On-road NO_x and smoke emissions of diesel light commercial vehicles – Combining remote sensing measurements from across Europe

Yuche Chen[‡] *, *Ruixiao Sun*[‡], *Jens Borken-Kleefeld*[†]

[‡]Department of Civil and Environmental Engineering, University of South Carolina, USA

[†]International Institute for Applied Systems Analysis, Laxenburg, Austria

* Corresponding author: Yuche Chen, chenyuc@cec.sc.edu

Key words: diesel light duty truck, in-use surveillance, in situ remote emission sensing

ABSTRACT

Light commercial vehicles account for about 10-15% of road traffic in Europe. There have only been few investigations in their on-road emissions performance. Here, on-road remote sensing vehicle emission measurements from eighteen locations across four European countries are combined for a comprehensive analysis of NO_x and smoke emission rates from diesel light commercial vehicle (LCVs) across the past two decades. This allows differentiating the performance by emission standard, model year, curb weight, engine load, manufacturer, vehicle age and temperature, as well as by measurement device. We find in general consistency between devices and countries. On-road NO_x emission rates have been much higher than type approval limit values for all manufacturers, but some perform systematically better than others. Emission rates went down only with the introduction of Euro 6a,b emission standards since the year 2015. Smoke emission rates are considered as a proxy for particulate emissions. Their emissions decrease substantially from the year 2010 onwards for all countries measured and size classes. This is consistent with the substantial tightening of the PM emission limit value that typically forced the introduction of a diesel particulate filter. The average NO_x emission rate increases with engine load and decreasing ambient temperatures, particularly for Euro 4 and 5 emission classes. This explains to a large extent the differences in absolute level between the measurement sites, together with differences

in fleet composition. These dependencies have already been observed earlier with diesel passenger cars; they are considered part of an abnormal emission control strategy. Some limited increase of the NO_x emission rate is observed for Euro 3 vehicles older than ten years. The strong increase for the youngest Euro 6 LCVs might rather reflect technology advances with successively younger models than genuine deterioration. However, the durability of emission controls for Euro 6 vehicles should better be monitored closely. Smoke emission rates continuously increase with vehicle age suggesting a deterioration of the after-treatment system with use.

INTRODUCTION

Monitoring the real-world emissions of road vehicles is important for evaluating the effectiveness of control measures and for planning potential future actions. In Europe, light commercial vehicles (LCVs) comprise approximately 10% of total annual sales of light-duty vehicle market[1]. With the growing demand for movement of goods in cities, particularly for first/last mile deliveries, it is expected that the share of LCVs will continue increasing in the future[2]. LCVs have been recognized as a significant contributor to mobile source air pollution[1,3,4,5]. One central emission control measure has been legislation on vehicle emission standards that are defined over a synthetic laboratory driving cycle. However, it has been shown extensively that real-world driving varies substantially from the official driving cycles in terms of accelerations and speeds and thus engine loads[6-9,45].

There is a noticeable lack of measurements and uncertainty about the actual emissions levels for diesel light commercial vehicles, making it difficult to evaluate the success of different emission control stages. Due to lack of data on LCVs, it is often assumed that their on-road emissions perform similar (proportional) to diesel car emissions[9]. Researchers studied on-road emissions of LCVs using portable emissions measurements system (PEMS), including CO_2 by Stewart et al.[10] and criteria pollutants by Vojtíšek-Lom et al. [11]. It was found that on-road NO_x emissions are much higher than the Euro 6a,b standard limits. PEMS can acquire detailed driving and emission data from one particular vehicle, but the measurement process is expensive and time-consuming and therefore could only test a limited number of vehicles. Another option is remote optical sensing at roadsides[13]. Remote sensing technologies have been used in various studies to assess on-road emission from passenger cars[3,14,15]. Studies that investigate LCV emissions using remote sensing only have measurements in a single year or snapshot[15], or do not contain LCVs with the most recent emission control technologies[4]. The International Council on Clean Transportation reported preliminary results for light commercial vehicles measured by remote sensing equipment in Zurich and several locations in Europe, but their analysis did not report emission trends over years and did not investigate the impacts of vehicle power, temperature, aging, etc.[16], which made it hard to evaluate the effectiveness of emission control policies over time.

In this study, we report on long-term (2011–2018) on-road vehicle emission measurements of diesel LCVs at multiple locations in Europe. This unique dataset covers a total of 86,000 valid emission measurements from diesel LCV between 2011 and 2018. One measurement refers to one record of the exhaust emissions of a certain pollutant for one vehicle when it passed the measurement site. These records represent a wide range of real-world driving and environmental conditions and a broad spectrum of Europe's diesel LCV fleet. Each single campaign has only a limited data size for LCVs, therefore we combine the different campaigns and investigate how much more differentiated the emissions can be analysed.

MATERIALS AND METHODS

Remote sensing set-up

In this study, the NO_x and black smoke emission rates are analysed for diesel LCVs from model years 2000 to 2018. The data are a combined set of in total 86,000 records of hot on-road emissions measured between 2011 and 2018 at 18 locations in Switzerland, Spain, Sweden and the United Kingdom. This dataset stems from the so-called CONOX database[17] that has been used previously in analyses of passenger car emissions[16-18,22].

A light commercial vehicle (LCV) is a vehicle used for the transport of goods or passengers with a maximum mass not exceeding 3,500 kg (category N1 according to the UN-ECE vehicle classification). LCVs are classified into three classes according to their curb weight: N1-I, II, and III for N1 vehicles with curb weight less than 1,350 kg, between 1,350 and

1,760 kg, and between 1,760 and 3,500 kg, respectively. Almost 60% of valid records refer to the biggest class III, 30% to class II and only 15% to class I. This reflects the preferences of LCV users in Europe. We focus on diesel powered LCVs here that represent more than 90% of all LCVs.

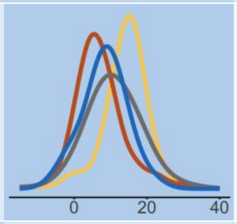
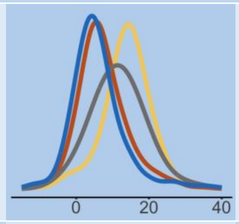
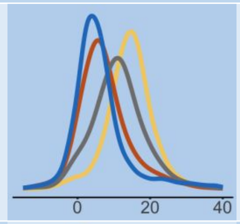
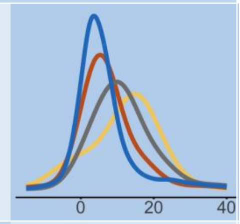
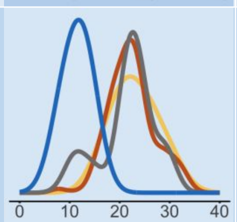
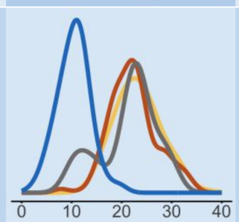
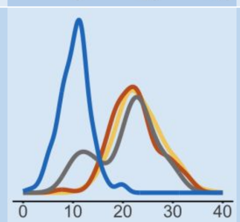
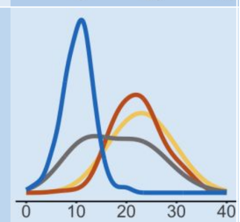
The majority of records was collected using the Opus AccuScan RSD 4600 and RSD 5000 remote sensing devices. UK data has additional entries from two measurement campaigns using the FEAT instrument from the University of Denver. This offers ample opportunity to cross-compare results within a country but with different instruments, or across countries with the same equipment. All instruments have been discussed extensively in previous studies[3,8,19-21]. In summary, each remote sensing device projects light of specific bandwidths through a vehicle's exhaust plume. Its attenuation is proportional to the concentration of certain pollutants; the increment of the concentration over the concentration measured immediately before the passage of the vehicle (the background) is attributed to the vehicle exhaust. The vehicle-related pollutant concentrations are then divided by the incremental concentration of CO_2, as a proxy for fuel consumption by the engine, to determine the instantaneous fuel specific emission rate of a passing vehicle.

The measurement devices were regularly calibrated against a gas of known concentrations. Speed and acceleration of each passing vehicles are recorded simultaneously; they provide a measure for the instantaneous engine power and are associated with the emission rate measured. Positive acceleration is important to obtain valid instantaneous emission records. Therefore, most measurement sites have some uphill grade. Vehicle license plates were recorded, and the vehicles' essential technical data (fuel type, emission classification, model year, manufacturer, and weight) were retrieved from national registration records. .

The measurement locations include one site in Spain (3.8% grade), one site in Sweden (3% grade), two sites in Switzerland (9.4% and 4.4% grade), and fourteen sites in United Kingdom with grades ranging from -1.7% to 5.2%. These sites cover a wide range of driving conditions ranging up to 28 kW power per ton vehicle mass (95th percentile). Highest average engine loads were typically recorded at Gockhauser Strasse, a site close to Zurich, Switzerland with 9% uphill road grade. The vehicles measured were new (certified to Euro 6 with model year 2018) up to 20 years old beginning with model year 2000 (certified to Euro 3 emission standard). The measurements comprise all relevant LCV manufacturers in Europe. While the UK, Sweden, Switzerland, and Spain may not be representative for Europe as a whole, their vehicles have the same emission control technologies as elsewhere in the European Union, and in fact outside as well, and vehicles have to comply to the same emission control regulations[43]. In addition, ambient temperatures during measurements ranged from close to 0°C in the UK up to 30°C and more in Spain. This large spectrum will be seen quite relevant for an understanding of emission rates across sites. Thus, this dataset provides an unprecedented opportunity to comprehensively evaluate the on-road emission behavior of diesel light commercial vehicles in Europe. Table 1 summarizes the different measurement conditions in terms of when and where were the campaigns were conducted, average vehicle age, vehicle specific power and ambient temperature distribution for diesel LCV N1-III of Euro 3 to Euro 6a,b. Information for LCVs N1-I and N1-II are presented in Supporting Information Tables S1-S2.

Table 1. Summary of remote sensing testing conditions and diesel LCV N1-III fleet characteristics in the UK, Sweden, Spain, and Switzerland.

		Euro 3 N1-III	Euro 4 N1-III	Euro 5 N1-III	Euro 6a,b N1-III
# of records	**UK**	329	2567	11248	2680
	SE	257	625	2245	182
	ES	2955	4192	4575	719
	CH	2613	6224	6842	105
Measurement year and instrument	**UK**	FEAT: 2012, 2013, 2017, 2018; RSD 4600: 2013, 2015; RSD 5000: 2017, 2018			
	SE	RSD 5000: 2016			
	ES	RSD 5000: 2017			
	CH	RSD 4600: 2011, 2012, 2013, 2014, 2015; RSD 5000: 2016, 2017			

Average age (years)	**UK** **SE** **ES** **CH**	9.4 11.8 13.5 14.4	6.5 6.6 9.3 9.5	3.1 2.7 3.0 4.5	0.9 0.5 0.6 0.9
VSP (kW/ton)	UK SE ES CH				
Ambient Temperature (C)	UK SE ES CH				

Driving conditions and data treatment

The measurement device returned incremental concentrations of pollutants (%NO, $\%NO_2$, %HC, %CO and $\%CO_2$) in the exhaust plume. These were converted into emission factors in grams per kg of fuel burned assuming complete combustion and using the formula detailed in Pokharel et al. [23] Specifically, emission factors for NO and NO_2 were $r_{NO} = \frac{30 * Q_{NO} * 86}{(1 + Q_{CO} + 6Q_{HC}) * 12}$ and $r_{NO_2} = \frac{46 * Q_{NO_2} * 86}{(1 + Q_{CO} + 6Q_{HC}) * 12}$, respectively[23], $Q_{CO} = \frac{\%CO}{\%CO_2}$, $Q_{HC} = \frac{\%HC}{\%CO_2}$, $Q_{NO} = \frac{\%NO}{\%CO_2}$. Thus, NO_x rate is calculated by summing rates of NO and NO_2 in terms of NO_2-equivalents. The RSD 4600 instrument cannot measure NO_2 but only NO emissions. We estimated total NO_x emissions in that case from the measured NO divided by the ratio of NO over NO_x derived from the other instrument (RSD 5000) for each country and emission control class. The black smoke emission factors in unit of gram smoke per kilogram fuel are also measured by Opus AccuScan RSD 4600 and RSD 5000. These devices can distinguish black from blue or white smoke normally generated by oil or coolant. [40] The calculations are based on measurement of opacity, smoke particles fraction per cross-sectional area, amount of plume CO_2, CO and HC percentages according to the manufacturer. [39]

Chen et al. [18] investigated the minimum sample size of on-road measurements for a statistically robust emission estimation. They concluded that a sample size of 200 could guarantee 80% accuracy for mean estimation of emission for Euro 3 to Euro 6 vehicles. Therefore, for all results discussed in this paper, we try to follow that guidance as much as possible.

First, the on-road emission rates are analyzed by model year for each LCV class, country and measurement device separately. This is the basis for pooling the data from the single campaigns in order to have a sufficient sample for more differentiated analyses: The influence of vehicle power (using VSP as a proxy variable), manufacturer, age and temperature on the average emissions is reviewed. All this has been found important for diesel passenger cars [8, 16, 6, 34].

RESULTS AND DISCUSSION

Development of real-driving emissions over model years

Vehicle emissions can be affected by instantaneous driving conditions and vehicle weight. To filter out these possible impacts, we evaluated the variation in vehicle specific power and curb weight across different model years in the data. Vehicle specific power (VSP) is a proxy for engine power and was calculated based on vehicle speed, acceleration and road grade[33]. Figure 2 shows that the VSP, although showing variations, was mainly approximately 9 kW/ton for diesel LCVs N1-I to N1-III. The only exception is that the average VSP for LCV N1-III drops from around 10.5 kW/ton to 8.5 kW/ton after model year 2015. This is mainly due to a significant drop of data from Switzerland (from around 25% to 3% after 2015) which contains vehicles with high VSP because of a high slope. In addition, the average curb weights per model year remained constant at about 1,200, 1,550, and 2,200 kg for classes N1-I, II, and III, respectively. Therefore, pooling of the data from different countries and campaigns appears reasonable given this consistency across time and fleets.

It is worth noting that LCVs service a wide range of transport requirements, thus, there is a greater variability in vehicle operating characteristics (e.g. urban delivery with routinely short and slow speed trips, v.s. intracity highway delivery with high speed driving) and loading situations. The impacts of these factors are not analysed in this paper but can be directions of future research.

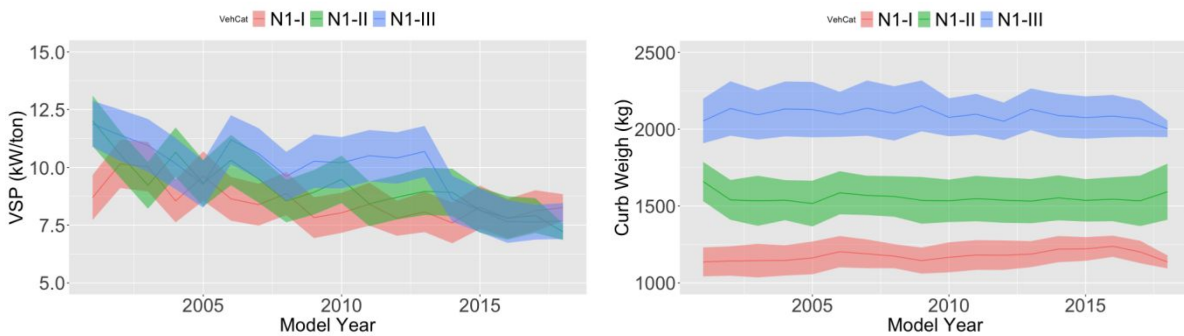


Figure 1. Mean and 95% confidence interval for Vehicle Specific Power, VSP (left) and curb weight (right) for diesel light commercial vehicles (LCVs) N1-I to III as a function of model year.

Figures 2 and 3 report mean and 95% confidence intervals for NO_x and black smoke emission rates by vehicle model year for diesel LCVs by country and instrument (values of emissions rates are reported in Supporting Information Table S4). Countries (as a proxy for fleets and site specific ambient and driving conditions) and instruments are presented separately to allow for an examination of their respective consistency before any further aggregation. For reference the average on-road emission rate is compared to emission factors from the most recent HBEFA 4.1[24], with converted legislative limit values over the type approval test cycle and with RS on-road emissions from diesel passenger cars from the respective campaigns.

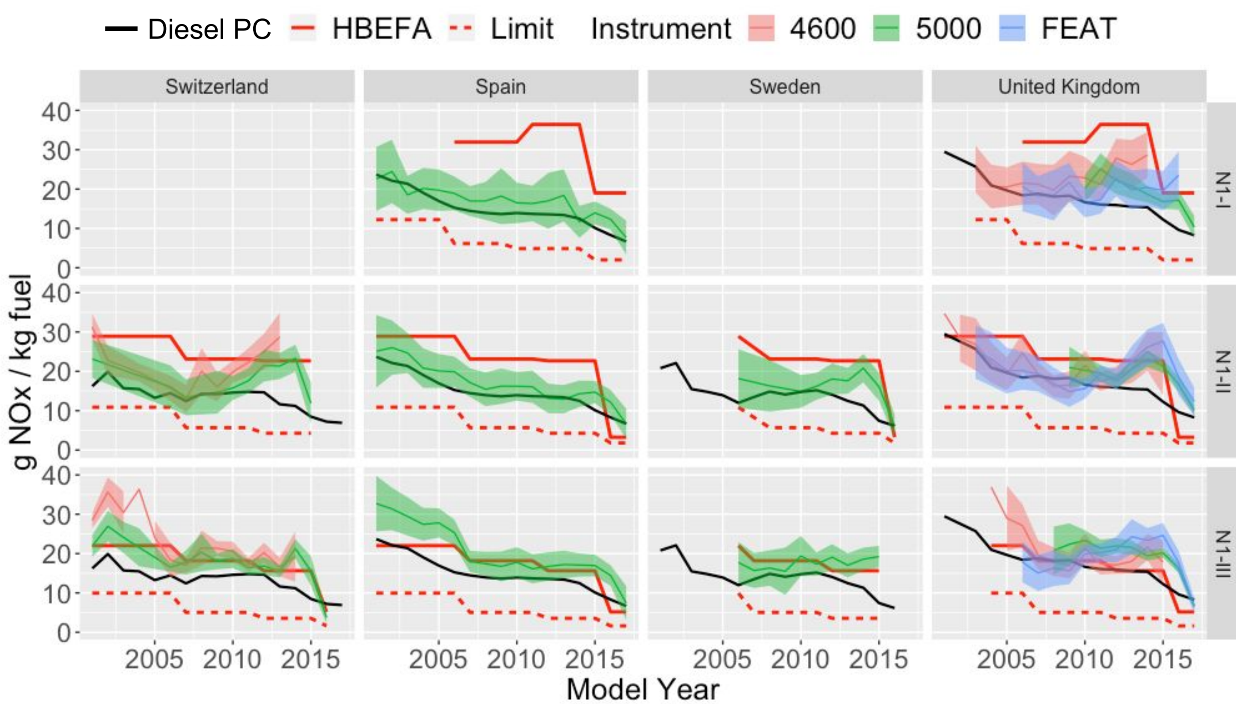


Figure 2. Mean hot NO_x emission factors (g per kg fuel) and 95% confidence interval (shaded area) for diesel light commercial vehicles (LCVs) N1-I, II, and III as a function of model year by measurement locations and instrument. Added are the emission factors used by HBEFA 4.1 and type approval limit values over the homologation test cycle in force in the respective year. The emissions rates of diesel LCVs in g per km are converted to g per kg fuel using measured fuel consumption rates in g per km from Hausberger in HBEFA 4.1[24]. NO_x emissions factors of diesel passenger cars measured by remote sensing in these countries are added for reference.

On-road NO_x emission rates have been persistently above the type approval limits for all Euro stages, LCV size classes, fleets (or countries respectively) and observed driving conditions. This pattern is already familiar from diesel passenger cars in Europe[1,3] and is one marker of the diesel emission scandal. With model year 2015, or the introduction of the Euro 6 emission standard respectively, there is a marked decrease in the average on-road emission rate for LCVs of all sizes and fleets (or countries), though the level is still above the limit value. Results from different instruments in Switzerland and the UK are consistent within their respective confidence intervals with only five exceptions: Model year 2012 and 2013 for N1-III and II in Switzerland, respectively, and model year 2006 for N1-III, and model years 2011 and 2013 for N1-I in the UK. This good consistency is a prerequisite for pooling data from different campaigns together. The smaller discrepancies cannot be explained at the moment. However, it is important to note that they do not refer to an identical situation or vehicle; these measurements were taken during different campaigns and refer to different vehicles, driving and ambient conditions.

On-road emissions are at the higher end in the UK; that will be explained in the following as a consequence of the rather low ambient temperatures during the measurements, particularly relevant for Euro 4 and 5 vehicles. High emission rates in Switzerland are associated with the very high road gradient of 9% at the main measurement site (Gockhauser Strasse).

The most recent HBEFA 4.1 updated emission factors for LCVs. They clearly reflect the stagnation of the emission rate at high levels for all LCV size classes and emission classes including Euro 5, that is observed in the on-road data. Differences in level might suggest further refinement of the modeled emission factors.

Note that there are several, progressively more stringent sub-tiers for Euro 6, termed Euro 6a/b, Euro 6d-temp, and Euro 6d. The Euro 6d-temp and 6d correspond to vehicle registered after 2018 and after 2019. It is expected that cars first registered in 2017 are certified to no more than Euro 6b emission standard.

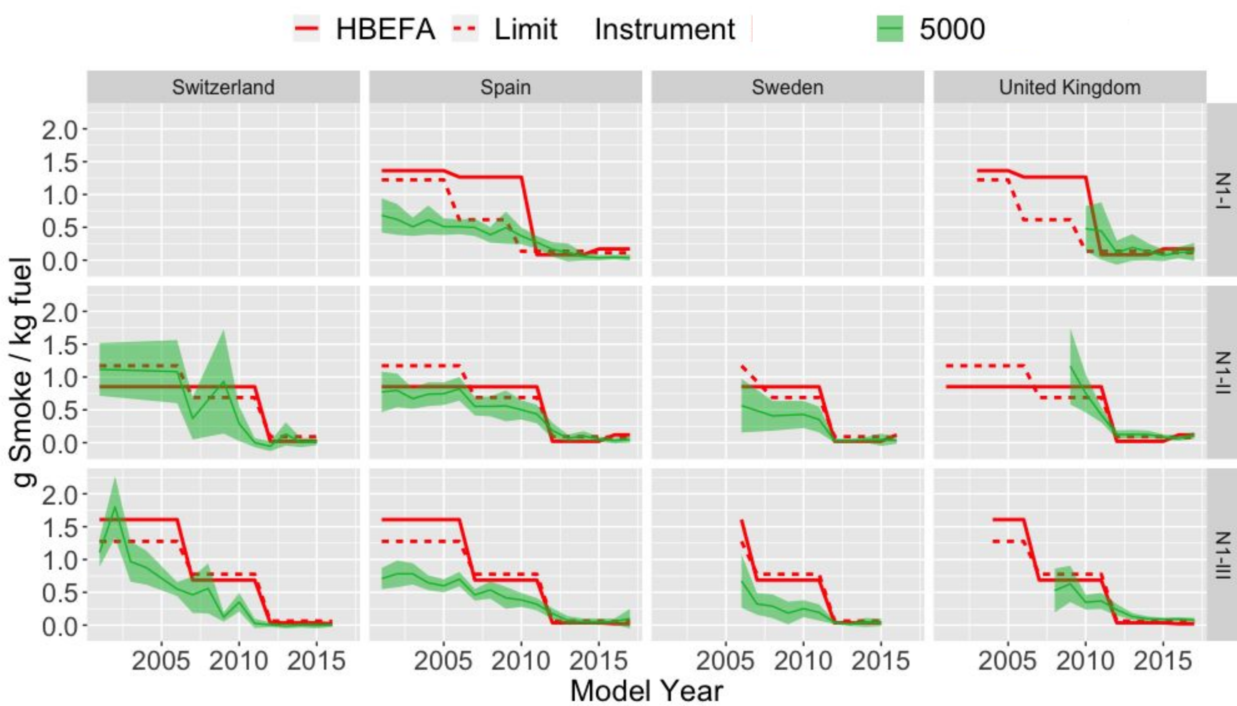


Figure 3. Mean hot black smoke (smoke) emission factors (g per kg fuel) and 95% confidence interval (shaded area) for diesel light commercial vehicles (LCVs) N1-I, II, and III as a function of model year by measurement location. Added are the PM emission factors used by HBEFA 4.1 and type approval limit values over the homologation test cycle in force for the respective year. The emissions rates of diesel LCVs in g per km were converted to g per kg fuel using measured fuel consumption rates in g per km from Hausberger in HBEFA 4.1[24].

Only the RSD 5000 equipment provide enough records to report black smoke emissions (**Figure 3**). Smoke as measured in absorption spectroscopy is a collection of airborne solid and liquid particulates and gases (CO, NO_x, SO_x, etc.) generated during combustion. Particulate matter (PM) as regulated in vehicle emission standards is all material collected on a specified filter and still not evaporated after heating up to 52°C. Clearly, particulate matter (PM) and black smoke are not the same entities, but have been shown to correspond under normal circumstances for diesel engine vehicles[41]. With this in mind results for smoke measurements are presented here as best available proxy for primary particulate exhaust emissions.

Contrary to the NO_x emissions, the changes in real-world black smoke emissions have been following changes in PM legislation limits. In particular, a steady reduction between 2005 and 2015 is observed, demonstrating efforts to control particular matter emissions with the introduction of particle filters in Euro 4 and Euro 5 vehicles. In addition, smoke emissions (particularly for N1-III) in Sweden dropped long before 2010 (the year Euro 5 was introduced). This can be explained by the fact that Sweden was offering incentives for early adoption of the diesel particle filter. Trends suggest that the automobile industry focused efforts on reducing particulate matter (PM) emissions. On-road emission rates, legislative PM limit values as well as HBEFA emission factors consistently follow the same trends suggesting after model year 2005.

Next, detailed emission rates are aggregated to averages per Euro standard and size class Figure 4 (values of emission factors are reported in Supplement Information Table S5). The plot for smoke emissions of diesel LCVs grouped by each Euro emission standard is provided in Supporting Information Figure S3. These are compared to the emissions factors used in HBEFA 4.1 and the corresponding legislative limits during type approval. The results showed that the emission levels for Euro 3 to 6 diesel LCVs N1-1 to III exceeded 3 to 7 times the corresponding legislative limits. These findings were consistent with previous studies with more limited study scopes[6,15]. The trends for NO_x emissions of diesel LCVs were also aligned with the observations of NO_x emissions from diesel passenger cars found in other studies[16] where NO_x emissions of diesel cars were stable for Euro 3 to Euro 5 (model years 2000–2014) and significantly decreased in the Euro 6a,b fleet, although they were still higher than the legislative limits. The biggest variability in emission rate between countries is for Euro 6 vehicles. We speculate that this reflects uncertainty (in the registration data) as to whether the vehicle was actually certified to the higher Euro 6b or the lower Euro 6d-temp standard. NO_x emission factors for Euro 3 to 5 used in HBEFA 4.1 agree with on-road emission rates notably for the heavy class III. However, it seems that emission rates for N1-I and II vehicles are underestimated by sometimes 30%.

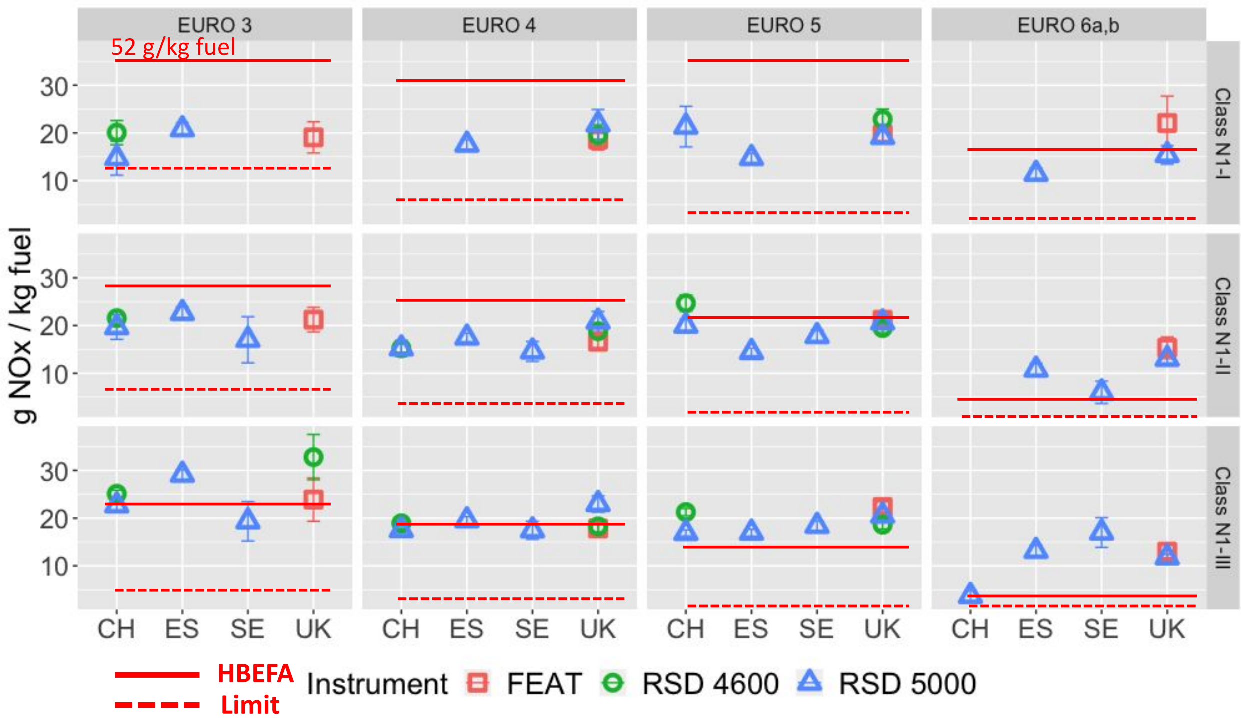


Figure 4. Mean and 95% confidence interval hot NO_x emissions factors for diesel light commercial vehicles (LCVs) as a function of Euro emission standards by measurement locations and instrument. Added are the emission factors used by HBEFA 4.1 and type approval limit values over the homologation test cycle in force in the respective year. The emissions rates of diesel LCVs in g per km were converted to g per kg fuel using measured fuel consumption rates in kg per km from Hausberger in HBEAF 4.1[24].

Influence of engine power on emissions

Figure 5 shows the NO_x emissions of diesel LCVs Euro 3 to 6 as a function of instantaneous vehicle specific power (values of emission factors are reported in Supplement Information Table S6). Supporting Information Tables S7 to S9 show the number of vehicles measured for each category, which indicated that the majority of those categories have large enough sample sizes for robust statistical analysis. Higher VSP leads to higher NO_x emissions levels for N1-II and III of Euro 3 to 5, particularly at VSPs greater than 12 kW/ton. There was no dependency of NO_x emissions on VSP for the Euro 6a,b fleet. This might be attributed to the changed test procedure reflecting better the range of engine loads observed in on-road driving, thus forcing more comprehensive emission control strategies. Similar dependency effects were found by a previous study in the United Kingdom[8] and one in Switzerland[42] on diesel passenger cars, which found higher NO_x emissions with higher VSP for Euro 4 and Euro 5 fleets and less dependence of NO_x emissions on VSP for the Euro 6a,b fleet[16].

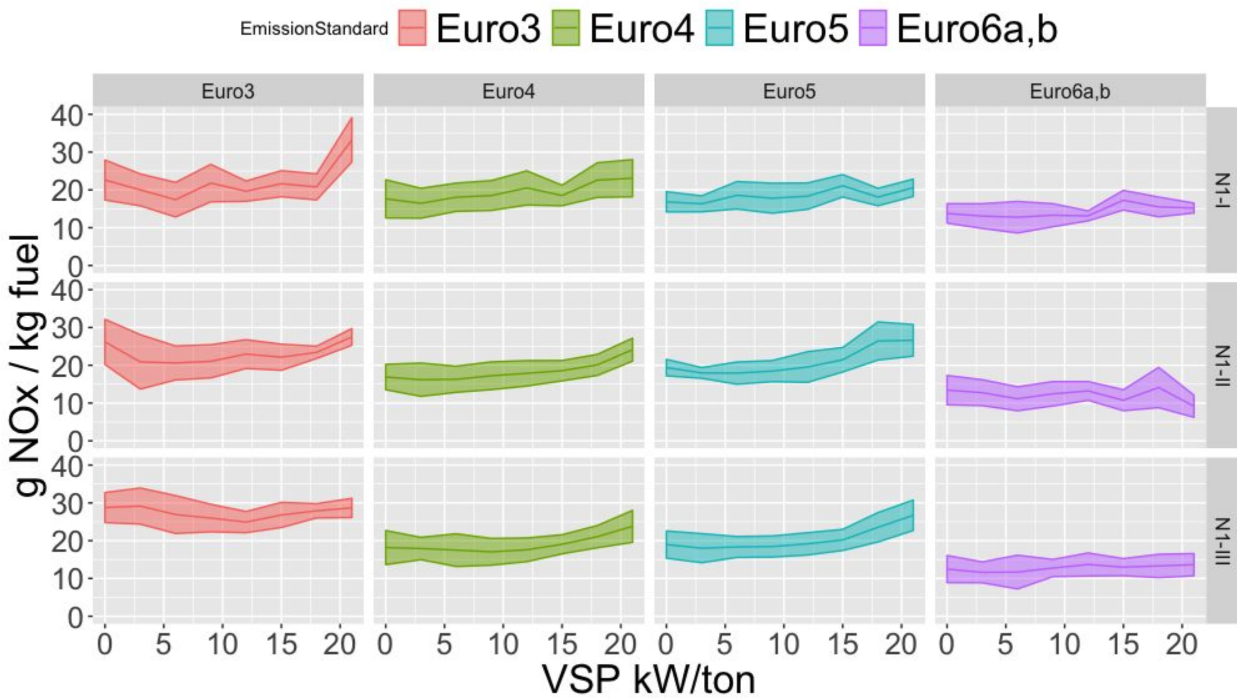


Figure 5. Mean hot NO_x emission factors (g per kg fuel) and 95% confidence interval (shaded area) for diesel light commercial vehicles (LCVs) N1-I, II, and III as a function of VSP derived from RSD across all countries and campaigns.

LCVs' smoke emission by VSP bins are shown in Supporting Information Figure S1. We found no clear dependency of smoke emissions on VSP for Euro 5 and Euro 6a,b diesel LCVs. For Euro 3 and Euro 4 diesel LCVs, there was an increasing trend in smoke emissions when the VSP increased from 6 to 12 kW/ton; smoke emission levels plateaued with higher VSP values. These smoke emissions results were promising and showed the effort by manufacturers to reduce PM emissions by introducing various technologies, such as diesel particle filters.

Influence of Manufacturer on Emissions

Figure 6 presents NO_x emissions by Euro emission standard for diesel LCVs grouped by major vehicle manufacturers (sample size information is provided in Supporting Information Tables S10 and S11 and numbers of emission factors are reported in Supplement Information Table S12). The plot for smoke emissions of diesel LCVs grouped by major vehicle manufacturers is provided in Supporting Information Figure S4. The majority of manufacturers show similar NO_x and smoke emissions across Euro 3 to 6a,b, but some perform better or worse than others. For example, Nissan-Renault reported higher NO_x emission for Euro 5 and 6a,b in N1-I category. Mercedes reported higher NO_x emission for Euro 5 and 6a,b in N1-II category. Volkswagen have lowest absolute emissions for Euro 6a,b in class N1-II. Toyota had a much lower NO_x emission for Euro 5 and 6a,b in the N1-III category. For all these cases the VSP values were comparable; this shows that manufacturers employ different in-use emission control strategies with some being more stringent (or lenient) than others. This analysis indicates that differences between countries in on-road NO_x emissions of LCVs can be partially explained by different fleet mix (in terms of manufacturers) in those countries. This is particularly true when one or several manufacturers dominate a country's LCV market and those manufacturers report higher emissions levels compared with other manufacturers.

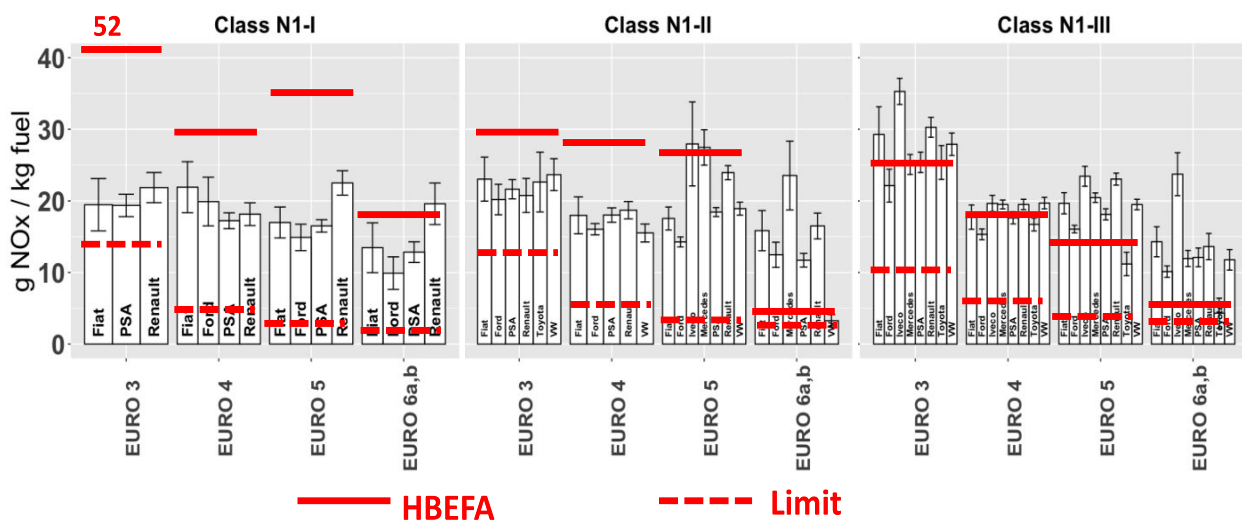


Figure 6. Mean hot NO_x emission factors (g per kg fuel) and 95% confidence interval of diesel light commercial vehicles N1-I to III as a function of vehicle manufacturer, derived from RSD.

Emission performance of diesel LCVs over time

Chen and Borken-Kleefeld[3] did not find a relevant decrease in NO_x emissions for Euro 4 diesel passenger cars. More recently, Carslaw et al. did not find a decrease for diesel Euro 5 and Euro 6a or b passenger cars[22]. We investigated whether the aging effect exists in LCVs. For each measurement, the data showed the model year, measurement year (thus the difference in vehicle age) and Euro standard for each vehicle. Figure 7 presents NO_x and smoke emission rates and 95% confidence intervals by vehicle age for each Euro emission standard group (numbers of emission factors are reported in Supplement Information Table S13). We could not determine aging effects for the majority of vehicle categories. However, Euro 3 of N1-II showed an increase in NO_x emission from 6 to 10 years old and then plateaued from 10 to 15 years. Euro 5 of N1-III showed an increasing trend between years 5 and 7, but there was not enough data to prove the trend will continue. Euro 6a,b of N1-II showed an increasing NO_x emission trend in the first two years of driving. Whether this continues and is also present in other vehicle generations should be closely monitored.

There was an increase in smoke emissions as vehicles aged in Euro 4 and Euro 5 across N1-I, II, and III. For Euro 3 vehicles, N1-I and II showed mainly consistent smoke emissions with aging, though they both experienced a big drop from age 11 to 12. N1-III smoke emissions increased as vehicle age increased from 11 to 15 years old, but there was a significant drop after that. The smoke emissions for Euro 6a,b (both 2016 and 2017 model year) were stable and low with the limited 2 years on the market. These were promising observations that suggested successful emission control. Similar observations of successful particular matter emission control have been demonstrated for diesel passenger cars and heavy-duty trucks, which could be explained by better PM emission control technologies[31]. As explained previously, we acknowledge the risk of proxying PM emission with smoke, but the results can still shed lights on PM real-world emissions trends of diesel LCVs given that this is one of the few relevant on-road emissions datasets.

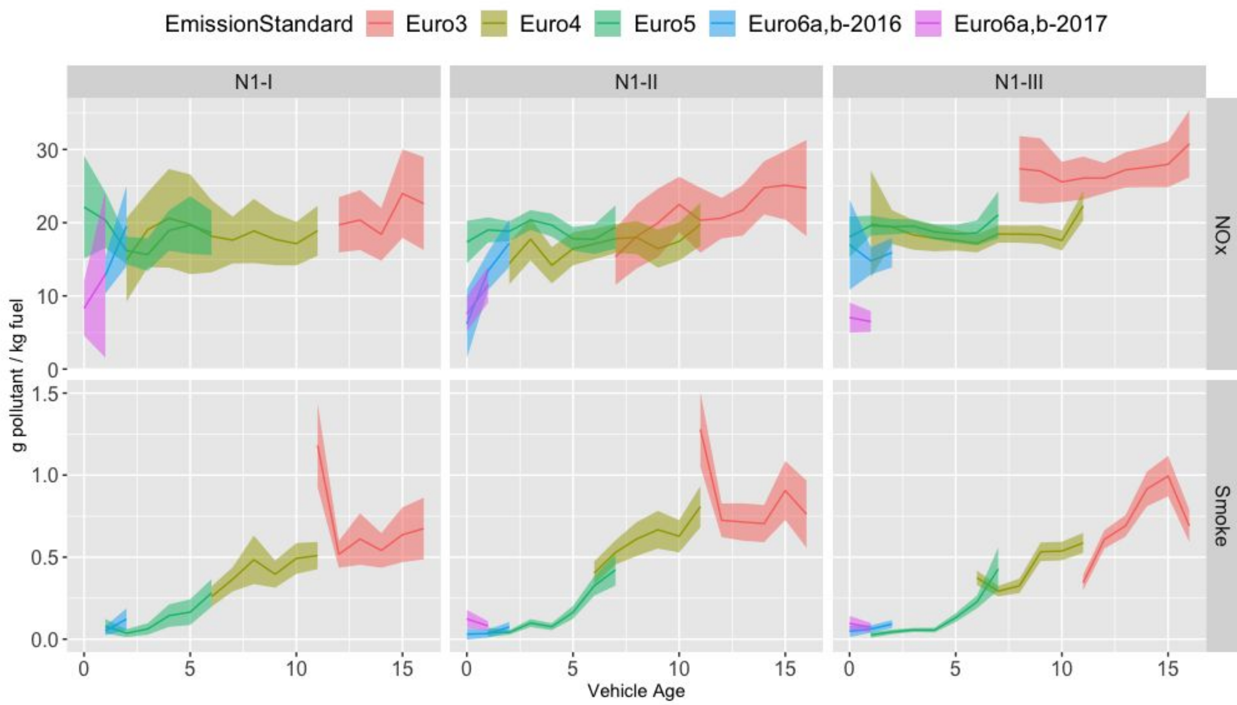


Figure 7. Mean hot NO_x and smoke emission factors (g per kg fuel) and 95% confidence interval (shaded area) for diesel light commercial vehicles (LCVs) N1-I, II, and III under Euro 3 to Euro 6a,b emission standards as a function of age, derived from RSD.

Influence of Ambient Temperature on NO_x Emissions

For diesel passenger car NO_x emissions increase with decreasing temperature[34]. Similarly lower temperatures are associated with higher NOx emissions for Euro 3 to 5 diesel LCVs (Figure 8). (sample size information is provided in Supporting Information Tables S14 and S15 and numbers of emission factors are reported in Supplement Information Table S16). Previous literature showed Euro 6 diesel cars demonstrated a weaker temperature dependence compared to Euro 3 to 5 cars. A higher stability of NO_x emissions was also observed for Euro 6a,b diesel LCVs. Grange et al.[34] attributed the weaker temperature dependence of NO_x emissions for diesel cars to advanced technologies, e.g., lean NO_x traps and selective catalytic reduction, which manufacturers needed to achieve the more stringent Euro 6 compliance. This explanation likely also applied to our findings on LCVs.

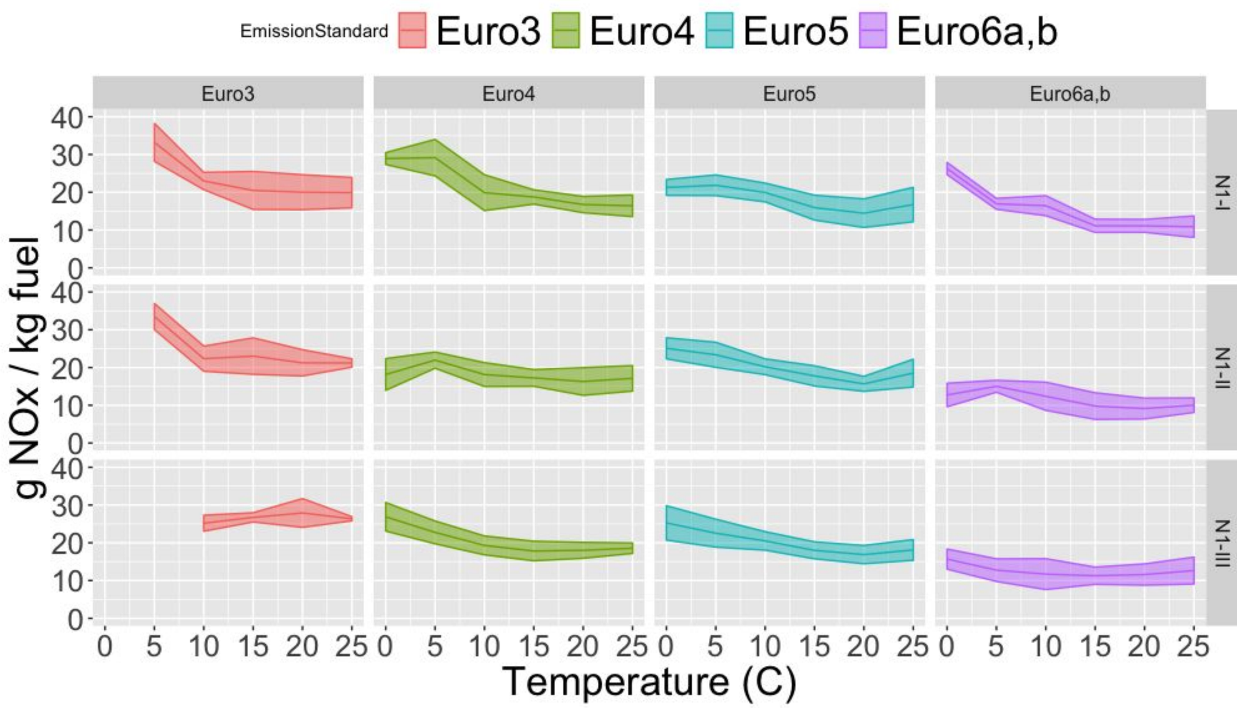


Figure 8. Mean hot NOx emission factors (g per kg fuel) and 95% confidence interval (shaded area) for diesel light commercial vehicles (LCVs) N1-I, II, and III as a function of temperature, derived from RSD.

Our results and trends of NO_x and smoke emissions for diesel LCVs are consistent with remote sensing studies of diesel cars conducted in Europe related to temperature dependence of NO_x

emission[34], aging effect on NO_x emission[22], impacts of engine load on NO_x emission[8,16,42]. The unique dataset of LCVs provides insights on on-road emission behavior of LCVs for the first time in literature. It is also worth to compare on-road emissions measured in Europe with those measured in United States (US). There are recent studies in US that used remote sensing technologies to measure on-road vehicle emissions[46-49], though most of studies are conducted in targeted locations. The trend and magnitude of NO_x emissions of gasoline light duty vehicles in US as reported in literature[46-49] are consistent with those reported in European studies[3,6]. Thus gasoline light duty vehicles in US and Europe follow changes in Euro emission standards over time, which is a clear evidence of manufacturers adopting similar emission control technologies on vehicles sold in the two continents. Diesel light-duty vehicle (car and light duty truck) accounts a very small ratio (less than 2%) in light duty vehicle fleet in US.[50] For the limited US data on diesel light-duty vehicle, for example, mean NO_x emission in Fresno, California, is about 20 g NO_x / kg fuel for diesel vans (similar to light commercial vehicle in Europe) with model year 2007[49], which is comparable to NO_x emission of diesel LCVs showed in this study. Bishop et al. [46] found a clear pattern of higher NO_x emission for high mileage gasoline Taxi operated in Los Angeles, California. We could not verify the impacts of mileage on diesel

LCVs due to the lack of data. But this will be an interesting future research direction. Overall, there exists consistency in on-road NO_x emission for light duty vehicle across US and Europe based on remote sensing measurements, though data on diesel light duty vehicles for US are limited due to its small share in US market. But the results show promising of using remote sensing technologies to investigate on-road emission behavior of vehicles in different geographic regions.

The results of this paper on diesel LCVs have implications. Although progress is observed on reducing on-road NO_x emission from diesel LCVs, their values are still significantly above legislative values across N-I to N-III types. The PM emission of diesel LCVs successfully follow changes in legislative values. This demands continuing regulation and monitoring on NO_x emission of diesel LCVs. The inclusion of real driving emission test procedure in type approval certification in Europe results in reduction in NO_x emission of Euro 6a,b of diesel LCVs. And the continuous monitoring of on-road emissions using remote sensing technologies in countries across Europe generates helpful information for emission control authorities to understand on-road vehicle emissions and enhance efficiency of vehicle emission monitoring. The consistency of NO_x and smoke emission rates between emission inventory model (i.e. HBEFA) and remote sensing measurement implies the model has successfully represent emissions of diesel LCVs. The development of emission rates in inventory model normally is based on dynamometer test or portable emissions measurements system test, which are capable of capturing vehicle emissions under real-world driving.[24] Thus, our results also suggest it is possible for emission inventory model developers to develop rates using emission tests and then adjust rates based on measurements of remote sensing campaign.

AUTHOR INFORMATION

Corresponding Author: Yuche Chen
Phone: +1-803 777 9105; Fax: +1-8037770670; E-mail: chenyuc@cec.sc.edu

Supporting Information

The supporting information is available free of charge.

Tables and figures addressing: 1) Summary of remote sensing testing conditions and light commercial vehicle fleet characteristics at measurement sites; 2) Mean hot NO_x and smoke emission factors and 95% confidence interval for diesel light commercial vehicles as a function of model year and as a function of Euro emission standards by measurement locations and instrument; 3) Mean hot NO_x emission factors and 95% confidence interval for diesel light commercial vehicles by Euro standards and vehicle specific power bins; 4) sample size by Euro Standards and vehicle specific power bins, by Euro standards and makers for diesel light commercial vehicles; 5) Mean hot NO_x emission factors and 95% confidence interval for diesel light commercial vehicles by Euro standards and manufacturers; 6) Mean hot NOx and Smoke emission factors (g per kg fuel) for diesel light commercial vehicles by Euro standards as a function of age; 7) Sample size by Euro Standards and Temperature bins for diesel light commercial vehicles; 8) Mean and 95% confidence interval (CI) hot NOx emission factors (g per kg fuel) for diesel light commercial vehicles by temperature; 9) Figure for smoke emissions and for diesel light-commercial vehicles by VSP bins; 10) Figure for mean hot NO emission factors (g per kg fuel) and 95% confidence interval for diesel light commercial vehicles by model year, measurement locations and instrument; 11) Figure for mean and 95% confidence interval hot NOx and smoke emissions factors for diesel light commercial vehicles by Euro emission standards, measurement locations and instrument; 12) Figure for mean hot NOx and Smoke emission factors (g per kg fuel) and 95% confidence interval of diesel light commercial vehicles by vehicle manufacturer.

ACKNOWLEDGEMENTS

The authors are indebted to the contributors of the CONOX db[17], which comprises remote sensing data from campaigns across Europe, as contributed notably by AWEL Zurich (G-M Alt), ICCT Europe (P.Mock), ITS Leeds (J. Tate), IVL Sweden (A.Sjodin), RSELab Spain (J. de la Fuente) and University of York (D. Carslaw). We gratefully acknowledge discussions with Zhuoqian Yang (ITS Leeds) and Javier Buhigas (OPUS RSE). The authors would like to thank anonymous reviewers' comments which helped to improve the paper.

REFERENCES

(1) Zacharof, N., Tietge, U., Franco, V. and Mock, P., 2016. Type approval and real-world CO_2 and NOx emissions from EU light commercial vehicles. Energy Policy, 97, pp.540-548.

(2) Joerss, M., Schröder, J., Neuhaus, F., Klink, C. and Mann, F., 2016. Parcel delivery: The future of last mile. McKinsey & Company.

(3) Chen, Y. and Borken-Kleefeld, J., 2014. Real-driving emissions from cars and light commercial vehicles–Results from 13 years remote sensing at Zurich/CH. Atmospheric Environment, 88, pp.157-164.

(4) Bishop, G.A. and Stedman, D.H., 2014. The recession of 2008 and its impact on light-duty vehicle emissions in three western United States cities. Environmental science & technology, 48(24), pp.14822-14827.

(5) Anenberg, S.C., Miller, J., Minjares, R., Du, L., Henze, D.K., Lacey, F., Malley, C.S., Emberson, L., Franco, V., Klimont, Z. and Heyes, C., 2017. Impacts and mitigation of excess diesel-related NO x emissions in 11 major vehicle markets. Nature, 545(7655), p.467.

(6) Chen, Y. and Borken-Kleefeld, J., 2016. NO x emissions from diesel passenger cars worsen with age. Environmental science & technology, 50(7), pp.3327-3332.

(7) Carslaw, D.C., Beevers, S.D., Tate, J.E., Westmoreland, E.J. and Williams, M.L., 2011. Recent evidence concerning higher NOx emissions from passenger cars and light duty vehicles. Atmospheric Environment, 45(39), pp.7053-7063.

(8) Carslaw, D.C., Williams, M.L., Tate, J.E. and Beevers, S.D., 2013. The importance of high vehicle power for passenger car emissions. Atmospheric environment, 68, pp.8-16.

(9) Weiss, M., Bonnel, P., Hummel, R., Provenza, A. and Manfredi, U., 2011. On-road emissions of light-duty vehicles in Europe. Environmental science & technology, 45(19), pp.8575-8581.

(10) Stewart, A., Hope-Morley, A., Mock, P. and Tietge, U., 2015. Quantifying the impact of real-world driving on total CO_2 emissions from UK cars and vans. The International Council on Clean Transportation.

(11) Vojtíšek-Lom, M., Beranek, V., Klír, V., Jindra, P., Pechout, M. and Voříšek, T., 2018. On-road and laboratory emissions of NO, NO2, NH3, N2O and CH4 from late-model EU light utility vehicles: Comparison of diesel and CNG. Science of The Total Environment, 616, pp.774-784.

(12) Shen, X., Yao, Z., Zhang, Q., Wagner, D.V., Huo, H., Zhang, Y., Zheng, B. and He, K., 2015. Development of database of real-world diesel vehicle emission factors for China. Journal of Environmental Sciences, 31, pp.209-220.

(13) Zhang, Y., Stedman, D.H., Bishop, G.A., Guenther, P.L., Beaton, S.P. and Peterson, J.E., 1993. On-road hydrocarbon remote sensing in the Denver area. Environmental science & technology, 27(9), pp.1885-1891.

(14) Carslaw, D.C. and Rhys-Tyler, G., 2013. New insights from comprehensive on-road measurements of NO_x, NO_2 and NH3 from vehicle emission remote sensing in London, UK. Atmospheric Environment, 81, pp.339-347.

(15) Ropkins, K., DeFries, T.H., Pope, F., Green, D.C., Kemper, J., Kishan, S., Fuller, G.W., Li, H., Sidebottom, J., Crilley, L.R. and Kramer, L., 2017. Evaluation of EDAR vehicle emissions remote sensing technology. Science of the Total Environment, 609, pp.1464-1474.

(16) Tietge, U., Bernard, Y., German, J. and Muncrief, R., 2019. A Comparison of Light-duty Vehicle NO_x Emissions Measured by Remote Sensing in Zurich and Europe. Available at https://theicct.org/sites/default/files/publications/ICCT_LDV_NOx_emissions_Zurich_20190628_1.pdf

(17) Sjödin, Å, Borken-Kleefeld, J., Carslaw, D., Tate, J., G.-M. Alt, J. Dela Fuente, Y., Bernard, P McClintock, R Gentala, N Vescio, and S Hausberger. "Real-Driving Emissions from Diesel Passenger Cars Measured by Remote Sensing and as Compared with PEMS and Chassis Dynamometer Measurements - CONOX Task 2 Report." C 294. Gothenburg, Sweden: IVL Swedish Environmental Research Institute, 2018.

(18) Chen, Y., Zhang, Y. and Borken-Kleefeld, J., 2019. When is enough? Minimum sample sizes for on-road measurements of car emissions. Environmental Science & Technology, 53(22), pp.13284-13292.

(19) Borken-Kleefeld, J. and Chen, Y., 2015. New emission deterioration rates for gasoline cars–Results from long-term measurements. Atmospheric Environment, 101, pp.58-64.

(20) Bishop, G.A., Stedman, D.H. and Ashbaugh, L., 1996. Motor vehicle emissions variability. Journal of the Air & Waste Management Association, 46(7), pp.667-675.

(21) Rushton, C.E., Tate, J.E., Shepherd, S.P. and Carslaw, D.C., 2018. Interinstrument comparison of remote-sensing devices and a new method for calculating on-road nitrogen oxides emissions and validation of vehicle-specific power. Journal of the Air & Waste Management Association, 68(2), pp.111-122.

(22) Carslaw, D.; Farren, N.; Borken-Kleefeld, J.; Sjödin, å., 2019. Study on 602 the Durability of European Passenger Car Emission Control Systems 603 Utilizing Remote Sensing Data; C509 387. IVL Swedish Environmental 604 Research Institute: Gothenburg, Sweden.

(23) Pokharel, S.S., Bishop, G.A. and Stedman, D.H., 2002. An on-road motor vehicle emissions inventory for Denver: an efficient alternative to modeling. Atmospheric Environment, 36(33), pp.5177-5184.

(24) HBEFA 4.1, 2019. HBEFA - Handbook Emission Factors for Road Transport. Available at: http://www.hbefa.net/d/index.html [Accessed Oct 20, 2019].

(25) André, M., 2004. The ARTEMIS European driving cycles for measuring car pollutant emissions. Science of the total Environment, 334, pp.73-84.

(26) Ntziachristos, L. and Samaras, Z., 2001. An empirical method for predicting exhaust emissions of regulated pollutants from future vehicle technologies. Atmospheric Environment, 35(11), pp.1985-1999.

(27) HBEFA 3.1, 2010. HBEFA - Handbook Emission Factors for Road Transport. Available at: http://www.hbefa.net/d/index.html [Accessed March 20, 2012].

(28) Joumard, R., André, J.M., Rapone, M., Zallinger, M., Kljun, N., André, M., Samaras, Z., Roujol, S., Laurikko, J., Weilenmann, M. and Markewitz, K., 2007. Emission factor modelling and database for light vehicles. Artemis deliverable, 3, p.237.

(29) Ntziachristos, L., Samaras, Z., Eggleston, S., Gorissen, N., Hassel, D. and Hickman, A.J., 2000. Copert iii. Computer Programme to calculate emissions from road transport, methodology and emission factors (version 2.1), European Energy Agency (EEA), Copenhagen.

(30) Hausberger, S., 2010. Fuel consumption and emissions of modern passenger cars. IVK, TU Graz, Graz, Austria.

(31) Williams, M. and Minjares, R., 2016. A technical summary of Euro 6/VI vehicle emission standards. International Council for Clean Transportation (ICCT), Washington, DC, accessed July, 10, p.2017.

(32) Campestrini, M. and Mock, P., 2018. European vehicle market statistics. ICCT, Washington.

(33) Jimenez-Palacios, J.L., 1998. Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing. Massachusetts Institute of Technology.

(34) Grange, S.K., Farren, N.J., Vaughan, A.R., Rose, R.A. and Carslaw, D.C., 2019. Strong Temperature Dependence for Light-Duty Diesel Vehicle NO x Emissions. Environmental science & technology, 53(11), pp.6587-6596.

(35) Yang, L., Franco, V., Campestrini, A., German, J. and Mock, P., 2015. NOx control technologies for Euro 6 diesel passenger cars. Int. Council Clean Transportation, white paper, pp.1-22.

(36) Carslaw, D.C., Farren, N.J., Vaughan, A.R., Drysdale, W.S., Young, S. and Lee, J.D., 2019. The diminishing importance of nitrogen dioxide emissions from road vehicle exhaust. Atmospheric Environment: X, 1, p.100002.

(37) ADAC, 2019. ADAC releases test results of retrofit SCR systems for EU cars and LCVs

https://dieselnet.com/news/2019/03adac.php. Accessed on Feb 25, 2020.

(38) Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P. and Sandler, R., 2011. Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. Environmental Modelling & Software, 26(12), pp.1489-1501.

(39) Stedman, D., ESP-RSD Engineering Department, 2004. Memorandum on remote sensing smoke. Available at https://www.esp-global.com/downloads/RSDSmokeMeasurement.pdf

(40) Borken-Kleefeld, J., 2013. Guidance note about on-road vehicle emissions remote sensing. The international council for clean transportation. Available at https://theicct.org/sites/default/files/publications/RSD_Guidance_BorKlee.pdf

(41) Black, J., Eastwood, P.G., Tufail, K., Winstanley, T., Hardalupas, Y. and Taylor, A.M.K.P., 2007. Inter-correlations between smoke opacity, Legal Particulate Sampling (LPS) and TEOM, during transient operation of a diesel engine. SAE Transactions, pp.726-737.

(42) J. Sintermann, G.-M. Alt, M. Goetsch, F. Baum, V. Delb, "Langjährige Abgasmessungen Im Realen Fahrbetrieb Mittels Remote Sensing" (Zurich, Switzerland: Kanton Zurich, Amt für Abfall, Wasser, Energie und Luft, April 23, 2018), https://awel.zh.ch/content/dam/baudirektion/awel/luft_asbest_elektrosmog/verkehr/rsd/dokumente/RSD_Bericht_2017.pdf.

(43) Luftreinhalte-Verordnung (LRV) vom 16. Dezember 1985 (Stand am 1. April 2020).

https://www.admin.ch/opc/de/classified-compilation/19850321/index.html

(44) Carslaw, D.C., 2005. Evidence of an increasing NO2/NOx emissions ratio from road traffic emissions. Atmospheric Environment, 39(26), pp.4793-4802.

(45) Sun, K., Tao, L., Miller, D.J., Khan, M.A. and Zondlo, M.A., 2014. On-road ammonia emissions characterized by mobile, open-path measurements. Environmental science & technology, 48(7), pp.3943-3950.

(46) Bishop, G.A., Stedman, D.H., Burgard, D.A. and Atkinson, O., 2016. High-mileage light-duty fleet vehicle emissions: Their potentially overlooked importance. Environmental Science & Technology, 50(10), pp.5405-5411.

(47) Bishop, G.A. and Stedman, D.H., 2015. Reactive nitrogen species emission trends in three light-/medium-duty United States fleets. Environmental science & technology, 49(18), pp.11234-11240.

(48) Bishop, G.A. and Stedman, D.H., 2014. The recession of 2008 and its impact on light-duty vehicle emissions in three western United States cities. Environmental science & technology, 48(24), pp.14822-14827.

(49) Bishop, G.A., Peddle, A.M., Stedman, D.H. and Zhan, T., 2010. On-road emission measurements of reactive nitrogen compounds from three California cities. Environmental Science & Technology, 44(9), pp.3616-3620.

(50) Chambers, M. and Schmitt, R.R., 2015. Diesel-powered Passenger Cars and Light Trucks.