective vehicle. To our knowledge, such temperature dependence is so far not well represented in emission modelling for use in air quality dispersion modelling. Dispersion modelling is the basis for air quality forecasts as well as for air quality action plans and analysis of different traffic measures to reduce emissions. When using dispersion models with hourly time resolution, a dynamic temperature dependence of the exhaust emissions should be included to improve model results. The version 3.3 update of the Handbook Emission Factors for Road Transport (HBEFA) gives a temperature correction (Keller et al., Notter).

The basis for the temperature dependence is, however, still limited and they outline a linear dependence down to zero degrees. Such correlation with temperature was not found by O'Driscoll et al. (O'Driscoll et al., 2018) (supplementary information) for Euro 6, although it was somewhat present for Euro 5. The results in O'Driscoll et al. are based on portable emissions measurement systems (PEMS), but the range does not include below zero temperatures and the trips do not include cold starts. It can be noted that the measurement results from our study have been shared to be included in the European Research for Mobile Emission Sources (ERMES) database used by HBEFA.

For the compounds and vehicles where the cold start results in a large contribution to the emissions, short trips will be relatively more polluting than longer trips (per km). According to national travel statistics in Norway, 45% of trips by car are less than 5 km (Hjorthol et al., 2014). This is also similar to what has been found for French cars, which had a median trip distance of 3 km (André, 1003). From our results (and those of others), a part of these trips would hence be performed without a functioning exhaust emission reduction system. A relevant question is then if some of these trips are consecutive, with parking times short enough to limit the number of cold starts. Weiss et al. (Weiss et al., 2760) found a median distance of 20 km travelled between two cold starts. They then used a 3 h parking time window to separate cold start trips. This time window of 3 h was based on data of coolant temperature drop at an ambient temperature of 15 °C.

Such a time window would likely be much smaller in cold ambient temperatures and a larger fraction of the trips would include a cold start compared to the study of Weiss et al. .

Cold starts might therefore be even more important in Nordic conditions through a double effect of more emissions at cold temperature and a larger fraction of trips with a cold start. Hence, specifically targeting these short trips with relevant measures might have a larger effect than expected from evaluations using models with emission factors that often discard cold start effects and low ambient temperatures (Høiskar et al., 2017).

City and national authorities in Norway increasingly promote biking and walking to cover short distance trips. The extra cold start and cold temperature contribution would strengthen the argument for supporting such measures even if they are considered to have less effect on the total traffic work reductions. Better knowledge of temperature dependence and cold starts is also relevant for the discussion about secondary organic aerosols and the relative contribution from vehicle exhaust emissions to particulate pollution ((Platt et al., 2014)).

The data presented here will contribute to a better knowledge basis around cold starts in Nordic temperatures. For example, the total emission E_{total} for a $d = 35$ km work-home round trip with $n =$ two cold starts can be calculated for different temperatures:

$$E_{total} = d * EF + n * CS, \quad (1)$$

where EF is the respective emission factor. For example, vehicle DC 2013, the total CO_2 emission for this trip will increase from 8.4 to 9.4 kg, when the outside temperature decreases from +23 °C to −7 °C. This is in line with the ranges of fuel consumption increase presented by Roberts et al. (2014). Performing this exercise for vehicle DD 2013, and the total amount of NO_x emitted, we find an increase from 12.8 to 19.8 g when going from +23 °C to −7 °C. Obviously, this will significantly increase NO_x levels in a city.

6. Conclusion

Gasoline direct injection (GDI) technology was developed with the aim to meet low fuel consumption incentives, demanded both by the customer and the regulation authorities. However, due to an increase of in-cylinder pressures, although combustion is more efficient it appears that issues previously linked to diesel direct injection (DI) engines become relevant also for gasoline vehicles. The increase of PM and PN has been foreseen by regulators and is the cause of the introduction of PN limit values for the GDIs from 2019. With the next step of Euro 6 legislation, most new GDI models are expected to be equipped with particulate filters.

Independent laboratory measurements will prove whether the expected reduction in PM emission will be realised. Two of the GDI vehicles in this study had NO_x emissions in the range of the "best" diesel vehicles during cold starts in warm temperature, and it is the first time to our knowledge that NO_x emissions above the type approval value have been measured and reported for GDIs. Even though this emission is lower than from the diesel vehicles, further measurements will be required to investigate whether these results are the beginning of a new trend of high NO_x emissions from GDIs, or if these results represent singular events. In the case of the GDI vehicles with relatively high NO_x emission, further NO_x traps or catalysts will be required. For the diesel vehicles, cold temperatures have large effects on the total emissions of NO_x and also other components, but the emission behaviour is not consistent for all vehicles and components indicating a need for more data to explain the causes. The effect of cold temperatures is, however, a significant cause of emission increases. For some vehicles there is also a clear extra contribution from the cold start.

We consider our measurements especially relevant for cold climate conditions and the common travel behaviour of several short trips by car. As emission regulations get stricter the cold start contributions may also become increasingly signficant. In the RDE regulations cold starts will be included, addressing NO_x and PN as well as CO and THC. Our findings support the need for this latest change in the regulation. The extended temperature conditions should also address some of the problems indicated by this study, but it remains to be seen if the vehicles will comply within the time frame given, and how the RDE regulation will function in practice.

Acknowledgement

This study was funded through the EMIROAD-programme (EMIssions from ROAD transport vehicles, 2013-2016) and subsequent research collaborations granted by the Norwegian Public Roads Administration. The funding, as well as fruitful discussions with the colleagues at VTT in Helsinki, Finland, who conducted the emission measurements, are thankfully acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2019.02.031.

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